Association of State Dam Safety Officials/
Federal Emergency Management Agency

In Association with the
US Society on Dams
Working Group on Dam Safety Risk Assessment
Committee on Dam Safety

Specialty Workshop on

Risk Assessment for Dams

June 2001

Hosted and Organized by

Institute for Dam Safety Risk Management
Utah State University

Summary of Workshop Findings[1]

Failure Modes Identification (FMI) Approaches

1) Failure Modes Identification, which is an early step in performing a risk assessment, should also be standard practice for traditional standards-based approaches to dam safety evaluation and design.

2) Failure Modes Identification provides a more comprehensive safety evaluation of a dam and a basis for strengthening many aspects of a dam safety program (e.g. instrumented and visual monitoring, emergency preparedness planning, O&M, etc.).

3) Guidance is urgently needed for performing Failure Modes Identification.

4) Users must recognize that Failure Modes Identification is a qualitative approach and not a decision tool.

Portfolio Risk Assessment (PRA) Approaches:

1) PRA is a valuable and increasingly accepted approach for cost effectively prioritizing dam safety remedial measures and further investigations for a group of dams.

2) It provides insights that can better inform owners about the business and liability implications of dam ownership.

3) PRA outcomes must be used with regard for the limitations of the approach and should be periodically updated.

Index Prioritization Approaches:

1) Index approaches are a valuable and increasingly utilized approach for prioritizing dam safety issues and investigations, but should be calibrated and must incorporate a risk metric to be considered risk-based.

2) They are generally less costly to use than PRA, but are more limited in the scope of their outcomes.

Detailed Quantitative Risk Assessment (QRA) Approaches

1) Detailed QRA approaches are valuable for providing insights and understanding of failure modes and associated risks (probability and consequences) for stakeholders.

2) Uncertainties in inputs and outcomes must be taken into account.

3) Improved approaches to estimation of probabilities and consequences are needed.

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[1] Developed in Consolidation Session of Workshop and revised by USSD Working Group, July 10, 2000.

4) Acceptable/tolerable risk criteria need development and are yet to gain widespread acceptance.

5) Stakeholders must decide on issues of appropriate use and defensibility.

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1.0 Background and Purpose of Workshop

1.1 Sponsorship

The ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams was held March 7 – 9, 2000 at Utah State University (USU), Logan, Utah. The workshop was one of a series of Dam Safety Research Workshops, which are funded by the FEMA National Dam Safety Program Act (NDSPA, P.L. 104-303). ASDSO was the contractor to FEMA. Through the Institute for Dam Safety Risk Management, USU subcontracted to the ASDSO to host and organize the workshop. The ASDSO established a Steering Committee chaired by Doug Johnson, Supervisor, Dam Safety, State of Washington and an ASDSO Board Member.

The workshop was linked to the Working Group on Risk Assessment of the USSD (formerly USCOLD) Committee on Dam Safety. This linkage was through the participation of Working Group members in the workshop, and through the use of the workshop to develop the basis for a USSD White Paper on Dam Safety Risk Assessment.

1.2 Purpose

The purpose of the workshop was as follows:

> To conduct a review of the **state-of-the-practice** of dam safety risk assessment, to identify **research needs**, and to recommend an approach for addressing these needs.

For the purposes of the workshop, we interpreted "**state-of the-practice**" to include only approaches that are currently being used (i.e. in practice) by dam owners and their engineers to provide inputs for dam safety decisions. We did not limit the types of decisions to only the selection of a target level of safety for an existing dam or a proposed remedial measure. Instead, we included any type of decision that affects any aspect of dam safety, including monitoring and instrumentation, reservoir operating level, investigations, and emergency preparedness planning.

By "**research needs**" we understood the interest of the National Dam Safety Program to encompass both short-term (i.e. immediate) and long-term research and development needs, including technology transfer needs. These may include such areas as the following: a vision for the future of applications of risk assessment to dam safety, training in its application, and tools to facilitate its application by practitioners. Identified research needs were to be passed on to the ICODS Research Subcommittee for their consideration in recommending the use of FEMA National Dam Safety Program Act funds for research projects.

A group of experienced dam safety professionals was invited to participate in the workshop. The group was drawn from a broad cross-section of employment affiliations, and a mixture of those with and without risk assessment experience. The workshop was not intended to be a gathering of only those with expertise in dam safety risk assessment. Nor was it intended to be an opportunity to cross-fertilize risk assessment practice from other fields into the dam safety field, as some have suggested. While these are worthwhile objectives, it was not possible to combine them with the objectives established by FEMA. Future workshops should be considered to pursue these purposes.

At the outset of the workshop, we recognized that different information needs can exist for different stakeholders in any given dam safety decision. Thus, information that may play an essential role in an owner's decision-making process may not be needed at all by a regulator who oversees the owner's decision outcomes. Since the information needs of different organizations can vary widely, we recognized that it would be unrealistic to expect that any single approach to risk assessment would meet the needs of all organizations. Therefore, an introductory workshop session was devoted to identifying, "Information needs for dam safety evaluation and management" for the following six types of organizations: the government owner, the large private owner, the small private owner, the federal regulator, the state regulator, and the consulting engineer. The outcomes of this session were used to form a broad basis for evaluating the strengths and limitations of a range of risk assessment approaches and for identifying research needs. Thus, the workshop did not recommend one particular method of risk assessment for all dam safety organizations.

In addition to this report to FEMA, major products from the workshop have included a ring binder containing copies of all presentations and other handouts provided to participants (listed in Appendix C), a bibliography, and the USSD White Paper on Dam Safety Risk Assessment. A draft of the Summary of Findings was distributed at the USCOLD Annual Lecture in Seattle in June 2000 and was presented at the ICOLD 2000 Congress in Beijing. A summary document containing the Summary of Findings and the priorities for technology transfer and research and development was provided to the ICODS Research Subcommittee for its July 2000 meeting. A panel presentation of workshop findings was included at the USCOLD 2000 Annual Lecture and the ASDSO 2001 Annual Conference.

1.3 Use of the Term "Risk Assessment"

The term "Risk Assessment" appears in the title of this workshop. It is a term that does not have a universally accepted meaning and is frequently misused. Below we define this term and several others that are needed to appreciate the format of the workshop. Most of these definitions are taken from a draft of the ICOLD Bulletin on risk assessment (Version 10, August 2000). Their use does not imply any endorsement of the draft bulletin by the workshop participants, organizers, or sponsors. Their interrelationship is illustrated in Figure 1.1.

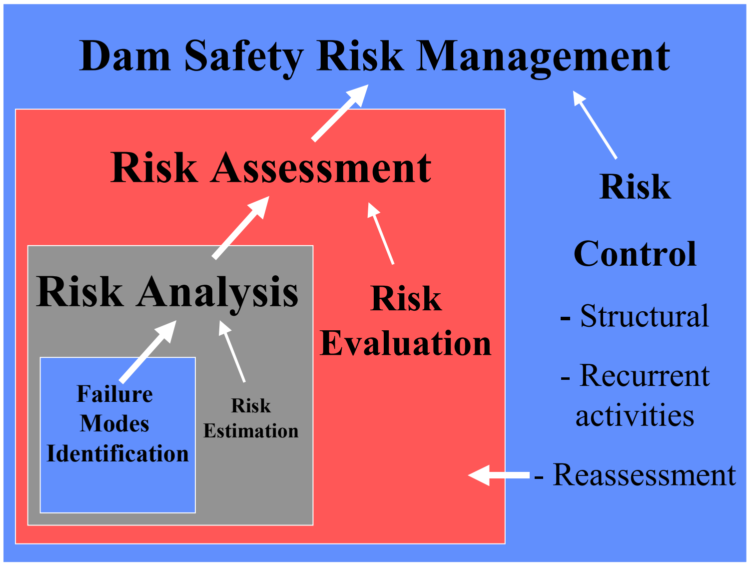

Figure 1.1. Interrelationship between components of risk assessment and risk management (Bowles et al 1999)

Failure Modes Identification:	A procedure by which potential failure modes in a technical system are identified.
Risk:	A measure of the likelihood and severity of adverse consequences (National Research Council 1983). Risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (i.e. the product of the probability of occurrence and the consequence) or, alternatively, by the triplet of scenario, probability of occurrence and the consequence. (ICOLD 2000)
Risk Analysis:	The use of available information to estimate the risk to individuals or populations, property or the environment, from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification, and risk estimation (ICOLD 2000).
Risk Assessment:	The process of deciding whether existing risks are tolerable and present risk control measures are adequate and if not, whether alternative risk control measures are justified. Risk assessment incorporates the risk analysis and risk evaluation phases (ICOLD 2000).
Risk Control:	The implementation and enforcement of actions to control risk, and the periodic re-evaluation of the effectiveness of these actions (ICOLD 2000).
Risk Estimation:	The process of quantifying the probability and consequences components of risk.
Risk Evaluation:	The process of examining and judging the significance of risk (ICOLD 2000).
Risk Identification:	The process of determining what can go wrong, why and how (ICOLD 2000).
Risk Management:	The systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, treating and monitoring risk (ICOLD 2000).

When we use the term "risk assessment" in this report it refers to a process that includes at least one of the components that make up the overall process of risk assessment (see Figure 1.1). For example, in the next section we mention that approximately one half the workshop participants were known to have some experience with applying risk assessment to dams. That does not mean that each experienced participant has used all component processes that comprise risk assessment in Figure 1.1. Some may only have experience with one component process, such as failure modes identification.

1.4 Workshop Format

Workshop participants came mainly from the US dam engineering community, but included two representatives from Australia and four from Canada. The 32 participants included four state regulators, two federal regulators, five large private owners, one local government owner, four federal government owners, three industry associations, and eight consulting engineers, and five academics with significant consulting experience. Just over one half of the participants were known to have some level of experience with applying risk assessment to dam safety problems.

The workshop organizing group comprised the following: David Achterberg (USBR and ICODS Research Subcommittee), Doug Johnson (State of Washington and ASDSO), Dan Mahoney (FERC and ASCE Task Committee on Risk Assessment of Dams and Hydroelectric Facilities), Lori Spragens (ASDSO), and David Bowles, Chair (Utah State University/RAC Engineers & Economists).

In preparing the workshop agenda, the organizing group recognized that although the primary purpose of the workshop was not training, it would be necessary to provide some presentations of the current state-of-the-practice, especially for the benefit of those with limited or no risk assessment experience. This review also provided an important basis for identifying those areas in which research and development is needed to strengthen the current state-of-the-practice. The workshop agenda is presented in Appendix A. It included presentations and facilitated consensus building sessions for the following three areas of risk assessment applications:

- Failure Modes Identification (referred to as "Qualitative Approaches" in the agenda)
- Portfolio Risk Assessment and Index Prioritization Approaches (referred to as "Prioritization and Portfolio Approaches" in the agenda)
- Detailed Quantitative Approaches (referred to as "Quantitative Approaches" in the agenda)

The organizing group divided applications into these three areas based on the observation that the degree of acceptance of risk assessment approaches seemed to be markedly different in each area. In the consolidation session, at the end of the workshop, it was agreed to further divide Portfolio Risk Assessment and Index Prioritization into two approaches because it was recognized that although they shared some common attributes they had significantly different scopes and some differing strengths and limitations. Thus, this report presents the assessment of the state-of-the-practice and research needs for four risk assessment applications areas.

Dr. David Harris of the USBR served as the Workshop Facilitator. Overall outcomes of the workshop were consolidated into prioritized technology transfer and training needs and research and development needs to be provided to FEMA and the ICODS Research Subcommittee. An additional consolidation session was held to discuss the use of workshop outcomes in the USSD White Paper.

Most participants were provided electronic or hard copies of the following documents:

- Guidelines for Dam Safety Risk Management, Dam Safety Interest Group of the Canadian Electricity Association, Interim issue of Part 1 of a four part document.
- A Guide to Risk Management for UK Reservoirs, Construction Industry Research Information Association (CIRIA), Draft 3, October 1999.
- Dam Safety Risk Analysis Methodology, Technical Services Center, USBR, Version 3.3, September 1999.
- Reducing Risks, Protecting People, UK Health and Safety Executive, 1999 Draft Version.
- Risk Assessment as an Aid to Dam Safety Management, Draft ICOLD Bulletin, 1999.

In addition, a bibliography was developed by USU and distributed at the workshop.

1.5 Report Purpose and Outline

The purpose of this report is to document the purpose, methodology and outcomes of the Specialty Workshop. This report is not intended to include any commentary on the findings reached. The USSD White Paper will be the forum for such commentary.

This report is divided into seven chapters and eleven appendices.

Section 2.0 contains a summary of the methodology that was used to achieve the workshop outcomes specified in the workshop purpose. Section 3.0 summarizes the information needs that were identified by speakers and participants.

Workshop outcomes are summarized in Sections 4.0 – 6.0. The assessment of the strengths and weaknesses of the four major areas of current practice is presented in Section 4.0. Prioritized technology transfer and training needs are presented in Section 5.0. Prioritized research needs are presented in Section 6.0. Section 7.0 proposes an integrated approach comprising twelve overall research projects that address both the technology transfer and training and the research and development needs.

Appendices A, B and C contain the workshop agenda, list of participants, and list of handouts, respectively. Appendix D contains participant input on expectations and issues for the workshop. Appendix E contains participant input on information needs for dam safety evaluation and management. Appendices F, G and H contain participant input on failure modes identification (qualitative approaches), portfolio and index approaches (prioritization and portfolio approaches), and quantitative approaches, respectively. Appendix I contains sorted participant input on strengths and limitations for each risk assessment application area. Appendix J contains participant voting on technology transfer and training needs and Appendix K contains participant input on research and development needs categories.

2.0 Outline of Workshop Methodology

2.1 Introduction

The stated workshop purpose (see Section 1.1) can be divided into three parts, as follows:

1) To conduct a review of the state-of-the-practice of dam safety risk assessment
2) To identify research needs
3) To recommend an approach for addressing these needs

Workshop products in each of these areas were developed through a coordinated set of workshop activities, which are summarized in Section 2.2. These activities included presentations, discussions, obtaining participant inputs, consensus categorization of inputs into Research and Development (R&D) needs and Technology Transfer & Training (T^3) needs, voting on the importance and difficulty of each category, and development of research proposals.

Underlying the workshop activities was a strategic planning process, which is summarized in Section 2.3. The interrelationship between workshop activities and the strategic planning process is represented schematically in Figure 2.1.

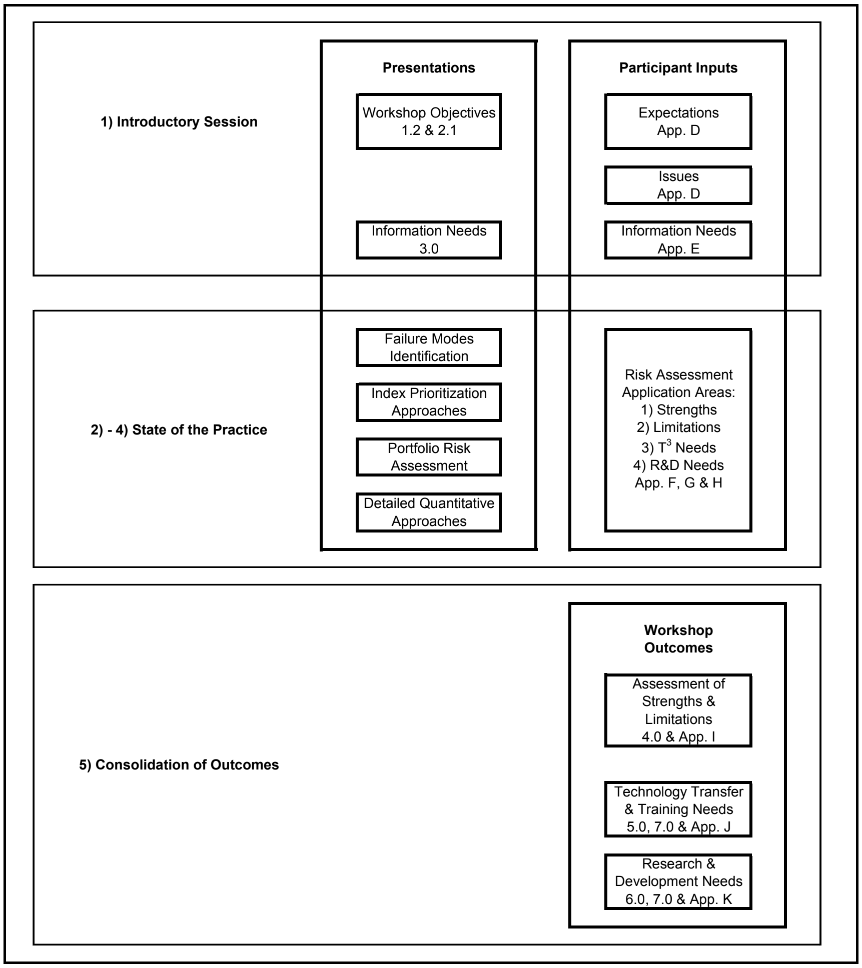

Figure 2.1. Overall interrelationship between workshop activities and strategic planning process.

2.2 Workshop Activities

2.2.1 Introductory session

At the outset of the workshop, statements on the Workshop Objectives were made by Doug Johnson, representing the ASDSO, Gus Tjoumas, for USCOLD, and David Bowles for the Organizing Group. Participants were then asked to state both their expectations for the workshop and issues that they would like to see addressed during the workshop. Input was collected from participants on index cards, read aloud by the facilitator, Dr David Harris, and displayed on a board at the front of the room.

Participant input on expectations and issues is listed in Appendix D. No attempt was made to collate this input. However, items from both lists were incorporated into research needs categories at the end of the workshop.

2.2.2 Review of the state-of-the-practice of dam safety risk assessment

Presentations on the state-of-the-practice were made in the following three applications areas:

1) Failure Modes Identification (referred to as "Qualitative Approaches" in the agenda)
2) Portfolio Risk Assessment and Index Prioritization Approaches (referred to as "Prioritization and Portfolio Approaches" in the agenda)
3) Detailed Quantitative Approaches (referred to as "Quantitative Approaches" in the agenda)

At the completion of presentations for each of these areas, input was collected on index cards from participants to address the following questions applied to each application area:

1) What are its strengths?
2) What are its limitations?
3) What are its Technology Transfer & Training Needs?
4) What are its Research and Development needs?

Responses to Questions 1 and 2 formed the basis for the evaluation of the current state-of-the-practice in each application area. A preliminary categorization of strengths and weaknesses by the Organizing Group Chair was reviewed and revised at a meeting of the USSD Working Group on Dam Safety Risk Assessment at the June 2000 USSD Annual Lecture. The Working Group also divided inputs between the Index Prioritization and Portfolio Risk Assessment application areas.

The results of the review of the state-of-the-practice in the four risk assessment application areas are summarized in Section 4.0. Detailed inputs are presented in Appendices E.

2.2.3 Identification of research needs

Research needs were divided into two types as follows: Research and Development (R&D) needs and Technology Transfer & Training (T^3) needs. Inputs for identifying research needs were obtained from the responses to Questions 1 – 4 (see Section 2.2.2) for each of the application areas, the participant's inputs on expectations and issues, and other inputs, which were made at various other times, such as during question and answer sessions following presentations. All inputs were categorized, as described in Section 2.3.2. In reviewing T^3 needs at a meeting of the USSD Working Group on Dam Safety Risk Assessment at the June 2000 USSD Annual Lecture, the Working Group suggested some additional T^3 approaches, which were incorporated into workshop recommendations.

The identified T^3 and R&D needs are summarized in Sections 5.0 and 6.0, respectively. Detailed inputs are presented in Appendices F, G, and H.

An integrated research plan, which combined both T^3 and R&D needs, was developed by the Organizing Group Chair and is presented in Section 7.0. This was also provided to the ICODS Research Subcommittee for consideration at its July 2000 meeting.

2.2.4 Recommendation of approaches for addressing needs

Categorized research needs were prioritized following a process described in Section 2.3.3. These prioritizations are also presented in Sections 5.0 and 6.0.

Small groups of participants provided suggestions for the ICODS Research Subcommittee to use in deciding how to follow-up on several priority research needs using a format presented in Section 2.3.4. The notes prepared by each group are presented in Section 6.6.

2.2.5 Summary of findings

A consolidation session was held at the end of the Workshop to prepare a draft of the Summary of Workshop Findings. This draft was reviewed and revised at a meeting of the USSD Working Group on Dam Safety Risk Assessment at the June 2000 USSD Annual Lecture.

A table of contents for this report was drafted during the consolidation session and the draft outline for the USSD Working Paper was reviewed and revised. Both the report and working paper outlines were further reviewed and revised at the June 2000 meeting of the USSD Working Group.

2.3 Strategic Planning Process

Dr. David W. Harris from the U.S. Bureau of Reclamation Laboratories served as the facilitator for the Workshop. Dr Harris has served in this capacity for other FEMA Research Workshops. In all cases he has used a Strategic Planning Process, based on the IBM "MetaPlan" approach. The following description of the four phases of this planning process is adapted from a general description prepared by Dr. Harris.

2.3.1 The input phase

Input from participants was collected on index cards, a few words per card. All participants did this simultaneously. The intent of this step was to collect as many ideas as possible from a fairly large group in a time efficient manner.

The cards were collected by the facilitator as completed, or at any time during the session. The cards were read aloud by the facilitator and displayed on a board, sorted into columns of similar topics, at the front of the room. All participants were encouraged to take part in the interaction to determine which column to place each card in, although perfect distinctions were not necessary in this phase.

2.3.2 The research category identification phase

With all cards sorted into columns, the test of distinction was to see if a heading could be established for each column. Some movement of initial cards was necessary during this process. New cards were added at any time as participants thought of new ideas, wanted to clarify their previously submitted ideas, or found items that may belong in more than one category. The continued intention was to collect as much information as is possible in a limited time. The heading for any given column became a research category with different aspects or possible tasks detailed within the column.

2.3.3 The research category prioritization phase

Participants were next asked to cast a total of ten votes for the importance that they associated with each category. Votes were recorded using ten glued dots that were placed by each participant on the board next to each column heading. Each participant was permitted to distribute their voting dots across all the categories. It was permitted to use as many as three dots for any one category to represent increased importance of that category to the participant.

All votes were counted for each research category. The votes were used to create bar charts for the research categories as shown in Figures 5.1 in Section 5.0 and Figures 6.2 and 6.3 in Section 6.1. The larger the number of votes, the greater the importance that was assigned to a particular research category.

A second vote took place based on the perceived difficulty of each research category. Difficulty could be interpreted to mean expensive, technically challenging, complex, or some other measure of difficulty, which the participant chose for any given category. In this case each participant assigned each and every research category a score between 0 and 10, with 0 being easy and 10 being really hard. Participant scores were averaged.

These data provided a second dimension for prioritizing research categories. When plotted this produced a decision quad of the research categories. The decision quad was formed by four quadrants of the "difficulty-importance" votes, each of which was given a descriptive name, as follows:

- Low Hanging Fruit - Easy and important
- Strategic Items - Hard and important
- Do later - Easy but less important
- Consider - Hard and less important

The resulting decision quad is presented in Figure 6.3 in Section 6.1.

2.3.4 The research proposal development phase

Workshop participants chose a research category and then worked with others in small groups to further develop each research idea. This provided additional input for use by the ICODS Research Subcommittee. The suggested form of the input was to address six "W" questions, as follows:

Who
What
Why
Where
When
hoW

An example of the work sheet provided for this purpose is contained in Figure 2.2.

Topic developed for Research

Title: (*describe the research item in 10 words or less*)

Description:

a. *Why is this a priority research item*?

b. *What is the expected outcome*?

Project Tasks and Needs (*What (tasks) is to be done and How (needs) is this problem to be solved*?)

Project Lead and Contract:

a. *Who is working in this area*?

b. *Who might be able to lead the project*?

c. *Who are good candidates to complete the work*?

Figure 2.2. Example of work sheet provided for the Research Proposal Development Phase

3.0 Information Needs for Dam Safety Evaluation and Management

3.1 Introduction

As mentioned in Section 1.2, the information needs of different organizations can vary widely. It was therefore recognized by the workshop-organizing group that it would be unrealistic to expect that any single approach to risk assessment would meet the needs of all organizations. An introductory workshop session was devoted to identifying, "Information needs for dam safety evaluation and management" for the following six types of organizations: the government owner, the large private owner, the small private owner, the federal regulator, the state regulator, and the consulting engineer. The presentations made in this session are summarized below in Sections 3.2 – 3.7. No attempt has been made to adapt the presentations to fit a common format.

The facilitator led the participants in an exercise to summarize information needs. The result was a list, which is presented in Appendix E.1. Each of the major topics in the list was expanded into some notes following the format of Table 3.1. These notes are presented in Appendix E.2.

Identified information needs were intended to be used by participants to form a broad basis for evaluating the strengths and limitations of a range of risk assessment approaches and for identifying research needs.

Table 3.1. Format for Notes on Information Needs

Information needs for dam safety evaluation and management

What: (Name of a need)

Who: (Needs this)

Why/When: (Do they need it)

Where will it be used: (In-house, public meetings)

How will it be used:

3.2 Government Owner Information Needs - John Smart, USBR, Denver, Colorado

- Risks associated with all dams owned
- Risks that should be reduced
- Risks that should be reduced in the short-term
- Risk management options that make most effective use of available resources in the risk identification and risk reduction processes
- Credibility in all of the above
- Uncertainties associated with all of the above
- Legal and political constraints that may affect the implementation of risk management actions

3.3 Large Private Owner – David Bowles[1], Utah State University/RAC Engineers & Economists

3.3.1 Regulatory environment

The regulatory environment in which a private dam owner operates can have a significant influence on the approach to dam safety management. Cases of hard, soft and no dam safety regulator are contrasted below:

- Hard – FERC, California, New South Wales Dam Safety Committee, Australia
  - Regulatory requirements may completely determine dam safety program and fixes
- Soft – Utah, Victoria, Australia
  - Less influence of regulatory requirements
  - Greater flexibility in rate and extent of fixes
  - BUT, what are the drivers?
- None – US Bureau of Reclamation, US Army Corps of Engineers, Tasmania, Australia
  - No regulatory requirements
  - AGAIN, what are the drivers?

3.3.2 Commercial context for dam safety decisions

A private dam owner must find a feasible approach to dam safety management within the various constraints and goals that determine the commercial context within which it exists, such as the following:

- Rate of return target
- Safety goal
- Pricing constraint
- Borrowings limit

This is illustrated in Figure 3.1

---

[1] An employee of a large private owner had been assigned the task of providing the perspective of a large private owner, but unfortunately he had to withdraw shortly before the workshop. Other participants who are associated with large private owners did not feel that they could address this topic at short notice and so David Bowles provided this perspective. He based his contribution on the information needs that have been identified to him by large private owners for whom he has worked as a dam safety management consultant.

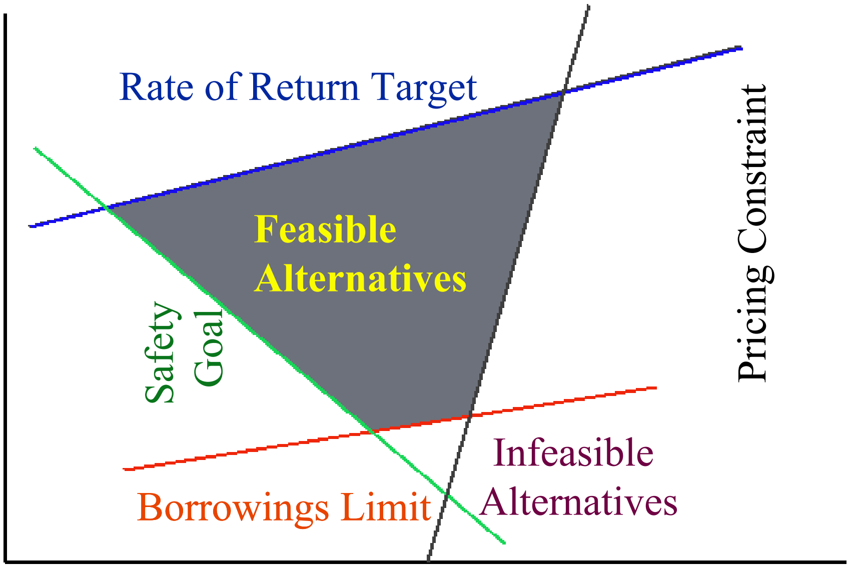

Figure 3.1. **Illustration of the commercial context for identifying a feasible dam safety management program**

3.3.3 Risk treatment options:

From a business or management perspective, risk treatment options can be grouped into the following categories, although they are "not necessarily mutually exclusive or appropriate in all circumstances" [AS/NZS 1995]:

- *Avoid the risk*—this is a choice that can be made before a dam is built, or perhaps through decommissioning an existing dam.
- *Reduce (prevent) the probability of occurrence*—typically through structural measures, or dam safety management activities such as monitoring, surveillance, and periodic inspections.
- *Reduce (mitigate) the consequences*—for example, by effective emergency evacuation planning or by relocating exposed populations at risk.
- *Transfer the risk*—for example, by contractual arrangements or title transfer of an asset.
- *Retain (accept) the risk*—after risks have been reduced or transferred, residual risks are retained and may require risk financing (e.g., insurance).

Figure 3.2 illustrates these categories of risk treatment.

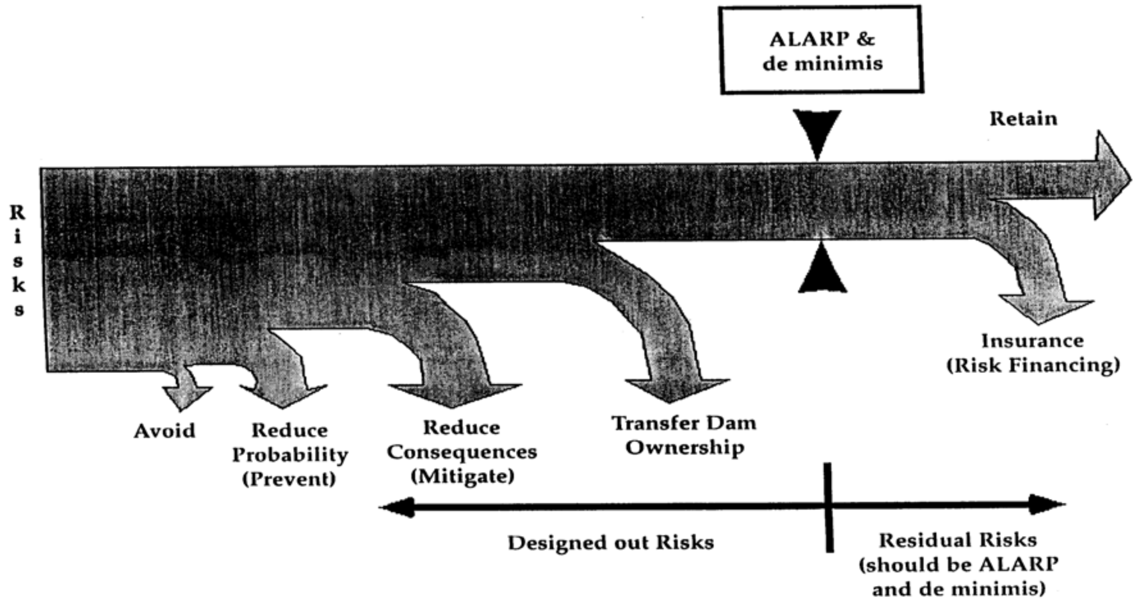

Figure 3.2 Categories of risk treatment

3.3.4 Outcome targeting

The right side of Figure 3.3 represents the information or outcome “targets” that can benefit a private owner’s dam safety program and related business processes in addition to other stakeholders in dam safety decisions. Some dam owners focus only on externally imposed requirements such as those of a regulator or engineering standards or guidelines without giving adequate consideration to internal considerations such as business criticality or alternatives for replacing project functionality (e.g. dam decommissioning), which might be less costly than dam safety rehabilitation. It is important that an effective outcome targeting process be accomplished, for example, at the outset of the portfolio risk assessment (PRA) process. It is also important that the PRA process is adapted to meet the specific information needs associated with each portfolio of dams rather than develop a standard set of outcomes.

Figure 3.3 also depicts the flow of information inputs into a PRA from activities that already exist in most dam safety programs (e.g. inspections, design reviews, etc.). It also shows the addition of specialized information, which may be needed to complete a PRA (e.g. inundation modeling and consequences estimation).

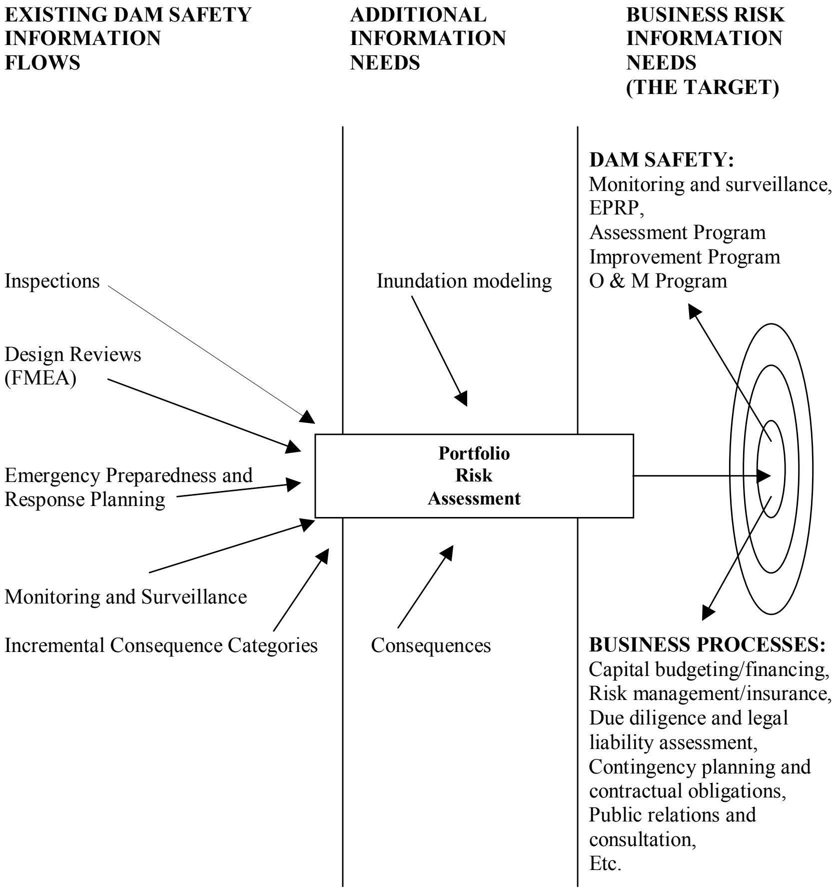

Figure 3.3. Capturing PRA inputs and targeting and integrating PRA outcomes into the owner's dam safety program and business processes.

3.3.5 Investment drivers – Information needs

In summary, the drivers that can influence private owners' dam safety decisions can include the following:

- Regulatory Considerations
    - Breaches of regulations, legal requirements and licenses
- Public Safety
    - Engineering Standards/Guidelines and Current Practice - Benchmarking
    - Risk-based guidelines - Benchmarking
    - As low as reasonably practicable (ALARP) principle
    - Extent of potential life loss
    - Community and political expectations
- Legal Liability
    - Duty of care, due diligence
    - "Reasonable person" – benchmarking (timing and extent)
    - Negligence of owner
    - Engineer's liability position

- Retention of Insurance Cover
- Business Viability/Financial
    - Third party liability and cost of lawsuits
    - Organizational breakup, public enquiries, restrictive legislation
    - Effects on key business results areas
        - Loss of revenue generation
        - Competitive position, dividends
        - Opportunities forgone/postponed
- Public Trust and Reputation
    - Customers - Extent of adverse impact on internal and external customers
    - External Perceptions - Extent of adverse community or political response on owner
    - Public consultation
- Additional Factors:
    - Cost effectiveness of fix(es)/staging
    - Priority relative to other dams/assets
    - Opportunity for increased capacity
    - Effects of delays/staging
    - Non-structural options

3.4 Small Private Owner Information Needs – Jim Doane, Bureau of Water Works, Portland, Oregon

3.4.1 Discussion

In order to gain the perspective of the small private dam owner, we need to determine what separates the small private dam owner from other dam owners. For the purpose of this discussion, I'll define the small private dam owner as a person or non-federal organization that owns no more than ten dams -- the dams can be small or large (of any hazard classification). For the purpose of this discussion, I am limiting it to the issues of small private dam owners who, if asked, would say and believe they are responsible dam owners.

What separates small private dam owners from other dam owners is that the operation and maintenance of the dam is not the core business of the organization but a way for providing water for the core business. For the small private dam owner, the storage of water is a way of providing for the core business be it water supply for irrigation, water supply for municipal purposes, flood control, water for flow augmentation, or water for industrial purposes. Small private dam owners also store water for hydroelectric production, recreation, cooling, etc.

One other characteristic of the small private dam owner is that their focus on the core business may lead to a situation where they do not understand the business and societal risks associated with the ownership, operation and maintenance of dams. They may look upon the risks much more casually than they should -- they may try to deal with them as underestimated normal business risks without even factoring in the societal risks. The lack of understanding of the risks and the nature of these owners (they tend to have small technical staffs) frequently leads to the situation where their staff is too small to have a resident dam expert available. It is even less likely that if there is a corporate risk manager, that risk manager will understand the risks associated with dams. It is unlikely that the majority of small private dam owner will have anyone with much knowledge of the concepts we are talking about in Logan today.

I found that the power companies seem to have in-house staffs that have a very good handle on the technical issues and many of the risk issues that come with dam ownership. This may be the result of the power companies having sufficient technical staff with knowledge of dams, dealing successfully with other business risks (and regulators), and a basic understanding of risks of dams. Other small dam owners might have a person responsible for dams on their technical staffs but that person frequently had other work as their primary focus. Most small dam owners were dependent on the work of consultants to actually deal with the technical issues associated with dam ownership. Most small dam owners did not have an understanding of the societal risk issues or of the risk concepts we are talking about here. Fortunately, the federal and state regulators did a good job of bringing the potential problems to the attention of the small dam owner.

What are the issues that tend to keep the owners of small private dams from understanding the issues inherent in having dams? I found that the owners, managers or boards are focused on their core business. They don't view their core business as having much to do with dam ownership. These owners seem to understand and generally fully appreciate the risks in what they view as their core business. They are striving to understand deregulation, new competitiveness, privatization, tight budgets, changes caused by endangered species listings, etc. New demands are placed on them every day. In this circumstance it is easy for them to just follow the lead of the regulators for dams as they follow the lead of regulators in so many aspects of their business. These owners tend to view the standard of the regulators as sufficient if not overly conservative. The safety record of dams may also lead them into a sense of security.

3.4.2 What are the information needs of the small dam owner?

The small dam owner needs to know the basics of managing all the risks inherent in the operation of the business. Concerning dams, the owner needs to be able to:

- Determine how to integrate or rely on someone who can integrate the commercial and societal risks of owning, operating, and maintaining dams into the overall risk management of the organization.

- Understand or rely on someone who understands the societal risk of dam ownership and know the impact that not managing that risk could have on the organization.

- Have knowledge of, or rely on someone who has a basic understanding of, mechanisms that result in common types of dam failures.

- Have knowledge of or rely on someone who has knowledge of probability as well as the basic elements that go into the risk analysis of dams -- especially the limitations and uncertainties.

- Understand that the amount of analysis that is required to address a specific problem is dependent on several factors:

    – The complexity of the problem being studied (generally the harder the problem, the more involved the analysis),
    – The reason the problem is being studied (is the analysis being internally or externally driven?),
    – The consequence of not managing the problem (does the failure result in the loss of a small amount of corporate resource or perhaps injury and losses to third parties?),
    – The degree of certainty desired (how sure does the owner need to be?), and
    – The amount of scrutiny anticipated by internal and external organizations and stakeholders

The owner should also understand that peer review of any significant analysis is always very desirable. The more complex the analysis and significant the outcome, the greater the need for peer review.

We need to somehow convince the small dam owner that risk analysis of dams is important without seeming like just another demand on the owner's time. This is really a powerful tool that can be used to help the small dam owner make good corporate decisions … decisions that can protect what the owner believes is the core business of the organization.

3.4.3 Presentation notes

Small Dam Owner

- Generally an individual or organization that owns one or a few dams (<10) of any size or hazard classification.
- Ownership, operation, and maintenance of the dams is not generally the core business of the organization.

Dams are used to store water to provide for the delivery of the core business:

- Water supply (irrigation, municipal, flood control, flow augmentation)
- Hydroelectric power
- Recreation, etc.

Primary focus on their core business (i.e., Issues other than dams):

- May not understand the business and societal risks associated with the ownership, operation and maintenance of dams.

Only a few structures to deal with:

- May not be able to have experts on staff or available as consultants to deal with emerging relatively sophisticated concepts such as risk assessment.

Changing Environment:

- Deregulation
- Tight budgets
- Endangered species listings
- Elected board or chairperson who may not have the background in risk issues

Issues of Owners:

- Business and societal risks inherent in dam ownership may not be fully appreciated or understood.
- Business risks or other issues associated with the core business fully appreciated and understood.
- Standards of the regulators may be deemed sufficient.
- Excellent safety record of dams may also cause a lack of appreciation for the risks.

Information Needs of Small Dam Owners:

- Need to know the basics of risk management for all risks at dams.
- Need to have access to or an understanding of:
  - Business risk of their core operations and relation to business risk of being the owner of dams.
  - Societal risk of being an owner of dams and the impact of not managing that risk.
- Basic knowledge of the elements that go into a risk analysis for dams.
- Limitations and uncertainties of the risk assessment process.

Knowledge that the amount of analysis required must be related to:

- Complexity of the problem
- Reason the problem is being addressed
- Consequences of not managing the problem
- Degree of certainty desired
- Scrutiny of internal and external organizations
- Desirability of having the work reviewed by peers

The owner should have:

- Basic understanding of common definitions used in the risk analysis and evaluation of dams.
- Basic understanding of the mechanisms that result in common types of dam failures.
- Basic understanding of probability (in order to be able to interpret the results).
- Understanding of the aversion of the general population to risk from dams.

Conclusion:

Risk assessment and risk evaluation can be used to help a small dam owner:

- Learn about the business and societal risks of dam ownership.
- Prioritize the various risks at a dam or for a group of dams.
- Determine the relative risk of owning dams to other corporate risk.
- Determine the overall risk that is acceptable.

3.5 Federal Regulator Information Needs - Dan Mahoney, FERC, Washington, D.C.

Regulator Perspective:

- There are benefits from risk assessment for dam safety evaluations

Where Risk Assessment Could be Used Effectively:

- Process gives a comprehensive, thorough evaluation of structure
- Prioritization of risks for owners of many dams
- Fixing dam safety deficiencies, which represent the highest risk first
- More definitive understanding of “hazard” rating

Dispel Notion:

- Risk assessment means not fixing dams

Hurdles for Regulators:

- Procedures and practices that are universal and accepted
- Common understanding and definitions
- Probabilities of extreme events are accurate and based on solid science
- Impact on conclusions of "Low" probabilities of extreme events

Major Hurdles for Regulators:

- Concept of "allowable levels of Loss of Life"
- Current methods of calculating Loss of Life from population at risk

Challenge for Workshop:

- Concept of "allowable levels of Loss of Life"
- Current methods of calculating Loss of Life from populations at risk

3.6 State Regulator Information Needs

3.6.1 A state dam safety regulator's perspective- Stephen Verigin, California Division of Safety of Dams, Sacramento, California

1. Need a procedure to quickly and easily classify dam safety risk. (Hazard classification rating.)

2. All dams that pose any potential loss of life and/or significant loss of property are high hazard.

3. Where there is (high) exposure to loss of life and/or property, use the very highest design requirements.

4. Use risk to identify problems but not as a basis for safety.

5. Establish a maximum size beneath which there is no risk to life or property.

6. Establish a minimum size above which the most conservative design standards should be used.

7. When using a hazard classification rating system to set work and resource priorities, do not assume that a low priority dam is safe. Accept it as a low priority with respect to risk exposure.

8. Most states must show that there is an actual threat to life and property and then must ensure that dams are designed and constructed with a reasonable factor of safety against failure.

9. Do not use risk analysis to avoid making necessary (and costly?) repairs. Owners have options of operating safe dams or removing them from service. A third alternative should not be placing life or property in peril because the cost of repair is too high.

10. Do not depend on emergency action plans or early warning systems to save lives. Time of failure, duration of failure, and complexity of evacuations prevent this from being a safety feature. An EAP is a response feature that will hopefully limit losses.

11. Risk analysis is not used in the design of new dams. Why is it appropriate for use on existing dams?

Methodology

1. The database of dam failures, when used to predict where problems will occur in the future, is not a strong tool. It is most likely a measure of past engineering standard deficiencies, undeveloped technology, or poor design and construction practices. It is not a measure of random phenomenon (i.e. piping is more likely in nature than rare storm events).

2. The numbers used to calculate the probabilities used in risk analysis are subjective, leading to results that have a very weak link to actual probabilistic forecasts. Good engineering judgment and a proactive inspection program are much more reliable.

3.6.2 Another state dam safety regulator's perspective – Doug Johnson, State of Washington, Olympia, Washington

In general, I would agree that Mr. Verigan's comments apply to most of the state dam safety programs. However, there are a few states that utilize risk-based standards, such as Washington and Montana. Furthermore, I think that all states could benefit from the knowledge of what level of risk their standards provide, even if they use deterministic standards. A key issue is using percent-PMP as a design event for smaller dams where loss of a few lives is possible. Once you move away from PMP you have no idea what level of protection is provided, unless you can determine the probability of the percent-PMP event. Thus, since some of the states use percent-PMP as a design standard, they are already accepting risk, only they have no idea of what level of risk they are facing! While I think it would be far more useful to approach this from the risk side and determine "acceptable risk" for these smaller dams, I understand that some states are not comfortable with this concept. However, all states could benefit from understanding the risks posed by their dams in decision-making. Based on these points, I submit the following comments (in italics) to Mr. Verigan's points.

1. Need a procedure to quickly and easily classify dam safety risk. (Hazard classification rating *and dam break analysis)*

2. All dams that pose any potential loss of life and/or significant loss of property are high hazard. *Although this is now the federal definition, not all states follow this. Washington still has a significant hazard rating with 1 or 2 homes at risk. I know several states that have this set in their regulations.*

3. Where there is (high) exposure to loss of life and/or property, use the very highest design requirements. *Agreed, but the highest design requirements shouldn't kick in where only a few lives at risk. This is why most states use percent-PMP for smaller dams with a few lives at risk.*

4. Use risk to identify problems but not as a basis for safety. -*Many states may feel this way, but not Montana and Washington. And actually, once the states allow percent-PMP as a design event, where lives are at risk, they are accepting risk as a basis for safety. However, we don't know in most cases what level of risk a percentage of PMP gives. This is a very important area where research is needed.*

5. Establish a maximum size beneath which there is no risk to life or property. *This would be nice, but it really all depends on the project. I have some six-foot high dams that are riskier than 20-foot high dams.*

6. Establish a minimum size above which the most conservative design standards should be used. *Also should consider hazard setting*

7. When using a hazard classification rating system to set work and resource priorities, do not assume that a low priority dam is safe. Accept it as a low priority with respect to risk exposure. *Agreed*

8. Most states must show that there are an actual threat to life and property and then must ensure that dams are designed and constructed with a reasonable factor of safety against failure. *Agreed, but the problem is defining "reasonable". There are probably 50 different opinions on this one. I think it would be very useful to the states to know what probability is associated with their specified design levels. That would really help in decision-making.*

9. Do not use risk analysis to avoid making necessary (and costly?) repairs. Owners have options of operating safe dams or removing them from service. A third alternative should not be placing life or property in peril because the cost of repair is too high. *I understand this is a feeling shared by many critics of risk analysis. It's viewed a way of getting out of doing anything at a dam. Again, for very large dams with thousands of lives at risk, I agree wholeheartedly. But most of the dams regulated by the states fall into the gray area, small dams with a few lives at risk. The standards set for these smaller dams can be determined by the level of risk posed, not by an arbitrary percentage of a design event. By allowing anything less than full PMP/MCE, the states are tacitly accepting something other than near-zero risk.*

10. Do not depend on emergency action plans or early warning systems to save lives. Time of failure, duration of failure, and complexity of evacuations prevent this from being a safety feature. An EAP is a response feature that will hopefully limit losses. *Agreed*

11. Risk analysis is not used in the design of new dams. Why is it appropriate for use on existing dams? *Actually, in Washington and partially in Montana, our design standards are based on risk. However, this is still a good question.*

Methodology

1. The database of dam failures, when used to predict where problems will occur in the future, is not a strong tool. It is most likely a measure of past engineering standard deficiencies, undeveloped technology, or poor design and construction practices. It is not a measure of random phenomenon (i.e. piping is more likely in nature than rare storm events). *Agreed.*

2. The numbers used to calculate the probabilities used in risk analysis are subjective, leading to results that have a very weak link to actual probabilistic forecasts. Good engineering judgment and a proactive inspection program are much more reliable. *This depends on which probabilities we are considering. For the triggering events such as floods and earthquakes, we can get fairly good statistical estimates of the probability, out to maybe 1 in 5,000 or even 1 in 10,000. For the other failure modes, I agree that they are subjective. However, engineering judgment is very subjective, isn't it?*

3.7 Consulting Engineer Information Needs - John W. France, URS Corporation, Denver, Colorado

Consulting Engineer’s Roles:

- Technical Adviser
- Technical Problem Solver
- Technical Advocate
- Designer
- Construction Manager

Whose Risk is it Anyway?

- Risks, and rewards, are the Owner’s.
- Engineer needs to keep his risks balanced with his rewards.

Standard of Care:

- Services same as provided by similar professionals at the same time and same location.
- Importance of established standards of practice for risk analysis.

Research and Practice Needs:

- Guidelines for risk assessment for dams: Standard of care
- Greater acceptance of risk by the public and its representatives: buy-in
- Establishing accepted levels of risk
- Improved Tools
- Loss of life estimates
- Case history compilations
- Expanded databases of failures and incidents
- Methods for assessment of seepage risks
- Verification/Confidence Building
- Parallel risk assessments of same cases

4.0 Assessment of State of the Practice

4.1 Introduction

Four risk assessment application areas were discussed at the workshop, ranging from qualitative to quantitative approaches, and progressing from more generalized approaches to approaches requiring more detailed analyses. The four application areas were as follows:

- Failure Modes Identification Approaches (Qualitative Approaches)
- Index Prioritization Approaches
- Portfolio Risk Assessment Approaches
- Detailed Quantitative Risk Assessment Approaches

Lists of strengths and limitations of the four risk assessment application areas are presented in this section. Detailed participant input for each strength and limitation listed below is presented in Appendix I. Detailed input from individual participants was grouped into the listed categories using the procedure described in Section 2.2.2. These categories are listed in this section in decreasing order of the number of participant comments in each category. Bar charts of the number of comments for strengths and limitations are presented for each application area.

As with other parts of this report it is not intended to include any commentary on results of participant input.

4.2 Failure Modes Identification Approaches (Qualitative Approaches)

Failure Modes Identification (FMI) applied to a dam is a procedure by which potential failure modes are identified. A failure mode is a sequence of system response events, triggered by an initiating event, which could culminate in dam failure. Procedures for FMI vary, but in a typical approach, a small team of dam engineers, who have a knowledge of historical dam failure mechanisms, would develop a list of failure modes. The form of the FMI outcome may vary from simply the list of failure modes, to a tabulation that lists associated effects, consequences, compensating factors, and risk reduction measures. In some cases an event tree or other graphical representations failure modes may also be included. FMI normally does not include quantification of risks. It is therefore, by itself, not a risk analysis, although it is one of the first steps in performing a dam safety risk analysis. Examples of FMI, which were presented at the workshop by VonThun and Anderson, are included in the workshop proceedings.

4.2.1 Strengths

Figure 4.1 shows the number of participant comments that were grouped under each of the following categories in descending order of the number of comments received in each category:

- Failure modes paradigm
- Relatively low effort
- Broad interdisciplinary team approach
- Enhances understanding
- Wide acceptability
- Strengthens traditional approach/Quality Assurance
- Identifying additional information needs

- Aids in prioritization of issues
- Aids in communicating risks
- Tool for achieving integration of dam safety program
- Aids in identification of risk reduction measures
- Systematic approach

4.2.2 Limitations

Figure 4.2 shows the number of participant comments that were grouped under each of the following categories in descending order of the number of comments received in each category:

- Qualitative - risk, ranking, compare with other dams, confidence/uncertainty
- Repeatability, consistency, influence of team members
- Lack of available guidance
- Cost
- Limited case histories to use as basis for FM identification
- Not a public-oriented process
- Requires information on dam

4.3 Index Prioritization Approaches

An index prioritization approach is a means of quickly ranking dams for addressing dam safety issues. The ranking is based on an index, calculated from a combination of weights, which are assigned to capture various attributes of identified dam safety deficiencies. The attributes and ranking procedures are usually prescribed in order to form a common basis for ranking between dams. These approaches are best used as an initial screening of a portfolio of dams, or a comparison to other forms of risk analysis. An example of an index prioritization approach that was presented at the workshop is the USBR's "Risk Based Profiling System" (USBR 2000).

4.3.1 Strengths

Figure 4.3 show the number of participant comments that were grouped under each of the following categories, including a comparison with portfolio risk assessment, in descending order of the number of comments received in each category for index prioritization approaches:

- Prioritization
- Efficient process
- Defensibility
- Justification
- Communication
- Systematic process
- Identification of dam safety issues
- Integrates dam safety program and into overall business

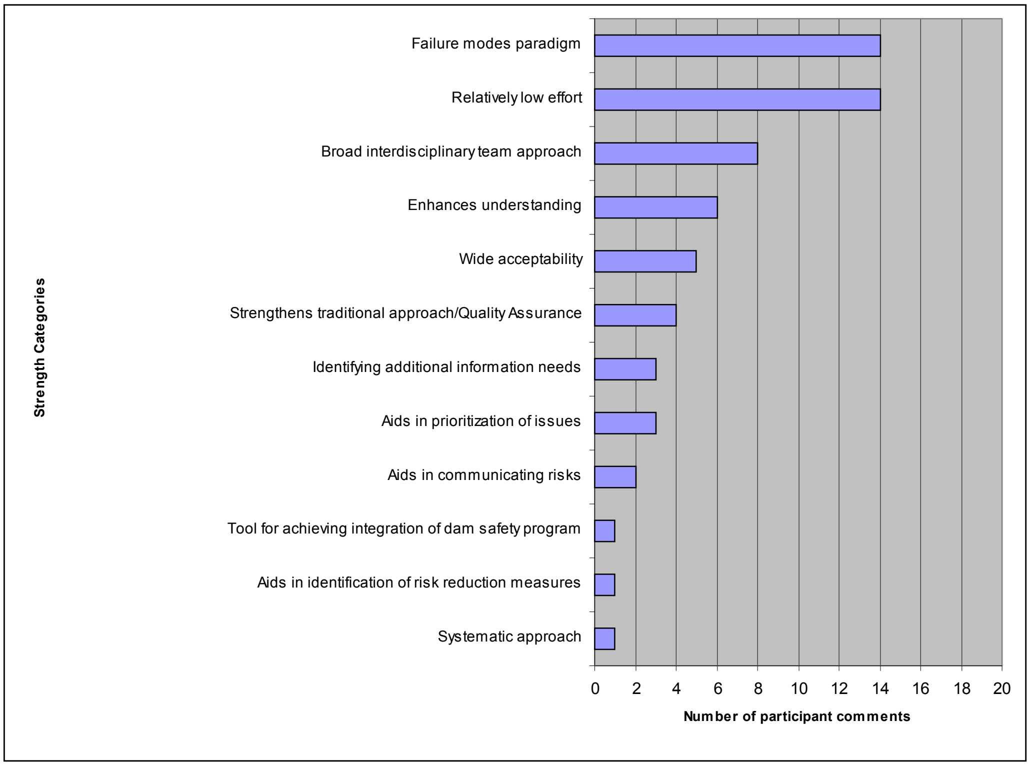

Figure 4.1. Strengths of failure modes identification approaches.

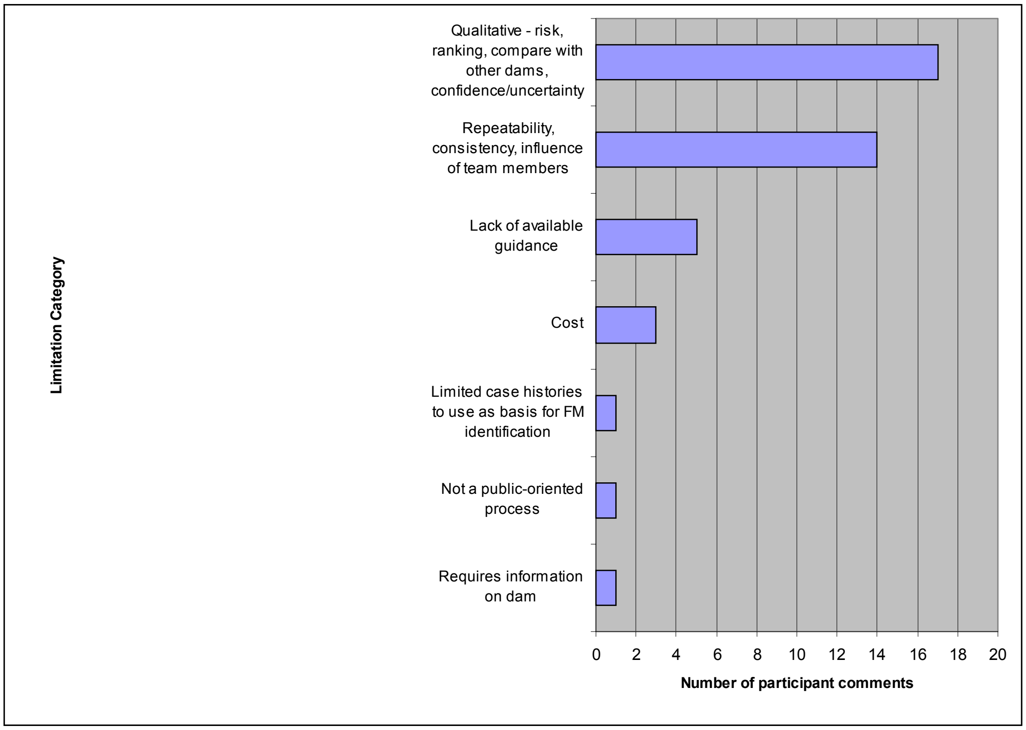

Figure 4.2. Limitations of failure modes identification approaches.

4.3.2 Limitations

Figure 4.4 show the number of participant comments that were grouped under each of the following categories, including a comparison with portfolio risk assessment, in descending order of the number of comments received in each category for index prioritization approaches:

- Danger of misusing results
- Not in-depth risk analysis
- Lack of published guidance
- Relative rather than absolute
- Defensibility
- Risk metric
- No sign off

4.4 Portfolio Risk Assessment Approaches

Portfolio risk assessment (PRA) involves the reconnaissance level application of the identification, estimation, and evaluation steps of dam safety risk assessment to a group of existing dams and risk reduction measures. The outcomes include an engineering standards assessment and risk profile for the existing dams, and a basis for developing and cost-effectively prioritizing risk reduction measures and supporting investigations. Other outcomes can be used to strengthen the owner's monitoring and surveillance program, and to provide inputs to various business processes, such as capital budgeting, legal evaluations, loss financing, and contingency planning. An example of PRA was presented in the workshop based on (Bowles 1999).

4.4.1 Strengths

Figure 4.3 show the number of participant comments that were grouped under each of the following categories, including a comparison with index prioritization, in descending order of the number of comments received in each category for index prioritization approaches:

- Prioritization
- Cost effectiveness risk reduction program
- Justification
- Communication
- Defensibility
- Risk metric
- Efficient process
- Identification of dam safety issues
- Integrates dam safety program and into overall business
- Systematic process

4.4.2 Limitations

Figure 4.4 show the number of participant comments that were grouped under each of the following categories, including a comparison with index prioritization, in descending order of the number of comments received in each category for index prioritization approaches:

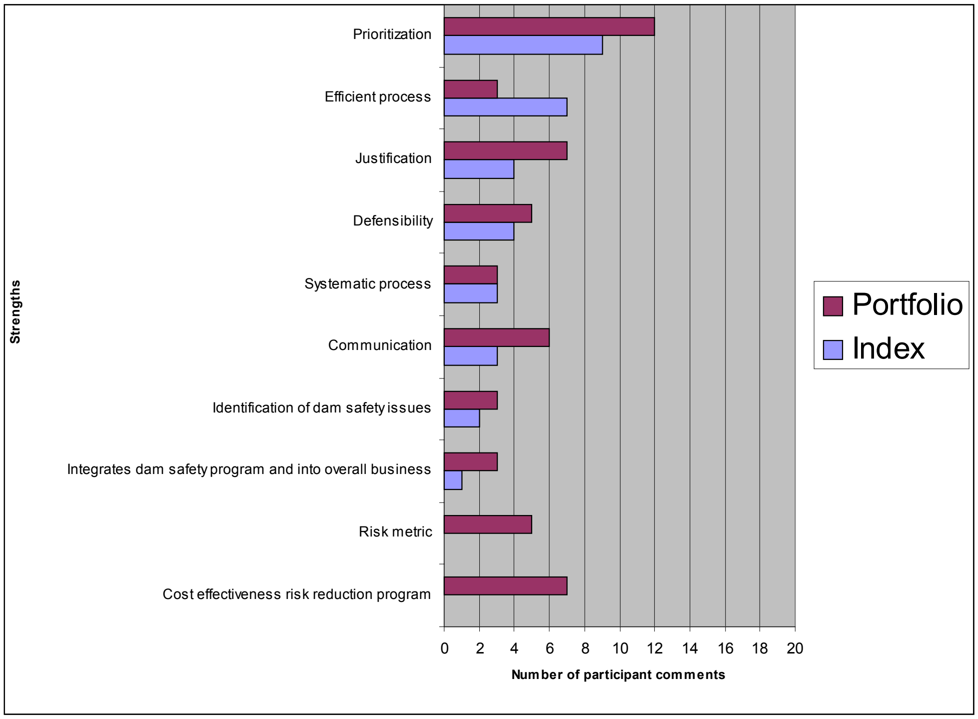

Figure 4.3. Comparison of strengths of index prioritization and portfolio risk assessment approaches

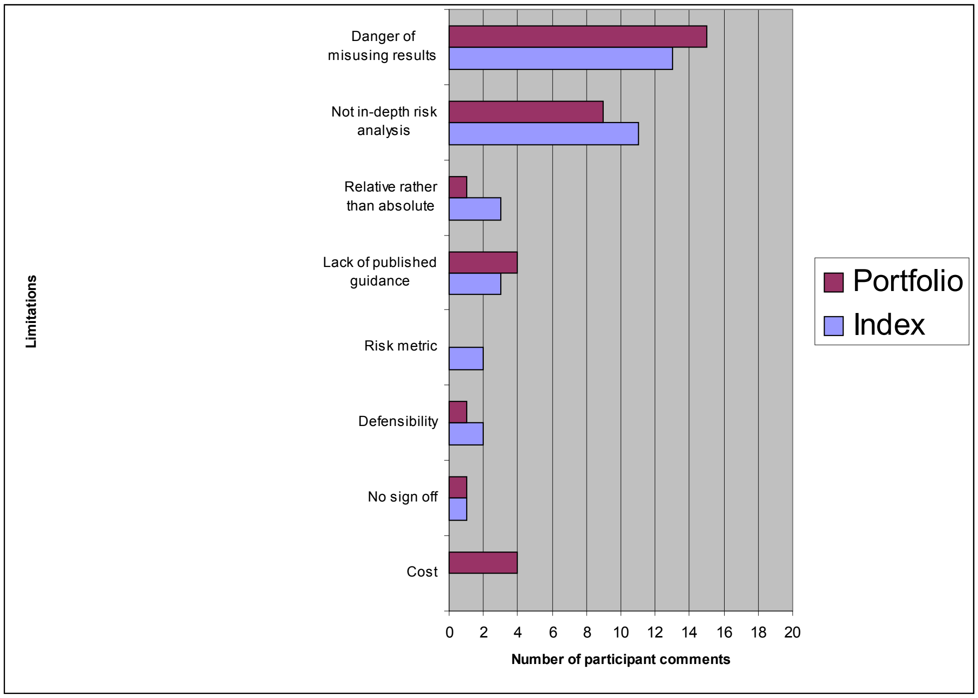

Figure 4.4. Comparison of limitations of index prioritization and portfolio risk assessment approaches.

- Danger of misusing results
- Not in-depth risk analysis
- Cost
- Lack of published guidance
- Defensibility
- No sign off
- Relative rather than absolute

4.5 Detailed Quantitative Risk Assessment Approaches

A detailed quantitative risk assessment comprises the steps of risk identification, estimation, and evaluation. The purpose of performing a detailed quantitative risk assessment is typically to provide insights into the adequacy of an existing dam, or to provide justification for risk reduction measures. Different owners vary in the level of detail that they require, but none rely on risk assessment alone for making such decisions. Two examples of detailed quantitative risk assessments were given in the workshop based on Dise and Vick (2000) and McDonald (1998).

4.5.1 Strengths

Figure 4.5 show the number of participant comments that were grouped under each of the following categories in descending order of the number of comments received in each category:

- Valuable as a decision tool
- Quantification using risk metric
- Understanding of failure modes
- Uncertainties considered
- In-depth supporting analyses
- Team process
- Defensibility
- Risk criteria evaluation
- Transparency in engineering judgments

4.5.2 Limitations

Figure 4.6 show the number of participant comments that were grouped under each of the following categories in descending order of the number of comments received in each category:

- Lack of standardized procedure and experienced practitioners
- Acceptable/tolerable risk criteria not agreed
- Uncertainty in estimating probabilities and life loss
- Communicating uncertainties to decision makers and others
- Cost
- New and complex terminology

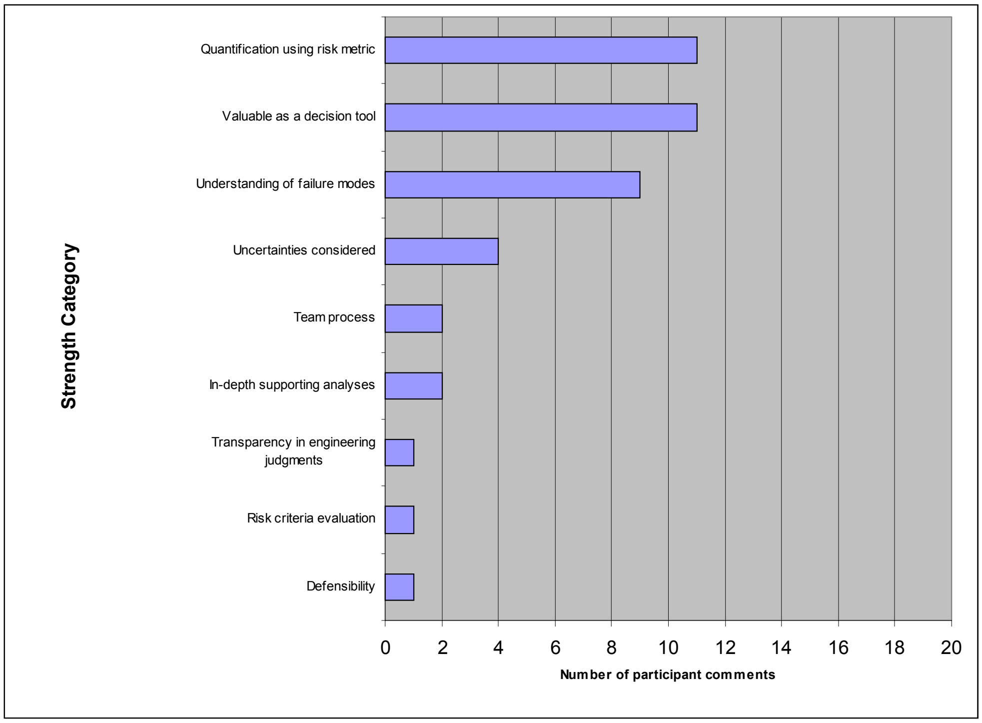

Figure 4.5. Strengths of detailed quantitative risk assessment approaches.

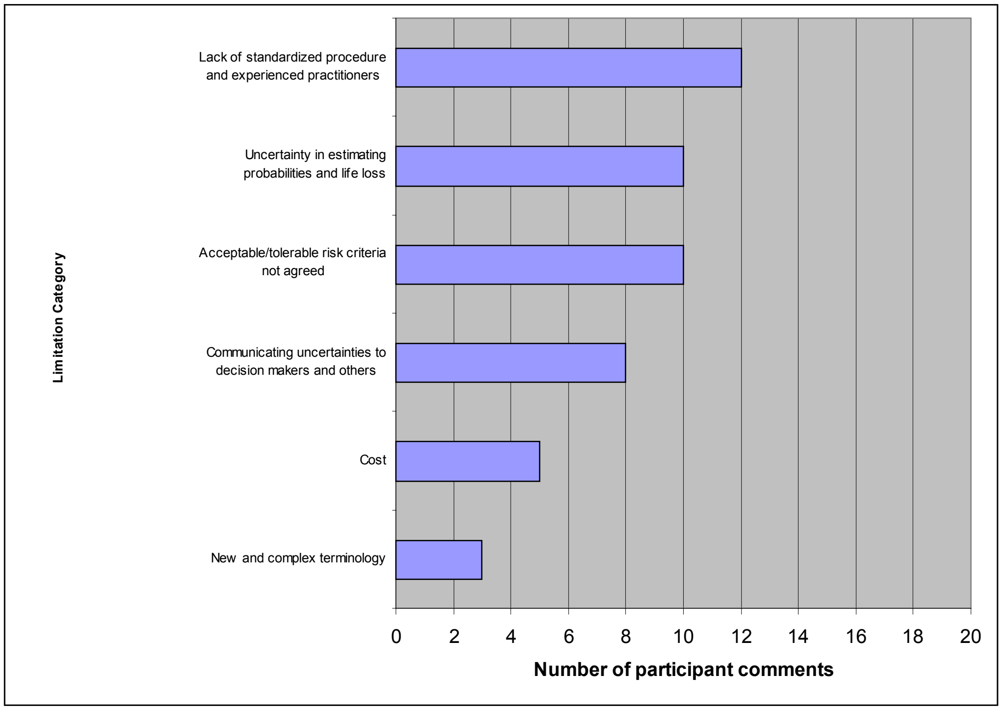

Figure 4.6. Limitations of detailed quantitative risk assessment approaches.

5.0 Technology Transfer and Training Needs

The prioritized technology transfer and training (T^3) needs categories resulting from the procedure described in Section 2.3 are listed in Table 5.1. The risk assessment application area for each need is indicated and some suggested modes of technology transfer and training suited to each need.

A bar chart of the importance of T^3 needs is presented in Figure 5.1 based on the number of votes for each need. Needs with less than three votes were omitted in this section, but are included in Appendix J.

Numerical codes in the second column provide a means of tracking the categorization process that the group followed under the lead of the facilitator.

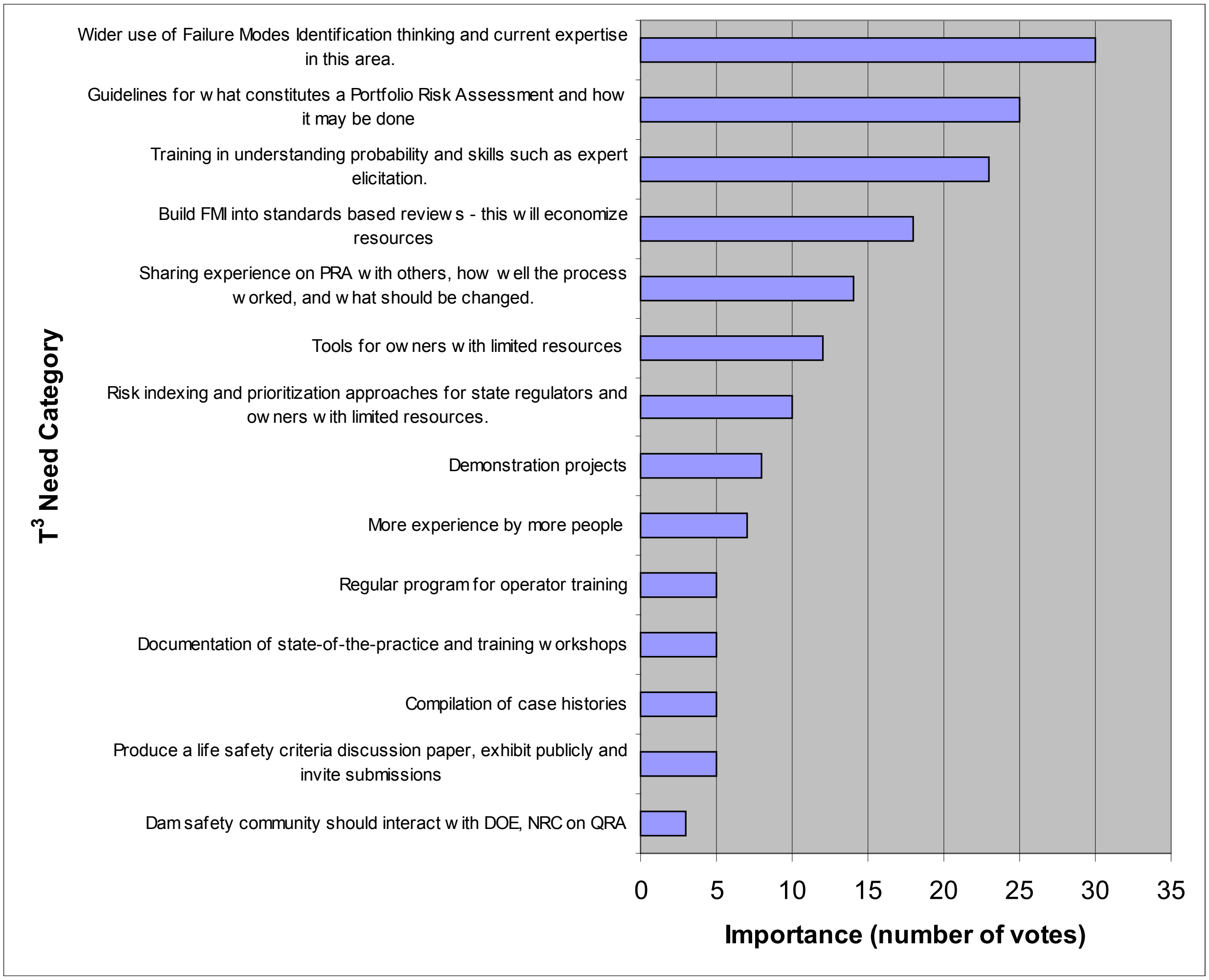

Figure 5.1. Importance of T^3 needs based on the number of votes for each need

Table 5.1. Prioritized Technology Transfer and Training Needs

Priority	Need		Votes	Suggested Modes of T^3	Risk Assessment Approach
1	3	Wider use of Failure Modes Identification thinking and current expertise in this area.	30	Document process. Document case histories, Training seminars, Hands-on workshops, Train facilitators, NPDP collect and disseminate (journal or web-based) case histories.	Failure Modes Identification
2	1	Guidelines for what constitutes a Portfolio Risk Assessment and how it may be done	25	Guidelines	Portfolio Risk Assessment
3	2	Training in understanding probability and skills such as expert elicitation.	23	Training seminars (e.g. FEMA) and web-based training for practicing engineers. Include risk and uncertainty in BS curriculum and make sure that they are part of accreditation requirements.	Detailed Quantitative
4	4	Build FMI into standards based reviews - this will economize resources	18	SIMILAR TO PRIORITY 1	Failure Modes Identification
5	6	Sharing experience on PRA with others, how well the process worked, and what should be changed.	14	Publish completed Portfolio Risk Assessments with assessments of their strengths and weaknesses and ways to improve	Portfolio Risk Assessment
6	5	Tools for owners with limited resources	12	Hire an engineer Do dams in groups with same experts	Failure Modes Identification
7	8	Risk indexing and prioritization approaches for state regulators and owners with limited resources.	10	Compilation and summary of existing approaches and development of an appropriate approach for the States, including equipping the states to evaluate risk assessment submittals.	Index Prioritization Approaches/ Portfolio Risk Assessment
8	7	Demonstration projects	8	Hands-on not just Observers at USBR RA; groups of owners	Detailed Quantitative
9	14	More experience by more people	7	Demonstration projects. Train more facilitators. Sponsor seminars aimed at educating non-technical staff among owners.	Index Prioritization Approaches/ Portfolio Risk Assessment
10	13	Regular program for operator training	5	Dam owner's responsibility - need for material from professional bodies etc for small dam owners	Failure Modes Identification
11	9	Documentation of state-of-the-practice and training workshops	5	Documentation and workshops	Detailed Quantitative
12	10	Compilation of case histories	5	Case histories	Detailed Quantitative
13	11	Produce a life safety criteria discussion paper, exhibit publicly and invite submissions	5	Discussion paper	Detailed Quantitative
14	16	Dam safety community should interact with DOE, NRC on QRA	3	Interaction	Detailed Quantitative

6.0 Research and Development Needs

6.1 Introduction

The prioritized research and development needs categories resulting from the procedure described in Section 2.3 are listed in Table 6.1. The table includes importance and difficulty votes and an assignment to one of the following quad categories:

- Low Hanging Fruit - Easy and important
- Strategic Items - Hard and important
- Do later - Easy but less important
- Consider - Hard and less important

The decision quad, formed by the four quadrants of the "difficulty-importance" votes, is presented in Figure 6.3. Bar charts of the importance and difficulty of research categories are presented in Figures 6.2 and 6.3, respectively.

Although not part of the original MetaPlan approach, research categories were ranked, separately within each quad category, by using a combination of the importance and difficulty votes, obtained as follows:

$$\text{Overall rank} = i * (10 - d)$$

in which:

i = Number of votes received based on importance of research category
d = Average score based on difficulty using a score between 0 and 10, with 0 being easy and 10 being really hard

Ranking by this approach took place after the workshop and so, although it is based solely on the input of workshop participants, it was not available at the time of the workshop. The ICODS Research Subcommittee may find this ranking helpful, but should not feel bound by this within-quad category ranking when they select projects for funding.

The priority assigned through this process to each of the research categories is shown in the first column of Table 6.1. A footnote in the first column for several research categories indicates that after all participant input was sorted by the facilitator, with the consensus of the participants; no input was left under these research categories. This may have occurred, for example, because a category was grouped with another category.

The letters in the second column are a code that is used to refer to research categories. Other numerical codes are left in the description column in order to provide a means of tracking the categorization process that the group followed under the lead of the facilitator.

In the Sections 6.2 – 6.5, respectively, the input provided by participants is listed for each of the research categories under each of the four decision quads. The input is reproduced as provided by participants with no attempt to interpret it or present it in a uniform format.

Table 6.1. Prioritized Research and Development Categories

Priority	Code	Description	Importance (i)	Difficulty (d)	i*(10-d)	Category	Interpretation of Category
1	F	**7,18,19 - Prioitization and Portfolio tools (F)**	32	4.13	188	Low Hanging Fruit	Easy and Important
2	K	13 - Data Base of Failure Case Histories (K)	21	3.5	137	Low Hanging Fruit	Easy and Important
3	B	**2,6 - Tolerable Risk/Criteria (B)**	49	7.14	140	Strategic Plan	Hard and Important
4	M	**15 - Flood Loading (M)**	26	5.9	107	Strategic Plan	Hard and Important
5	G	**8 - Earthquake Response (G)**	26	6.5	91	Strategic Plan	Hard and Important
6	I	**10,21 - Improve Loss of Life Estimates (I)**	24	6.25	90	Strategic Plan	Hard and Important
7	J	12 - Risk Communication (J)	22	6	88	Strategic Plan	Hard and Important
8	C	**3 - Subjective Probability (C)**	20	5.7	86	Strategic Plan	Hard and Important
9	E	5 - Uncertainity (E)	14	4	84	Do Later	Easy but Less Important
10	N	16 - Risk Process (N)	13	4.8	68	Do Later	Easy but Less Important
11	D	4 - Skills to Identify Failure Modes (D)	7	2.9	50	Do Later	Easy but Less Important
12	A	1 - Standards (A)	5	3.4	33	Do Later	Easy but Less Important
a	P	20 - Debate Mechanisms (P)	3	4.1	18	Do Later	Easy but Less Important
14	H	**9 - Static Response (H)**	1	3.33	7	Do Later	Easy but Less Important
15	S	Portfolio - Learn to Improve (S)	0	3.79	0	Do Later	Easy but Less Important
a	T	26 - Debate Concepts (T)	0	3.4	0	Do Later	Easy but Less Important
17	L	14 - Earthqauke Loading (L)	13	6.40	47	Consider	Hard and Less Important
a	O	17 - Analyze NPDP (O)	9	5.5	41	Consider	Hard and Less Important
a	R	24 - Include Failure Modes Identifcation in schools (R)	7	6.65	23	Consider	Hard and Less Important
a	Q	22 - Communicate Best Practice (Q)	1	5	5	Consider	Hard and Less Important

a) No input was provided by workshop participants on these needs and so they were dropped from the list of priorities

b) Needs with descriptions in bold were developed into a brief research proposal at the workshop.

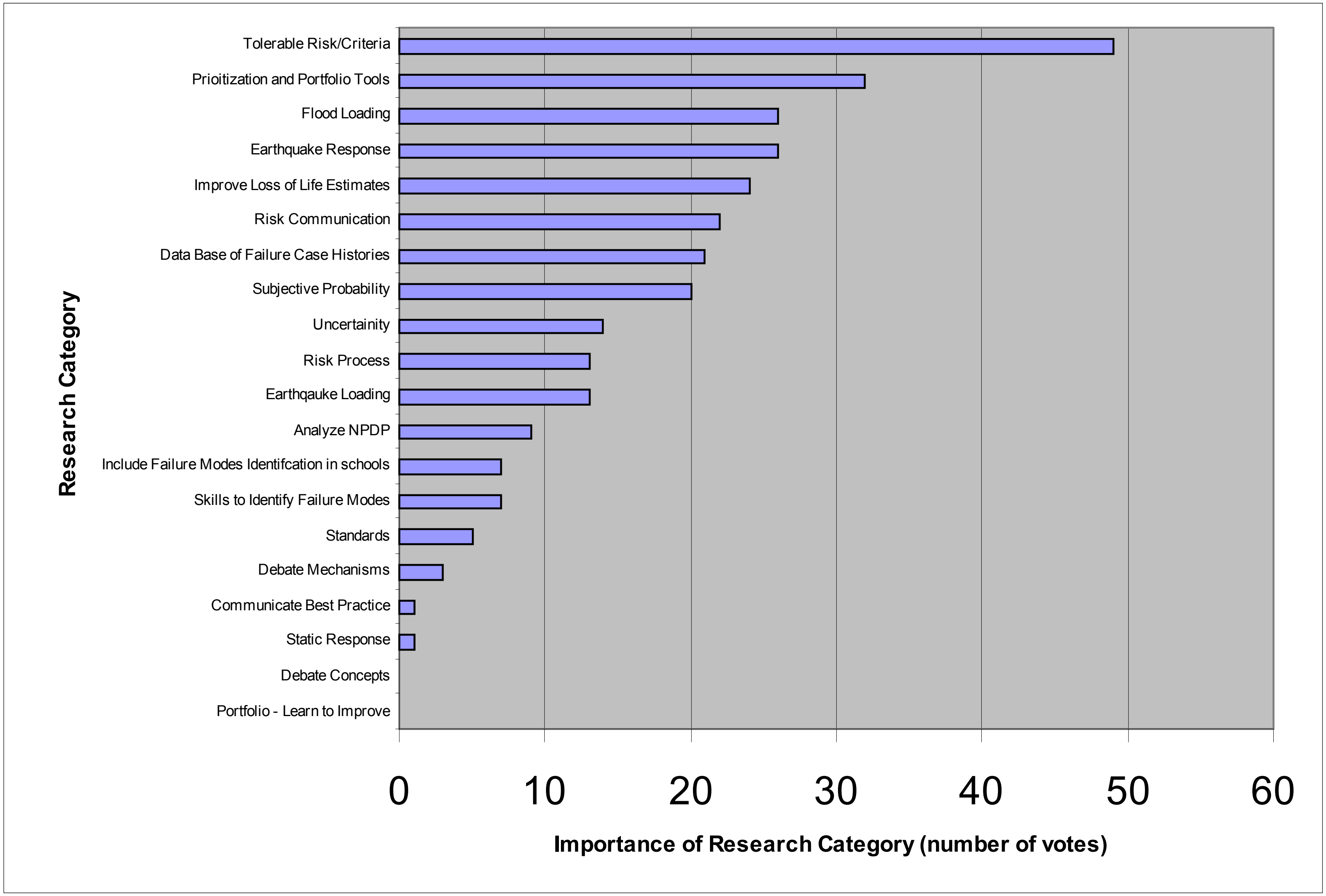

Figure 6.1. **Bar Chart for Importance of Research Category**

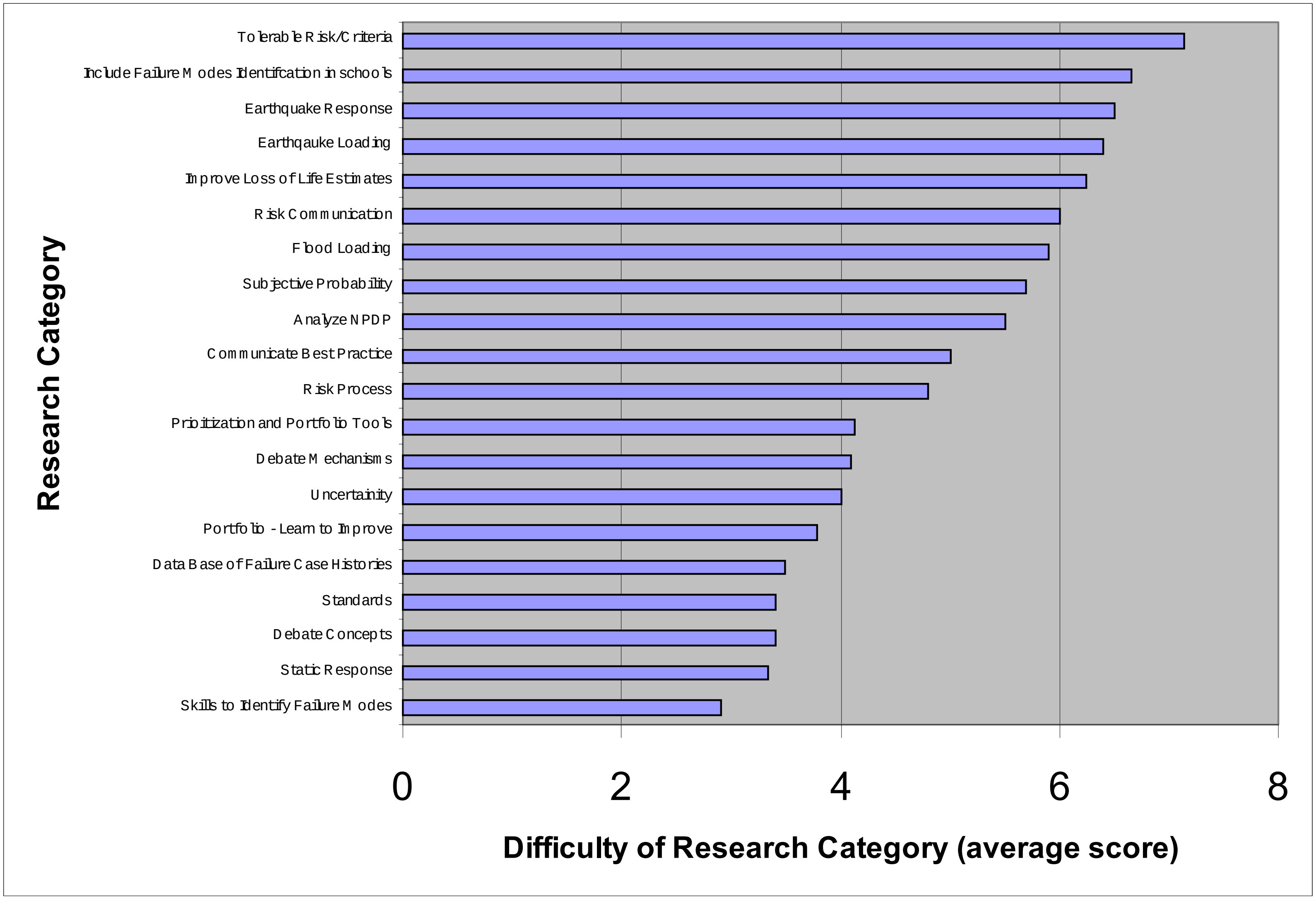

Figure 6.2. **Bar Chart for Difficulty of Research Category**

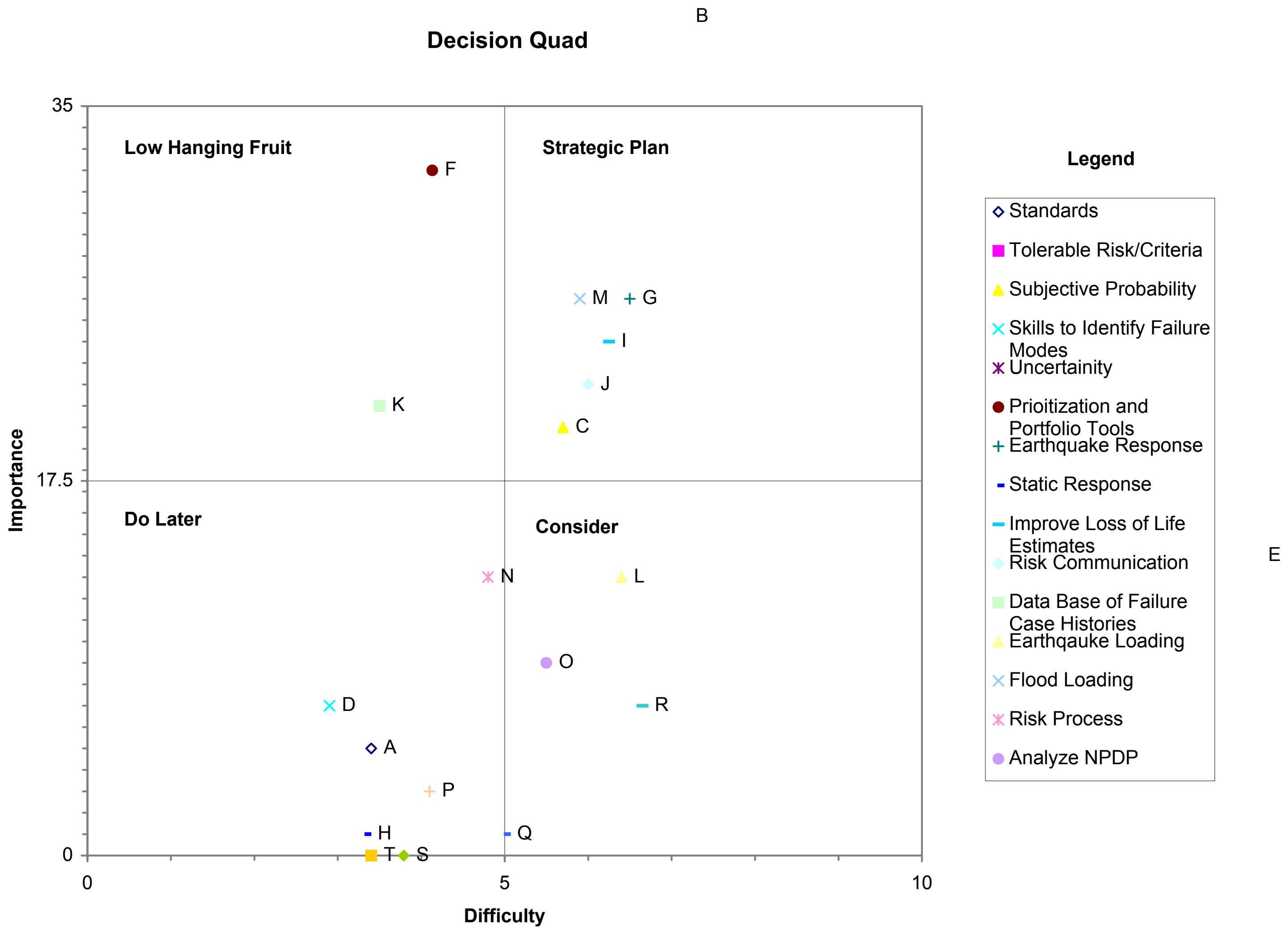

Figure 6.3. Decision Quad for Research Categories

6.2 Low Hanging Fruit - Easy and Important

6.2.1 Priority 1 – (7, 18, 19) Prioritization and portfolio tools (F)

- Develop guidelines for prioritization and portfolio approach
- Develop simple, easy to use approach that will gain general acceptance
- Most state dam safety programs have no program for profiling and prioritization. Consider developing index system that state dam safety programs could use for profiling dams that they regulate
- Check USBR index system against portfolio method and try to assess how effective it is and whether it is good for state officials
- Are rating points systems worth doing without Failure Modes Identification procedure? There is a high chance of missing the critical issue.
- Can a prioritization index system be consistent with a risk (metric) analysis approach?
- Can portfolio risk assessment be used for prioritization of known deficiencies (e.g. as opposed to USBR prioritization)?

6.2.2 Priority 2 – (13) Database of failure case histories (K)

- Case history compilations needs to be parameter specific

6.3 Strategic Plan - Hard and Important

6.3.1 Priority 3 – (2, 6) Tolerable risk/criteria (B)

- Is legislative intent to get to zero risk to life?
- State legislation says, “remove the risk”; implies that there could be zero risk. Not possible.
- Regulators need to educate government that “safe” means a low probability of failure, not "no chance" of failure.
- Public aversion or intolerance to imposed risks
- The public is extremely risk adverse about dams. How can you get acceptance of risk levels given that?
- Who decides “RP” in ALARP?
- Who decides what is tolerable risk for dams?
- How do we get public input for risk criteria/public protection guidelines?
- Who will (should) establish life safety criteria? Is it practical for them to do so?
- Obtain public & political input to debate on acceptance limits
- Tolerable risk criteria as an interim step on the constant path of risk reduction
- Accepted level of risk is an organization to organization, case by case, aspect
- The FEMA requirements are impossible if followed rigidly
- Legislators, not the Regulators should determine risk level accepted.
- Dams are only one piece of society’s risk pool.
- Strive for consistent risk.
- Is it reasonable to rely on warnings and evacuation as a risk reduction measure?
- EAP vs. fixing dam
- EAPs not a substitute for structural fix
- Engineers + Lawyers = inferior dam safety decisions

- Who could go to jail if the dam fails?
- Acceptance of loss of life?
- If risk is the owner's what does this mean for non-owner beneficiaries to share risk?
- <1 lives/yr does not communicate with the public. Why aren't we looking at calculating the probability of one or more lives lost by a particular event, then ask what the acceptable probability for public would be?
- What to do if repair may pose more risk than existing conditions (no-fix)?

6.3.2 Priority 4 – (15) Flood loading (M)

- Regional analyses of extreme precipitation probabilities for entire U.S. – allows states to estimate % PMP probabilities
- Extreme event probability determination improvement
- Reduce uncertainty in hydrologic process evaluation
- Continued support for development of methods for processing hydrologic information for characterizing extreme floods
- Development of procedures for better understanding and incorporating uncertainty in characterization of floods
- Comprehensive program for collection of climate flood and paleoflood data on regional basis to support regional analyses
- Studies to investigate spatial distribution for large watersheds using probabilistic methods
- Confidence in extreme event estimates
- Variability in PMF computations of uncertainty of parameters

6.3.3 Priority 5 – (8) Earthquake response (G)

- Develop more realistic earthquake displacement and liquefaction models.
- Develop better methods for structural response of:
    - Concrete gravity dams in earthquake
    - Embankment stability
    - Piping, static and post earthquake
- RA is very good where there is no standards-based analytical tool e.g. Navaho Drain Tunnel
- Factor of safety vs. probability of failure. Need conservative strengths for FS = 1.5 to represent low probability of failure.
- Inter-related failure modes
- Does number of steps included in event tree fundamentally affect resulting probability?
- Length of dam and number (?) effects on probability estimates
- Develop capability to derive failure probability analytically
- Need to improve understanding and ways to predict system response probabilities
- Failure mechanism understanding and modeling
- Develop failure models that use probabilistic input both for loads and resistance
- Adapt failure models for nodes of event trees

6.3.4 Priority 6 – (10, 21) Improve loss of life estimates (I)

- Improve life loss estimation
- LOL estimate should consider EAP
- Assessment of evacuation capability for large population centers

- Develop procedures to understand and assess the effectiveness of EAP/EPP
- Role of EAP in loss of life estimates
- Long term effectiveness of warning and evacuation systems
- Relationship between life loss and proximity to the dam?
- Improve confidence of loss of life estimates

6.3.5 Priority 7 – (12) Risk communication (J)

- What do the numbers resulting from quantitative risk analysis really mean?
- Hazard (seismic), Hazard (downstream): 1) drop both uses, 2) use Seismic loading, 3) use consequence
- Can we build public confidence in life loss estimates?
- Owners: be able to defend what you are doing as being reasonable and prudent
- Need for common language between technical specialists and international (English (geotech) → English (financial) → English (probability) → English (international) → English (seismic) → English (H&H) → English (owner) → English (lawyers).
- Public buy-in for risk-based decisions

6.3.6 Priority 8 – (3) Subjective probability (C)

A. Immediate
  - Develop an improved understanding of probability interpretations and corresponding expectations of those using, interpreting, or considering quantitative methods.
  - Develop better ways for adapting criteria to probability (rather than vice-versa) and operating within its capabilities.

B. Intermediate-term
  - Education and training of probability assessors in cognitive processes, heuristics and biases.
  - Development and application of de-biasing techniques adapted in positive ways to how people think and how they conceptualize subjective uncertainty judgments.
  - Education and training in *basic* probability theory (axioms, etc.)

C. Longer-term
  - Improve judgment of probability assessor
    - What is judgment?
    - How does substantive expertise differ from normative expertise?
    - Role of inductive vs. deductive reasoning strategies
    - How is judgment enhanced?

- Adapt and merge ongoing R&D from institutions, e.g. Stanford University regarding human thought processes
- What is the value to the public of subjective probability estimates?
- Dam response probability subjective estimate divergence theory: If team thinks failure mode is a problem based on discussion, then the subjective value is higher. If team thinks failure mode is not a problem then subjective estimate is lower.
- Effects of distributions on event probability estimates.
- Uncertainty analysis approaches beginning from probability estimation, failure mode identification through presentation of outcomes to decision makers
- Compare on equal basis judgment and unknowns for loads, responses and life loss.
- Assess repeatability – considering uncertainty ranges (not just point estimates)
- How do we reflect uncertainty in perfect history database?

- How do amount and quality of data affect confidence in RA results?

6.4 Do Later - Easy but Less Important

6.4.1 Priority 9 – (5) Uncertainty (E)

- LUMPED WITH PRIORITY 9

6.4.2 Priority 10 – (16) Risk process (N)

- Long dams; multiple dam reservoirs need probabilistic concepts to be ‘correct’
- Repeatability: (even for qualitative methods)

6.4.3 Priority 11 – (4) Skills to identify failure modes (D)

- Change paradigm for quantitative risk analysis

6.4.4 Priority 12 – (1) Standards (A)

- All Civil Engineering is empirical, therefore, it is risk based! FS = 1.5 means low risk, not zero risk.
- How do the new computer tools encroach on FS in standards based designs and how does this change 100 yr database?
- ~ 1 in 100 dams fail
- How do we change standards without addressing risk?
- Dams with no possibility of life loss
- Large dams that must meet PMF and MCE
- What is a “reasonable FS”? Is the MCE adequately conservative?
- Parallel risk assessments of the same dam
- Incentive/need to undertake risk assessment if dams meet standards regulations
- Is a standards approach a zero risk approach?
- Subjective probabilities bad for quantitative RA but OK for standards?
- Standards ≠ restrictive thinking
- Failure modes identification should always be performed
- Missing failure modes
- Also a problem with defensibility of standards
- How do engineering/subjective judgments affect traditional approach outcomes vs. risk-based approach outcomes?
- Risk seems to add to short comings of standards approach as opposed to avoid (parameter uncertainty analysis)
- New dams vs. existing dams

6.4.5 Priority 13 – (9) Static response (H)

- Improve estimates of failure probabilities for static stability piping failure, etc.
- Research needed to develop better models for:
    - Failure
    - Piping

  - Loss of life
- How confident are we in characterization of piping failures – embankment, foundation, etc.?
- Seepage rate is not a good guide to problems. Changes, not correlating with reservoir is better.
- Piping failures take less than 24 hrs, mostly < 6 hrs, to develop. They historically occur at reservoir level ≤ 1m below historic high level.
- Develop risk analysis procedures to account for time-dependent aspects of piping.
- RA is very good where there is no standards based analytical tool e.g. Navaho Dam Tunnel
- Factor of safety vs. probability of failure. Need conservative strengths for FS = 1.5 to represent low probability of failure.
- Inter-related failure modes
- Does number of steps included in event tree fundamentally affect resulting probability?
- Length of dam and number (?) effects on probability estimates
- Develop capability to derive failure probability analytically
- Need to improve understanding/ways to predict system response probabilities
- Failure mechanism understanding and modeling
- Develop failure models that use probabilistic input both for loads and resistance
- Adapt failure models for nodes of event trees

6.4.6 Priority 14 - Portfolio - Learn to improve (S)

- Learn how to improve PRA by evaluating changes resulting from updating
- More input from users on information needs

6.5 Consider - Hard and Less Important

6.5.1 Priority 15 - Earthquake loading (L)

- Reduce uncertainty and minimize compounding of conservatism in earthquake risk assessment
- Earthquake loads need:
  - Additional data collection – slip rates
  - Site response data
  - Recurrence models
  - Robust estimates of time histories for use in RA
  - Better integration with engineering analyses
  - Portray uncertainty in an understandable fashion
- Characterize AEP of earthquake loading using magnitude as well pga
- Reduce errors in catalogue of recorded earthquake accelerations (data cleaning)
- Uncertainties in recurrence characteristics for known faults

6.6 Research Proposals

Following the format of the worksheet presented in Figure 2.2, small groups of participants prepared some suggestions for several of the higher priority research categories for consideration by the ICODS Research Subcommittee. Time was quite limited for this activity. A recommendation would be that more time be assigned to this activity in future Research Specialty Workshops.

The completed worksheets are presented below for eight research categories. These are indicated in a bold typeface in Table 6.1. Content varies depending on the group that prepared them.

Title: PRIORITY 1 - **Develop Guidelines for profiling and prioritization system**

Description:

a. Why is this a priority research item?

- For most state dam safety agencies, no prioritization system in place
- Provide for improvement in overall national dam safety by providing tool for states to prioritize unsafe dams
- Allows for a national assessment of safety of dams and to show year to year improvement for the NDSP (National Dam Safety Program)

b. What is the expected outcome?

- Greater efficiency in fixing dams that pose greatest risk
- Improved national dam safety
-

Project Tasks and Needs:

1. Hire contractor
2. Compile info on existing prioritization systems
3. Consult with state agencies and other dam safety agencies
4. Develop guidelines
5. Peer review
6. Publish

Project Lead and Contract:

a. Who is working in this area?

USBR, Australia, Washington State, Utah State University, Corps of Engineers

b. Who might be able to lead the project?

FEMA → ASDSO steering committee

c. Who are good candidates to complete the work?

Marty McCann, Stanford University
David Bowles, Utah State University
USBR
Corps

Title: PRIORITY 3 - **Tolerable Risk Criteria**

Description:

Develop an approach for setting of tolerable risk criteria for the various classes of dam failure consequence

a. *Why is this a priority research item*?
Because it is essential to development of the full potential of risk assessment for dams.

b. *What is the expected outcome*?
An approach that will facilitate the setting of tolerable risk criteria that will have a good level of acceptance.

Project Tasks and Needs:

1. Research approaches to the setting of tolerable risk levels in other industries and other countries
2. Research approaches, in other industries and countries, to gaining acceptance for criteria
3. Research legislative and regulatory intent and approaches to amendment of legislation

Project Lead and Contract

1. FEMA
2. Bowles - USU

Title: PRIORITY 4 - **Flood Loading**

Description: Development of estimates of probabilities for extreme flood events/ Needed for both site-specific studies and portfolio approaches.

Project Tasks and Needs:

- Investigate spatial distribution of precipitation/ floods for a variety of basin sizes.
- Incorporate bounds
- Develop meaningful uncertainty estimates incorporating model and parametric uncertainties.
- Regional analysis of extreme precipitation events to relate existing state safety criteria to AEP.
- Develop program of collection of climate, flood, and paleoflood data on a regional basis to support regional analyses.

Project Lead and Contract:

Mel Schaefer – MGS
Dave Goldman – USCOE
Dan Levish – USBR
Jerry Stedinger – Cornell

Title: PRIORITY 5 - **Develop new structural method of calculating probability of failure from probabilistic dynamic loading and dynamic strength values**

Description:

a. *Why is this a priority research item*?
Probability of failure cannot be reliably estimated

b. *What is the expected outcome*?
More reliable methods for estimates
Embankment dams – Liquefaction and non-liquefaction induced deformations and seepage erosion and piping
Concrete and masonry gravity dams – The probability and extent of displacement and damage including where the dam is cracked, displaced but may not lead to break.

Project Tasks and Needs:

Embankment dams

- Case studies for details of deformation and cracking
- Tying together the state of art in liquefaction, post liquefaction strength and deformations
- Linking to piping

Concrete and masonry gravity dams

- Simplified displacement method based on a Newmark type analysis

Project Lead and Contract:

Embankment liquefaction –
Utah State (Loren Anderson)
Bureau of Reclamation
Corps of Engineers
Concrete and masonry - Chopra at UC Berkeley
Bureau and Corps

Title: PRIORITY 6 - **Loss of life estimates**

Description:

a. *Why is this a priority research item*?
  - Public safety is paramount
  - A main criteria for decision making
  - No accepted practice today

b. *What is the expected outcome*?
Improve effectiveness of EAP

Project Tasks and Needs:

Start with Graham '99 method. Assemble a qualified group to critically review. Evaluate and specify improvements (if required) to the method. Publish and publicize this method

Project Lead and Contract:

a. *Who is working in this area*?
Wayne Graham, USBR
Utah State, David Bowles & Duane McClelland
BC Hydro, Al Imrie (contact person)

b. *Who might be able to lead the project*?
One of the above – group to determine

c. *Who are good candidates to complete the work*?
Wayne Graham, USBR
Utah State, David Bowles & Duane McClelland
BC Hydro, Al Imrie (contact person)

Note that USU-USBR-BC Hydro are coordinating R&D activities in this area. USU is currently funding by Corps/USBR/ANCOLD, but additional funding is needed to complete case histories characterizations and life loss model development.

Title: PRIORITY 6 - **Early Warning Systems (Advance Indication of Incipient Dam Failure) – EAP**

Description:

a. *Why is this a priority research item*?
Public safety is paramount – early warning can save lives

b. *What is the expected outcome*?
Earlier notification of emergency response officials who are responsible for evacuation of public.

Project Tasks and Needs:

Define critical parameters to monitor, technologies to improve monitoring (the assumption is that a process for conducting FMEA will already be developed)

Project Lead and Contract

CEA Dam Safety Interest Group (for embankment dams)
- Project underway to identify anomalies in embankment dams using geophysical techniques

Cross reference to static response priority # 9.

Title: PRIORITY 8 - **Subjective Probability, Engineering Judgment and Inductive Processes**

Description:

a. Why is this a priority research item?
Risk Assessment Relies on Quantifying Subjective Judgment

b. What is the expected outcome?
Enhanced quality of RA results

Project Tasks and Needs:

Develop understanding of probability interpretations in engineering context
Develop understanding of cognitive processes in engineering context
Develop understanding of engineering judgment
Develop understanding of inductive reasoning in engineering context
Develop understanding of heuristics and biases in engineering context
Develop understanding of de-biasing techniques in engineering context

Project Lead and Contract

a. Who is working in this area?
S. Vick, C. Papay (Bechtel), various cognitive psychologists

b. Who might be able to lead the project?
S. Vick

c. Who are good candidates to complete the work?
S. Vick

Title: PRIORITY 13 - **Develop new structural methods of calculating probability of failure from probabilistic loads and resistance values**

Description:

a. *Why is this a priority research item*?
   Probability of failure cannot be calculated reliably

b. *What is the expected outcome*?
   Methods for calculating probability of failure

   Embankment dams – piping, slope stability, and combined
   Concrete and masonry gravity dams – sliding, piping, and overtopping scour for both Embankment and Concrete.

Project Tasks and Needs:

Embankment dams
  Piping – Exclusive laboratory erosion testing
    Case study decomposition
    Estimation of erosion (all modes)
  Slope stability - Develop practical methods from the available methods (incorporating spatial variability and foundation geological factors)

Concrete and masonry gravity dams
  Uncertainty in the geometry, … …, shear and tensile strengths, and uplift and 3D effects
  Piping - (covered in embankment)

Project Lead and Contact:

Embankment dams – Piping
  UNSW (R. Fell)
  Corps of Engineers (Art Waltz)

Embankment dams – Slope stability
  Utah State (Loren Anderson)
  Maryland (G. Baecher)

Concrete and masonry gravity dams
  UNSW (R. Fell, K. Douglas)
  Shear strength of rock and a little on concrete strength
  - Corps of Engineers
  - Chopra at U.C. Berkeley
  - David Goodman, HEC/Corps
  Others

7.0 Integrated Approach to Meeting Research Needs

From an examination of the 14 T^3 and 15 R&D prioritized needs listed in Tables 5.1 and 6.1, respectively, it can be seen that there are common topics amongst the different needs. Table 7.1 is an attempt to group the T^3 and R&D needs based on topics and risk assessment application areas.

Based on the grouping in Table 7.1, 12 integrated projects have been identified. Each project combines both R&D and T^3 needs. These projects are listed in Table 7.2, which shows the individual T^3 and R&D needs that are grouped together to form the integrated projects. They are listed in order of the highest priority T^3 or R&D need grouped under each integrated project, as determined by workshop participant voting.

Additional assumptions were made in developing the list of integrated projects is as follows:

1) The working group questioned if T-6 (Failure Modes Identification Tools for owners with limited resources) is achievable. They felt that owners should hire a qualified engineer rather than rely on tools alone.
2) The working group felt that T-10 (Regular program for operator training in Failure Modes Identification) is responsibility of individual owners.
3) The working group felt that T-3 (Training in understanding probability and skills such as expert elicitation) should be blended with other training for profession and the B.S. Civil Engineering curriculum.

The integrated project approach has the advantage of addressing related aspects of a topic first with research and then with T^3 activities that are linked to the research outcomes to disseminate them amongst the dam engineering community.

Table 7.1. Relationship between Integrated Projects (I - XII), Risk Assessment Application Areas, and Separate T^3 and R&D Projects

Topics	Risk Assessment Application Areas							
	Failure modes identification		Index approaches		Portfolio risk assessment		Detailed quantitative risk assessment	
	Research	Training	Research	Training	Research	Training	Research	Training
Guidelines	I(R-11)	I(T-1) I(T-4) T-6[b)]	II(R-1)			III(T-2)	IX(R-8) IX(R-9) X(R-10)	X(T-11) X(T-14)
Case histories	R-2[a)]	I(T-1) I(T-4)		II(T-7)	III(R-14)	III(T-5)		X(T-12)
Loading probabilities estimation							V(R-4) XII(R-15)	
Response probabilities estimation							VI(R-5) XI(R-13)	
Life loss estimation							VII(R-6)	
Tolerable risk guidelines							IV(R-3) IV(R-12)	IV(T-13) IV(T-14)
Risk communication							VIII(R-7)	
Training		I(T-1) I(T-4)		II(T-9)		III(T-9)		X(T-11)
Demonstration projects				II(T-9)		III(T-2) III(T-9)		X(T-8)

a) Assumed that NPDP is funded
b) Questionable if achievable - need to hire a qualified engineer
c) T-10 is responsibility of owner
d) Blend T-3 training with other training for profession PLUS for BS Curriculum

Table 7.2. Integrated T^3 and R&D Projects

Integrated Research Project		Priority as Voted on in Workshop as a separate T^3 or R&D Need		Separate T^3 or R&D Need						
				Code	Application Type	Description a)	Approach	Research Need Priority Category	Interpretation of Research Need Category	Importance Rating
I	**Failure Modes Identification for Standards-based Practice and Risk Assessment: Guidelines and Training**	T	1	3	Failure Modes Identification	Wider use of Failure Modes Identification thinking and current expertise in this area.	Document process. Document case histories, Training seminars, Hands-on workshops, Train facilitators, NPDP collect and estimate (journal or web-based) case histories.			30
		T	4	4	Failure Modes Identification	Build FMI into standards based reviews - this will economize resources				18
		R	11	D	Failure Modes Identification	Skills to identify failure modes		Do Later	Easy but Less Important	7
II	**Development of a prioritization tool for the states and small dam owners**	R	1	F	Prioritization/Index	**Prioritization Tools**		Low Hanging Fruit	Easy and Important	32
		T	7	8	Prioritization/Index	**Risk indexing and prioritization approaches for state regulators and owners with limited resources.**	Compilation and summary of existing approaches and development of an appropriate approach for the States, including equipping the states to evaluate risk assessment submittals.			10
		T	9	14	Portfolio	More experience by more people	Demonstration projects. Train more facilitators. Sponsor seminars aimed at educating non-technical staff among owners.			7
III	**Portfolio Risk Assessment: Guidelines, case histories and training.**	T	2	1	Portfolio	Guidelines for what constitutes a Portfolio Risk Assessment and how it may be done	Guidelines			25
		T	5	6	Portfolio	Sharing experience on PRA with others, how well the process worked, and what should be changed.	Publish completed Portfolio Risk Assessments with assessments of their strengths and weaknesses and ways to improve			14
		T	9	14	Portfolio	More experience by more people	Demonstration projects. Train more facilitators. Sponsor seminars aimed at educating non-technical staff among owners.			7
		R	14	S	Portfolio	Portfolio - Learn to improve (S)		Do Later	Easy but Less Important	0
IV	**How safe is safe enough? Tolerable public safety/risk criteria and standards approach.**	R	3	B	Detailed Quantitative	**Tolerable Risk Criteria**		Strategic Plan	Hard and Important	49
		R	12	A	Detailed Quantitative	Standards		Do Later	Easy but Less Important	5
		T	13	11	Detailed Quantitative	Produce a life safety criteria discussion paper, exhibit publicly and invite submissions	Discussion paper			5
V	**Estimation of Flood Loading**	R	4	M	Detailed Quantitative	**Flood Loading**		Strategic Plan	Hard and Important	26
VI	**Prediction of Earthquake Response of Dams**	R	5	G	Detailed Quantitative	**Earthquake Response**		Strategic Plan	Hard and Important	26
VII	**Estimation of Loss of Life**	R	6	I	Detailed Quantitative	**Loss of Life Estimation**		Strategic Plan	Hard and Important	24
VIII	**Communicating risk in dam safety**	R	7	J	Detailed Quantitative	Risk Communication		Strategic Plan	Hard and Important	22
IX	**Subjective probability**	R	8	C	Detailed Quantitative	**Subjective Probability**		Strategic Plan	Hard and Important	20
		R	9	E	Detailed Quantitative	Uncertainty		Do Later	Easy but Less Important	14
X	**Detailed quantitative risk assessment: guidelines, case histories and training**	R	10	N	Detailed Quantitative	Risk Processes		Do Later	Easy but Less Important	13
		T	8	7	Detailed Quantitative	Demonstration projects	Hands-on not just Observers at USBR RA; groups of owners			8
		T	11	9	Detailed Quantitative	Documentation of state-of-the-practice and training workshops	Documentation and workshops			5
		T	12	10	Detailed Quantitative	Compilation of case histories	Case histories			5
		T	14	16	Detailed Quantitative	Dam safety community should interact with DOE, NRC on QRA	Interaction			3
XI	**Prediction of Normal Operating Condition (Static) Failure for Dams**	R	13	H	Detailed Quantitative	**Static Response**		Do Later	Easy but Less Important	1
XII	**Estimation of Earthquake Loading**	R	15	L	Detailed Quantitative	Earthquake Loading		Consider	Hard and Less Important	13

a) Research proposal suggestions were developed for projects listed in bold (see Section 6.6)

8.0 References

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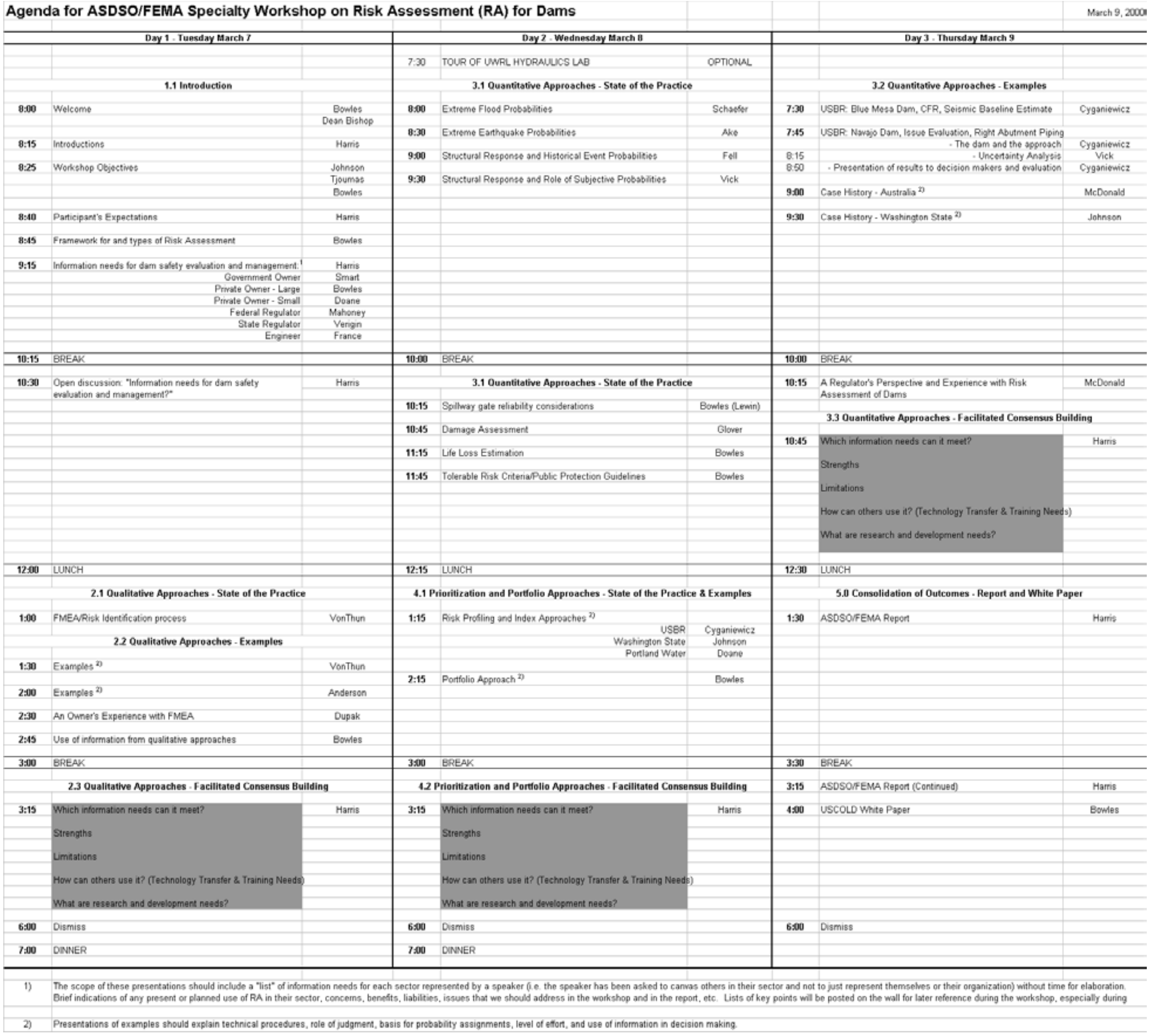
Appendices

Appendix A. Workshop Agenda



Agenda for ASDSO/FEMA Specialty Workshop on Risk Assessment (RA) for Dams

March 9, 200

Day 1 - Tuesday March 7			Day 2 - Wednesday March 8			Day 3 - Thursday March 9		
			7:30	TOUR OF UWRL HYDRAULICS LAB	OPTIONAL			
	1.1 Introduction			**3.1 Quantitative Approaches - State of the Practice**			**3.2 Quantitative Approaches - Examples**	
8:00	Welcome	Bowles	**8:00**	Extreme Flood Probabilities	Schaefer	**7:30**	USBR: Blue Mesa Dam, CFR, Seismic Baseline Estimate	Cyganiewicz
		Dean Bishop						
			8:30	Extreme Earthquake Probabilities	Ake	**7:45**	USBR: Navajo Dam, Issue Evaluation, Right Abutment Piping	
8:15	Introductions	Harris					- The dam and the approach	Cyganiewicz
			9:00	Structural Response and Historical Event Probabilities	Fell	8:15	- Uncertainty Analysis	Vick
8:25	Workshop Objectives	Johnson				8:50	- Presentation of results to decision makers and evaluation	Cyganiewicz
		Tjoumas	**9:30**	Structural Response and Role of Subjective Probabilities	Vick			
		Bowles				**9:00**	Case History - Australia 2)	McDonald
8:40	Participant's Expectations	Harris				**9:30**	Case History - Washington State 2)	Johnson
8:45	Framework for and types of Risk Assessment	Bowles						
9:15	Information needs for dam safety evaluation and management:[1]	Harris						
	Government Owner	Smart						
	Private Owner - Large	Bowles						
	Private Owner - Small	Doane						
	Federal Regulator	Mahoney						
	State Regulator	Vergin						
	Engineer	France						
10:15	BREAK		**10:00**	BREAK		**10:00**	BREAK	
10:30	Open discussion: "Information needs for dam safety evaluation and management?"	Harris		**3.1 Quantitative Approaches - State of the Practice**		**10:15**	A Regulator's Perspective and Experience with Risk Assessment of Dams	McDonald
			10:15	Spillway gate reliability considerations	Bowles (Lewin)			
							3.3 Quantitative Approaches - Facilitated Consensus Building	
			10:45	Damage Assessment	Glover			
						10:45	Which information needs can it meet?	Harris
			11:15	Life Loss Estimation	Bowles			
							Strengths	
			11:45	Tolerable Risk Criteria/Public Protection Guidelines	Bowles			
							Limitations	
							How can others use it? (Technology Transfer & Training Needs)	
							What are research and development needs?	
12:00	LUNCH		**12:15**	LUNCH		**12:30**	LUNCH	
	2.1 Qualitative Approaches - State of the Practice			**4.1 Prioritization and Portfolio Approaches - State of the Practice & Examples**			**5.0 Consolidation of Outcomes - Report and White Paper**	
1:00	FMEA/Risk Identification process	VonThun	**1:15**	Risk Profiling and Index Approaches 2)		**1:30**	ASDSO/FEMA Report	Harris
				USBR	Cyganiewicz			
	2.2 Qualitative Approaches - Examples			Washington State	Johnson			
				Portland Water	Doane			
1:30	Examples 2)	VonThun						
			2:15	Portfolio Approach 2)	Bowles			
2:00	Examples 2)	Anderson						
2:30	An Owner's Experience with FMEA	Dupak						
2:45	Use of information from qualitative approaches	Bowles						
3:00	BREAK		**3:00**	BREAK		**3:30**	BREAK	
	2.3 Qualitative Approaches - Facilitated Consensus Building			**4.2 Prioritization and Portfolio Approaches - Facilitated Consensus Building**		**3:15**	ASDSO/FEMA Report (Continued)	Harris
3:15	Which information needs can it meet?	Harris	**3:15**	Which information needs can it meet?	Harris	**4:00**	USCOLD White Paper	Bowles
	Strengths			Strengths				
	Limitations			Limitations				
	How can others use it? (Technology Transfer & Training Needs)			How can others use it? (Technology Transfer & Training Needs)				
	What are research and development needs?			What are research and development needs?				
6:00	Dismiss		**6:00**	Dismiss		**6:00**	Dismiss	
7:00	DINNER		**7:00**	DINNER				

1) The scope of these presentations should include a "list" of information needs for each sector represented by a speaker (i.e. the speaker has been asked to canvas others in their sector and not to just represent themselves or their organization) without time for elaboration. Brief indications of any present or planned use of RA in their sector, concerns, benefits, liabilities, issues that we should address in the workshop and in the report, etc. Lists of key points will be posted on the wall for later reference during the workshop, especially during

2) Presentations of examples should explain technical procedures, role of judgment, basis for probability assignments, level of effort, and use of information in decision making.

Appendix B. List of Participants

Name	Affiliation	Address
Ake, Jon	USBR	PO Box 25007 D-6600, Denver, CO 80225
Akridge, Mike	Southern Services, Alabama Power	PO Box 2641, 16N-0380, Birmingham, AL 35291
Anderson, Loren	Utah State University/RAC Engineers & Economists	Civil & Environmental Engineering, Utah State University, Logan UT 84322-
Bahleda, Mike	EPRI	3412 Hillview Ave., Palo Alto, CA 94304
Bechai, Mona	Ontario Power Generation	700 University Ave., Toronto, Ontario M5G 1X6, Canada
Bowles, David	Utah State University/RAC Engineers & Economists	Utah Water Research Laboratory, Utah State University, Logan UT 84322-8200
Chauhan, Sanjay	Utah State University/RAC Engineers & Economists	Utah Water Research Laboratory, Utah State University, Logan UT 84322-8200
Cyganiewicz, John	USBR	PO Box 25007 D-8311, Denver, CO 80225
Davis, Al	Alton P. Davis Jr. Consultant	12 Old Mill Road, PO Box 223, W Ossipee NH 03890
Doane, Jim	Portland Water Bureau	1120 SW 5th Ave, Room 600, Portland, OR 97204-1926
Dupak, Dan	Ontario Power Generation	700 University Ave., Toronto, Ontario M5G 1X6, Canada
Fell, Robin	University of New South Wales	University of New South Wales, Syndye NSW Australia
France, John	URS Greiner Woodward Clyde	Stanford Place 3, Ste 1000, 4582 S Ulster St Pkwy, Denver, CO 80237
Glover, Terry	Utah State University/RAC Engineers & Economists	Economics Dept., Logan, UT 84322-3530
Hampton, Terry	Mead & Hunt	6501 Watts Rd, Ste 101, Madison, WI 53719
Harris, David	USBR	PO Box 25007 D-8180, Denver, CO 80225
Johnson, Doug	Washington State/ASDSO	Dept. of Ecology, PO Box 47600, Olympia, WA 98504-7600
Lindon, Matt	State of Utah	Div. Of Water Rights, PO Box 146300, SLC UT 84114-6300
Mahoney, Dan	FERC	888 1st Street NE, Rm 61-05, Washington, DC 20426
Marshall, Kevin	Portland General Electric	121 SW Salmon St., Portland, OR 97204
McDonald, Len	L.A. McDonald	6 Kiama St, Greystanes NSW 2145 AUSTRALIA
Salmon, Gary	coordinator, dam safety interest group	1251 Clyde Ave., West Vancouver, BC, CANADA V7T 1E6
Schaefer, Mel	MGS Engineering	7326 Boston Harbor Rd NE, Olympia, WA 98506
Smart, John	USBR	
Smith, Grant	Ontario Power Generation	700 University Ave., Toronto, Ontario M5G 1X6, Canada
Tarbox, Glenn	Harza Engineering	2353 130th Ave, NE, Ste. 200, Bellevue, WA 98005
Tjoumas, Gus	FERC	888 1st Street NE, Rm 6A-11, Washington, DC 20426
Verigin, Steve	Design Engineering	CA Division of Safety of Dams, 2200 X St. Ste 200, Sacramento, CA 95818
Vick, Steve	Consultant	42 Holmes Gulch Way, Bailey, CO 80421
VonThun, Larry	Consultant	820 S Estes St., Lakewood, CO 80226
Zeizel, Gene	FEMA	MTTS 500 "C" St. SW, Rm. 418, Washington, DC 20472

Appendix C. List of Handouts

Item #	Speaker	Description
Workshop Agenda		
List of Attendees		
Section 1.0 INTRODUCTION		
1a	D. Bowles	PowerPoint (PP) presentation - Workshop Objectives
1b	D. Bowles	PP Presentation - Framework for and types of Risk Assessment
2		Paper - "The Practice of Dam Safety Risk Assessment and Management: Its Roots, Its Brances, and Its Fruit"
3		Paper - "A Role for Risk Assessment in Dam Safety Management"
4		Paper - "Understanding and Managing the Risks of Agin Dams: Principles and Case Studies"
5		Report - "Dam Safety Risk Analysis Methodology" by USBR
6		Paper - "Engineering Application of Dam Safety Risk Analysis" by S. Vick
7	J. Smart	Overhead - "Government Owner Information Needs"
8	D. Bowles	PP Presentation - "Large Private Owners"
9	J. Doane	Handout - "The Perspective of the Small Dam Owner"
10	D. Mahoney	PP Presentation - "What Regulators Need"
11a	S. Verigin	Handout - "ASDSO/FEMA Specialty Workshop Risk Assessment for Dams"
11b		Handout - Risk and Liability
12		Handout - Comments by Doug Johnson
13	J. France	Overhead - "Information Needs for Dam Safety Evaluation and Management - Engineer's Perspective"
Section 2.0 QUALITATIVE APPROACHES		
Sub-Section 2.1 State of the Practice		
14	L. VonThun	Overheads - "A Qualitative Approach - FMEA+Failure Mode and Effects Analyses+"
15		Handout - "Broad Based Approach to Dam Safety Risk Assessment"
Sub-Section 2.2 Examples		
16	L. VonThun	Handout - "Experiences and Results from FMEA's Case A - Composite Embankment and Gravity Dam"
17	L. Anderson	PP Presentation - "Framework Components"
18	D. Dupak	Handout - "An Owner's Experience with FMEA"
19	D. Bowles	PP Presentation - "Use of Information from Qualitative Approaches"
Sub-Section 2.3 Consensus Building		
Section 3.0 QUANTITATIVE APPROACHES		

Item #	Speaker	Description
Sub-Section 3.1 State of the Practice		
20	M. Schaefer	Presentation - "Estimating Probabilities of Extreme Floods"
21		Paper - "A Framework for Characterization of Extreme Floods for Dam Safety Risk Assessment" by R. Swain, et al.
22		Paper - "A Probability-Neutral Approach to the Estimation of Design Snowmelt Floods" by R. Nathan and D. Bowles
23	J. Ake	Presentation - "Development of Probabilistic Earthquake Loading Functions for Use in Dam Safety Evaluations"
24	R. Fell	Handout - "Quantitative Risk Assessment of Dams Estimation of Probabilities of Failure"
25	S. Vick	Handout - "Structural Response and Role of Subjective Probability"
26		Report - "Considerations for Estimating Structural Response Probabilities in Dam Safety Risk Analysis"
27	D. Bowles (J. Lewin)	Paper - "Hydraulic Water Control Structures for Dams - How Reliable?" ICODS Technical Seminar by J. Lewin
28	T. Glover	Overheads - "Damage Assessment"
29	D. Bowles	PP Presentation - "Life Loss Estimation"
30		Paper - "Life-Loss Estimation: What Can We Learn from Case Histories?"
31		Paper - "A Procedure for Estimating Loss of Life Caused by Dam Failure" by W. Graham USBR
32	D. Bowles	PP Presentation - "Tolerable Risk Criteria/Public Protection Guidelines"
33		Overhead - "Dam Safety Risk Based Dam Safety Criteria and Guidelines"
34		Paper - "Guidelines for Achieving Public Protection in Dam Safety Decision Making" USBR
Sub-Section 3.2 Examples		
	J. Cyganiwicz	
35	J. Cyganiewicz & S. Vick	Overhead - "Navajo Dam Risk Analysis 1998"
36		Paper - "Dam Safety Risk Analysis for Navajo Dam" by K. Dise and S. Vick
37	L. McDonald	Handout - "Case Study - Australia, Intitial Phase of Risk Assessment"
38	D. Johnson	Handout - "Application of Risk Concepts in a Standards-Based Framework for Dam Safety in the State of Washington"
39		Paper - "Alamo Dam Demonstration Risk Assessment" by D. Bowles, et al.
40		Group of 5 Papers - "Dam Safety Evaluation for a Series of Utah Power and Light Hydropower Dams, Including Risk Assessment"
41	L. McDonald	Handout - "A Regulator's Perspective and Experience with Risk Assessment for Dams"
42		Handout - "Areas for Improvement, Based on Experience with Risk Assessment for Dams in Victoria, Australia" by D. Watson
43		Memorandum - "Subject: Advice - Liability - Risk Assessment" by N. Himsley
44		Paper - "ANCOLD Guidelines on Risk Assessment Position Paper on Revised Criteria for Acceptable Risk to Life" by ANCOLD Working Group on Risk Assessment
Sub-Section 3.3 Consensus Building		
Section 4.0 PRIORITIZATION & PORTFOLIO APPROACHES		
Sub-Section 4.1 State of the Practice and Examples		
45	J. Cyganieqicz	Bound report insert - "Risk Based Profiling System" USBR
46	D. Johnson	Handout - "Commentary on Algorithm for Prioritization Ranking of Dams with Safety Deficiencies"
47	J. Doane	Overhead - "Portland Oregon's Experience with Risk Assessment"
48	J. Doane	Handout - "Portland Oregon's Experience with Risk Assessment"
49	D. Bowles	PP Presentation - "Portfolio Approaches: Principles and Case Study"
50		Paper - "Portfolio Risk Assessment: A Tool for Dam Safety Risk Management"
51		Paper - "Portfolio Risk Assessment: A Basis for Prioritizing and Coordinating Dam Safety Activities"
Sub-Section 4.2 Consensus Building		
Section 5.0 CONSOLIDATION OF OUTCOME		
Sub-Section 5.1 ASDSO/FEMA Report		
52		Revised Proposed Outline - USCOLD White Paper
Sub-Section 5.2 USCOLD White Paper		
Section 6.0 BIBLIOGRAPHY		
53		Draft Bibliography: Risk Assessment for Dams

Appendix D. Participants Expectations and Issues

D.1 Expectations

Blending FMEA into standards based dam safety program
Recognize and acknowledge different needs for different strengths.
A prioritized list of risk assessment, research needs, and who will conduct the studies.
Help owners (large majority) and engineers get value from risk assessment.
Hear state of practice view of the non-believers and help inform.
Sniff the other dogs.
Identify benefits of using risk-methodology in state programs.
Identified data sources.
Took risk from gut to head.
Attached risk component to federal funds to states.
Understanding regulator's perspective.
Move towards understanding of state and practices.
Did not write guidelines.
State of practice, strengths/weaknesses, where can apply how, research needs, how to strengthen, how to facilitate others using it.
Ideas to improve my dam safety program.
Identified sources of fear
Identify areas where risk research would benefit states.
Help other uncomfortable with risk concepts betters understand them.
Viewpoints of regulators and owners.
Understood how to "sell" the concept back home.
Identified areas of collaboration.
Does practiced mean right!
Brought to light issues affecting RA.
Catch 22, you don't know, I won't vie you the money to find out.
Identified research needs to better explain options to the public.
Improve knowledge on FMEA.
To learn, to gain acceptance of RA.
Developed necessary perspectives.
Began to discuss role of subjective probabilities in quantitative RA.
Compare what we are doing to what others are doing, looking for different ideas.
How to develop a standardized RA method so the general profession can adopt and use it.
We found out how RA will develop.
Update on state-of-the practice.
Consensus on priority research needs.

D.2 Issues

Major benefit from getting a team approach? Still requires a standard process.
It is reasonable to rely on warning and evacuation as a risk reduction measure.
Risk seems to add to shortcomings of standards approach as opposed to avoid. Parameter uncertainty analysis.
Change paradigm for quantitative risk analysis.
Who could go to jail if the dam fails?
About 1 in 100 dams fails.

Regulators need to educate government that “safe” means a low probability of failure, not "no chance" of failure.
The FEMA requirements are impossible if followed rigidly.
Phase I → Phase II
FMEA → RAM → RAS
Fix Remove Dam?
Technical advocate as consulting engineer is a valid concern.
Example of a lot of calculation at Keenley Side Dam.
Parallel risk assessments of the same dam.
EAP vs. fixing dam.
How can RA benefit owners of one or a few dams?
Now dams vs. existing dams.
Missing failure modes.
Also a problem with defensibility of standards.
Incentive/need to undertake risk assessment if dams meet standards/regulations.
Repeatability (even for qualitative methods).
How do we change standards without addressing risk?
Legislature, not the regulator should determine risk level accepted.
Dams are only one piece of society‘s risk pool.
Strive for consistent risk.
All civil engineering is empirical. It is risk-based!
FS = 1.5 means low risk, not zero risk.
Standards: What is a reasonable FS?
Is the MCE adequately conservative?
Dams with no possibility of life loss.
Large dams that must meet PMF/MCE.
The public is extremely risk adverse about dams. How can you get acceptance of risk levels given that?
Is standard approach a zero risk approach?
Acceptance of loss of life.
Engineers and lawyers = inferior dam safety decisions.
Is legislative intent to get to zero risk to life?
Profiling, Portfolios, ?? (classifications) all require quantification.
Prioritization means some things are not done.
Standards are not restrictive thinking.
Failure modes should always be considered.
Accepted levels of risk are an organization-by-organization case-by-case aspect.
The risk is the owner’s, what is the means for non-owner beneficiaries to share the risk.
Owner be able to defend what you are doing as being reasonable and prudent.
Case history compilations need to be parameter specific.
Ultimately public must buy into risk. Right now if an individual is financially involved, risk is considered. If the owner is the financial source, the public wants zero risk.
State legislation says ‘remove the risk’, implies that there could be zero risk. Not possible.
Subjective probabilities bad for quantitative RA but OK for standards?

D.3 How others can use it? (Technology Transfer and Training Needs?)

Build FMEA into standards based reviews—economy of resources.
Someone (FEMA/ASDSO/ICODS)? Should develop a “methodology” that tries to standardize the process.
Do dams in groups with same experts.

Need ways to get limited expertise applied more broadly.
Regular program for operator training.
Focus on integration with existing efforts.
Review case histories.
Failure mode thinking.
Documented case histories.
Training seminars.
Hands-on workshops.
Systematic approach—list elements and ask how can find.
RAC could share some of their failure mode spreadsheets with the rest of us.
Documented reports of use.
Focus on integration with existing efforts.
Tools for owners with limited resources.
Get smaller group of experienced FMEA experts to write down the logic/process of how to do FMEA.
Avoid monopoly.
Develop more people as qualified facilitators.

Appendix E. Participant Input on Information Needs for Dam Safety Evaluation and Management

E.1 Summary of Information Needs

1. Establish Evaluation Process
    - a. Protection of life and property
    - b. Develop no risk class
    - c. Develop standards
    - d. Establish guidelines
    - e. Public safety
    - f. Acceptance by public
    - g. Accepted levels of risk

2. Risk Identification
    - a. Use risk to identify problems
    - b. Procedure for quickly and easily classify
    - c. Team approach generates a good evaluation
    - d. FMEA

3. Hazard Classification and Consequences
    - a. Hazard classification
    - b. Define hazard ratings

4. Confidence Level
    - a. Know uncertainties
    - b. Degree of uncertainty
    - c. Credibility verification/confidence building
    - d. Standard/regulations sufficient
    - e. Public trust and reputation

5. General Risk Management Considerations
    - a. Risk management options
    - b. Risks that should be reduced in the short-term
    - c. Risks that should be reduced
    - d. Cost effectiveness
    - e. Tight budget
    - f. Risks associated with all dams around
    - g. Risk is removed
    - h. Prioritization

6. Business/Legal/Political Considerations
    - a. Effect of delays

b. Legal and political constraints
c. Endangered species
d. Business viability
e. Not lives if business
f. Regulatory considerations
g. Business risk
h. Legal liability
I. Societal risk
j. Retention of insurance coverage

7. Risk Analysis

a. Common understanding of definitions
b. Procedures and practices
c. Concept and calculation of loss of life
d. Probabilities of extreme events are accurate
e. Basics of risk management
f. Establish process
g. Basic knowledge of risk analysis
h. Improved tools

E.2 Notes on Information Needs

Information needs for dam safety evaluation and management

What: (Name of a need)

1. Establish Evaluation Process Risk Acceptance Criteria

Who: (Needs this)

Decision makers (owners), regulators, and public (to know there is a process).

Why/When: (Do they need it)

To set the framework for the rest of the process
Beginning—a set of expectations.

Where will it be used: (In-house, public meetings)

In making the decisions on the dam.

How will it be used:

Risk will be compared with the expectations.

Information needs for dam safety evaluation and management

What: (Name of a need)

2. Procedures for accomplishing risk identification

Who: (Needs this)

75,000
25,000
The majority of dam owners and engineers who do their evaluation (if any) and regulators.

Why/When: (Do they need it)

For inspection/evaluation/monitoring for public safety
Money being spent in right places
Yesterday/ASAP

Where will it be used: (In-house, public meetings)

By regulators
By owners/engineers

How will it be used:

To identify dam safety actions
- monitoring
- investigating
- inspections
- analyzing/evaluation
- modifications/improvements
- prioritization
- getting funding or assistance

Information needs for dam safety evaluation and management

What: (Name of a need)

3. Hazard classification and consequences

A list of considerations:

Traditional Issues:
- Height
- Volume
- People
- Property

Modern Issues:
- Social effects
- Environment
- Political
- Legal

Who: (Needs this)

- Owners
- Engineers
- Regulators
- Government (decision makers, politicians)
- Public

Why/When: (Do they need it)

They need it today. (When) Need continuous updating.
They need it to understand the hazard that the dam is posing. (Why)

Where will it be used: (In-house, public meetings)

It will be used wherever it is necessary to inform recipient of dam hazard, both individually and relatively (portfolio).

How will it be used:

4) Set priorities
5) Maintain awareness

Information needs for dam safety evaluation and management

What: (Name of a need)

4. Confidence Level

Who: (Needs this)

Regulators, legislators, public, owners, engineers (stakeholders).

Why/When: (Do they need it)

Decision time.

Where will it be used: (In-house, public meetings)

Need to understand the variability from an absolute answer in the decision process (credibility).

How will it be used:

To make informal and accepted decisions (uncertainty analysis).

Information needs for dam safety evaluation and management

What: (Name of a need)

5. Decision-making for Risk Management/Risk Reduction

Who: (Needs this)

Owners, regulators, decision-makers, technical advisers to decisions.

Why/When: (Do they need it)

Sequence, timing, and extent of risk reduction actions and justification of proposed plan.

Where will it be used: (In-house, public meetings)

In-house, public meetings.

How will it be used:

Use risk-based information to make decisions.

Information needs for dam safety evaluation and management

What: (Name of a need)

6. Business criteria/legal framework & Political realities-risk perception

Who: (Needs this)

Owner
Public-lawmakers
Planners-developers
Engineer knowing the business parameters
Insurance industry
Private persons - liability issues - environmental

Why/When: (Do they need it)

Why - regulatory issues; protection of private and public assets
When - design-planning phase; operation phase; decommissioning phase

Where will it be used: (In-house, public meetings)

Same as Why/When
Public policy bodies
Business policy bodies

How will it be used:

Risk management decisions at each phase of the life cycle

Information needs for dam safety evaluation and management

What: (Name of a need)

7. Understanding the meaning of probabilities in general

Who: (Needs this)

All interpreting probabilities

Why/When: (Do they need it)

Before starting a RA

Where will it be used: (In-house, public meetings)

Yes (in-house, public meetings).

How will it be used:

To understand the meaning of a probability estimate

Information needs for dam safety evaluation and management

What: (Name of a need)

7. Reliable and acceptable methods for determining probability and extent of failure

Who: (Needs this)

1. Engineers
2. Regulators
3. Others

Why/When: (Do they need it)

Why - To get reliable, consistent, and defensible answers (legally defensible)

Where will it be used: (In-house, public meetings)

In the process of carrying out R/A and in presenting it to others

How will it be used:

Evaluating safety of dams

Appendix F. Participant Input on Failure Modes Identification (Qualitative Approaches)

F.1 Strengths

Identification of failure mechanisms otherwise been over looked.
Identify alternative failure modes.
Increase understanding of dam
Bring in Electrical, Mechanical, Environmental views.
Develop transitions between specialists and engineering consultants
Help initial prioritization of issues.
Identify uncertainties.
Start public involvement.
Identify new data needs.
Identifies failure modes.
Team approach provides variety of viewpoints.
Failure mode identification.
Can use to evaluate and synthesize various aspects of dam safety program.
Can use as QA tool to evaluate remedial design.
Strengthens the diligence.
Can piggyback on periodic design review.
Prioritize Risk.
Apples to apples.
Less data requirements.
Quicker to complete.
Considers factors that are difficult to quantify.
Can get by off by staff.
Can get buy in of regulator/Dam safety decision makers efficient.
Provides a supplement to standards based.
Simple.
Helps with surveillance.
Identifies all failure modes.
Gives crude identification of critical failure modes.
Raises awareness of issues with management.
Failure mode identification is 1/2 value of RA vs. deterministic thinking.
Identifies simple, cost-effective risk reduction measures.
Quick.
Broad.
Some useful information provided.
Helps identify all failure modes.
Identifies unusual failure modes—the oddball failure mode.
More people buy into the process.
Helps you think more broadly.
Simple.
Identification of risk otherwise not noted.
Better than no RA at all.
Easily done.
Wide acceptability.
Valuable information.
Organized focus on failure modes. FMEA more likely to identify potential failure modes.

Identified dam's weak link(s).
A lot of information with little effort.
Comprehensive.
Systematic.
Brings balance to Dam Safety programs.
Brings insight and understanding.
Broad-based more likely to have acceptance in standards-based community.
Improved understanding of strengths and vulnerabilities of dam.
Identifies safety issues beyond standards based.
Teach approach.
The concepts better understood.
Involves more individuals.
Relatively simple.
Identifies failure modes quickly.
Process encourages discovery of all failure modes.
Makes use of available materials (studies).
Helps to prioritize fixes.
It is a start.
Provides something to react to.

F.2 Limitations

Repeatability.
Reliability.
Biases.
Not much relative ranking provided.
Not much existing direction on "how to" available.
May be difficult to dams with little background information.
Resource limitation of organization (staffing).
Still lacks quantification in making a choice of what's most important.
Does not quantify risk.
Ultimately requires decisions on basis of old standards.
Lack of quantification.
Affected by experience of the team.
Magnitude of risks from various sources hard to compare.
Indicator only. Not quantifier.
More difficult to portray confidence level.
Personalities within the team.
Defensibility.
Repeatability.
Based on opinion.
No "standard" of good practice.
Not fool proof.
Difficult to compare importance (risk) from each failure mode.
Difficult to compare dams.
Not acceptable criteria.
Procedure may not be consistent from team to team.
Does not provide a measure of risk.
Does not reveal relative risks as required by dam safety decisions.
Lack of universally approved methodology.
Limited use to small dam owners (i.e., cannot afford the process).

Are the regulations met?
Uses the word “failure.”
Parameter uncertainty not included.
Dollar cost of process may limit application.
No quantification.
Lack of accepted standards.
Not a public oriented process.
Subjective—may not be repeatable.
Limited by efforts allocated and composition of team.
Lack of prioritization.
Reliant on “judgment” to exclude.
Team affected by “Group Think.”
Limited data extrapolations (i.e., failure modes, static, gates, filter, drains, structures ..).

F.3 What are research and development needs?

Identify skills required to identify failure modes.
Build database of case histories.
Include curriculum in schools in failure modes.
Analyze data from NPDP on failures and repair.
Communicate best practices to others.

F.4 How can Qualitative Approaches be Improved?

List all elements of dam system (includes foundations, slopes, abutments, etc.)
How can each element fail to function as intended?
What is effect?
Exclude likelihood of outset—list all conceivable modes.
Address likelihood as a second step.
Include 2-3 experienced failure mode thinkers.
Reduce bias by assuming failure, than looking for possible reasons.
Need to involve the operators.
Develop generic list of failure modes.
Collect/summarize failure/accident data for main failure modes and disseminate the data (as much as which did not fail despite starting to)
Think like ECK.
Big picture vs. small view. Persons must see the whole picture to predict most likely failure mode.
Digital view vs. analog view.
Focus on benefits not just difficulties.
Process needs to be molded into dam inspections.
Provide process that is scalable to range of available resources.
Include details of effects of methodologies and technical knowledge with their effects on the process.
Learn by doing.
Develop skills through case history studies.
Look at dams with failure scenarios developing conditions in mind.
Review of only failure of accident (i.e., NASA), can lead to insight in how they happen so they can be prevented.
Imagine failure in hypothetical hindsight.
Examine dams with failure modes in mind.
Focus on asking the failure mode questions.

Appendix G. Participant Input on Portfolio and Index Approaches (Prioritization and Portfolio Approaches)

G.1 Strengths

Able to identify relative needs for repairs.
Based on existing data.
Dam safety sooner.
Do most in shortest time with least resources.
Identify priority for risk reduction measures.
Provide some level of justification for proceeding with/deferring fixes.
Helpful to owners with a new dam safety program.
Non-judgmental between dams.
Help with obtaining funding.
Builds consensus on priorities.
Common currency across owners, dams elements, failure-modes.
Rational basis for priorities.
Paints picture liabilities.
Allows comparison.
Input to decision-making.
Provides better picture of the dam system.
Site to site comparisons possible.
Provides insight into sensible strategies.
Provides true measure of risk.
Coordination of engineering issues with business needs, objectives and priorities.
Integration of all aspects of dam safety program.
Flexible—can be adjusted to desired level of detail.
Logical, defensible prioritization of risk.
Provides basis for better use of limited funds.
Provides means to gain management support.
Creates mechanism to improve loss of life criteria economically.
Generally defendable for action—no action.
More bang for the buck.
Gives owner “high level” understanding of risks.
Allows rapid and consistent evaluation of portfolio, also cost effective.
Quick.
Forces judgment.
All components of risk can be quantified.
Allows priorities without dealing in absolutes.
Has room for unknown or unresolved issues.
It’s systematic.
It’s explainable.
Can probably repeat results.
Identifies entire scope of dam safety needs.
Identifies urgent (quick fix) needs.
Allows the maximization of risk reduction for each Dollar.
Organized approach to develop relative ranked order of projects with deficiencies.
If dam low on priority list fails, provides some defense to regulator.
Allows regulator to apply limited resources to project posing most risk.
Allows identification of deficiencies (through FMEA), and risk calculation.
Prioritizes these in loss of life and financial terms.

Economic if done in groups of dams.
Gives overall risk profile.
Allows prioritization of investigations and monitoring.
Compares: 1) dams and performance; 2) criteria; and 3) consequences.
Leads to cost-effective further investigations.
Can be done based on existing data.
Provides prioritization and justification for fixes and investigations.
Provides basis for risk reduction program/meets due diligence.
Preserves probability metric.
Initial identification of dam safety issues.
Puts dam safety issues into a form that owner's decision matters can relate to, especially if they are non-technical people.
Identifies highest priority projects.

G.2 Limitations

Are the numbers believable?
Evaluation is more broad-brush.
Isn't absolute.
Doesn't say how fast.
Based on existing data.
Using the results beyond intentions.
Variation among different systems.
Too great a variability in risk numbers.
Defensibility sometimes questionable.
Is it practical other than for owners of large numbers of dams?
Limited number of experienced and qualified facilitators.
May provide a false sense of security.
"Broad brush" may not reveal all-important vulnerabilities.
Less useful for small owners with few dams.
Can provide excuse not to proceed with detailed assessments.
Priorities may change.
Identifies deficiency. Does not force fix. Negligence?
Can mislead.
Can be misused.
Beyond defensibility.
Do we have to spell prioritization with an "S"?'
No published standards for performing.
Incorrect existing data could lead to incorrect conclusions.
Difficult to communicate limitations.
May be too crude.
High probability failure modes may not receive proper consideration.
Limited by easily available data and analysis—probability not constant across inventory.
May be superficial.
How to deal with dams with a lot of information vs. those with little or no information.
Costs.
Index approaches not true utilization of risk assessment and FMEA.
Only gives owner "high level" understanding of risks.
Prioritization means some things are not done.
Owners and engineers start to believe the risks absolutely and want to sign off without detailed RA and detailed engineering.

Not clear in regard to uncertainty.
It is seldom quantified.
Some techniques for estimation of, e.g., consequences, are limited accuracy.
May mis-prioritize.
No accepted approach for consistent application.
Index methods may not preserve probability metric and therefore may distort priorities.
Does not maximize rate of cost-effectiveness.
No sign off.
Risk criteria evaluations may be assumed to be final.
Haste may miss important failure mode.
May be too costly for small owners.
Must keep uncertainties in inputs on the screen for decision makers.

G.3 How Can It Be Improved?

Leave it alone and don't mess it up.
More defendable relationships between ranking variables.
Develop process standards for some level of consistency.
Develop procedure or guideline by having a general documentation of PRA methods.
Need tier system so we can meet owner resource availability.
Prepare consensus statement on uses and limitations.
Use high-level review panel for key inputs to portfolio RA.
Develop and make available portfolio software.

G.4 How Can Others Use it (Technology Transfer and Training Needs)?

Seems that transfer must be done one to one coaching.
Develop guidelines for what constitutes a portfolio assessment and how it may be done.
Sponsor seminars aimed at educating non-technical staff among owners.
More experience by more people.
By sharing experience on PRA with others on how well the process worked and what should be changed.
Demonstration projects.
Train more facilitators.
Publish complete portfolio risk assessment case study(ies) as a general study(ies) include strength and weaknesses.
ASDSO could compile risk indexing and prioritization approach and provide summary to states.

G.5 What are R&D Needs?

Debate underlying concept → consensus concept.
Debate mechanics → consensus on mechanics.
Most state dam safety programs have no program for profiling and prioritization. Consider developing index system that state dam safety programs could use for profiling dams that they regulate.
Improve confidence of loss of life estimates.
Develop guidelines for prioritization and portfolio approach.
"Learn how to improve" PRA by evaluating changes resulting from updating.
Develop simple easy to use approach that will gain general acceptance.
More input from users on information needs.
Check USBR index system against portfolio method and try to assess how effective it is good for state officials.

1. Are rating points system worth doing without FMEA procedure, there is a chance of missing the critical issue?
2. Can portfolio assessment be used for prioritization of known deficiencies (e.g., as opposed to USBR prioritization)?
3. Can a prioritization index system be consistent with a risk analysis approach?

Appendix H. Participant Input on Quantitative Approaches

H.1 Strengths

Regulator imposed requirements are more fair for various dam owners.
Common basis for comparing risks between various hazards and between dams.
Supports need for remedial measures identified by traditional approach.
Identifies and quantifies deficiencies that were previously unrecognized.
Much greater insight into the mechanics of failure.
Provides a very useful tool for dam safety upgrade decision-making.
Methods for estimation of probabilities of failure are mostly based on traditional eng. inferring methods of analysis.
Makes process of engineering judgment more transparent.
Gives owner, regulator a better idea of what risk a dam poses.
Removes some ambiguity. Answers question of how bad/how good.
Allows comparison with acceptance criteria, and more accurate assessments of what drives the risk.
Allows explicit representation of uncertainties.
A more balanced assessment of risks from "normal" conditions and extreme events.
Assessment of relative risks of different failure modes.
Systematic consideration of dam safety – all aspects.
More "bang for the buck" in selecting preferred rehabilitation alternatives.
Group thinking and group input.
Provides insights into most critical factors affecting early failure mode and therefore most effective ways to reduce probability of failure.
More in depth analyses typically performed.
More defensible.
More illuminating.
Better treatment of uncertainty.
Allows best "dissection" of failure mode.
Compare between failure modes is good.
Can (should) include explicit consideration of uncertainty.
Careful consideration of steps leading to failure.
Helps owner understand his/her exposure.
If well done, focuses on owner's information needs, not just engineering issues.
Creates a measurable approach for comparison.
Detailed discussions of factors affecting events leading to failure.
Good tool for managing risk across a large portfolio of dams.
Provides insights into relative risk (probability and consequences) of failure.
Group judgments can outperform individuals (some times).
Reveals relative importance of particular features, conditions, and actions.
Quantifies relative importance of failure mechanisms.
Identifies where further info/investigations/analyses most useful and beneficial.
Shows decision makers why things are important.
Allows state of knowledge/ignorance to be expressed.
Puts complex engineering issues into a form (common risk currency) that often convinces lay decision makers to a more than traditional engineering only approach.
Allows for failure mode decomposition.

H.2 Limitations

Hydrologic — Not much available on parameter variation (uncertainty) determination analyses.
Structural — (Concrete and earth). Not much available on parameter variation (uncertainty) determination analyses.
Uncertainties used appear to be subjective and not objective.
To date limited input from outside dam safety comm. (i.e., little general public input).
Results can be heavily affected by knowledge and experience of team.
Methods for estimating probability of failure by piping, earthquake on concrete dams, and stability of embankments dam need development.
We need to develop methods for conveying uncertainty in answer and in “acceptance” criteria (to avoid the point and line approach).
Who dictates acceptable risk?
    Engineer
    Public
    Politicians
    Courts.
Does not resolve the “acceptable” risk quandary.
Methodologies require much more development.
Costly at present.
Lack of acceptance for life safety criteria.
Difficulties in communicating risks to owners, others.
Many pitfalls in performing the risk calculations, making probability estimates, and post processing.
Very difficult to make probability assessments for events with very limited historical case histories.
May be prohibitively expensive and time consuming if not done under ‘expert’ supervision.
Criteria may put too much emphasis on EAP for loss of life reduction.
Procedure is not standardized.
Results between evaluators are not generally consistent.
Believing numbers/results without understanding the uncertainties.
Uncertainties in resulting numbers.
Possible misuse of resulting numbers.
Lack of people experienced and qualified to estimate probabilities.
Possible bias of existing dam risk assessment practitioners.
Process can be dominated by a few individuals.
Probability of failure estimates not fully defensible.
Experienced engineer needed—they are dwindling.
Can be high cost.
Needs to be toned down to recognizable terms for acceptance to general dam safety community.
Probabilities of extreme events/loading not readily available for much of U.S.
Too complex and time consuming for most state regulated dams.
Insufficient data to estimate probabilities with confidence.
Cost.
Difficult for dams that present no symptoms.
Yet to account for all human reasoning and judgment processes.
Lack of risk tolerance limits established for broad applications.
Can imply more knowledge than there is, if improperly presented or quoted.
Requires experienced, broadly trained professionals (rare), with previous exposure to all facts of dam engineering.
Danger of believing the numbers.
Subjective results are made to appear objective.
Focus on engineering wants rather than owner needs.

Lack of benchmarks. How to compare RA site A to B to C.
Terminology.
No widely accepted loss of life criteria are available.
Methods for estimating loss of life totally inadequate—much worse than those for estimating probability of failure.
Tolerable risk criteria difficult or impossible to establish.

H.3 Technology Transfer and Training Needs

Limited probability training for engineers
Demonstration projects
Need to document detailed QRA method state-of-practice and run training workshops
Need bulletin of R/A for dams that assembles all case histories et. al.
Produce a life safety discussion paper, exhibit publicly and invite submissions
Dam safety community should interact with DOE, NRC on QRA
Training in basic skills such as understanding probability & expert elicitation
Can you generalize information or "Education" from stochastic

H.4 Research and Development Needs

CARDS SUBMITTED IN THIS CATEGORY WERE COMBINED INTO OVERALL R&D NEEDS (SEE APPENDIX J) BEFORE THEY COULD BE RECORDED SEPARATELY

H.5 How Can it Be Improved?

Maintain separate pairs of probability consequences where the probability speaks directly to the consequence.
Just do it.
Examples developed noting uncertainty inclusion.
OTHER CARDS SUBMITTED IN THIS CATEGORY WERE COMBINED INTO OVERALL R&D NEEDS (SEE APPENDIX J) BEFORE THEY COULD BE RECORDED SEPARATELY

Appendix I. Sorted Participant Input on Strengths and Limitations of the State of the Practice

I.1 Failure Modes Identification

I.1.1 Strengths

1 Failure modes paradigm

Identification of failure mechanisms otherwise been over looked.
Identify alternative failure modes.
Identifies failure modes.
Failure mode identification.
Identifies all failure modes.
Gives crude identification of critical failure modes.
Helps identify all failure modes.
Identifies unusual failure modes-the oddball failure mode.
Identification of risk otherwise not noted.
Organized focus on failure modes. FMEA more likely to identify potential failure modes.
Identified dam's weak link(s).
Improved understanding of strengths and vulnerabilities of dam.
Identifies safety issues beyond standards based.
Process encourages discovery of all failure modes

2 Relatively low effort

Can piggyback on periodic design review.
Less data requirements.
Quicker to complete.
Considers factors that are difficult to quantify.
Simple.
Failure mode identification is 1/2 value of RA vs. deterministic thinking.
Quick.
Simple.
Better than no RA at all.
Easily done.
A lot of information with little effort.
Relatively simple.
Identifies failure modes quickly.
It is a start.

3 Broad interdisciplinary team approach

Bring in Electrical, Mechanical, Environmental views.
Develop transitions between specialists engineering consultant and ??
Team approach provides variety of viewpoints.
Broad.
Helps you think more broadly.
Comprehensive.
Involves more individuals.
Makes use of available materials (studies).

4 Enhances understanding

Increase understanding of dam
Some useful information provided.
Valuable information.
Brings insight and understanding.
The concepts better understood.
Provides something to react to.

5 Wide acceptability

Can get buy in of staff.
Can get buy in of regulator/Dam safety decision makers efficient.
More people buy into the process.
Wide acceptability.
Broad-based more likely to have acceptance in standards-based community.

6 Strengthens traditional approach/Quality Assurance

Can use as QA tool to evaluate remedial design.
Strengthens the diligence.
Provides a supplement to standards based.
Brings balance to Dam Safety programs.

7 Identifying additional information needs

Identify uncertainties.
Identify new data needs.
Helps with surveillance.

8 Aids in prioritization of issues

Help initial prioritization of issues.
Prioritize Risk.
Helps to prioritize fixes.

9 Aids in communicating risks

Start public involvement.
Raises awareness of issues with management.

10 Tool for achieving integration of dam safety program

Can use to evaluate and synthesize various aspects of dam safety program.

11 Aids in identification of risk reduction measures

Identifies simple, cost-effective risk reduction measures.

12 Systematic approach

Systematic

I.1.2 Limitations

1 Qualitative - risk, ranking, compare with other dams, confidence/uncertainty

Not much relative ranking provided.
Still lacks quantification in making a choice of what's most important.
Does not quantify risk.
Ultimately requires decisions on basis of old standards.
Lack of quantification.
Magnitude of risks from various sources hard to compare.
Indicator only. Not quantifier.
More difficult to portray confidence level.
Difficult to compare importance (risk) from each failure mode.
Difficult to compare dams.
Does not provide a measure of risk.
Does not reveal relative risks as required by dam safety decisions.
Are the regulations met?
Parameter uncertainty not included.
No quantification.
Limited by efforts allocated and composition of team.
Lack of prioritization.

2 Repeatability, consistency, influence of team members

Repeatability.
Reliability.
Biases.
Affected by experience of the team.
Personalities within the team.
Defensibility.
Repeatability.
Based on opinion.
Not fool proof.
Procedure may not be consistent from team to team.
Subjective-may not be repeatable.
Limited by efforts allocated and composition of team.
Reliant on "judgment" to exclude.
Team affected by "Group Think."

3 Lack of available guidance

Not much existing direction on "how to" available.
No "standard" of good practice.
Not acceptable criteria.
Lack of universally approved methodology.
Lack of accepted standards.

4 Cost

Resource limitation of organization (staffing).
Limited use to small dam owners (i.e., cannot afford the process).
Dollar cost of process may limit application.

5 Limited case histories to use as basis for FM identification

Limited data extrapolations (i.e., failure modes, static, gates, filter, drains, structures ..).

6 Not a public-oriented process

Not a public oriented process.

7 Requires information on dam

May be difficult to dams with little background information.

I.2 Index Prioritization

I.2.1 Strengths

1 Prioritization

Able to identify relative needs for repairs.
Non-judgmental between dams.
Allows comparison.
Site to site comparisons possible.
Allows priorities without dealing in absolutes.
Identifies urgent (quick fix) needs.
Organized approach to develop relative ranked order of projects with deficiencies.
Allows prioritization of investigations and monitoring.
Identifies highest priority projects.

2 Efficient process

Allows regulator to apply limited resources to project posing most risk.
Flexible-can be adjusted to desired level of detail.
Economic if done in groups of dams.
Based on existing data.
Allows rapid and consistent evaluation of portfolio, also cost effective.
Quick.
Can be done based on existing data.

3 Defensibility

Provide some level of justification for proceeding with/deferring fixes.
Generally defendable for action - deferred/screening - no action.
If dam low on priority list fails, provides some defense to regulator.
Provides basis for risk reduction program/meets due diligence.

4 Justification

Help with obtaining funding.
Builds consensus on priorities.
Rational basis for priorities.
Provides means to gain management support.

5 Communication

Input to decision-making.
Gives owner "high level" understanding of risks.
It's explainable.
Puts dam safety issues into a form that owner's decision matters can relate to, especially if they are non-technical people.

6 Systematic process

Forces judgment.
It's systematic.
Can probably repeat results.

7 Identification of dam safety issues

Allows identification of deficiencies (through FMEA), and risk calculation.
Initial identification of dam safety issues.

8 Integrates dam safety program and into overall business

Helpful to owners with a new dam safety program.

I.2.2 Limitations

1 Danger of misusing results

Doesn't say how fast.
Using the results beyond intentions.
May provide a false sense of security.
Can provide excuse not to proceed with detailed assessments.
Priorities may change.
Identifies deficiency. Does not force fix. Negligence?
Can mislead.
Can be misused.
Difficult to communicate limitations.
How to deal with dams with a lot of information vs. those with little or no information.
Prioritization means some things are not done.
Must keep uncertainties in inputs on the screen for decision makers.
High probability failure modes may not receive proper consideration.

2 Not in-depth risk analysis

Are the numbers believable?
Based on existing data.
Incorrect existing data could lead to incorrect conclusions.
May be too crude.
Not clear in regard to uncertainty.
May mis-prioritize.
Haste may miss important failure mode.
Evaluation is more broad-brush.
Broad brush may not reveal all-important vulnerabilities.
Limited by easily available data and analysis-probability not constant across inventory.
May be superficial.

3 Lack of published guidance

Variation among different systems.
No published standards for performing.
No accepted approach for consistent application.

4 Relative rather than absolute

Isn't absolute.
It is seldom quantified.
Does not maximize rate of cost-effectiveness.

5 Defensibility

Defensibility sometimes questionable.
Beyond defensibility.

6 Risk metric

Index approaches not true utilization of risk assessment and FMEA.
Index methods may not preserve probability metric and therefore may distort priorities.

7 No sign off

No sign off.

I.3 Portfolio Risk Assessment

I.3.1 Strengths

1 Prioritization

Able to identify relative needs for repairs.
Non-judgmental between dams.
Allows comparison.
Site to site comparisons possible.
Allows priorities without dealing in absolutes.
Identifies urgent (quick fix) needs.

Organized approach to develop relative ranked order of projects with deficiencies.
Allows prioritization of investigations and monitoring.
Identifies highest priority projects.
Identify priority for risk reduction measures.
Prioritizes these in loss of life and financial terms.
Provides prioritization and justification for fixes and investigations.

2 Cost effectiveness risk reduction program

Dam safety sooner.
Do most in shortest time with least resources.
Provides basis for better use of limited funds.
Creates mechanism to improve/reduce loss of life criteria consequences economically.
More bang for the buck.
Allows the maximization of risk reduction for each Dollar.
Leads to cost-effective further investigations.

3 Justification

Help with obtaining funding.
Builds consensus on priorities.
Rational basis for priorities.
Provides means to gain management support.
Provides insight into sensible strategies.
Provides prioritization and justification for fixes and investigations.
Provides basis for risk reduction program/meets due diligence.

4 Communication

Input to decision-making.
Gives owner "high level" understanding of risks.
It's explainable.
Puts dam safety issues into a form that owner's decision matters can relate to, especially if they are non-technical people.
Paints picture liabilities.
Provides better picture of the dam system.
Gives overall risk profile.

5 Defensibility

Provide some level of justification for proceeding with/deferring fixes.
Generally defendable for action - deferred/screening - no action.
If dam low on priority list fails, provides some defense to regulator.
Provides basis for risk reduction program/meets due diligence.
Logical, defensible prioritization of risk.

6 Risk metric

Common currency across owners, dams elements (e.g. penstocks vs canals etc.), failure-modes.
Provides true measure of risk.
All components of risk can be quantified.

Compares: 1) dams and performance; 2) criteria; and 3) consequences.
Preserves probability metric.

7 Efficient process

Allows regulator to apply limited resources to project posing most risk.
Flexible - can be adjusted to desired level of detail.
Economic if done in groups of dams.

8 Identification of dam safety issues

Allows identification of deficiencies (through FMEA), and risk calculation.
Initial identification of dam safety issues.

9 Integrates dam safety program and into overall business

Coordination of engineering issues with business needs, objectives and priorities.
Integration of all aspects of dam safety program.
Identifies entire scope of dam safety needs.

10 Systematic process

Forces judgment.
It's systematic.
Has room for unknown or unresolved issues.

I.3.2 Limitations

1 Danger of misusing results

Doesn't say how fast.
Using the results beyond intentions.
May provide a false sense of security.
Can provide excuse not to proceed with detailed assessments.
Priorities may change.
Identifies deficiency. Does not force fix. Negligence?
Can mislead.
Can be misused.
Difficult to communicate limitations.
How to deal with dams with a lot of information vs. those with little or no information.
Prioritization means some things are not done.
Must keep uncertainties in inputs on the screen for decision makers.
Only gives owner "high level" understanding of risks.
Owners and engineers start to believe the risks absolutely and want to sign off without detailed RA and detailed engineering.
Risk criteria evaluations may be assumed to be final.

2 Not in-depth risk analysis

Are the numbers believable?

Based on existing data.
Incorrect existing data could lead to incorrect conclusions.
May be too crude.
Not clear in regard to uncertainty.
May mis-prioritize.
Haste may miss important failure mode.
Too great a variability in risk numbers.
Some techniques for estimation of, e.g., consequences, are limited accuracy.

3 Cost

Is it practical other than for owners of large numbers of dams?
Less useful for small owners with few dams.
Costs.
May be too costly for small owners.

4 Lack of published guidance

Variation among different systems.
No published standards for performing.
No accepted approach for consistent application.
Limited number of experienced and qualified facilitators.

5 Defensibility

Defensibility sometimes questionable.

6 No sign off

No sign off.

7 Relative rather than absolute

Isn't absolute.

I.4 Detailed Quantitative Risk Assessment

I.4.1 Strengths

1 Valuable as a decision tool

Regulator imposed requirements are more fair for various dam owners.
Supports need for remedial measures identified by traditional approach.
Provides a very useful tool for dam safety upgrade decision-making.
More "bang for the buck" in selecting preferred rehabilitation alternatives.
Provides insights into most critical factors affecting early failure mode and therefore most effective ways to reduce probability of failure.
Helps owner understand his/her exposure.
If well done, focuses on owner's information needs, not just engineering issues.
Good tool for managing risk across a large portfolio of dams.

Identifies where further info/investigations/analyses most useful and beneficial.
Shows decision makers why things are important.
Puts complex engineering issues into a form (common risk currency) that often convinces lay decision makers to a more than traditional engineering only approach.

2 Quantification using risk metric

Common basis for comparing risks between various hazards and between dams.
Identifies and quantifies deficiencies that were previously unrecognized.
A more balanced assessment of risks from "normal" conditions and extreme events.
Assessment of relative risks of different failure modes.
Systematic consideration of dam safety - all aspects.
Compare between failure modes is good.
Creates a measurable approach for comparison.
Provides insights into relative risk (probability and consequences) of failure.
Reveals relative importance of particular features, conditions, and actions.
Quantifies relative importance of failure mechanisms.
Allows for failure mode decomposition.

3 Understanding of failure modes

Much greater insight into the mechanics of failure.
Gives owner, regulator a better idea of what risk a dam poses.
Removes some ambiguity. Answers question of how bad/how good.
Allows comparison with acceptance criteria, and more accurate assessments of what drives the risk.
Provides insights into most critical factors affecting early failure mode and therefore most effective ways to reduce probability of failure.
More illuminating.
Allows best "dissection" of failure mode.
Careful consideration of steps leading to failure.
Detailed discussions of factors affecting events leading to failure.

4 Uncertainties considered

Allows explicit representation of uncertainties.
Better treatment of uncertainty.
Can (should) include explicit consideration of uncertainty.
Allows state of knowledge/ignorance to be expressed.

5 In-depth supporting analyses

Methods for estimation of probabilities of failure are mostly based on traditional eng. inferring methods of analysis.
More in depth analyses typically performed.

6 Team process

Group thinking and group input.
Group judgments can outperform individuals (some times).

7 Defensibility

More defensible.

8 Risk criteria evaluation

Allows comparison with acceptance criteria, and more accurate assessments of what drives the risk.

9 Transparency in engineering judgments

Makes process of engineering judgment more transparent.

I.4.2 Limitations

1 Lack of standardized procedure and experienced practitioners

To date limited input from outside dam safety comm. (i.e., little general public input).
Results can be heavily affected by knowledge and experience of team.
Methods for estimating probability of failure by piping, earthquake on concrete dams, and stability of embankments dam need development.
Methodologies require much more development.
Many pitfalls in performing the risk calculations, making probability estimates, and post processing.
Procedure is not standardized.
Results between evaluators are not generally consistent.
Lack of people experienced and qualified to estimate probabilities.
Possible bias of existing dam risk assessment practitioners.
Process can be dominated by a few individuals.
Experienced engineers needed - they are dwindling.
Requires experienced, broadly trained professionals (rare), with previous exposure to all facts of dam engineering.

2 Acceptable/tolerable risk criteria not agreed

To date limited input from outside dam safety comm. (i.e., little general public input).
We need to develop methods for conveying uncertainty in answer and in "acceptance" criteria (to avoid the point and line approach).
Who dictates acceptable risk? Engineer, Public, Politicians, Courts
Does not resolve the "acceptable" risk quandary.
Lack of acceptance for life safety criteria.
Criteria may put too much emphasis on EAP for loss of life reduction.
Lack of risk tolerance limits established for broad applications.
Focus on engineering wants rater than owner needs.
Lack of benchmarks. How to compare RA site A to B to C.
No widely accepted loss of life criteria are available.

3 Uncertainty in estimating probabilities and life loss

Hydrologic - Not much available on parameter variation (uncertainty) determination analyses.

Structural - (Concrete and earth). Not much available on parameter variation (uncertainty) determination analyses.
Uncertainties used appear to be subjective and not objective.
Very difficult to make probability assessments for events with very limited historical case histories.
Probability of failure estimates not fully defensible.
Probabilities of extreme events/loading not readily available for much of U.S.
Insufficient data to estimate probabilities with confidence.
Difficult for dams that present no symptoms.
Yet to account for all human reasoning and judgment processes.
Methods for estimating loss of life totally inadequate-much worse than those for estimating probability of failure.

4 Communicating uncertainties to decision makers and others

We need to develop methods for conveying uncertainty in answer and in "acceptance" criteria (to avoid the point and line approach).
Difficulties in communicating risks to owners, others.
Believing numbers/results without understanding the uncertainties.
Uncertainties in resulting numbers.
Possible misuse of resulting numbers.
Can imply more knowledge than there is, if improperly presented or quoted.
Danger of believing the numbers.
Subjective results are made to appear objective.

5 Cost

Costly at present.
May be prohibitively expensive and time consuming if not done under 'expert' supervision.
Can be high cost.
Too complex and time consuming for most state regulated dams.
Cost.

6 New and complex terminology

Needs to be toned down to recognizable terms for acceptance to general dam safety community.
Too complex and time consuming for most state regulated dams.
Terminology.

Appendix J. Participant Voting on Technology Transfer and Training Needs

Failure Modes Identification Approaches

Issues	Votes
Failure mode thinking- (Documented case histories; Training seminars; Hands-on workshops; Systematic approach [list elements & ask how can fail])	21
Build FMEA into standards based reviews - economy of resources	18
Tools for owners with limited resources	11
Regular program for operator training	5
RAC could share some of their failure mode spreadsheets with the rest of us	4
Someone (FEMA/ASDSO/ICODS?) should develop a 'methodology' that tries to standardize the process	2
Develop more people as qualified facilitators	2
Review case histories	1
How can RA benefit owners of 1 or a few dams?	1
Do dams in groups with same experts	0
Need ways to get limited expertise applied more broadly	0
Avoid monopoly	0
Documented reports of use	0
Get small group of experienced FMEA experts to write down the logic/process of how to do FMEA	0
Focus on integration with existing efforts	0

Index Prioritization and Portfolio Risk Assessment Approaches

Issues	Votes
Develop guidelines for what constitutes a Portfolio Assessment and how it may be done	25
Publish complete Portfolio Risk Assessment case study (s) as a generic study (s) include strength & weaknesses	9
ASDSO could compile risk indexing and prioritization approaches & provide summary to states	7
By sharing experience on PRA with others on how well the process worked & what should be changed	5
More experience by more people	4
Need tier system so we can meet owner resource availability	3
Demonstration projects	3
Seems that transfer must be done [through] one to one coaching	0
Sponsor seminars aimed at educating non-technical staff among owners	0
Train more facilitators	0

Detailed Quantitative Approaches

Issues	Votes
Limited probability training for engineers	22
Demonstration projects	8
Need to document detailed QRA method state-of-practice and run training workshops	5
Need bulletin of R/A for dams that assembles all case histories et. al.	5
Produce a life safety discussion paper, exhibit publicly and invite submissions	5
Dam safety community should interact with DOE, NRC on QRA	3
Training in basic skills such as understanding probability & expert elicitation	1
Can you generalize information or "Education" from stochastic	0

Appendix K. Participant Input on Research and Development Needs Categories

1 - **Standards (A)**

- All Civil Engineering is empirical, therefore, it is risk based! FS = 1.5 means low risk, not zero risk.
- How do the new computer tool encroach on FS in standards based designs and how does this change 100 yr database?
- ~ 1 in 100 dams fail
- How do we change standards without addressing risk?
- Dams with no possibility of life loss
- Large dams that must meet PMF & MCE
- What is a "reasonable FS"? Is the MCE adequately conservative?
- Parallel risk assessments of the same dam
- Incentive/need to undertake risk assessment if dams meet standards regulations
- Is a standards approach a zero risk approach?
- Subjective probabilities bad for quantitative RA but OK for standards?
- Standards ≠restrictive thinking
- Failure mode should always be considered
- Missing failure modes
- Also a problem with defensibility of standards
- How do engineering/subjective judgments affect traditional approach outcomes vs. risk-based approach outcomes?
- Risk seems to add to short comings of standards approach as opposed to avoid (parameter uncertainty analysis)
- New dams vs. existing dams

2, 6 - **Tolerable Risk/Criteria (B)**

- Is legislative intent to get to zero risk to life?
- Public aversion or intolerance to imposed risks
- Who decided "RP" in ALARP?
- Who decides what is tolerable risk for dams?
- Tolerable risk criteria as an interim step on the constant path of risk reduction
- State legislation says, "remove the risk"; implies that there could be zero risk. Not possible.
- Accepted level of risk is a organization to organization, case by case aspect
- Regulators need to educate government that "safe" means a low probability of failure, not "no chance" of failure.
- The FEMA requirements are impossible if followed rigidly
- Legislators, not the Regulators should determine risk level accepted.
- Dams are only one piece of society's risk pool.
- Strive for consistent risk.
- Is it reasonable to rely on warnings and evacuation as a risk reduction measure?
- Engineers + Lawyers = inferior dam safety decisions
- Who could go to jail if the dam fails?
- Acceptance of loss of life?
- EAP vs. fixing dam
- The public is extremely risk adverse about dams. How can you get acceptance of risk levels given that?

- Get out of jail free card

Criteria:

- If risk is the owner's what does this mean for non-owner beneficiaries to share risk?
- <1 lives/yr does not communicate with the public. Why aren't we looking at calculating the probability of one or more lives lost by a particular event, then ask what the acceptable probability for public would be
- How do we get public input for risk criteria/public protection guidelines?
- EAPs not a substitute for structural fix
- What to do if repair may pose more risk than existing conditions (no-fix)?
- Who will (should) establish life safety criteria? Is it practical for them to do so?
- Obtain public & political input to debate on acceptance limits

3 - **Subjective Probability (C)**

- R & D needs:
  A. Immediate
     Develop an improved understanding of probability interpretations and corresponding expectations of those using, interpreting, or considering quantitative methods.
     Develop better ways for adapting criteria to probability (rather than vice-versa) and operating within its capabilities.
  B. Intermediate-term
     Education and training of probability assessors in cognitive processes, heuristics and biases.
     Development and application of de-biasing techniques adapted in positive ways to how people think and how they conceptualize subjective uncertainty judgments.
     Education and training in *basic* probability theory (axioms, etc.)
  C. Longer-term
     Improve judgment of probability assessor
     What is judgment?
     How does substantive expertise differ from normative expertise?
     Role of inductive vs. deductive reasoning strategies
     How is judgment enhanced?
- Adapt and merge ongoing R&D from institutions, e.g. Stanford University regarding human thought processes (R&D card)
- What is the value to the public of subjective probability estimates? (issue card)
- Dam response probability subjective estimate divergence theory: If team thinks failure mode is a problem based on discussion, then the subjective value is higher. If team thinks failure mode is not a problem then subjective estimate is lower. (issue card)

4 - **Skills to Identify Failure Modes (D)**

- Change paradigm for quantitative risk analysis

5 - **Uncertainty (E)**

- Effects of distributions on event probability estimates.

7, 18, 19 - **Prioritization and Portfolio Tools (F)**

- Develop guidelines for prioritization & portfolio approach
- Develop simple, easy to use approach that will gain general acceptance
- Most state dam safety programs have no program for profiling & prioritization. Consider developing index system that state dam safety programs could use for profiling dams that they regulate
- Check USBR index system against portfolio method and try to assess how effective it is. Good for state officials
- Are rating points systems worth doing without FMEA procedure? There is a high chance of missing the critical issue
- Can a prioritization index system be consistent with a risk analysis approach?
- Can portfolio assessment be used for prioritization of known deficiencies (e.g. as opposed to USBR prioritization)
- Improve confidence of loss of life estimates

8 - **Earthquake Response (G)**

- Develop more realistic seismic displacement and liquefaction models.
- Develop better methods for structural response of:
    - Concrete gravity dams in earthquake
    - Embankment stability
    - Piping, static and post earthquake
- RA is very good where there is no standards based analytical tool e.g. Navaho Drain Tunnel
- Factor of safety vs. probability of failure. Need conservative strengths for FS = 1.5 to represent low probability of failure.
- Inter-related failure modes
- Does number of steps included in event tree fundamentally affect resulting probability?
- Length and number effects on probability estimates
- Develop capability to derive failure probability analytically
- Need to improve understanding/ways to predict system response probabilities
- Failure mechanism understanding and modeling
- Develop failure models that use probabilistic input both for loads and resistance
- Adapt failure models for nodes of event trees

9 - **Static Response (H)**

- Improve estimates of failure probabilities for static stability piping failure, etc.
- Research need:
    - Failure models
    - Piping models
    - Loss of life models
- How confident are we in characterization of piping failures – embankment, foundation, etc.?
- Seepage rate is not a good guide to problems. Changes, not correlating with reservoir is better.
- Piping failures take less than 24 hrs, mostly < 6 hrs, to develop. They historically occur at reservoir level about 1m below historic high level.
- Develop risk analysis procedures to account for time-dependent aspects of piping.
- RA is very good where there is no standards based analytical tool e.g. Navaho Drain Tunnel
- Factor of safety vs. probability of failure. Need conservative strengths for FS = 1.5 to represent low probability of failure.
- Inter-related failure modes

- Does number of steps included in event tree fundamentally affect resulting probability?
- Length and number effects on probability estimates
- Develop capability to derive failure probability analytically
- Need to improve understanding/ways to predict system response probabilities
- Failure mechanism understanding and modeling
- Develop failure models that use probabilistic input both for loads and resistance
- Adapt failure models for nodes of event trees

10, 21 - **Improve Loss of Life Estimation (I)**

- R&D life loss estimation
- LOL estimate should consider EAP
- Assessment of evacuation capability for large population centers
- Develop procedures to assess (understand) effectiveness of EAP/EPP
- Existence of EAP in loss of life estimates
- Long term effectiveness of warning and evacuation systems
- Relationship between life loss & proximity to the dam?

12 - **Risk Communication (J)**

- What do the numbers resulting from QRA really mean? (issue card)
- Hazard (seismic), Hazard (downstream): 1) drop both uses, 2) use Seismic loading, 3) use consequence (issue card)
- Can we build public confidence in life loss estimates? (issue card)
- Owners: be able to defend what you are doing as being reasonable and prudent (issue card)
- Need for common language between technical specialists & international (English (geotech) → English (financial) → English (probability) → English (international) → English (seismic) → English (H&H) → English (owner) → English (lawyers). (issue card)
- Public buy-in for risk-based decisions (issue card)

13 - **Dam Break Failure Case Histories (K)**

- Case history compilations need to be parameter specific

14 - **Earthquake Loading (L)**

- Reduce uncertainty & minimize compounding of conservatism in seismic risk assessment
- Seismic loads need:
    - Additional data collection – slip rates
    - Site response data
    - Recurrence models
    - Robust estimates of time histories for use in RA
    - Better integration with engineering analyses
    - Portray uncertainty in an understandable fashion
- 0.2 g for 1/10,000 event what magnitude?
- Reduce errors in catalogue of recorded seismic accelerations (data cleaning)
- Uncertainties in recurrence characteristics for known faults

15 - **Flood Loading (M)**

- Regional analyses of extreme precipitation probabilities for entire U.S. – allows states to estimate % PMP probabilities
- Extreme event probability determination improvement
- Reduce uncertainty in hydrologic process evaluation
- Continued support for development of methods for processing hydrologic info for characterizing extreme floods
- Development of procedures for better understanding and incorporating uncertainty in characterization of floods
- Comprehensive program for collection of climate flood & paleoflood data on regional basis to support regional analyses
- Studies to investigate spatial distribution for large watersheds using probabilistic methods
- Confidence in extreme event estimates
- Variability in PMF computations uncertainty of parameters

16 - **Risk Process (N)**

- Compare on equal basis judgment & unknowns for Load; Response; Life loss
- Uncertainty analysis approaches beginning from probability estimation, failure mode identification through presentation of outcomes to decision makers
- Assess repeatability – considering uncertainty ranges (not just point estimates)
- How do we reflect uncertainty in perfect history database?
- (To John Ake) Do you really do all what you describe for QRA studies, particularly screening level?
- How do amount & quality of data affect confidence in RA results?
- Long dams; multiple dam reservoirs need probabilistic concepts to be ‘correct’
- Repeatability: (even for qualitative methods)

17 - **Analyze NPDP (O)**

- No cards

20 - **Debate Mechanisms (P)**

- No cards

22 - **Communicate Best Practice (Q)**

- No cards

24 - **Include Failure Modes Identification in schools (R)**

- No cards

Portfolio - Learn to improve (S)

- Learn how to improve PRA by evaluating changes resulting from updating
- More input from users on info needs

26 - **Debate Concepts (T)**

- No cards

ASDSO/FEMA Specialty Workshop on
Risk Assessment for Dams

Session 1.0 - Introduction:

Risk Assessment Framework and Types

March 7, 2000

David S. Bowles
Utah State University and RAC Engineers & Economists

The Challenge of Aging Dams and Risk Management

- Technical issues
  - more stringent standards
  - improved design and construction practice
- Commercial environment
  - liability
  - need to justify investments (GPRA)
  - "From engineers on top to engineers on tap" (Haisman 1998)

Risk Assessment is "an *additional tool* to improve decisions and risk management practices"

Achterberg, Hennig and Redlinger, 1998

Risk guided

Risk enhanced

Risk informed

Risk-enhanced approach

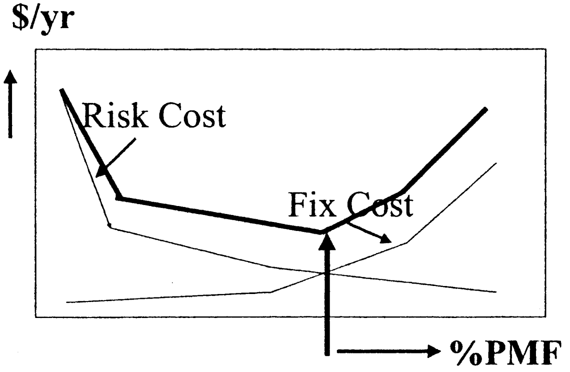
- Supplementing engineering standards evaluations with information from RA
- Avoid the shortcomings of an engineering standards-only approach
- Better communicates to (lay) decision makers
  - the significance of dam safety issues
  - justifications for actions

Traditional vs. Risk-*Enhanced* Approaches

- Engineering focus
- Standards issues
- Safety factors
- Maximum loads
- Hazard - PAR

- Owner's business/ mission focus
- Failure modes
- Risk estimates
- Full range of loading
- Consequences - loss of life, financial, etc.
- Justification for risk reduction

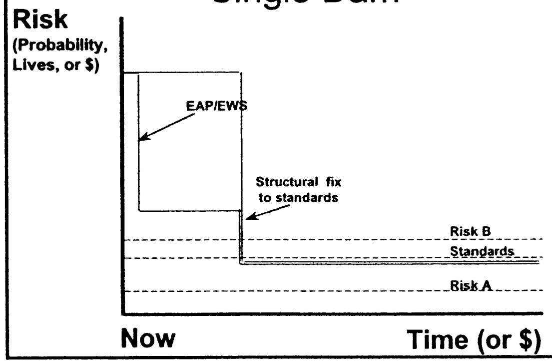
Economic Risk Analysis

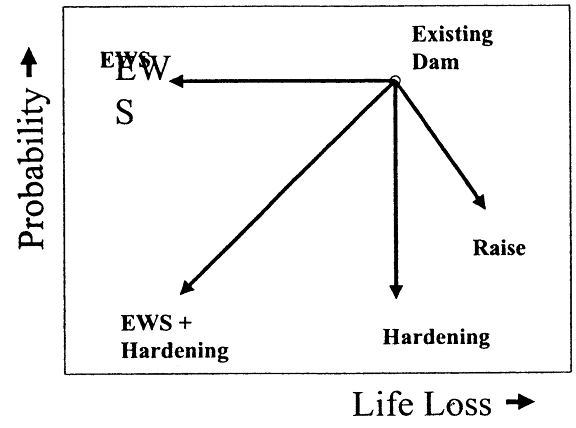


Most Dam Safety Programs Have ...

- *Well defined dam safety goals*
  - standards, criteria
- BUT a *poorly-defined pathway* for achieving those goals

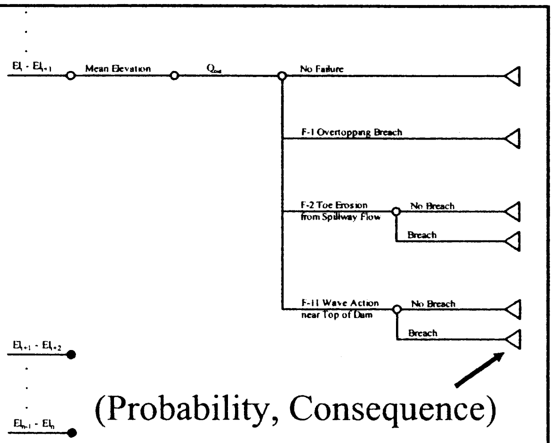
Single Dam





Risk = Probability * Consequences

Special Case – Annualized Risk

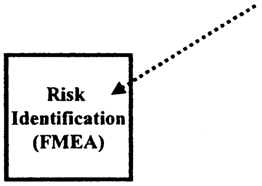


(Probability, Consequence)

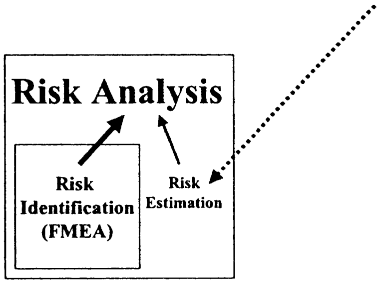
Risk

- In general:
  - (Probability, Consequences)
  - $(P_1,C_1), (P_2,C_2), \dots, (P_n,C_n)$
- Special case - Average annual risk
  - "Expected value"
  - SUM $^i{}_n$ $(P_i * C_i)$
  - lives/yr, $/yr (risk cost)

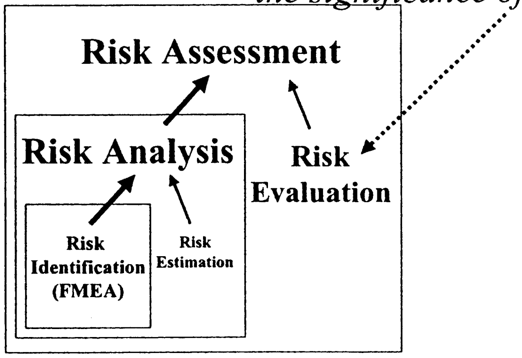
The process of determining a) what can go wrong, why and how, and b) its (project) effects and consequences



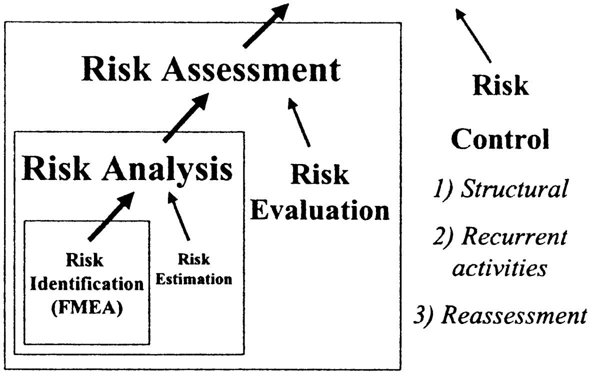
The process of quantifying risk - probability and consequences



The process of examining and judging the significance of risk



Dam Safety Risk Management



Risk Assessment

Risk Analysis

Risk Identification (FMEA)

Risk Estimation

Risk Evaluation

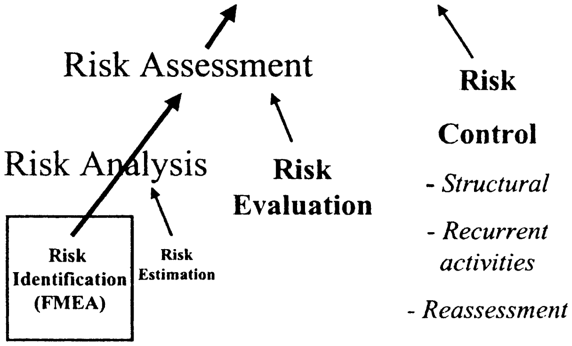
Risk Control

1) Structural

2) Recurrent activities

3) Reassessment

Dam Safety Risk Management



Risk Assessment

Risk Analysis

Risk Identification (FMEA)

Risk Estimation

Risk Evaluation

Risk Control

- *Structural*
- *Recurrent activities*
- *Reassessment*

Types of Risk Assessment

1) Qualitative

Failure Modes & Effects Analysis

Review

Site visit

FMEA team meeting

[illegible] table

[illegible]

[illegible]

Failure Modes & Effects Analysis (FMEA) Engineering Criteria Evaluation Example

Loading	**Subsystem**	**Rating**	**Failure Mode**	**Effects**
			Description	
Hydrologic	Spillway	ANP	Overtop main	Breach
			Overtop dyke section	Partial breach
			Spillway training wall	Erosion of abutment -> breach
			Piping in left abutment	Breach
	Dike		Piping in dyke	Breach
	Embankment		Piping in main dam	Breach
Earthquake	**Embankment**	P	Newmark type	SEC -> breach
	Foundation	P		
	O/W	AP		
Internal	Embankment	P	Slope stability	Breach
	Foundation	P	Foundation	Breach
			Piping	Breach

Acceptance of Dam Safety RA

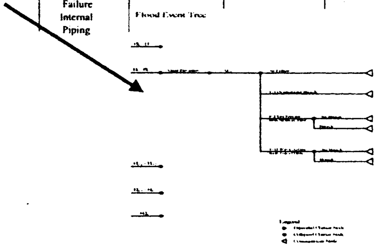
- (1) *Portfolio* Risk Assessment (PRA)
  - risk profiling and prioritization of mitigation
- (1) *Qualitative* RA
  - risk understanding
- (2) *Quantitative* RA
  - *justifying full standards fix*
- (3) *Quantitative* RA
  - *justifying less than full standards fix*
  - *degree of defensibility*

Types of Risk Assessment

1) Quantitative

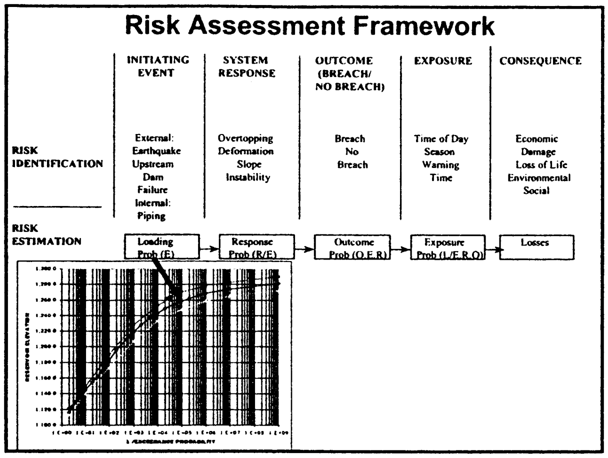
Risk Assessment Framework

	INITIATING EVENT	SYSTEM RESPONSE	OUTCOME (BREACH/ NO BREACH)	EXPOSURE	CONSEQUENCE
RISK IDENTIFICATION	External Earthquake Upstream Dam Failure Internal Piping	Overtopping Deformation Slope Instability	Breach No Breach	Time of Day Season Warning Time	Economic Damage Loss of Life Environmental Social



Risk Assessment Framework

	INITIATING EVENT	SYSTEM RESPONSE	OUTCOME (BREACH/ NO BREACH)	EXPOSURE	CONSEQUENCE
RISK IDENTIFICATION	External: Earthquake Upstream Dam Failure Internal: Piping	Overtopping Deformation Slope Instability	Breach No Breach	Time of Day Season Warning Time	Economic Damage Loss of Life Environmental Social
RISK ESTIMATION	Loading Prob (E) →	Response Prob (R/E) →	Outcome Prob (O,E,R) →	Exposure Prob (L/E,R,O) →	Losses



Risk Assessment Framework

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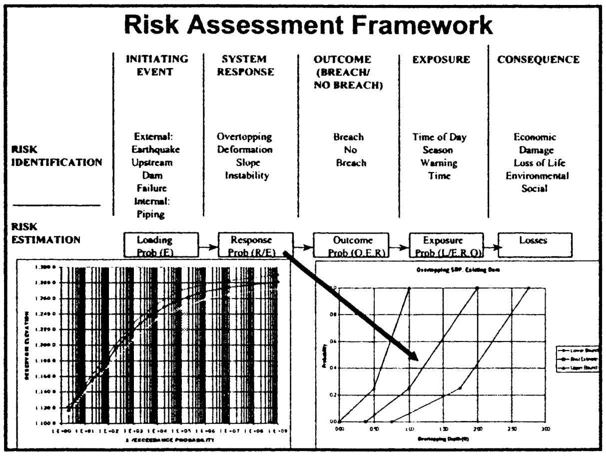

Risk Assessment Framework

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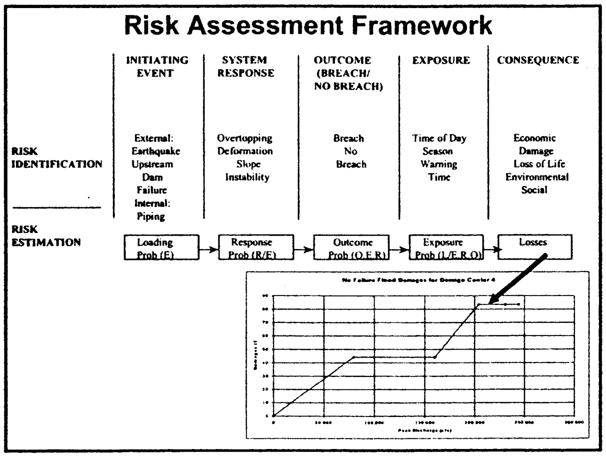

Risk Assessment Framework

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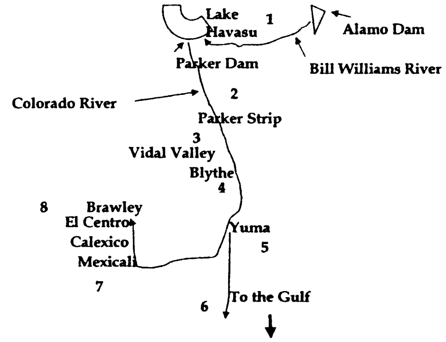
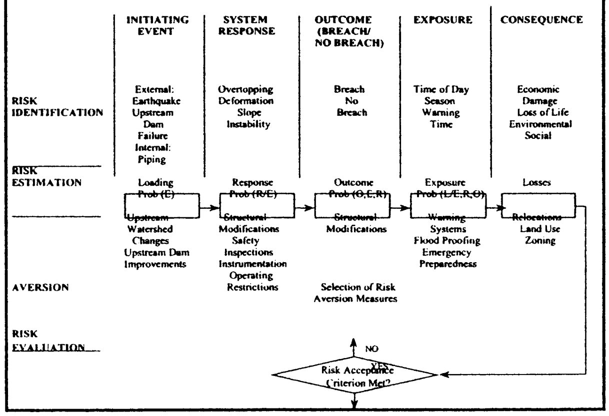
RISK ESTIMATION	Loading Prob (E)	Response Prob (R/E)	Outcome Prob (O.E.R)	Exposure Prob (L/E.R.O)	Losses

Consequence Centers



Risk Assessment Framework


INITIATING EVENT | SYSTEM RESPONSE | OUTCOME (BREACH/ NO BREACH) | EXPOSURE | CONSEQUENCE

RISK IDENTIFICATION

External: Earthquake Upstream Dam Failure Internal: Piping

Overtopping Deformation Slope Instability

Breach No Breach

Time of Day Season Warning Time

Economic Damage Loss of Life Environmental Social

RISK ESTIMATION

Loading Prob (E)

Response Prob (R/E)

Outcome Prob (O,E,R)

Exposure Prob (L/E,R,O)

Losses

AVERSION

Upstream Watershed Changes Upstream Dam Improvements

Structural Modifications Safety Inspections Instrumentation Operating Restrictions

Structural Modifications

Warning Systems Flood Proofing Emergency Preparedness

Relocations Land Use Zoning

Selection of Risk Aversion Measures

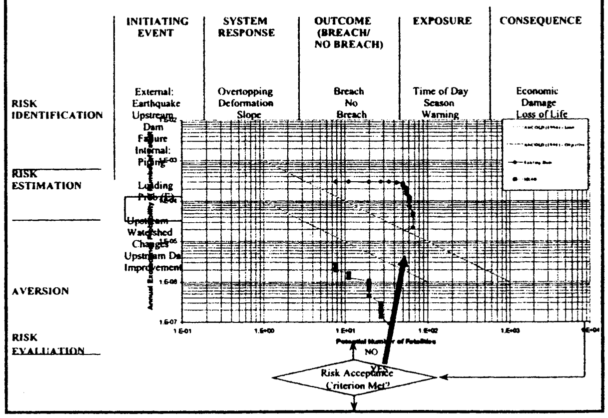
RISK EVALUATION

NO

YES

Risk Acceptance Criterion Met?

Risk Assessment Framework


INITIATING EVENT | SYSTEM RESPONSE | OUTCOME (BREACH/ NO BREACH) | EXPOSURE | CONSEQUENCE

RISK IDENTIFICATION

External: Earthquake Upstream Dam Failure Internal: Piping

Overtopping Deformation Slope

Breach No Breach

Time of Day Season Warning

Economic Damage Loss of Life

RISK ESTIMATION

Loading Prob (E)

AVERSION

Upstream Watershed Changes Upstream Dam Improvements

RISK EVALUATION

NO

YES

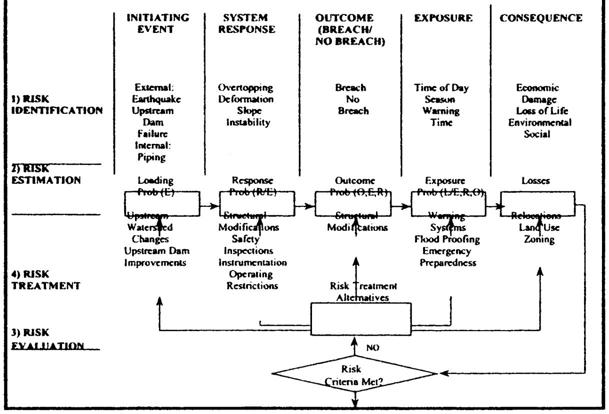
Risk Acceptance Criterion Met?

ALARP Principle

"as low as reasonably practicable"

- Risks are "acceptable only if reasonable practical measures have been taken to reduce risks" (IAEA 1992)
- Economic basis for ALARP (Rowe 1977):
  - Cost-per-life-saved
  - Diminishing economic returns

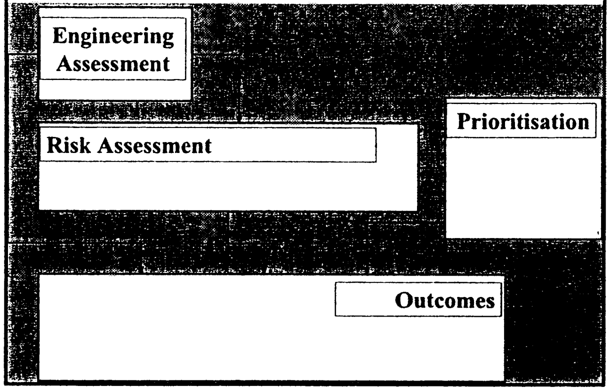
Risk Assessment Framework



Types of Risk Assessment

3) Portfolio, Risk Profiling, Prioritization

Portfolio Risk Assessment



Engineering Assessment

Risk Assessment

Prioritisation

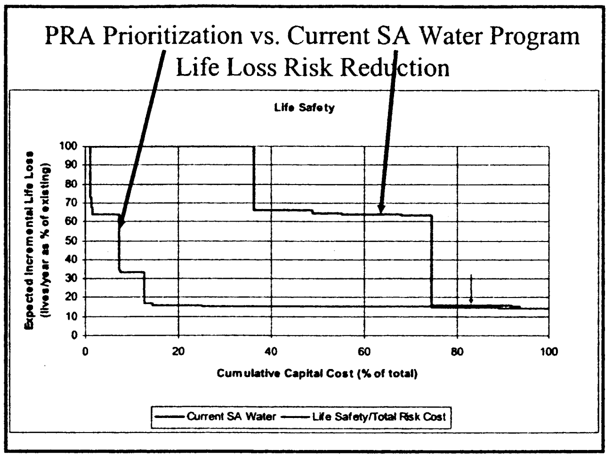
Outcomes

Portfolio Risk Assessment Outcomes

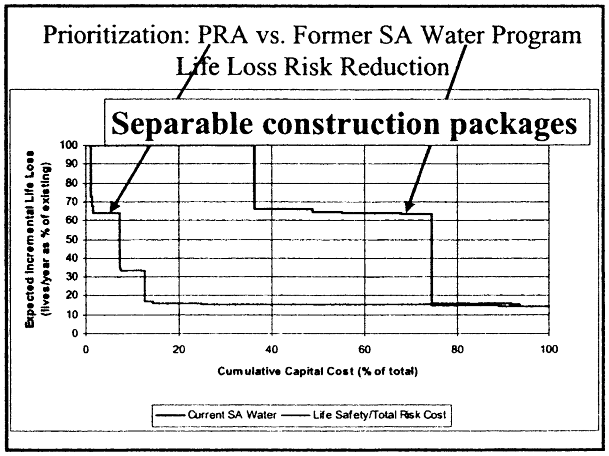
- Risk profile for *existing dams*
  - *engineering standards*
  - *risk criteria*

Portfolio Risk Assessment Outcomes

- Risk profile for *existing dams*
  - *engineering standards*
  - *risk criteria*
- *Potential risk reduction measures*
- Basis for *dam safety program*:
  - *priority of investigations*
  - *priority of fixes*
  - *strengthen on-going activities*

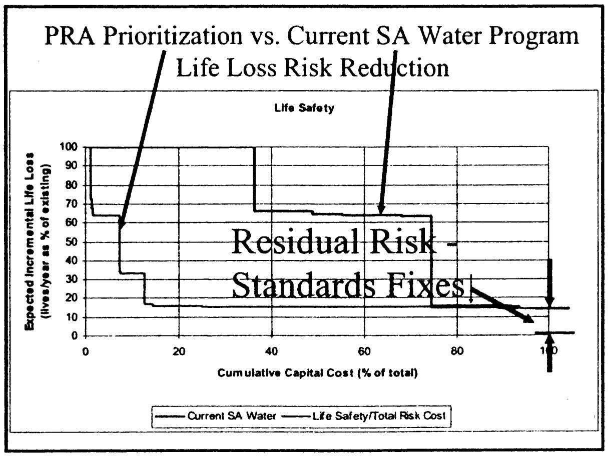


PRA Prioritization vs. Current SA Water Program
Life Loss Risk Reduction



Prioritization: PRA vs. Former SA Water Program
Life Loss Risk Reduction

Separable construction packages



PRA Prioritization vs. Current SA Water Program
Life Loss Risk Reduction

Residual Risk -
Standards Fixes

Portfolio Risk Assessment Outcomes

- Risk profile for *existing dams*
  - *engineering standards*
  - *risk criteria*
- *Potential risk reduction measures*
- Basis for *dam safety program*:
  - *priority of investigations*
  - *priority of fixes*
  - *strengthen on-going activities*
- Relates dams to *overall business*
  - *Insurance, legal, capital requirements, etc.*
- Basis for a "*living document*"

USES OF RISK ASSESSMENT

- UNDERSTANDING the risk
  - qualitative
  - quantitative
- MANAGING the risk
  - exploring options
  - justifying actions
  - prioritizing actions

Proper *Motivation* for Dam Safety Risk Assessment/Management

- More *safety*
- More *rapidly*
- More *cost effectively*
- More *understanding by all stakeholders*
- More *integration across dam safety program*

Presented at the Eighteenth USCOLD Annual Meeting and Lecture, Buffalo, New York, August 8-14, 1998

THE PRACTICE OF DAM SAFETY RISK ASSESSMENT AND MANAGEMENT: ITS ROOTS, ITS BRANCHES, AND ITS FRUIT

David S. Bowles[1], Loren R. Anderson[2] and Terry F. Glover[3]

ABSTRACT

This paper provides an overview and introduction to the current practice of dam safety risk assessment and management. It includes a summary of the history and development ("roots"), various facets and roles ("branches"), and benefits, limitations and future growth ("fruit") of risk assessment and management. A broad role for risk assessment at the core of a comprehensive dam safety management program is proposed. In this role, the results of risk assessment are used to feed business and management processes such as, capital project evaluation and budgeting, loss financing and insurance, legal liability and due diligence assessment, and emergency preparedness and contingency planning. Contrasts are made with traditional dam engineering practice and the standards approach. The paper draws on the experience of the authors in conducting risk assessments on more than 130 dams for government and private owners and regulators in the U.S. and Australia.

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INTRODUCTION

The "sapling" of dam safety risk assessment and risk management is growing in the risk environment in which dams exist. Bowles et al (1997) state that, "*Practical dam safety management is intrinsically risk management*". The recent report, Whither Civil Engineering?, from the U.K. Institution of Civil Engineers (1996) states that, "*Risk cannot be eliminated; therefore it must be managed*". While few would deny that dam engineering and dam safety management deal intrinsically with risk, opinions differ as to how explicitly and how quantitatively risk should be addressed in practice. In this paper, which was written to introduce a one day session on Dam Safety Risk Management at the Eighteenth USCOLD Annual Lecture, we seek to provide an overview and introduction to the current practice of dam safety risk assessment and management. The paper summarizes its history and development ("roots"), its various facets and roles ("branches"), and its benefits, limitations and future growth ("fruit").

The scope of this paper is broader than making decisions about whether or not to proceed with structural works to improve the safety of an individual dam. It takes the perspective that risk assessment outcomes have an important role to play in all aspects of dam safety management. Risk assessment for individual dams and portfolios of dams are viewed as a valuable core activity in a dam safety program. When properly applied, risk assessment can play a vital role in the integration of other dam safety activities, such as operations and maintenance, routine inspections, monitoring and surveillance, periodic safety reviews, staff training and awareness, and emergency planning. Unlike the extreme loading conditions which have become a focus of traditional dam safety practice, these other activities affect the management of dam safety risks on a day-to-day basis.

ITS ROOTS - HISTORY AND DEVELOPMENT

The "roots" of dam safety risk assessment and management can be traced from the "seeds" of the technical procedures and philosophies of dam engineering and risk assessment which have germinated and grown in the "soil" of a demand for the approach. In the first subsection we review engineering, societal, business and public policy drivers which are leading private and governmental dam owners to use risk-based approaches. In the second subsection we focus on the technical basis for the risk-based approach.

Drivers

The following is a summary of some of the important drivers which have lead dam owners to take the risk-based approach:

Engineering considerations

- Existing dams which do not satisfy current flood and earthquake loading criteria
- Existing dams which were not built to meet the current state-of-the-practice.
- The aging and deterioration process in dams.
- The significant cost of complying with standards.

Societal considerations

- Increased downstream development below dams.
- Increased risk aversity and societal expectations for greater protection from natural and man-made hazards.
- Growing expectations that the community will be involved in decisions which affect its safety.
- Difficulty in relating to low probability risks which are associated with dams.

Business and public policy considerations

- "Reinvention of Government" which has resulted in a greater emphasis on performance-based budget justification, the "user pays" principle, and diminished governmental funding.
- A shift away from prescriptive regulation to "lighter regulation", including the sunsetting of manuals.
- A governmental emphasis on risk-benefit justifications for health, safety and environmental regulations.
- Deregulation of the electrical utility industry and other pressures on corporations to improve business performance of all assets, including dams, as indicated by the growing emphasis on asset management approaches.
- Corporatization and privatization of dams which were previously owned and operated by governmental agencies, and removal of the shield of governmental immunity leaving directors and management personally liable for dam safety decisions and practices.

Ironically, the increased severity of design flood and earthquake standards has not always lead to safer dams. Where a regulator, such as the FERC, has the power to require dam safety improvements, they have taken place. However, state regulators do not always have similar powers. In one state, its legislature has instructed the dam safety regulator not to require dam safety improvements, except in an emergency, or if the state contributes 80% of the cost from a limited fund. This state has dam safety standards which are as severe as most states, but has made little progress towards achieving them. So merely having severe standards is not a sufficient condition for achieving them.

In many cases, decision makers are not convinced of the justification for engineering standards that are cited as the basis for costly dam safety works at their dams. As a result, priority has not been given to these works, unless a powerful regulator has required it. Some private dam owners, such as irrigation districts, simply cannot afford to meet these standards. In the public sector the available funds for dam safety improvements fall significantly short of those that are needed to achieve compliance with engineering standards.

In contrast to the state in which the legislature has "tied the hands" of its dam safety regulator, there is another state in which the regulator has aggressively pursued partial dam safety fixes. This has been done through a consideration of the risks associated with each dam, and by negotiating dam safety fixes to a point at which they can be afforded by the dam owner. As a result, some level of risk reduction, albeit in many cases to less than a full standards level, has been achieved at the overwhelming majority of dams in the this state. Although the first state has adopted standards level criteria, little if any risk reduction has been achieved, whereas the second state has achieved significant risk reduction, in a generally cost effective manner through using a risk-based approach.

Those who favor a "hard" regulatory approach may suggest that all that is needed is to give regulators the power to require that owners implement dam safety fixes. However, this would likely result in less than an optimal rate of risk reduction (Bowles et al 1995 and Bowles et al 1998), and would be inconsistent with the trend towards requiring that regulations be justified using a "risk-benefit" rationale. This trend is driven by a concern that we can no longer justify or afford compliance with many health, safety and environmental regulations (Howard 1994), and that in many of these regulations have been neither cost effective, consistent, nor "sensible" in their risk reduction (OMB 1992). An example of these concerns in dam safety is in cases where risk reduction for extreme event fixes is negligibly small, but very costly when compared with risk reduction opportunities at other dams or in other fields.

A risk-based approach to dam safety management offers an alternative to the "broad brush" and often cost ineffective character of an engineering standards approach, and to the "stalemate" which sometimes exists in jurisdictions in which a regulator lacks the power to enforce dam safety regulations. If properly applied, risk-based approaches can provide the justification for a responsible dam owner to take action to reduce significant dam safety risks. To make a convincing case for a costly dam safety measure to a private board of directors typically requires more than a statement that a dam does not meet an engineering standard. In our experience, the case for or against risk reduction measures can be made clearly by presenting the results of a risk assessment in business terms such as cost effectiveness of risk reduction, legal and insurance implications, and risk-based benchmarking against safety practice in dam safety and other fields. This approach has worked even in cases where no dam safety regulator exists.

Some have suggested that the underlying motivation for the risk-based approach is to save money by either not fixing dams or by fixing them to a lower standard of safety. Although this motivation does exist in some cases, our experience is that dam owners are prepared to proceed with justifiable works when a convincing case is made based on risk assessment outcomes. Thus, when properly applied, the risk-based approach can result in a more rapid reduction in dam safety risks than may occur using the traditional approach. This is particularly true when portfolio risk assessment is used to prioritize risk reduction measure across a group of dams (Bowles et al 1998). When a risk-based approach is used, the owner may still choose a standards-based safety level. In some cases we have seen that the risk-based approach leads to justification of safety levels which are more stringent than a standards level (Bowles et al 1998). In addition, by relating risk identification information to day-to-day dam safety practice, significant reduction of risks, which are much more likely to be realized than extreme loading condition, can be achieved.

Technical Origins

Early interest in applying risk-based approaches to spillway sizing dates back to the ASCE Task Committee on the "Reevaluation of the Adequacy of Spillways of Existing Dams" (ASCE 1973). The efforts of this group were controversial because they advocated placing a value on human life and then basing spillway sizing on a purely economic analysis to determine the least total economic cost based on summing risk costs and annualized costs of a dam safety fix.

In the USA, the 1976 failure of Teton Dam and the later failure of Taccoa Falls Dam, lead to an Executive Order being issued by President Jimmy Carter which instructed federal government agencies to explore *"the degree to which probabilities or risk based analysis is incorporated into the process of site selection, design, construction, and operation."* This lead to several research projects funded by federal agencies (e.g. Howell et al 1980 and McCann et al 1985) and some in-house efforts by the U.S. Bureau of Reclamation (1989) and the U.S. Army Corps of Engineers (1987). These efforts did little to address the issue of how to incorporate loss of life considerations into dam safety decision making. FERC (1986) regulatory guidelines were modified to include the possibility of the economic risk analysis in cases where no loss of life was expected. ASCE(1988) published another report on "Evaluation Procedures for Hydrologic Safety of Dams". Although this report did not resolve how to consider loss of life, it did propose a loss financing approach using indemnity costs.

In the 1980's, several risk assessment applications were conducted by the authors for dam owners in the western U.S (Bowles 1990). Two of these applications utilized cost-per-(statistical) life-saved as a measure of the cost effectiveness of reducing life safety risks to address loss of life considerations (Bowles et al 1998).

In the early 90's, B.C. Hydro(1993) and the Australian Committee on Large Dams (ANCOLD 1994) developed interim life loss tolerable risk criteria based on practices in other fields, such as industrial facility siting and nuclear power. Although interim, by explicitly addressing loss of life considerations, these criteria proved to be a turning point in the application of dam safety risk assessment. In 1995 the U.S. Bureau of Reclamation began to develop risk assessment procedures and interim Public Protection Guidelines (USBR 1997). Since then the USBR has performed dozens of risk assessments and is currently the largest user of the approach for making dam safety decisions. The USBR is also integrating risk assessment outcomes into other aspects of its dam safety management program.

In 1997, an International Workshop on Risk-Based Dam Safety Evaluations was held in Trondheim, Norway. The workshop participants were drawn from about twenty countries. Although research and development efforts were presented by most of these countries, applications of risk analysis were limited to only a few countries such as Australia, Canada, South Africa, and the USA.

From a philosophical perspective, some roots of dam safety risk assessment can be traced to concepts which were developed in the fields of "decision analysis under uncertainty" and probabilistic risk assessment in the nuclear and aerospace industries. However, there are some significant differences between these fields and dam safety. For example, decision analysis under uncertainty, which is built on an expected value decision criterion, may be suitable for business risk problems involving relatively high frequency-low consequence events in which an averaging process can be realized. However, this criterion has been widely questioned for application to fields such as dam safety, which involve low probability-high consequence events, because the averaging process which justifies the expected value approach may not exist in practice. Also, dam safety engineering deals with very extreme loading conditions, the severity of which, have rarely been approached. It also deals with foundation and other materials properties which are not as well defined as in mechanical and electrical systems.

Although it is true that the paradigm for a risk-based approach to dam safety is distinctly different from the traditional standards-based approach (Bowles et al 1997), there is much that we have learned in the traditional approach which must be part of a risk-based approach. Thus it is not surprising that traditional dam engineering analysis has been "grafted" into the current practice in dam safety risk assessment. That is, since new analysis techniques, which explicitly account for reliability and uncertainty in the performance of dams are not generally available for practical application, traditional analysis procedures are currently adapted for analyses that support dam safety risk analysis.

ITS BRANCHES - FACETS AND ROLES

The major "branches" of dam safety risk management include risk analysis, risk evaluation, and risk treatment (reduction). Risk assessment combines the first two branches and risk management combines all three. Various levels of effort have been proposed for performing risk assessments (McCann and Castro 1998), but underlying these is the concept that risk assessments should be staged, with greater detail being justified by the value expected to be added for decision making (Bowles et al 1978). This is referred to as a "decision-driven" approach (NRC 1996).

A framework for dam safety risk assessment is presented in Figure 1. As shown by the "column" structure in this figure, the risk assessment process follows a five step sequence from initiating events to system responses, outcomes, exposure factors and consequences. Both external (e.g. floods, earthquakes and upstream dam failures) and internal (e.g. the initiation of piping in an embankment dam under static loading) initiating events are considered. Each external initiating event is described by a number of loading ranges. Several steps may be necessary to fully describe the system response to a given initiating event leading to an outcome of dam failure or no failure. Various types of consequences of dam failure may be considered, including loss of life, economic damages, environmental damages, and societal effects.

There are four major steps in a risk assessment as illustrated by the "row" structure of Figure 1. These steps are as follows: 1) risk identification, 2) risk estimation, 3) risk evaluation, and 4) risk treatment. In Figure 1, the term, risk treatment, refers to the consideration of risk treatment (reduction) alternatives using risk analysis and risk assessment. Implementation of risk treatment is part of risk management.

Risk Analysis

Risk analysis involves both risk identification and risk estimation (first two rows in Figure 1). Risk identification is the process of recognizing the plausible failure modes if the dam were subjected to each type of initiating event. Typically failure modes are represented in an event tree, which becomes the risk analysis model.

Risk estimation consists of determining loading, system response and outcome probabilities, and the consequences of various dam failure scenarios and no-failure scenarios, so that incremental consequences can be estimated. Probability and consequence estimates are then applied to the various branches of the event tree model. Consequences are a function of many factors including, the extent and character of flooding, the season of the year, the warning time and effectiveness of evacuation, and the effectiveness of contingency plans. Risk reduction alternatives are developed and analyzed in a similar manner to the existing dam, by changing various inputs (e.g. system response probabilities and consequences) to represent the improved performance of each alternative.

Risk Evaluation

Once risks have been identified and quantified for an existing dam and risk reduction alternatives, they are evaluated against risk-based criteria. Some considerations in applying these criteria, including ALARP (as low as reasonably practicable) and de minimis risk considerations, are summarized in the section on Risk-Based Criteria in Bowles et al (1998).

Risk Treatment

From a business or management perspective, risk treatment options can be grouped into the following categories, although they are "are not necessarily mutually exclusive or appropriate in all circumstances" (AS/NZS 1995):

- "Avoid the risk" - this is choice which can be made before a dam is built or perhaps through decommissioning an existing dam.
- "Reduce (prevent) the probability of occurrence" - typically through structural measures, or dam safety management activities such as monitoring and surveillance, and periodic inspections.
- "Reduce (mitigate) the consequences" - for example by effective early warning systems or relocating exposed populations at risk.

- "Transfer the risk" - for example by contractual arrangements or transfer of an asset.
- "Retain (accept) the risk" - "after risks have been reduced or transferred, ... residual risks ... are retained and ... may require risk financing."

While the first three options reduce the risk to which third parties are exposed, the fourth and fifth options only affect the risk that the owner is responsible for and not the risk to which third parties are exposed.

ITS FRUIT - BENEFITS, LIMITATIONS AND FUTURE GROWTH

Benefits

Just as good fruit is the product of good husbandry, valid and useful results from risk assessment and risk management are produced by a valid process that is conducted by qualified professionals. Examples of the benefits ("fruit") which have been experienced by both the practitioners and customers of dam safety risk management are summarized below:

Risk Analysis including Risk Identification

- Systematic identification of potential failure modes including some which may have gone unrecognized using traditional approaches.
- Improved understanding of dam performance by the responsible engineers, including the event sequences which could lead to failure.
- More comprehensive engineering analysis than is typical using traditional approaches.
- Facilitates effective technical review and quality assurance.
- Facilitates ranking of failure modes and directing analysis effort to important issues which are not necessarily those which are amenable to analysis, such as seepage and piping.
- Provides basis for identification of effective structural and non-structural risk reduction measures.

Risk Assessment including Risk Evaluation

- Accounts for site specific aspects.

- Justification for the extent and timing of risk reduction measures.
- Facilitates (benchmarking) comparison with risks at other dams or other types of facilities.
- Provides inputs to the decision process but does not prescribe the decision.

Risk Management including Risk Treatment/Reduction

- Facilitates transparency in the decision process.
- Facilitates effective communication between all parties.
- Provides managers and decision-makers an improved understanding of the significance of dam safety issues (e.g. criticality of gate operations and emergency preparedness planning).
- Provides a basis for deciding on additional investigations, analyses, monitoring and surveillance
- Provides inputs to assessing legal liability, due diligence, business risks, and loss financing positions
- Facilitates a systematic and cost effective approach to justification of risk reduction measures.
- Provides a basis for prioritization of risk reduction measures across dams to maximize the rate of risk reduction (Bowles et al 1998)

Limitations and Future Growth

To a large degree the limitations of the current state-of-the-practice in dam safety risk assessment are also the limitations of the current state-of-the-practice in dam engineering. Our analysis tools are imperfect and available information on material properties (including foundation conditions) is often far less than would be the normal practice in other branches of engineering.

Just as judgement is a key element in dam engineering it is a key factor in dam safety risk assessment. In performing a risk assessment, the engineer and others are expected to quantify their judgements and the associated uncertainties in probabilistic terms.

Improved techniques are needed for developing technical inputs to risk analysis. These procedures should represent both reliability and uncertainty considerations. Also improved procedures for eliciting professional judgements and minimizing biases which might exist in these judgements should be developed. The efficiency of risk analysis calculations and procedures for consequence estimation are undergoing continuous improvement. Also several efforts are underway to develop dam safety risk analysis and risk assessment guidelines (e.g. ASCE, CEA, ICOLD, USBR).

However, it is important to remember that the underlying purpose of risk assessment is to assist decision makers to make better decisions. We are not dealing with the pursuit of scientific enquiry, although we obviously desire as firm a scientific foundation for dam safety risk assessment as can be provided at any point in time. The following quotation from a recent essay on Uncertainties in Global Climate Change Estimate by Pate-Cornell(1996) is pertinent here:

> *When science can progress quietly, independently from the pressures of pubic policy making, the scientific community has ample time to fight its internal battles and to prove or disprove each element of the problem. There is no need to synthesize the state of knowledge until the problem is considered resolved by most. ... When decisions need to be made along the way, based on partial and incomplete information for private purposes or public sector regulations, one does not have the luxury of taking the time to reach a complete, unquestioned consensus. In that case, the available information, imperfect as it is, must be synthesized at a particular stage to represent as closely as possible the state of knowledge at that time.*

One of the most beneficial ways of adding to our capability in this developing field is through the performance of risk assessments for actual dams involving their engineers and decision makers. There is an urgent need for benchmarking information on the risk profiles of existing dams and even more importantly on the risk reduction characteristics of implemented measures. This information will be invaluable to decision makers for interpreting risk assessment results, including ALARP and de minimis risk considerations (Bowles et al 1998).

SUMMARY AND CONCLUSIONS

Risk assessment and risk management can be an important enhancement to traditional dam engineering approaches. Whilst their successful application requires a paradigm shift, it is essential that qualified and experienced dam engineers be responsible for their execution.

While engineering standards have served a valuable role in enhancing dam safety, there are many cases around the world in which they have also served as a deterrent to the achievement of any significant risk reduction. If the goal is avoidance of dam failure and reducing risk as soon and as cost effectively as possible, then dam safety risk assessment and risk management have a key role to play as core activities in modern dam safety programs.

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Risk Assessment Framework

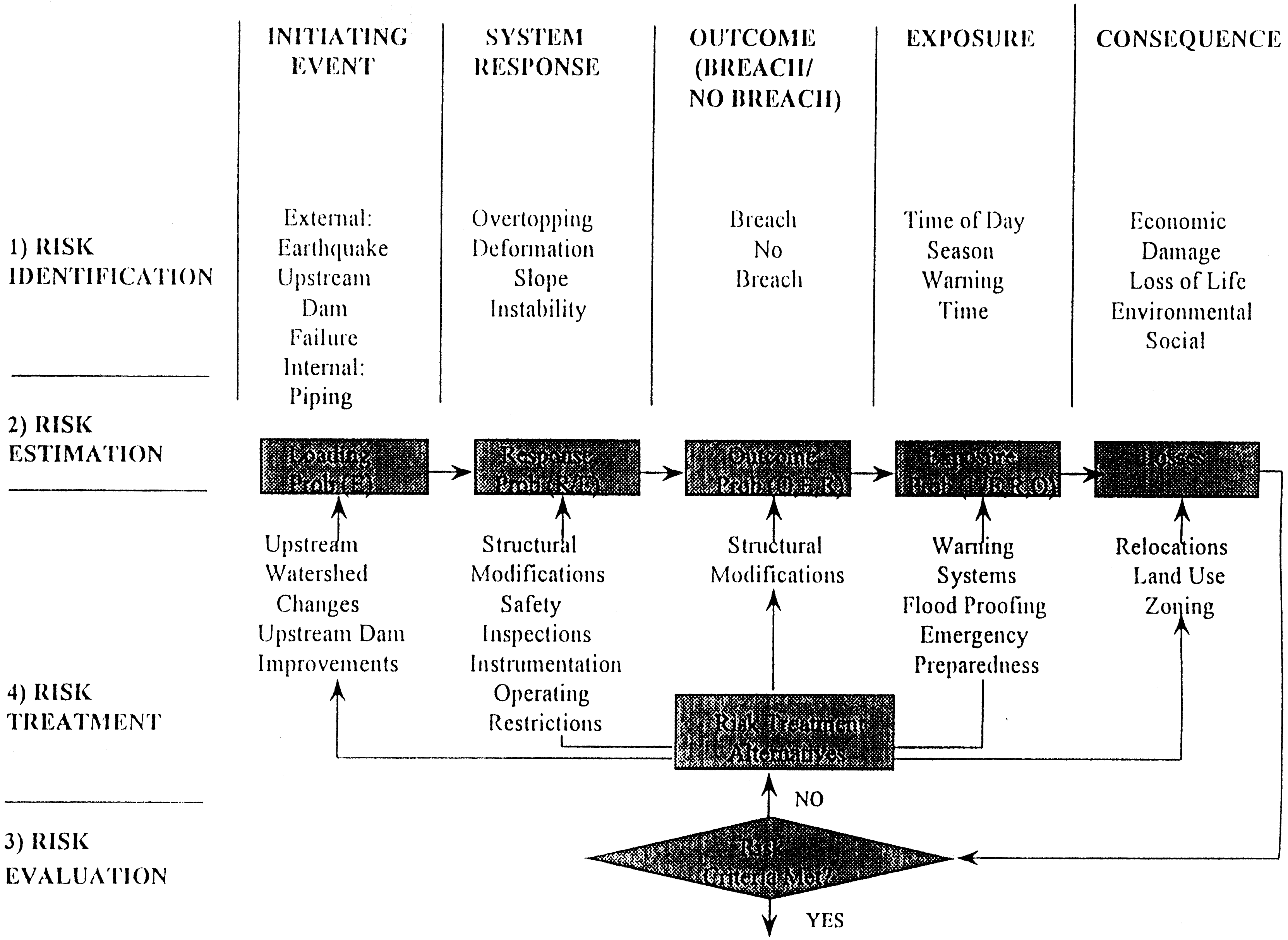

Figure 1. Framework for dam safety risk assessment.

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A Role for Risk Assessment in Dam Safety Management

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ABSTRACT: In this paper we examine various factors which have lead to the trend for using the risk based approach to support dam safety decision making. The relationship between the standards based and risk based approaches is reviewed. Dam safety management is cast in the context of comprehensive risk management. The importance of defining the decision process, the role of decision criteria, and the involvement of owners and stakeholder in a "decision-driven" and staged risk assessment process is presented. The role of risk assessment in short term (emergency) dam safety decisions is addressed, in addition to long term decisions on meeting extreme events.

1. INTRODUCTION

Risk assessment is still a relatively new approach in the field of dam safety evaluation and decision making. When properly conducted it can provide valuable information which may not otherwise be available from conventional approaches. Quantitative examples include: estimated probabilities of dam failure and the consequences of failure, and estimates of risk reduction for various structural and non-structural rehabilitation alternatives. In addition, the process of conducting a risk assessment can provide qualitative benefits such as insights into the relative importance of various failure modes and loading types and ranges, and the potential value of additional analyses or field investigations. Even for high hazard dams, where acceptable risk considerations may lead to the adoption of "worst case" (evaluation) events, the systematic risk assessment process can be useful as a quality assurance tool for identifying risk reduction options in the design of rehabilitation measures, project operation, or emergency action planning. Also the open display of information obtained from a risk assessment can be a very useful means of conveying the implications of highly technical issues to non-technical owners and to the general public.

Dam safety management is intrinsically a problem in risk management and decision making under uncertainty. In the past we have tended to view dam safety as primarily an engineering problem. In many countries engineering standards approaches are leading to requirements for very costly remedial measures at existing dams. As a result, the underlying foundations for these standards are being examined and risk assessment approaches are being adopted to make explicit tradeoffs of risks, costs, and benefits. This leads us to ask the following questions. Are the standards based and risk based approaches incompatible? What is driving the trend towards risk based approaches? How should risk assessment approaches fit into the broad framework of dam safety decision making in a world in which regulations are becoming less prescriptive; dams are being moved from public to private responsibility; there is growing competition for financial resources; and the public is becoming more risk averse and wants to be more involved in decisions which effect their well being?

In this paper we seek to address these questions based on the current state-of-the-practice in dam safety risk assessment and our experience in performing such assessment for public and private sector clients in the USA and other countries. For a discussion of risk assessment procedures and several case studies, the interested reader is directed to Bowles (1990).

2 COMPREHENSIVE RISK MANAGEMENT

As dam safety evaluation is to dam safety management, so is risk assessment to risk management. A comprehensive dam safety risk management program should include many other components in addition to risk assessment for evaluating existing dam safety and alternative remedial actions. These other components should include the following:

1. Provision of an appropriately designed, well maintained, and regularly exercised emergency warning system and emergency action plan.
2. A comprehensive monitoring and surveillance program with clear assignment of responsibilities for timely review and follow-up on collected data and reports.
3. A well trained operations and maintenance staff.
4. A well planned, adequately funded, and properly executed maintenance program.
5. Routine inspections and periodic in-depth inspections and comprehensive dam safety reviews and updates of any previously conducted risk assessments that are being relied upon for dam safety decisions.
6. An effective public consultation program.

All of these are important interrelated components in a comprehensive risk management program for any high hazard dam. Each is necessary for the proper exercise of duty of care of the owner and each should play a coordinated role in managing dam safety risks. A fragmentary approach to dam safety management can lead to overlooking the implications of information held in other program components. Dams are integral structures and their safety should be managed in a holistic manner (Perrow 1984).

The on-going aspects of a comprehensive dam safety program, such as monitoring and surveillance, should play an important and complementary role to periodic comprehensive dam safety reviews. Neither the engineering analysis tools that are used in these reviews nor the monitoring and surveillance programs provide perfectly accurate or complete insights into dam performance (Fanelli 1992). Analysis tools are based on idealized representations of complex structures and their foundations and must rely on estimates of materials properties and postulated future loading conditions. Monitoring and surveillance of actual performance can be important in verifying the results of theoretical analyses. They can also provide valuable information where no analysis tools currently exist. However, monitoring and surveillance cannot always directly measure or observe the parameters which are of direct importance, and it takes time and expertise to make interpretations. Analysis tools must often be used as part of the interpretation process for monitoring data, or for predicting the limits of acceptable behavior against which satisfactory performance is judged. Thus in an overall risk management program both on-going observations and on-going analysis are important for developing confidence that a dam is, or is not, performing satisfactorily. Observations and analyses complement each other and neither can be entirely substituted for the other.

It is normal practice to perform comprehensive dam safety reviews approximately every five years (ICOLD 1987). In part, the purpose of such reviews is to assess the effects on dam safety of any changes in technical standards or the state-of-the-art. If a risk based approach is adopted, the risk assessment should be updated as part of the comprehensive review. Any changes to risk assessment inputs, such as loading conditions, factors that would effect predicted performance of the dam, the consequences of failure, or other operational outcomes should be updated. In this way a risk assessment becomes a "living document" which can be used by decision makers to periodically reassess their current duty of care position in light of changing business considerations, evolving community values, and other factors.

3 TREND TOWARD RISK BASED APPROACH

Interest in the potential for applying risk based approaches to dam safety decision making has accelerated in the last two decades. An increasing number of organizations have begun to routinely use risk based approaches in dam safety evaluation. These now include the U.S. Bureau of Reclamation (Von Thun and Smart 1996), the Government of South Africa (Oosthuizen et al, 1991), the Government of the Netherlands (CUR 1990), various Australian dam owners and regulators (SMEC/RAC 1995), and B.C. Hydro (1993). Many other organizations are actively considering using the risk based approach.

Some factors which have lead to the increasing use of risk based approaches are common to dam owners and operators in different countries. They include the following:

1. The absence of functional features, which are now considered to be the state-of-the-art in dam design, but which were not incorporated in many existing dams (e.g. downstream filters in embankments to dissipate pore pressure in the event of significant seepage).

2. The greater magnitude of extreme (worst case) evaluation (design) flood and earthquake events (i.e. PMF and MCE, respectively) which are prescribed using today's standards based approaches compared with those for which existing dams were designed or are capable of accommodating.

3. The high cost of correcting state-of-the-art and extreme event "deficiencies" which has lead to question the justification for the standards, cost effectiveness, and due diligence from a legal and overall business perspective.

When considering the need for remedial works to address state-of-the-art "deficiencies" under a risk based approach, the goal should be to confidently predict that the dam will perform satisfactorily under a full range of loading conditions. Satisfactory performance can be defined using tolerable risk criteria such as those summarized in Section 6.

One of the following four outcomes could result from a risk based evaluation of an existing dam with state-of-the-art and extreme event "deficiencies":

1. Accept the existing dam, without modification, if it can be demonstrated, with sufficient confidence, that the existing dam can be expected to perform satisfactorily, even though it might not meet current standards.

2. Modify the existing dam so that the modified dam would be expected to perform satisfactorily, with sufficient confidence, but not necessarily to current standards.

3. Remove and reconstruct the dam, so that the new dam would be expected to perform satisfactorily, with sufficient confidence, and meet current standards.

3. Decommission the dam so that it no longer poses a threat to downstream populations at risk.

The costs and risks associated with the drastic action of removing an existing dam and reconstructing it would often be unacceptably large, and the resulting benefits might be questionable or difficult to prove. Nevertheless, in some cases this may be the only way to achieve the goal of satisfactory predicted performance with sufficient confidence.

Satisfactory performance under loading conditions that are within the range experienced at an existing dam may be demonstrated through monitoring and surveillance and engineering analysis. For extreme floods, earthquakes, and static loading conditions, which are outside of the range that has been experienced since a dam was constructed, the sole use of monitoring and surveillance to demonstrate satisfactory performance is problematic. However, testing of material properties, structural and stability analyses, and the transfer of experience from similar dams can all be used to predict performance under extreme loading conditions.

The degree of confidence in performance predictions can often be improved with additional testing, monitoring, and analysis. Risk based approaches focus on predicting dam performance and the confidence (or uncertainty) associated with these predictions. In contrast, the sole use of traditional approaches emphasizes factors of safety and compliance with standards provides only vague indications of the level of confidence that is being attained in achieving satisfactory performance. Thus it is seldom clear if the level of confidence is unjustifiably excessive or undesirably small.

The magnitudes of extreme evaluation events have increased over the past few decades for various reasons, including the following:

1. The "unknowable" nature of worst case events.

2. Changing methodologies which tend to produce increasingly more conservative design events.

3. Difficulty in determining the plausibility of combinations of contributing factors used to calculate worst case events (e.g. very small loss rates coinciding with worst case precipitation to define a probable maximum flood event).

4. The tendency for design professionals to favor more conservative definitions of worst case events.

5. An improved understanding of the potential for inadequate performance of dams and their foundations under dynamic seismic loads.

A danger of focusing dam safety studies on worst case scenarios is that deficiencies associated with lower magnitude more frequently occurring loading conditions may be given too little attention. Thus, by focusing on the most unlikely fraction of one percent of the event magnitudes, one might overlook the range of events which are much more likely to cause failure of an existing dam. An example would be focusing on the capability of a spillway to cope with a PMF while deficiencies under static (water) loads are given little attention.

4 STANDARDS *V.* RISK BASED APPROACHES

We use the term, "standards based approach", to refer to the approach to design and evaluation of dams in which a satisfactory safety condition is defined by either: a) compliance with prescribed performance measures or loading conditions; or b) use of the current state-of-the-art (or practice) meaning the generally accepted present-day approach to dam design, evaluation, and construction.

The term "risk based approach" is used to refer to the approach to design and evaluation of dams in which an acceptable safety condition is defined using information provided from a risk assessment and other decision inputs. Risk assessment is a systematic process wherein experienced dam engineering professionals provide decision makers with estimates of the risks and associated uncertainties of system responses, outcomes, and consequences, which characterize the performance of an existing dam and various remedial action alternatives under a full range of loading conditions.

It might appear that the choice between a standards based *v.* a risk based approach is between a "clear cut" standards approach and a risk based approach which might lead to the acceptance of a higher risk of failure than would be the case under the standards approach. However, a standards based approach is not necessarily as clear cut as it might first appear. For example, under the standards based approach professional opinions and practice can vary over the selection of appropriate design criteria. A standards based approach does not ensure a "zero risk" solution to a dam safety concern. Furthermore, a standards based approach involves "blind" risk tradeoffs whereas these tradeoffs can be made more explicit under the risk based approach. If a purely standards based approach is used it is unlikely that the implied risk tradeoffs will be understood by the decision makers, their technical advisors, other stakeholders, and their legal and financial advisors. In contrast, a properly conducted and well communicated risk assessment can be expected to provide all parties with valuable understanding and insights of potential risk tradeoffs. In addition, risk assessment can be expected to provide: a basis for prioritizing remedial works; a clearer picture of the potential benefits of non-structural measures, such as emergency warning systems and a basis for deciding on any temporary operating restrictions.

In some cases the outcome of a risk assessment could be a decision to adopt standards based design criteria. In fact, the standards based approach can be thought of as a prescribed point on a continuum of different performance standards or design (evaluation) loading conditions. The risk based approach can be readily used to examine a range of these performance measures or loading conditions to evaluate the effects on reliability, consequences, cost effectiveness, and due diligence of deviating from the standards based approach. In this way the risk based approach can be used to explore the appropriateness of a standards based approach. Sole use of a standards based approach without risk assessment can lead to the adoption of design criteria which might be unjustifiably conservative or lax for a particular dam.

There is an important difference between the way in which the standards and risk based approaches treat different worst case event estimates. The standards based approach tends to treat less conservative and more conservative estimates of evaluation events without recognition that they differ in their likelihood of occurring. In the risk based approach smaller probabilities of occurrence (annual exceedance probabilities) can be associated with more conservative estimates of extreme events. In this way, risk assessment provides a framework within which differences in the degree of conservatism in extreme even estimates can be accounted for in selecting and justifying an evaluation event for a particular dam. This can be done using the joint probability distribution for the occurrence of various contributing factors which define an evaluation event (e.g. initial reservoir level and antecedent moisture levels for a flood event). It also provides a means for quantifying the uncertainties that exist in defining worst case event scenarios. Other benefits of using a risk based approach are presented in Bowles (1996b) and Bowles (1987).

5 DEFINING THE DECISION PROCESS

In our experience it is important to clearly define the decision process that will be used to make a dam safety decision. Ideally this should be done before a risk assessment can be designed, in consultation with the stakeholders, to provide information inputs that will be useful at each stage in the process, and on an agreed upon schedule. The National Research Council (1996) refers to this type of approach to risk assessment as "decision driven". Adopting such an approach will provide a basis for appropriate and justifiable limits on the level and detail of risk assessment efforts. This is important since there is virtually no end to the amount of effort which could be put into a detailed risk assessment. It is therefore important to remember that risk assessment should become an end in itself; the end should be a quality, well communicated and highly defensible dam safety decision.

In clearly defining the decision process the following questions should be addressed:

1. Who are the decision makers?
2. What will be the role for community consultation and for the various stakeholders in the decision process?
3. What decision criteria will be used by the decision makers? This should include an evaluation of the entire framework in which the dam safety decision will be made including regulatory, legal, financial, business, economic, environmental, social, and other considerations.
4. What information from risk assessment is needed by the decision makers and stakeholders throughout the decision process?

6 DECISION CRITERIA

Various criteria can be useful to judge results from a risk assessment when a long term dam safety decision (Bowles 1996a) is to be made (for a short term decisions see Section 9). They include life safety, economic, and other types of criteria. Care must be taken that the selected criteria are consistent with the dam safety decision framework and that they serve the dam safety decision process which is identified at the outset of the risk assessment (see Section 5). A search for internationally applicable dam safety risk criteria could result in criteria which do not serve all dam owners in all countries equally well. This is particularly true if, as is often the case with a strict standards approach to accommodating extreme events, the focus is on selecting and meeting a criterion rather than prioritizing a sequence of risk reduction measures, giving consideration to the cost effectiveness of each measure.

Life safety is always an important consideration. It can be evaluated using both societal and individual tolerable risk criteria such as those in the ANCOLD (1994) Guidelines on Risk Assessment and by BC Hydro (1993). Societal criteria are commonly expressed as F-N curves of cumulative frequency, F, of life loss exceeding various magnitudes, N. It provides a means of judging the scale of potential life loss from individual failure modes, or combinations of failure modes, for a single dam. Overall life loss can also be evaluated against an expected annual life loss criterion as in USBR (1997). In either case it is still important to evaluate individual life safety criteria to assess the potential for individuals to be excessively exposed to the risk of dam failure.

Public and private investments are typically evaluated against a benefit/cost or rate of return criterion. Dam safety projects seldom fair well in such evaluations because the probability of failure is often small and thus the expected benefits are very small relative to the certain investment of capital and maintenance funds. Out of more than seventy dam safety risk assessments we have completed only one has shown a benefit/cost ratio greater than unity. Benefit/cost ratios could be increased by adding a value for human life to the assessment of benefits. However, we feel that this raises serious ethical and moral issues and we do not recommend such an approach to evaluating the benefits of increased public safety.

We have found that a useful approach to considering the benefits of increased public safety is to evaluate the cost effectiveness of structural and non-structural alternatives. This can be done by calculating a cost-per-life-saved for each alternative and comparing these with similar costs for other facilities which expose the public to risk of life loss. By pursuing alternatives with costs-per-life-saved which are less than those in these other fields, an owner is at least being consistent with the extent to which these other fields invest in public safety. Care must be exercised in selecting fields in which risks are similar in nature to those created by dams. The U.S. Office of Management and Budget (OMB 1992) argued that the cost effectiveness approach is a "sensible" way to justify the investment of federal government dollars, or private funds as the result of regulations in public health and safety measures.

Cost effectiveness measures can also provide a very useful basis for prioritizing dam safety investments such that those which are expected to result in the greatest reductions in risk for a given level of available funding are undertaken first. When this approach is applied to a portfolio of dams it should maximize the rate of (public) risk reduction to which the dam owner is exposed. Typically one can expect that such an approach to prioritization will lead to a high priority being given in a dam safety program to implementation of early warning systems (EWS). In this case, EWSs would not necessarily be used as a substitute for structural options, but as an early and typically very cost effective step in improving public safety. If structural measures are subsequently implemented, an EWS might be retained as a supplement to structural measures.

In addition to these life safety and economic criteria, consideration should be given to financial, business, legal, and other factors which the owner and other stakeholders must take into account in their decision process. This should include an appropriate role for community consultation in the overall decision process so that the dam owner meets its social responsibilities as well as its business objectives and regulatory requirements.

7 STAGED APPROACH TO RISK ASSESSMENT

Much of the information needed to perform a risk assessment is commonly developed in the course of a traditional periodic comprehensive dam safety review. However, some additional work is always required to provide the necessary inputs for a risk assessment. The amount of additional work depends on the scope and level of detail of the risk assessment.

In conventional engineering analysis it is common practice to select parameters conservatively. In performing these analyses to provide inputs to risk assessment, it is usually desirable to rerun these analyses using best estimates of parameters to obtain realistic performance predictions. Also it may be useful to analyze steps partially failed sections in the case of progressive failure mechanisms that would be expected to result from foundation liquefaction, for example. In addition, sensitivity analyses using ranges of values for key input parameters can provide valuable information upon which to base risk assessment inputs and judgements that experienced engineers are expected to make in conducting risk assessments.

We advocate using a staged approach to risk assessment. Under this approach, later more detailed stages are performed only if warranted by the potential value added to the dam safety decision making process through reduction in the level of uncertainty in risk assessment outputs. More detailed stages of risk assessment usually require that more detailed inputs be obtained from additional field investigations, testing, or engineering analyses. Before proceeding with a more detailed risk assessment, the extra cost it would entail should be weighed against the expected improvement in the quality of the decision that is to be made using risk assessment outputs. This is another example of making dam safety risk assessment a "decision driven" activity.

8 OWNER AND STAKEHOLDER INVOLVEMENT

We have had direct experience with involving water users groups, regulators, owners, operators, legal advisors, senior management, and politicians in the dam safety decision process using risk assessment. So far our involvement with community groups has been mainly through our clients. However, we have found that in most cases the understanding provided by the systematic and transparent risk assessment process has been acclaimed by all parties. In our experience it has been important to involve these groups throughout the process and not just through the presentation of a final report. Such a process of continual involvement presents communications challenges and one must be careful in presenting preliminary risk assessment results to lay audiences. Credibility can be shaken if significant changes occur in these results in later stages of the risk assessment. Of course similar difficulties can exist with a standards based approach if conclusions based on preliminary analyses are made public, and significantly different conclusions are released after additional analyses are completed. The open and honest communication of uncertainties is highly recommended. Also it is recommended that the technical risk assessment team enlist the assistance of experts in risk communication and community consultation.

Where they exist, community consultation requirements contained in environmental impact assessment processes might be used to provide for community consultation in dam safety decision making. However, care should be taken to avoid diluting dam safety issues.

We have repeatedly found that it is difficult for lay people, and in many cases technical people, to have a holistic and balanced perspective on dam safety issues when a purely standards based approach is used. The difficulty is that the standards approach often masks the true nature of dam safety management which is intrinsically a problem in risk management and decision making under uncertainty. When a standards approach is used, there is a danger of misleading the public into thinking that the adoption of standards based design (evaluation) criteria will provide absolute protection against the risk of dam failure (i.e. zero risk). This is obviously false and the fact that dams have been built to meet these standards have failed proves the point. Even though following a risk based approach presents challenges in risk communication, we have found that the additional effort is well worthwhile considering the benefits of sharing a more complete and honest picture of the true risks and uncertainties that are inextricably associated with dam safety decisions. This has been repeatedly borne out by client testimonials such as Waite (1989).

9 LONG TERM AND SHORT TERM DECISIONS

Dam safety risk assessments have most commonly been conducted to provide inputs to long term decisions on the level and priority of remedial works needed to meet extreme events. Risk assessment can also be used to provide inputs for short term decisions, including emergencies and the need for reservoir operating restrictions (for example, USBR 1996). Three time frames can be distinguished for such decisions:

1. Prior to construction of remedial works;
2. During construction of each phase of remedial works; and
3. At the completion of each phase of remedial works.

The outcome of these short term decisions can be used to establish reservoir level restrictions during each phase of remedial work, and perhaps the timing of the works with respect to seasonal reservoir inflows. At the completion of each phase of remedial works, risk assessment can be used to provide inputs to the decision to allow increases reservoir levels as a result of the additional margin of safety added by those remedial works.

In long term decision applications of risk assessment the emphasis is on balancing risks, costs, and benefits over a long period of time when selecting an appropriate level of protection against extreme events. When using risk assessment in support of short term decisions the concern is for the imminent development of a failure condition. In this case the long term time frame can not be counted on for balancing risks, costs, and benefits. We suggest that when used in support of short term decisions, risk assessment should be used for the following primary purposes:

1. To identify the relative risk (likelihood and consequences) of various failure modes; and
2. To reduce the risk of each failure mode through a) management actions (e.g. reservoir operating restrictions, emergency repairs); b) improved detection of worsened conditions that could lead to failure; c) contingency planning covering all aspects of the owner's responsibilities, including the decision and notification steps that lead to initiating a downstream evacuation; and d) coordination of contingency planning with the local authorities who are responsible for evacuation.

It must be stressed that the use of risk assessment in support of short term decisions must not delay taking immediate emergency action, when such action is prudent and necessary. However, we believe that even when immediate action has been taken risk assessment can be used to help guide the on-going decision process. Benefits of this use of risk assessment in this short term context include the following:

1. Understanding of the development of event sequences which might lead to imminent failure.
2. Assessment of the need for additional instrumentation to identify changed conditions.
3. Identification of critical values of performance parameters for initiating additional investigation or emergency action.
4. Assessment of the benefits of various short term actions such as reducing reservoir levels, or improving response times for making emergency releases.
5. Assessment of the adequacy of warning time and ways to increase warning time and its reliability.

10 CONCLUSIONS

We have stated that the true nature of dam safety management is intrinsically a problem in risk management and decision making under uncertainty. In a world in which regulations are becoming less prescriptive, dams are being moved from public to private responsibility. There is growing competition for financial resources, and the public is becoming more risk averse and wants to be more involved in decisions which effect their well being. The continuous risk management framework can provide a valuable approach to meeting these challenges. The risk management approach should treat dams as integral structures whose safety should be managed in a holistic manner. It should also take into account the uncertainties which exist as a result of the current limitations in our capabilities to predict and monitor dam performance.

Risk assessment is a component of the risk management approach. It provides the opportunity for engineering inputs to be considered along side the many other factors that owners and others must consider when making dam safety decisions. In our experience it is important to clearly define the decision process that will be used. Adopting a "decision driven" approach to risk assessment will provide a basis for appropriate and justifiable limits on the level and detail of risk assessment efforts with the goal of reaching a quality, well communicated and highly defensible dam safety decision.

In some situations the funds needed to meet extreme event standards simply do not exist. In many other cases reliance on a purely standards based approach does not provide adequate justification to convince lay decision makers of the need to meet these standards and a "stalemate" has resulted. We do not argue with the desirability, and even the necessity, of meeting extreme event standards in many cases. However, we observe so many cases in different countries in which no risk reduction has been accomplished even though it is well recognized that standards are not being met. We suggest that in many cases the focus should be on identifying and justifying the next most cost effective risk reduction steps rather than waiting to meeting an extreme event standard. In addition, correcting for all state-of-the-art "deficiencies" is often impracticable and must be addressed by risk management rather than structural approaches. The irony is that even when expensive works are completed to meet standards, a dam may remain much more at risk to the malfunctioning of gate systems, to inadequately trained operators, or to the absence of a properly maintained early warning system, than it was to undercapacity of a spillway, for example. Of course each case must be individually evaluated, and as we have sought to emphasize, in some cases standards based solutions will be justified. When properly implemented, risk assessment can serve as a valuable tool within a comprehensive risk management framework for effective dam safety management. We further suggest that such a comprehensive and systematic approach is necessary for the proper exercise of duty of care of a dam owner and to assist in meeting due diligence.

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UNDERSTANDING AND MANAGING THE RISKS OF AGING DAMS: PRINCIPLES AND CASE STUDIES

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ABSTRACT

Risk management can enhance all aspects of the management of aging dams. Risk analysis can strengthen the identification and understanding of dam safety issues. Risk assessment can provide valuable information on the risk reduction characteristics and benefits of structural and non-structural risk reduction options. In addition, to being useful for technical purposes, risk assessment outcomes can strengthen the case for funding capital improvements, additional investigations, and on-going dam safety activities, such as monitoring and surveillance and emergency management. A portfolio risk assessment and an individual dam risk assessment, which the authors have completed for owners and a regulator, are summarized to provide specific examples of the use of risk analysis, risk assessment and risk management in gaining insights, exploring options, and justifying safety improvements at aging dams.

INTRODUCTION

The challenge of managing aging dams is rapidly becoming a principal focus of dam engineering throughout the world. At

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least a quarter of the dams listed in the U.S. Army Corps of Engineers (USACE 1997) National Inventory of Dams are more than 50 years old. The fact that these dams are the products of a different generation of design standards and construction practices is generally of greater concern than the aging process itself. The risks associated with aging dams are typically of low probability but high consequence. They usually affect third parties, which in many cases may not realize that they are at risk. The underlying dam safety issues are usually technically complex and information about foundations, and even the materials from which the dam itself is constructed, is less than desirable. Typically, justifications for expending large sums to reduce dam safety risks have been based mainly on non-compliance with engineering standards, and are found to be unconvincing by non-technical decision makers (Bowles et al 1997 and 1998a).

A primary objective of dam owners and regulators should be to ensure that aging dams "do not create unacceptable risks to public safety and welfare, property, the environment, and cultural resources" (USBR 1993). The manner in which dam safety decisions are made varies from one owner to another, but increasingly these decisions are being made by non-engineers ["From engineers on top to engineers on tap" (Haisman 1998)]. In this setting, engineering inputs are considered along with a multitude of other business-related considerations. Thus, simply requiring that dams meet engineering standards is often not the most effective way to manage the safety of aging dams (Bowles et al 1998a and 1998b). The risk-enhanced approach is an alternative that is being increasingly used. When properly implemented, it can result in a more rapid and more cost effective achievement of risk reduction at aging dams. This approach seeks to a) develop an thorough understanding of the dam safety risks, and b) explore the options and provide a basis for managing these risks in the context of the owner's business.

This paper is divided into four main major sections. The next two sections summarize ways in which risk management can be used to better understand and manage dam safety risks. In the following section we summarize a portfolio risk assessment and a risk assessment for an individual, which we have completed for owners and a regulator. These case studies provide specific examples of the use of risk analysis, risk assessment and risk management for gaining insights, exploring options and justifying safety improvements at aging dams. The paper closes with a summary and conclusions section.

UNDERSTANDING THE RISK

Qualitative Insights - Risk Identification

One of the first steps in performing a dam safety risk analysis is the identification of potential failure modes over full ranges of flood and earthquake loading and also for normal operating conditions. Risk identification is a qualitative process of listing potential failure modes as sequences of events or combinations of conditions, which are considered to be necessary for dam failure to occur. This process is driven by repeatedly asking the simple question, "If a certain range of loading were to occur, what would be the resulting effect on and response of the dam-spillway-foundation-abutment-reservoir system?" The outcomes of the risk identification process can improve the recognition and understanding of dam safety issues even before quantitative risk analysis. Risk identification can aid with the recognition of cases in which, even though conditions may exist for an incident to occur, other conditions that are necessary for dam failure to result may not be present. For example, earthquake-induced localized liquefaction may not be of sufficient severity and extent to lead to a deformation on a scale sufficient to lead to a loss of the reservoir contents. Even if significant deformation occurs, reservoir levels may or may not be high enough to lead to an immediate overtopping dam failure (e.g. Lower San Fernando Dam) and delayed failure modes may be avoided by an emergency drawdown of the reservoir pool.

In our experience, with risk assessments on almost 150 dams, we have seen many cases in which application of a systematic risk identification process has lead to the recognition of failure modes that had previously been missed (see Pykes Creek case study in this paper). Although there is no guarantee that all failure modes will be identified, the likelihood that all significant failure modes will be recognized should be improved when a systematic risk identification process is properly applied by experienced dam safety engineers.

The insights gained through the risk identification process can be most valuable in positioning the engineer to design against specific failure modes. They can also lead to ideas for effective risk reduction measures, which might not otherwise have been suggested. Risks associated with human errors, communications and access problems, or institutional arrangements associated with operations and maintenance and monitoring and surveillance activities may be recognized for the first time; thus positioning the owner to take actions to lesson these risks. The potential for human intervention to reduce the likelihood of dam failure during an incident, or to

mitigate its consequences, might be recognized. Valuable ideas for contingency planning may be developed. The vulnerability of a structure to malfunctioning of spillway gates may be better understood.
The identification of specific failure modes frequently leads to the recognition of gaps in the information that is needed before a quantitative assessment can be performed. Such gaps may be filled through field investigations, materials testing, engineering analysis or seeking expert inputs. Traditionally, the scoping of dam safety investigations and evaluations has been heavily influenced by the identification of deficiencies defined with respect to engineering standards. Efforts are sometimes allocated disproportionately to those deficiencies which are most amenable to analysis, and not necessarily to those which pose the greatest risk, or offer the greatest opportunity for cost effective risk reduction. Ideally, efforts invested in investigations should justified by the reduction of uncertainties or the improvement in the confidence in engineering and other inputs to dam safety decisions.

The insights gained from risk identification may lead to shifts in the emphasis of investigative programs. For example, there may be a shift from focusing on spillway deficiencies for very rare floods, to concerns about piping or seepage, which are associated with much more frequent loading conditions and which could lead to a sudden and possibly undetected failure. In one of our early risk assessments (Bowles 1988), the shift was from performing a dynamic seismic stability analysis, to better defining the problems associated with evacuation of a large metropolitan area in the event of an upstream dam failure.

Quantitative Risk Assessment

Moving from the qualitative step of risk identification to quantitative risk assessment enhances the insights and other benefits that can be developed during risk identification. To obtain quantitative estimates of the risks associated with an existing dam requires that flood, earthquake and static loads be described using probability distributions. It also requires that the system responses, which comprise failure modes, and which were identified as part of the risk identification step, be characterized using conditional probabilities, and that consequences be estimated, together with exposure conditions that affect life safety risks. Thus the estimated risk is represented in terms of probabilities and consequences of failure for various failure modes of the existing dam. Similar estimates are made for structural and non-structural risk reduction measures. For each measure, appropriate changes are made to the system response characteristics and other relationships, such as, reservoir stage-annual exceedance probability (AEP), stage-discharge, and consequences.

Uncertainty is intrinsic to dam engineering and can be quantified using uncertainty analysis in conjunction with risk analysis. If uncertainty about foundation conditions or materials properties are considered to be too large to proceed with confidence, the value of obtaining additional information through investigation, testing, and analysis can be assessed, and used as a basis for deciding if these efforts are worthwhile.

MANAGING THE RISK

Exploring Options

Risk assessment provides a valuable framework within which to compare a range of risk reduction measures. It provides insights into the unique risk reduction characteristics of each measure in a form that has been found useful to engineers and understandable to non-engineering decision makers. For example, increasing spillway capacity by lowering the spillway crest would be expected to increase the frequency of operational flood damages while decreasing the probability of dam failure. Raising a dam would reduce the probability of failure, but in the event of a failure the extent of damages will likely be increased. An emergency warning system may not provide an opportunity to reduce the probability of dam failure, but should decrease the potential for loss of life. If spillway gates are present, the many factors, which affect their operational reliability, can be explored so that the most effective means of improving reliability can be formulated. Figure 1 illustrates the differing life safety risk reduction characteristics of some different flood risk reduction measures.

The insights obtained through the qualitative and quantitative aspects of risk assessment can improve the range of risk reduction measures, which are identified. In some cases combinations of structural and non-structural measures may be significantly more cost effective, or even the only way to reduce risks to tolerable levels. We have seen several dams for which even a state-of-the-art structural fix is not sufficient to reduce risk to tolerable levels where a dam is located immediately above a populated area.

Justifying Actions

The need for better justification of both capital works and on-going dam safety management activities has probably never been greater than it is in these days of privatization, deregulation, and reinvention of government. Traditionally, a deficiency with respect to an engineering standard was considered to be sufficient justification for proceeding with a dam safety fix. Today, a strong business-related justification must frequently be made. Such a justification should include an explanation of the risks, including the consequences for the owner and third parties, for the existing dam and for various risk reduction alternatives. It should include an assessment of the implications of each alternative for such business processes as capital budgeting, due diligence and liability, contingency planning and business criticality, and loss financing and insurance coverages. In addition, a firm basis should be provided for monitoring and surveillance, operations and maintenance, and emergency preparedness planning.

Various criteria have been developed for use in evaluating dam safety risk assessment results. Amongst the most important are tolerable risk-to-life criteria. These are generally based on the probability and consequences associated with the failure (performance) of a dam. Risk and safety levels can be compared with those expected for other types of facilities, such as hazardous industry siting and nuclear power plants. Thus, by supplementing engineering standards with information obtained from risk assessment, the risk-enhanced approach can avoid the shortcomings of a engineering standards-only approach, while better communicating the significance of dam safety issues and justifications for actions to lay decision makers.

In addition to life safety criteria, other criteria which can be useful for justifying dam safety actions can include estimates of financial liabilities for comparison with insurance coverages, rate of return and benefit:cost information, and estimates of the cost effectiveness of risk reduction actions. The role of cost effectiveness, including cost-per-(statistical) life-saved (CPLS), for prioritizing dam safety risk reduction measures is further discussed in the following subsection. CPLS can also be useful for benchmarking the level of expenditure by other dam owners in protecting public safety.

By obtaining estimates of dam safety risks, a basis can be established for comparing risk reduction decisions within and between portfolios of dams. These benchmarking exercises are becoming of great interest to dam owners, especially in times of deregulation and increasing competition. They should also be of interest to regulators. Such comparisons can provide a relatively objective measure of due diligence and might be used in an adversarial setting in the event of a dam failure, or if third parties were to question the adequacy of an owner's dam safety program.

Prioritizing Actions

Actions to reduce the risk associated with existing dams can be prioritized in various ways. Traditionally hazard ratings have been used to sort dams into different groups. Greater effort is then invested in dam safety management for high hazard dams than for low hazard dams. However, hazard rating systems are typically of little use for prioritization of a group of dams because hazard categories lump many dams into a single high hazard category (Bowles et al 1995). Also, hazard, as defined by these rating systems, has no relationship to the probability of failure and little relationship to the consequences of failure.

Risk-based approaches for prioritizing dam safety improvements can be based on the level of existing risk, the amount of risk reduction, or the cost effectiveness of risk reduction (i.e. risk reduction per dollar expended or "bang for the buck"). To maximize the rate of risk reduction for a single dam or over a portfolio of dams those risk reduction actions with the greatest cost effectiveness should be given the highest priority. This is clearly demonstrated in the portfolio risk assessment case study presented in the following section.

The most cost effective actions may include low cost measures, such as emergency preparedness planning or a parapet wall. These measures may not be complete fixes, and their implementation might be only a first phase or an interim measure in a multi-phased dam safety improvement program. The Pykes Creek Dam case study illustrates a phased approach for addressing flood deficiencies. When risks are high, relatively expensive measures can be cost effective if the resulting risk reduction is large. The as-low-as-reasonably-practicable (ALARP) condition can be considered to be satisfied when actions are no longer cost effective, as indicated by a very large cost for a very small risk reduction (e.g. a very large CPLS).

CASE STUDIES

Two risk assessment projects, which the authors have performed for clients in Australia, are summarized in this section. The first project is a portfolio risk assessment of 17 large dams. The second project is for individual dam, and was a demonstration project sponsored by the owners and the regulator in the State of Victoria in south-eastern Australia. The regulator is developing and promoting a Business Risk approach to dam safety regulation and management (Watson

1998). These demonstration risk assessments were part of a program for implementing the approach throughout Victoria in response to the Victorian Review of Headworks (SMEC/RAC 1995), which recommended that "a staged risk assessment approach should be thoroughly integrated into the practice of dam safety evaluation ... in the State of Victoria ...". Each case study is summarized in the following four parts: a) purpose and overview, b) results, c) outcomes and d) benefits of using a risk-enhanced approach to evaluating and managing the safety of existing (aging) dams.

Portfolio Risk Assessment

a) Purpose and Overview

The South Australian Water Corporation (SA Water) changed from a state government department to a public corporation in July 1995. It provides water and wastewater services to a population of more than 1 million people throughout South Australia. SA Water operates and maintains 16 large dams as part of the bulk water system and one flood control dam. It is self-regulated with respect to dam safety and has a good dam safety record. However, more than half its portfolio of large dams is older than 75 years, and in many cases they do not meet modern engineering standards. A number of dams are located on streams that run through metropolitan Adelaide where the consequences of a dam failure would be catastrophic.

SA Water will need to make some important choices on how much dam safety improvement is justifiable at each of its dams, how to prioritize these improvements, and at what rate to proceed. Such decisions will be made within the framework of expectations of long term profitability and improving the Corporation's business value. To provide inputs to these important decisions, and in view of the move to risk-based dam safety decision making in Australia, SA Water commissioned an initial portfolio risk assessment (PRA). The PRA was designed to provide a baseline assessment of the existing dams and an initial prioritization of future investigations and possible risk reduction measures. The PRA comprised a reconnaissance-level engineering assessment and risk assessment. These assessments were performed for flood, earthquake, and static loading. Various structural and non-structural risk reduction measures were developed and evaluated. Bowles et al (1998c) provides additional details on this study.

b) i) Results - Existing Dams

Results from the engineering and risk assessments of the existing dams are summarized for each type of loading, as follows:

- Floods: Over the portfolio, flood failure modes account for more than 90% of the probability of failure and about 80% of the total risk costs, but only about 30% of the life loss risk. Only one dam is expected to meet ANCOLD flood guidelines.
- Earthquakes: Earthquake failure modes are estimated to contribute about 1% or less to the portfolio probability of failure, total risk costs, and life loss risk. Current practice for earthquake resistance is expected to be met by five dams.
- Static: Over the portfolio, static loading (normal operating conditions) failure modes appear to contribute less than 10% to the probability of failure and less than 20% to the total risk costs, but almost 70% to the life loss risk, due to the lack of warning time needed for evacuation. Current practice for static loading is expected to be satisfied by 14 dams.

For ANCOLD (1996) revised interim societal (life safety) risk criteria, five existing dams do not appear to meet the limit criterion, and an additional six dams do not appear to meet the objective criterion.

b) ii) Results - Risk Reduction Measures

A total of 23 structural risk reduction measures were formulated at a reconnaissance level as logically separable construction packages. Each measure was developed with the intent of meeting an engineering standards level of risk reduction. Even so, some are not expected to meet ANCOLD or other societal risk criteria for life loss, due to their close proximity to a population at risk.

Benefit:cost ratios greater than one were identified for only two structural measures: installing external back-up seals on the upstream face of a concrete faced rockfill dam (approximately 2:1); and stabilizing a free standing crest structure used for raising another dam (greater than 40:1). Net present value is estimated to be positive for only the second of these structural measures.

Four ALARP (as low as reasonably practicable) justification ratings ("very strong", "strong", "moderate", and "poor") were proposed for use in the SA Water PRA based on increasing order of magnitude of cost-per-life-saved (CPLS), which is a measure of the cost effectiveness of improving life safety. Of the 23 structural measures, there are three "very strong" ALARP justification ratings, three "strong" ratings, three "moderate" ratings, and 14 "poor" ratings. These ratings were used in developing implementation phases, which is described in the next subsection on outcomes.

c) Outcomes

The Dam Safety Improvement Program (DSIP) component of SA Water's overall dam safety program will comprise further engineering evaluations and the implementation of structural and non-structural risk reduction measures. Evaluations will include engineering investigations and detailed risk assessments. These will be of sufficient depth to achieve a "sign off" level confidence in dam safety evaluations and decision making, and to provide sufficient information for design of structural and non-structural measures.

An initial priority for implementing the 23 structural risk reduction measures was developed to maximize the rate of estimated risk reduction for the expenditure of capital funds for dam safety improvement. First priority was given to reducing life safety risks until a point of diminishing returns is reached after the first eight measures, which have the smallest CPLS values. Second priority was given to reducing total risk costs (i.e. direct SA Water and third party). The resulting prioritization is referred to as "the PRA prioritization".

The estimated rate of life safety risk reduction is significantly greater for the PRA prioritization than for the current SA Water program prioritization (Figure 2). It is estimated that the proposed DSIP would achieve 98% of the total life loss risk reduction for about 15% of the total capital costs, compared with about 75% of the total capital costs to achieve the same level of risk reduction under the current SA Water prioritization. Risk reduction measures were assigned to four implementation phases based on the PRA prioritization and various risk-based ratings thresholds. These are described in Bowles et al (1998c).

On the basis of the PRA, a number of recommendations were made so that SA Water can effectively integrate and apply the PRA findings within its existing dam safety program. Key actions that SA Water is, or will be taking, include the following:

- High priority is being given to establishing and implementing a risk-based DSIP comprising further investigations, implementation of all reasonable and practical structural and non-structural measures with the goal of reducing risks to tolerable levels, and consideration of emergency preparedness plans (EPP) and early warning systems (EWS) for all dams.

- The PRA indicated that at some dams there are high life safety risks or a high probability of failure. High priority is being given to evaluating the need for short term measures to reduce risks in these cases.
- Existing dam safety management program activities and contingency planning will be reviewed based on insights developed in the PRA.
- Consistent with the baseline nature of the initial PRA, it is intended to regularly update the PRA as additional information becomes available.
- Based on the PRA, it is expected that detailed risk assessments will be justified at a number of dams. As a minimum, the initial risk identification step of detailed risk assessment will be applied to all dams.

d) Benefits

Many useful insights into dam safety issues, which might not otherwise have been obtained, were provided by the PRA process. SA Water now has an overall picture of the current dam safety status of its large dams from both a standards-based perspective and a risk-based perspective. The proposed phased implementation of structural measures and further evaluations is proving useful for prioritizing and managing dam safety evaluation and improvement efforts, and importantly, is regarded as a defensible strategy for reduction of risk.

Another significant benefit of conducting the PRA is that it identified a more rapid approach to risk reduction than the existing dam safety program prioritization, which was based on traditional approaches. By taking a risk-based approach to prioritizing dam safety evaluations and improvements, SA Water has obtained information that is useful for integrating dam safety issues into overall business planning. However, the owner can still choose whether or not to adopt a standards-based or risk-enhanced approach to establishing safety targets for long-term risk reduction at each dam.

The close partnership between the consultant and SA Water technical staff and the periodic involvement of SA Water executives and the Board contributed to the effective conduct of the PRA. This level of interaction is clearly an essential ingredient for maximizing the value of a PRA process to the owner and achieving rapid acceptance of PRA outcomes.

Pykes Creek Dam

a) Purpose and Overview

Pykes Creek Reservoir is located west of Melbourne, Victoria, Australia, in the 121 km^2 Werribee Basin. It supplies irrigation water and some supplemental urban water. Rapid urban development is expected to continue and has encroached on the floodplain. The original embankment dam was completed in 1911 with a 3.35 m raise in 1930 resulting in its present reservoir capacity of 23,900 ML. Recent safety reviews had identified a number of dam safety issues, as follows:

- A spillway capacity estimated to have an AEP of 1 in 16,000, but which was less than that called for in ANCOLD flood guidelines for this dam.
- An intake tower that only just passes the 1 in 1,000 AEP design seismic event, although the embankment dam should withstand the 1 in 10,000 AEP design seismic event.
- The inability to inspect the intake tower guard gates and outlet conduit due to excessive leakage past the remaining guard gate.

The owner, Southern Rural Water (SRW), initiated a risk assessment of the dam with the stated objective, "to identify those deficiencies … which present an unacceptable liability to SRW and to recommend prioritized cost effective remedial measures." The risk assessment addressed potential flood and earthquake failure modes and possible internal failure modes in the dam or its foundation under static loading.

The main components of Pykes Creek Dam are as follows (see Figure 3):

- Embankment: A zoned embankment with a central puddle clay core supported by shells of stony material with rockfill toes. In 1967 a highway embankment was constructed on the downstream toe of the dam and crosses over the dam crest near the spillway on the right abutment. The highway embankment divides the dam into two parts, which we refer to as embankments 1 and 2 (see Figure 3).
- Outlet tower: The unreinforced concrete tower is 29.2 m high with a low level inlet and four operating inlet ports. Problems with the tower include an inability to dewater for guard gate maintenance, the condition of the guard gates, concrete structural integrity under seismic loading, and siltation. Up to 15% material loss through graphitic corrosion of the guard gate has been found, although the gate is considered to retain sufficient structural strength to withstand full storage hydrostatic loads.
- Outlet works: The outlet works consist of a 900 mm diameter reinforced concrete encased outlet conduit with two downstream control valves.

- Spillway: The spillway consists of a mass concrete ogee fixed crest 4.3 m high and 92 m long. The spillway chute is in competent rock and is unlined, except for the apron and training wall along part of the left abutment. There is an approximate 10 m vertical drop to the natural stream bed below.

Existing information was reviewed and some additional analyses were performed. Potential failure modes were identified and formed the basis for an event tree risk model. System response probabilities were estimated for various ranges of inflow floods and earthquakes that might lead to dam failure. Dam breach analyses and flood routings were completed and were used to estimate the consequences for each failure mode. The principal identified flood failure modes were:

- Overtopping and erosional failure of embankment 1 and the highway embankment - the role of the highway embankment as a "second line of defense" had not been accounted for in previous dam safety reviews.
- Overtopping and erosional failure of embankment 2 - the lesser consequences associated with failure of this lower section of embankment had not been recognized previously.
- Overtopping of left spillway training wall leading to erosional failure of embankment 2 - this failure mode had not been previously recognized and was identified through the systematic risk identification process.

Identified earthquake failure modes were:

- Embankment 1 deformation leading to overtopping erosional failure and failure of the highway embankment.
- Embankment 2 deformation leading to overtopping erosional failure.
- Outlet works rupture leading to piping failure due to loss of upstream control.

Potential internal (normal operating conditions) failure modes under static loading were:

- Piping of embankments 1 and 2.
- Slope instability of embankments 1 and 2.
- Piping along the outlet works.

In the event of failure of embankment 1 by piping or slope instability it would be necessary for the highway embankment to fail before there would be a release of the reservoir contents.

b) i) Results - Existing Dam

The existing Pykes Creek Reservoir has a relatively high probability of dam failure (3 x 10^{-3} per year) and economic risk cost ($137,000 per year), but a relatively low annualized incremental life loss totaled over flood, earthquake and internal failure modes (7 x 10^{-5} lives per year). Financial loss was estimated at AU$50M (plus personal injuries and losses downstream of Melton Dam which were not assessed in this study) with approximately 40% of this amount being direct losses to the owner.

Approximately 95% of the probability of failure and risk costs were attributed to an erosional failure of the embankment initiated by overtopping of the training wall of the emergency spillway. Overtopping is estimated to begin during relatively minor flood events (with an approximate AEP of 1 in 15) and has been confirmed by observation. This potential failure mode had not been recognized in previous dam safety evaluations but was identified through the risk identification process.

For best estimates of warning time, the existing dam satisfies the ANCOLD (1994, 1996) amended interim societal risk objective criterion, individual at greatest risk limit criterion (3 x 10^{-5} per year compared with the criterion: 1 x 10^{-4} per year), and individual risk objective criterion averaged over the population at risk (PAR) (1.5 x 10^{-7} per year compared with the criterion: 1 x 10^{-5} per year). The existing dam also satisfies the Tier 1 USBR (1997) Public Protection guidelines and B.C. Hydro (1993) interim criterion for annualized incremental life loss. However, it does not satisfy ANCOLD's individual at greatest risk objective criterion. Also, considering the magnitude and likelihood of economic consequences for flood-induced failures, the New South Wales (NSW 1993) Total Asset Management example guidelines would suggest that "corrective action *(is)* required in a reasonable time frame" based on the best estimate and that it is "imperative to suppress risk to lower level" based on the high confidence estimate.

Sensitivity of existing dam risk assessment results to a one hour reduction in warning time for flood failure modes, showed that annualized incremental life loss would increase by more than two orders of magnitude. At this level it would not meet the Tier 1 USBR Public Protection Guidelines or the B.C. Hydro societal risk interim criterion. The limit values of the ANCOLD interim societal and individual risk criteria would no longer be met. Thus it is very important to develop sufficient confidence that the warning time for flood-induced failure modes of the existing dam can be achieved.

b) ii) Results - Phase 1 Risk Reduction

A significant risk reduction can be achieved by raising the spillway training wall to protect against erosion of embankment 2. This relatively inexpensive measure was considered as a Phase 1 risk reduction measure with all other risk reduction alternatives being considered under Phase 2. Based on best estimates, Phase 1 risk reductions from the existing dam, are as follows:

- Probability of failure: from 3×10^{-3} to 1.5×10^{-4} per year
- Annualized life loss: from 7×10^{-5} to 2×10^{-5} lives per year
- Average individual: from 1.5×10^{-7} to 4.9×10^{-8} per year
- Most exposed individual: from 3×10^{-5} to 1.1×10^{-6} per year

The Phase 1 benefit:cost ratio is estimated to be about 12.5 and hence the CPLS is zero. Clearly Phase 1 measures are justified economically. With Phase 1 risk reduction, the NSW (1993) Total Asset Management example risk category would change from "medium" for the best estimate and "major" for the high confidence estimate, to "low" for flood loading with both best and high confidence estimates. In the low category, "corrective action *(is recommended)* where practicable". Phase 1 appears to satisfy all the risk-based criteria, which were considered in this study, except for the Tier 2 USBR Public Protection Guideline (1.5×10^{-4} per year compared with the guideline: 1.0×10^{-4} per year).

Sensitivity studies on loading and system response probabilities did not change the outcomes of the evaluations of the Phase 1 measure against any of the risk-based criteria. Decreasing warning time by one hour was shown to change only one evaluation against risk-based criteria: the ANCOLD (1996) interim societal objective criterion would no longer be met. However, it was recommended that a more detailed assessment of the effects of warning time should be conducted to develop the necessary confidence in warning time estimates used in this study.

b) iii) Results - Phase 2 Risk Reduction

Phase 2 risk reduction measures were examined to determine if they can be justified by ALARP using CPLS estimates or "de minimis" risk considerations. The following nine alternatives were considered:

- AR-1: Flood early warning system
- AR-2: Convert highway embankment into a retention dam

- AR-3: Decommission
- AR-4: Raise embankment
- HR-2: Lower spillway crest
- HR-3: Hydro Plus spillway gates
- ER-2: Increase stability of downstream embankment slopes
- IR-1: Replace guard gate
- IR-2: Raise clay core to the dam crest

Justification for risk reduction measures was examined against the existing dam including the Phase 1 risk reduction. With the exception of the flood early warning system, none of the Phase 2 alternatives were estimated to have a strong economic (i.e. benefit:cost ratio) or life safety (i.e. ALARP based on CPLS cost effectiveness considerations) justification. It appears that business considerations related to loss financing or public trust may dominate a decision on Phase 2 measures. Also, some Phase 2 alternatives may be justified based on the "de minimis risk" principle, which tends to support implementing low cost risk reduction measures even though other justifications may be lacking.

c) Outcomes

Even before the draft report to SRW was finalized, they engaged an engineer to design the Phase 1 raise of the spillway training wall. Considering the relatively high probability of dam failure (3×10^{-3} per year or an AEP of about 1 in 330) and economic risk cost ($137,000 per year), especially compared with the earlier estimates of an imminent failure flood with AEP of 1 in 16,000, such prompt action was justified.

Phase 2 risk reduction alternatives have less justification than Phase 1. Nevertheless, it may be appropriate to implement some Phase 2 measures at Pykes Creek Dam. However, it was recommended that SRW conduct a PRA of their portfolio of eight dams so that they could prioritize risk reduction opportunities across all their dams. SRW has now completed a PRA.

d) Benefits

Benefits of this risk assessment are summarized as follows:

- A better overall understanding of failure modes including the role of the highway embankment in dividing the dam into two sections of embankment with one having a "second line of defense" provided by the highway embankment and the other having a much lower breach flow potential since it is a lower section on a rock foundation.

- The previously unrecognized spillway training wall deficiency was identified as a result of the systematic risk identification process carried out at the beginning of the risk assessment.
- Concerns about the performance of the outlet tower and outlet works during earthquakes were shown to be very minor risks in comparison to flood risks and yet engineering effort had been focused on the outlet tower prior to performing the risk assessment.
- Risk assessment outcomes were valuable in developing a phased approach to risk reduction and relating the implications of dam safety risks to the owner's business. In contrast the traditional safety review approach did not provide any prioritization between deficiencies nor did it provide information needed for evaluation of the business risk associated with the *do nothing* scenario.
- The critical role of warning time for evacuation was recognized - a more in-depth evaluation of warning times for various failure modes was recommended to develop sufficient confidence that warning times estimate for the risk assessment could be achieved in practice.
- After completing the Pykes Creek Risk Assessment, the client recognized the value of the risk assessment process. As a result SRW decided to conduct a PRA of their portfolio of eight dams to pursue similar benefits for their other dams and to prioritize risk reduction measures across their portfolio.

SUMMARY AND CONCLUSIONS

Through discussion of principles and cases studies, we have sought to present some of the benefits of the risk-enhanced approach to managing the safety of aging dams. When properly applied by experienced dam engineers, risk assessment procedures can provide qualitative insights and quantitative estimates of risk and risk reduction. These can be valuable to engineers and to non-technical decision makers. For owners of many dams a good starting point is an initial portfolio risk assessment, to prioritize future efforts across all aspects of their dam safety program. Individual dam risk assessments should be carried out to a level of detail justified by the decisions that will depend on them. This typically should involve a staged approach in which additional effort is expended on developing risk assessment inputs only as justified by the degree of confidence and defensibility needed for the decisions that are to be made. It is therefore important that the uncertainties associated with risk estimates be carried through the risk assessment and presented to decision makers in a manner that is understandable and useful to them.

The challenge of managing aging dams is not just a technical matter, it should also be seen in the overall context of the owner's business with manifold considerations such as customer service and business criticality, contractual obligations, capital budgeting, improving business value, legal implications, emergency and contingency planning, loss financing and insurance, public perception, and many others. To fail to see this threatens our ability to win the necessary financial and other resources necessary to achieve and maintain safe aging dams. Through the systematic approach of risk assessment, technical and business understanding can be improved and strategies for cost effective risk reduction through structural and non-structural means can be formulated, explored, justified, and prioritized.

Risk analysis should not be an end in itself. It should serve the purpose of better understanding and managing the risks; or as a recent National Research Council (NRC 1996) report puts it, "Risk characterization should be a decision-driven activity, directed toward informing choices and solving problems."

Although risk assessment has sometimes been criticized as a tool for justifying less safety, we submit that the opposite should be true. The proper motivation for dam safety risk assessment and risk management should be to achieve:

- More safety
- More rapidly
- More cost effectively, with
- More understanding by all stakeholders, and
- More integration across all aspects of the dam safety program.

Engineering standards have played a useful role in our profession and should not displaced by risk assessment. However, by supplementing engineering standards with information obtained from risk assessment, the "risk-enhanced" approach can avoid the shortcomings of the "engineering standards only" approach, while providing ways to better communicate problem understanding and justifications for actions to lay decision makers. As such we believe that an appropriate level of risk assessment should become the cornerstone for all dam safety programs. As Bowles stated in the oral presentation of Bowles et al (1998a), "I can foresee the time, when dam safety evaluation will not be best practice, unless a properly conducted risk assessment is included."

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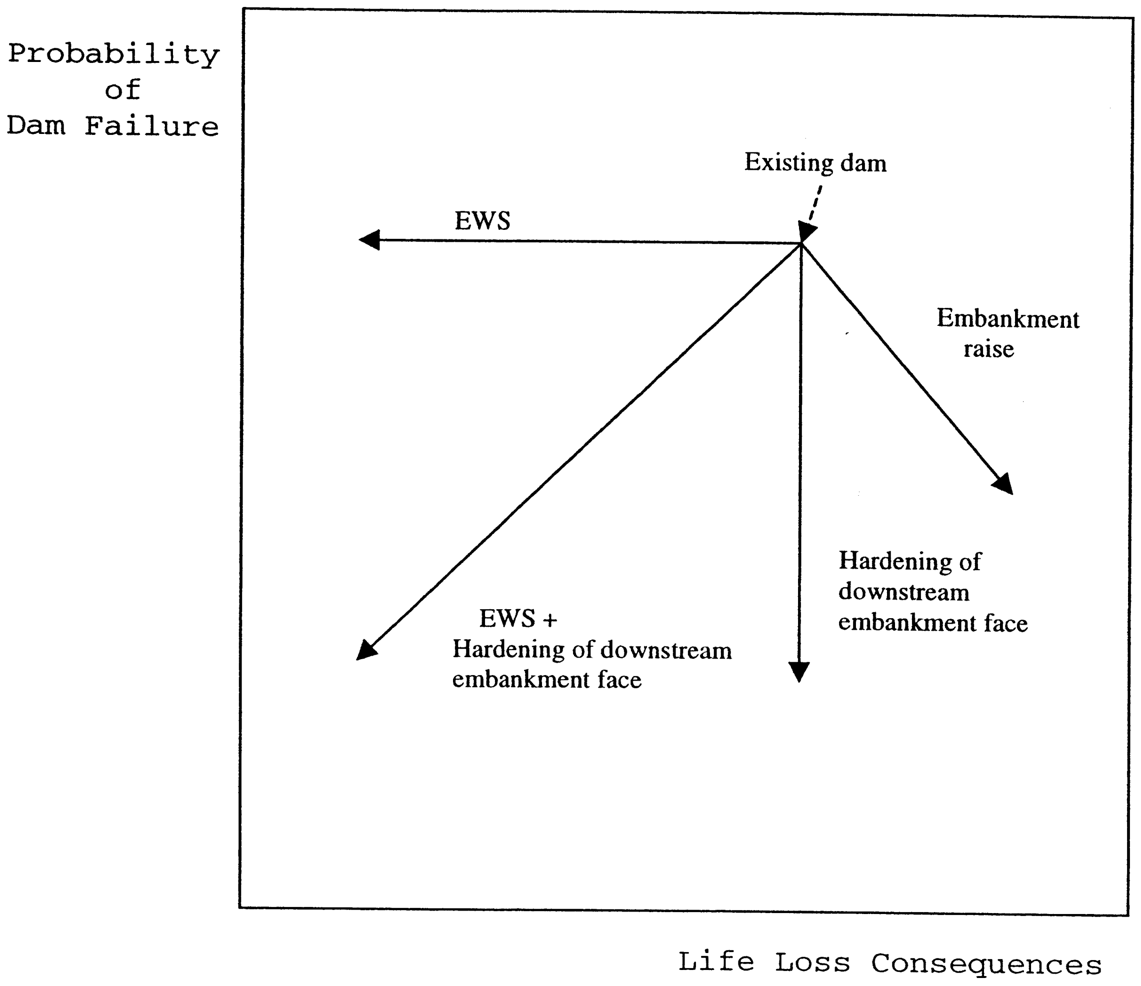

Figure 1. Differing life safety risk reduction characteristics of some flood risk reduction measures.

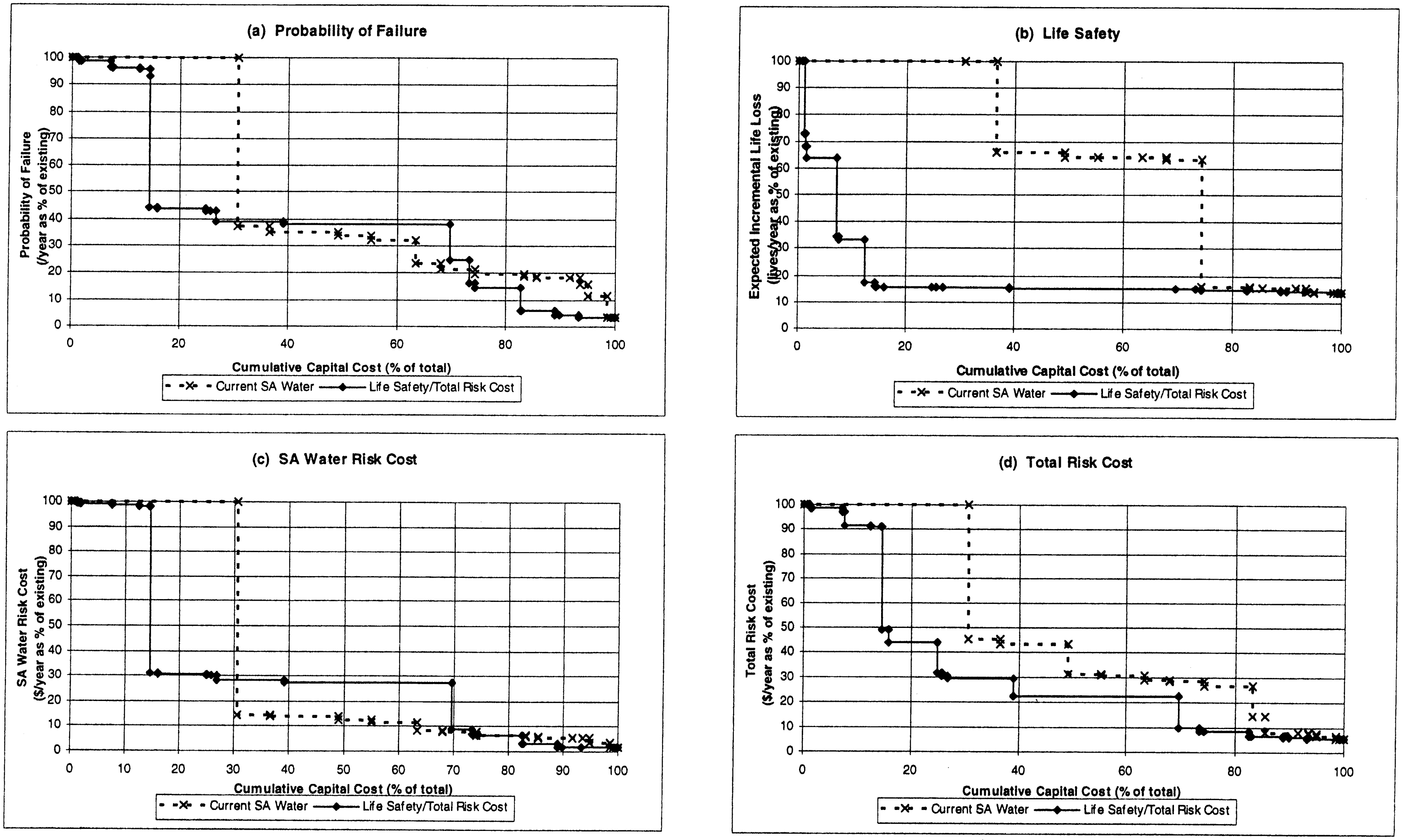

Figure 2 Comparison of residual risks based on PRA prioritization and the current SA Water program

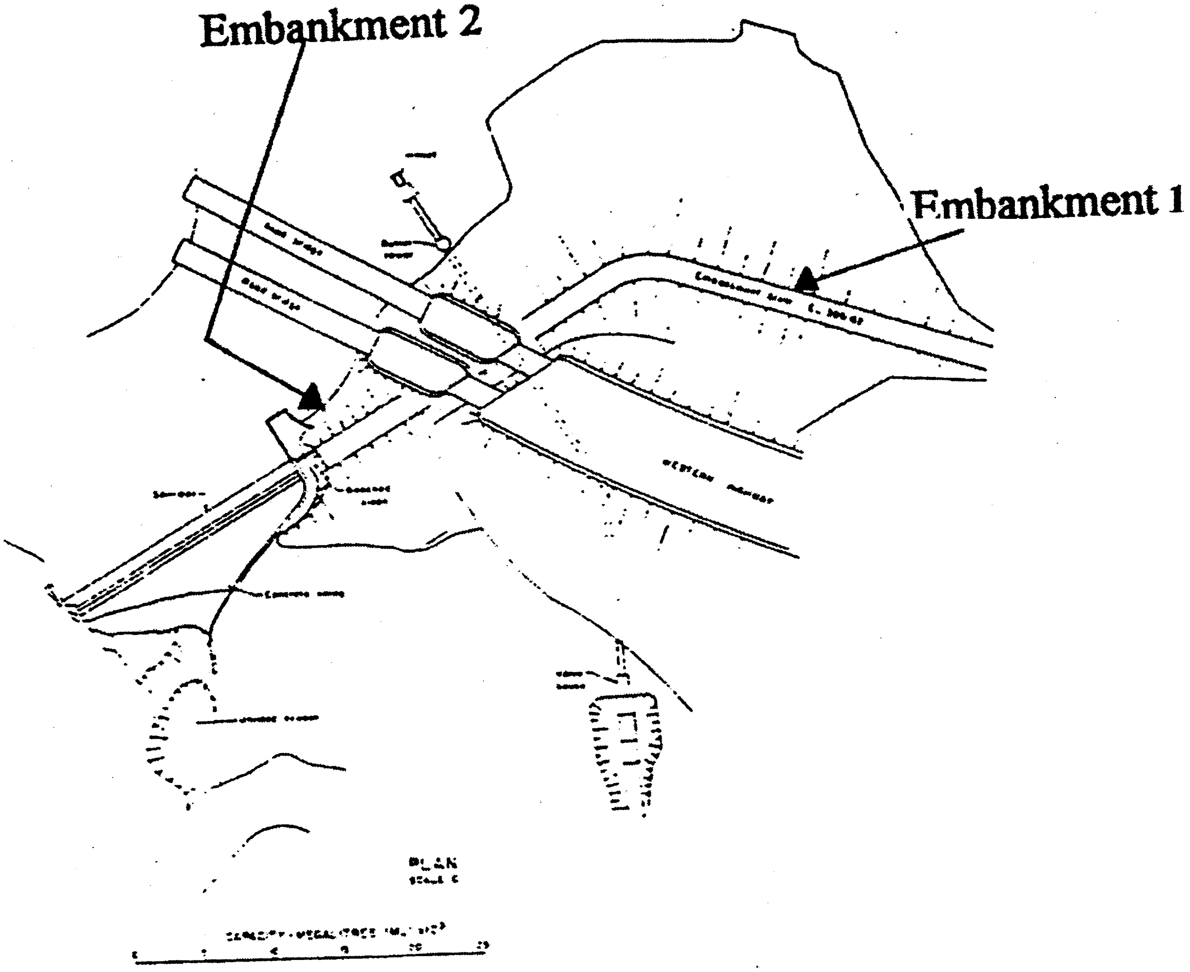

Figure 3. Pykes Creek Dam

TECHNICAL SERVICE CENTER
Denver, Colorado

Dam Safety Risk Analysis Methodology

U.S. Department of the Interior
Bureau of Reclamation

VERSION 3.3
September 1999

This draft methodology was prepared by John Cyganiewicz, Karl Dise, Dave Hinchliff, Dave Mayer, and Bruce Muller; and Peer Review was by Bill Engemoen and Gregg Scott.

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DRAFT RISK ANALYSIS METHODOLOGY
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Appendix A - Considerations for Estimating Structural Response Probabilities in Dam Safety Risk Analysis, by Steven G. Vick

I. Introduction

Each and every day Reclamation decides to operate a facility, it is implicitly accepting the risks posed by the structure. By using risk analysis techniques Reclamation is attempting to understand the nature and severity of the risks so that it can make informed decisions. Tightening budget constraints suggest it is appropriate to use risk determinations as a tool to direct funding to those issues presenting the greatest risks. Thus it is imperative that each facility's risk be identified and analyzed to provide correct information to the dam safety decision process.

This document is mostly about risk analysis, that is, how to identify loading conditions, potential failure modes, and consequences, and how to estimate the probabilities for each event. Questions like "does the identified risk justify further action" or "what should be done to reduce risk" belong to risk assessment, and are beyond the scope of this document. While the primary topic is risk analysis, this document starts by providing a brief introduction to risk assessment and risk management concepts. This is so that the reader can understand where risk analysis fits into the entire dam safety process, what the legislative mandate for risk analysis is, and what are some of the appropriate uses for risk analysis. After this brief introduction, the remainder of the document will discuss how to prepare for a risk analysis, how to conduct a risk analysis, and how to report the findings from a risk analysis.

A. Role of Risk Analysis and Assessment in the Dam Safety Program

Risk and uncertainty are intrinsic in water resource management activities. Uncertainty arises from the lack of information about the loads that a dam will actually experience, the lack of perfect information about the manner in which the dam will respond to those loads, and limited information about what the resulting consequences would be. Risk arises from undesirable consequences and the uncertainty over whether or not those consequences will actually occur. Risk analysis and risk assessment should not be confused with risk taking. Contrary to risk taking, risk analysis and assessment provides a method to better manage risks with available resources. Estimating the probability and magnitude of consequences of potential options facilitates decisions that focus available funds where the greatest risk reduction and benefit can be attained. Figure 1 portrays a simple model of how dam safety issues proceed from identification to risk analysis to risk assessment and decision making.

RISK ANALYSIS/RISK ASSESSMENT PROCESS

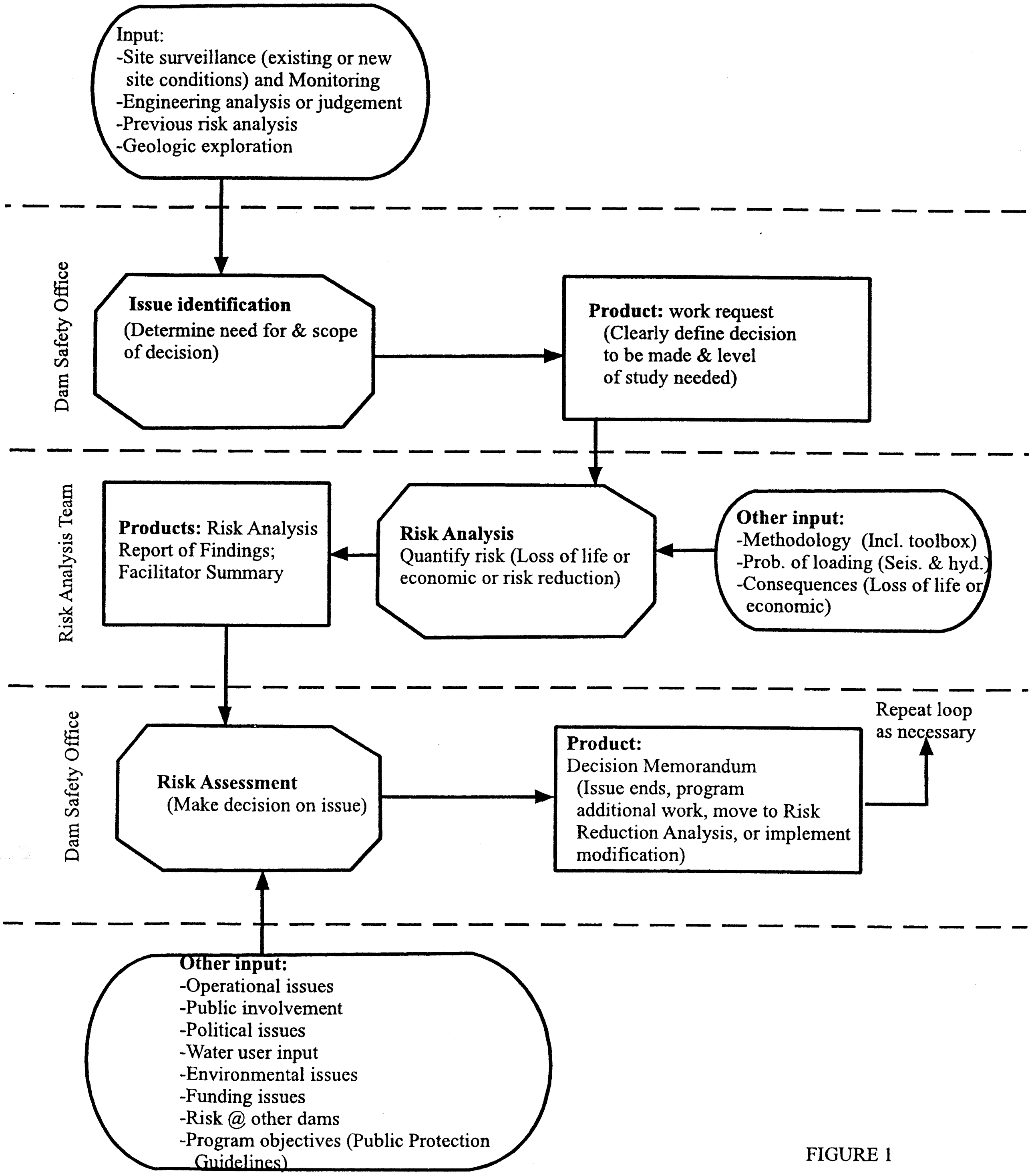


FIGURE 1

The objective of Reclamation's Dam Safety Program is to ensure that Reclamation water impounding structures do not create unacceptable risks to public safety and welfare, property, the environment, or cultural resources. This objective is aimed at fulfilling the Federal Government's trust responsibilities for the safety and welfare of the downstream public. The authorizing legislation for the dam safety program [1] states:

> *"In order to preserve the structural safety of Bureau of Reclamation dams and related facilities, the Secretary of the Interior is authorized to perform such modifications as he determines to be reasonably required."*

Responding to the congressional mandate, Reclamation has refined the goal as follows [2]:

> *"The objective of the Safety of Dams Program is to ensure that Reclamation structures do not present unacceptable risks to public safety, property, and welfare. This requires identifying structures which pose unacceptable risks and taking corrective actions to reduce or eliminate these risks in an efficient and cost effective manner. Reclamation policy is to provide safe structures, but this does not imply a risk free environment. A safe dam is one which performs its intended functions without imposing unacceptable risks to the public by its presence."*

Risk analysis procedures help organize engineering approaches to credibly identify potential failure modes and related downstream consequences which are often the fundamental information necessary to make decisions related to program objectives. However, risk analysis should only be viewed as one of the inputs to the overall risk assessment and decision process. Other typical inputs to the assessment process are traditional engineering analyses and judgements, funding considerations, environmental considerations, public involvement, political considerations and economic considerations. Thus the quantitative and qualitative results of a risk analysis must be melded with the quantitative and qualitative information from these other inputs to form the final decision.

While describing the process of determining unacceptable risks is beyond the scope of this document, additional information may be found in the Reclamation's *Policy and Procedures for Dam Safety Modification Decisionmaking* [2]; *Guidelines for Achieving Public Protection in Dam Safety Decision Making* [3]; and *Policy for Decisions Related to Dam Safety Issues* [4].

B. Meaning of Risk and Probability

Among the many concepts proposed for defining risk, the meaning adopted here is most succinctly expressed by Webster's Dictionary as *"the possibility of loss."* This risk definition incorporates the dual concepts of uncertainty about the occurrence of some event (possibility), and the adverse consequences should it occur (loss). In a dam safety context, the event of interest is an uncontrolled release of the reservoir and the resulting consequences which may include loss of life, economic loss, or other adverse consequences. As implied in the definition, there is uncertainty in predicting the future performance of the dam, including the loading conditions it may experience, its response to these loads, and estimating failure consequences. Such uncertainties are inevitable to varying degrees in any risk analysis because of imperfect knowledge or incomplete information about the physical processes involved.

Quantitative estimates of dam failure risk require quantifying the likelihood of loads, adverse responses given the load, and adverse consequences given a failure occurs as well as the uncertainties associated with each. The estimation process relies on engineering techniques whose applications differ little in principle from deterministic dam safety assessments. The difference in a risk analysis is the requirement for quantifying uncertainties in all of their various forms. Probabilistic methods inherently address these uncertainties.

In this sense, probability is a quantified statement of likelihood based on one's degree of belief or level of confidence in the occurrence of a certain outcome, a certain response, or the presence of a certain condition. In most cases the probability of occurrence is not determined solely on the basis of data, analysis or performance. While the estimation of the probability of occurrence can consider such information, there are typically other factors that also impact the estimate. Such factors would include those issues that cannot be quantified or that are statistically verifiable. The probability estimates for all aspects of the problem depend on the state of knowledge at the time of their assessment and the ability of the assessor to express all of the contributing factors and uncertainties as fairly and honestly as possible. In this respect, probability and hence risk itself, are best viewed as the quantified expression of engineering judgment.

At its most fundamental level, the concept of risk analysis embodies identifying and quantifying three elements: (1) the events and conditions that could cause failure, (2) their likelihood, and (3) their consequences. Or more simply put:

- How could failure occur?
- How likely is it?
- What would happen if it did?

Answering these questions provides the data necessary to estimate a quantitative measure of risk as computed by the following equation:

Risk = P[load] x P[Adverse Response given the load] x Adverse Consequence given the failure

C. Intended Audience

This document presents a general approach for analyzing the risk posed by dams. It is intended that this analysis, along with other input, be used by decision makers within the Bureau of Reclamation concerning dam safety.

Within Reclamation, this document is intended to benefit a broad cross section of the staff. Facilitators can use the methods outlined as a road map for guiding risk analysis teams through the process of estimating and documenting risks. Risk analysis participants may use the document to learn how to follow the process. Dam safety decision makers may wish to use the document to gain some background on the methods used to develop the risk analysis results which are being presented to them. The intent during the development of the document was to focus on the facilitators' needs while providing sufficient detail to be educationally valuable to others.

D. Developmental Nature of the Methodology

This document presents methods which are considered to be most reasonable for meeting the objectives of the Dam Safety Program at the present time. As the application of risk based methods in water resources management (and more specifically in Dam Safety) spreads, there will undoubtedly be improved methods developed. When these new methods and supporting toolboxes are developed for Reclamation, this document will be revised to include them.

There will also be specific situations arise which are not adequately addressed by the methods presented in this document. In these cases, risk analysis teams and facilitators are encouraged to:

- Seek out examples of similar situations at other dams
- Seek advice from other employees and/or consultants
- Propose/develop workable solutions which are consistent with the principles of the methods provided in this document.

When these actions result in additional methods or insights which would have benefit to other risk analyses, they will be included in subsequent revisions of this document.

II. Purposes of Risk Analysis

The broad purpose of risk analysis as a dam safety tool is to improve the effectiveness and efficiency of Reclamation's dam safety efforts. However, it is important to recognize that risk analysis, while key to decision making, does not alone constitute a dam safety decision. A number of factors, many external to the analysis, are incorporated and synthesized at the decision making level. The value of risk analysis is derived nearly equally from: 1) the process itself that helps develop a deeper understanding of the dam and the key dam safety issues, and 2) the numerical results that are used in the decision making process, especially for setting priorities. The following discussions describe the various goals that risk analysis should seek to achieve.

A. Communicating Risk

A primary purpose of the risk analysis is to communicate risk judgments, both to the decision maker and within the study team itself. Whereas a deterministic dam safety assessment can identify potential dam safety deficiencies, communicating the associated risks enhances information content by expressing judgments about the relative severity and importance of the risks. Quantified risk analysis results provide a common denominator for comparing conditions that could not otherwise be related to each other (for example, post-liquefaction FS = 0.9 versus 80% PMF spillway capacity), both for a given dam and among different dams.

If risk analyses are to serve the decision maker in this way, the risk must be communicated clearly and unambiguously, and the various sources of risk for a given dam must be explicitly identified. It is not sufficient to determine the total risk associated with a dam without also explaining the underlying rationale for why the value resulted and how it was derived. This includes the identification of the major sources of risk (loading conditions and failure modes). The logic structure contained in the event tree generated as part of a risk analysis can be a significant aid to this end if it is constructed with appropriate logic and clarity of communication in mind, as discussed subsequently in Section IV.B (Developing Event Trees). In addition, any risk analysis will itself be subject to uncertainty arising from different interpretations of the information available. The risk communicated to the decision maker needs to be accompanied by some statement of the confidence to be placed on it, and various means for doing so are described in Section V.B (Uncertainty Analysis). All of these aspects of risk communication depend heavily on the presentation and completeness of the risk analysis documentation, matters addressed in Section V (Documentation and Presentation).

An equally important aspect of risk analysis is to promote interchange among the team members during the process. Here too, discussions centered on risk provide a focused format for comparing and relating the significance of potential failure modes and processes across the boundaries of the various technical disciplines involved. A sense of scale and proportion to the importance of specific analysis and evaluation efforts emerges as the corresponding risk contributions from these studies are identified. The participation of field personnel as well can be invaluable. Certain site-specific features whose significance might not otherwise be obvious can assume critical importance when viewed in the kinds of risk-related contexts that these interactions provide.

B. Improving Understanding of Dam Behavior

The safety of a dam can most effectively be improved if its design, construction, and behavior are thoroughly understood. Therefore, another primary purpose of risk analysis is to enhance this understanding by more explicitly identifying the features and conditions of the dam that contribute to its vulnerability or robustness. This can come about in several ways.

The process of detailing potential failure modes and the requirements for those failure modes to develop into an uncontrolled release of the reservoir provides a very different perspective on dam behavior than the perspective obtained from a design point of view. When the participants are challenged to find ways in which a dam could fail, they are more likely to identify vulnerabilities. Recognizing such potential vulnerabilities provides a better basis for understanding the manner in which the dam will respond to a variety of loading conditions. By asking "how could this dam fail?" it encourages greater attention to the unique conditions and performance history of each individual structure. The result can be to identify important mechanisms and conditions that might otherwise have been overlooked. A relative sense of urgency associated with the various risk scenarios is also obtained.

The outcome of the risk analysis will provide information that permits comparison of the relative risk contributions of each potential failure mode and the relative risk contributions of each loading increment considered. In relation to the total risk for the dam, this information allows the dominant risk-producing conditions to be identified, which in turn can then serve to focus efforts on the most critical aspects of the project. For example, determining that spillway erosion under 100-year recurrence interval floods would produce significantly greater risk than overtopping under PMF conditions would lead to greater emphasis on the risk of the more frequent, but perhaps less catastrophic erosion problem. Deriving the risk contribution for each potential failure mode promotes a more balanced view by reducing overemphasis on those mechanisms for which advanced analytical methods may be available at the expense of those for which computational techniques are less well-developed or not available.

Seen in this light, risk analysis is a dam safety tool for refining engineering insight.

C. Identifying Information Needs

A further purpose of risk analyses is to provide a road map for guiding any additional dam safety investigations. Logically, those failure modes that produce the largest risk contributions should receive greatest attention. Conversely, further investigations may provide fewer benefits for those failure modes shown to contribute little to total estimated risk.

In some cases where little information is available, confidence limits on the results of the risk analysis may be comparatively wide. If greater refinement is necessary for decision making purposes, information from further investigations or technical analyses may have the potential to narrow these limits if targeted to the more significant risk contributors. On the other hand, additional information unlikely to substantially influence the estimate of risk may not be warranted. "Information" in this context includes not only field exploration data and consequence estimates, but also more readily-obtained information from such sources as construction records, case-history literature, or analyses that may not have been available at the time of the previous risk analysis stage.

Risk analysis should not be seen as discouraging the gathering of information that is critical to understanding the behavior of the dam. Rather, the intent is to use risk as a means for more precisely targeting the areas where further information is most required and pinpoint the types of information of greatest benefit.

D. Formulating Corrective Action Alternatives

When it is necessary to develop alternatives for reducing risk at a particular structure, the information developed in the course of preparing a risk analysis will aid in formulating alternatives which effectively mitigate the risks identified. By understanding the goal of risk reduction, the nature of the risks involved, and the operational needs of the project, a group of effective alternatives can be developed and evaluated. When risk reduction becomes an evaluation criterion along with cost optimization and any other appropriate objectives, the resulting evaluation criteria provide an effective framework for developing alternatives.

By applying the evaluation criteria to brainstorming alternatives, inferior alternatives can be identified and eliminated from further consideration at an early stage. The goal is to eliminate those alternatives which have no reasonable chance of being selected as the alternative to be implemented. For example, an alternative with higher costs and lower risk reduction is inferior to an alternative with lower cost and greater risk reduction when there are no other criteria to be evaluated.

E. Allocating Resources

Reclamation's available resources for studying dam safety issues are finite. Limitations may include availability of key personnel, equipment, funding, and/or time. In each of these cases, choices must be made concerning the priorities for addressing the various risks at Reclamation facilities.

With over 300 dams categorized as high hazard structures, Reclamation is constantly assessing load, response, and consequence data for its inventory of dams. While the assessment may not be in great detail, it provides a general indication of which dams contribute the greatest risks to the public and therefore require additional investigation to better quantify the risks and support decisions of whether or not to make dam safety related modifications to reduce risk at a dam. With so many dams in Reclamation's inventory, it is unlikely that up-to-date documented risk analyses will be available for all dams when resource allocations for dam safety enhancement are necessary. However, it is still prudent to set priorities on the basis of our best knowledge of the potential risk to the public at any given point in time. Prioritization of issues can occur for a given dam (i.e. treat a piping problem but defer the hydrologic investigations) or for a group of dams (i.e. when several dams are situated in the same drainage basin or in the same vicinity).

Since perceived risk is not static over time, risk analysis also provides a basis for revising priorities when the estimated risk to the public changes. Such changes may be the result of changes in the population at risk, changes in our understanding of the loading conditions, changes in reservoir operations, or the development of unexpected behavior in the dam. When changes in the risk parameters occur, the risk analysis should be revisited to determine if the allocation of additional resources for dam safety enhancement is necessary to provide adequate public protection.

III. Preparing for a Risk Analysis

A. Defining Study Objectives

Since a risk analysis can be used beneficially for a variety of purposes, the specific objectives of the risk analysis and questions to be answered should be addressed prior to the risk analysis team meeting (described in Section IV). The scope of the work to be performed, time and budget constraints, and target audience for the risk analysis must be documented such that there are common expectations for the results (and how those results will be used) between those performing the risk analysis and those using the results. As the risk analysis is planned, it is important to ensure that the scope of the work planned results in information which is valuable to the decision makers in Reclamation. Once the plan has been developed, it is important to recognize that unexpected information revealed during the risk analysis can lead to the revision of the study plan and objectives.

1. Risk Analysis Categories. - For the purpose of this methodology as it relates to Reclamation's Dam Safety Risk Management process, there are two basic categories of risk analyses. The first, termed "Baseline Risk Analysis," determines the risk represented by the existing structure as it now stands and how it is currently operated. If there is a decision made that the baseline risk justifies additional action, then a second category of risk analysis may be employed. This second category, termed "Risk Reduction Analysis," determines the potential risk reduction from the baseline condition for various alternatives that might be applicable at the site.

It is important when planning for a Risk Analysis to understand the current status of risk studies for the dam so appropriate comparisons can be made. Performing a Risk Reduction Analysis without having already developed the baseline risk is inappropriate.

The different types of risk analyses for each category are described below.

Baseline Risk Analysis. - There are generally three types of Baseline Risk Analysis used in Reclamation:

Portfolio Risk Analysis: Within the U. S. Department of the Interior, there is a Technical Priority Ranking (TPR) system in use for Dam Safety. The existing TPR system has been in use for more than a decade to prioritize dams for study or funding. The TPR is established and updated by the Dam Safety Inspector (Examiner) during preparation of the SEED inspection report. Existing information on the dam and observations made during the inspection are used in determining the TPR.

There are currently ~~some~~ initiatives within the Department to replace the existing TPR with a system that is risk-based. As they are developed and implemented, this portion of this methodology document will be revised as appropriate.

Comprehensive Facility Review (CFR): Senior Engineers preparing the Report of Findings (ROF) portion of the CFR estimate the risk posed by the existing structure.

The results are generally reported in terms of the Tier 1 and Tier 2 guidelines [3] and while typically less refined than the "Issue Evaluation Risk Analysis" described below, the CFR still establishes an approximate baseline risk analysis of the structure. The risk analysis portion of the CFR includes a definition of loading conditions, failure modes, and consequences for all load classes (static, hydrologic, and seismic). Structural failure modes are identified that improve the understanding of the dam's behavior, however, response probabilities and associated uncertainties are typically only considered in a global sense and detailed event trees are usually not prepared. Estimates are generally only prepared by the Senior Engineer and they are peer reviewed by a senior member of the staff. These estimates are based on the experience of the engineer and on the data which is readily available. Uncertainty of the quantitative estimates is generally not considered at this stage but qualitative discussions of uncertainty may be included to help the decision makers when assessing the report.

All the information on the dam that exists at the time the ROF is prepared is used as input to the CFR risk analysis. The Senior Engineer will also consider information gained from the CFR site inspection. Hydrologic and seismic hazard studies are also to be prepared for the CFR process and should be used by the Senior Engineer when performing the risk analysis for the structure.

Issue Evaluation Risk Analysis: This level of risk analysis is generally the most refined of the baseline risk analyses. The decision makers may decide from the results of the CFR or other recent information that a Issue Evaluation Risk Analysis be commissioned. Once commissioned, the Facilitator(s) and Team Leader would put together a team typically consisting of personnel from the TSC, Area, and Regional Offices. The team may be asked to verify the existing risk by considering existing risk analyses, additional data that may have been obtained since any previous risk analysis were performed, or to consider additional expertise (in the form of the experience of the personnel included in the team) while estimating risk.

The team estimates risk in terms of Tier 1 and Tier 2 guidelines and will include a portrayal of uncertainty in their estimates.

This level of risk analysis typically involves developing event trees describing failure modes and estimating structural response probabilities, load probabilities, and consequences. At this stage, the appropriate technical staff becomes involved in the process by sharing their knowledge of the dam and how it will respond to various loads as well as participating in estimating response probabilities. Areas of uncertainty will be identified for consideration by the decision makers during their assessment of the risk. The team should identify data needs where data collection would be expected to significantly improve risk estimates at an economical cost in terms of time and money.

Over time there may be multiple Issue Evaluation Risk Analyses commissioned to continue to refine the baseline risk as more data is collected, different site information is obtained, other expertise is brought in, or as modifications are made to the structure. The goal is to progress to a baseline risk analysis that is adequate for the decision makers to continue to make assessments of the appropriate response to take for the structure.

Risk Reduction Analysis. - A Risk Reduction Analysis is an analysis that examines alternatives as to their impact on the baseline risk. This category of analysis is begun once the baseline risk indicates corrective action is necessary.

Alternative Identification Analysis - At this level of analysis, the goal is to determine what alternatives would potentially reduce the risk to acceptable levels so that further design concepts and cost estimates can be developed. While a team approach is typically used, the team is small and the process at first is not very detailed. The team would examine the baseline risk for the components that are producing the highest risk and brainstorm alternatives that would have a good chance of economically reducing risk to acceptable levels. Alternatives could be both structural and non-structural and should consider all the components of the risk. The risk reduction may not be actually quantified but at a minimum the key concepts of where risk reduction is anticipated should be reported.

Alternative Evaluation Analysis - At this level of analysis the goal is to fully examine alternatives for their ability to reduce risk. The team should use all previous analyses and information to estimate the potential risk reduction of the alternatives. If alternatives include structural modifications, a certain level of design detail will be needed to make the estimates such that the strengths and weaknesses of the proposed modifications can be studied. Costs of the alternatives may be needed if there is a need to quantify the economic risk reduction or if risk reduction indices [3] are to used by the decision makers. Previously developed event trees can be revised to study and quantify the effects of the alternatives on the components of risk.

Table 1. - SUMMARY OF BASELINE RISK AND RISK REDUCTION ANALYSES

Category	Type	Product(s)	Staffing	Duration	Methods Used	Data Used
Baseline Risk Analysis	Portfolio	TPR	Examiner	few hours	Prescripted	- available data - field observations - known conditions
	CFR	ROF	Senior Engineer	1-2 days	- historical failure probability - simple event trees - back calculation to Tier 1 & 2	- above data - experience of Senior Engineer - hydrologic & seismic hazard study
	Issue Evaluation	ROF	Team	1-10 days for meeting 1-20 days for documentation	- detailed event trees - decomposition to estimate response probabilities	- above data - new data - experience of team members
Risk Reduction Analysis	Alternative identification	- ROF - FER - Service agreement	Team	1-10 days for meeting 1-10 days for documentation	Brainstorming based on baseline risk	Results of Project team baseline risk analysis
	Alternative evaluation	ROF	Team	1-10 days for meeting 1-10 days for documentation	Revise event trees for each alternative	Field data; designs; and cost estimates

2. Documenting the Scope of Work. - The Dam Safety Office, Regional Dam Safety Coordinator, Area Office representatives, and Team Leader define specific risk analysis study objectives, including the basis for any decision to be made and the questions to be answered by the risk analysis study team. The objectives may include an assessment of the risk of loss of life and risk costs, or a determination of areas of concerns that need additional data collection and analysis. The level of effort required for the risk analysis is one of the outcomes of this discussion.

A written scope of work, prepared by the Team Leader, is extremely valuable in defining the effort required for the risk analysis . While the document should have sufficient data to provide a common understanding of the expectations, it can be prepared in a simple format such as the worksheets shown in Figures 3a and 3b. The key elements to be identified include the objectives of the Dam Safety Office, products expected, participants, a schedule and budget, data availability and requirements, and the level of effort required from the participants. When completed, the scope of work should also meet the requirements of Technical Service Center (TSC) Memorandum No. 3, which describes the preparation of service agreements.

The products of a risk analysis will vary with the objectives of the risk analysis. The products can generally be classified as those which provide a description of the baseline risk at the dam and those which frame potential future actions on the impacts to the baseline risk. Products which describe the baseline risk could include event trees, descriptions of potential failure modes, descriptions of loading and exposure conditions, evaluation of existing data and analysis, and charts showing risk and consequences associated with the dam in its present condition. Products which frame future action could include evaluation of additional data which would add value to the analysis of risks, relative ranking of potential risk reduction alternatives with respect to risk, and estimates of the cost effectiveness of potential risk reduction alternatives.

As the plan for the risk analysis is being formulated, it is also important to recognize that there may be key questions from decision makers or others which need to be answered as part of the process. The risk analysis will be of greater value to the decision makers if these questions are identified and documented at the start of the process so that they may be directly addressed. Some examples of the types of questions frequently asked include:

- Which failure modes contribute the greatest risk?
- What uncertainties enter into the estimates of risk?
- What information could be generated to reduce the uncertainty?
- What outcomes could reasonably be expected to result from collecting the information?
- How would the risk be affected by each of these outcomes?
- What are reasonable alternatives for future action and what will they cost?

While not all of these questions need to be answered for all risk analyses (depending on the category), the risk analysis participants need to identify what questions are important to the decision makers and answer those questions through the risk analysis process.

Since risk analyses can be performed to varying degrees of detail, the detail required should be documented at the beginning of the study. Issues to be addressed would include targeted failure modes (if any), the availability of data, and any specific desires of the decision makers regarding format of the results.

Risk Analysis Scope of Work

Dam: ____________________ Date: ____________

Risk Analysis Category: ☐ Baseline
☐ Identify Risk Reduction Alternatives ☐ Evaluate Risk Reduction Alternatives

Dam Safety Office Objectives:

- ☐ Determine whether or not identified dam safety issues require further investigation
- ☐ Identify key sources of risk and uncertainty
- ☐ Identify future data and analyses needed to determine if risk reduction is required
- ☐ Identify alternative courses of action for risk reduction
- ☐ Quantify risk reduction for alternative actions
- ☐ Other ____

Required Products:

- ☐ Risk Analysis Report
- ☐ Draft service agreement for next phase
- ☐ Other ____________________

Risk Analysis Participants: (indicate which team member will serve as the recorder and prepare the report) (not all of these participants may be required)

☐ Facilitator(s)	____________________
☐ Team Leader	____________________
☐ Geotechnical	____________________
☐ Structural	____________________
☐ Waterways	____________________
☐ Geology	____________________
☐ @Risk Resource	____________________
☐ Region	____________________
☐ Area Office	____________________

Risk Analysis Consultants: (Provide data and may participate part time)

Flood Hydrology/Paleoflood	____________________
Seismic Hazards	____________________
Consequences	____________________
Other	____________________

Schedule:

Start	__/__/__	Draft products complete	__/__/__
Data complete	__/__/__	Meeting complete	__/__/__
Products delivered to DSO	__/__/__		

Figure 3a - Worksheet for Risk Analysis Scope of Work

Data Availability:

Data Type	Data Currently Available	Data Required	Date to be Completed
Flood Hydrology			
Paleo Flood(s)			
Seismic Hazard Curves			
Dam Breach Parameters/ Inundation Mapping			
Consequences			
Other			
Other			

Staff-day Estimate:

Code	Data Collection	Risk Analysis	Draft Products	Review	Final Products
D-8110					
D-8130					
D-831_					
D-832_					
D-8330					
D-8530					
D-8540					
Total					

Client Approval: ______________________________ ____________

Dam Safety Coordinator Date

Figure 3b - Worksheet for Risk Analysis Scope of Work (continued)

3. Time and Budget Considerations. - Time and budget constraints play a key role in defining the study objectives. Time, budget, and the scope of the services to be performed are closely related and must be balanced to achieve desired results. A key consideration is whether or not the analysis is allotted a specific budget. If a specific budget and/or time is allotted, the scope of work must be adapted to generate the most valuable risk information within the allotted time and budget. If the time and budget are flexible, the scope of work must be negotiated with the decision makers such that the scope of work will yield the required results in a cost effective manner. When developing a scope of work and associated time and budget estimates, some considerations include:

- Stage of Dam Safety Process - For Baseline Risk Analyses, decision makers may only need information on the need for additional data collection or they may desire more detailed information in later stages of the dam safety process to complete their risk assessments.

- Potential for Adverse Consequences - Risk analyses for major storage dams tend to require greater effort than small dams with small reservoirs. In addition, dams with large downstream populations may require more attention than those with small downstream populations.

- Public Awareness - Risk analyses for dams with higher degrees of public scrutiny may require the same effort to reach problem understanding as other dams, but will likely require greater attention to presentation and documentation of the risks associated with alternatives than those with lesser public concern.

By addressing these considerations in combination with developing an acceptable scope of work, an appropriate schedule and budget can be developed for the risk analysis.

4. Target Audience. - The target audience of every risk analysis is the group of decision makers who must determine what future actions, if any, are required with respect to the safety of the dam. In accordance with *Policy for Decisions Related to Dam Safety Issues* [4], this group generally consists of the Regional Director, Area Office Manager, and Chief of the Dam Safety Office, or their representatives. The objectives of the risk analysis should ensure that concise and adequate information concerning risks and consequences is provided to these individuals for their evaluation. In defining the objectives of the risk analysis, participants in the process must understand that their role is focused on providing risk based information rather than making the decision.

While the primary audience of the risk analysis is decision makers, there are likely to be other audiences which derive benefits. These groups may include the risk analysis participants who gain a better understanding of the performance of a dam, operations or water district personnel who gain a better understanding of how their operations decisions impact the risk to the public, and program managers who may use the risk analysis for prioritizing future work. While each of these groups has a valid interest in the risk analysis process and results, it is important to ensure that the focus of the risk analysis is maintained on providing the decision makers with information that contributes to their decisions.

5. Approval. - The final step of defining the risk analysis objectives is to obtain approval from the Dam Safety Office. This part of the process is complete when there is agreement on the scope of work, schedule, estimated cost, and intermediate checkpoints. While there can be some effort involved in reaching this agreement and approval, it is generally helpful in ensuring that all participants have a clear understanding of the expected outcomes of the risk analysis.

B. Establishing the Study Participants

1. Composition. - Participants in the risk analysis depend on the type and complexity of risk analysis being conducted. It is difficult to define a generic list of participants that could conduct all types of risk analyses. The composition of the team will depend on the objectives of the analysis and on the level of detail expected.

For the Baseline Risk Analysis in the CFR process, a senior engineer typically prepares the risk analysis and a peer reviewer provides the technical review of their analysis. Since the purpose of the analysis is usually to identify and prioritize dam safety issues in need of additional attention, the senior engineer needs a strong familiarity with risk analysis procedures and failure mechanisms at the dam. The engineer usually has many years of experience evaluating dam safety deficiencies, but should not hesitate to draw upon other technical specialists as needed to address other areas of expertise.

For an Issue Evaluation Baseline Risk Analysis, the participants usually consist of a facilitator(s), recorder or note-taker, team leader, and a various number of team members and technical specialists (including someone to operate the software to manage the information generated - currently @Risk and Precision Tree). The technical specialists participate on an as-needed basis to understand and guide the thought process of the team and to provide specialized information needed for the analysis.

2. Group Size and Organization. - Selection of the risk analysis participants is an important step in preparing for a risk analyses. The number of participants requires balancing inclusiveness and diversity against group effectiveness and cost. Potential participants include technical staff familiar with the dam; operations personnel; technical specialists familiar with loading conditions (loading specialists), failure consequences, or dam safety issues; Regional and/or Area Office dam safety coordinators; Dam Safety Office program managers; outside experts; and others who may be able to assist in assessing the critical safety issues for the dam. To keep the process as efficient and effective as possible, participants may need to function in more than one role, as long as they are qualified for each role. For example, the team leader may also serve as the author of the risk analysis report, or a technical specialist may function as the recorder.

For an Issue Evaluation Baseline Risk Analysis, participation by regional and area office personnel is generally very beneficial since they generally have a good understanding of the local conditions and dam operations. For a Risk Reduction Analysis, some of the same individuals may have important contributions in the analysis of alternatives. Area Office and Regional Personnel may also participate in a risk analysis to gain knowledge of the analysis so that their job of disseminating the information to the public is made easier.

The size of the risk analysis team and how it is organized are integrally related. While there are few rigid rules for either, some general guidance can be offered.

- Ordinarily, most risk analyses will consider seismic, hydrologic, and static failure modes, supported by individual technical specialists in these areas. It is useful to conduct an introductory session with all team members in attendance during which basic information about the dam and downstream consequences are reviewed, and the study objectives are established. It is also desirable for all participants to assist in identifying loading conditions, failure modes, and consequence scenarios. This provides a common basis for understanding and sets the stage for the task ahead. Similarly, a closing session with all team members is important for communicating and synthesizing the outcome of the analysis, establishing consensus on the meaning of its results, pointing the way toward identifying data needs, formulating corrective alternatives, and achieving several of the other purposes outlined previously in Section II.

- For an Issue Evaluation Baseline Risk Analysis during which event trees are prepared and probabilities assigned, it can be useful to convene separate subgroups for the seismic, hydrologic, and static aspects. If subgroups are established, it is important that there be a core group of participants that are active in all subgroups in order to ensure consistent treatment of information between groups. For any one of these subgroups (seismic, hydrologic, or static), the following numbers of participants are generally considered, though not all are necessarily required:

Participant	Number	Role
Facilitators	1-2	leads discussion (full-time)
Team Leader	1	overall coordination, ensures consistency (full-time)
Recorder	1	compiles information for documentation (full-time)
Technical specialists	1 - 2	provides seismic, hydrologic, or static response input (full-time, may be an identified participant in the risk analysis or a person with specialized knowledge in the subject matter.)
O&M personnel	1 - 2	provides detailed site information (full-time)
Loading specialists	1 - 2	explains derivation of flood or earthquake recurrence relationships (part-time)
Consequence specialist	1	provides guidance and estimates on downstream consequences
Precision Tree/ @Risk operator	1	assists participants with capturing and displaying event trees and probabilities so that failure modes and risks can be understood real-time (full-time)

These numbers seek a balance between the need for a full range of skills in providing information and conducting the analysis on one hand, and the desire to keep the group to a manageable size on the other. In some cases, more than about ten participants can considerably complicate the task of the facilitator(s) in moving the process forward without providing significant perceived benefit in terms of improved input.

3. Roles and Responsibilities. - Every participant has a unique role on the risk analysis team. The team leader is given the task of coordinating and ensuring completion of the risk analysis. Therefore, the team leader's first job is to obtain a trained facilitator or co-facilitators. The facilitator(s) work with the team leader and Dam Safety Office Program Manager to determine the expertise needed and establish the objectives and makeup of the team. One of the goals in establishing the participants is to select people whose qualifications make the process and results credible. The team leader and facilitator(s) should communicate the study objectives and individual roles and responsibilities to the team members at the beginning of the study. They should consult with the technical and loading specialists before the risk analysis to determine what information is available or needed for the risk analysis. The following paragraphs describe the various team members' roles and responsibilities that are typically needed to conduct a risk analysis.

The team leader makes arrangements for obtaining the necessary resources to conduct the risk analysis and is responsible for scheduling and budgeting. The leader's duties include preparing service agreements, establishing meeting times, arranging conference rooms, and communicating the budget and schedule to each team member and the client. The team leader should also collect relevant reading materials and make them available to the team before the first meeting.

The facilitator(s) should thoroughly understand the risk analysis process and have considerable experience leading and participating on risk analysis teams. The team leader relies on the facilitator(s) to provide direction and advice and to draw out ideas and opinions while conducting the risk analysis. Together, they share ownership in the analysis and help each other in keeping within budget and on schedule, while attaining the study objectives. Several key characteristics are needed in a facilitator to assure a successful risk analysis. The facilitator should have participated in several risk analyses as a participant before attempting to facilitate and should have good communication skills. He/she should be able to run an effective meeting and to elicit ideas and opinions in an impartial manner. The facilitator should understand group dynamics to deter strong personalities from dominating the risk analysis and unduly influencing others. The facilitator should also be knowledgeable about dam failure modes and event tree construction, and should have experience in bringing the risk analysis process to closure. The facilitator(s) are responsible for running the meetings, summarizing key points in the discussion, eliciting expert opinion, leading development of the event tree, assisting the participants in interpreting the results, and ensuring the recorder gets the necessary information documented. The facilitator also needs to be adept at recognizing individual biases and take steps to avoid allowing personal agendas to sway the results. The facilitator(s) will run the meeting using the processes as outlined in Section IV.

Responsibility for calculation of final probabilities and development of the event tree should be assigned to the operator of the @Risk software or another participant. Loading specialists have the responsibility to document the justification for loading condition probabilities and consequences.

Risk analysis participants should represent a variety of viewpoints and specialties. The group should be tailored to address the specific questions that have been defined in developing the study objectives. The participants should have extensive experience in their field of expertise and should have considerable project-specific knowledge. Ideally, at least one or more participant should have extensive knowledge of the operation and maintenance of the structure, and usually will come from an Area or Regional Office.

Where a team is conducting a risk analysis, a subgroup of the participants knowledgeable about a certain failure mode or loading condition may be responsible for development of system response probabilities. While these participants are meeting, loading specialists, technical specialists, and other technical staff can be called in, as needed, to supplement their expertise. These specialists might have extensive knowledge about the potential loading conditions, engineering analyses, consequences of dam failure, economics, etc. These experts are encouraged to help the team in estimating system response probabilities.

Specialists are responsible for development of loading conditions and probabilities (e.g., earthquakes, floods) and for development of consequences. Together, the specialists and other participants will develop warning time scenarios for use in consequence evaluations. Other specialists may also be called upon to conduct additional analyses of structural response; provide briefings on specific aspects of response analysis; and assist in determining system response probabilities as required. While briefing the team, the technical specialists must convey an understanding of the assumptions and uncertainties of their analyses to the rest of the team.

4. Recognizing Limitations. - The composition of the study team will generally consist of staff members with varying degrees of knowledge and enthusiasm for the risk analysis process. The facilitator(s) should be aware of potential biases which individuals may have relating to estimating probabilities. Although bias can take many forms as discussed subsequently in Appendix A, one of the more significant is known as motivational bias, when the probability estimator has some stake or interest in the outcome of the analysis. This might occur, for example, if a team member were to attempt to please a superior with a "favorable" outcome, or were to promote the adoption of some particular modification measure, or stood to benefit from adopting certain investigation techniques that the analysis might recommend.

The facilitator(s) needs to be alert to the potential for motivational bias among members of the study team. In unusual cases, such persons might be given the opportunity to be excused from a particular risk analysis, but more typically a candid discussion emphasizing the need for impartial judgments without preconceived outcomes may help to achieve the same end by conveying the facilitator's awareness of these effects. If there is reason to suspect that motivational bias may have substantially influenced the outcome of a risk analysis, the facilitator(s) are obliged to make this known in the documentation and communication of results.

C. Risk Analysis Reading Materials

Participants in the risk analysis need to come to the initial team meeting prepared to discuss project-specific failure modes, loading conditions, operations, and the potential consequences of dam failure. This requires each participant to familiarize themselves with the project and risk analysis procedures before the meeting.

The team leader is responsible for assembling a package of pre-risk analysis reading materials and distributing the information to the team. The purpose of assembling the package of reading materials is to begin to create equal understanding among participants about the risk analysis process and problems at the dam, so that each member can confidently contribute to the analysis. The materials should include project-specific reports and general information describing the methodology for conducting a risk analysis.

If risk analysis participants would like to know more about the overall risk analysis process, general information describing how to conduct a risk analysis is contained in this document. Toolboxes (various methods, processes, and information related to risk analyses) are currently being developed that will enhance the risk analysis process described in this methodology, and these toolboxes will be included with this document as they are completed. Information concerning the manner in which the results of the risk analysis are used is included in *Guidelines for Achieving Public Protection in Dam Safety Decision Making*, Bureau of Reclamation; April 4, 1997. In addition, the participants should have access to any previous risk analysis reports for the dam and/or an example of a recent risk analysis report and case histories of dam incidents/failures for similar facilities.

Project-specific reports and evaluations should also be collected. This material includes field inspection reports, construction and operations histories, as-built drawings, previous dam safety evaluations and analyses, geologic data, seismotectonic reports, flood studies, reservoir routings, performance parameters, early warning system reliability studies, operating criteria, and pertinent correspondence. The SEED Data Books and project files are sources of most of these materials for Reclamation dams. The State Engineer's Office, other Federal agencies, or private owners are possible sources of information for non-Reclamation dams.

IV. The Team Meeting

The information presented in this section was written primarily as a guide for the facilitators and participants in Issue Evaluation or Risk Reduction analyses, though much of the information may be useful to those preparing Comprehensive Facility Review level risk analyses.

A. Meeting Agenda

As with nearly all meetings, an agenda for the risk analysis meeting should be developed. It should be developed jointly by the team leader and facilitator(s) in advance of the actual meeting and sent to all participants. The agenda should be detailed enough to serve several functions as follows:

- To give a broad overview of the actual meeting to help members understand the issues to be discussed
- To structure the meeting to help achieve a time frame for the topics (the agenda should include a timetable for each major discussion)
- To provide information to those who will be attending on a part time basis when their input will be necessary (i.e. load specialists, response specialists, consequence specialists, etc.)

While most of the typical agenda items are discussed in other sections of this document, some particular sections of the agenda deserve further explanation and are as follows:

1. Introduction. - When a team is first assembled for a risk analysis, it is imperative that all members be quickly brought to an enhanced understanding of technical and operational issues associated with the dam. While this objective can be partially met through disseminating background information prior to the team meeting, schedules do not always allow for everyone to arrive at the meeting fully knowledgeable of the information provided. This part of the meeting is extremely important as a time for becoming familiar with the dam, the risk analysis process, and other team members. Even though some of the topics might seem trivial, obtaining early participation by all members is just as important as the information to be conveyed. If members of the group can become comfortable participating in this part of the meeting, they will more freely share their insights as the discussions become more technical. Suggested topics to include in this part of the meeting include:

- Client Expectations - Study objectives which have been agreed upon with the client should be shared with the team members for the purposes of making client satisfaction a team goal and for identifying any obstacles to meeting the client's expectations. It is often worthwhile to have the client attend this portion of the meeting so that any obstacles can be resolved quickly thus allowing the team to quickly focus in on their task.
- Team Members - Each team member should be asked to introduce themselves with more than the customary background information. Information about each team member's previous experience with the dam and with risk analyses in general will help all to better understand the resources available to the team as a whole. Each team member should also be encouraged to express any expectations that they have about the process including areas that they believe need to be investigated or even aspects of the dam that they intuitively believe to be high risk. As the meeting goes on, it will be

important to be able to address the individual needs and expectations of the team members in order for them to constructively contribute to the risk analysis process.

- Risk Analysis Process - A brief overview of the risk analysis process should be provided with special emphasis on the importance of the knowledge and judgement of each of the participants. Although some participants may have previous experience performing risk analyses, there may be some minor changes to the approach which are particular to the dam being considered. The follow-on use of the analysis results by the decision makers (i.e. risk assessment process) should also be explained.

2. Make Report Writing Assignments. - One person is responsible for pulling a final risk analysis report together. In most cases this will be the Team Leader. Others can be assigned responsibility for portions of the report, but the Team Leader will typically be required to compile and generate the final product. A person will still need to serve in the role of Recorder. This person captures the details of discussion as the risk analysis progresses. Team Leaders will most often not be the Recorder since they are required to participate intimately in the risk analysis process and would not be able to perform the duties of Team Leader and Recorder simultaneously.

3. Reviews. - An introduction to the dam and its appurtenant structures will help participants to understand the physical features and operational aspects of the dam. Summaries of identified dam safety concerns, previous analysis, data collection programs, and past performance will help the team members to frame their input during subsequent parts of the meeting. This can take up to several hours for a typical Issue Evaluation risk analysis.

4. Potential Failure Modes. - A potential failure mode is an existing inadequacy or defect originating from a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir. The participants should go through a discussion of all potential failure modes, and develop a thorough understanding of any failure mode, and screen out failure modes that are judged to be inappropriate or unrealistic.

5. Loss of Life Estimates and Other Consequences from Dam Failure. - All loss of life information, including population at risk, potential warning times and evacuation processes are discussed. In addition, Region, Area and Project personnel are queried directly about knowledge they possess regarding potential for loss of life. This helps ensure that loss of life estimates are characterized to the best degree possible for use in the risk analysis. Economic, social, environmental, and cultural consequences should also be discussed so that all risk analysis participants are aware of the broad spectrum of possible consequences associated with dam failure.

6. Risk Analysis Calculations. - The Facilitator(s) should briefly discuss how probability estimates will be solicited from participants and how this information will be used in calculations of risk. This should include how uncertainty will be portrayed and how the @Risk Software utilizes this information.

7. Conclusions. - When the probability estimates are completed and the event tree has been calculated, the team should discuss the results. Sometimes, where there is statistical information on the failure mode being reviewed, the team may consider how their results compare to the known failure rates. Most importantly the team should be considering whether or not the results seem to make sense in terms of their understanding of the known conditions at the dam. If there seem to be discrepancies, a review of the logic and probability estimates that have been prepared may provide a better understanding or identify a need to reevaluate the estimates. Facilitators serve a key role in ensuring that riak has been properly characterized in a fashion useable by the decision makers.

When the results appear reasonable to the team members, it is frequently beneficial for the team to develop a summary of their findings. Six questions have been developed as a means of addressing key areas of the summary. The questions are:

- Which failure modes contribute the greatest risk?
- What uncertainties enter into the estimates of risk?
- What information could be generated to reduce the uncertainty?
- What outcomes could reasonably be expected to result from collecting the information?
- How would the risk be affected by each of these outcomes?
- What are reasonable options/courses of action and what will they cost ?

Depending on the level of the analysis, answering these questions (as applicable) should provide valuable information to the risk assessment process.

8. Future schedules. - It is important for the team to understand the anticipated schedule to be followed after the meeting. While schedules for report completion will typically be determined at the time the project plan is developed, team members should freely discuss their commitment to the schedule. In addition, there may be a need to brief other portions of the organization and the team members need to be made aware of these briefings.

B. Developing Event Trees

1. Principles. - Event trees are used to represent sequences or progressions of events that could result in adverse consequences when a dam or associated structure responds to various loading conditions. By providing a graphical representation of the logic structure for the progression of each failure mode, an event tree becomes the template for subsequent assignment of event probabilities and calculation of risk. The event tree is also a tool for evaluating changes in risk given certain actions and assumptions. In addition, it is a means for identifying where the greatest potential risks are. And perhaps most importantly, it fosters common knowledge and understanding of failure modes, and synergetic discussion of various issues associated with failure modes. The risk associated with one sequence in the event tree is the product of the load probability, the structural response (failure) probability given that the load has occurred, the adverse consequence given that the load and failure have both occurred, and the magnitude of that consequence. The total risk for the load category is the sum of the products for all event tree paths.

An event tree consists of a series of linked nodes and branches. Each node represents an uncertain event or condition. Each branch represents one possible outcome of the event or one possible state that a condition may assume. Together, all of the branches emanating from a node should represent the mutually exclusive and collectively exhaustive set of possible outcomes or states (this is typically not done in the load range branches). The branches are mutually exclusive if each branch unambiguously describes one and only one possible outcome (i.e. there is no "overlap" among them), and they are collectively exhaustive if together they describe all possible outcomes (i.e. probabilities add up to 1.0).

The event tree is constructed from left to right, starting with some initiator event and proceeding through events describing the response of the dam to each level of the initiator. These event sequences are developed all the way to breach of the dam, and finally to consequences that result. Each event node is predicated on the occurrence of all directly-linked branches that precede it in the tree.

The best way to start creating an event tree is to establish failure modes through a failure mode screening process. Once a failure mode has been identified, the event tree should be formulated to show the sequence of events and/or conditions which would have to take place or exist in order for the dam to respond in an adverse manner. Often it is useful to begin with "logic diagrams" that generally list the various sequential steps needed to take place during a given failure mode. These diagrams are less complex than the formally constructed event trees. The event tree should also identify possible interventions which could terminate the development of the adverse consequence. An example of this might be consideration of construction of an alternative(s) that would prevent the continued development of adverse consequences. For instance - have an "intervention" node in an event tree for a seepage related failure mode where the probability of successfully constructing say filters, or drains, or a berm, etc., is considered. Successful intervention would terminate one path of the event tree.

Performance Parameter Technical Memorandums (PPTMs) are particularly helpful for identifying failure modes. If a PPTM exists, the performance parameter team has already done most or all of the ground work by listing and describing failure modes along with monitoring that can help detect initiation of a failure sequence. The risk analysis participants should still try to identify additional failure modes, or, if necessary, revise the ones listed in the PPTM. If the risk analysis participants do discover something missing in the PPTM, they should recommend a revision to that document.

Case histories can provide additional insight for identifying failure modes and for breaking down the modes into sequences of events, a process sometimes called "failure mode decomposition". Failure and incident information provided in case history reports describe the progression and sequence of the events that have occurred for other dams. This information provides the means for conceptualizing and specifying the occurrences, conditions, and interventions that could be pertinent to the dam under consideration. For many dam types and applicable failure modes, there are often one or more especially well-documented failure(s) or incident(s) that chart the progression of events in some detail. Incidents that have progressed nearly to failure but have stopped for some reason provide information that is as valuable as information regarding complete failures.

The potential failure modes should be identified and each event in the progression should be explicitly and unambiguously documented (such that all team members have a common understanding of the potential failure modes) for later use in the structural response probability estimation phase. Considerable effort should be devoted to determining atypical failure modes that might be unique to the dam in question. The potential for adverse consequences associated with improper operation of the facilities should be considered as one of these unique failure modes.

2. Complexity. - The size and complexity of the event tree depend on what is known about the dam and its expected behavior under different loading conditions, on the complexity of the failure modes considered, on the number of load ranges needed, and to some degree on the purpose of the risk analysis. The event tree must balance needs for comprehensiveness and detail against needs for consistency, clarity, and communication. Too little detail can reduce the ability to target specific risk contributors and can create problems in making reasonable structural response probability estimates. Too much detail, and the event tree becomes unmanageable or incomprehensible to a degree that important insights are lost. Techniques for achieving an appropriate level of detail in the event trees include the following:

- Truncate non-failure branch pathways as early as possible - There is no need to propagate event sequences once it becomes apparent that they cannot lead to an uncontrolled release of the reservoir. The reasons why an event sequence branch is truncated are an important part of the risk analysis documentation.

- Construct separate event trees for each load type, and sometimes, for each load increment - These trees will often be similar or identical, but constructing them separately and sequentially better organizes the process.

- Use a staged approach - As with any other engineering analysis, it is unreasonable to expect that everything can be fully captured in an event tree on the first pass through the problem. A comparatively simple initial effort can identify the key elements in the tree that need to be expanded and less important parts that can be pruned in subsequent iterations.

- Limit the number of load increments for initiator events - Bounds for load increments should be chosen specifically to bracket load ranges where it is expected that the structural response (or the consequences of dam failure) will be fundamentally different from the structure's response (or the dam failure consequences) in other load ranges. Sometimes load ranges are selected to represent information available from related analyses. Dividing the full range of possible loading values into a few increments is usually sufficient for most problems. While any number of increments can be used, there must be sufficient reason to suspect that considering different load increments will lead to different structural responses or to some fundamental change in the adverse consequences.

3. Load Ranges and Increments. - The flood or earthquake initiator events can take on any value over very wide limits of the recurrence curve. It is necessary to confine these limits to a sensible range of values that can affect the structural response or consequences in a significant way. The number of increments and how they are defined have important implications on design of the event tree that affect its size and the ease with which subsequent structural response probabilities can be estimated. Two threshold load levels naturally suggest themselves: a threshold below which no structural damage or adverse consequences are expected, and a threshold above which structural failure is almost certain to happen. Between these thresholds is a load range where structural damage or adverse consequences is possible to varying degrees. Within this range other threshold load levels can be identified where significant changes in structural response or possible adverse consequences take place.

Often, the maximum load already experienced by the dam may be selected as the threshold below which no structural damage or adverse consequences are expected. The dam has survived this load, and one can usually assume that the dam will survive a repeat of this load, unless there is some progressive degradation mechanism at work. Parametric studies conducted as part of a previous dam safety analysis can also provide insight regarding this lower bound threshold. Examples of these approaches to developing load ranges are:

Hydrologic Loading - Using the flood of record to establish the threshold of adequate spillway performance. The spillway either successfully passed or did not pass the flood of record.

Seismic Loading - A comparison of available liquefaction susceptibility studies to potential earthquake induced peak horizontal accelerations at a dam site can be used to set the lower bound of earthquake shaking that a structure can withstand without failure of the structure, .i.e., the acceleration bound below which no liquefaction is expected to occur.

Static (normal) Loading - There may be a geologic feature located at an elevation within a reservoir storage area where inundation by water begins development of potentially adverse seepage conditions. Below the elevation of this geologic feature dam performance related to seepage is adequate. The time period the reservoir water surface is below the elevation of the geologic feature would be one bound on the static loading.

The lowest load range is very important due to its relatively high occurrence probability. This load range should establish the load range for which the dam is expected to perform without failure. Typically, this load range is called the "threshold" range for initiation of failure. Participants must be careful to assess the failure threshold value realistically. A "conservative" threshold estimate which underestimates the load level at which failure can occur will significantly increase the perceived risk at the dam.

Arbitrary designations such as the Probable Maximum Flood (PMF) or Maximum Credible Earthquake (MCE) generally should not be used as threshold levels. Deterministic analyses to create a PMF hydrograph and route the hydrograph through the dam's spillway and outlet works usually indicate the dam will overtop at some level well below the PMF. Likewise, some dams would not be able to withstand earthquake loading well below the MCE. Furthermore, it is difficult to accurately associate return frequencies with a PMF or MCE.

The resulting threshold levels, and the corresponding ranges between them, may initially be chosen inappropriately by the participants. The calculated risk for a particular event tree branch may appear intuitively incorrect. This particularly happens when the chosen ranges are too wide. Risk analysis participants typically estimate a high structural response probability for a given range that might be more correctly associated with just the upper end of the range. The lower end of range determines high frequency of load occurrence. When the selected probabilities are multiplied through the branch, the calculated risk appears too high. If the result does not make sense, the participants should try splitting the load range so the probability estimates more accurately reflect the anticipated performance of the dam.

C. Estimating Load Probabilities

The three categories of loading conditions typically required in risk analysis are static, hydrologic, and seismic. Each of these loading conditions is briefly described in the following paragraphs. The discussion emphasizes the products needed by the participants, the range of extrapolation, and the uncertainty of the structural response probability estimates. The technical details for developing the loads are not described, but may be found in numerous engineering textbooks and manuals. The responsibility for estimating load probabilities lies with the supporting technical specialists and the technical staff participating in the risk analysis.

Generally, load probabilities are estimated using the staged approach. The level of detail of the risk analysis determines the amount and quality of information used in the analysis. More detailed stages of risk analysis may require more detailed loading condition information. Additional work on the loading conditions is performed only if warranted by the value added to the dam safety decision process (through the reduction or better portrayal of uncertainty). Extra study cost should be weighed against the expected improvement in the quality of the dam safety decision.

The failure of upstream dams should not be considered as loading conditions in a risk analysis. The risk of multiple dam failures/incidents are addressed by assigning the cause of failure to the most upstream dam failure and including the resulting dam failures as consequences for that dam.

1. Static Loads. - The static loading condition encompasses a wide variety of specific loading conditions to which a dam is routinely exposed during the course of normal operation. These loads can include hydrostatic loads imposed by the reservoir, static and dynamic loads imposed by operating various components of the dam and its appurtenant structures, loads induced by landslides at the dam or on the reservoir rim, or by the hydraulic phenomena (seepage, erosion, cavitation) associated with water passing through and around the dam.

Most static loading conditions are related to the reservoir level either in terms of the magnitude of the load, time of exposure to the load, or the potential for adverse consequences. Therefore, historical reservoir elevation records are an important information source for assessing the likelihood of failure modes associated with static loading conditions. When evaluating the historical reservoir information, it is important to consider the data in a fashion which is consistent with the failure mode being developed. In the case of gates, the exposure is directly related to exposure time above a given reservoir water surface elevation. In the case of piping, the exposure may be more related to whether or not the reservoir has reached a specific level at some previous time. In each case, the historical data must be organized in a fashion which yields meaningful information for the anticipated potential failure mode.

For most team risk analyses it is likely that a Reservoir Load Frequency Curve will need to be developed by Reclamation's Structural Behavior and Instrumentation Group. In some cases information available on reservoir elevations is incomplete and additional information for development of a Reservoir Load Frequency Curve will need to be obtained through Region, Area or Project Offices. In addition, it will be necessary to evaluate what, if any, load ranges need to be considered when performing a given risk analysis (see additional discussion of load ranges in Section IV.B, "Developing Event Trees"). The load ranges may be discrete elevations of concern (i.e., there might be a geologic formation at a given elevation that relates specifically to a given failure mode) or there could be a continuous loading condition (i.e., the failure mode is seepage through the embankment/foundation contact when the reservoir fills each year and the structure responds quickly and fully saturates).

2. Hydrologic Loads. - The development of flood frequency relationships and reservoir inflow hydrographs are important inputs to the risk analysis process. For risk analysis, the focus of flood evaluations shifts from a single maximum event, like the probable maximum flood, to describing a range of plausible inflow flood events. The products developed for a particular risk analysis depend on the level of study and the information available. In some cases, concurrent hydrographs are needed for tributaries located downstream of study dams so that flow conditions can be defined for analysis of the consequences of flood induced failure modes. Likewise, for more detailed risk analyses, regional and site-specific hydrologic and paleoflood investigations may be necessary to determine the flood potential and frequency.

Following are several types of studies which may be performed to generate the necessary flood frequency information for a risk analysis. The risk analysis participants should evaluate the currently available flood routing and flood frequency information in conjunction with the flood hydrology technical specialists to determine what type of study, if any, is required.

- Preliminary Flood Frequency Analysis - The analysis will use available information including recorded stream flows, paleoflood data, regional envelope curves, rainfall frequency relationships, and historical accounts of large floods. This information will be combined and synthesized into a flood frequency relationship for peak inflow at the study dam. The curve will extend to floods with return periods in the range of the 1,000- to 10,000-year events and include an estimate of the associated uncertainty.

- Flood Hydrograph Analysis - This analysis builds on the information generated in the preliminary flood frequency analysis. Along with the updated flood frequency analysis, hydrographs will be generated and routed in an attempt to identify the effects of reservoir storage and flood volumes on downstream releases. Simplified approaches will be used to minimize the cost of the study effort.

- Detailed Flood Frequency Analysis - A combination of methods will be used to analyze the problem. The appropriate tools depend on the available information. Some of the tools available include detailed paleoflood investigations, design event-based precipitation-runoff modeling, stochastic event-based precipitation-runoff modeling, meteorological studies, atmospheric storm modeling, continuous simulation modeling, etc. Confidence in the results comes from combining appropriate methodologies.

3. Seismic Loads. - For utilization within a risk-based framework, seismic hazard evaluation must explicitly contain information on the frequency of occurrence (and/or exceedence) of relevant loading parameters. The currently accepted practice for evaluating and conveying seismic hazard information in this fashion is probabilistic seismic hazard assessment (PSHA). The first step in any seismic hazard evaluation is source characterization. For use in risk analyses, both fault and areal (background or random) sources should be incorporated into the hazard evaluation. PSHA attempts to incorporate uncertainty in source characterization by allowing for alternative source and recurrence models as well as uncertainty in recurrence parameters. For fault sources, uncertainty in source dimensions, sense of slip, and orientation (and hence maximum magnitude) should be incorporated for detailed studies. Definition of earthquake recurrence for both areal and fault sources should incorporate some estimate of the uncertainty in seismicity rate and the assumed magnitude/recurrence relationship. The ultimate goal of PSHA is specification of ground motions. For use in risk analysis, ground motion estimation should incorporate uncertainties in source-site distance, selection of attenuation relationships, and observed variability in ground motions (sigma) in the final product.

By definition, PSHA integrates contributions over the entire spectrum of magnitude and distance from each defined source and then sums contributions from each source to develop a distribution of ground motion level for each annual frequency of exceedence. The most frequently used seismic hazard product is a simple hazard curve that relates a ground motion parameter (often peak horizontal acceleration, PHA) to annual probability of exceedence. Because PSHA is integrative, this curve contains contributions from all sources, magnitudes and distances. The risk analysis team may find it useful to consider alternative representations of the hazard. Frequently used options include: breaking out contributing sources individually; portraying contributions by magnitude level; sorting the hazard into discrete magnitude and hazard "bins"; considering alternative ground motion parameters such as response spectrum ordinate(s), acceleration or velocity spectrum intensity, or Arias intensity.

For use in liquefaction evaluations, consideration of ground motions organized by magnitude levels is often quite useful. Risk contributions from the various magnitude levels are then summed. This allows for integration with commonly used geotechnical parameters (such as magnitude adjustment factor) when evaluating liquefaction likelihood. Likewise, acceleration spectrum intensities (ASI) is commonly used as input for the structural analysis of concrete dams, spillways, and outlet works intake towers when subjected to seismic loads. This information can then be used to estimate the probabilities of the various responses of the dam or appurtenant structures to the seismic loading conditions being evaluated.

D. Estimating Structural Response Probabilities

Estimating structural response probabilities is generally the most difficult and time-consuming activities faced by a risk analysis team. It is also probably the area of the whole process that might change most with time. Steve Vick has prepared an excellent summary of the factors, influences, and considerations that should be understood and incorporated into a risk analysis when undertaking this task. This information is provided in Appendix A.

Summarized below is a process for making structural response probability estimates that has been found to work well for various risk analyses. All steps described below are performed jointly by all the participants of the risk analysis team.

Step 1. - The first step is to be sure each team member has a clear understanding of each node of the event tree. (An event tree node represents a choice at which the preceding event must be considered to have happened and two or more subsequent events could take place.) This is best done by having the facilitator(s) write out the description of the node at the top of a flip chart (or some other visual means that is readily accessible at any time). An open discussion usually takes place during this step where team members freely discuss their understandings of the event node and the wording being proposed. The facilitator should then capture the thoughts of the group into the description of the node. For instance, a node description for "unfiltered exit" might be:

> "the soil particles that are being carried by seepage flow must exit from the dam at a location where there is no filter present to trap the soil. A filter is defined as a soil that reasonably meets Reclamation's design standard for filters."

It is perfectly acceptable to further decompose the node in the word description. For instance, a node description as above might also add:

> "The zone 2 of the embankment must reasonably meet filter criteria for the zone 1. The zone 3 outer shell must reasonably meet filter criteria for the zone 2"

Step 2. - The group then 'brainstorms' any and all information that is pertinent to the event node being discussed. Each piece of information is listed on the flip chart in either a 'factors leading to a higher probability' or 'factors leading to a lower probability' column depending on whether the information is can be used as evidence to support or oppose belief in the event. The listing is usually done on the same chart immediately below the node description. The terms 'factors leading to a higher probability' and 'factors leading to a lower probability' are used in terms of the event node, as described, actually happening. The team should agree that the information is being placed in the correct column. Disagreements are usually solved by using clear wording that describes the information or by adding an opposing view in the opposite column. The purpose of this step in the process is to display all the information that will be used in making the estimate for all team members to see and discuss. As described below in step 3, the team members can judge for themselves the importance of the information being listed as they make their estimates.

Nearly any type of information is permissible to be listed if it helps the team members make their estimates. For instance, "gradation limits in construction specification meet filter criteria for the zone 1" might be listed in the 'factors leading to a lower probability ' column for the 'unfiltered exit' description discussed above in step 1. Others might be "93 out of 95 gradation tests of as-constructed earthfill showed acceptable limits were achieved" [factors leading to a lower probability]; "2 out of 95 gradation tests of as-constructed earthfill failed the limits and were left in place" [factors leading to a higher probability]; "the specified gradation is likely to segregate during placement" [factors leading to a higher probability].

Also to be listed are any similarities/dissimilarities with the case histories being used as a comparison. For instance, "the zone 2 for 'Dam X' (the case history dam) was much less compatible for the zone 1 than is the dam under study" [factors leading to a lower probability].

Even information of a general nature or member biases can be listed. For instance, one team member might want to list his/her concerns as to the appropriateness of the filter criteria used in the listing of the above information and include this in the 'factors leading to a higher probability ' column. An example showing a record of steps 1 and 2 is shown below. Considerable report-writing time can be saved if this chart can be created on a computer as the discussion takes place.

Record of Discussion for Probability Estimates

Dam Component: Senator Wash Dam	Alternative: Reservoir Restricted to 238 ft.
Failure Mode: **1a**- Piping from embankment into foundation- **Alluvial** - RESERVOIR RANGE 230-240	
Event: ***Unprotected exit*** -does not have ability to block particle movement (exit that has large open volume to store and/ or pass embankment materials such that a piping initiated breach of the structure would not be prevented)	
Factors leading to higher probability	Factors leading to lower probability
Open work gravel seen in 2 test pits and 1 exposure	**Alluvium appears to meet filter criteria for zone 1 & 2 embankment (based on sampling 50+-tests)**
Sampling method used for **Alluvium appears to meet filter criteria for zone 1 & 2 embankment (based on sampling 50+-tests)** may not have gotten the fabric of the soils.	gravels are probably discontinuous with intervening finer grained materials
1 outlier of samples did not meet filter criteria.	Construction process (for emb) would have tended to mix some finer material into open gravels.
Original design probably did not account for filter criteria	**High gradient across thin us blanket (even cracked) therefore no piping**
	Zone 2 from alluvial source
	Discontinuity of material

Estimates:

Reasonable Low: _______________

Reasonable High: _______________

Distribution of estimates between reasonable low and reasonable high: _______________

Step 3. - Once a clear understanding of what the node of the event tree represents has been established (step 1), and all relevant issues by team members related to that node have been aired and summarized (step 2), then a probability estimate may be made for the node of interest.

The team should obtain "reasonable high" and "reasonable low" probability estimates. Elicit a "reasonable low" probability estimate by selecting a trial value and asking "Is it unlikely that the actual probability value is less than this value?" Elicit a "reasonable high" estimate by selecting a trial value and asking "Is it likely that the actual probability is less than this value.

Determine if the group feels that any given value within the established range should be more likely than any other. Stated another way, does the group feel that all values within the range are equally likely? If there is no single "most reasonable" or "popular value", then a uniform distribution should be used. If there are reasons to suspect one value is more likely, these reasons should be stated for the record and a triangular distribution should be used with the peak of the triangle placed at the value which would be expected to occur most often. Related discussions on establishing estimate distributions are provided in section V.B.

The team should be told how the distributions will be used in the Monte Carlo analysis. The expected value for the both the uniform distribution and the triangular distribution will be the mean value of all the random selections for each variable during the simulation. For the uniform distribution this should not be a problem. However, if the group believes that an erroneous mean value is to be used about which the random simulation should pick values equally distributed, then the group might reconsider if a triangular distribution should be used.

The mean of the triangular distribution is often not the same as the mode. During the simulation, values will be equally distributed about the mean. The mode will be the value randomly selected more often than any other during the simulation, but the 50th percentile will often be some other value. If many of the distributions for events in the event tree are skewed like this, it may result in the "most popular" estimate calculated for annualized life loss being off-center within the range estimated from the Monte Carlo simulation. This is not a technical problem, but it may be difficult to communicate the reasons to those not well versed in probability and statistics.

Verbal descriptors can be used for assigning response probabilities when there is not a basis (i.e. appropriate statistical information) for use of what can be termed the "known" failure frequency rate method. For example, under these circumstances the team members can use the subjective information that was generated during step 2 ("factors leading to a higher probability " versus "factors leading to a lower probability " exercise) to judge if the event tree node designated "unfiltered exits" is more likely or unlikely relative to the scale of verbal descriptors as shown in the following table:

VERBAL DESCRIPTORS

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Background information related to the development of relationships between verbal descriptors and probability estimates can be found in Appendix A.

In the example being used, the team members might assign a verbal descriptor of "very unlikely" (probability of 0.01) to the node described as "unfiltered exit" in step 1 above based on the available information:

> "93 of 95 gradation tests of as-constructed zone 3 earthfill materials generally met Reclamation filter criteria for the zone 2 earthfill material where seepage might exit"
>
> "Zone 3 earthfill materials are such that they are not likely to separate and segregate during placement"
>
> "As-built drawings indicate that zone 2 and zone 3 earthfill materials were placed to the lines and grades specified"

Estimates of response probabilities can sometimes be made on a more quantitative basis by comparing known historical or statistical databases that are relevant to the node for which a response probability is being estimated. An example of this method for estimating a response probability for a node described as "unfiltered exit" might be:

> "Reclamation has about 150 dams that have clay tile drains"
>
> "22 of these clay tile drain systems have been shown to have defects or crushed zones that compromise the integrity of the drain"
>
> "While none of these 22 compromised clay tile drain systems have lead to failure of a Reclamation structure, there have been 6 incidences where material was piped through the compromised portions of the clay tile drain system, i.e., Clark Canyon Dam"

Based on the outlined information, one could assign an estimated response probability of 0.04 (6/150) for an "unfiltered exit" related to Reclamation dams with clay tile drain systems. The statistical information presented here for drains and piping incidents is only hypothetical, but this type of information could be gathered in many cases to help make probability estimates. Any available statistical information of this nature should be presented in establishing the likely ranges for the probability estimate.

Another useful way to incorporate performance based probability assessments is to consider certain repeated events or multiple examples of an identical condition as repeated Bernoulli trials. If a random event has a probability of occurrence of p, the probability that this event will occur in n independent trials, p_n, is given by the following equation:

$$p_n = 1 - (1 - p)^n$$

An example would be a pair of fair dice thrown 10 times. The probability of getting two sixes each time the dice are thrown is 1/36. The probability of getting the two sixes at least once in 10 throws is $1 - (1 - 1/36)^{10}$, or about 25 percent.

It is appropriate to consider this equation in two situations where structural response probabilities are being estimated. One situation is where a potential initiating event takes place many times over the life of a dam, and each time the event occurs there is the same probability that this event will trigger some other event. In this situation, p is the probability that the initiating event will trigger some other event, and n is the number of times the initiating event has occurred. Another situation is where many dams have the same component, and if this component is present, there is a certain probability it will cause some other event or condition to happen. In this situation, n is the number of dams and p is the probability the condition will cause the other event to happen.

One way this can be used is to check the reasonableness of a probability estimate. Assume a given reservoir has reached elevation 5340 fifteen times in the last forty years, and that no soil materials have appeared in seepage collection weirs during that time period. Assume that when the team is considering piping, the team members estimate the probability is .3 that material movement would begin should the reservoir reach elevation 5340 in any given year. The above equation says it is nearly certain (a 99.53 percent chance) that material movement should begin if the reservoir rises above 5340 fifteen times. Since the reservoir has been above that elevation fifteen times and no material has been observed, the .3 probability estimate would seem unreasonable (unless other factors could be placed in the "factors leading to a higher probability" evidence column).

Step 4. - The risk analysis participants then identify the factors from step 2 that had the greatest effect on the probability estimate generated in step 3. Returning to the flip chart containing the factors pertinent to the event, the team should identify those items on the flip chart which were most important in arriving at the probability estimates. In addition, the team should indicate why it believes the most significant factors should receive more weight than others. This can include a discussion of what adverse situations actually exist versus what adverse situations only have the potential to occur. While this process may result in debate among the participants, this discussion can bring out additional information which was not previously available or readily understood. This information and discussion should be documented by the recorder.

Step 5. - The facilitator(s) should ensure the risk analysis participants have reached consensus on the probability and uncertainty estimates. **This does not mean that the facilitator(s) must force all members to accept a single estimate.** Rather, the facilitator(s) must sense the group's feeling as discussion takes place, suggest a reasonable starting place as a best estimate, and canvass the group's willingness to accept the estimate. The facilitator(s) may use words like "I'm sensing the group feels fairly neutral about this estimate, how about 0.5?" Or, "I sense there are more reasons to believe we are on the likely rather than the unlikely side of being neutral." If the discussion indicates the event is not very probable, the facilitator(s) could use the verbal descriptors by suggesting: "I sense the group feels this event is not very likely, should this be very unlikely or virtually impossible?"

If the group cannot agree on an estimate, the divergent opinions must be accounted for in the analysis. At this point, the facilitator(s) should focus more on getting agreement on the possible range and characteristic probability distribution for the estimate (see Section V). The facilitator(s) should lead the discussion between the protagonists of the opposing views and identify the underlying premises or key evidence supporting each argument. This is a very fruitful area to obtain ideas that would suggest further exploration or analysis to resolve the differences. The use of the software "Precision Tree" and "@Risk" makes it very easy to carry a range or different distributions through the risk analysis calculations, and to examine "what if" scenarios to determine how a given piece of information might affect the outcome.

If the group cannot agree that a range or distribution will adequately characterize their judgement, then the analysis can be conducted using each representative estimate in separate calculations. The separate calculations for risk would then be reported along with the descriptions of the conflicting ways the group members saw the problem.

Step 6. - Once consensus is reached on the specific response probability estimate and uncertainty, the process continues by repeating steps 1 through 5 for each remaining node of the event tree.

When steps 1 through 6 have been completed for all the event nodes, the risk analysis process continues by considering and quantifying what adverse consequences could occur, as described in the following section.

E. Estimating Consequences

Potential consequences resulting from an uncontrolled release of a reservoir have several different dimensions. In addition to the economic losses related to lost project benefits and potential damage to property in the inundated area, there is the potential for loss of life, alteration of the habitat and environment, social impacts on the local community, and loss of confidence in the dam owner and operators. Since these consequences are not directly commensurable, the weights given to each for decision making are generally made separately from the technical analysis. The process of weighing different values in decision making is called risk assessment, as opposed to risk analysis. However, certain technical data is required by the decision makers to understand the magnitudes of the various dimensions of the consequences. The following sections provide general considerations for estimating the potential magnitudes of uncontrolled outflows, the extent of the inundated area, and the resulting potential for loss of life and economic damages.

1. Dam breach parameters. - The breach parameters identified for each failure mode, especially the time for a breach to form, greatly affect the downstream flow rate from dam failure and the time available to warn the downstream population. Breach parameters assumed to develop inundation maps for Emergency Action Plans are generally conservative. During an Issue Evaluation risk analysis, it may be important to examine these assumptions. This is specially true if the reservoir storage is small and if a significant portion of the reservoir is released as the breach forms.

Breach formation parameters in embankment dams depend primarily on the amount of water in the reservoir, the hydraulic height, the methods of the dam's design and construction, and the type of failure. Empirical methods are used to determine the width, side slope angle, and the bottom elevation, and the breach development time [5,6,7,8,9]. Breach parameters can vary in a given dam depending on embankment height and foundation geology. The time for full breach development can depend on failure type. For example, a flow slide in an earthquake will result in immediate overtopping of severely disturbed embankment materials, whereas overtopping during a flood encounters intact materials. The breach development time can also vary according to the erosion resistance of the embankment materials and the degree of overtopping.

Breach development in concrete dams depends on the bedrock conditions (rock quality and jointing), the dam jointing and block size, and the type of dam. Breach development time for seismic loading might be sudden whereas the breach development time for hydrologic loading might take more time. In the case of gravity dams, individual blocks of the dam are capable of resisting reservoir loads without the support of adjacent blocks, which provides for the possibility of only a partial breach of a dam. However, arch dams depend upon the support of adjacent blocks to transfer loads to the foundation. If one block is removed, there is generally inadequate support for adjacent blocks.

2. Determining Inundated Areas. - A computer program, such as DAMBRK, is typically used to calculate peak outflows, flood routing parameters, and downstream inundation. Inundation maps contained in the SOP can generally be used as a conservative estimate for most risk analyses. Dambreak analyses for the SOP have traditionally been conducted assuming PMF level flooding. If life loss situations from lesser flooding, or from sunny day failure modes are found to be significant contributors to risk, there may be justification to recommend additional dambreak analyses. In areas where river confluence effects are significant, or where several stream courses inundate a given area, a two-dimensional program such as UNET can be used. More detailed guidance regarding flood inundation studies can be found in *Policy and Procedures for Dam Safety Decision Making* (Section II).

3. Warning time. - The time before a warning is issued can be broken down into a detection period, a decision period, a notification period, and a implementation period. After an event that initiates dam failure, time can pass before operations personnel detect a potential problem at the dam. This is the detection period. The decision period comes after the situation is observed, when outside expertise and decision makers may be consulted, and a decision is made that the situation will lead to a dam failure. Once this decision is made, the notification period follows during which the proper emergency response authorities are contacted and convinced that an evacuation is appropriate. Once the proper authorities have been notified, the warning may take time to reach those who must evacuate.

The time between the initiation of a dam failure and the issuance of a notice to evacuate a population, added to the time it takes for the flood wave to travel to the population, is the warning time. An upper limit to warning time assumes someone is at the dam to notice the failure, that this someone can make the decision that the dam is failing and that people should evacuate, that authorities are available and can be contacted to initiate evacuation, and that there is an effective way to notify the population at risk. To the degree that any of the above warning time components are missing or do not function properly, warning time is reduced accordingly.

The components of warning time are dependent on physical as well as human factors. The physical factors may be functions of the event time (hour, weekday, season) and the conditions after the event (e.g. extent of damage to infrastructure, evacuation routes, or communications). The human factors include reluctance to issue an evacuation warning and degree of emergency preparedness.

Note that the empirical formulas correlating life loss to population at risk and warning time are based on many different warning scenarios. In most cases, warning actually came through unofficial channels. Someone notices higher than normal stream channel flows and the word starts to spread.

The risk analysis team should consider worst case and best case scenarios for each failure mode investigated to determine a representative range of warning times. The risk analysis team should consult with regional and/or area office staff familiar with the local state of emergency preparedness when discussing these scenarios.

4. Potential for loss of life. - Wayne Graham has provided a simplified procedure where much of the following is considered. If a more rigorous risk analysis is being performed, for each load case/failure mode for which loss of life is possible, the following procedure should be followed:

- Determine if there are seasonal changes to habitation or facility usage below the dam (or consider some other time period(s) that will reflect different uses of the flood plain). If there are significant differences in the number of people at risk from one time period to the next, assign probability estimates to the chance that the dam will fail within each time period by proportioning the number of days in these time periods to the number of days in a year.

- Estimate the probability that the dam failure will occur during daylight, during night when people are usually awake, during night when people are usually asleep.

- Estimate the number of people at risk. Sometimes the number of people at risk can vary significantly even after the seasonal and time of day determination has been made. For example, there may a campground that has 100 campers on Friday and Saturday nights and only 10 people the other 5 nights. In this case, the population at risk should be 100 with a probability of .29 and 10 people with a probability of .71. Select the number of categories to minimize the computational effort, yet still display the varying usage of the flood plain.

- Estimate potential for loss of life. Estimates of the potential loss of life are then based on the empirical data for lives lost in historic dam failures which has been gathered by Wayne Graham [10]. The best estimate for warning time, and the range of possible values for warning time should be carried through the analysis.

5. Evaluate economic losses. - ACER TM #7 [10] sets forth the procedures typically used by Reclamation to assess the risk for economic losses.

V. Documentation and Presentation

A. Event Tree Computations and Review

Risk is computed by finding the product of probabilities and consequences for each path in the event tree.

$$\mathit{Risk} = \left[\begin{array}{c}\mathit{Probability}\\ \mathit{of}\\ \mathit{Load}\end{array}\right] x \left[\begin{array}{c}\mathit{Probability}\\ \mathit{of\ \ Adverse}\\ \mathit{Response}\\ \mathit{Given}\\ \mathit{Load}\end{array}\right] x \quad \mathit{Consequences} \quad \mathit{Given} \quad \mathit{Response}$$

By summing the values from all paths, the total risk can be determined. It is usually assumed in these computations that the outcomes for each event are mutually exclusive (i.e. there is no chance of combinations of more than one outcome) such that the risk can be computed by summing the individual pathway risk values. While the events are not always mutually exclusive, their probabilities in a dam safety context are generally small and the resulting joint probabilities have little impact on the accuracy of the computations. When the summed failure probabilities (non-mutually exclusive) from an event exceed 0.3, the outcome probabilities should be adjusted as shown in the example below.

Spreadsheets and decision analysis software provide for rapid reduction of the vast quantity of numbers generated during a risk analysis. One such combination is Microsoft Excel with the Decision Suite addin programs from Palisade Corporation. The Precision Tree portion of the addin provides the graphics and computations associated with an event tree while allowing the individual input values to be entered either manually or based on computations from other cells in the spreadsheet. The consensus estimates of the reasonable low and reasonable high values by risk analysis participants should be used to record estimated distributions of parameters in the spreadsheet. While the spreadsheet offers great flexibility in structuring the computations, it also carries with it significant risk of errors in the equations if they are not carefully crafted and copied from one cell to another. Some checks that can be performed to help ensure accuracy include:

- Entry of the event tree and values during the meeting of the risk analysis participants using a projector so that the participants can observe the tree and spot any data entry or logic errors as the event tree is being developed.

- Summing the probabilities for each set of branches from a single node in the tree to ensure that the probabilities sum to 1.0.

- Checking equations for linkages to the proper cells when event tree values are computed from other data in the spreadsheet.

- Review of the computed risk and/or probability estimates by participants to ensure that these values reflect their common judgement.

While conducting the risk analysis, there are often changes that are made to the event tree. Tree branches with no reasonable probability of occurrence and non-failure paths are truncated from the tree. Additional failure modes or additional detail to existing modes are added to the tree. In some cases a failure mode may be identified which will clearly not impact decision making based on the unlikelihood a number of events occurring in sequence. In these cases, it is acceptable to simply document the reasons why the failure probability is negligible without making specific probability estimates. Prior to finalizing computations, the structure of the event tree should be reviewed to ensure that it is consistent with the team's interpretation of the potential risks posed by the dam.

The final check of the spreadsheet should be a review of the risk results by the team members to ensure that the results reflect the collective judgement of the participants. Following the team meeting, many team members will have an intuitive feel for the greatest risks to the dam. If the computed risks show differently, this is an indication that the estimates and equations along the subject path need to be reevaluated to ensure their accuracy. Whether the discrepancy is due to error or lack of understanding of an event/response, this is an important part of the team developing a consensus that the risk values portray a reasonable estimate of the risk at that dam.

Example

In some cases, an event can lead to multiple possible outcomes which each have a relatively high probability. Consider the case of a hypothetical concrete arch dam. Participants in a risk analysis have determined that the dam could potentially fail by three different means following the occurrence of a large earthquake. The identified potential responses of the dam to a large ground motion were as follows:

Outcome	Failure Probability
A) Structural Failure of the Arch Dam	0.7
B) Failure of a Foundation Block on the Abutment	0.5
C) Failure of the Thrust Block	0.5

These three potential outcomes are not mutually exclusive since any one or a combination of the three outcomes could occur. Therefore, the probabilities must be adjusted to ensure that the sum of the probabilities of all possible outcomes equals 1.0. It can be assumed that the probabilities are statistically independent since the occurrence of one failure mode would not impact the estimates for the probability of occurrence of the other failure modes.

Step 1: Compute the probability of no failure occurring

This is best done using the following diagram to visualize the relationships of the probabilities (see Figure 4).

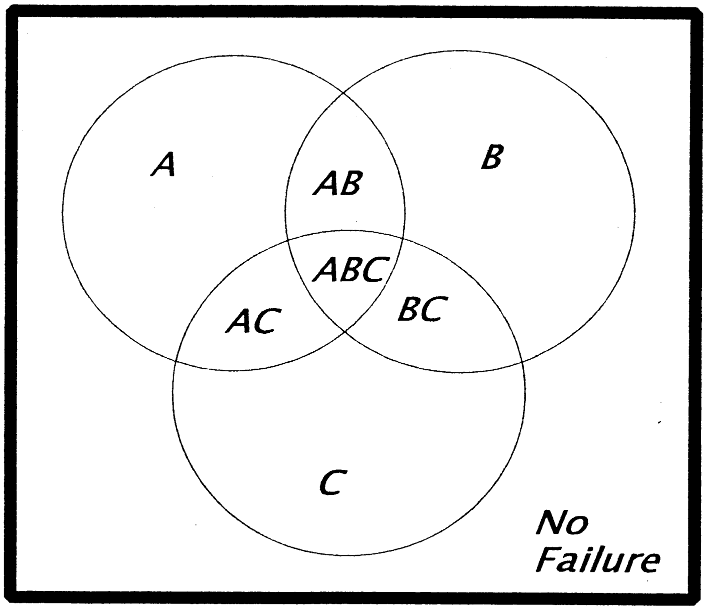


Figure 4

P[No Failure] (probability of no failure) = (1 - P[A]) x (1 - P[B]) x (1 - P[C])

= (1 - .7) x (1 - .5) x (1 - .5)

= (.3 x .5 x .5) = 0.075

Step 2. - Allocate a failure probability of (1- .075) = .925 among the failure modes.

The failure probability adjustment can be accomplished by normalizing the failure mode probabilities on the basis of the original estimates, or by allowing the team to estimate a new set of probabilities which sum to 0.925. Assuming that the original probabilities were estimated relative to one another, the normalizing procedure is preferable. Using the normalizing procedure, the adjusted probabilities for outcomes A, B, and C are:

P[A] = (.925/1.7) * .7 = 0.381
P[B] = (.925/1.7) * .5 = 0.272
P[C] = (.925/1.7) * .5 = 0.272

B. Uncertainty Analysis

When a value of risk or a probability of failure is computed, it is important to also characterize the uncertainty associated with those values. There are two characteristics of event tree input parameters which lead to uncertainty in the computed results.

The first characteristic is the natural variability of an input parameter as it occurs in nature. An example would be the reservoir water surface elevation behind a dam. While there may be a general pattern exhibited, there is a certain amount of variability due to variation in inflows and demands. This variability leads to uncertainty about the risk posed by a dam since a dam with a very low reservoir elevation has much less chance of uncontrolled release than a dam with a full reservoir.

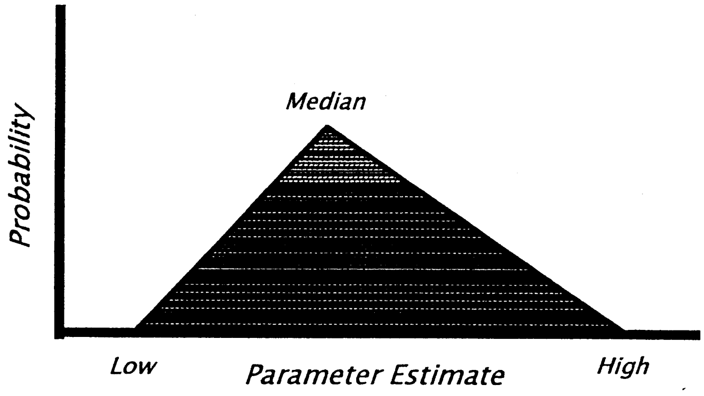
A second characteristic which leads to uncertainty in the results is a lack of knowledge about a particular process or mechanism represented by an input parameter. This type of uncertainty in the results acknowledges that the values of input parameters can be different from those estimated which would alter the results. This type of uncertainty can result from using idealized models to simulate complex processes, lack of understanding of natural processes, or the inability to obtain desired information.

Both types of uncertainty in the results should be evaluated simultaneously using a Monte Carlo Simulation process to combine the variations in and lack of knowledge about various input parameters. In a Monte Carlo process, the values of the input parameters are randomly generated based on each parameter's assigned distribution and the resulting risk and/or probability of failure is computed. When repeated many times, the results of the trials form a distribution for the expected values of the output (risk or probability of failure). It is recommended that the criterion for stopping the simulation be based on the output distribution statistics changing less than 1% in the last 100 iterations.

Input parameters can take on many types of distributions. When the team is estimating the event tree branch probabilities, they should also reach consensus on one of the following means of representing the input parameter:

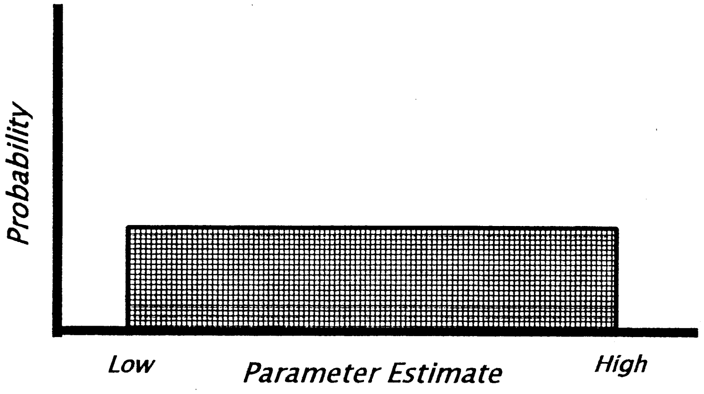
- Point Estimate - Point estimates are used when the probability estimates on the event trees are known, the team agrees that a single value is appropriate, or there is no reason to believe the estimates could vary significantly. Point estimates are also acceptable for preliminary risk analyses where the objective is to determine the relative magnitude of the risks.

- Triangular Distribution - A triangular distribution is used to represent a range of possible values in which the central values in the range are believed to have a greater chance of occurring or being the correct estimates. This distribution allows the effects of outlying estimates to be considered while placing primary emphasis on the consensus best estimate from the participants. The participants should develop consensus estimates of the reasonable low and reasonable high values which could be expected (see Step 3 in Section IV.D).



Triangular Distribution

- Uniform Distribution - A uniform distribution is used to represent a range of possible values in which all values are believed to have a equal chance of occurring or being the correct estimates. This distribution places placing primary emphasis on the extremes which define the range of possible estimates from the participants. The participants should develop consensus estimates of the reasonable low and reasonable high values which could be expected (see Step 3 in Section IV.D).



Uniform Distribution

While other distributions may appear justified for a particular parameter, the representations above provide a level of accuracy commensurate with the data generally available for performing the risk analysis. If the participants feel strongly that another distribution is justified, the purpose for its use should be documented.

The Monte Carlo analysis can be performed directly on event trees constructed with the Precision Tree software package using another component of the software called @RISK. Key steps of the Monte Carlo analysis include:

- Defining the output variables for which distributions are desired
- Defining the input variables to be estimated by distributions (distribution functions should already exist in those cells)
- Setting the simulation parameters to calculate expected values of the tree on each pass
- Setting the convergence criteria
- Running the simulation
- Graphing the results

At the conclusion of the risk analysis there will be a variety of numeric values related to the risk, P(load) x P(response) x (consequences), associated with the static, seismic and hydrologic loading conditions. A group of experts, led by the facilitator(s), then must reach a consensus on a portrayal of the risk associated with the various loading conditions considering any and all available information.

C. Report Preparation

Documentation of a risk analysis serves two principal purposes. One purpose is to provide a record of the risk analysis thought processes, assumptions, and estimates which influenced the outcome of the risk analysis, and what information would be of use to future investigations of the safety of the dam. Another purpose is to provide decision makers with sufficient information to allow them to incorporate risk based information into the decision making process for deciding whether or not to take action and what action to take. The objective of the documentation is to meet these goals with a reasonable level of effort.

To accomplish the above purposes, this section provides a suggested general framework for the documentation. The format is provided simply as a guideline to help the team identify information which would be appropriate to include. Each risk analysis will likely have its own unique circumstances which must be documented, therefore the emphasis in this section is on a general arrangement of information for the benefit of decision makers and future investigators. Documentation for both baseline and risk reduction type risk analyses will generally follow the format outlined below in the "Suggested Topics for a Risk Analysis Report."

One of the most important areas to document is that of the assumptions and/or exclusions made during the various stages of the risk analysis. The decision by members of the team to assume various values or to exclude some conditions can significantly alter the reported risk. This information should be identified for decision makers to ensure there is a common understanding of the risk analysis results.

1. Suggested Topics for a Risk Analysis Report - While the conditions and the associated risks at each dam are unique, there are similarities in the information needs of the decision makers. The following topics should be considered for inclusion into the documentation of a risk analysis:

- Participants - This section should identify the personnel who participated in the risk analysis and identify the roles that they filled.

- Scope - This section should include a summary of the purpose of the risk analysis, what are the problems and issues being addressed, and the depth of analysis performed to support the estimates and judgements made in the process. If any unusual processes were employed, they should be described here.

- Description of Facilities - This section should contain a brief description of the dam and its appurtenant structures to familiarize the reader with the facilities for which the risk is being analyzed. If the risk analysis is for the purpose of evaluating risk reduction alternatives, a brief description of each alternative should also be provided.

- Failure Modes - This section should summarize the ways in which the dam could reasonably be expected to fail. Each failure mode should described in sufficient detail to demonstrate how the failure mode would develop starting from the initiating conditions or event and leading to the uncontrolled release of the reservoir.

- Descriptions of Loads and Responses - This section should describe the static, hydrologic, and seismic loading conditions to which the dam is subjected. The information provided should include:
  - load ranges selected and the reasoning for selecting those ranges
  - probabilities of the selected load ranges (or a reference to their origin)
  - responses to the loading conditions
  - key factors at the dam which lead to increased or decreased estimates of the failure probability of the dam
  - estimated consequences if the failure mode were to occur (include information on population at risk, breach parameters, and warning time estimates)
  - uncertainties associated with the failure mode or the data used for making the probability estimates

- Summary/Conclusions/Recommendations - This section should include a summary of the key findings and essential information generated from the risk analysis process and address the following questions:

  Which failure modes and loading conditions contribute the greatest risk?
  What uncertainties enter into the estimates of risk?
  What information could be generated to reduce the uncertainty?
  What outcomes could reasonably be expected to result from collecting the information?
  How would the risk be affected by each of these outcomes?
  What are reasonable options for future action and what will they cost?

These questions will help to focus the team on credible information which will assist decision makers in determining future actions to be taken.

The final documentation should present results and reasonable options for action for consideration by the decision makers. Decisions of future actions to be taken are more appropriately documented in separate documents prepared by or on the behalf of the decision makers.

Note: - In some cases, it will become apparent that there are some low cost actions which could make immediate reductions in risk at the dam. Examples may include simple changes in operating procedures or maintenance practices which result in more reliable operations. Risk can also be reduced by exercising the emergency action plan or by helping operations personnel to understand the importance of the visual monitoring parameters in the performance parameters technical memorandum. Any such opportunities for low cost risk reduction should be brought to the attention of the decision makers promptly.

- Appendices - The attachments to the report of findings should include the following items:

  - A list of reference materials used for the risk analysis
  - Copies of the event trees developed
  - Copies of the flip chart information documenting the important factors in making the probability estimates
  - Any other information needed to convey an understanding of how the estimated risks were developed

2. **Authorship** - The team leader, or another person(s), designated prior to beginning the risk analysis and with Group Managers assistance, will be responsible for writing risk analysis reports. The facilitators can assist with identification of an appropriate author(s). The responsible author will request any necessary help (from within or outside the Team) to ensure that information is adequately recorded for future reference. Facilitators will work with the team during the risk analysis to capture as much of the information as possible in event trees, logic diagrams, "pros" and "cons" of estimate sheets, etc. Facilitators will also assist in identifying critical information that should be recorded for incorporation into the report.

3. **Checking** - The process for checking event tree inputs and outputs, tables and figures should be in place prior to beginning the risk analysis. Facilitators can assist the team leader in outlining this process and identifying resources (with Group Manager help). Checking should include verifying that all probability estimates, and their distributions, were entered correctly. Accuracy of tables and figures should be verified. In addition, construction of the event trees in the spreadsheets should be checked. The latter may be completed by different persons, since a limited number of people have experience with the software currently used.

4. **Facilitators and Certification** - Review and certification of the risk analysis will be performed by the facilitators. Facilitators will be involved in the report preparation until the product has been certified as final, but facilitators will not write the report. In most cases these reviews and certification will be in lieu of a review by Group Managers. In addition, the facilitators will work with the team, Group Managers and the Dam Safety Office to identify contentious or specific issues that may require special consideration before proceeding with risk analysis.

5. **Signatures (and what they mean)** -

- **Author's Signature** - This is the signature of the person or persons with primary responsibility for writing the risk analysis report. All team signatures, such as concurrence, are not required. However, signature of the document by the author(s) does signify that a draft document was provided to team members, and that they had an opportunity to comment on the draft. The author(s) signature also implies that comments were considered and that any critical issues or influencing factors were incorporated into the document.

- **Certification Signature** - Certification signatures will be those of the persons who co-facilitated the risk analysis. These signatures will signify that Reclamation methodology, processes, and requirements were followed. In addition, these signatures verify that qualifications of the persons making various probability estimates were appropriate. The purpose of endorsing qualifications is to reduce the potential for inappropriate estimates, or conflicts, arising from limited qualifications that result in total rejection of risk analysis findings during organizational reviews (such as DSAT). Certification signatures will also signify that the spirit of the risk analysis and team dynamics are represented by the document. In other words, that any divergent views, critical issues, or significant influencing factors have been captured. This is a check of the author's responsibility to fully capture and represent the team's thinking. Finally, certification will serve to document that load specialists input and feedback were solicited.

- **Checked Signature** - Checking signatures will verify that all probability estimates, inputs and outputs and their distributions, were entered correctly into event trees, and that any other calculations, figures or tables have been checked. This may include "back-of-the-envelope" calculations performed during the risk analysis but not documented other than in the report. In addition, the accuracy of computer spreadsheets should be checked. These checks are likely to be made by different persons thus requiring two signatures, since a limited number of people have experience with the software currently used.

6. Distribution of Draft and Final Decision Memos - Since concurrence signatures from team members are not required on TRA reports, draft and final decision memos should be provided to team members as they become available. This is done out of courtesy, to ensure that folks know how the input they provided was ultimately used by Reclamation, and to ensure that all team members are cognizant of project issues and decisions.

7. Project (Overall) Peer Reviewer Participation - Group Managers and Senior Technical Specialists (or any one qualified with substantial corporate knowledge) may want to schedule time to participate on key risk analyses, perhaps on those where the "stakes" are particularly high or where there is significant controversy/divergent views. This would help ensure that all pertinent information is brought to the table and considered. Involving senior staff in this manner, on an as needed basis, would assist facilitators and teams in ensuring a proper scope for the risk analyses.

The signature and certification process above does not imply that the individuals signing these documents are validating the numerical values produced during the team risk analysis. Nor does the signature process indicate TSC concurrence. Signing individuals are not shouldering the burden of making decisions for the TSC or Reclamation. The risk analysis document is only one part of many inputs that are required to make decisions related to dam safety. TSC organizational peer review will still occur as various projects proceed through appropriate milestones in the dam safety process. In addition, the forum of Dam Safety Advisory Team (DSAT) can be used by the Dam Safety Office to provide any critical feedback on the risk analysis. Decisions on dam safety issues will continue to be made by the Dam Safety Office, Region, and Area Office personnel.

References

[1] Public Law 95-578, The Reclamation Safety of Dams Act, November 2, 1978 (as amended by Public Law 98-404).

[2] "Policy and Procedures for Dam Safety Modification Decisionmaking", U.S. Bureau of Reclamation document, April 1989 (Interim Guidelines)

[3] "Guidelines for Achieving Public Protection in Dam Safety Decision Making", U.S. Bureau of Reclamation document, January 8, 1997 (Interim Guidelines)

[4] Reclamation Manual / Policy FAC P02, February 17, 1998

[5] MacDonald, T.C. and Langridge-Monopolis, J., "Breaching Characteristics of Dam Failures", ASCE Journal of Hydraulic Engineering, Volume 110, No. 5, May, 1984.

[6] Von Thun, J. L., and Gillette, D. G., "Guidance on Breach Parameters", unpublished internal memorandum, U. S. Bureau of Reclamation, Denver Technical Center, March, 1990.

[7] Wahl, T. L., "Prediction of Embankment Dam Breach Parameters: Literature Review and Needs Assessment (draft)", U. S. Bureau of Reclamation, Water Resources Research Laboratory, PAP-735, Denver, Colorado, 1996

[8] Susilo, K. J., Mineart, P. R., and MacDonald, T. C., "Does Selection of Published Dam Breach Parameters Ensure Reasonable Results?", Proceedings ASDSO Western Regional Conference, Oklahoma City, OK, May, 1997.

[9] Susilo, K. J., Mineart, P. R., and MacDonald, T. C., "Considerations When Selecting Parameters for Dam Breach Analyses", Proceedings ASDSO Annual Conference, Pittsburgh, Pennsylvania, September, 1997.

[10] U.S. Bureau of Reclamation, "Guidelines to Decision Analysis", ACER Technical Memorandum No. 7, Denver, Colorado, 1986.

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Beijing, 2000

ENGINEERING APPLICATION OF DAM SAFETY RISK ANALYSIS(*)

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1. INTRODUCTION

Formal procedures for probabilistic risk assessment are of growing interest and application in dam safety practice. When used in conjunction with risk-based safety criteria, these methods provide a valuable decisionmaking tool for evaluating the safety status of a particular dam and determining if safety modifications are warranted. Additional benefits derive from improving the understanding of dam behavior, targeting investigations and analyses to the primary risk contributors, and evaluating the effectiveness of various potential modification measures according to the risk reduction they produce [1].

Criteria for determining risk acceptability are central to these decisionmaking applications, and several such criteria have been proposed. However, for various reasons some damowners may be reluctant to adopt them. These can include a general aversion to designating risk to life in any degree as "acceptable;" the programmatic departure of risk-based standards from traditional dam safety criteria; or the limited precedent for risk acceptance criteria in industry and regulatory practice. For some, the issues associated with acceptable risk criteria can be seen as an impediment to the use of risk assessment in dam safety decisionmaking, and therefore by extension to the application of risk analysis in any fashion at all.

(*) *Applications de l'analyse de risque dans le domaine de la sécurité des barrages*

This need not be the case. Risk analysis remains a powerful engineering methodology in itself, regardless of whether risk-based decision criteria are adopted or not. Termed here "diagnostic" to distinguish them from decisionmaking applications, these engineering uses of risk analysis do not seek to determine whether risk meets some fixed standard, but rather to improve understanding of dam behavior by identifying and prioritizing the various elements that produce the risk. Seen in this context, risk analysis becomes an engineering tool like any other, but one with a unique ability to guide and direct other dam safety investigations to risk contributors that are most significant. By doing so, diagnostic risk analysis can make a substantial contribution to improving the safety of the dam.

As a stand-alone application, diagnostic risk analysis avoids perceived difficulties with acceptable risk criteria by truncating the risk assessment process short of a formalized determination of risk acceptability. It thereby produces a measure of the safety of the dam, but without determining its safety status on an absolute basis according to rigid risk standards that require a strictly binary ("safe" or "unsafe") outcome.

Sensibly conducted and interpreted, almost any risk analysis performed for decisionmaking purposes will incorporate the elements of a diagnostic assessment as well. However, viewing the fundamental role of risk analysis as an engineering technique for improving insight into dam behavior helps avoid undue emphasis on calculated risk results and the unwarranted perception of their precision that can come about when decisionmaking is seen as the sole purpose of the exercise and the calculated result as an end in itself [2].

2. COMPARISON TO CONVENTIONAL APPROACHES

Conventional dam safety assessments adopt deterministic (non-probabilistic) methods and criteria for evaluating potential dam safety deficiencies individually. For seismic and hydrologic loading, predicted response is evaluated under extreme event criteria such as Probable Maximum Flood (PMF) or Maximum Credible Earthquake (MCE) conditions, and if the dam meets these criteria it is ordinarily presumed to be safe under lesser loadings as well. For static conditions, minimum factor of safety criteria apply in a similar way to matters such as sliding of concrete dams, while some important static failure modes such as internal erosion are evaluated largely on the basis of engineering judgment alone.

While these procedures may be adequate for identifying most dam safety deficiencies, they have several shortcomings. First, they do not allow the relative severity of deficiencies to be compared. They provide no means, for example, of assessing whether a spillway that passes only 80% of the PMF would be a more serious situation than foundation materials that could withstand only 50% of MCE ground motions, nor whether remediating one deficiency would produce greater safety improvement than the other. Second, some potential problems are unique to the conditions of a particular dam, and do not fall neatly into the categories of loading or types of dam safety analyses customarily performed. Flood-induced reservoir levels, for example, can affect static failure modes like piping, and seismic shaking can affect internal erosion processes. These interactive influences can be easy to overlook. Thirdly, there is a tendency for the severity of a particular deficiency to be judged in relation to the analytical effort devoted to evaluating it. This can place disproportionate emphasis on conditions amenable to complex analysis procedures, at the expense of those for which quantitative analysis techniques are more limited or may not exist at all.

Diagnostic risk analysis addresses these limitations using risk as the common denominator for identifying and comparing all of the processes and levels of loading that could cause the dam to fail. Emphasis on failure processes rather than analytical techniques themselves promotes more balanced attention to all potential risk contributors and better assures that none is overlooked. Those potential failure modes that produce the largest contributions to overall risk are identified, allowing further dam safety analysis, investigation, and monitoring efforts to be targeted to these areas. This enhances the efficiency of these efforts by directing resources to the aspects of greatest importance, and it provides an overall "roadmap" for planning and conducting subsequent dam safety investigations.

The diagnostic risk analysis process itself often reveals potential risk reduction measures that might not otherwise be apparent, and their effectiveness can be judged according to the degree of risk reduction they produce. Evaluating these measures in terms of their cost per increment of risk reduction can highlight the benefit of simple but efficient risk-reduction measures, such as enhanced monitoring or improved operational procedures, in many situations.

Diagnostic risk analysis can be particularly useful for evaluating dams with complex conditions, unusual features, or multiple dam safety deficiencies whose relative influence would otherwise be difficult to establish. As a supplement to conventional dam safety assessment procedures, its unique capabilities as an engineering tool provide an added dimension for understanding and evaluating dam behavior.

3. QUANTITATIVE METHODS

3.1 CONSEQUENCE CONSIDERATIONS

Risk is customarily defined in dam safety as the product of failure probability and failure consequences expressed as loss of life. For any given loading condition (hydrologic, static, or seismic), it is often the case that failure consequences for a particular dam are largely independent of the specific failure mode. For example, the consequences of seismic failure of an embankment dam by foundation liquefaction, crest deformation, or some other seismic failure mode may not be fundamentally different. This may allow failure probability alone to be used as a surrogate for risk, for purposes of failure mode comparison in diagnostic applications. Similarly, failure consequences for different loading conditions may be sufficiently comparable, particularly where loss of life is relatively insensitive to warning time, to allow comparison of failure modes for different loading conditions according to their respective probabilities. As a first approximation, assuming invariant consequences for a particular dam can simplify the diagnostic analysis by eliminating the need to evaluate and incorporate loss of life considerations. This simplifying assumption is adopted in the following discussions, where relative differences in failure probability correspond to differences in risk.

3.2 PROCEDURES

Diagnostic risk analysis uses the same procedures as decisionmaking applications for determining failure probability under various loading conditions and failure modes. These are described more fully elsewhere [3] and are briefly summarized here.

The first stage of the process uses failure mode screening to identify all of the mechanisms and conditions with the potential to cause failure. This is accompanied by compilation and review of information about the dam, including construction records, instrumentation data, analyses performed in conjunction with any previous dam safety assessments, and related field performance case history information.

The potential failure modes that result from the screening process are then developed in event tree format, incorporating the full range of possible values for extreme-event initiators. Each failure mode is decomposed into component events that together describe the occurrences and conditions necessary for the failure sequence to take place.

Probabilities are assigned to each component event then mathematically aggregated to derive conditional probabilities for the various failure modes and initiator loading levels, as well as the total probability of failure from all such conditions. Since there are typically few component events whose probabilities can be adequately derived from statistical sampling or repeated trials, most adopt a subjective, degree-of-belief approach that expresses likelihood of occurrence as quantified engineering judgment. Under this interpretation, the probability of failure becomes a measure of the perceived degree of safety of the dam according to the state of knowledge about it, incorporating all information available at the time it is derived. As such, failure probability changes in response to new information as it is generated throughout the dam safety assessment process [4].

All of these procedural elements are conducted in a group setting with the participation of not only specialists in applicable technical disciplines, but also those familiar with the performance and instrumentation history of the dam and its operation. The group interactions and interdisciplinary interchange that occur are an essential part of any diagnostic risk analysis, and enhanced understanding of dam behavior is brought about at least as much by these aspects of the process as by its numerical results.

The process is also iterative. The initial effort using available information usually points to additional analyses, investigations, or other data needed for refining key aspects. After this new information has been gathered, additional iterations of the risk analysis are performed to incorporate it, modifying probability estimates accordingly. As these evaluations proceed potential risk-reduction measures also become apparent, and revised failure mode probabilities that reflect their effectiveness can be compared to base-case values for existing conditions.

In this way, the diagnostic risk analysis becomes an integral part of the dam safety assessment process itself. Carefully documented, it can be incorporated into periodic dam safety reviews and updated to account for changes in the condition of the dam, its performance, understanding of loading conditions, or other factors that may vary over time, so that it becomes a “living document” [5].

3.3 EXAMPLES

Quantitative methods for diagnostic risk analysis are best illustrated by examples that show the kinds of outcomes it produces. The literature contains a number of such examples, and three are selected here with reference to seismic, hydrologic, and static loading conditions.

3.3.1 *Seismic risk*

Terzaghi Dam is a 60 m high earth and rockfill structure in western Canada with an intricate and complex arrangement of internal zoning and foundation cutoff features. Terzaghi and Lacroix [6] recount the epic challenges that were confronted during its design and construction, and the dam has since performed successfully. The nature of the filters and transitions is such that sinkholes periodically form in the upstream clay core, as anticipated and understood by the original designers, and these are repaired when the reservoir is drawn down for routine maintenance.

Initial seismic analyses performed under MCE ground motions of 0.15g (peak horizontal ground acceleration) had focused on the potential for liquefaction of cohesionless foundation soils beneath the upstream and downstream shells of the dam. Liquefaction considerations assumed even greater importance when new seismotectonic studies increased MCE ground motions to 0.26g, and a first-iteration risk analysis was performed to better evaluate the effects of this change [3]. Failure mode screening identified potential failure modes related to these liquefaction conditions, as well as shearing or deformation of weak cohesive foundation materials, and seismically-induced landslides into the reservoir. An additional failure mode designated "vibration" was identified to address the potential for inertial forces to reactivate internal erosion during seismic shaking.

Table 1 shows these failure modes and their relation to various probabilities derived in the analysis. The first column shows the three ranges of peak ground acceleration (PGA) denoted a_i that together encompass all possible values that could occur. The second column shows the annual occurrence or exceedance probabilities for each range from site-specific seismic hazard studies performed for the analysis. The third column lists the failure modes (m_i) described above, and the fourth column provides the conditional probability for each failure mode given a_i denoted as $p[m_i|a_i]$. Most of these probabilities increase to varying degrees at greater PGA levels except for landslide triggering which is primarily a function of earthquake magnitude [7]. Magnitude contributions to the various PGA levels were indicated by the seismic hazard studies to be approximately equal for the damsite.

The individual conditional probabilities are summed over all failure modes assuming probabilistic independence, to yield $p[f|a_i]$ in the fifth column, which expresses the conditional probability of failure given the PGA range. The final column of the table provides the joint probability of failure for each PGA, and these values are summed to find the total seismic failure probability.

TABLE 1
TERZAGHI DAM SEISMIC FAILURE PROBABILITIES

PGA, a_i	$p[a_i]$	failure mode m_i	$p[m_i \mid a_i]$	$p[f \mid a_i]$	$p[a_i]p[f \mid a_i]$
a_1: <0.10g	0.0015	m_1: DS liquefaction m_2: US liquefaction m_3: fdn. shearing m_4: reservoir slide m_5: vibration	0.000055 0.00028 0.0035 0.002 0.14	0.15	0.00023
a_2: 0.10- 0.25g	0.0001	m_1: DS liquefaction m_2: US liquefaction m_3: fdn. shearing m_4: reservoir slide m_5: vibration	0.0006 0.0348 0.04 0.002 0.35	0.43	0.00004
a_3: >0.25g	0.00002	m_1: DS liquefaction m_2: US liquefaction m_3: fdn. shearing m_4: reservoir slide m_5: vibration	0.012 0.327 0.159 0.002 0.352	0.85	0.00002
total p_f for all a_i and m_i					$\sum$=0.00029/yr =3x10^{-4}/yr

Table 1 provides several key insights into seismic behavior of the dam. First, despite the increase in MCE ground motion estimates, their contribution to seismic failure probability (PGA range a_3) represents less than 10% of the total. Instead, the largest contributor producing almost 80% of the total comes from a_1 category motions less than 0.10g, whose average recurrence interval (the inverse of their 0.0015 exceedance probability) is only about 670 years. Closer inspection of the conditional failure mode probabilities for a_1 ground motions shows that the largest such probability ($p[m_5 \mid a_1]=0.14$) is for failure mode m_5 representing inertially-induced reactivation of internal erosion, rather than either of the foundation liquefaction failure modes that had originally received greatest attention. The risk analysis in this case therefore identified a particular failure mode unique to Terzaghi Dam, and it indicated vulnerability to seismic failure to be derived principally from ground motions much less than the MCE. Since this was a first-iteration analysis, subsequent studies were directed toward further investigating the effects of seismic shaking on reactivation of particle transport.

3.3.2 *Hydrologic risk*

Dravladalsvatn Dam is a 29-metre-high moraine-core rockfill dam. Located in a remote region of western Norway at the foot of the Folgefonni glacial icefield, the damsite experiences some 2500 mm annual precipitation mostly as snowfall. The dam incorporates a spillway tunnel and bathtub-type intake channel, a low-level outlet tunnel from construction diversion works, and a headrace tunnel. These facilities satisfy Norwegian requirements that the spillway and outlet tunnels together pass the 1000-year recurrence inflow flood, with PMF inflows accommodated by reservoir surcharge.

Details of the hydrologic risk analysis conducted for Dravladalsvatn Dam are described by Johansen and Rikartsen [8]. Failure mode screening identified the potential for blockage of the spillway intake channel by compaction and transformation of deep, drifted snow accumulations into ice. Although this process has not affected the dam to date, it has been observed at other locations. Resulting uncertainties regarding the extent of ice formation, its bonding to rock surfaces, and its erosional resistance under spillway flows caused this to be a primary contributor to hydrologic failure probability for flood recurrence intervals as low as 10 to 100 years under certain inflow conditions.

The outcome of the analysis identified the need for additional research into these mechanisms of ice formation and erosion. It also suggested potential dam safety improvements for hydrologic and other loading conditions that included measures for remote detection of incipient overtopping or related conditions, improved access and operability of outlet gates, as well as armoring of the downstream rockfill toe with large rock fragments to enhance overtopping resistance. By contrast, the susceptibility of the dam to terrorist acts, which under Norwegian regulations would require costly structural modifications, was indicated to be a comparatively small risk contributor.

3.3.3 *Static (internal erosion) risk*

Viddalsvatn Dam is an 80-metre-high moraine-core rockfill dam also in western Norway. As first described by Vestad [9], the dam has experienced several incidents of briefly increased seepage (termed "leakages"), some accompanied by turbid conditions and sinkhole formation on the dam crest. These incidents result from internal erosion, and their transient nature to date is attributed to the self-healing nature of the broadly-graded dam core materials. Due to several such occurrences the dam has experienced, seepage is closely monitored.

Johansen, et. al. [10] describe the results of internal erosion risk analyses for Viddalsvatn Dam and two other dams of its class that provide a relative basis for comparison. The results showed that internal erosion failure probability is mitigated to varying degrees in all cases by the high resistance of the rockfill to large seepage discharges at the downstream toe [11], and by the capability for rapid reservoir drawdown that their comparatively large outlet works discharge capacities provide. For Viddalsvatn Dam, the risk analysis quantified these factors, showing them to be equal contributors to its internal erosion failure resistance. The internal erosion failure probability was higher than that for the related dams, but not as much so as its performance history might otherwise suggest largely because of the monitoring provisions it incorporates. The risk analysis also identified placement of large-sized rockfill at the dam toe as a means for increasing its ability to accommodate large seepage discharges, with a corresponding potential for reducing internal erosion failure probability by as much as a factor of 10.

3.3.4 *Discussion*

The examples described above illustrate how diagnostic risk analysis uses relative failure probabilities for various failure modes and loading ranges to determine the significance of various risk contributors. The structure of Table 1 has been found to be a useful presentation format that can be generalized to other cases for characterizing these contributions. The Terzaghi Dam and Dravladalsvatn Dam examples illustrate another common finding: that the greatest risks can derive from extreme events far smaller than the MCE or PMF, simply because they occur much more frequently. Diagnostic risk analysis places a more proportionate emphasis on potential deficiencies that can occur within or just beyond the loadings imposed during normal operation, highlighting failure modes related to such mechanisms as internal erosion, spillway debris plugging, or spillway erosion. As the Viddalsvatn Dam example shows, the beneficial effects of specific features of the dam, its operating characteristics, and monitoring provisions can also be incorporated and quantified.

The examples also illustrate how diagnostic risk analysis can better identify failure modes or related conditions that are unique to a particular structure or its setting. Some of these, like the seismic influence on internal erosion for Terzaghi Dam, result from combined effects that might otherwise be difficult to strictly classify within the categories of conventional dam safety analyses. Because risk analysis is governed by failure processes rather than prescriptive analysis, these kinds of issues and their significance are more readily recognized.

Additionally, the examples demonstrate how the diagnostic risk analysis process is used to guide other dam safety investigations by directing additional information or studies to those factors that produce the greatest risk. An important outcome of these cases is to identify similarly directed dam safety improvements, and it is not unusual to find that such measures can reduce risk more effectively or efficiently than measures for accommodating larger extreme events.

4.0 CONCLUSIONS

The process of diagnostic risk analysis aids engineering assessments of dam safety by revealing the potential vulnerabilities unique to a particular dam and the conditions or features that produce them. At the same time, it extends conventional deterministic dam safety practices by quantifying the relative significance of various failure processes, allowing them to be compared. This guides and directs the conduct of dam safety investigations and points to those potential dam safety improvements with greatest effectiveness. The iterative nature of the process also lends itself to the sequential stages of information gathering and analysis that accompany any dam safety evaluation. In these respects, diagnostic applications can be viewed as an adjunct to conventional dam safety practices and programs that enhance their effectiveness and thereby ultimately improve the safety of the dam.

As a stand-alone engineering tool, diagnostic risk analysis achieves many of the benefits of decisionmaking risk analysis applications, but without invoking the formalized risk acceptance criteria they require. Even without formal criteria, the need for risk reduction for some dams can be sufficiently evident to support more broadly-based decisions for implementing the kind of specifically-targeted measures that these applications can identify.

In this context, diagnostic methods occupy a position intermediate between conventional deterministic procedures and formalized decisionmaking approaches in the spectrum of risk analysis application. This may best suit the needs and preferences of some damowners. For others, diagnostic applications can be readily extended to formal decisionmaking risk assessments by invoking risk acceptance criteria in relation to loss of life. In either case, the elements of the risk analysis process described here can offer understanding and insight into engineering aspects of dam behavior not possible to achieve in any other way.

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GOVERNMENT OWNER INFORMATION NEEDS

RISKS ASSOCIATED WITH ALL DAMS OWNED

RISKS THAT SHOULD BE REDUCED

RISKS THAT SHOULD BE REDUCED IN THE SHORT-TERM

RISK MANAGEMENT OPTIONS THAT MAKE MOST EFFECTIVE USE OF AVAILABLE RESOURCES IN THE RISK IDENTIFICATION AND RISK REDUCTION PROCESSES

CREDIBILITY IN ALL OF THE ABOVE

UNCERTAINTIES ASSOCIATED WITH ALL OF THE ABOVE

LEGAL AND POLITICAL CONSTRAINTS THAT MAY AFFECT THE IMPLEMENTATION OF RISK MANAGEMENT ACTIONS

ASDSO/FEMA Specialty Workshop on
Risk Assessment for Dams

Session 1.0 - Introduction:

Information Needs for Dam Safety Evaluation and Management:

Large Private Owners

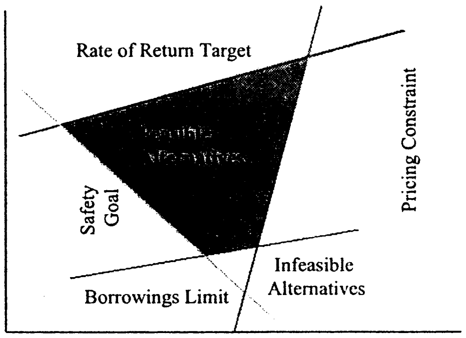
March 7, 2000

David S. Bowles
Utah State University and RAC Engineers & Economists

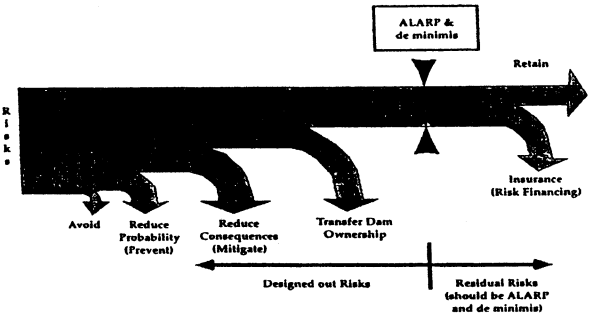
Regulatory Environment

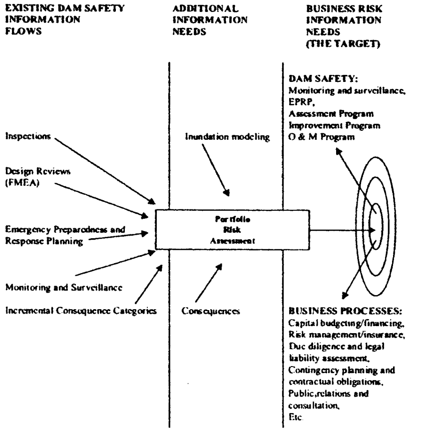
- Hard – FERC, CA
  - Regulatory requirements may completely determine dam safety program and fixes
- Soft – UT, Victoria
  - Less influence of regulatory requirements
  - Greater flexibility in rate and extent of fixes
  - BUT what are the drivers?
- None – USBR, Corps, Tasmania
  - No regulatory requirements
  - AGAIN, what are the drivers?

Commercial Context for Dam Safety Decisions



Risk Treatment Options





EXISTING DAM SAFETY INFORMATION FLOWS

- Inspections
- Design Reviews (FMEA)
- Emergency Preparedness and Response Planning
- Monitoring and Surveillance
- Incremental Consequence Categories

ADDITIONAL INFORMATION NEEDS

- Inundation modeling
- Consequences

Portfolio Risk Assessment

BUSINESS RISK INFORMATION NEEDS (THE TARGET)

DAM SAFETY:
Monitoring and surveillance,
EPRP,
Assessment Program
Improvement Program
O & M Program

BUSINESS PROCESSES:
Capital budgeting/financing,
Risk management/insurance,
Due diligence and legal liability assessment,
Contingency planning and contractual obligations,
Public,relations and consultation,
Etc.

Investment drivers – Information Needs

- Regulatory Considerations
  - Breaches of regulations, legal requirements and licenses
- Public Safety
  - Engineering Standards/Guidelines and Current Practice - Benchmarking
  - Risk-based guidelines - Benchmarking
  - ALARP principle
  - Extent of potential life loss
- Legal Liability
  - Duty of care, due diligence
  - "Reasonable person" – benchmarking (timing and extent)
  - Negligence of owner
  - Engineer's liability position

Investment Drivers – Information Needs (continued)

- Retention of Insurance Cover
- Business Viability/Financial
  - Third party liability and cost of law suits
  - Organizational breakup, public enquiries, restrictive legislation
  - Effects on key business results areas
    - Loss of revenue generation
    - Competitive position, dividends
    - Opportunities forgone/postponed
- Public Trust and Reputation
  - Customers - Extent of adverse impact on internal and external customers
  - External Perceptions - Extent of adverse community or political response on owner
  - Public consultation

Investment Drivers – Information Needs (continued)

- Additional Factors:
  - Cost effectiveness of fix(es)/staging
  - Priority relative to other dams/assets
  - Opportunity for increased capacity
  - Effects of delays/staging
  - Non-structural options

THE PERSPECTIVE OF THE SMALL DAM OWNER

ASDSO/FEMA Specialty Workshop
On
Risk Assessment for Dams

Logan, Utah
March 7-9, 2000

James L. Doane PE
Principal Engineer
Bureau of Water Works
Portland, Oregon
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Jim Doane PE

DAMS ARE ONE OF MY
CAUSES

A FAIRLY TYPICAL
SMALL DAM OWNER

Small Dam Owner

- Generally an individual or organization that owns one or a few dams (<10) of any size or hazard classification.

- Ownership, operation, and maintenance of the dams is not generally the core business of the organization.

Dams are used to:

Store water to provide for the delivery of the core business:

- Water supply (irrigation, municipal, flood control, flow augmentation)
- Hydroelectric power
- Recreation, etc.

Primary focus on their core business (ie. Issues other than dams):

- **May not understand the business and societal risks associated with the ownership, operation and maintenance of dams.**

Only a few structures to deal with:

- **May not be able to have experts on staff or available as consultants to deal with emerging relatively sophisticated concepts such as risk assessment.**

Changing Environment:

- Deregulation
- Tight budgets
- Endangered species listings
- Elected board or chairperson who may not have the background in risk issues

Issues of Owners

- Business and societal risks inherent in dam ownership may not be fully appreciated or understood.

- Business risks or other issues associated with the core business fully appreciated and understood.

- Standards of the regulators may be deemed sufficient.

- Excellent safety record of dams may also cause a lack of appreciation for the risks.

MY BOSS UNDERSTANDS

Information Needs of Small Dam Owners

- Need to know the basics of risk management for all risks at dams.

- Need to have access to or an understanding of:
  - Business risk of their core operations and relation to business risk of being the owner of dams.

  - Societal risk of being an owner of dams and the impact of not managing that risk.

  - Basic knowledge of the elements that go into a risk analysis for dams.

- Limitations and uncertainties of the risk assessment process.

Need to UNDERSTAND THAT [illegible]

Knowledge that the amount of analysis required must be related to:

- Complexity of the problem
- Reason the problem is being addressed
- Consequences of not managing the problem
- Degree of certainty desired
- Scrutiny of internal and external organizations
- Desirability of having the work reviewed by peers

The owner should have:

- **Basic understanding of common definitions used in the risk analysis and evaluation of dams.**
- **Basic understanding of the mechanism that result in common types of dam failures.**
- **Basic understand of probability (in order to be able to interpret the results).**
- **Understanding of the aversion of the general population to risk from dams.**

Conclusion

Risk assessment and risk evaluation can be used to help a small dam owner:

- **Learn about the business and societal risks of dam ownership.**
- **Prioritize the various risks at a dam or for a group of dams.**
- **Determine the relative risk of owning dams to other corporate risk.**
- **Determine the overall risk that is acceptable.**

ASDSO/FEMA
SPECIALTY WORKSHOP
on
RISK ASSESSMENT FOR DAMS

Federal Regulators Information Needs
for
Dam Safety Evaluation and Management

Daniel J. Mahoney, Deputy Director
Division of Dam Safety and Inspections
Federal Energy Regulatory Commission

What Regulators Need

Regulators Perspective

There are Benefits
From Risk Assessment For
Dam Safety Evaluations

What Regulators Need

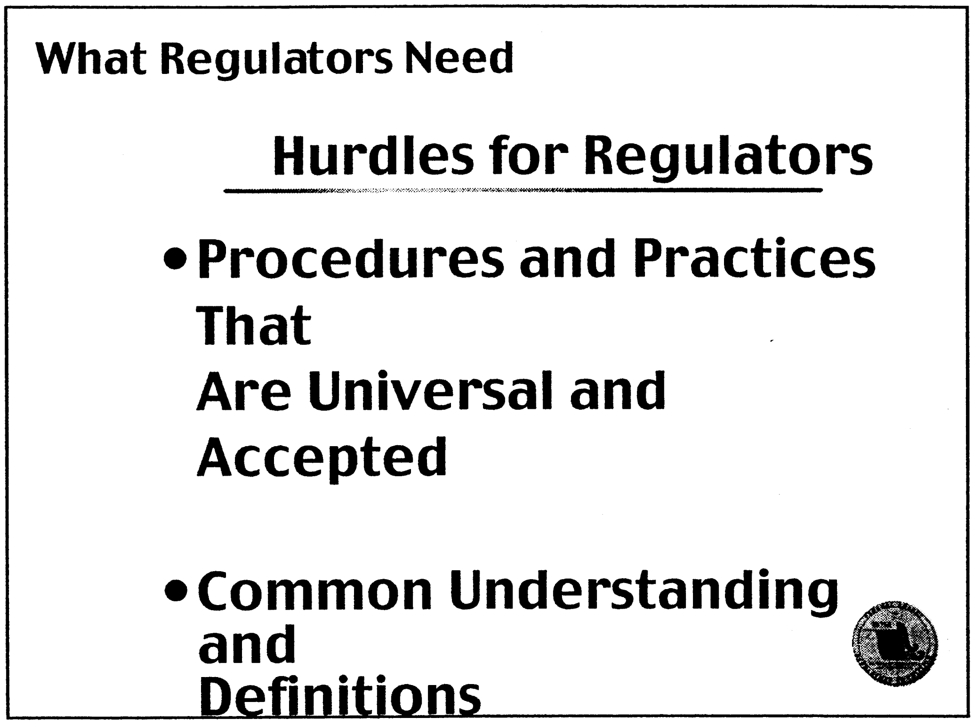
Where Risk Assessment Could Be Used Effectively

- Process Gives a Comprehensive, Thorough Evaluation of Structure
- Prioritization of Risks for Owners of Many Dams
- Fixing Dam safety Deficiencies which Represent the Highest Risk First
- More Definitive Understanding of “Hazard” Rating

What Regulators Need

Dispel Notion –

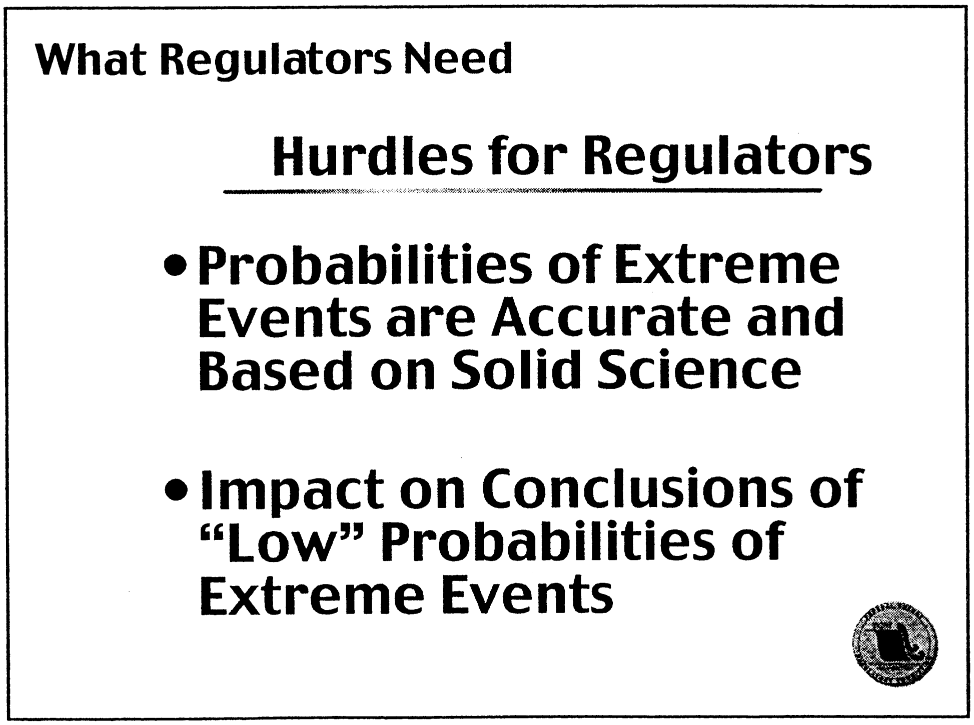
Risk Assessment Means Not Fixing Dams



What Regulators Need

Hurdles for Regulators

- Procedures and Practices That Are Universal and Accepted
- Common Understanding and Definitions



What Regulators Need

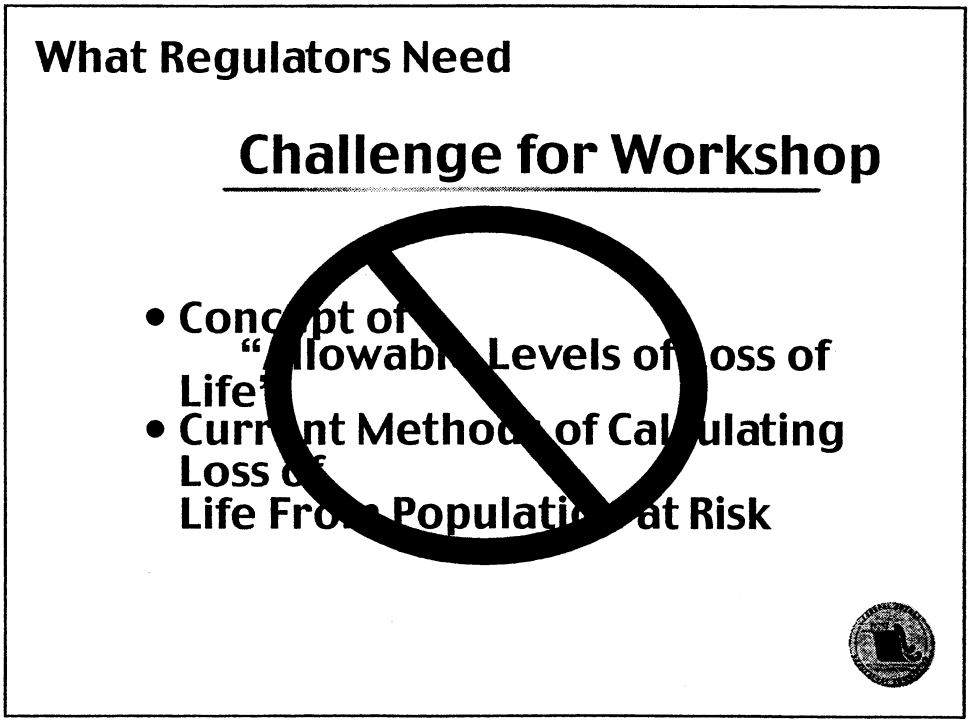
Hurdles for Regulators

- Probabilities of Extreme Events are Accurate and Based on Solid Science
- Impact on Conclusions of “Low” Probabilities of Extreme Events

What Regulators Need

Major Hurdles for Regulators

- Concept of
  "Allowable Levels of Loss of Life"
- Current Methods of Calculating Loss of
  Life From Population at Risk

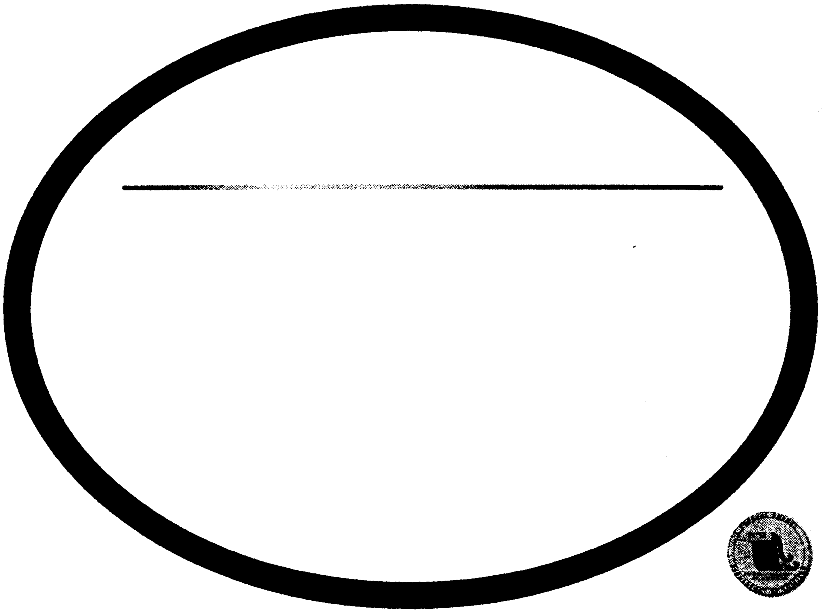


What Regulators Need

Challenge for Workshop

- Conc pt of
  " llowab Levels of oss of
  Life
- Curr nt Metho of Ca ulating
  Loss
  Life Fr Populat at Risk

What Regulators Need



STATE OF CALIFORNIA -- THE RESOURCES AGENCY
GRAY DAVIS, *Governor*

DEPARTMENT OF WATER RESOURCES
1416 NINTH STREET, P.O. BOX 942836
ACRAMENTO, CA 94236-0001
16) 653-5791

ASDSO/FEMA Specialty Workshop
"Risk Assessment for Dams"
Utah State University (USU), Logan, Utah
March 7-9, 2000

Prepared and Presented by:
Stephen W. Verigin, Chief
California Division of Safety of Dams
Member, ASDSO Oversight Committee

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State Dam Safety Regulators Perspective

1. Need a procedure to quickly and easily classify dam safety risk. (Hazard classification rating.)

2. All dams that pose any potential loss of life and/or significant loss of property are high hazard.

3. Where there is (high) exposure to loss of life and/or property, use the very highest design requirements.

4. Use risk to identify problems but not as a basis for safety.

5. Establish a maximum size beneath which there is no risk to life or property.

6. Establish a minimum size above which the most conservative design standards should be used.

7. When using a hazard classification rating system to set work and resource priorities, do not assume that a low priority dam is safe. Accept it as a low priority with respect to risk exposure.

8. Most states must show that there is an actual threat to life and property and then must ensure that dams are designed and constructed with a reasonable factor of safety against failure.

9. Do not use risk analysis to avoid making necessary (and costly?) repairs. Owners have options of operating safe dams or removing them from service. A third alternative should not be placing life or property in peril because the cost of repair is too high.

10. Do not depend on emergency action plans or early warning systems to save lives. Time of failure, duration of failure, and complexity of evacuations prevent this from being a safety feature. An EAP is a response feature that will hopefully limit losses.

11. Risk analysis is not used in the design of new dams. Why is it appropriate for use on existing dams?

Methodology

1. The database of dam failures, when used to predict where problems will occur in the future, is not a strong tool. It is most likely a measure of past engineering standard deficiencies, undeveloped technology, or poor design and construction practices. It is not a measure of random phenomenon (i.e. piping is more likely in nature than rare storm events).

2. The numbers used to calculate the probabilities used in risk analysis are subjective, leading to results that have a very weak link to actual probabilistic forecasts. Good engineering judgment and a proactive inspection program are much more reliable.

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RISK AND LIABILITY

Comment

For the State dam safety official, risk cannot be implemented without consideration of liability, particularly when monetary values are being placed on human life and property. It is a very long standing precedent under tort law that if you own a dam that causes damage to others you may be liable for those damages through either negligence or strict liability. State officials could also be liable if found negligent in performing their duties. When tested in court it will come down to the judgment of whether engineers provided a reasonable margin of safety to the downstream public, or if they negligently placed those citizens at unacceptable risk.

This is not a new discussion; it has been documented[1] since 1975, but is presently taking a back seat to instruction of the methodology for performing risk analysis.

State dam safety programs have commonly evolved under the following philosophy:

1) The regulator must be able to demonstrate that there is an actual threat to downstream life and/or property.

2) The regulator must protect downstream life and property by ensuring reasonable factors of safety against failure with respect to established professional standards.

3) The owner has the option of operating and maintaining the dam at the established standard or removing the dam from service.

---

[1] "Responsibility and Liability of Public and Private Interests on Dams, An Engineering Foundation Conference, published by American Society of Civil Engineers, Chairman Joseph J. Ellam, 1975.

Attempting to balance the cost of repairs against the price of potential loss of human life or property was not a part of that original philosophy, nor has it gained support through the courts. The most important question for State dam safety officials to ask is: "Is it appropriate for State dam safety officials to use risk analysis to protect life and property from the disaster of a dam failure?" If the answer is yes, then the follow-up question is: "To what degree?". In a 1965 report to the Governor of California entitled "The Report of the Committee on Dam Safety," an appointed committee found the following:

> "A classification system for dams under State jurisdiction should be developed by the Safety of Dams Office for internal use in order to have information readily available as to hazardous or [the] possible hazardous condition of any dam. The classification should be based on the location of the structure, age, condition, geologic setting, possible danger to life and property, and the relative risk of failure and exposure of life and property to injury. The classification should be made on a broad basis, taking into consideration all dams under State jurisdiction. Each class should have stipulations as to the frequency of inspections, surveillance data required of the owner, duration of the validity of the certificate of approval, and special procedures for reporting the status of dams to top management."

Published Statements on Liability

The following quotes should be considered by State dam safety officials that are thinking about using risk analysis as a basis for not meeting an engineering standard:

> "CONCLUSION. One added comment should be made here. It should be emphasized that tort law in general, whether the theory is negligence or strict liability, is moving in the direction of victim compensation. Consequently, as in Dawson v. Chrysler Corp. discussed above, most courts strain to invoke liability, particularly when personal injury or death is involved. The odds are substantial that regardless of the theory cited, the result will be a finding of liability in the case of a dam failure involving loss of life."

Safety of Dams,
Flood and Earthquake Criteria
National Research Council
National Academy Press, 1985

> "Under the California Tort Liability act, public agencies are liable if they have actual or constructive notice of the dangerous condition of public property (Government Code Section 835). However, in California most cases involving such liability are not brought on this basis, but rather on the basis of inverse condemnation under Article I, Section 14 of the State Constitution which imposes liability for taking or damaging of property.
>
> At the present time under either the Tort Liability Act or inverse condemnation there must be a finding of negligence by the public agency dam owner. However, there is a growing trend for the California courts to impose absolute liability for public agency activities. See Albers v. Los Angeles County, 62 Cal.2d, 250, 42 Cal. Rptr. 89 (1965)."
>
> Robert W. James, Deputy Director
> Department of Water Resources
> State of California, 1975.

Note

State dam safety officials considering use of risk analysis should note the price of these past failures:

Date of Failure	Dam Name	Lives Lost	Damages Settled
1927	St. Francis	450	$ 10,000,000
1963	Baldwin Hills	5	15,000,000
1976	Teton	11	315,000,000

These figures indicate that the actual cost of a dam failure, in todays dollars far exceeds the one to several million dollars per life that is commonly mentioned.

+30

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State Dam Safety Regulators Perspective

Steve, my overall comment is that these statement are quite strong to be speaking for all 50 states. Certainly they don't speak for Washington and Montana, where we utilize risk-based standards. Please consider my comments in perhaps softening your points. I think that as a minimum, all states could benefit from the knowledge of what level of risk their standards provide. My key issue is using %PMP (or %MCE) as a design event for smaller dams where loss of a few lives is possible. Once you move away from PMP, you have no idea what level of protection is provided, unless you can determine the probability of the %PMP event. Thus, since some of the states use %PMP as a design standard, they are already accepting risk, only they have no idea of what level of risk they are facing! I think it would be far more useful to approach this from the risk side and determine "acceptable risk" for these smaller dams. Washington, Montana, USBR and others have already started using this approach. As far as concern for state liability in case of a failure, in today's litigious society, is any standard really bulletproof? If a dam fails, you can be darn sure the state will be named as a defendant, and could lose, no matter what standard is applied.

1. Need a procedure to quickly and easily classify dam safety risk. (Hazard classification rating.and dam break analysis)

2. All dams that pose any potential loss of life and/or significant loss of property are high hazard. (Steve, not all states follow this. Washington still has a significant hazard with 1 or 2 homes at risk. I know several states that have this set in their regs.

3. Where there is (high) exposure to loss of life and/or property, use the very highest design requirements. (Agreed, but the highest design requirements shouldn't kick in where only a few lives at risk. This is why most states use %PMP for smaller dams with a few lives at risk.

4. Use risk to identify problems but not as a basis for safety. (Many states may feel this way, but not Montana and Washington. And actually, once the states allow % PMP as a design event where lives are at risk, they ARE accepting risk as a basis for safety. However, we don't know in most cases what level

of risk a % of PMP gives. This is a very important area where research is needed.

5. Establish a maximum size beneath which there is no risk to life or property. This would be nice, but it really all depends on the project. I have some six foot high dams that are riskier than 20 foot high dams.

6. Establish a minimum size above which the most conservative design standards should be used. Also consider hazard setting

7. When using a hazard classification rating system to set work and resource priorities, do not assume that a low priority dam is safe. Accept it as a low priority with respect to risk exposure. Makes Sense

8. Most states must show that there is an actual threat to life and property and then must ensure that dams are designed and constructed with a reasonable factor of safety against failure. Agreed, but the problem is defining "reasonable". There are probably 50 different opinions on this one. I think it would be very useful to the states to know what probability is associated with their specified design levels. That would really help in decision making.

9. Do not use risk analysis to avoid making necessary (and costly?) repairs. Owners have options of operating safe dams or removing them from service. A third alternative should not be placing life or property in peril because the cost of repair is too high. Yes, I know this is a feeling shared by many critics of risk analysis. It's a way of getting out of doing anything. Again, for very large dams with thousands of lives at risk, I agree wholeheartedly. But most of the dams regulated by the states fall into the gray area, small dams with a few lives at risk. The standards set for these smaller dams can be determined by the level of risk posed, not by an arbitrary percentage of a design event. By allowing anything less than full PMP/MCE, the states are tacitly accepting risk. The only way around this would be to design everything to the theoretical maximum.

10. Do not depend on emergency action plans or early warning systems to save lives. Time of failure, duration of failure, and complexity of evacuations prevent this from being a safety feature. An EAP is a response feature that will hopefully limit losses. Agreed

11. Risk analysis is not used in the design of new dams. Why is it appropriate for use on existing dams? Actually, in Washington and partially in Montana, our design standards are based on risk. However, this is a good question.

Methodology

1. The database of dam failures, when used to predict where problems will occur in the future, is not a strong tool. It is most likely a measure of past engineering standard deficiencies, undeveloped technology, or poor design and construction practices. It is not a measure of random phenomenon (i.e. piping is more likely in nature than rare storm events). Agreed

2. The numbers used to calculate the probabilities used in risk analysis are subjective, leading to results that have a very weak link to actual probabilistic forecasts. Good engineering judgment and a proactive inspection program are much more reliable. This depends on which probabilities we are considering. For the triggering events such as floods and earthquakes, we can get fairly good statistical estimates of the probability, out to maybe 1 in 5000 or 1 in 10,000. For the other failure modes, I agree that they are subjective. However, engineering judgement is very subjective, isn't it?

SVerigin:mw
C:WPFILES:WORD:RISKANL
Spell Check: 2/22/00

INFORMATION NEEDS FOR DAM SAFETY EVALUATION AND MANAGEMENT — ENGINEER'S PERSPECTIVE

By John W. France, P.E.

March 7, 2000

Consulting Engineer's Roles

- Technical Adviser
- Technical Problem Solver
- Technical Advocate
- Designer
- Construction Manager

Whose Risk is it Anyway?

- Risks, and rewards, are the Owner's.
- Engineer needs to keep his risks balanced with his rewards.

Standard of Care

- Services same as provided by similar professionals at the same time and same location.
- Importance of established standards of practice for risk analysis.

Research and Practice Needs

- Guidelines for risk assessment for dams: standard of care
- Greater acceptance of risk by the public and its representatives: buy-in
  - Establishing accepted levels of risk
- Improved Tools
  - Loss of life estimates
  - Case history compilations
  - Expanded databases of failures and incidents
  - Methods for assessment of seepage risks
- Verification/Confidence Building
  - Parallel risk assessments of same cases

2000 ASDSO Risk Assessment Workshop

A Qualitative Approach - FMEA+ Failure Mode and Effects Analyses +

- What needs to be done / included to make the FMEA + analysis effective ?

- What is the nature of this "Qualitative" approach?

- Efficient / effective resource utilization in practice

  Dam owner - A&E - Risk Assessment Facilitator

- What can the FMEA + provide for the dam owner?

- Is that all there is?

Dam Safety and Risk Assessment

I like to think of efforts toward Dam Safety as falling into 4 major categories.

1. **Surveillance and Monitoring**
   - Includes personnel who regularly at dam
   - routine inspections and maintenance

2. **Emergency Preparedness**
   - program development
   - regular testing of program

3. **Periodic inspection and analysis review**
   - 5 or 6 year comprehensive site review
   - periodic analytical review for updated procedures or data

4. **Structural & Operational Modifications**

The real test is ---

How well does Risk Assessment and the **FMEA +** in particular, contribute to dam safety in each of the above categories?

An FMEA + Put Simply

Input / Prerequisites

- Traditional Engineering Analysis
- Hazard Analysis / EPP awareness

Advance Preparation

- Collect all past records, photos, reports analyses and studies
- Obtain historic and current record of instrumentation and surveillance data
- Site Review – thinking failure modes
- Three people independently review all materials
- Request input from people (resources) who have knowledge of the dam

Conduct FMEA Meeting

- Assemble Team and Facilitator

(See additional discussion on conduct of FMEA meeting below)

Document Meeting and Recommendations

- Major Findings and Understandings
  (complete and provide to team within one week)
- Draft Report (complete and provide to team within two months)

Guidance on Effective Ways to Implement an FMEA + to Aid in Risk Assessment

Goal of the FMEA + ------ Achieve a good understanding of:

- the most significant site specific failure modes,
- the possible failure scenarios and potential consequences
- effective risk reduction measures and dam safety related actions

(this includes investigations, studies, and analyses (even quantitative risk analyses) where the team was not able to be confident or definitive about establishing or highlighting a failure mode as significant)

Implementation of a Failure Mode and Effects Analysis

- Gather all data relative to the dam – design and construction records, analyses, inspection reports, photographs, and drawings – do an exhaustive search! This includes all traditional, standards based studies that have been completed on the structures. These studies are vital to the risk assessment.

- Select and assign three experienced dam safety personnel (familiar with dam design and analysis, dam failures and failure modes and that have an inquisitive, investigative nature) to comprehensively review all information before the failure mode identification session

- Assemble a team consisting of the field and design/analysis personnel who have familiarity with the performance, design and analyses of the dam and appurtenant facilities. Include a facilitator and the readers of all the background materials. Have resource people on tap.

- Carry out a failure mode identification, and consequence evaluation session (about 1 full day). For each significant failure mode delineate the specific events that must occur to lead to a breach, the nature of the breach, and the various failure scenarios affecting the magnitude of the consequences.

- Document the discussions promptly and have the team review. Summarize the major findings and understandings achieved as a result of the discussions. The report should include in text and/or table format (see example table below) the following information for each major project component:

- **initiating condition or event**
- **detailed description**/characterization **of the failure mode** including the fundamental reasons why the failure mode is physically possible
- **nature of the breach** – dimensions, timing, precursory signals
- detailed **description** of the **consequence scenario** factors
- reasons **why and why not this failure mode is likely to occur**
- **potential risk reduction measures**

Failure Mode and Effects Analysis --- Data Table

Page __ of __

Project - __________ Structure – Main Dam Load Condition - Static

Failure Mode Considered - Description	Character of Breach	Consequences - various failure scenarios	Confidence and judgments on failure mode – likely/ not likely	Potential risk-reduction measures	Comments - data needs – monitoring / surveillance

What is the nature of this "Qualitative" FMEA + approach?

- Examines technical details to reach judgments on failure modes [does not assign qualitative ranking]
- through examination of the facts and discussion much of the understanding that would be necessary to assign subjective response probability is developed - but is not done in FMEA
- load probability is incorporated in judgments on failure mode significance

The Focus is on developing **understanding** this is achieved by gathering and discussing all available information and listening to different points of view (field / analysis / O&M - inspectors/ dam safety / EPP)

Understanding goes in before the numbers [probability estimate] comes out.

Completing an FMEA using a Multi-Resource Team Approach

Dam owner - small utility to large organization
Strengths:
- People with historic knowledge of dam
- Vested interest in dam safety
- Attentive to cost effectiveness

Liability:
- Lack of adequate resources (time and/or capability) to devote to FMEA preparation and documentation

A&E Firm
Strengths:
- People with capability to do FMEA preparatory work, to participate in FMEA and to prepare FMEA report
- Will complete work on schedule

Liability:
- Liability (and possible conflict of interest)

FMEA facilitator
Strengths:
- Experienced with process and has technical background on dams, dam safety & failure modes
- Represents owners interest in dam safety and cost effectiveness
- Independent / fresh view of situation

Liability: - Needs technical support – not one person job

Team Approach

Owner:

- collects background materials
- provides team members and resource contacts for FMEA
- may or may not provide core team member (review all background material)

A&E:

- performs prerequisite analyses for owner (if not previously done)
- supplies core team members for FMEA
- documents FMEA meeting for owner

Facilitator:

- leads FMEA meeting
- reviews draft and final FMEA report for owner ensuring accuracy of content and intent

Major advantages

- diversity of views are incorporated
- helps ensure quality and consistency
- timely completion

What can the FMEA + provide for the dam owner?

The effort expended in the FMEA can provide significant benefits through:

- **assisting with decisions on a course of action relative to dam safety**
- **enhancing the long term dam safety monitoring and dam surveillance program**
- **improving the emergency preparedness program**

These potential benefits are possible whether or not further work on risk quantification is accomplished.

The work done in an FMEA is fundamental to risk assessment and to any further steps employing quantitative risk analysis,

Recent comment by Steve Vick on – Levels of Effort in Risk Analysis / Risk Assessment

"As engineers, we usually choose the simplest tool that accomplishes the purpose we want to achieve. Often very simple tools can serve admirably for even complex problems, and there is no reason why risk assessment should be any different in this respect. What risk assessment, simple or complex seeks to do is address uncertainties in a systematic way, and different risk assessment tools can satisfactorily serve this end. But they should be selected by the user to best accomplish the purpose the user defines. Also the user is reminded that how much comes out depends on how much is put in."

LVT – for example FMEA + does not provide the owner with a relative risk measure among highlighted failure modes

Is that all there is?
Not Necessarily – Owner has three choices here relative to Risk Assessment and Dam Safety Decision Making

1. **Use the traditional standards-based analyses results along with the input from the FMEA for Dam Safety Decision Making and determining /prioritizing dam safety risk reduction actions**

2. **Supplement the FMEA with a screening level risk analysis for all highlighted failure modes to incorporate a probability of occurrence component to aid in Dam Safety Decision Making and determining /prioritizing dam safety risk reduction actions**

3. **Use the FMEA as the initial phase of a comprehensive risk analysis**

Steps in Conducting the FMEA

- Assemble FMEA Team with Experienced Leader/Facilitator
- Identify Potential Failure Modes
- Examine Nature and Impact of Breach
- Identify Risk Reduction Measures {including monitoring & surveillance enhancements or requirements}
- Establish failure modes that should be highlighted as most important to be brought to the attention of the Dam Safety Decision - physical flaw

(For each significant failure mode **delineate the specific events that must occur** to lead to a breach, the nature of the breach, and the various failure scenarios affecting the magnitude of the consequences)

- Identify risk reduction action items and risk reduction alternatives for study
- Identify key data or analysis needs that prevented a firm conclusion on highlighting

Major Findings and Understandings From the FMEA

This is a summary listing of pieces of information or conceptual understandings that are the key "new" facts or understandings that the team learned during the FMEA process – they typically play an important role in determining whether or not a potential failure mode should be highlighted. Sometimes several of the findings relate to a certain failure mode and sometimes a finding relates to more than one mode. It is not the intent to develop the logic / rationale for the failure modes here – it is just to set out some key information as we begin to describe that process. I have found [recently – as this is a new procedure] that this is an extremely effective means of quickly recovering and getting at the guts [not results] of what was done and learned at the FMEA meeting. I suggest putting this information at the outset of the FMEA report in order to give the reader these key facts as they go through the report.

BROAD BASED APPROACH TO DAM SAFETY RISK ASSESSMENT

By J. Lawrence Von Thun
Presentation for the ASDSO Annual Conference - October 1999

Introduction

- Risk assessment **in its most fundamental form** has been and always is used by decision-makers in making decisions related to dam safety.

- Risk assessment **as a specifically recognized process or tool** to assist in dam safety decision making has been in use by various organizations, firms and owners for about the past 20 years. The failure of Teton Dam helped trigger development and use of risk based decision tools for dam safety related applications. Risk based analysis for civil applications was under development in universities for years previous to this.

- Application of Risk Assessment is often characterized or thought of either in terms of **a complex mathematical process** or a **subjective process devoid of traditional engineering input**. These are incorrect generalizations of the available tools and uses. Good engineering analysis and evaluation is an essential ingredient of risk assessment. **Application of risk assessment is not about what is left out of a dam safety evaluation but about what is added!**

- Risk Assessment should be recognized as a **supportive tool for dam safety evaluation and management that adds or ensures that the following information is included** in the dam safety evaluation and decision process.

    - identification of **key failure modes** affecting the dam and project
    - realistic, quantitative **understanding of the consequences** of failure
    - **comprehensive consideration of loading** applied to the dam and appurtenant structures from the threshold of load that can cause failure to maximum loading
    - **risk reduction value of alternative corrective action measures** considered for the dam and appurtenant structures

- Although the terms and terminology related to risk assessment vary by organization, a generally accepted breakdown of the key risk application terms and those being used for the purposes of this presentation are:

Risk Assessment - the overall, risk based process of examination of the possible courses of action related to the safety of structure(s) in light of all the decision factors -(operations, public, cost, time, environmental aspects. risk analysis results/insights, etc.)

Risk Analysis - the process of identifying potential dam failure modes and then estimating the probability of the loading, the likelihood of dam failure given the loading, and dam failure consequences.

Risk Management - evaluation of risk reduction courses of action versus cost over a complete inventory of dams and the associated dam safety program.

Presentation Content

Now with the above as background the key questions for this presentation are:

1. **Are Risk Assessment Methods and Tools Broad Based? – That is, can they be used by engineers and dam owners representing Small, Medium Sized and Large Inventories of Dams?**
2. **Would the usage vary depending on the size of the dam safety program?**
3. **What is the most effective way to implement the tools and procedures considering size of inventories, engineering budgets, experience and skill levels of personnel available to perform the safety evaluations?**

The purpose of this presentation is to address these questions for dam owners and for engineers or regulators representing or advising dam owners?

Broad-based use of Risk Assessment

Risk Assessment methods and tools can be used whether one is dealing with a single dam or a large inventory. The fundamental purpose for using risk assessment is to improve decision-making related to dams and dam safety. The way that is done is by achieving improved understanding of:

- the risks,
- the relative likelihood of potential failure modes
- the consequences of failure, and
- the risk reduction benefits of alternative courses of action.

Using this enhanced information base can improve decisions.

Variation in Risk Assessment use as a function of of dam inventory size

The way risk assessment tools and methods are used may vary as a function of the number of dams in an owners inventory. The basic difference is that a larger program provides the opportunity to estimate and evaluate relative risk reduction benefits among dams in the inventory and among risk reduction activities in the overall dam safety program (instrumental monitoring, surveillance, safety inspection, structural repair, analysis, non-structural actions, emergency preparedness testing, etc.). However, the degree to which risk assessment is actually implemented, by an owner, is fully flexible and should be based on what can be most effectively accomplished considering the engineering resources available for use by the owner.

Guidance on the Most Effective Ways to Implement the Use of Risk Assessment

Although tools and procedures may vary as a function of the size of the inventory of dams, engineering budgets, experience and skill levels of personnel available to perform the safety evaluations, the following activities are considered to be essential and very effective whether one dam or many are to be evaluated. This implementation guidance recognizes the variable nature of the engineering support available to the owner;

- little or no in-house staff
- some in-house staff but bulk of the work is contracted
- primarily in-house staff

First Phase – Failure Modes and Effects Analysis

Goal - Achieve understanding of the most significant site-specific failure modes and the potential consequences of the failure.

This phase is fundamental to risk assessment and to any further steps employing quantitative risk analysis. It is important to note that the effort expended in this activity can provide significant benefits through:

- assisting with decisions on a course of action relative to the safety of the dam being evaluated
- enhancing the long term dam safety monitoring and dam surveillance program
- improving the emergency preparedness program

These potential benefits are possible whether or not further work on risk quantification is accomplished.

Implementation of a Failure Mode and Effects Analysis

This is my suggested plan of action that needs to be incorporated in your study to ensure an effective failure mode and consequence analysis:

- Gather **all** data relative to the dam – design and construction records, analyses, inspection reports, photographs, and drawings – do an exhaustive search! It is important to point out that **this includes all traditional, standards based studies that have been completed on the structures**. These studies are an integral part of the risk assessment.

- Select and assign three persons to comprehensively review all of this information in advance of the failure mode identification session– if you do not do this advance preparation, the value of the study diminishes and the ultimate cost of the investigation is greater. The assigned persons should be experienced dam safety personnel – familiar with dam design and analysis, dam failures and failure modes and an inquisitive, investigative nature.

- Assemble a team consisting of the field and design/analysis personnel who have familiarity with the performance, design and analyses of the dam and appurtenant facilities. Include a facilitator and the persons assigned to read all background materials. Have resource people on tap.

- Carry out a failure mode identification, and consequence evaluation session (about 1 full day). For each significant failure mode delineate the specific events that must occur to lead to a breach, the nature of the breach, and the various failure scenarios (exposure, warning) that can impact the magnitude of the consequences.

- Document the discussions promptly and have the team review for completeness. Summarize the **major findings and understandings** achieved as a result of the discussions. The report should include in text and/or table format the following information for each major project component (e.g. each dam or dike, spillway, etc):
    - initiating condition or event
    - detailed description/characterization of the failure mode including the fundamental reasons why the failure mode is physically possible (see attachment A)
    - nature of the breach – dimensions, timing, precursory signals
    - detailed description of the consequence scenario factors
    - reasons why and why not this failure mode is likely to occur(see attachment A)
    - potential risk reduction measures

Now before going on to the direct use of the information gathered above in a risk analysis or a dam safety decision there are three indirect or associated actions which can result from the failure mode and consequence study, they are:

- Performance of investigations or analyses which were highlighted as important gaps in information related to identification of the validity or significance of a potential failure mode

- Use of the results to help focus the instrumented monitoring program and the surveillance program toward the most relevant failure modes at the site

- Use of the results to improve or enhance the emergency preparedness planning via improved understanding of the nature of the breach and the potential adverse consequence scenarios

Decision Point on the Nature of the Second Phase in Risk Assessment

The understanding of risk achieved on the basis of the activities described above is qualitative. At this point there are basically two ways to proceed:

1. Proceed to a decision on a course of action - The information and understandings achieved through the failure mode and consequence identification are used as input along with all other relevant information (economic, public input, environmental) in a risk based decision process,

This would constitute the second phase and conclude the risk assessment if this path is chosen. This is a good and fully acceptable choice to make, however, an owner could,

2. Proceed with a quantitative risk analysis - In this case the information developed in the first phase is incorporated directly into a risk analysis and the risk assessment / decision process occurs after its completion.

Second Phase – Quantitative Risk Analysis

Goal – Obtain a quantitative estimate of the risk associated with dam failure and a quantitative estimate of the reduction in risk achieved from risk reduction alternatives.

In this phase the probability associated with external loads applied to the structures, the probability of an adverse response of the structures to those loads, and the likelihood and magnitude of various consequence scenarios are estimated. The likelihood of dam failure for all the combinations of loading and failure response and the magnitude of the associated adverse consequences are combined to represent the risk.

There are three primary advantages of including a quantitative risk analysis in the overall risk assessment process. They are:

- Added help in decision making. Having an estimate the product of the load probability, failure likelihood given the load and magnitude of consequence over the full range of loading for each of the most significant failure modes provides a good, quantitative sense of the relative seriousness of the various issues associated with the structures
- The level of completeness and rigor that is necessary to allow a quantitative estimate to be made, especially in the area of structural response of the system, will almost always result in an enhancement of the understanding of the problem and lead to more insight and ultimately help improve the quality of decisions.

- The opportunity to use / incorporate the quantitative results of risk estimates for each structure, each failure mode, each consequence scenario and each risk reduction alternative (including ongoing dam safety programs) to guide a risk management program

The primary deterrents to incorporation of quantitative risk analysis as part of the risk assessment process are:

- Represents a real step up in complexity. Requires a significant commitment in money and time to obtain good external resources or accomplish the in-house training necessary to staff the conduct of this work and to deal with the issues of how the results will be used.

- The focus of the application can turn from use of the process to enhance understanding and assist in decision making to one of providing the results for the decision.

Implementation of a Quantitative Risk Analysis

If the decision is made to incorporate the use of risk analysis on a project, several projects or as a part of an owners overall dam safety program, this is my suggested plan of action to ensure an effective and efficient risk analysis is carried out:

- Accomplish all the actions discussed under the failure mode and consequence analysis. These actions are the first steps in a risk analysis
- Obtain the services of an experienced risk analysis advisor/ facilitator / trainer to help:
    - layout the scope of the risk analysis to be performed,
    - provide training, guidance and direction to the in-house staff, engineering firm personnel (or combination) who will be carrying out the analysis
    - facilitate / lead the risk analysis

This risk analysis advisor can be borrowed, obtained in-house or hired externally, but in any case should directly represent and work on behalf of the dam owner and be independent of the primary engineering consultant being used by the owner. This person serves as the seat of discernment for the owner relative to the implementation and application of risk analysis.

- Establish the goals, objectives, level of effort for the analysis, process to be used in performing the risk analysis and the way the results will be presented and used in the risk assessment / decision process. If this has been done for a previous analysis this step only involves discussion of any proposed modifications or revisions to the study plan or process. Guidance on selection of level of effort [1] has been developed to help ensure that an owners use of risk analysis is efficient and cost effective and is tailored to the purpose and intend use of the risk analysis.

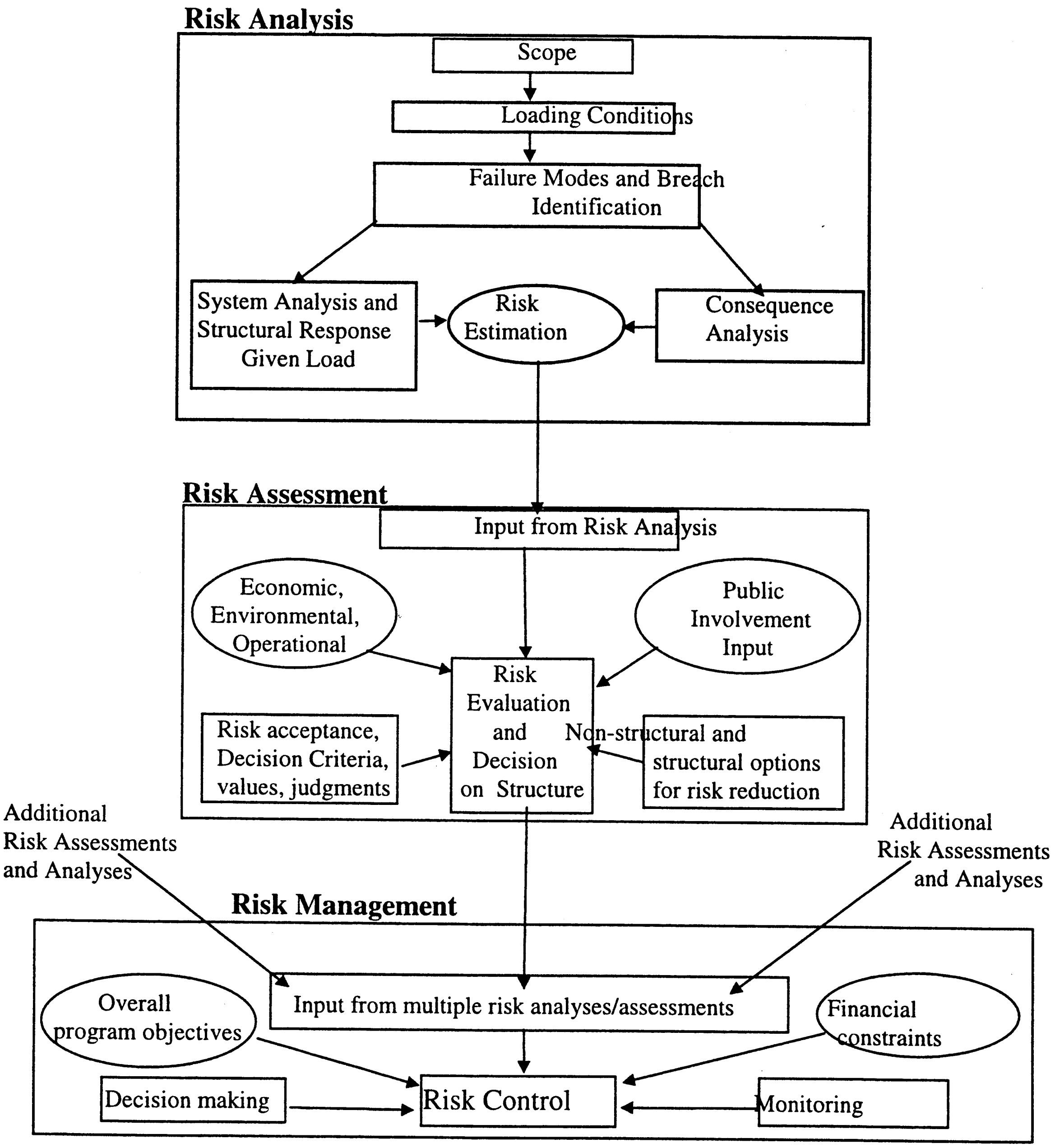
- Consider development of a risk analysis cadre whose members would be trained to perform risk analyses. This cadre, with the facilitator would be the core group for carrying out all the risk analyses for the organization. Technical support staff in specialist disciplines and individual technical expert resources would be included in the risk analysis as needed. This approach would provide for the consistency in application of risk analysis and facilitate use of the results of the studies in ranking the severity of various issues and the risk reduction merit of proposed actions. This cadre may be a combination between in-house and external resources. The key is that the personnel have a strong technical background and good aptitude and enthusiasm for this type of study.

- Perform through documentation of the risk analysis, in as much or greater detail as would be done for any engineering study. This includes recording the specific data and information that was brought to bear in estimating the probability of each event in the event tree. This documentation becomes, in essence, the engineering report of the study and the technical rationale for each sub-decision is recorded.

Completing the Risk Assessment Process When A Quantitative Risk Analysis Has Been Completed

Once completed the risk analysis is input into a project specific risk assessment / decision process and, if applicable, a risk management process as illustrated on Figure 1.

Figure 1 - Relationship Between Risk Analysis, Risk Assessment and Risk Management in Dam Safety Decision Making



Conclusion

Risk assessment tools and procedures can be efficiently and effectively added to or incorporated into dam safety evaluations made by an owner of one, several or many projects. An owner may opt for a qualitative risk assessment process using the results of a failure mode and consequence analysis or a quantitative process using a risk analysis. In either case the purpose of application of these additional tools is to improve the quality of decision making and this is accomplished by enhanced understanding of the failure modes, consequences and risk posed by the dam and appurtenant structures. This enhanced understanding is achieved by identifying and comprehensively scrutinizing the loading, failure modes and consequences that are most significant to the project within a systems analysis framework.

References

1. "A Framework for Applying and Conducting Risk-Based Analysis For Dams", Martin W. McCann, Jr. and Gonzalo Castro, Proceedings of 1998 USCOLD Annual Meeting, Buffalo, New York

Attachment A - POTENTIAL FAILURE MODE – Example Description

Park Dam and Dikes have performed well since construction in 1946, but there are conditions that warrant diligent monitoring at the dam and dikes relative to the failure modes described below. **The following potential failure modes are highlighted** because the specific conditions at the dam and appurtenant structures are such that **these failure modes are physically possible** and are the **most significant failure modes definable at this site**. Park Dam and Dikes pose a high hazard, and diligence in monitoring for development of these failure modes is warranted.

The potential failure modes described below cover failure modes for Park Dam and "dikes" the dikes, however, are of significant size and are unique from the dam in design, construction and foundation conditions.

Failure Mode 1 - Seepage Erosion and Piping

Dikes 1 and 2

During site investigation the foundation of these dikes was found to contain joints much more open than anticipated, based on pre-construction investigations. These joints provide a potential path for subsurface erosion of the Zone 1 material leading to an unprotected exit downstream of the dam.

Although grouting was performed following construction (during the first filling of the reservoir) and the seepage levels were reduced, the fundamental failure mode remains (see figure 2). The presence of 4 to 5 ft^3/s of seepage from a dike of moderate height and length attests to the possibility of open joints in the foundation capable of carrying adequate flow to result in erosion, and transport of eroded material downstream. The specific failure mode paths and the factors relative to the likelihood for the development of this failure mode are as follows:

Failure mode paths - there are two primary potential paths for seepage erosion/piping to take place through the foundation jointing and two of lesser likelihood. These are:

Flow through the dike embankment across the Zone 1/ foundation interface. This could result in the Zone 1 materials eroding and being carried through the open joints to an unprotected exit downstream. (Failure would result if backward erosion (piping) through the Zone 1 materials reached the reservoir source. An ever increasing flow potential could then progressively enlarge the flow channel downstream of the point of erosion initiation in the core to an extent large enough to carry continually increasing flows).

- Flow under the foundation attacking the base of the Zone 1 material and removing it by seepage erosion through the foundation jointing.

- The other two potential flow paths leading to a seepage erosion/piping failure are (1) piping of the Zone 1 through the foundation alluvium and (2) seepage erosion of the foundation alluvium exiting through the open joints in the rock. These are considered to be of significantly lesser likelihood

Factors increasing the likelihood of this failure mode developing include:

- the observation of very open joints in the foundation (greater than 2" wide)
- surface treatment was not provided to exposed bedrock
- grouting procedures used likely resulted in some of the most open joints remaining open due to the presence of the reservoir produced seepage flows during the grouting (this is most likely in the higher head, lower elevation portion of the dikes)
- grouting near the surface was likely not very effective, considering the method used
- large seepage flows are occurring, which can dilute and potentially mask observation of particles being carried by the flows. If an attack begins, large flows can erode large amounts of material relatively quietly.

Factors indicating less likelihood of this failure mode developing include:

- There has been no observation of any material being carried by seepage flows at these dikes.
- The Zone 1 appears to be clayey, very impervious, and not easily erodible.
- The placement of the Zone 1 cutoff-wall well upstream of the dike centerline creates a closer source for the reservoir's water, but a large portion of the dikes would remain if an erosion path develop at the base of the cutoff.
- The lack of water in the toe drains is a likely indicator that the dikes have not saturated and that the foundation rock behaves as a drain keeping water away from or at low pressures at the dam/foundation contact.
- Seepage flows started downstream of the dikes prior to the water reaching the upstream toe of the dikes. This indicates the pervious nature of the foundation and the likelihood that a large portion of the seepage water passes beneath the dikes (relatively independent of it).

Experiences and Results from FMEA's Case A – Composite Embankment and Gravity Dam

Main Results / Recommendations to the owner from a recent, traditional, dam safety assessment that included site review and standards based analytical study

- Significant discharge deficiency – can only pass 59% of the PMF - determine most cost effective way to increase capacity
- Concrete structures do not meet the required earthquake dam / fnd stability standard for MDE (0.2g) about a 1/10000 annual exceedance event – need to obtain cores for rock shear strength at contact, re run stability and instrument to measure uplift
- Embankment dam has no piezometers – need to install and run stability study

Major findings / recommendations from FMEA review (1 day meeting)

1. Identified piping failure as the most significant potential failure mode to highlight. (This finding was based on review of photos from construction revealing problems with sheet pile installation and a photo from first filling which revealed a sink hole at the crest of the dam directly above the location of the sheet pile problem)

   Risk Reduction Recommendation – Enhanced surveillance and monitoring. Heightened awareness should be given to field staff and inspectors.

2. Potential post seismic structural deficiency of bulkhead section was not highlighted as a significant failure mode due to concrete keys tying this short section to adjacent stronger sections.

   Risk Reduction Recommendation – verify support of bulkhead by adjacent sections --monitoring pins or marks should be established across contraction joints

3. Encroachment of standards in water elevation during passage of major flooding was not highlighted - in fact a further variance from standards was recommended (allowing concrete structures to overtop) in order to enhance protection of more vulnerable structures downstream:
   Risk Reduction Recommendation - allow full utilization of available freeboard on the embankment

4. Recognize under the EPP the lack of the possibility to provide any reasonable warning time under the piping failure mode
   Risk Reduction Recommendation - Emphasize the need for specific observation of conditions at the downstream toe of embankment during daily visits to the structure and in all inspections and periodic reviews.

Dam B – Embankment Dam

Main Results / Conclusions / Recommendations to the owner from a dam safety assessment that included a standards based analytical studies, extensive site exploration and re-analysis, and a risk analysis.

- Liquefaction potential was high under seismic loading but that loading was relatively remote.
- A discharge deficiency existed but the hydrologic events that would produce this deficiency were remote.
- The population at risk for the most part was located several miles from the dam and both of the above potential dam failure producing events would allow warning to be provided. Thus the selected dam safety action was to enhance the warning system and upgrade the EPP relative to potential failure from these two events.

Major findings / recommendations from the FMEA review

1. Potential, physically possible, piping and seepage related failure modes are evident based on review of the design, construction and performance of the structure. (See background on seepage and piping history below.) The failure modes are:

- Below the various crest modifications in the contact region between the relatively thin puddle core and these "stiffer" modifications - This zone has experienced piping in the past and may still have "residual" pipe channels present in the fill from past events. High water continued settlement of the embankment or separation at the contact between the crest modifications and the puddle core could reactivate this piping under very high water conditions or sustained high water conditions.

- At the embankment / foundation contact - the poor construction placement conditions (coarse and segregated material and low compactive effort) certainly left a zone of weakness at the contact with the possibility of development of seepage flow channels capable of eroding dam or foundation materials.

- Under or through the sheet pile cutoff or through the foundation.

- Outside of the channel area another area of piping susceptibility exists due to the lack of foundation treatment at the abutment rock/embankment contact and the pervious nature of the abutment as indicated by the historic seepage.

Risk Reduction Recommendation: The piping/seepage related failure modes should be given high priority for dam safety action with significant effort devoted to determining appropriate surveillance and monitoring for these failure modes and consideration should be given to structural remediation (filtered toe drain cutoff).

Background on Dam B Seepage and Piping that allowed identification of the piping related failure modes

The dam was constructed by hydraulic fill methods. The foundation cutoff through the alluvium (fine sand, silt and clay) filled channel section was accomplished by use of "jetted in" wooden sheet pile to a depth of about 33 feet. A "seamy" limestone formed the left abutment and spillway foundation. A drainage trench, which also served as the original toe drain) was cut across the profile (parallel to and downstream of the axis of the dam for dewatering during construction. However, the groundwater level was just below ground surface (about 4-6 feet below) and above the excavation level of the "clay lenses" removed from the foundation. This water level and excavation process resulted in a very sloppy foundation. Equipment could not be driven across the foundation (many reports of equipment being stuck) until a considerable thickness of material was dumped on the fill to serve as an initial platform for construction.

After construction and filling of the reservoir there was very heavy seepage. Total reported maximum seepage at a point 5 years after of construction (reservoir relatively high) was 6.4 cfs. Of that 2.2 cfs was at the lower end of the spillway channel and 4.2 cfs was along and below the toe of the dam and at a spring near the left abutment which responds to reservoir level and had a maximum flow of about 1 cfs. Seepage at the dam was considered to come both under and through the embankment and sheet pile cutoff placed at the upstream end of the puddle core - 70 feet from the axis. A 3 acre swamp area developed below the dam.

[The above data as well as the commentary on conditions was drawn from an inspection and report by a consulting engineer after 31 years of operation and was available in the project records.]

Because: (1) the puddle core had only been brought to about 8 feet below the original crest and (2) the core was thin, it was decided to construct a 10 foot deep 8" wide concrete "parapet wall" which would extend from the crest into the puddle core. (There was no indication in any reviewed report that seepage was observed on the upper portion of the embankment.) The concrete wall was constructed in after 11 years of operation. Following completion of the wall three subsidences were observed at the top of the dam. A test pit at the largest subsidence (18" deep) showed that piping was taking place under the base of the wall. This was not shown in the test pits at the other two subsidences. A subsequent crest modification removed a portion of the concrete wall and replaced it with soil cement placed to 4-6 feet into the puddle core.

As part of the dam safety investigations piezometers were installed in the dam and foundation in the 90's. The upstream piezometer holes are located upstream of the crest (about 50 U/S of the axis) through the puddle core and downstream of the sheet pile cutoff. Each of 4 holes has a piezometer near the foundation contact and another in the foundation (40-60 feet lower). The downstream piezometer holes are located near the toe of the dam each have two piezometers. The piezometers show a very interesting pressure/water flow regime (in that I have rarely seen this pattern). The upstream holes show a relative high pressure gradient from the dam to the foundation (10 to 20 feet of head differential. The downstream holes show the reverse with higher pressures in those at depth (some are artesian) than those nearer the ground surface. This presents a flow pattern conducive to piping from the dam through the foundation to the toe.

There is considerable more history and information related to the static performance and seepage history of this dam in the project records. I have just noted the highlights to focus on potential failure modes

Although there has only been the one piece of direct evidence of piping occurring at the dam it is quite evident that there has been little ability to detect or protect against piping via the drainage trench / and monitoring system present. No proper filtering of material exists in the drainage trenches and when the reservoir is high and seepage is at its greatest, the monitoring system is overwhelmed. If material was moving at those times it would not be likely to be detected. Due to the large amount of basically uncontrolled seepage at the dam under high reservoir, the presence of a flow and pressure regime that is unfavorable from the standpoint of piping susceptibility and the poor dam construction (hydraulic fill, unusually thin puddle core, high percentage of rock and coarse material in the dam and poor placement of materials at the contact) This failure mode should be highlighted and be the highest priority in the failure mode listing. Further significant effort needs to be devoted to determining appropriate surveillance and monitoring for this failure mode

Notice that the FMEA – identifies the potential concern – provides a definite "judgmental" indication of its relative importance, suggests potential risk reduction measures but does not develop the proposed solution as there are many considerations and possible studies required.

Dam C – Composite Embankment and Gravity Dam with a Powerplant

(The physical extent of each dam was dictated by the location of an active fault in the foundation)

Main Results / Conclusions / Recommendations to the owner from the traditional dam safety assessment that included standards based analytical studies and a periodic inspection.

- Carry out <u>further</u> seismotectonic investigations
- Carry out <u>further</u> comprehensive dynamic analyses of the concrete dam

Major findings / recommendations from FMEA review:

- No "traditional", static reservoir loading failure modes of significance were identified for highlighting.(i.e., sliding instability, piping, etc.). Thus, the failure modes highlighted are only those that are related to remote events (flood and earthquake fault rupture or strong shaking).

- One vulnerability to an "ever present" condition does exist. That is normal release of flows from the upstream reservoir. The potential failure modes described below emphasize, failure modes related to malfunction of gate operating systems with flows at or near normal range of releases and in conjunction with remote events. **Gated structures, without emergency spillways, present an especially difficult dam safety challenge.**

The potential failure modes determined for highlighting are:

Failure Mode 1 - <u>Overtopping of the Earth Dam Due to Gates Not Operating as Planned</u> (During flood or under normal operation)

This failure mode is overtopping of the embankment dam due to failure of the gates to operate as planned under flood conditions or under normal operations. Failure of the gates to operate as planned is characterized in three ways:

- Gates are not operated at all
- Gates are incorrectly operated
- Gates malfunction or are out of operation

The small difference between normal operating reservoir level and maximum reservoir elevations reached during flood events, (less than 1 meter for the 1000 year flood and about 2 meters for the PMF), reflects the large discharge capacity at the dam and reveals the sensitivity to and reliance on discharge capability. The discharge system is entirely gated and thus dam safety with respect to this failure mode depends entirely on successful gate operation.

This failure mode is physically possible but is not considered likely with systems and operations as currently in place. However, this failure mode is being highlighted to dam safety managers to emphasize the critical importance of maintaining the communications and operations in a manner comparable to the present system (e.g. - in the event of ownership change)

Risk Reduction Recommendation

Ensure successful gate operation by:

- Regular testing of the physical capability to open the gates by all means and locations, (both normal and emergency conditions should be emulated for all tests). Appropriate testing is currently specified and being carried out.
- Regular review and testing of communications and operational procedures for handling flood emergencies

Failure Mode 2 – Seepage Erosion Through Cracks in the Earth Dam Due To:

- Fault Rupture and Cracking of the Embankment Dam or,
- Differential Movement at the Concrete Dam Interface Due to Seismic Shaking

The failure mode would be initiated by earthquake induced differential movements across the core of the embankment dam. Two scenarios are considered plausible.

- The most direct would be formation of a gap (tensional failure) in the Zone 1 in the axial direction that would allow water to pass directly from the upstream Zone 2 into the materials downstream of the Zone 1, either at depth or near surface.
- The other possibility is differential displacement in a near vertical direction faulting the filter against the shoulder gravels.

If an opening developed, piping failure by tractive flow removing Zone 1 could occur if the flow velocity were great enough to erode the Zone 1 or by internal erosion, (true piping), of the Zone 1 into the shoulders. In either case increased flow, higher piezometric pressures and dirty water in the drain element should be observable.

Given the occurrence of a large earthquake (>M 6) on the nearby faults there is a reasonable likelihood that fault rupture would occur beneath the dam and that some displacement or separation would occur at the earth dam-concrete dam interface. The shoulder gravels and the good resistance of the core material provide defense against rapid failure and perhaps against any failure at all (likely time for failure development is estimated to be at least 1-3 days and perhaps very much longer). However, fault offset of the dam body would be a serious wound to the dam and the possibility of dam failure under such a condition should be considered serious and real.

Risk Reduction Recommendation

The key surveillance items for indication of a fault displacement related failure in progress is visual observation for turbid/muddy seepage exiting from:

- The drain element in the earth dam exiting in the right wall of the fish pass.
- The downstream face.

- The downstream face especially in the vicinity of any transverse surface cracks and at the earth dam-concrete dam interface.

Overall visual observation of the dam site and completion of the post earthquake checklist developed by the project should take place following an earthquake. Other key, surveillance that should take place to indicate the potential for development of this failure mode are:

- Measurement of the amount of offset at the ground surface at the surface fault trace location on the powerhouse access road curb downstream of the dam.
- Measurement of any change in water levels of the piezometers in the dam, the observation wells downstream of the dam and in those proposed to be added in the drain element.

Failure Mode No. 3 – Loss of Gate Operational Capability Due to Seismic Shaking

This failure mode involves loss of the ability to operate the gates as a result of either; (1) Loss of system capability to operate the gates with consequences as for failure mode 1 for normal flow conditions or (2) Damage from the earthquake, which could cause jamming, distortion, or structural failure of one or more components of the gate piers or bridge deck, with the consequence of not being able to draw down due to earthquake damage.

Some spillway gate malfunction under strong seismic loading is reasonably possible as it is judged that a number of components are overloaded that could cause significant gate distortion. In addition gate malfunction could result from the bridge deck coming off its bearings or from spillway pier deformation as they were designed for only a 0.1 g loading. Operating systems are considered to be secure only up to 0.25 g and maximum earthquake accelerations from the nearby faults are estimated at 0.73g and 0.85g respectively.

However, severe adverse impacts from this failure mode are considered unlikely because the sluice gates, are resistant to earthquake loading and likely to be operational following an earthquake. For a dam failure to occur subsequent to an earthquake , would require high upstream inflows, all gates being jammed and failure of the sluice gates to operate.

- The hardware, software and communications associated with the operational system are considered to be robust.
- There is a low probability of all five spillway gates jamming.
- There is a low probability of sluices not being operable.
- Storage time in the reservoir under normal peak machine flows upstream exceeds 30 hours. If spillway overpour is considered the time is much greater than 30 hours
- A single spillway gate and two sluices can pass over 2,000 m^3/s at normal operating levels.

Risk Reduction Recommendation

Ensure gate operation following an earthquake by:

- Regular testing of operation as for failure mode 1.
- Test gates immediately after a severe earthquake, even if they are not required immediately for spill

Dam D – Concrete Dam and Powerplant

Main Results / Recommendations to the owner from a recent, traditional, dam safety assessment that included site review and standards based analytical study

- There is a significant discharge inadequacy with respect to passing the PMF
- The most cost effective means of increasing the capacity should be determined.
- Perform additional stability studies on the East Dike

Major findings / understandings /recommendations from the FMEA review.

- The ability to pass the PMF at the site depends on the ability of the various flow controls components to function properly. The PMF at the site was determined as 2,290 m3/s. Of that amount, only the flow passing through the sluice gates can be considered to be "reliable" capacity, namely 1,170 m3/s. The remaining capacity comes from contributions from the power flow through the turbines (~480 m3/s), the emergency sluiceway (~255 m3/s) and the fuse plug on the West Dike (discharge varies according to width and depth eroded to form the fuse plug). All the components other than the sluicegates are vulnerable to being non-functional during a major flood for the reasons described below.
    - The emergency sluiceway has to be charged with explosives and blasted out for it to become functional and the decision to blast and has to be made prior to the water reaching the crest of these spillways
    - the power flow may have to be shut off if the turbine trips due to high tailwater or loss of the single transformer or transmission lines; and
    - the embankment in the area of the fuse plug currently is at the same height as the remainder of the West Dike and would need mechanical excavation of a portion of the crest to initiate the erosion of that portion of the Dike to allow the fuse plug to form.

- The West Dike fuse plug is not identified in the current operating procedures as a potential means to discharge flow from the reservoir during a major flood, and the FMEA team found that the design, location and operation of the fuse plug were all uncertain due to no definitive documentation being found to describe these aspects of this portion of the West Dike.

- The emergency sluiceway is designed such that the arch walls of the sluiceway are to be charged with explosives and demolished in the event of a major flood. The original intent was to provide a discharge facility at the Main Dam to discharge a flow equivalent to the power flow should the turbines trip. The FMEA team believes that the decision to blow the emergency sluiceway is fraught with problems regarding the timing, logistics and actual execution (safety, etc.) and may also have legal implications for the owner if it is blown, or if it is not blown, at the appropriate time.

- Maintaining the turbine power flow throughout the major flood event would have a greater positive impact on the ability to pass the PMF than would activating the emergency sluiceway. This is because the power flow through the turbines is greater than that which the emergency sluiceway is capable of discharging. However maintaining the power flow is dependent upon getting the electrical energy out of the generating station, and with the current arrangement of the "downstream parapet wall", the transformer will be flooded when the Main Dam overtops which will trip the turbine and reduce the power flow to an insignificant amount.

- The crest of the concrete gravity structures at the Main Dam was determined to be approximately 300 mm higher than that assumed in the routing analysis and this analysis did not include the effect the east parapet wall on the headworks deck would have in reducing the overtopping flow. The effect of this difference in assumptions would be that the water level in the reservoir would probably be higher than that determined in the routing analysis and overtopping of the earthfill structures (Saddle Dam, West Dike and East Dike) would be more likely.

- The current low point of the Saddle Dam is just above the crest elevation of the concrete structures of the Main Dam and thus the Saddle Dam dam would be overtopped under PMF conditions. The crest of the Saddle Dam has settled approximately 2 m since construction and is continuing to settle at a reduded but still significant rate.

- The foundation treatment of the rock under the Main Dam was extensive and well executed during construction. The treatment consisted of several rows of holes establishing a grout curtain, including consolidation and contact grouting. Drainage holes were then drilled to provide drainage within the foundation bedrock and at the contact of the rock/dam interface. Measured uplift pressures at the contact and within the bedrock indicate that the uplift pressures are well below the limiting values. Despite this extensive treatment, leakage into the drainage system increased after construction to the extent where remedial grouting was required to reduce the seepage. This is an indication that the structural nature of the bedrock is complex and there may still be unknown features in the foundation bedrock that could influence the stability of the concrete gravity structures.

- Movement of the downstream surface of the East Dike has been measured by instrumentation. This historical movement is believed to be a gradual mass movement in the upper 3 to 5 metres of the downstream shell. The berm placed recently to buttress the downstream slope of the East Dike should help to control this movement

- . A possible deeper seated movement in the East Dike, which was suspected based inclinometer results in conjunction with the observation of surface movements, does not appear to exist. The measured movement under the East Dike at foundation contact was found to be in the upstream direction and to the right, and was not believed to indicate the initiation of a slide. No movement in this area has taken place over the past 12 years and it is now believed that this apparent movement and anomalous readings related to problems with the inclinometer casing installation.

- The behavior of the Saddle Dam is largely influenced by the response of the foundation material under the dam, rather than by the response of the dam and weight berms themselves. The vulnerability of Saddle Dam is therefore in the foundation rather than in the dam itself.

- For Saddle Dam, the strain rate and pre-consolidation pressures in the foundation material are both marginal with respect to stability.

Risk Reduction Recommendations

- Protect the transformer area adjacent to the powerhouse against flooding if the Main Dam is overtopped.

- Establish how much and where excess flow (above spillway and power flow capacity) would go and where potential overtopping should occur. This includes evaluation of the procedure, timing and legal implications of using, or not using, the emergency (blast apart) sluice way to discharge flow. Then as appropriate:
    - Configure West Dike fuse plug to be operational or leave as currently configured and indicate in operational manual that it is not intended to be used
    - Raise Saddle Dam or use it as the emergency spillway / overtopping outlet
    - Install removable stop logs in the emergency spillway bays and cut out concrete plugs or establish procedures for removal of the bays by blasting

- Establish procedures for prompt interpretation of instrument readings at the Saddle Dam and establish limits and responses for each relevant Failure Mode based on those readings.

- Clarify the design, location and operation of the fuse plug in the West Dike.

- Route the floods with the upstream parapet and protected transformer considered to be in place.

- Consider Adoption of System Wide Reservoir Operational Procedures

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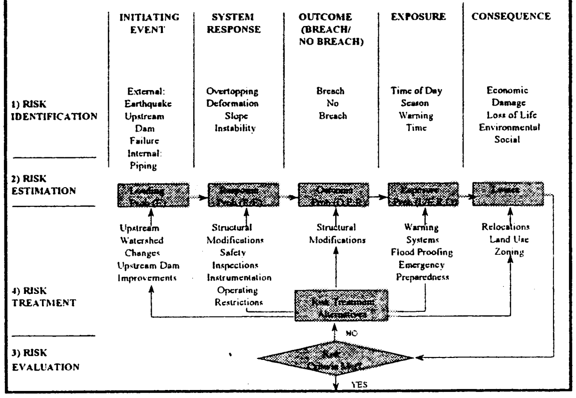
March [redacted] 200[redacted]

Loren R. An[redacted]on

Framework Components

Risk Assessment Framework



Risk Assessment Framework

- Five Steps
  - Initiating Event
  - System Response
  - Outcome
  - Exposure
  - Consequences

Risk Assessment Framework

- Four Phases
  - Risk Identification - the FMEA
  - Risk Estimation
  - Risk Evaluation
  - Risk Treatment - the FMEA will contribute

Risk Assessment Needs Risk-Based Criteria

- Life Safety
- Economic
- Environmental
- Social

Carrying out a FMEA

Advance Work

Advance Work is needed to Understand the System

- Structural and Hydraulic design
  - Threshold loads
  - Maximum loads
- Construction history
- Performance history
- Site conditions
- Consequence Centers

Practice of Subsurface Engineering

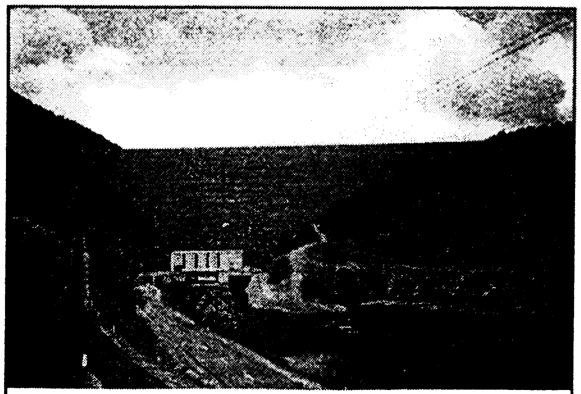
- Subsurface engineering is an art; soil mechanics is an engineering science… We would do well to recall and examine the attributes necessary for the successful practice of subsurface engineering. There are at least three: knowledge of precedents, familiarity with soil mechanics, and a working knowledge of geology… Peck (1962)

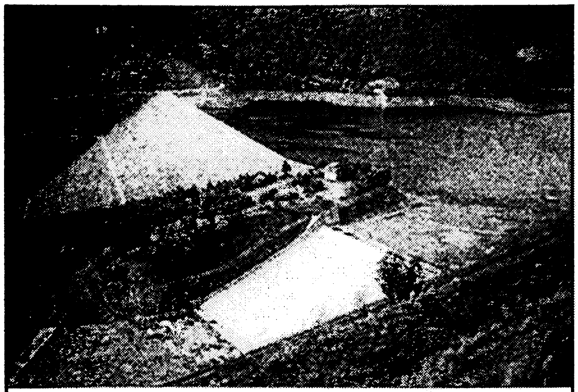
Big Dam
Risk Assessment
Engineering Team

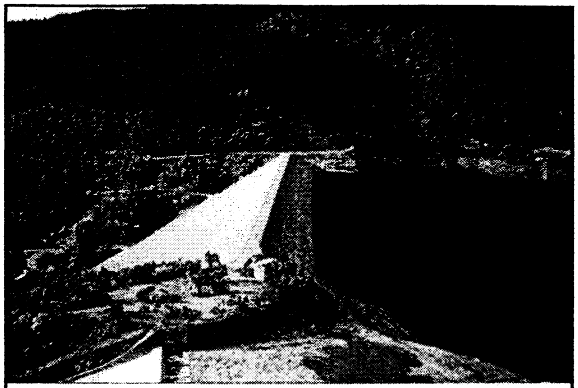
- Ian Howley
- David Stewart
- Raff Gangi
- Terry Court
- David Jeffery
- Kevin O'Brien
- Barrie Smith
- Tim Reid
- Loren Anderson

Big Dam

- Team meeting to understand the dam
- Site visit
  - Understand the dam
  - Identify failure modes
  - Identify risk reduction alternatives
- Team meeting
  - Identify failure modes
  - Develop event tree







Importance of Site Visit

- Understand the potential failure modes
- Understand potential risk reduction alternatives
- Understanding of surficial features
- Understand the setting

Big Dam

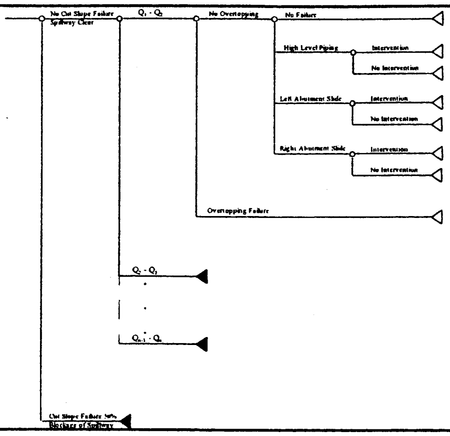
- Team meeting after site visit
  - Identify failure modes
  - Develop event tree
  - Identify needed analyses
- Team meeting after analyses
  - Discuss analyses results
  - "Trim" the tree

Big Dam Failure Modes

- Hydrologic
  - Cut Slope Failure - above spillway
  - Overtopping
  - High Level Piping
  - Left Abutment
  - Right Abutment Slide
  - Spillway Cut d/s of Ogee

Big Dam Event Trees

- Flood Event Tree

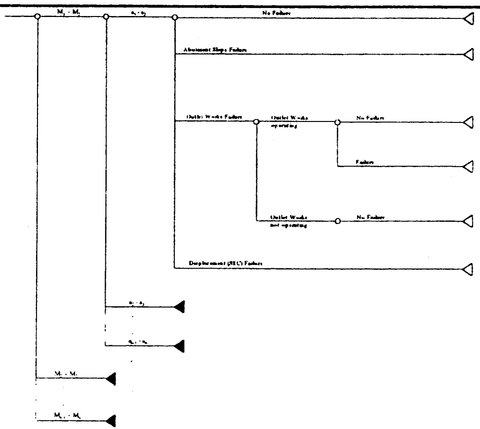


Big Dam Failure Modes

- Earthquake
  - Magnitude / Acceleration
  - Displacement
    - Below Res Elev
    - Disrupt Internal Drainage
  - Abutment Slope
  - Embankment Slope
  - Outlet Works

Big Dam Event Trees

- Flood Event Tree
- Earthquake Event Tree

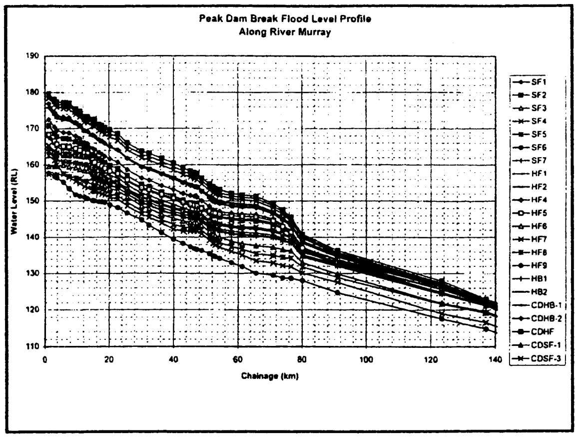


Big Dam Failure Modes

- Internal
  - Piping
  - Embankment Slope Stability
  - Stable Foundation - not a failure mode

Flood Routing is Needed for Consequence Assessment

- Big Dam Flood Routing for a variety of failure modes
- Pick representative routings for detailed consequence assessment



Portfolio
Risk Assessment

- Use of FMEA spreadsheet
- Continual updating of the spreadsheet
- Used a check sheet and rating system

FMECA - Failure Modes Effects Criticality Analysis

Dam:
Type:
Location:
Haz Class (Safe/Crit):
Height:
Res Capacity:
Year Const:
Year Rehab:
Last Report:

Loading	Subsystem	Rating	Failure Mode		Effects	Compensating Factors	Failure Likelihood		Consequences			Remedial Action	
			Description	Analysis			Prob	Confidence	Life Loss	Economic	Criticality	Description	Cost
Hydrologic													
Earthquake													
Internal													

Notes:
Rating refers to rating of the dam according to current criteria

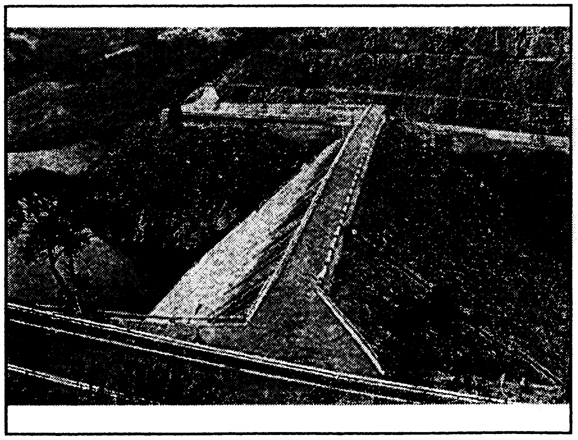
Pass	(P)
Apparent Pass	(AP)
Apparent No Pass	(ANP)
No Pass	(NP)
Insufficient Information	(II)

Potential for Static Failure				Potential for Earthquake Induced Failure		
Embankment Dams		Concrete Dams		Embankment Dams		Concrete Dams
Failure Mode	Rating	Failure Mode	Rating	Liq Material in Dam		
Piping		Concrete Dam Rating		Liq Matrl in foundation		
Slope Stability		Foundation Rating		Outlet Works		
Piping OW				EQ Rating		Rating
Found / Misc						

Potential for Induced Failure from a Hydrologic Event		
Dam Feature	Yes/No	Comment
Unprotected Crest		
Paved Crest		
Parapet wall on crest		
Level Crest		
D/S slope H:V		
Material on D/S Slope:		
Sandy or silty w/ grass		
Dense gravel		
Riprap		
Rockfill		
Unusual geometric condition:		
Concrete Dams		
Foundation Resistant		
Abutments Resistant		

Monitoring/Surveillance	
Rating	

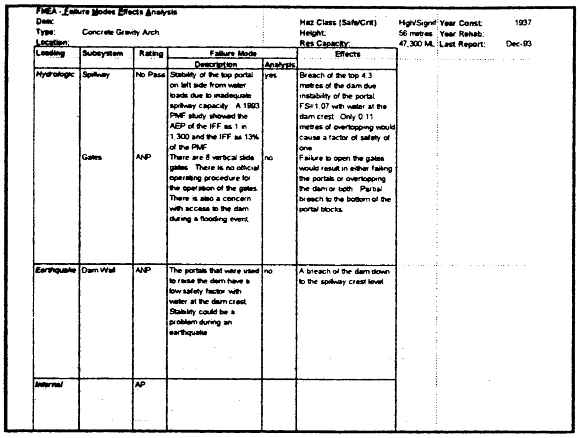
Spillway Assessment	Rating
Structural Assessment	
Hydraulic Assessment	



FMEA - Failure Modes Effects Analysis

Dam:
Type: Concret Face Rockfill
Location:
Haz Class (Safe/Crit): High/Signif
Height: 64 metres
Res Capacity: 19 000 ML
Year Const: 1969
Year Rehab:
Last Report:

Loading	Subsystem	Rating	Failure Mode		Effects
			Description	Analysis	
Hydrologic	Spillway	No Pass	Overtopping due to inadequate spillway capacity The AEP of the IFF is 1 in 8,500 based on the 1995 study The IFF is 23% of the PMF	yes	Overtopping would fall directly on to the d/s face of the dam as the water goes over the added crest structure However this is a rockfill slope and should have some resistance to the flow Failure would result in a breach of the dam
	Spillway	No Pass	Instability of the crest structure during the IFF loading	yes	Breach of the dam
Earthquake	Embankment Wall	ANP	Potential instability of the crest structure	yes	Problem would be above the normal reservoir level and no loss of the reservoir.
	Embankment wall	ANP	Movement of the upstream concrete face and the loss of water stop integrity		Could lead to a breach of the dam; would be a slow breach
	Embankment wall	AP	Settlement of the upstream concrete face at the toe near the grout cap.		There are adequate filters and the settlement should not result in a problem.
Internal	Piping and Slope Stability	AP			



FMEA - Failure Modes Effects Analysis

Dam:
Type: Concrete Gravity Arch
Location:

Haz Class (Safe/Crit): High/Signif
Height: 56 metres
Res Capacity: 47,300 ML

Year Const: 1937
Year Rehab:
Last Report: Dec-93

Loading	Subsystem	Rating	Failure Mode		Effects
			Description	Analysis	
Hydrologic	Spillway	No Pass	Stability of the top portal on left side from water loads due to inadequate spillway capacity. A 1993 PMF study showed the AEP of the IFF as 1 in 1,300 and the IFF as 13% of the PMF	yes	Breach of the top 4.3 metres of the dam due instability of the portal. FS=1.07 with water at the dam crest. Only 0.11 metres of overtopping would cause a factor of safety of one
	Gates	ANP	There are 8 vertical slide gates. There is no official operating procedure for the operation of the gates. There is also a concern with access to the dam during a flooding event.	no	Failure to open the gates would result in either failing the portals or overtopping the dam or both. Partial breach to the bottom of the portal blocks.
Earthquake	Dam Wall	ANP	The portals that were used to raise the dam have a low safety factor with water at the dam crest. Stability could be a problem during an earthquake	no	A breach of the dam down to the spillway crest level
Internal		AP			

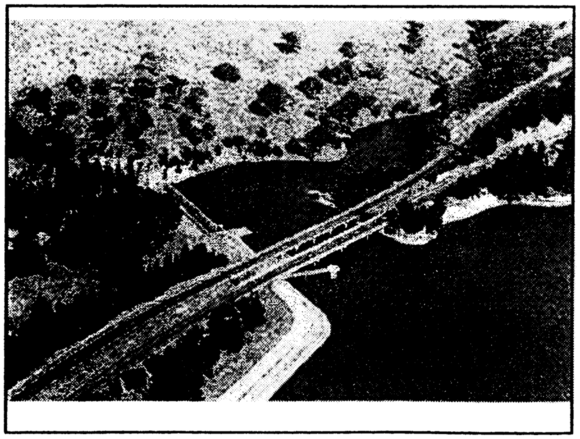
Portfolio Assessment

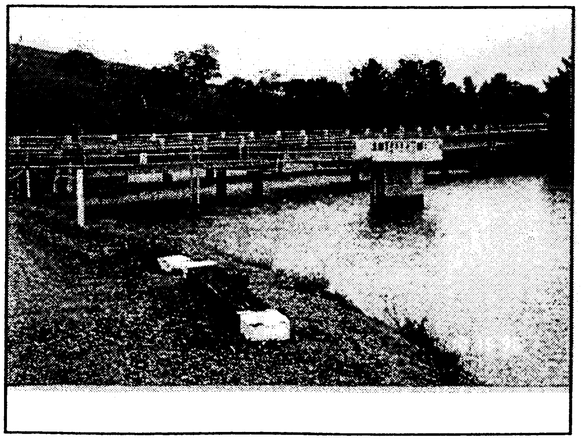
- Better understanding of the dams
- More efficient prioritization of risk reduction alternatives

Examples of Team Synergy

Creek Dam

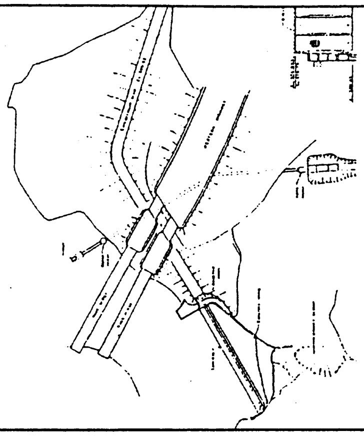
- Perceived Problem
  - Flood capacity of spillway AEP 1:14,000
  - No upstream control of outlet works

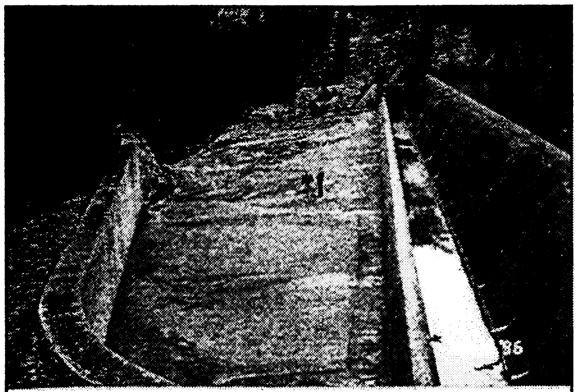


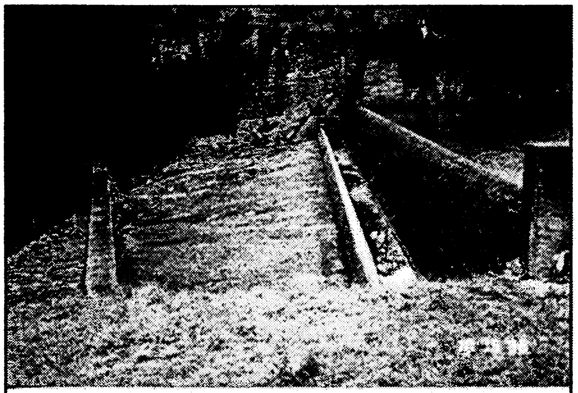


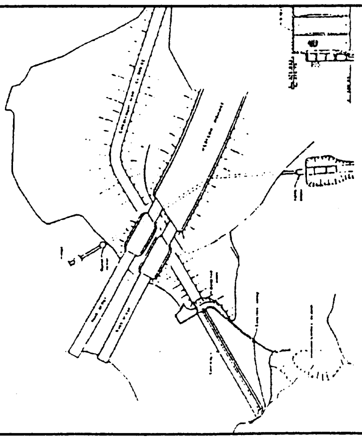
Creek Dam

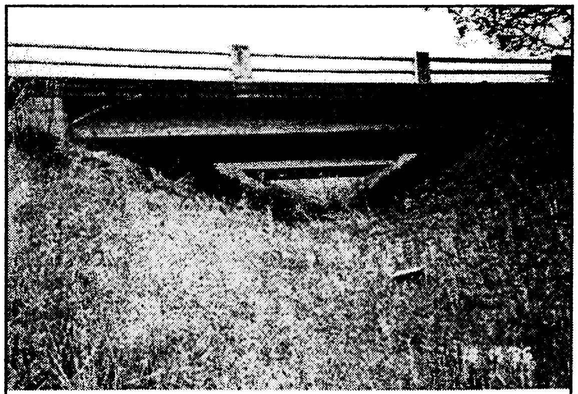
- Perceived Problem
  - Flood capacity of spillway AEP 1:14,000
  - No upstream control of outlet works
- Real Problem
  - Flood capacity of spillway AEP of 1:300









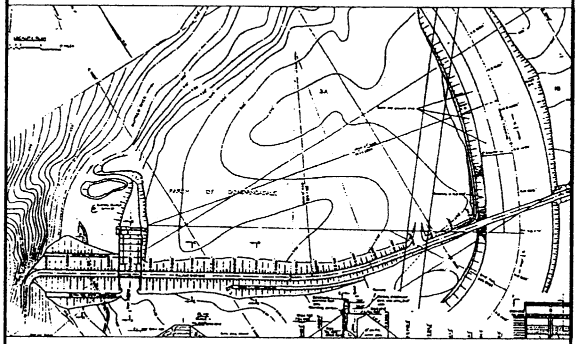


Creek Dam Insights

- Identified a critical failure mode
- Inexpensive repair that could be done immediately
- Improved safety sooner
- Identified other quick fixes
- Understood the dam much better
- Participation of the Dam Tender brought awareness and professional ownership

Lake Dam

- Originally built as a cofferdam
  - Inadequate spillway capacity
  - Concern for the integrity of the outlet works
- Gated spillway - 3 gates
- Lose access to the gates during high flows
- High cost to protect dam from overtopping

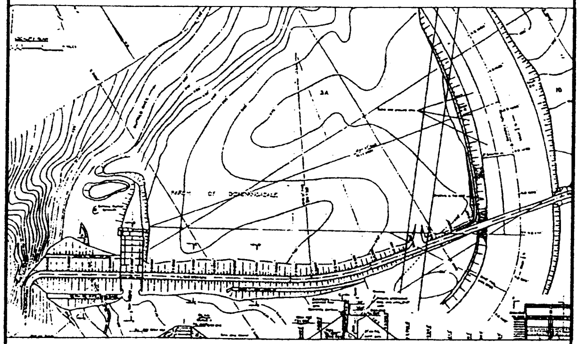


Lake Dam
Flood Failure Modes

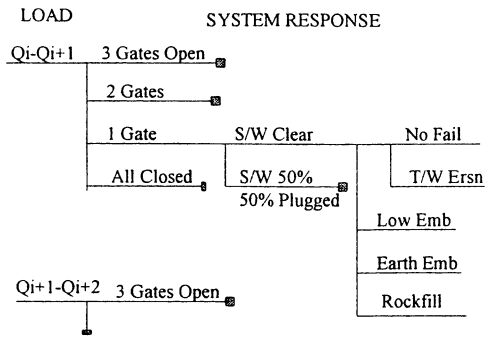
- Overtopping of the Dam from Floods
  - Rockfill (Main Dam) Section
  - Earth Embankment Section
  - Low Embankment Section
- Downstream flooding depends on the section that is breached

System Response Considerations

- Number of spillway gates that are open
  - Time of year
  - Operator availability
  - Mechanical Failure
- Gates plugged?
  - Debris in the reservoir
  - Size of the flood



Hydrologic Event Tree



Lake Dam

- FMEA provided
  - Better understanding of the failure modes
    - Not just the maximum section
  - Better definition of risk reduction alternatives
    - Lower cost alternative
    - Increased safety sooner
  - Better understanding of consequences
    - Effect of warning time on life loss estimates
    - Different flood routing for each failure mode

Horse Dam

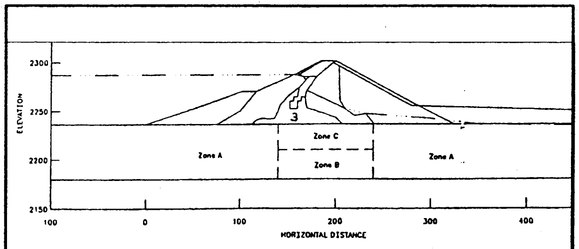
- Concrete Arch Dam on the Salt River
- Primary failure modes
  - Overstress the concrete arch
  - Stability of the right abutment
  - Rock fall from the left abutment into the spillway

Horse Dam

- FMEA gave better understanding of failure modes
  - Spillway plugging became less significant
  - Focused on overstress of dam and abutment failure (had been significant analysis of dam and abutment)

Event Tree Construction

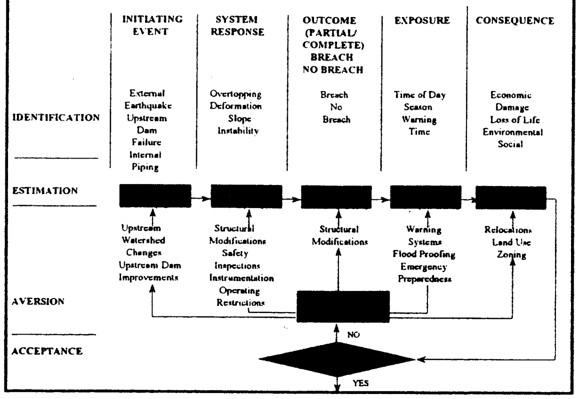
- Earthquake Event Tree for North Dam



MATERIAL PROPERTIES

Zone		CASE					
		Worst		Most Probable		Most Optimistic	
		Ø	C	Ø	C	Ø	C
A	H	0	150	0	250	0	250
	V	0	500	0	500	0	500
B	H	20	0	25	0	30	0
	V	20	0	25	0	30	0
C	H	0	150	0	250	25	0
	V	0	400	0	500	25	0

Risk Assessment Framework



INITIATING EVENT
External
Earthquake
Upstream
Dam
Failure
Internal
Piping

SYSTEM RESPONSE
Overtopping
Deformation
Slope
Instability

OUTCOME (PARTIAL/ COMPLETE) BREACH NO BREACH
Breach
No
Breach

EXPOSURE
Time of Day
Season
Warning
Time

CONSEQUENCE
Economic
Damage
Loss of Life
Environmental
Social

IDENTIFICATION

ESTIMATION

Upstream
Watershed
Changes
Upstream Dam
Improvements

Structural
Modifications
Safety
Inspections
Instrumentation
Operating
Restrictions

Structural
Modifications

Warning
Systems
Flood Proofing
Emergency
Preparedness

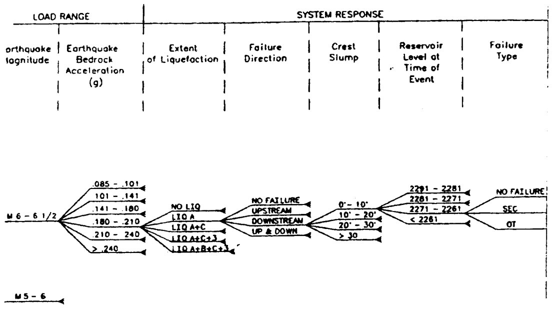
Relocations
Land Use
Zoning

AVERSION

ACCEPTANCE

NO

YES



North Dam Insights

- Looked at full range of loading conditions
- Benefited from a full RA team and support
- Better understanding/definition of failure modes and effective risk reduction alternatives
- Understood the sequence of events for failure to occur
- Identified supplementary analysis and geotechnical investigations that would reduce uncertainty
- Consequence assessment was critical
- Estimation phase also added significantly

Insights for a Pumped Storage Dam

- Confirmed a number of well recognized problems
- No automatic turnoff
- Crest elevation of embankment drops at the junction with the concrete dam
- Long dam with many consequence centers
- More complete understanding of dam performance

SAB Dam Insights Gained

- See list of issues
- See FMEA Chart
- See List of carry forward items

Items for Value Added

- Need to understand design parameters and the performance history of the dam
- Need a well informed team – all team members need to read all material and collectively need experience covering all critical areas
- Need dam performance experience on the team
- Need a final report clearly summarizing all findings and giving direction to the next step

An Owner's Experience with FMEA

Dupak, D.D., Smith, G.F., Bechai, M.
Ontario Power Generation Incorporated

Introduction

Hydroelectric power is a timeless renewable resource that fuelled Ontario's economic growth in the first half of the twentieth century and today accounts for about one-quarter of Ontario Power Generation's [OPGI] electricity production.

The historic importance and future potential of hydroelectric power can be attributed to its low production costs, reliability, flexibility to meet both ongoing base electricity needs and peak demands, and its reliance on water - an indigenous, renewable resource.

Ontario Power Generation operates and maintains 69 hydroelectric generating stations and almost 258 dam structures on 27 river systems across Ontario. The smallest station has a generating capacity of just one megawatt [MW], the largest more than 1,300 MW. Total installed capacity is more than 7,300 MW.

Our facilities are well maintained, and we are carrying out a long-term upgrading program to make more efficient use of water resources and improve environmental performance.

Because many users share the water we depend on, Ontario Power Generation maintains strong partnerships with governments, local industry, environmental groups, recreational users and other community stakeholders.

Background

To ensure the safe and continued operation of our generating stations the Dam Safety Program was created in the mid 80's to assess all of our dams. Ontario Power Generation's Dam Safety Policy commits to maintaining and operating the Corporation's dams in a manner that meets or exceeds the Canadian Dam Association [CDA] Dam Safety Guidelines. Our internal Standards are regularly reviewed to ensure we meet this goal. We have now completed an assessment of all of our dams and have completed all major rehabilitation. We are currently in the process of commencing the first periodic reviews.

Our assessments and periodic reviews are based on the CDA approach, which is primarily a Standards-based approach. Typically this means analysing the dam for normal and extreme loading conditions.

The dam safety industry began exploring the applicability of risk-based methods to dam safety a number of years ago. We have followed these developments closely. However, it is clear that there are still many uncertainties with the application of these methods to dam safety assessments. In 1998 we explored the value of applying Failure Modes and Effects Analysis [FMEA] as an add-on to our standards-based assessments. A pilot project was undertaken which is described in this presentation.

Pilot Objective

The objective of this pilot project was to go beyond the traditional methods of analyzing the safety of our dams and attempt to identify dam safety related aspects of the river and dam system and station operation that may not have been explicitly covered by the Standard-based method. This, we hoped would broaden our perspective of dam safety issues and allow us to readily identify adverse situations or circumstances that could lead to a safety related incident. The intent was to review and assess the impact various initiating events would have on our dams to ensure ourselves, that the qualitative aspects are not overlooked.

The expectation of FMEA was to identify deficiencies in the existing information, data and analyzes, establish the need for further investigations and studies if required, identify the need for monitoring and detection requirements and identify the critical components for the continued safe operation of the dam.

Pilot Project Organisation

The project team was assembled with representation from Ontario Power Generation and an Engineering Consultant under the guidance of a Facilitator. Team members were selected based on their knowledge and understanding of the dam and its appurtenant structures and incorporated the following disciplines:

- Hydraulic
- Structural
- Geotechnical
- Mechanical/Electrical
- Plant Group/Operations

Ontario Power Generation assumed the lead role in planning, co-ordinating and administering the project. In addition, engineers familiar with the dams participated in the technical development of event scenarios and assessment.

The Engineering Consultant provided administrative and technical expertise in managing and participating in the project. Prior to undertaking this component of the project the consultant completed the standards-based periodic review that formed the basis for conducting the study. In addition the consultant assembled and documented the input from the meetings and team members, prepared the report and presented the results for technical review.

A facilitator with experience in FMEA applications for dams was retained by Ontario Power Generation to guide the team during meetings. The facilitator reviewed the aspects of the dam and became familiar with the dam safety studies; lead the team meetings and provided advice and guidance with respect to conducting the study. The facilitator also carried out a technical review of the report.

Additional support resources within Ontario Power Generation were required from time to time to answer specific questions raised during team meetings. These support resources were brought into or consulted during the process as required.

Training

During the initial project stages it was recognized that the individuals who would be involved in completing the FMEA did not have sufficient background or knowledge. In addition different consultants were used on the two project pilot studies. Therefore to maintain consistency in understanding and application of the methodology a training workshop was conducted.

The training consisted of a 2-day workshop lead by Larry Von Thun, David Bowles and Loren Anderson. This provided OPGI dam safety and plant group staff and several consultants the opportunity to learn about the process. In addition a considerable amount of background literature was provided to keep everyone abreast of this type of work.

However, it was recognized that the bulk of the learning would occur during the actual FMEA.

Process

The process followed during the pilots consisted of the following key components.

- Review of Existing Data and Information
- Site Inspection
- Development of Event Sequence

- Identification of Failure Modes and Effects
- Consequence Analysis
- Qualitative Assessment
- Identification of Mitigating Factors
- Documentation
- Technical Review

The pilots were essentially a learning experience with the intent to apply "lessons learned" upon completion of the work to modify and improve the approach and process.

Review of Existing Data and Information

Data and information for the study was derived from existing dam safety inspection and assessment reports, instrumentation and monitoring, design, construction, operation and maintenance records and Emergency Preparedness Plan. A package of information and data was assembled and distributed to all team members at the commencement of the project. No new analysis was undertaken. The need for additional analysis if required was identified during the study.

Site Inspection

A site inspection of the dam and its appurtenant structures was mandatory to obtain a thorough understanding of the site conditions, operational aspects and performance of the dam. Prior to the site inspection each team member reviewed the available information and considered potential event scenarios to be reviewed during the site inspection.

Most team members were present during the site inspection at which time various event scenarios and their effects were discussed. In addition, discussions took place with the operators and maintenance personnel with respect to the long-term performance and operation of the facility. A good photographic and video record of current site conditions was considered essential.

Event Sequence

We have defined an initiating event as the occurrence of an event that leads to a significant change in the loading conditions imposed on the dam or one of its components. This could be due to flood, earthquake, normal static loading or unusual causes.

It was considered important to identify the loading conditions and also consider the full range of loads to which the structure could be subjected. For example when considering floods, the full range of flood levels should be reviewed from minor floods of frequent occurrence to rare events such as the Probable Maximum Flood. In addition the total range of loading from the threshold of failure to the maximum loading should be considered. If different increments of load result in different impacts, then each increment resulting in a different impact with respect to dam response should be identified. The major initiating events considered were:

- Hydrologic [flood]
- Seismic [earthquake]
- Static [normal operating conditions]
- Unusual [vandalism, fire, etc]

Failure Mode Identification

The identification of failure modes provided the basis for determining the consequences of failure due to an initiating event. This required a critical review of the dam, its systems and sub-systems identifying those components that could fail.

An attempt was made to identify and describe all possible failure modes regardless of their likelihood of occurrence.

Effects - Dam Response Analysis

Dam Response Analysis consisted of the analysis of the dam response to the new loading conditions. Dam response was evaluated for the range of loading conditions imposed by various initiating events. The FMEA went beyond a stability assessment reviewing situations such as malfunctioning of the sluiceway, overtopping, piping, operator error, etc. All items that could affect the safe operation of the dam were reviewed and assessed.

All credible event scenarios were identified regardless of their likelihood of occurrence. Event scenarios that can be demonstrated to be physically impossible were noted for the record, described and eliminated.

An FMEA is generally descriptive in nature and is presented in a technical report format with all related aspects summarized in a tabular format.

Consequence Analysis

Consequence analysis involved estimating the effects of the event scenario and dam response both upstream and downstream of the dam. In order for emergency personnel to respond to a dam safety incident a clear picture of the consequences was provided. The philosophical approach was to actively seek the answer to the question:

> ***"What would happen?"***
> ***"Who and what would be affected?"***

The analysis consisted of the identification of all potential losses that might be incurred. This involved the determination of:

- life safety issues
- potential impact on property
- environmental impacts
- socio-economic impacts

The nature and magnitude of consequences was estimated based on field surveys, inundation mapping and discussions. The discussion of breach characterization and resulting consequences was intended to develop an understanding of the sequence of events that occur relative to detection, intervention, warning notification and evacuation in order to identify potential vulnerabilities in the Emergency Preparedness and Response Plan [EPRP] process and/or to identify potential improvements to the EPRP.

In these studies incremental consequences was used. The incremental consequences are equal to the losses that would occur with dam breach minus the losses that would occur without dam breach for the same initiating event.

Qualitative Assessment

Through the development of various event scenarios an assessment of the impact they could have on the integrity of the dam system was performed. The assessment was made with respect to the ability of the dam to adequately and safely respond to circumstances that could have repercussions on life safety, environmental protection and economic impacts.

Typically a study at this initial level does not possess sufficient information or analysis to make a decision on dam modifications. However, it may help prioritise decisions made under the standards-based assessment.

Mitigating Factors

A monitoring and surveillance program is critical to the early detection of the development of a potential dam safety incident. In this context the current monitoring and detection practice was reviewed and assessed as to whether it appeared adequate. If methods of detecting a dam safety incident were not provided or were less than what is considered acceptable, the FMEA recommended further studies to improve the instrumentation at the site.

During an initiating event Plant Group staff may be able to take some action to reduce either the likelihood that a dam safety incident will occur or may be able to take action to reduce the severity of the consequences. Current operating practices were reviewed and assessed as to whether these would have a mitigating effect. Additional actions or modification of existing practice were identified to assist in mitigating the adverse effect.

Documentation

Throughout the FMEA process good documentation is essential. As such the results of the assessment were compiled and presented in a report format. Tables, graphs and drawings were used to more clearly explain the results.

The report was expressed in simple terms and completed to sufficient clarity and consistency. Text and/or diagrams were used to clearly describe the logical sequence of events assumed to lead to a dam safety incident. All conclusions and recommendations were presented with the underlying assumptions to indicate their context and limitations.

Some indication was provided in the analysis, assessment and documentation as to the degree of uncertainty in the data and the level of confidence in the results, conclusions and recommendations.

Technical Review

The reports were reviewed by the team members, the facilitator and others within OPGI to provide assurances that the process for conducting the assessment were followed and that the evaluations were consistent with current technology and understanding.

Given that OPGI had limited experience with FMEA analysis, the process and its pilot applications were also reviewed externally.

Benefits

The primary benefit of conducting the FMEA pilot project was an improved understanding of the dam system and its response to an initiating event. Other benefits realised as a result of this study were:

- enabled us to assess the dam system reliability and safety under various operating scenarios
- identified with greater clarity dam safety issues such as operational, debris, mechanical
- identified improvements to detection and intervention measures, such as instrumentation and monitoring
- identified mitigating measures

Conclusions

The development and implementation of FMEA is a good start towards enhancing Ontario Power Generation's dam safety periodic reviews. The process is currently evolving with several improvements identified as a result of these pilot projects.

- better integration with the dam surveillance and monitoring program
- improve and refine the process
- improved knowledge and understanding of the FMEA process

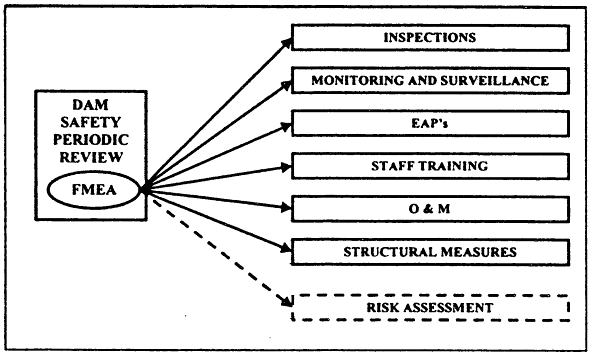
ASDSO/FEMA Specialty Workshop on
Risk Assessment for Dams

Session 2.1 – Qualitative Approaches:

Use of Information from Qualitative Approaches

March 7, 2000

David S. Bowles
Utah State University and RAC Engineers & Economists



DAM SAFETY PERIODIC REVIEW

FMEA

INSPECTIONS

MONITORING AND SURVEILLANCE

EAP's

STAFF TRAINING

O & M

STRUCTURAL MEASURES

RISK ASSESSMENT

Failure Modes & Effects Analysis

Institute for Dam Safety Risk Assessment
Utah State University

ASDSO/FEMA Specialty Workshop on

Risk Assessment for Dams

in association with
USCOLD Committee on Dam Safety
Working Group on Risk Assessment

March 7 - 9, 2000

Workshop Objectives

1) Review and evaluate state-of-the-practice
2) Identify research needs
   - and recommend approaches for addressing these needs

"State-of the-practice"

- Currently being used
- Range of types of decisions
  - Not limited to target safety levels
  - Monitoring and surveillance, reservoir operating level, investigations, etc.
- Recognize different information needs
  - Regulators
  - Owners
  - Engineers

“Research needs”

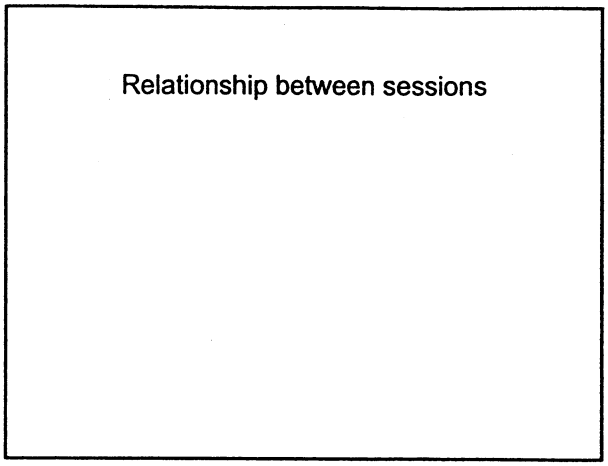
- Short-term
  - Technology transfer needs
  - Training
  - Tools development
- Long-term development

Workshop Approach

- Identify the breadth of information needs
  - government owner, private owner - large and small
  - federal and state regulator
  - engineer
- Do not expect that a single RA approach will meet all needs

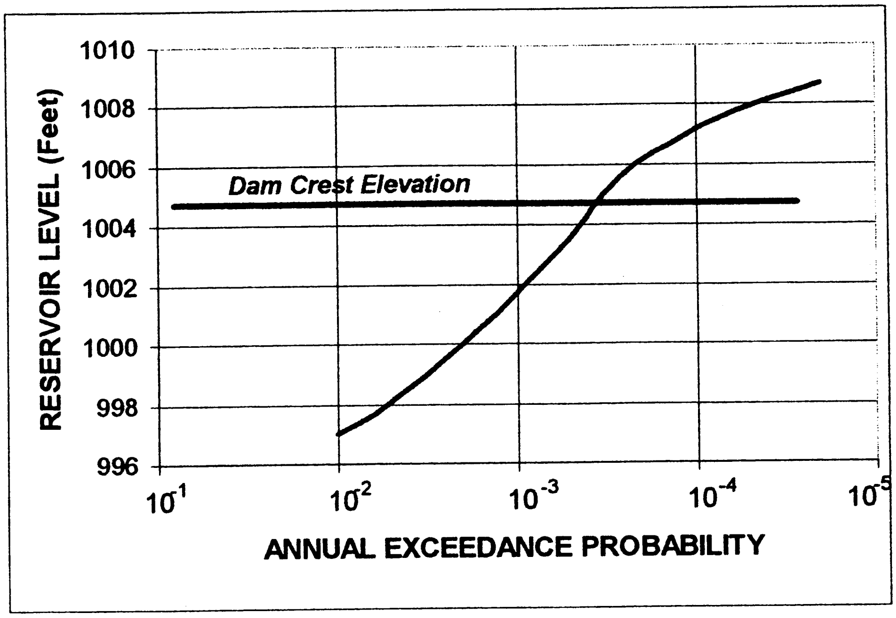
Information Needs will be used as a basis for …

- 1) evaluation of the strengths and weaknesses of current practice:
  - qualitative approaches
  - prioritization and portfolio approaches
  - quantitative approaches
- 2) the identification of research needs



Relationship between sessions

ESTIMATING PROBABILITIES OF EXTREME FLOODS



ASDSO/FEMA Specialty Workshop on Risk Assessment (RA) For Dams

Presented at Utah State University
Logan, Utah

March 8, 2000

by

MG Schaefer Ph.D. P.E.

MGS Engineering Consultants, Inc.

Estimating Extreme Flood Probabilities For Use In Risk Assessment

- *What does End-Product Look Like ?*
- *Where is it Applied ?*
- *What are Current Methodologies/Capabilities ?*
- *What Confidence can be Placed in Results ?*
- *What are Current Limitations/Problems/Needs ?*
- *What Research is Needed to Foster Improvements ?*

MGS Engineering Consultants, Inc

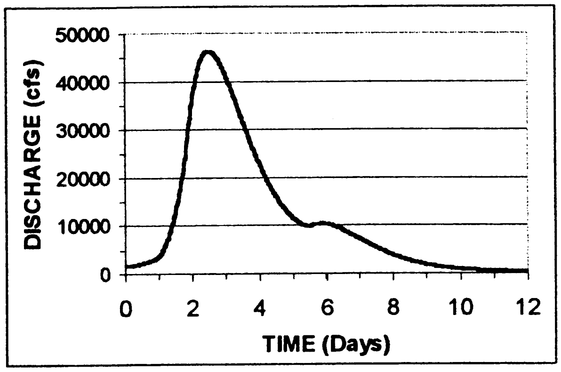
Recent Compendium of Data Needs, Methods of Analysis, Recommended Framework for Estimating Probabilities of Extreme Floods

"A Framework
for Characterizing Extreme Floods
for Dam Safety Risk Assessment"
Nov 1999

prepared by
International Group of
hydrologists,meteorologists and engineers
from United States, Canada, Australia and Europe

Deliverable for Deterministic Flood Analysis

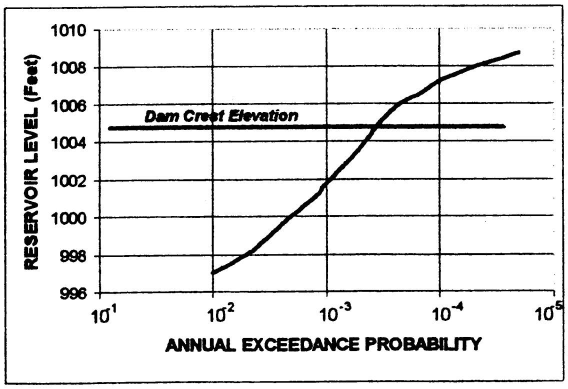
Inflow Design Flood



Maximum
Reservoir Level
Determined by :
Reservoir Routing of
Inflow Design Flood
based on Selected
Initial Reservoir Level
Reservoir Operations

Deliverable for Use in Risk Assessment

Magnitude-Frequency Curve for Reservoir Level



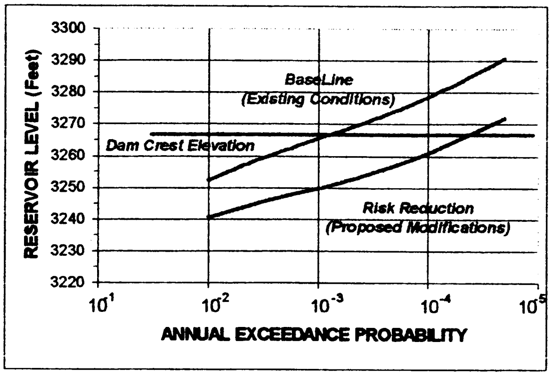
Integrates
Frequency Information
Flood Peak Discharge
Runoff Volume
Hydrograph Shape
Initial Reservoir Level
Reservoir Operations

Applications

Baseline Risk Analysis - Assess Existing Conditions

- *Screening Level - Preliminary Evaluation*
- *Detailed Level - Full Risk Analysis*

Risk Reduction Analysis - Assess Proposed Improvements



Methods and Capabilities

Capabilities Vary Amongst Methods

Desired Capabilities Include:

- ***Develop Magnitude-Frequency Curves for Peak Discharge***
  Runoff Volume
  Reservoir Level
- ***Conduct Analyses on Annual or Seasonal Basis***
- ***Ability to Evaluate Proposed Risk Reduction Measures***
  - Structural Improvements
  - Changes in Operation

Methods and Capabilities

The More Sophisticated Methods are Data Intensive and Require Fewer Assumptions and Judgments

CATEGORIES OF METHODS	CAPABILITIES					
	Peak Discharge	Runoff Volume	Flood Hydrographs	Reservoir Level	Seasonal Analysis	Risk Reduction
Flood-Frequency Analysis of Streamflow Record	x	x			x	
Paleoflood Frequency Analysis	x					
Design Event Rainfall-Runoff Modeling	x	x	x	x	x	x
Stochastic Rainfall-Runoff Modeling	x	x	x	x	x	x

State of the Art   State of the Practice

State of the Art

Atmospheric Modeling and Distributed Rainfall-Runoff Modeling (BChydro)

Data Generation and Continuous Simulation Modeling (UK)

Evolving from Art to Practice

Stochastic Event Rainfall-Runoff Modeling, Large Watersheds (USBR, COE)

Combining Regional Paleoflood Frequency with Other Methods (USBR)

State of the Practice

At-Site Flood-Frequency Analysis

Regional Flood-Frequency Analysis

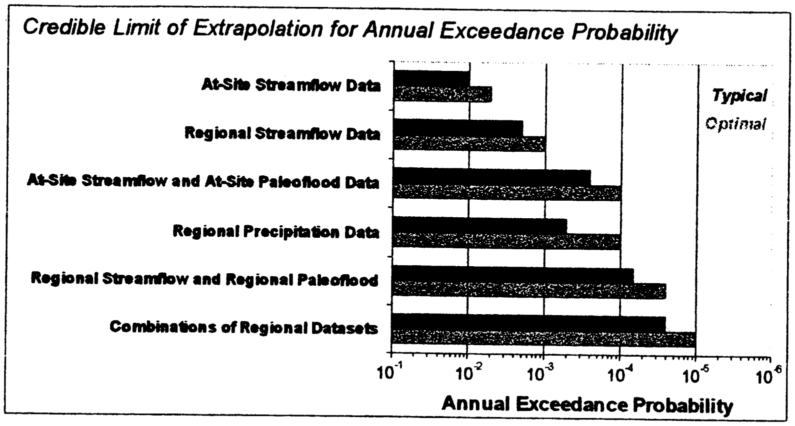
At-Site Paleoflood Frequency (USBR)

Design Event Rainfall-Runoff Modeling - AEP Neutral (Australia, UK)

Stochastic Event Rainfall-Runoff Modeling, Watersheds < 500 mi^2 (USBR)

Methods and Capabilities

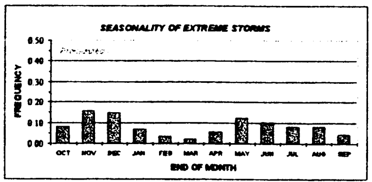
Calculation/Extrapolation Limits Based on Quantity and Quality of Available Data

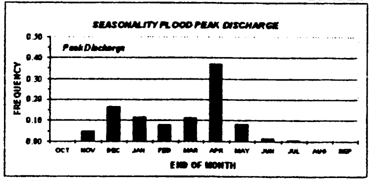


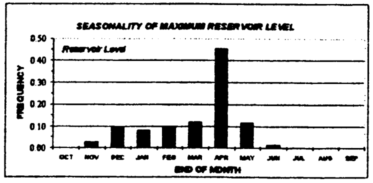
Stochastic Rainfall-Runoff Modeling
Basic Approach

1) *Use Deterministic Rainfall-Runoff Model*
2) *Treat Hydrometeorological Input Parameters as Variables*
3) *Stochastically Generate Multi-Thousand Years of Storms (Magnitude, Temporal and Spatial Distribution)*
4) *Select Values of Hydrometeorological Parameters to Accompany each Storm using Monte Carlo Methods*
5) *Compute Multi-Thousand Flood Annual-Maxima using Hydrologic Model and Assembled Datasets*
6) *Conduct Frequency Analyses of Hydrologic Model Outputs*
   for:
   Flood Peaks
   Runoff Volumes
   Reservoir Levels

Methods and Capabilities
Seasonality Analyses

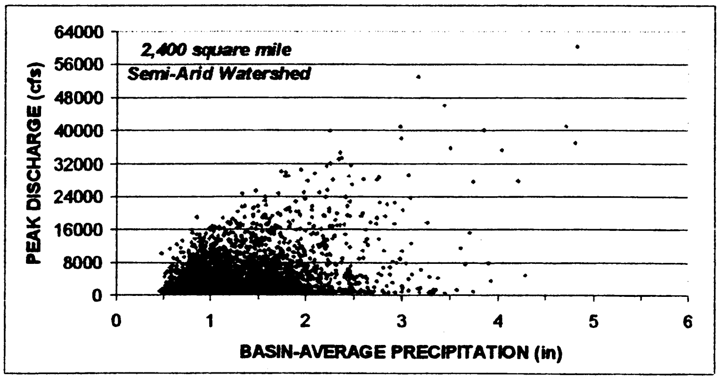


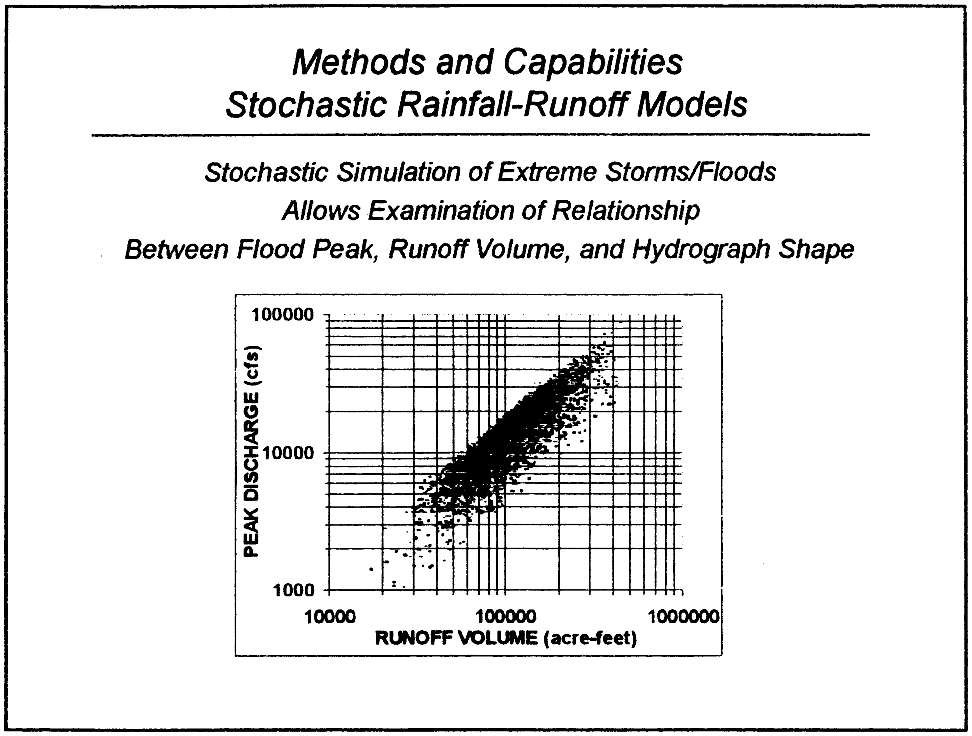




Methods and Capabilities
Stochastic Rainfall-Runoff Models

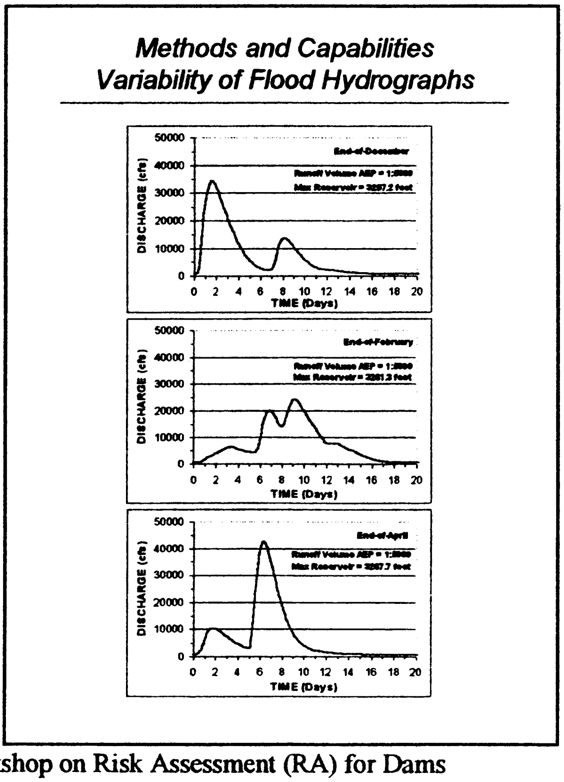
Stochastic Simulation of Extreme Storms/Floods
Allows Examination of Relationship
Between Storm Magnitude and Flood Magnitude





Methods and Capabilities
Stochastic Rainfall-Runoff Models

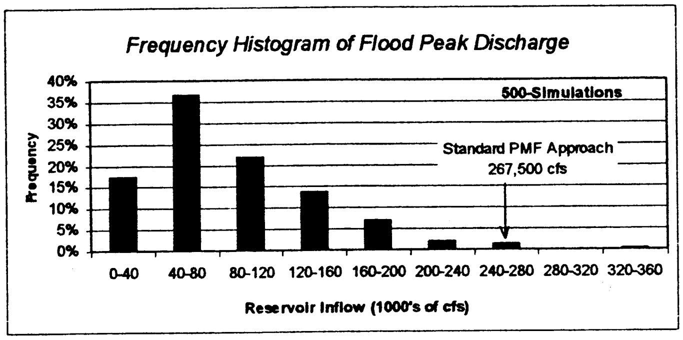
Stochastic Simulation of Extreme Storms/Floods
Allows Examination of Relationship
Between Flood Peak, Runoff Volume, and Hydrograph Shape



Methods and Capabilities
Variability of Flood Hydrographs

Methods and Capabilities
Stochastic Rainfall-Runoff Models

Stochastic Simulation of Extreme Storms/Floods
Allows Examination of Flood Characteristics
Conditioned on Occurrence of 24-Hour PMP



Confidence/Reliability of Results

Limit of Credible Calculation/Extrapolation

- *10^{-4} AEP using Single Method*
- *10^{-5} AEP using Multiple Methods*

Level of Confidence in Results based on :

- *Which Hydrometeorological Inputs have the Greatest Effect on Flood Outputs*
  - *- Quantity/Quality of Pertinent Data*
  - *- Level of Knowledge of Pertinent Processes*
- *Success in Calibration of Hydrologic Model to Large Historical Floods*
- *Corroboration of Results from Other Methods*

Current Limitations/Problems/Needs

Large Watersheds - Problems Posed by Spatial Variability

- *Spatial and Temporal Distribution of Storms*

Characterization of Uncertainties

- *Need for* ***Practical*** *Methodology for Developing Uncertainty Bounds*
  - *Convey Information about Uncertainties in Manner* ***Useful*** *to Decision-Makers*

Reconciling Differences Between Methods

- *Peak Discharges of Paleoflood Estimates and Other Methods*

Research Needs

- *Comprehensive program for collection of climate, flood and paleoflood data on regional basis to support regional analyses*
- *Continued support for the development of methods for processing hydrologic information for characterizing extreme floods*
- *Development of procedures for better understanding and incorporating uncertainty in the characterization of floods - in a manner useful for decision-makers*
- *Studies to investigate spatial distribution of storms for Large Watersheds (>5,000 mi^2) using probabilistic methods*

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A FRAMEWORK FOR CHARACTERIZATION OF EXTREME FLOODS FOR DAM SAFETY RISK ASSESSMENTS

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Abstract

Risk-based decisions require different types of information than standards-based decisions. Traditional sources of information used for estimating probabilities of extreme floods include gaged streamflow records, indirect discharge measurements, and precipitation records. Generally these data sources have records that are less than 100 years in length. This framework for flood characterization for risk assessments uses the length of the data record and other characteristics of the data to determine the credible extrapolation limits used in the flood frequency analysis. Because risk assessments require estimation of floods with annual exceedance probabilities of 1 in 10,000, or less, emphasis is placed on developing probabilistic estimates using regional hydrometeorological data and paleoflood information. The uncertainties associated with descriptions of flood flow exceedance probabilities are likely to be substantial and an important attribute to convey into the risk assessment.

No single approach is capable of providing estimates of extreme floods over the full range of annual exceedance probabilities required for risk assessment. Therefore, results from a number of approaches need to be combined to yield a composite flood characterization; this means several methods and sources of data are needed. The application of several independent methods applicable to the same range of annual exceedance probabilities will increase the credibility and resulting confidence in the results.

Introduction

The U.S. Bureau of Reclamation is now making extensive use of quantitative risk assessment in support of dam safety decision making (Von Thun and Smart, 1996). An important input to Dam Safety Risk Assessment is the development of probabilistic extreme flood estimates. This shifts the focus for dam safety flood evaluation from routing a single "maximum" event (i.e. the probable maximum flood, PMF) to consideration of the entire range of plausible inflow flood events, and ultimately to the magnitude-frequency relationship of maximum reservoir stages.

For floods, the risk assessment process involves selecting a spillway evaluation flood (SEF) based on the probability of dam failure and the severity of the incremental

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consequences of dam failure. Past practice also examined consequences, but without formal consideration of probability of failure; if consequences were judged to be large, the SEF was chosen as the PMF.

Reclamation has identified the need for a review of its present procedures for developing probabilistic extreme flood estimates and their associated uncertainties for use in dam safety risk assessment. Where practical, Reclamation would like to develop improved procedures. The overall objective is to develop a practical, robust, consistent, and credible framework for developing probabilistic extreme flood estimates for Dam Safety Risk Assessment. The desired outcome is a robust framework in which components can be improved in the future as the state-of-the-art develops.

The framework was developed by inviting a group of approximately 20 professionals with extensive experience in the theoretical and practical aspects of physical, paleo-, and statistical flood hydrology and hydrometeorology to participate in a one-week workshop held at Utah State University in June 1997. Participants from North America, Australia, and the United Kingdom reviewed current Reclamation practice, and evaluated various advances in developing probabilistic extreme flood estimates for their potential role in the needed framework. A smaller group met in Denver to develop the details of the framework. This paper summarizes the findings of these groups.

Risk Assessment Stages

Present Reclamation risk assessment practice uses a staged approach for conducting risk assessments (USBR, 1997a). Project schedule and budget constraints are considered in determining the type of flood assessment prepared at each stage. While each risk assessment is unique, the following stages are generally used in Reclamation risk assessments:

a) **Screening Level Risk Assessment**: An evaluation of risk that includes definition of load probabilities and consequences for all load classes (flood, earthquake, and static). Structure failure probabilities and associated uncertainties are also considered in a global sense, but detailed event trees are not usually prepared. An emphasis at this stage is to maximize the use of available information, without conducting new analyses or collecting additional data. The intent is to identify areas where risks are potentially high and to determine the need for further evaluations and data collection. Results of these evaluations are used to determine Reclamation's risk profile and to "screen" out dam safety issues where additional funding and effort appears to have little potential for reducing dam safety risks.

b) **Scoping Level Risk Assessment**: A more detailed evaluation of risks is performed for the dam safety issues identified in a screening level risk assessment. This level of risk assessment typically involves more detailed treatment of event trees, load probabilities, structural response, and consequences. The intent is to invest sufficient effort so that the risk assessment team understands the major contributors to risk to enable formulation of risk reduction strategies and to determine the need for additional analyses and investigations.

c) **Decision Level Risk Assessment**: At this level, more detailed evaluation of risks is performed to provide decision makers with the information necessary to reach a dam safety decision for a structure. The decision may be related to continuing project operations, correcting dam safety deficiencies, selecting among risk reduction alternatives, or determining the need for interim actions to reduce risk while long term plans are developed. The intent is to provide decision makers with sufficient pertinent risk information such that the risk reduction objective can be effectively considered along with other Reclamation objectives. At this level of risk assessment, detailed loading information, structural response analyses, and consequence evaluations are developed for all significant issues. This type of risk assessment focuses on reducing uncertainties in the risk estimates and evaluating risk reduction actions.

Data Sources

The proposed framework for developing probabilistic extreme flood estimates for risk assessment uses the length of record and other characteristics of the data to determine the extrapolation limits for flood frequency analysis. Traditional sources of information used for flood hazard analyses include streamflow and precipitation records. Generally, these data sources have records that are less than 100 years in length, although in some cases these records can be extended to about 150 years using historical information. Regional precipitation and streamflow data can create pooled data sets from short periods of observation, and paleoflood data can extend records of floods to periods of up to several thousand years.

Streamflow Data

Many different types of streamflow information are used in developing probabilistic extreme flood estimates for risk assessment. Streamflow data are used in flood hazard assessment as input for frequency studies or as the basis for developing flood hydrographs. The usual source of these data is the streamflow records collected and maintained by the U.S. Geological Survey. However, similar data are collected and archived by many other Federal and State government agencies and some non-government organizations. Streamflow records consist of data collected at established gaging stations and indirect measurements of streamflow at other sites. Streamflow data can include estimates of peak discharge, as well as average or mean discharge for various time periods. Most streamflow measurements on U.S. streams began after 1900 with only a few records dating back that far. Most often, streamflow records at a single site range in length from about 20 to 60 years. Completeness of the data set may vary from station to station.

Climate Data

Precipitation and weather data used in hydrologic models can include rainfall, snowfall, snow water equivalent, temperature, solar radiation, and wind speed and direction from individual weather stations, as well as remote sensing information and radar information for broader regions. Data types available from various sources vary greatly in record length and quality throughout the United States. Some of these types of data (i.e., snowfall, snow water equivalent, solar radiation, and wind) are limited to record lengths of less than about 30 years; basic rainfall and temperature data are available for some stations for up to 150 years, but in most cases are limited to less than 100 years.

Historical Data

Historical data can provide a means for extending the length of record for many types of data, in particular for observations of the most extreme events. These data are most commonly used to extend streamflow records of peak discharge prior to organized stream gaging. Historical observations can provide information for other types of data such as weather patterns and the frequency of extreme storm events, or changes in land use or vegetation that may be significant to runoff modeling calculations. However, as with any type of historical data, the accuracy and validity of the observations must be carefully assessed and compared to the other types of data used in the analysis.

Paleoflood Data

Paleoflood hydrology is the study of past or ancient flood events which occurred prior to the time of human observation or direct measurement by modern hydrological procedures (Baker, 1987). Unlike historical data, paleoflood data do not involve direct human observation of the flood events. Instead, the paleoflood investigator studies geomorphic and stratigraphic records (various indicators) of past floods, as well as the evidence of past floods and streamflow derived from historical, archeological, dendrochronologic, or other sources. The advantage of paleoflood data is that it is often possible to develop records that are 10 to 100 times longer than conventional or historical records from other data sources in the western United States. In addition, the paleoflood record is a long-term measure of the tendency of a river to produce large floods. In many cases, paleoflood studies can provide a long-term perspective, which can put exceptional annual peak discharge estimates in context and assist in reconciliation of conflicting historical records.

Paleoflood data generally include records of the largest floods, or commonly the limits on the stages of the largest floods over long time periods. This information can be converted to peak discharges using a hydraulic flow model. Generally, paleoflood data consist of two independent components. One component is a peak discharge estimate; the second is a time period or age over which the peak discharge estimate applies. Paleoflood studies can provide estimates of peak discharge for specific floods in the past, or they can provide exceedance and non-exceedance bounds for extended time periods. Each of these differing types of paleoflood data must be appropriately treated in flood frequency analyses.

Extrapolation Limits for Different Data Types

The primary basis for a limit on credible extrapolation of extreme flood estimates derives from the characteristics of the data and the record length used in the analysis. The data used in the analysis provide the only basis for verification of the analysis or modeling results, and as such, extensions beyond the data cannot be verified. Different risk assessments require flood estimates for different ranges of annual exceedance probability (AEP), and therefore analysis procedures and data sources should be selected to meet project requirements. The greatest gains to be made in providing credible estimates of extreme floods can be achieved by combining regional data from multiple sources. Thus, analysis approaches that pool data and information from regional precipitation, regional streamflow, and regional paleoflood sources should provide the highest assurance of credible characterization of low AEP floods.

For many Reclamation dam safety risk assessments, flood estimates are needed for AEPs of 1 in 10,000 and ranging down to 1 in 100,000, or even lower. Developing credible estimates at these low AEPs generally require combining data from multiple sources and a regional approach. Table 1 lists the different types of data which can be used as a basis for flood frequency estimates, and the typical and optimal limits of credible extrapolation for AEP, based on workshop discussions or subsequent communications. The limits presented in the table represent a general group consensus; however, opinions differed amongst workshop participants. In general, the optimal limits are based on the best combination(s) of data envisioned in the western U.S. in the foreseeable future. Typical limits are based on the combination(s) of data which would be commonly available and analyzed for most sites.

Many factors can affect the equivalent independent record length for the optimal case. For example, gaged streamflow records in the western United States only rarely exceed 100 years in length, and extrapolation beyond twice the length of record, or to about 1 in 200 AEP, is generally not recommended (IACWD, 1982). Likewise, for regional streamflow data the optimal limit of credible extrapolation is established at 1 in 1,000 AEP by considering the number of stations in the region, lengths of record, and degree of independence of these data (Hosking and Wallis, 1997). For paleoflood data, only in the Holocene epoch, or the past 10,000 years, is climate judged to be sufficiently like that of the present climate, for these types of records to have meaning in estimates of extreme floods for dam safety risk assessment. This climatic constraint indicates that an optimal limit for extrapolation from paleoflood data, when combined with at-site gaged data, for a single stream should be about 1 in 10,000 AEP. For regional precipitation data, a similar limit is imposed because of the difficulty in collecting sufficient station-years of clearly independent precipitation records in the orographically complex regions of the western United States. Combined data sets of regional gaged and regional paleoflood data can be extended to smaller AEPs, perhaps to about 1 in 40,000, in regions with abundant paleoflood data. Analysis approaches that combine all types of data are judged to be capable of providing credible estimates to an AEP limit of about 1 in 100,000 under optimal conditions.

In many situations, credible extrapolation limits may be less than optimal. Typical limits would need to reflect the practical constraints on the equivalent independent record length that apply for a particular location. For example, many at-site streamflow record lengths are shorter than 100 years. If in a typical situation the record length is only 50 years, then the limit of credible extrapolation might be an AEP of about 1 in 100. Similarly, many paleoflood records do not extend to 10,000 years, and extensive regional paleoflood data sets do not currently exist. Using a record length of about 4,000 years, a typical limit of credible extrapolation might be an AEP of 1 in 15,000 based on regional streamflow and regional paleoflood data.

The information presented in Table 1 is intended as a guide; each situation is different and should be assessed individually. The limits of extrapolation should be determined by evaluating the length of record, number of stations in a hydrologically homogeneous region, degree of correlation between stations, and other data characteristics which may affect the accuracy of the data.

Ideally, one would like to construct the flood frequency distribution for all floods that could conceivably occur. However, the limits of data and flood experience for any site or region place practical limits on the range of the floods to which AEPs can be assigned. There does not appear to be sufficient data to justify computation of AEPs less than 1 in 100,000. In general, the scientific limit to which the flood frequency relationship can be credibly extended, based upon any characteristics of the data and the record length, will fall short of the probable maximum flood (PMF) for a site. PMF estimates provide a useful reference to past practice and can be compared with extreme floods characterized for risk assessment. However, the workshop participants concluded that there is limited scientific basis for assigning an AEP to the PMF. For precipitation data, similar limitations apply to extrapolations that approach values described by probable maximum precipitation.

Table 1. **Hydrometeorological Data Types and Extrapolation Limits for Flood Frequency Analysis**

Type of Data Used for Flood Frequency Analysis	Limit of Credible Extrapolation for Annual Exceedance Probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 750	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

Methods of Analysis

At Site Flood Frequency Analysis

Frequency analysis is an information problem: if one had a sufficiently long record of flood flows, or perhaps rainfall for a basin, then a frequency distribution for a site could be determined with good precision, so long as change over time due to anthropogenic or natural processes did not alter the distribution of floods. In most situations available data are insufficient to precisely define the annual exceedance probability of large floods. This forces hydrologists to use practical knowledge of the physical processes involved, and efficient and robust statistical techniques, to develop their estimates (Stedinger et al., 1993).

Fitting a distribution to data sets allows both a compact and smoothed representation of the frequency distribution revealed by the available data, and a systematic procedure for extrapolation to frequencies beyond the range of the data set. Given a family of distributions, one can estimate the parameters of that distribution so that required quantiles and expectations can be calculated with the "fitted" model. Appropriate choices for distribution functions can be based upon examination of the data using probability plots, the physical origins of the data, previous experience, or prescriptive guidelines.

Several general approaches are available for estimating the parameters of a distribution. A simple approach is the *method of moments,* which uses the available sample to compute estimators of the distribution's parameters. The Federal guidelines published in Bulletin 17B (IACWD, 1982) recommend fitting a Pearson type 3 distribution to the common base 10 logarithms of the peak discharges. It uses at-site data to estimate the sample mean and variance of the logarithms of the flood flows, and a combination of at-site and regional information to estimate skewness.

Another method that may be used to estimate the parameters of a distribution for at-site frequency analysis is the Expected Moments Algorithm (EMA). EMA (Cohn et al., 1997) is a moments-based estimation procedure and is identical to the existing Bulletin 17B (IAWCD, 1982) approach when no high or low outliers are present. The EMA method was developed to utilize historical and paleoflood information in a censored data framework. This approach explicitly acknowledges the number of known and unknown values above and below a threshold, similar to a maximum-likelihood approach. Three types of at-site flood information are used: systematic stream gage records; information about the magnitudes of historical floods; and knowledge of the number of years in the historical period when no large flood occurred.

Still another method, which has strong statistical motivation, is the *method of maximum likelihood.* Maximum likelihood estimators (MLEs) have very good statistical properties in large samples, and experience has shown that they generally do well with records available in hydrology. In many cases MLEs cannot be reduced to simple formulas, so estimates must be calculated using numerical methods (Stedinger et al., 1988; O'Connell, 1997).

L-moments are another way to summarize the statistical properties of hydrologic data. Sample estimators of L-moments are linear combinations (and hence the name L-moments) of the ranked observations, and thus do not involve squaring or cubing the observed values as do the product-moment estimators. As a result L-moment estimators of the dimensionless coefficients of variation and skewness are almost unbiased and have very nearly a normal distribution (Hosking and Wallis, 1997).

Regional Flood Frequency Analysis

In hydrology, sufficient information is seldom available at a site to adequately determine the frequency of rare events using frequency analysis. This is certainly the case for the extremely rare events which are of interest in dam safety risk assessment. The National Research Council (1988) has proposed several general strategies, including substituting space for time for estimating extreme floods. One substitutes space for time by using hydrologic information at different locations in a region to compensate for short records at a single site.

Three approaches (Cudworth, 1989) have been considered for regional flood frequency analysis: (1) average parameter approach; (2) index flood approach; and (3) specific frequency approach. With the average parameter approach, some parameters are assigned average values based upon regional analyses, such as the log-space skew or standard deviation. Other parameters are estimated using at-site data, or regression on physiographic basin characteristics, perhaps the real or log-space mean. The index flood method is a special case of the average parameter approach. The specific frequency approach employs regression relationships between drainage basin characteristics and particular quantiles of a flood frequency distribution.

Index Flood Method. The index flood procedure is a simple regionalization technique with a long history in hydrology and flood frequency analysis (Dalrymple, 1960). It uses data sets from several sites in an effort to construct more reliable flood-quantile estimators. A similar regionalization approach in precipitation frequency analysis is the station-year method, which combines precipitation data from several sites without adjustment to obtain a large composite record to support frequency analyses. The concept underlying the index flood method is that the distributions of floods at different sites in a "region" are the same except for a scale or index-flood parameter which reflects the size, rainfall and runoff characteristics of each watershed. Generally the mean is employed as the index flood (Hosking and Wallis, 1997).

Average Shape Parameter. As at-site records increase in length, procedures that estimate two parameters, with at-site data to be used with a regional shape parameter, have been shown to perform better that index flood methods in many cases (Stedinger and Lu, 1995). For record lengths of even 100 years, 2-parameter estimators with a good estimate of the third shape parameter, are generally more accurate than are 3-parameter estimators (Lu and Stedinger, 1992; Stedinger and Lu, 1995). However, whether or not it is better to also regionalize the coefficient of variation depends upon the heterogeneity of the regions and the coefficients of variability of the flows. In regions with high coefficients of variation (and high coefficients of skewness) index flood methods are more attractive.

Regional Regression. Regional analysis can be used to derive equations to predict the values of various hydrologic statistics (including means, standard deviations, quantiles, and normalized regional flood quantiles) as a function of physiographic characteristics and other parameters. Stedinger and Tasker (1985, 1986a, 1986b) developed a specialized Generalized Least Squares (GLS) regression methodology to address the regionalization of hydrologic statistics. Advantages of the GLS procedure include more efficient parameter estimates when some sites have short records, an unbiased model-error estimator, and a better description of the relationship between hydrologic data and information for hydrologic network analysis and design.

Design Event-Based Precipitation-Runoff Modeling

Precipitation-runoff modeling is typically used as an event-based method for determining extreme floods. A single set of hydrometeorological parameters and watershed characteristics are used to simulate a design flood event. The major inputs to a design event-based precipitation-runoff model are: (1) climate data (rainfall, snowfall, and other variables needed to predict snowmelt); (2) losses (infiltration/interception); (3) physical watershed characteristics for runoff and routing simulations (drainage areas, watershed and channel slopes, lag times, antecedent moisture, etc.); (4) precipitation-runoff transformation function; and (5) runoff conveyance/routing mechanisms. Model output includes runoff hydrographs at user-specified locations, maximum peak discharges, and total runoff volumes. Examples of this type of model include HEC-1 (USACE, 1990) and RORB (Laurenson and Mein, 1995).

Stochastic Event-Based Precipitation-Runoff Modeling

In the stochastic approach, hydrologic model inputs are treated as random variables. Monte Carlo sampling procedures are used to allow the input variables to vary in accordance with their observed distributions, including the observed dependencies among some climatic and hydrologic parameters. The use of the stochastic approach with regional precipitation information allows the estimation of flood magnitude-frequency curves for flood peak discharge, flood runoff volume, and reservoir level. An example of this type of model is discussed by Barker et al. (1997).

Atmospheric Storm Modeling and Continuous Precipitation-Runoff Modeling

This method combines the work of atmospheric modelers and regional precipitation analysis to derive a precipitation magnitude-frequency curve (Chin et al., 1997). The atmospheric model is used to generate storms over the watershed, and the findings from the regional analysis are used to estimate the annual exceedance probability of point and areal precipitation generated by the model. Using distributed precipitation-runoff modeling, snowpack and other antecedent conditions can be combined to estimate a simulated flood frequency curve using a Monte Carlo approach.

Data Generation and Continuous Simulation Modeling

The data generation and continuous simulation modeling approach is based on Monte Carlo generation of long and detailed sequences of hydrometeorological variables, including precipitation, air temperature, and wind speed and direction. In order to represent spatial differences across the watershed adequately, it is necessary to generate hydrometeorological variables for several sites concurrently. Hydrological models of watershed behavior and hydraulic models of confluences, wave effects and reservoir outlets are used to simulate the reservoir water level continuously. An estimated magnitude-frequency relationship of maximum reservoir stages is input to the risk assessment (Calver and Lamb, 1996).

Combining Methods and Data Types

No single approach is capable of providing the needed characterization of extreme floods over the full range of annual exceedance probabilities that may be required for risk assessment. In particular, characterization of floods with AEPs less than 1 in 10,000 can be expected to require that results from a number of approaches, based on multiple data sources, need to be combined to yield a composite flood frequency description. The application of several independent methods and types of data applicable to the same range of annual exceedance probabilities will increase the credibility and resulting confidence in the results.

Table 2 lists various methodologies that were considered for characterizing extreme floods to support dam safety risk assessment. A flood frequency analysis must be combined with each of these methodologies to assign annual exceedance probabilities to the floods.

The framework developed for Reclamation does not propose a specific methodology for rigorously combining information from these differing data sources and methodologies in an overall statistical framework. In some cases the information may be combined statistically, and in other cases one set of results may be used as a bound on the frequency distribution obtained by analysis of other data. Clearly, this process will require a measure of judgement. Regardless of the approach taken for combining results, it should incorporate sound physical and scientific reasoning for weighting or combining results.

All floods characterized for the risk assessment process should display the uncertainties resulting from the analysis. As the risk assessment moves from the screening and scoping levels to the decision level, uncertainty should be reduced and better quantified so that appropriate information is included in the dam safety decision-making process.

Table 2. Applicability of Hydrologic Methods of Analysis to Various Risk Assessment Levels

Method of Analysis	Risk Assessment Level		
	Screening	Scoping	Decision
Flood frequency analysis	Yes	Yes	Yes
Design event-based precipitation-runoff modeling	No	Yes	Yes
Stochastic event-based precipitation-runoff modeling	No	Yes	Yes
Distributed simulation modeling	No	No	Yes
Atmospheric modeling and distributed precipitation-runoff modeling	No	No	Yes

Evaluation of Uncertainty

Uncertainty can be evaluated by applying Monte Carlo analysis to the overall risk assessment calculations. For example, consider the estimation of threat to life consequences and probability of failure associated with an existing dam and various risk reduction alternatives. One is concerned with uncertainty due to such risk assessment inputs as flood frequency distribution parameters, system response estimates, population at risk, warning time, and estimated loss of life. Then in each iteration of Monte Carlo analysis, one could generate likely values of each of these inputs and evaluate the threat to life and probability of failure. The expected annual life loss and the annual exceedance probability of failure, which are both used as Reclamation Public Protection Guidelines (USBR, 1997b), could be computed for each iteration. By generating many replicates, one obtains samples that describe the possible values of these risk measures (performance metrics).

Averaging over the replicates provides "expected" values of the quantities reflecting both the modeled probability distributions of the phenomena (risk assessment inputs) that are considered to be random variables, and the uncertainty in the parameters describing those distributions. The sample standard deviations describe the variability of the performance metrics. Replicates can be used to estimate frequency distributions which can be used for describing and evaluating the decision implications of uncertainty in the risk assessment inputs.

Calibration to Flood Frequency Quantiles

The ability of a flood event model to reproduce historic events certainly gives some confidence to the validity of subsequent estimates. However, even in a well gaged watershed the annual exceedance probabilities of the calibration floods are likely to range between 1 in 5 to 1 in 20, and only occasionally up to 1 in 100. While it would be expected that floods of these magnitudes will activate some floodplain storage, the non-linear nature of drainage basin flood response is such that the routing characteristics of larger events may be considerably different. Thus, while calibration of a model provides valuable information on the flood response of a drainage basin, caution is needed when using the calibrated model to estimate floods of much larger magnitudes (Pilgrim and Cordery, 1993).

Calibration to flood frequency quantiles using design rainfall inputs can provide important information on flood response characteristics for extreme design events (Nathan and Bowles, 1997; Nathan, 1992). With this approach, design rainfall information is prepared for a specified AEP, and then used with a given set of model parameters and input assumptions to derive a design hydrograph. The peak (or volume) of the design hydrograph can then be compared to the corresponding quantile obtained from a combined at-site/regional flood frequency analysis. The model inputs associated with the greatest uncertainty can be varied within appropriate limits to ensure agreement with the selected flood quantile. Model calibration should be undertaken for a range of AEPs to ensure a consistent variation of parameters with flood magnitude or AEP.

For risk-based studies based on a “design storm concept”, it is necessary to adopt an AEP-neutral approach, where the objective is to derive a flood with an AEP equivalent to its concomitant precipitation (Nathan and Bowles, 1997). The factors that influence the transfer between precipitation and runoff can be characterized by probability distributions, and ideally the design hydrograph should be determined by considering the joint probabilities of all the input factors. Monte-Carlo methods are ideally suited to the AEP-neutral objective, as they accommodate the observed variability of the inputs while still preserving the interdependencies between parameters. Simpler approaches may be appropriate, where the decrease in rigor is offset by the computational convenience and the transparency of the adopted functional relationships. For the least important parameters it may be appropriate to adopt a single representative (mean) value instead of the full distribution. However, the relationship between rainfall and runoff is non-linear, and adoption of a single representative value for the major inputs will introduce bias into the transformation. Accordingly, for more important inputs it is necessary to adopt a joint probability approach. The nature of the method can be tailored to suit the relative importance of the parameter concerned.

Conclusions

A framework has been developed for characterizing extreme floods for the purposes of dam safety risk assessment. By incorporating regional information on precipitation, floods, and paleofloods with good at-site records, it is possible to provide scientifically credible flood estimates to annual exceedance probabilities as low as 1 in 100,000, although higher AEP limits may exist in many cases. In general, the scientific limit to which the flood frequency relationship can be extended based upon available data will fall short of the PMF for a site. PMF estimates provide a useful reference to past practice and can be compared with floods characterized for risk assessment; however, there is limited scientific basis for assigning an annual exceedance probability to the PMF.

No single approach is capable of providing the needed characterization of extreme floods over the full range of AEPs required for risk assessment. Therefore, the results from several methods and sources of data should be combined to yield a composite characterization. The application of several independent methods applicable to the same range of AEPs will increase the credibility and resulting confidence of the results.

Uncertainties associated with descriptions of flood flow exceedance probabilities are likely to be substantial and an important attribute for the characterization of extreme floods. Flood characterization should include a "best estimate" of the annual exceedance probability of floods of different magnitudes and a description of the uncertainty in such results. Such uncertainties need to be honestly represented and considered throughout the risk assessment process.

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A Probability-Neutral Approach to the Estimation of Design Snowmelt Floods

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ABSTRACT

A large number of different methods are available for estimating snowmelt, though few procedures are directly applicable to the practical estimation of design floods in catchments with sparse data. This paper presents a methodology for the estimation of snowmelt design floods in which particular attention is given to ensuring that the exceedance probability of the snowmelt flood is the same as the concomitant rainfall. The method used to estimate snowmelt is based on a water budget approach developed by the U.S. Bureau of Reclamation. The method tracks changes in pack density with time due to changes in energy input and incident rainfall, and provides hourly estimates of the amount of water released from storage. The procedure was incorporated into the RORB runoff-routing model and used to provide estimates of snowmelt floods resulting from rainfalls of a specified exceedance probability. All inputs used to derive the snowmelt floods were selected to be representative of the correlations expected during extreme events. The influence of the antecedent snowpack depth was found to have an appreciable impact on the magnitude of the design flood, and accordingly a simple joint probability approach was adopted to avoid the introduction of bias.

KEYWORDS

snowmelt, design flood, probability, RORB

Hydrology and Water Resources Symposium: Wai-Whenua, November 1997, Auckland, 125-130.

A Probability-Neutral Approach to the Estimation of Design Snowmelt Floods

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SUMMARY: This paper presents a methodology for the estimation of snowmelt design floods in which particular attention is given to ensuring that the exceedance probability of the snowmelt flood is the same as the concomitant rainfall. The method used to estimate snowmelt is based on a water budget approach developed by the U.S. Bureau of Reclamation. All inputs used to derive the snowmelt floods were selected to be representative of the correlations expected during extreme events. The influence of the antecedent snowpack depth was found to have an appreciable impact on the magnitude of the design flood, and accordingly a simple joint probability approach was adopted to avoid the introduction of bias.

1 INTRODUCTION

Snowmelt can have an appreciable impact on the timing and magnitude of floods. While there is a considerable body of literature concerned with the simulation and quantification of snowmelt processes, there is little guidance on estimating the snowmelt component of design floods (ie floods of known annual exceedance probability).

Information on design floods is required in many aspects of civil engineering, including floodplain management and the design of major infrastructure (e.g. roads, bridges, and railways). The assessment of flood risk is of particular importance to the safe design, maintenance and operation of dams. In the past decade, the focus of attention has shifted from the design of new dams, to the periodic assessment of the safety aspects of existing dams.

The hydrologic aspects of dam safety evaluation are concerned with routing large floods through the reservoir to ascertain the adequacy of the spillway. Traditionally, a standards-based approach has been adopted, in which the adequacy of a spillway was assessed by its ability to pass the whole, or a specified fraction, of the Probable Maximum Flood (PMF). More recently, however, design guidelines (1,2) are moving towards a risk-based approach, in which attention is focused on establishing the exceedance probability of the maximum flood that can be safely passed by the spillway.

This shift in design paradigm has an important impact on the design process. In particular, it highlights the dichotomy between two important design concepts that are entrenched in Australian flood guidelines (3): the estimation of floods of known annual exceedance probability (AEP), and the estimation of the PMF. The former design concept is routinely used in the derivation of the more frequent design floods of interest, where issues related to the adoption of median loss rates and temporal patterns of average variability are integral to the process of converting 1:Y AEP design rainfalls to corresponding 1:Y AEP floods. With PMF estimates, average or median values of inputs are rejected in favour of more extreme inputs, where here the intention is to derive "the limiting value of floods that could be *reasonably* expected to occur" (3).

The PMF concept is fundamentally inconsistent with a risk-based approach to design as it is not possible to assign an AEP to such an event. The exceedance probability of the PMF can be decreased by several orders of magnitude by assuming that the factors that influence the transfer function between rainfall and runoff are selected to produce a maximum response (4). Examples of such factors include the areal and temporal distribution of the PMP, retention losses, antecedent conditions, and the assumed degree of catchment non-linearity.

When considering snowmelt runoff, there is a considerable increase in the number of factors that influence the transfer from rainfall to runoff. The salient factors depend on the nature of the transfer function used, but in general it is necessary to consider carefully the inputs related to initial depth and density of the snowpack, the nature and duration of antecedent conditions prior to the rainfall event, windspeed, and the temperature sequence.

In common with the prevailing concepts of the PMF, it is general international practice to maximise all salient factors contributing to rain-on-snow runoff (eg 5, 6, 7, 8, 9). Typically, the antecedent snowpack is set equal to the depth and areal extent corresponding to an extreme event with an exceedance probability of around 1:100, and the wind speed and temperature sequences are selected to maximise runoff. However, as discussed above, such approaches do not allow design floods of a specified AEP to be estimated.

This paper presents a methodology for the estimation of snowmelt floods resulting from extreme rainfall events occurring on catchments that accumulate snow. The main objective of this method is to obtain a probability-neutral transfer between rainfall and runoff, ie to estimate a snowmelt flood with an exceedance probability equivalent to its concomitant rainfall. The approach presented is not complicated, but is suited to the paucity of data typical of many situations for which design snowmelt floods are required.

Reed and Field (10) state that "the snowmelt allowance is one example where preoccupation with the concept of a Probable Maximum Flood seems to have got in the way of a more workmanlike statistical approach". Undoubtedly there remain a number of issues that require an "act of faith" (11) before design estimates of extreme events can be accepted for pragmatic purposes. However, it is intended that the following approach be considered as one example of a "workmanlike" approach that is consistent with a risk-based framework to the evaluation of spillway adequacy.

2 STUDY REGION

The methodology was developed during a study of spillway adequacy of all 17 dams in the Snowy Mountains Hydro-Electric Scheme (Figure 1). The Snowy Scheme consists of a network of dams, tunnels and aqueducts which supply water and electricity to much of south-east Australia. A comprehensive description of the scheme and its components is presented elsewhere (12).

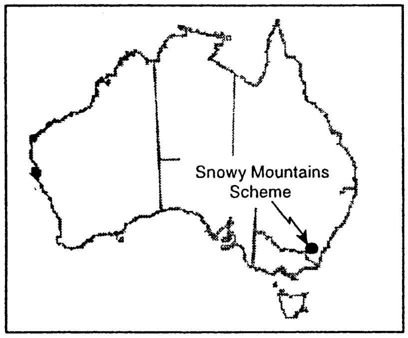

Figure 1. Location of study region.

The Snowy Mountains form an elevated plateau with extensive areas of broad, gently sloping uplands and few conspicuous mountain peaks; the plateau is deeply dissected by the valleys of major rivers.

The climatic data available in the study region includes rainfall, dry bulb and dew point temperatures, wind run, and the number of sunshine hours. This information is available at a number of sites throughout the study area, though generally these elements are only recorded concurrently at sub-daily intervals at one climate station (Cabramurra airstrip), for which around 40 years of record was available. Given the large area of the catchment and the mountainous terrain, it is considered that the spatial coverage of the available data is sparse.

3 SELECTION OF SNOWMELT MODEL

A large number of different methods are available for estimating snowmelt. The variety of available methods reflect the different purposes for which they have been developed, and the different data resources available for their use.

The adopted approach to model selection was to start with as simple an algorithm as possible, and to only increase modelling sophistication if justified by the quality of the results obtained and the nature of the available data. After some initial trials with simple degree-day type approaches and a review of the data requirements of more complex models (13), the method adopted for use was the Snow Compaction Procedure developed by the U.S. Bureau of Reclamation (14). It uses a water budget approach which is based on the concept of snow compaction and a threshold density. Key processes which are represented in the Snow Compaction Procedure are:

- retention of rainfall and snowmelt when snowpack density is less than a threshold value;
- release of stored rainfall and snowmelt when threshold density is exceeded;
- melting of snowpack due to longwave and shortwave radiation, convection and conduction associated with the overlying air mass, advection of energy associated with rainfall, and ground melt;
- compaction of the snowpack due to metamorphosis of its crystalline structure caused by the addition of rainfall.

The potential snowmelt during each time interval is calculated using the U.S. Corps of Engineers generalised snowmelt equations (based on a degree-hour approach) for either open or forested areas (5). Actual drainage from the snowpack is then calculated using a water budget approach in which the amount of water released from storage is evaluated by tracking the snowpack compaction resulting from the addition of rainfall (or temperature-induced melt water). Rainfall and snowmelt will gradually compact the snowpack until the threshold density is reached, whereupon the addition of further water results in an equivalent amount of drainage from the snowpack. Full details of the calculation steps and a discussion on the simplifying assumptions are presented in (14).

The runoff-routing model RORB (15) model was modified to compute the selected snowmelt algorithms. The modified model computes snowmelt for each elevation band within each sub-area, and the snowmelt runoff is routed through the model in exactly the same way as rainfall excess is routed in the original RORB model.

4 SELECTION OF MODEL PARAMETERS

For the adopted approach, the salient factors that influence the transfer function between rainfall and runoff are as follows: the areal and temporal distribution of the PMP, the initial and proportional loss rates, the RORB model parameters that control catchment routing, initial water content and density of the snowpack, and the wind and temperature sequences. Each of these factors can be characterised by probability distributions, and the probability distribution of catchment outflows is determined by the joint probabilities of all the input factors. If reservoir outflows are of interest, then it will also be necessary to consider the probability distribution of reservoir contents.

A full joint probability analysis of all the factors concerned would require a significant investment of effort, and accordingly where possible it is preferable to adopt a single representative (e.g. mean) value instead of the full distribution. This approach has traditionally been adopted in flood event modelling, where, for example, a single value of initial (or continuing) loss is used to derive the design floods. The relationship between rainfall and runoff is non-linear, and accordingly adoption of a single representative value of any of the major inputs will introduce bias into the transformation.

Laurenson (16) proposed a system for evaluating joint probabilities, but for multivariate problems the method is not easily applied. Monte-Carlo techniques are well suited to such problems, but where there is a paucity of data the numerical demands of the approach are perhaps inconsistent with the nature of the design assumptions that can be justified.

The approach adopted here is based on the use of a single representative value for those inputs that have a minor impact on the design outcome, and a simple joint probability analysis is used where the variation of an input over the plausible range of interest has an appreciable impact on the results. A sensitivity analysis was undertaken to determine which of the (less important) inputs could be represented by a single value, and which required a more complex analysis. It was found that the only snowmelt input that needed to be treated in a joint probability fashion was the initial snowpack water content. A joint probability analysis was also adopted for initial storage contents for derivation of reservoir outflows, and the combined computational burden of joint analyses of snowpack water content and initial reservoir level was appreciable. However, only the analyses associated with the snowmelt components are reported here.

The following sections detail the approach taken with the salient factors that influence the transfer function between rainfall and runoff. It should be noted that the discussion does not here attempt to justify the adoption of parameter values for events of extremely low exceedance probability, an area of design practice where even a high level of expertise cannot reduce the level of uncertainty involved. Where design assumptions border on the "unknowable" (17) the adopted procedures represent an objective device for extrapolating empirical evidence to recommendations contained in the relevant design guidelines.

4.1 Routing Parameters

In RORB, the k_c parameter controls the speed of response to rainfall excess, and the parameter m describes the degree of non-linearity of catchment response.

For snowmelt floods, the k_c parameter was varied linearly with the proportion of catchment covered by snow, which accounts for the increasing attenuation in the catchment response with increasing snowpack. The relationship between k_c and the proportion of catchment covered by snow was determined from calibration results, as shown schematically in Figure 2. For each design event, the modified RORB model calculated the proportion of the catchment covered by snow using the seasonal snowpack-elevation relationships (discussed in Section 4.1) and hypsometric information derived for each interstation area.

The degree of non-linearity in the storage discharge equation (parameter m) was set at 0.8 for all design events. This is the same value used during calibration and is consistent with design guidelines (3) for catchments where 'most of the valleys are V-shaped with only small flood plains'.

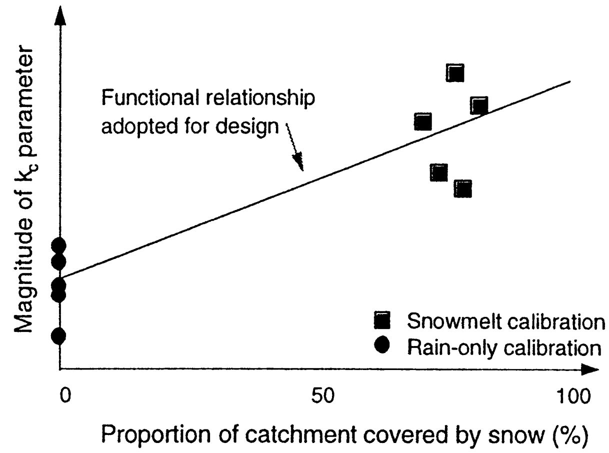

Figure 2. Schematic illustration of the specification of design relationship between k_c and the proportion of catchment covered by snow.

4.2 Initial Loss

Initial loss values used in design vary with both seasonal exceedance probability (SEP) and the proportion of catchment covered by snow.

For zero snow cover (ie rain-only events), the initial loss values used for the 1:50 SEP and 1:100 SEP events were based on median results obtained from calibration. The initial loss value for the $1{:}10^6$ SEP design event was assumed to be 0 mm for all storm durations, and values for intermediate probabilities were obtained by log-Normal interpolation. This approach is shown schematically in Figure 3 (the initial loss for the $1{:}10^6$ SEP design event was set to 0.1 mm to enable log-Normal interpolation).

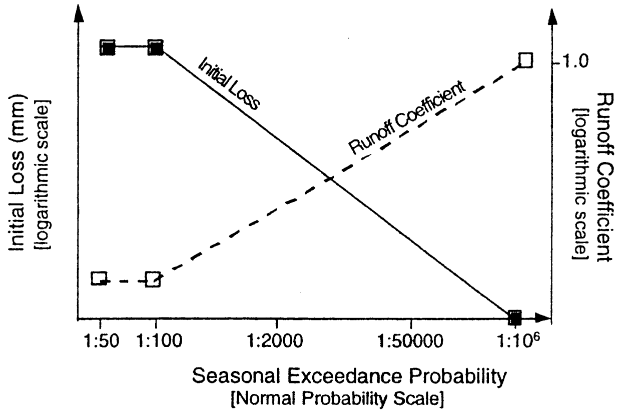

Figure 3. Schematic illustration of variation of initial and proportional loss with SEP.

A similar approach is adopted for varying initial loss with design SEP for snowmelt events. There is the added complication, however, that for a given SEP the initial loss is dependent upon the proportion of catchment covered by snow. If the entire catchment is covered by snow, it is reasonable to assume that the underlying soil is saturated and that all snowmelt appears as surface runoff. The results obtained from calibration support this assumption - i.e. initial loss was found to be inversely proportional to the proportion of the catchment covered by snow. Accordingly, for design events, it was assumed that initial loss varied linearly between the value adopted for rainonly events (at 0% snow cover) and 0 mm for the case where the catchment was completely covered by snow (Figure 4).

4.3 Runoff Coefficient

The approach taken with adoption of runoff coefficients is similar to that used for initial loss. For rain-only events, the runoff coefficients used for the 1:50 SEP and 1:100 SEP events were based on median results obtained from calibration. The runoff coefficient for the 1:10^6 design event was assumed to be around 0.97 for all storm durations, and values for intermediate probabilities were obtained by log-Normal interpolation. The precise value of the runoff coefficient for the 1:10^6 SEP event was calculated to yield the same peak flow as obtained from adoption of a continuing loss model using a loss rate of 1 mm/hr. This approach is shown schematically in Figure 3.

For snowmelt events, the runoff coefficient was varied with the proportion of catchment covered by snow. The justification for this is the same as used for initial loss, and again the results obtained from calibration support this assumption. Accordingly, for design events, it was assumed that runoff coefficient varied linearly between the value adopted for rainonly events (at 0% snow cover) and 1.0 for the case where the catchment was completely covered by snow (Figure 4).

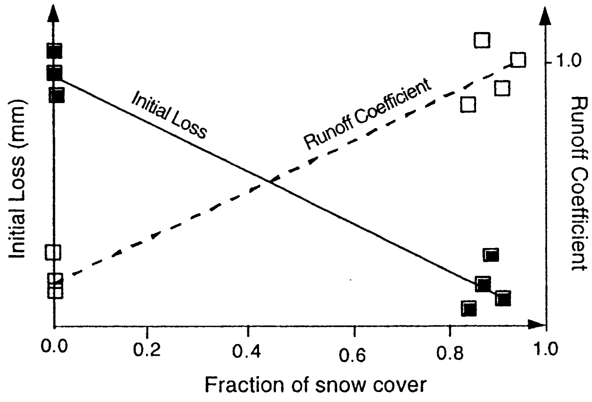

Figure 4. Schematic illustration of the specification of design relationship between initial and proportional loss and the proportion of catchment covered by snow.

4.4 Temperature Sequence

The appropriate temperature sequence for use with 1:50 SEP and 1:100 SEP design events was derived from an analysis of temperatures coincident with extreme rainfalls recorded at the Cabramurra climate station over a 42 year period. Seasonal coincident temperatures were plotted using the same plotting positions as were assigned to the rainfall maxima. An example plot illustrating the results for the June-September season is shown in Figure 5. The results of this analysis indicated that the temperatures were in the average range expected for the season, and that no significant change in temperature occurred with SEP. Accordingly, it was considered appropriate to use average seasonal temperatures for the 1:50 SEP and 1:100 SEP events, appropriately adjusted for differences in elevation.

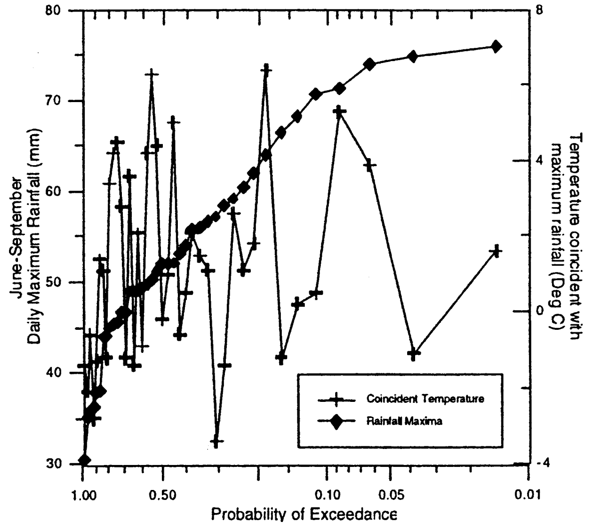

Figure 5. Sample relationship between temperature and maxima rainfalls

For more extreme events, the temperature sequence adopted was that assessed by the Bureau of Meteorology as being necessary to support a PMP event in the season of interest. A 2 °C diurnal cycle was superimposed on the daily temperatures adopted, which reflected the average fluctuation observed during large rainfall events.

4.5 Wind Speed Sequence

The magnitude of wind speed concurrent with extreme rainfall events was examined by analysis of wind speeds recorded at four climate stations during two of the most extreme major rainfall events that had occurred in the region. A frequency analysis of seasonal wind maxima was undertaken using the whole available period of record for each of the recording stations. It was found that the wind concomitant with the largest rainfalls on record for the region were approximately equal to the mean annual wind speed maximum at each of the sites.

To further investigate the relationship between wind speed and extreme storms, coincident wind data was obtained for twelve large storms recorded at the Cabramurra climate station. Instantaneous readings were available for wind speed at six hourly intervals, and rainfalls in the corresponding hour were extracted to provide a concurrent set of rainfall and wind speed data. The results clearly demonstrated that there is no discernible correlation between rainfall and wind. Based on this finding, average wind speeds were used for all design events.

4.6 Initial and Snowpack Density

The historic snowpack density data were analysed to investigate the frequency of occurrence and dependence of density on elevation and flood magnitude. A seasonal frequency analysis of all available density data at 14 long term snow course stations indicated that 50%-60% is a common threshold density for all seasons, regardless of catchment elevation. Analysis included an assessment of the correlation between snowpack density and seasonal flow maxima, and the results indicated that the density of the snowpack prior to maximum observed floods is generally equal to the threshold density.

There is a strong interaction between the values adopted for initial snowpack density and the threshold density at which snowmelt first starts to occur, and thus the effective density parameter of interest is the difference between the values of initial and threshold densities. Accordingly, the impact of different initial conditions and antecedent periods was carefully investigated.

Preliminary work entailed setting the initial snowpack density to average seasonal values, and tracking the change in snowpack density over a period leading up to the onset of the design rainfall event. During the lead up period average wind velocities were used, and temperatures were linearly increased from average seasonal values at the beginning of the period to the higher temperatures coincident with the design event; a 2 °C diurnal cycle was superimposed on the daily temperatures adopted, which reflected the average fluctuation observed during large rainfall events. The results of these runs indicated that for extreme events the snowpack invariably reached threshold density within the first time step of the rainfall event.

In consideration of the above, it was decided not to use a "lead-up" period prior to the onset of a design storm, but to set the initial snowpack density at the threshold value. The assumption of threshold density at the onset of the design rainfall event is further justified because antecedent rainfall is likely to occur prior to the onset of the extreme design rainfall burst.

4.7 Initial Snowpack Water Content

The selection of initial snowpack water content has an appreciable effect on the magnitude of the snowmelt flood. The proportion of the catchment covered by snow increases with increasing water content, and thus so does the potential for melt contribution to flood flow. Also, as discussed above, model parameters are dependent upon the proportion of the catchment covered by snow.

An analysis of the historic record indicated that there was no significant correlation between snowpack water content and extreme rainfalls. This lack of correlation and the sensitivity of runoff to initial snowpack values meant that it was necessary to account for the manner in which to the two processes of rainfall and snowpack combined to yield a design flood event.

A simple joint probability approach was adopted that was suited to the large computational requirements and the nature of the uncertainties involved. A frequency analysis was undertaken on snowpack water content data at 14 long term snowcourse stations, and a relationship between seasonal water content and elevation was derived for a range of non-exceedance frequencies. Design floods for a specified SEP were obtained by deriving snowmelt floods for the full range of water content exceedances, and calculating the statistically expected hydrograph. This was simply achieved by dividing the frequency distribution of seasonal water contents into twenty (equal probability) intervals, and determining the average hydrograph resulting from twenty different initial water content values. An example of the component hydrographs and the resultant weighted average obtained from the joint probability analysis is illustrated in Figure 6.

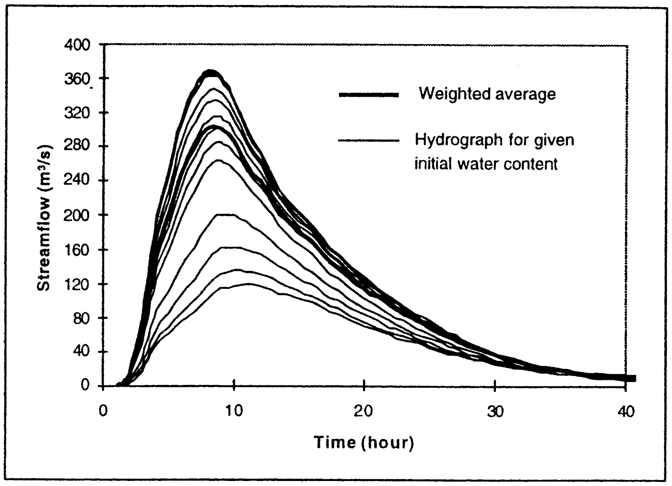

Figure 6. Example of snowmelt hydrographs derived using different initial snowpack water contents and weighted average hydrograph.

5 DERIVATION OF DESIGN FLOODS

Design floods of specified exceedance probability were obtained by using the above design assumptions in conjunction with seasonal design rainfalls. The seasonal design rainfalls were obtained in accordance with design guidelines (3). The required hydro-climatic elements were input into the modified RORB model, and the rainfall/snowmelt excess was routed through the catchment to produce catchment hydrographs for a range of storm durations over the required range of exceedance probabilities. This process yielded a set of seasonal flood frequency curves that related flood magnitude to the probability that the flood would be exceeded for the given season. The seasonal frequency curves were then combined to form annual frequency curves for design purposes.

6 VALIDATION OF DESIGN ESTIMATES

There were three sites in the study area with sufficient information to provide an independent check on the validity of the design approach. The length of record available at each site was around 35 years, and thus these data were used as an independent check of the design process, at least up to the 1:100 SEP design event.

A comparison between flood frequency results and runoff-routing design estimates for one of the sites (Geehi River upstream of Geehi Dam) is shown in Figure 7. It is seen that the runoff-routing snowmelt estimates agree closely with the flood frequency quantiles. The comparisons obtained for the other sites also support the validity of the adopted approach.

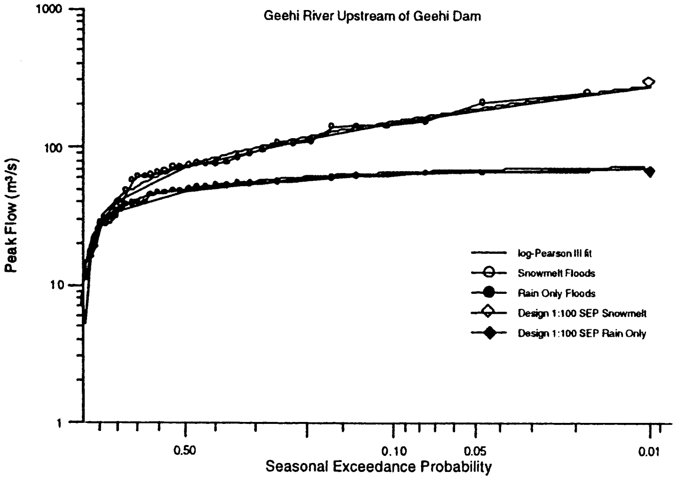

Figure 7. Comparison of flood frequency and runoff routing 1:100 SEP design flood estimates for Geehi River.

In addition, the design floods for all catchments considered corresponding to annual exceedance probabilities of $1{:}10^6$ were compared to the envelope of world maxima compiled by Rodier and Roche (18). The design flood peaks were found to fall within the scatter of observed flood maxima, which indicates that that the design estimates are not unreasonable.

7 CONCLUSIONS

In order to work within a risk-based approach to design it is necessary to derive hydrographs of known annual exceedance probability. The approach adopted in Australia is to derive all extreme flood hydrographs from design rainfall information, and thus it is necessary to adopt a probability-neutral transfer between rainfall and runoff. Where a catchment is subject to snow cover, there are a number of factors that require careful consideration to avoid the introduction of bias in the resultant exceedance probability. The investigations and procedures reported in this paper illustrate a practical approach to the determination of snowmelt design floods. Comparison of the design estimates with quantiles obtained from an independent statistical and analysis indicate that the method provides acceptable results for exceedance probabilities of up to 1:100. Comparison of more extreme design estimates were found to be consistent with observed world maxima.

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Development of Probabilistic Earthquake Loading Functions for Use in Dam Safety Evaluations

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Utah State University
March 8, Y2K

<u>Objectives:</u> Where have we been?

Where are we now?

Where are we going/what needs to done?

Deterministic Evaluations

Frequency of Occurrence:
incorporated only implicitly by criteria ("standards")

Fault Activity Criteria
Generally a Threshold Value

A *Standard*
A statement of acceptable risk

Annual Frequency: Implicit

Most remote events considered:
typically > $1x10^{-5}$ in western US

MCE- A standards-based approach.

Procedure: If a fault is “active”, estimate how large the magnitude could be (MCE).

What is the minimum source-site distance? Estimate ground motion parameter(s) of interest (median vs. 84th% ?).

Repeat for each potential source, stir vigorously and the result is a design earthquake.

Pitfalls: No consistent approach from agency-to-agency (criteria for “active” designation is not standard).

Huge differences in design hazard levels from site-to-site.

No mechanism for incorporation of uncertainty due to investigator-to-investigator differences of opinion.

No time dependent information contained in output.

Seismic Hazard Analysis
PSHA

Concepts:

(1) Contributions from all defined sources are considered collectively.

(2) The analysis considers the likelihood of various events (magnitude and distance) in a time, t.

(3) Uncertainty can be treated explicitly.

(4) Criteria-based activity rates irrelevant.

(5) Annual probabilities of ground motions are computed.

PSHA (Probabilistic Seismic Hazard Analysis)

History: Much of the fundamental development by Allin Cornell and his students (notably Robin McGuire) at the Civil Engineering Dept-MIT (1968-1976).

Why: Recognized the need to analyze critical structures within a probabilistic framework-motivated by the nuclear industry, DOE, building codes.

PSHA

$$E(z) = \sum_{i=1}^{N} \alpha_i \int_{m_0}^{m_u} \int_{r=0}^{r} f_i(m) f_i(r) P(Z > z|m, r)\,dr\,dm$$

where Z is peak ground motion and z is the exceedence threshold.
$E(z)$ = expected number of exceedences of z during time interval t.
α_i = rate of occurrences of earthquakes between m_0 and m_u for the i^{th} source.
$f_i(m)$ = pdf of magnitude (i.e., recurrence model) for the i^{th} source.
$f_i(r)$ = pdf of source distance for the i^{th} source.
$P(Z>z \mid m,r)$ = the probability that an event of m and r will produce ground motions > z, usually an empirical relation.

Uncertainty

Like it or not, it's everywhere. So we have to deal with it.

or *How I learned to stop worrying and love the uncertainty.*

A lot like Baskin-Robbins, lots of flavors and textures:

Parametric
Model
Epistemic
Aleatory
Objective
Subjective

PSHA-How do we conduct the analysis?

Two Portions of Analysis:

Source Characterization
and

Ground Motion Estimation

Source Characterization:

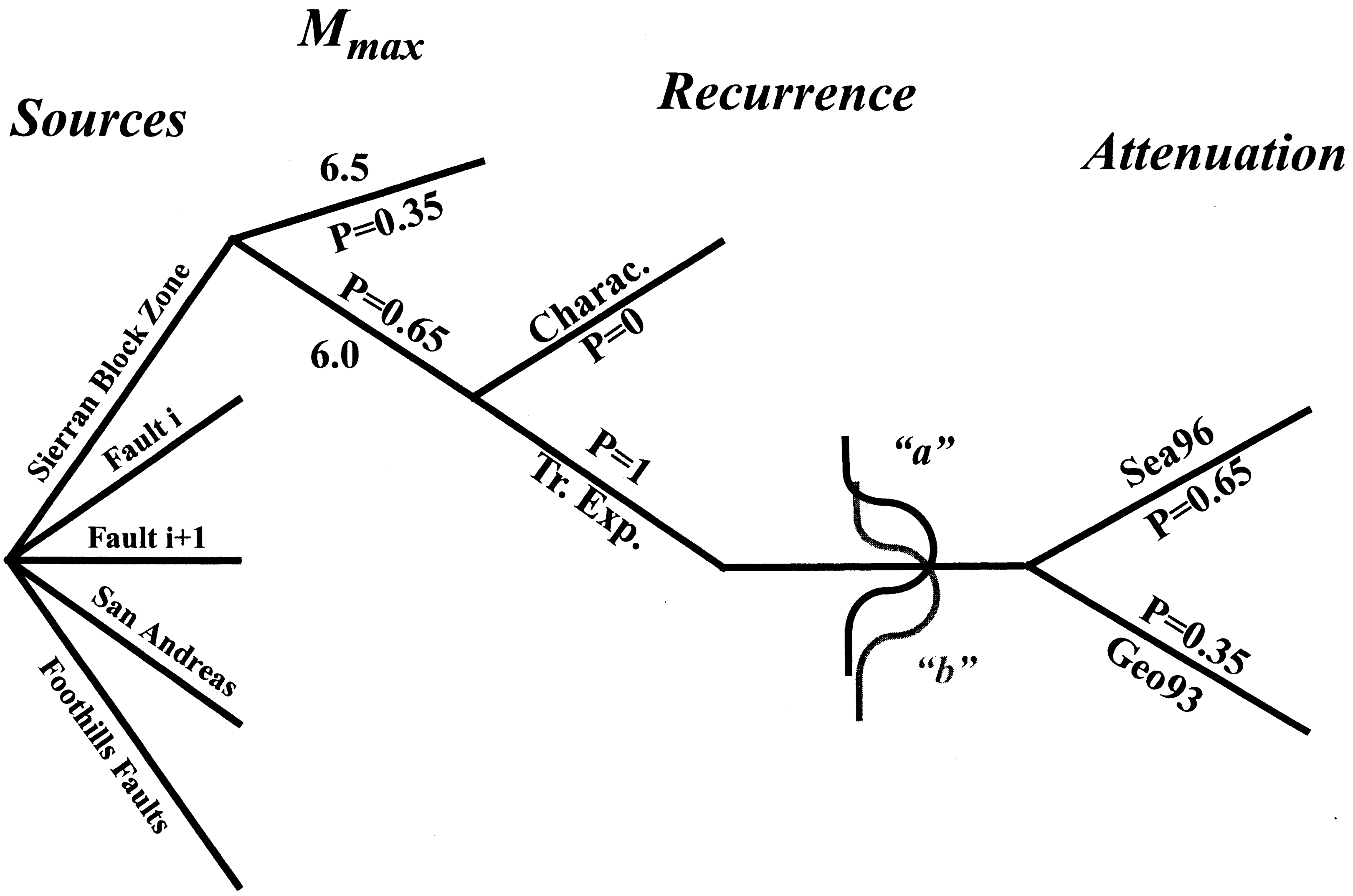
(1) Tectonic model
(2) Faults
  (a) Identification, total slip, sense of slip
  (b) Slip rate
  (c) Length, depth, dip
  (d) Maximum Magnitude
  (e) Recurrence Model
(3) Areal Sources (Not all significant earthquakes occur on faults w/ obvious surface manifestation, ex. El Asnam, Northridge, Whittier Narrows, Coalinga)
  (a) Boundaries -
  (b) Maximum Magnitude
  (c) Recurrence Model and Statistics

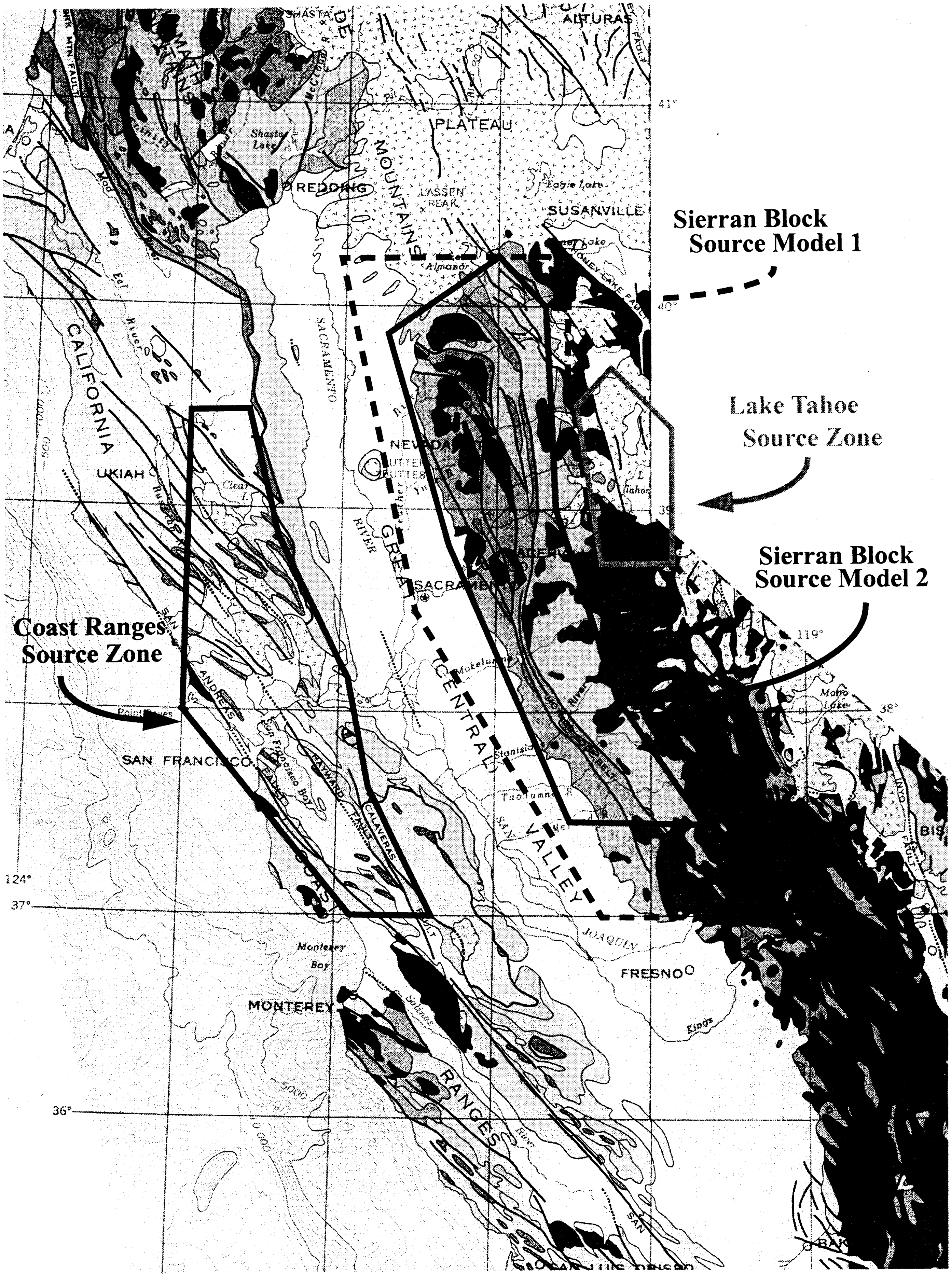
Ground Motion Estimation:

(1) Site conditions-site response?

(2) Attenuation Function(s)
  (a) Factors: Style of Faulting, Hanging Wall, Site

(3) What Parameter(s) are of Interest?
  (a) PHA, Peak Velocity, Response Spectra


Sources
M_{max}
Recurrence
Attenuation
Sierran Block Zone
Fault i
Fault i+1
San Andreas
Foothills Faults
6.5
P=0.35
P=0.65
6.0
Charac.
P=0
P=1
Tr. Exp.
"a"
"b"
Sea96
P=0.65
P=0.35
Geo93

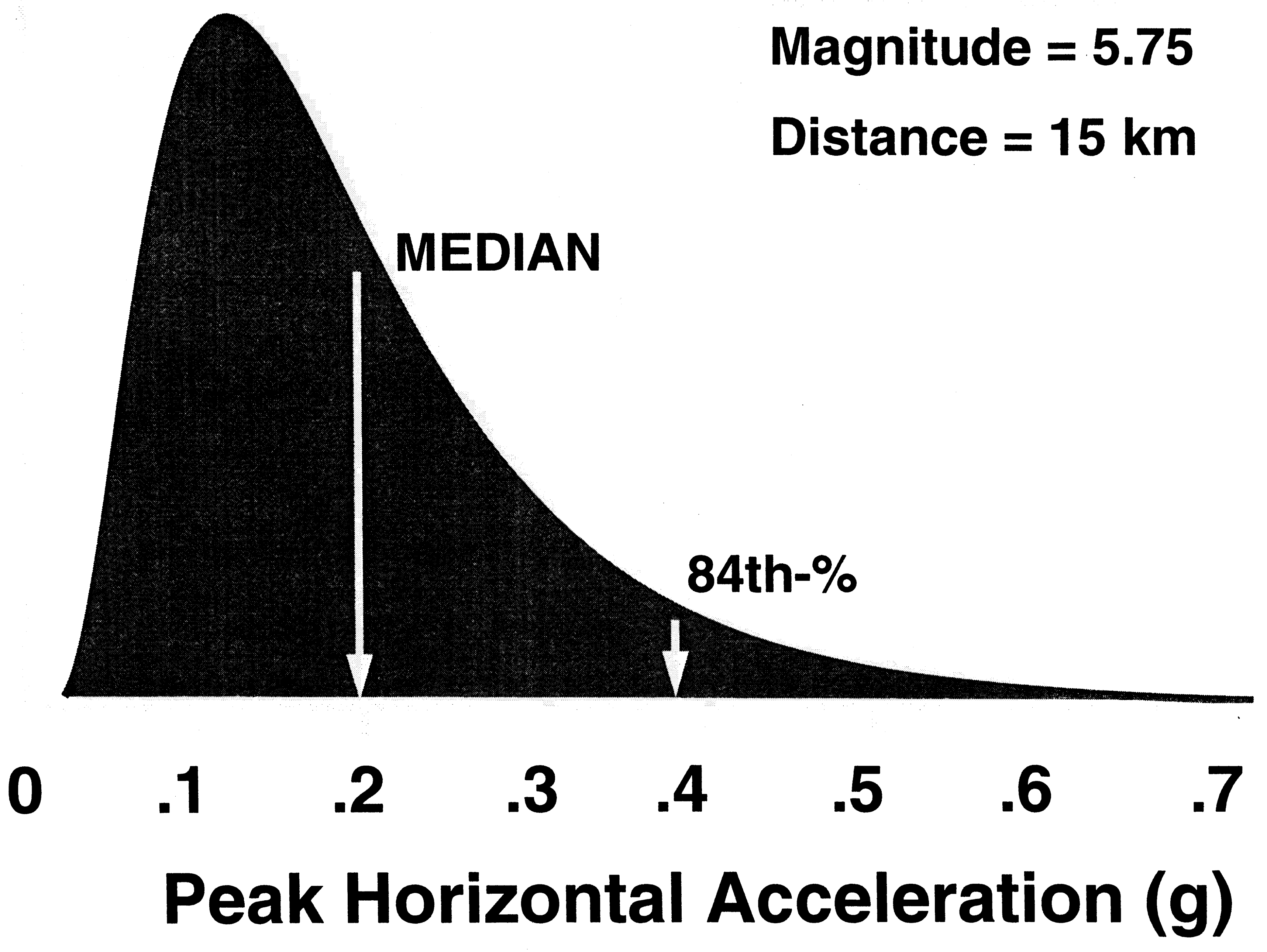


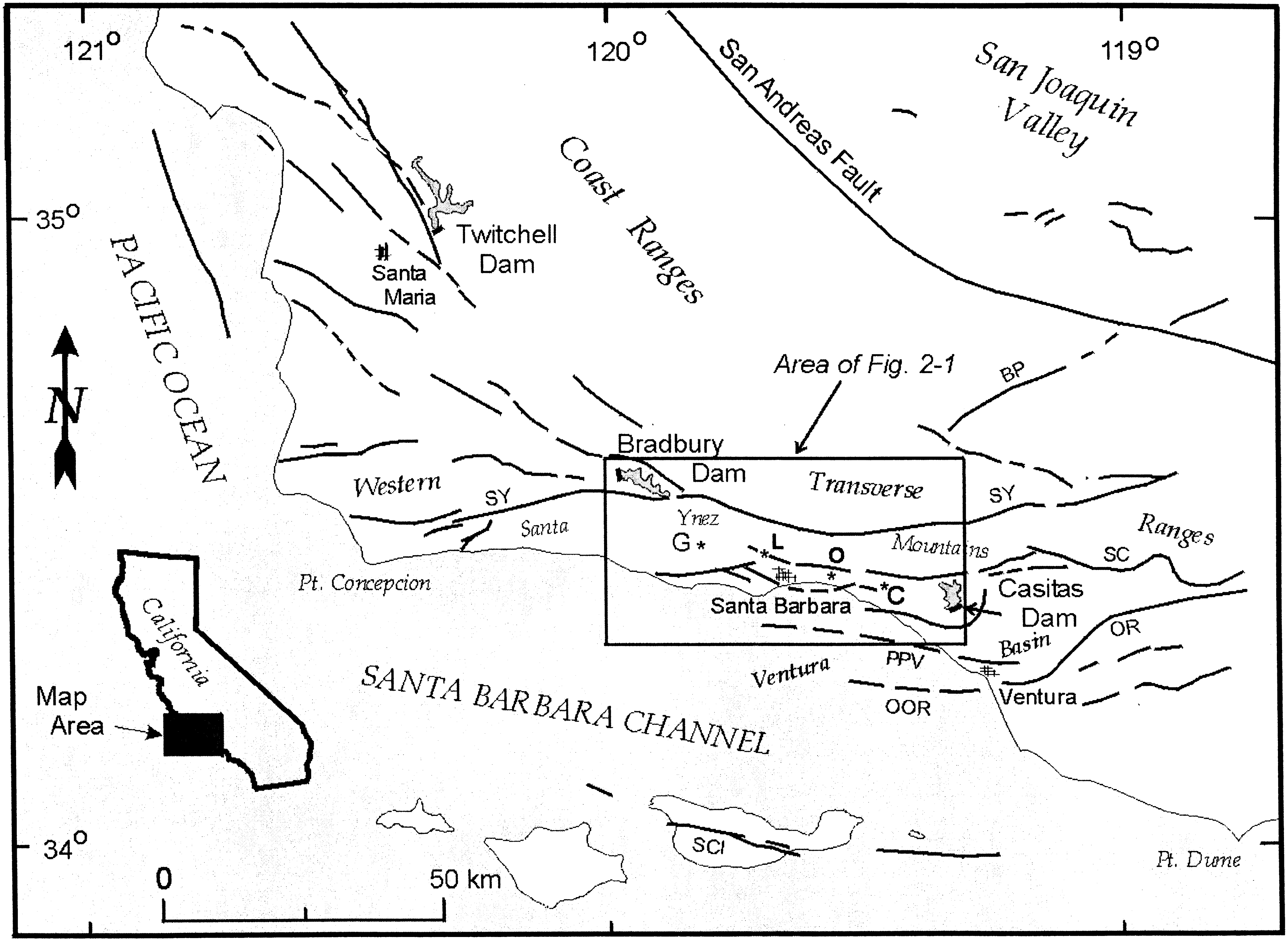
Sierran Block Source Model 1

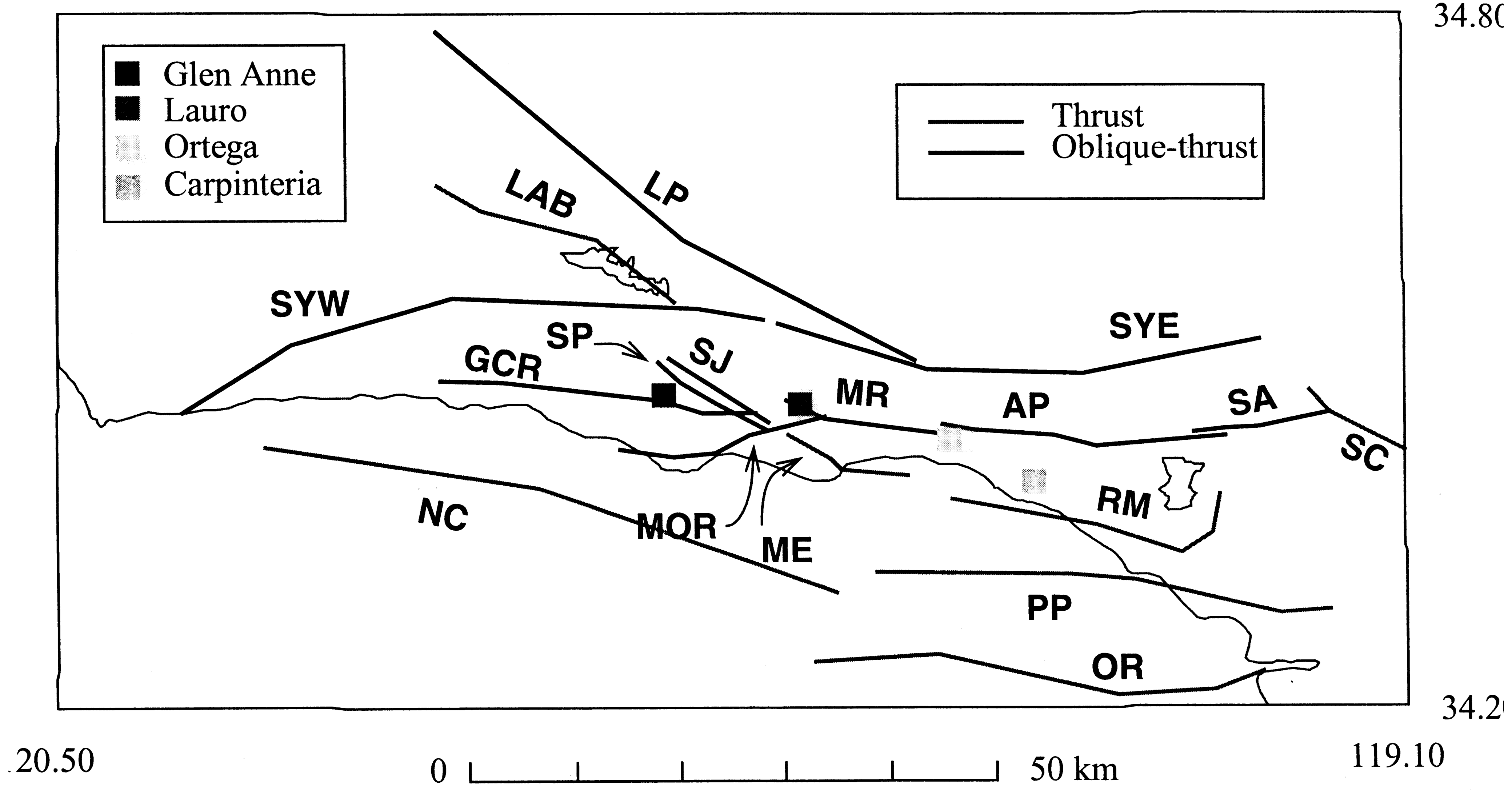
Lake Tahoe Source Zone

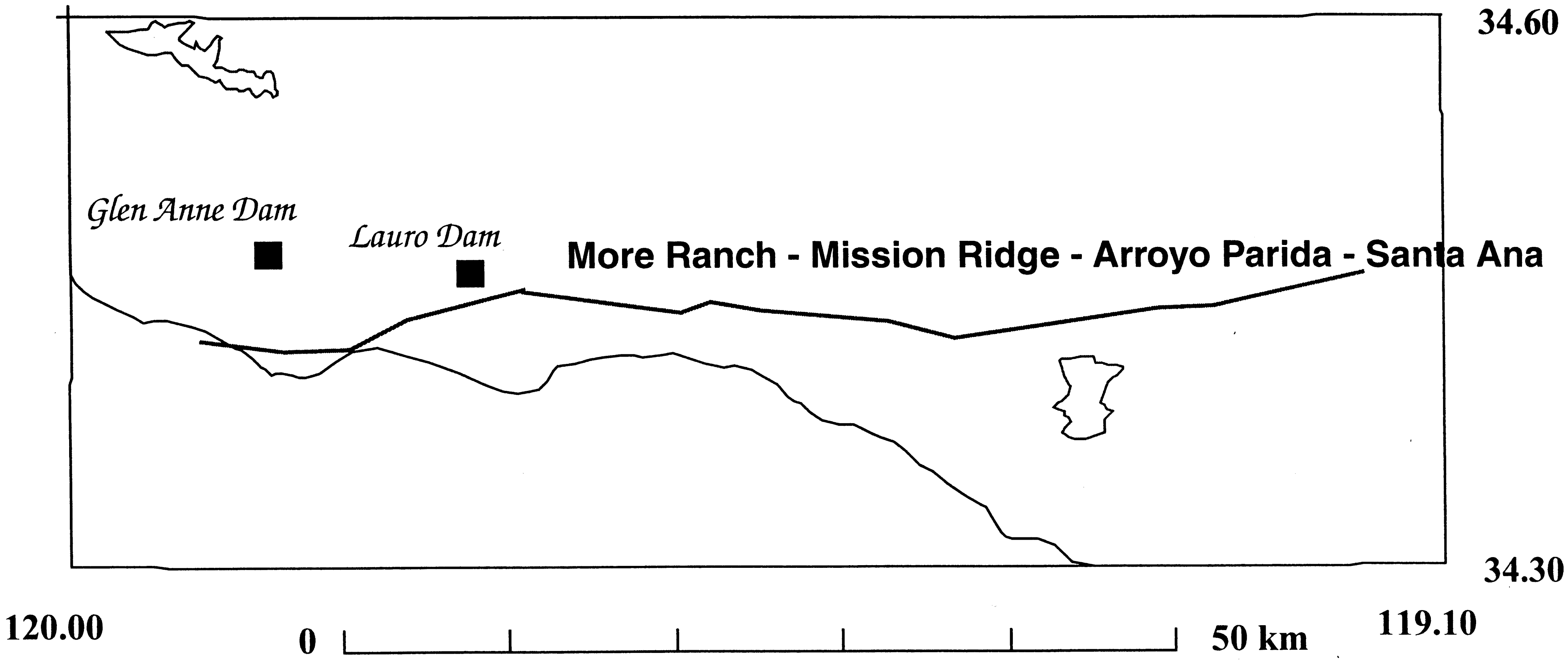
Sierran Block Source Model 2

Coast Ranges Source Zone

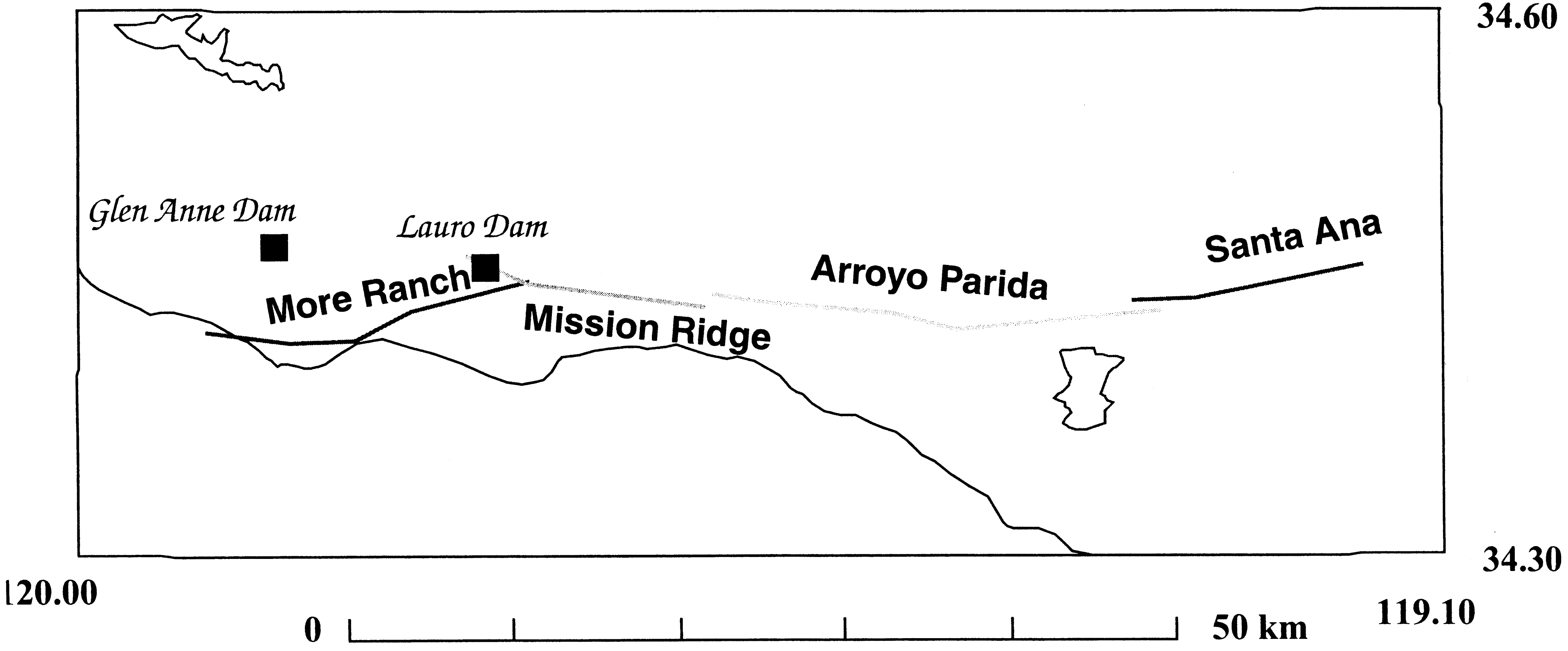

Magnitude = 5.75
Distance = 15 km
MEDIAN
84th-%
0
.1
.2
.3
.4
.5
.6
.7
Peak Horizontal Acceleration (g)


121°
120°
119°
35°
34°
San Andreas Fault
San Joaquin Valley
Coast Ranges
Twitchell Dam
Santa Maria
PACIFIC OCEAN
N
Area of Fig. 2-1
BP
Bradbury Dam
Transverse
Western
SY
Santa
Ynez
Mountains
SY
Ranges
SC
G
L
O
C
Casitas Dam
OR
Pt. Concepcion
Santa Barbara
Basin
PPV
Ventura
Ventura
OOR
California
Map Area
SANTA BARBARA CHANNEL
SCI
Pt. Dume
0
50 km


34.80
34.20
.20.50
119.10
Glen Anne
Lauro
Ortega
Carpinteria
Thrust
Oblique-thrust
LP
LAB
SYW
SP
GCR
SJ
MR
SYE
AP
SA
SC
RM
NC
MOR
ME
PP
OR
0
50 km



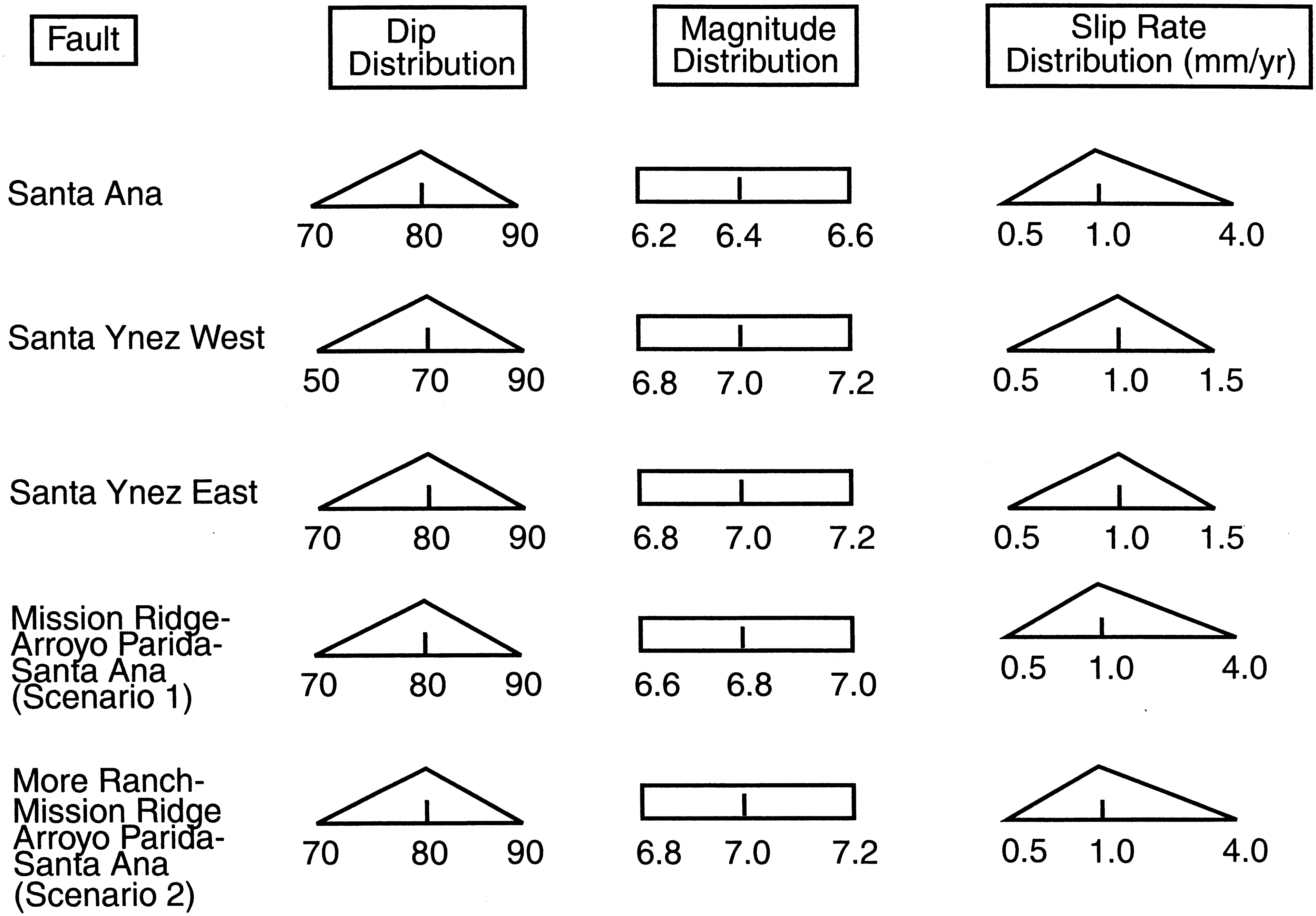
SINGLE SEGMENT RUPTURE

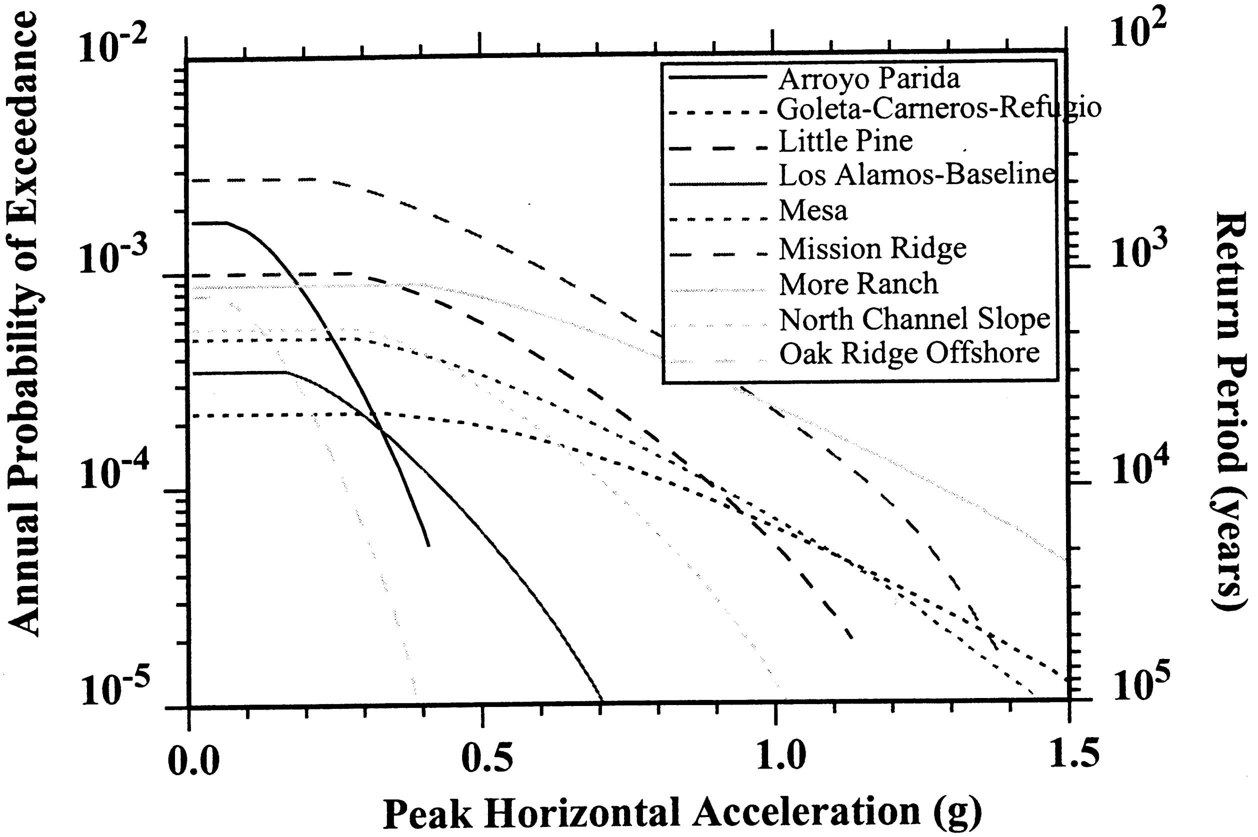


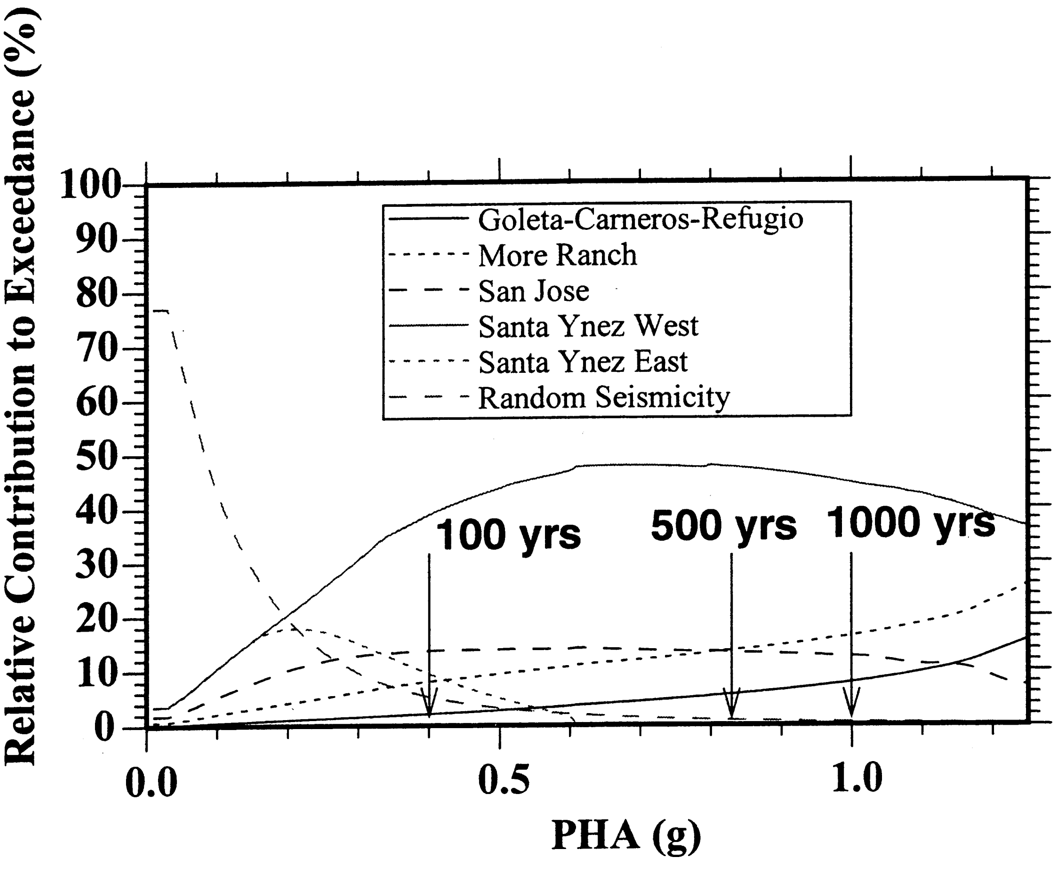
MULTIPLE SEGMENT RUPTURE

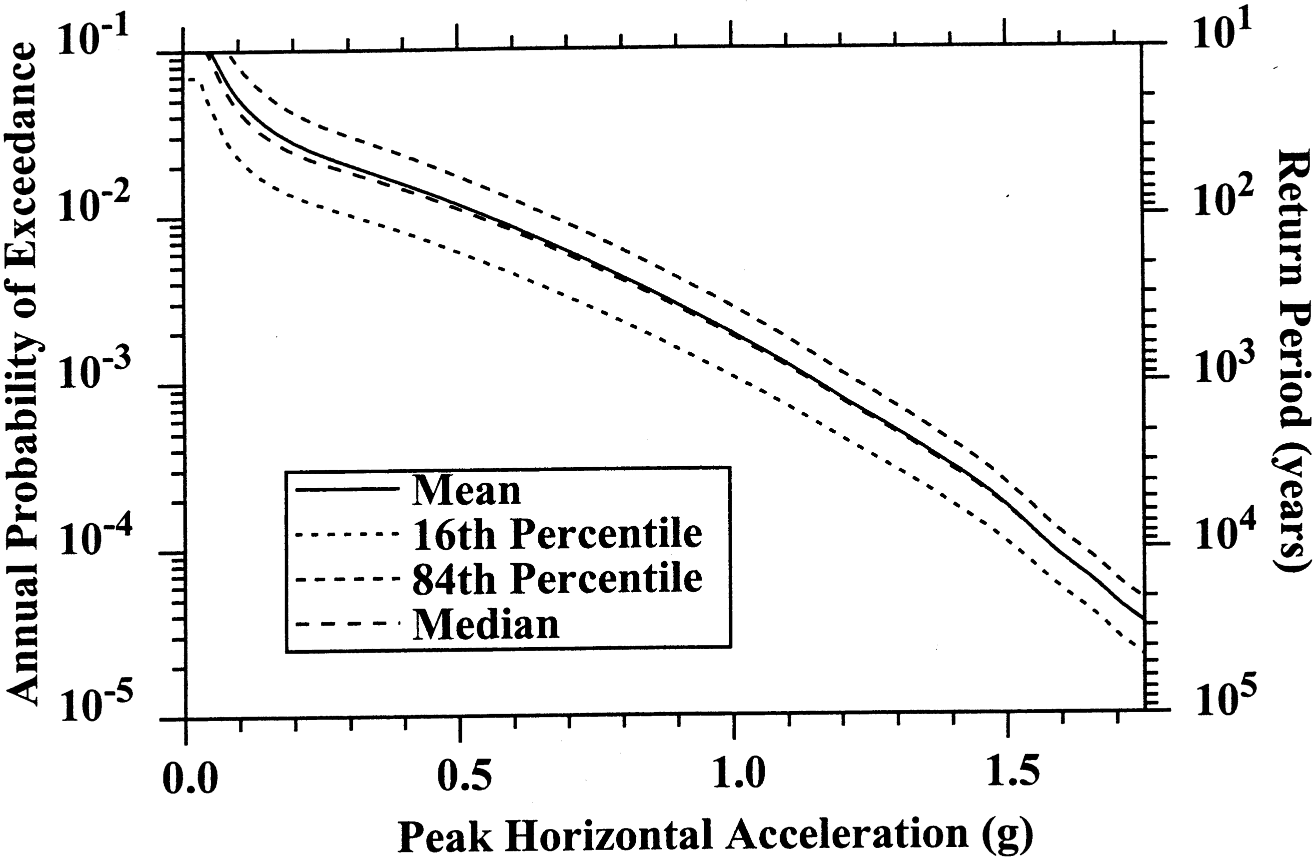
Table 3: Fault Parameters used in PSHA

Fault	Type	Dip	Depth Bounds (km)	Surface Length (km)	M_W for Surface Length	Rupture Area (km^2)	M_W for Rupture Area	Median M_W used in PSHA	Closest Distance to Dam (km)	
									Glen Anne	Lauro
Arroyo Parida	Oblique	70-90°S	0 - 10	27.1	6.76	278	6.47	6.6	30.7	18.2
Goleta-Carneros-Refugio	Oblique	70-90°S	0 - 12	30.1	6.80	366	6.40	6.6	0.3	1.5
Little Pine	Oblique	50-70°N	0 - 20	55.6	7.13	1253	6.89	6.9	15.7	10.5
Los Alamos-Baseline	Thrust	30-60°S	2 - 17	25.6	6.72	519	6.77	6.8	7.8	14.6
Mesa - Offshore	Thrust	50-80°S	0 - 12	12.4	6.33	181	6.36	6.4	16.1	4.9
Mission Ridge	Oblique	70-90°S	0 - 10	14.7	6.47	152	6.20	6.25	15.6	3.6
More Ranch	Oblique	65-85°S	0 - 10	20.2	6.59	208	6.42	6.5	5.5	3.5
North Channel	Thrust	25-50°N	0 - 20	56.2	7.13	1322	7.14	7.15	9.1	13.3
Oak Ridge (offshore)	Thrust	60-80°S	2 - 20	43.5	7.00	1178	7.09	7.0	31.9	33.5
Pitas Point	Thrust	30-60°N	0 - 20	43.6	7.00	790	6.94	7.0	27.4	19.4
Red Mountain	Thrust	40 -60°N	0 - 15	29.8	6.80	1142	7.02	6.9	33.1	31.2
San Andreas	Oblique	90°	0 - 15	158.1	7.62	1897	7.32	7.8	71.5	64.5
San Cayetano	Thrust	50-70°N	0 - 20	38.1	6.93	881	6.98	7.0	67.4	52.9
San Jose	Oblique	60-80°S	0 - 12	11.3	6.30	145	6.04	6.25	5.3	1.2
San Pedro	Oblique	60-80°S	0 - 12	12.1	6.34	162	6.08	6.25	4.4	2.3

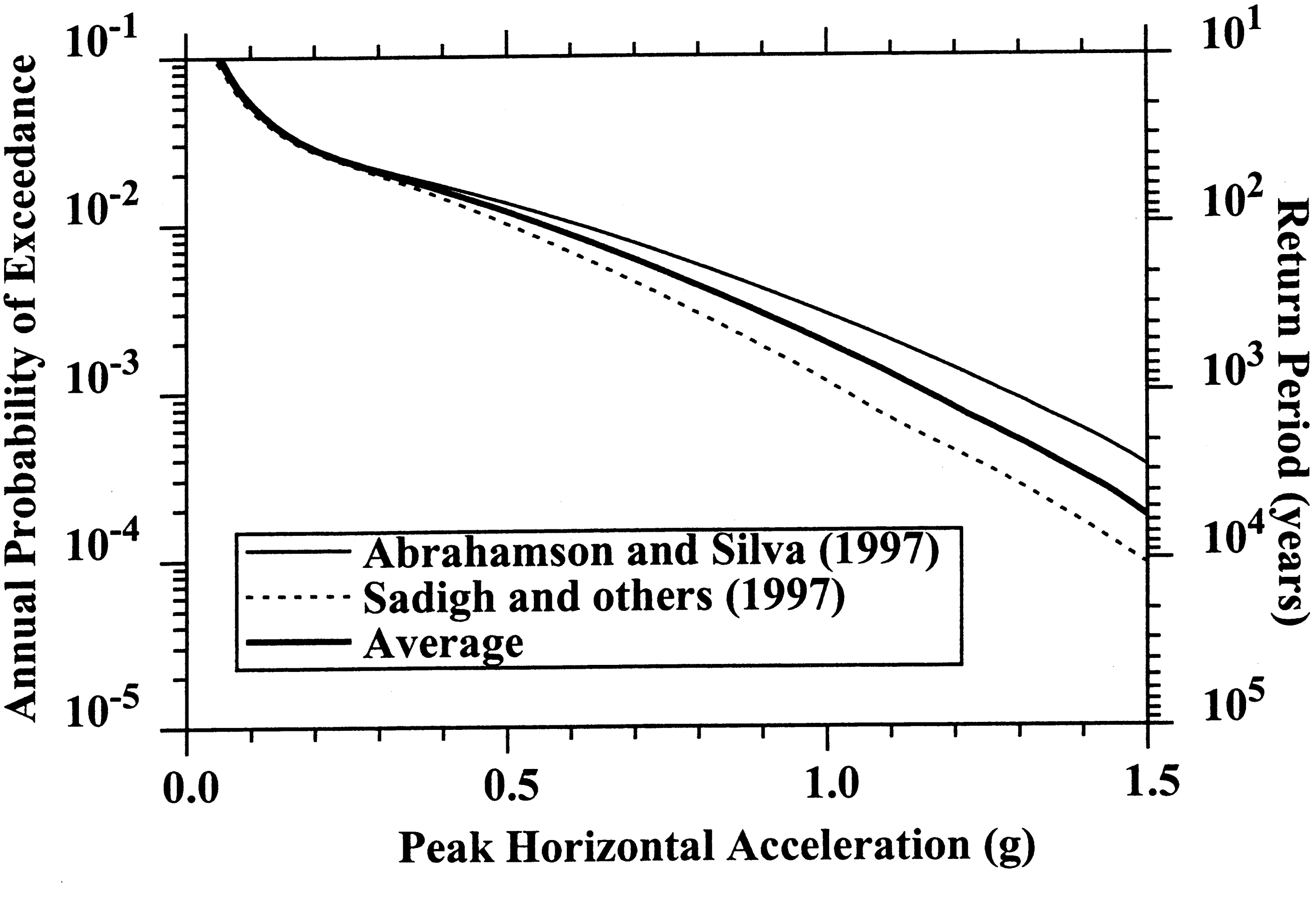

Fault
Dip Distribution
Magnitude Distribution
Slip Rate Distribution (mm/yr)
Santa Ana
70 80 90
6.2 6.4 6.6
0.5 1.0 4.0
Santa Ynez West
50 70 90
6.8 7.0 7.2
0.5 1.0 1.5
Santa Ynez East
70 80 90
6.8 7.0 7.2
0.5 1.0 1.5
Mission Ridge-Arroyo Parida-Santa Ana (Scenario 1)
70 80 90
6.6 6.8 7.0
0.5 1.0 4.0
More Ranch-Mission Ridge Arroyo Parida-Santa Ana (Scenario 2)
70 80 90
6.8 7.0 7.2
0.5 1.0 4.0


Annual Probability of Exceedance
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Return Period (years)
10^{2}
10^{3}
10^{4}
10^{5}
Arroyo Parida
Goleta-Carneros-Refugio
Little Pine
Los Alamos-Baseline
Mesa
Mission Ridge
More Ranch
North Channel Slope
Oak Ridge Offshore
0.0
0.5
1.0
1.5
Peak Horizontal Acceleration (g)


Relative Contribution to Exceedance (%)
100
90
80
70
60
50
40
30
20
10
0
Goleta-Carneros-Refugio
More Ranch
San Jose
Santa Ynez West
Santa Ynez East
Random Seismicity
100 yrs
500 yrs
1000 yrs
0.0
0.5
1.0
PHA (g)



Annual Probability of Exceedance
10-1
10-2
10-3
10-4
10-5
Return Period (years)
101
102
103
104
105
0.0
0.5
1.0
1.5
Peak Horizontal Acceleration (g)
Mean
16th Percentile
84th Percentile
Median



Annual Probability of Exceedance
10-1
10-2
10-3
10-4
10-5
Return Period (years)
101
102
103
104
105
0.0
0.5
1.0
1.5
Peak Horizontal Acceleration (g)
Abrahamson and Silva (1997)
Sadigh and others (1997)
Average

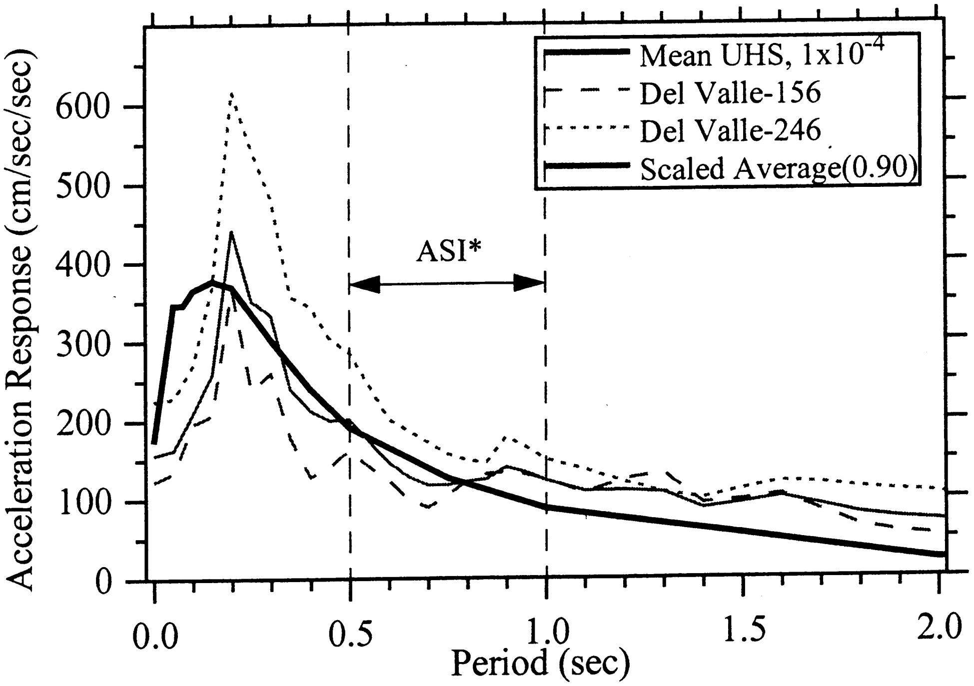


Figure 17. Target, mean UHS for AFE of $1x10^{-4}$ for Horsetooth site, magnitude range: 5.0-6.5 (shown in black). Horizontal components of Del Valle Dam recordings of 1980 Livermore, CA earthquake shown in red (dashed). Scaled average of two componets shown in solid red. Expected response band of dam/foundation shown by dashed black lines.

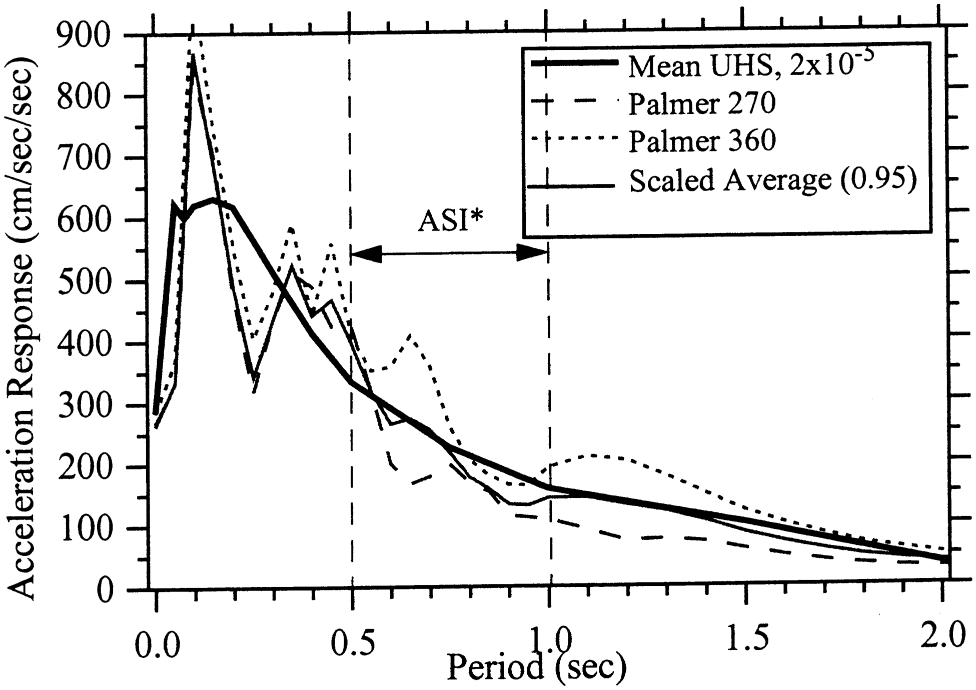


Figure 19. Target, mean UHS for AFE of $2x10^{-5}$ for Horsetooth site, magnitude range: 5.0-6.5 (shown in black). Horizontal components of Palmer Avenue recordings of 7/23/1983 aftershock of Coalinga, CA earthquake shown in blue (dashed). Scaled average of two components shown in solid blue. Expected response band of dam/foundation shown by dashed black lines.

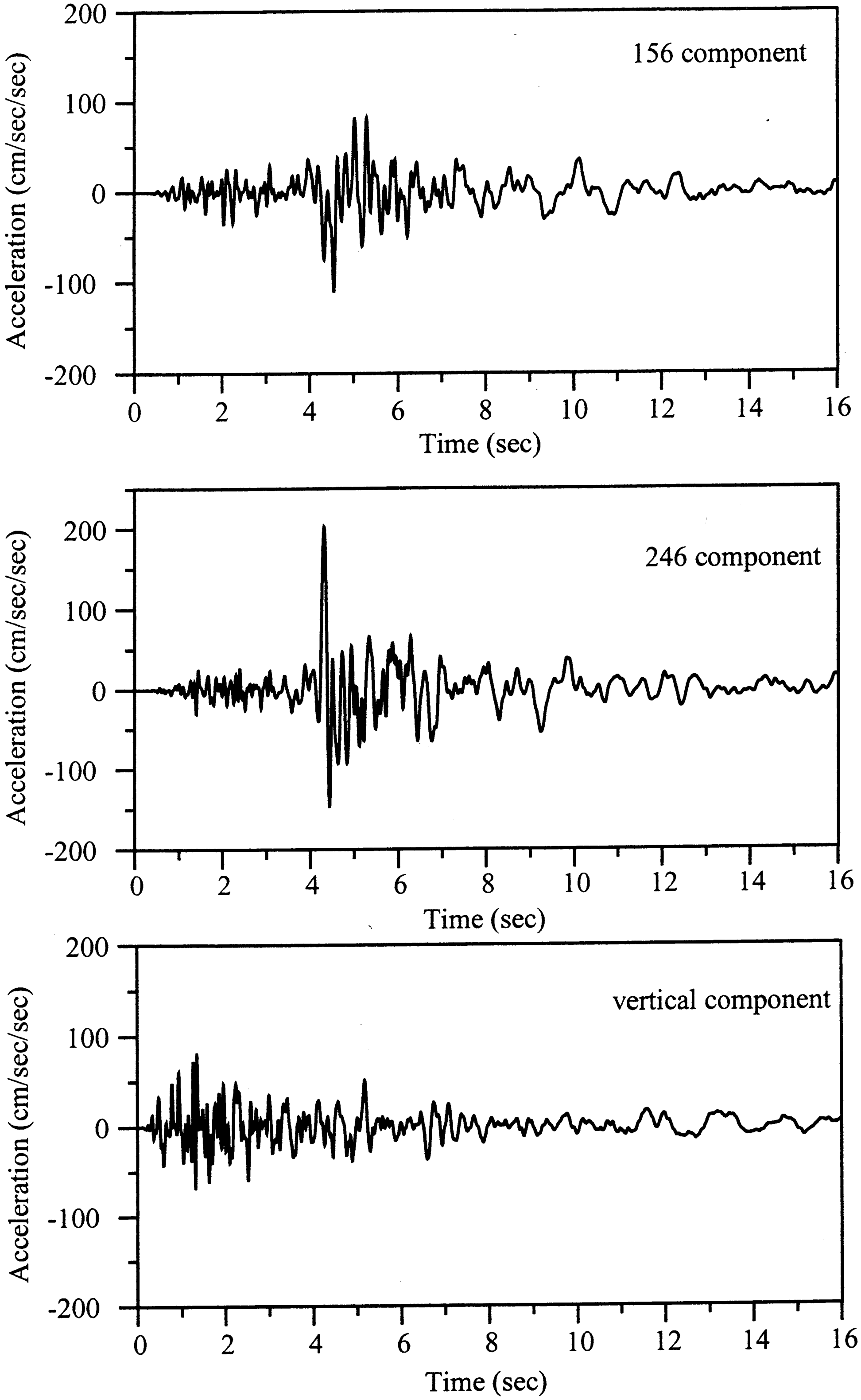
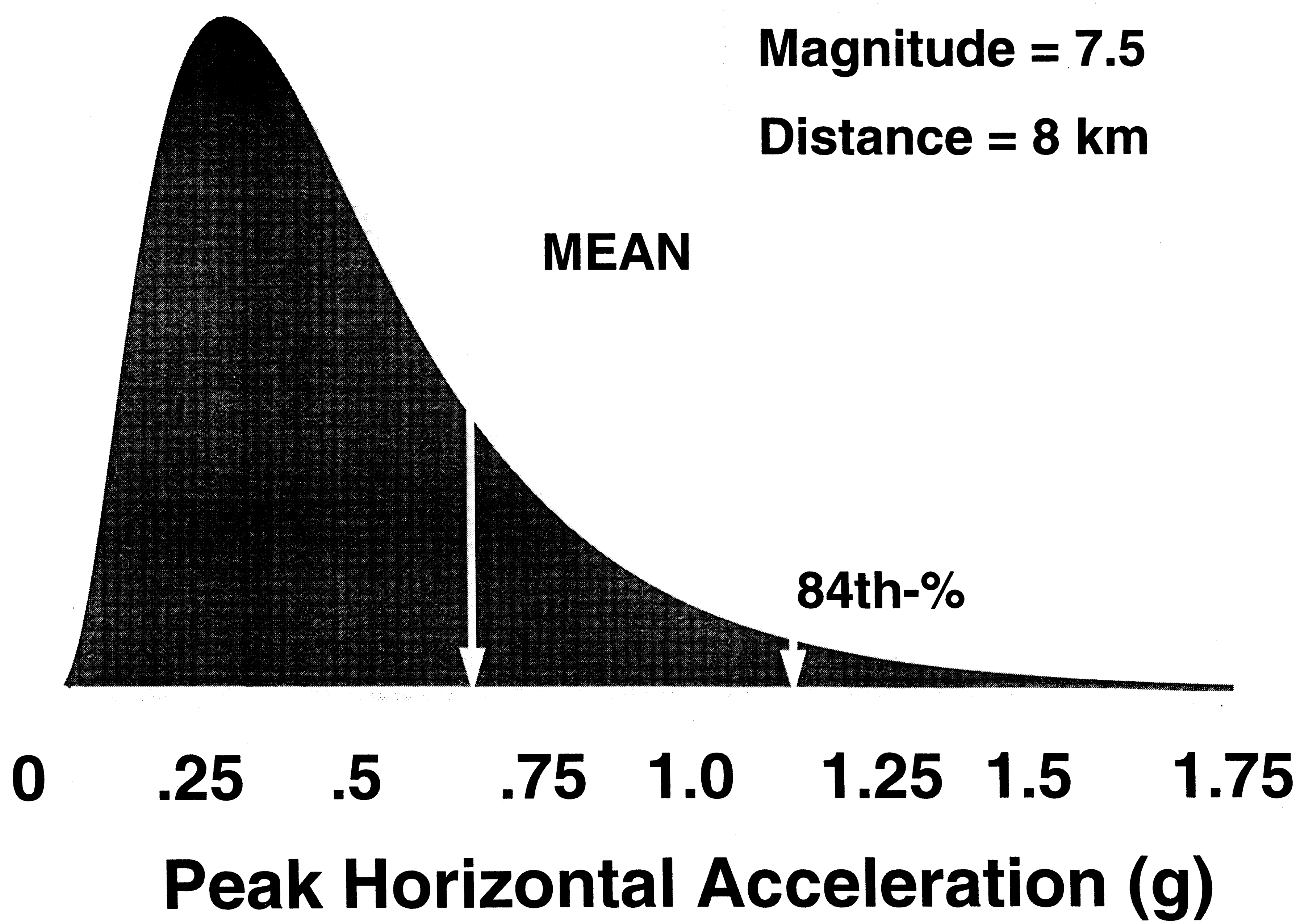


Figure 18. Acceleration time histories from Del Valle Dam (toe) of 24 January 1980, $\mathbf{M}_W$ 5.8 Livermore, CA, earthquake. Horizontal records scaled (factor=0.90), vertical unscaled. Selected to be consistent with mean UHS for AFE of $1x10^{-4}$ for Horsetooth site.


Magnitude = 7.5
Distance = 8 km
MEAN
84th-%
0
.25
.5
.75
1.0
1.25
1.5
1.75
Peak Horizontal Acceleration (g)

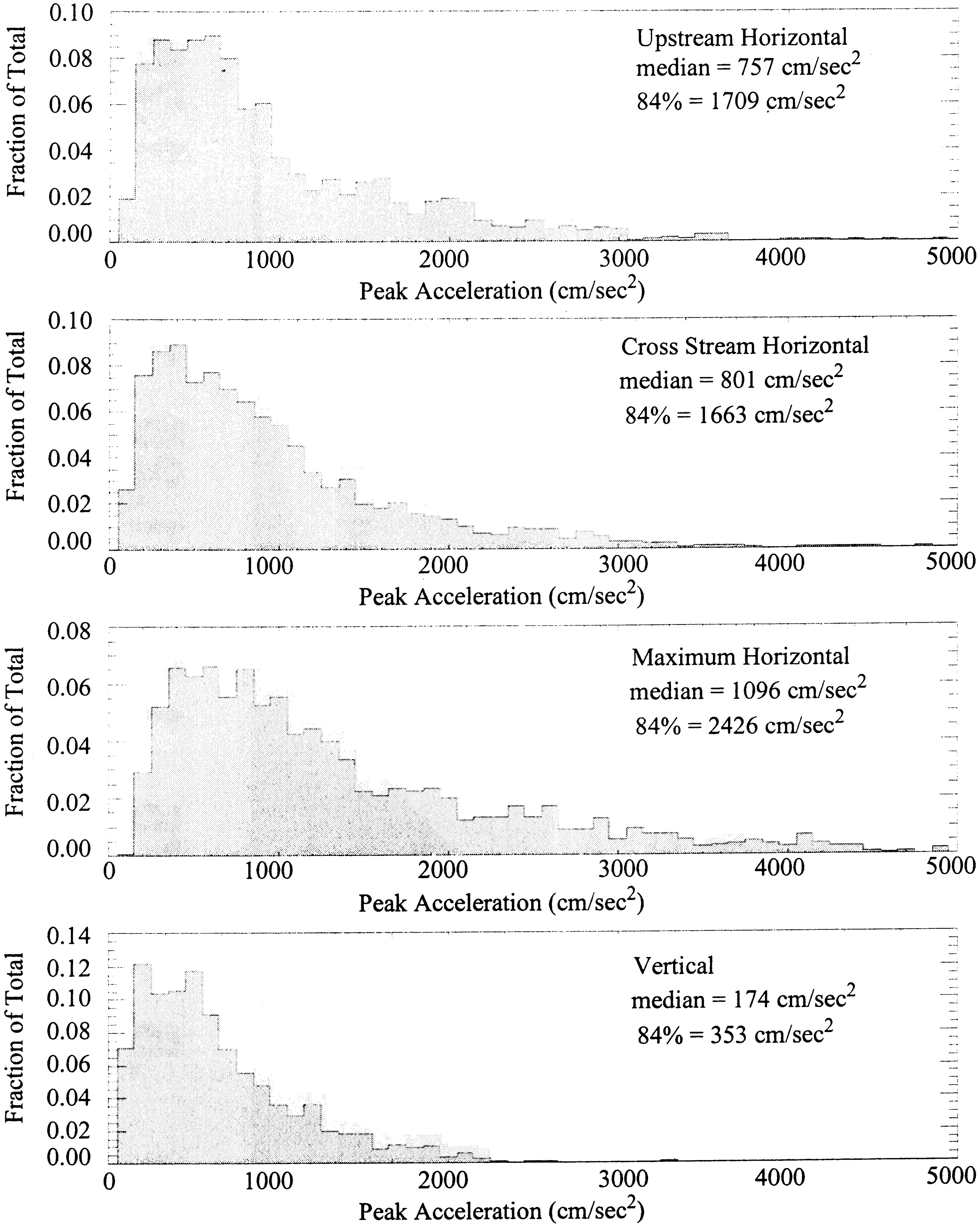
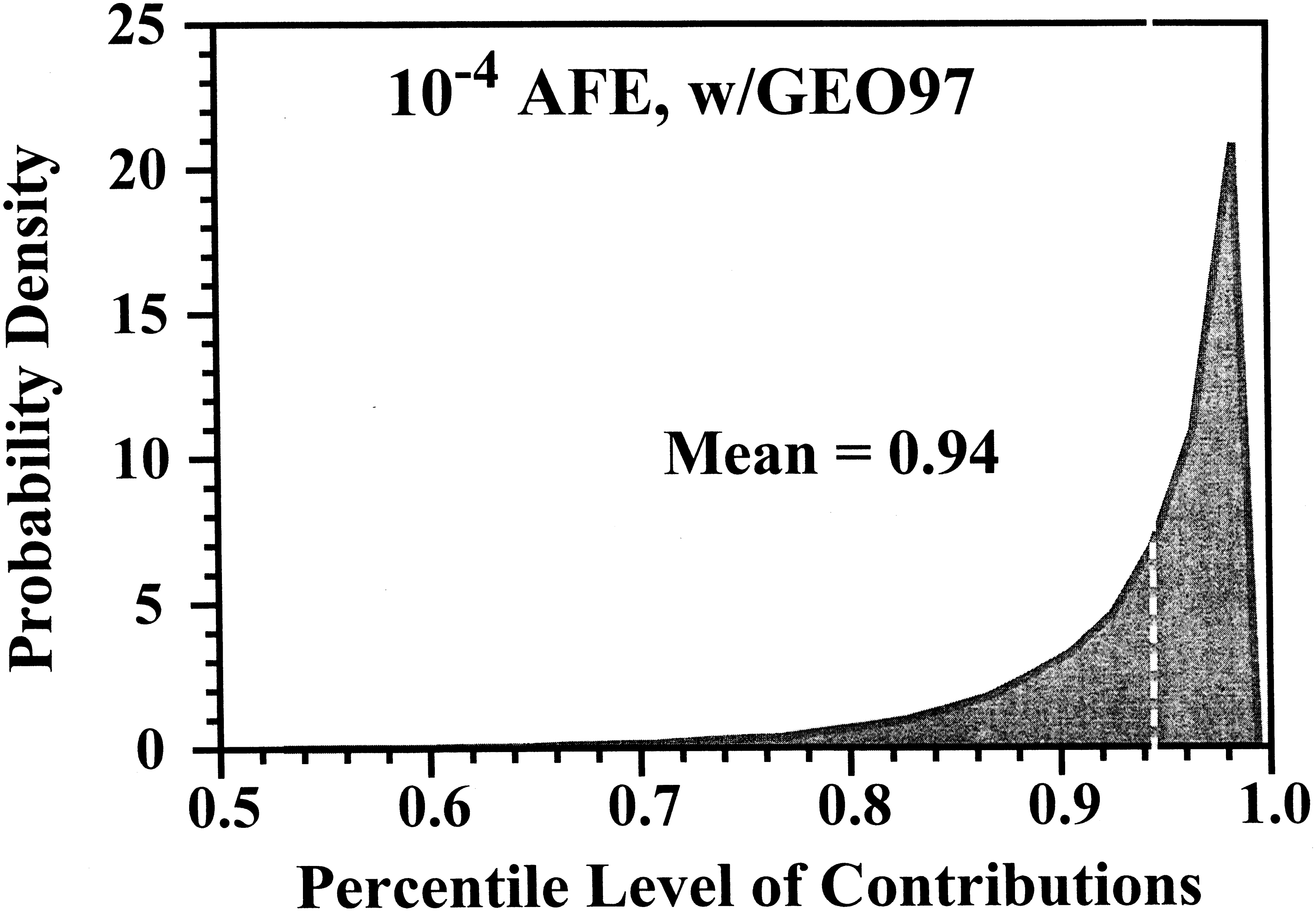


Figure 4-43. Histograms of peak accelerations from 2016 isochron simulations of the blind thrust earthquake.

ISB Background Source Zone



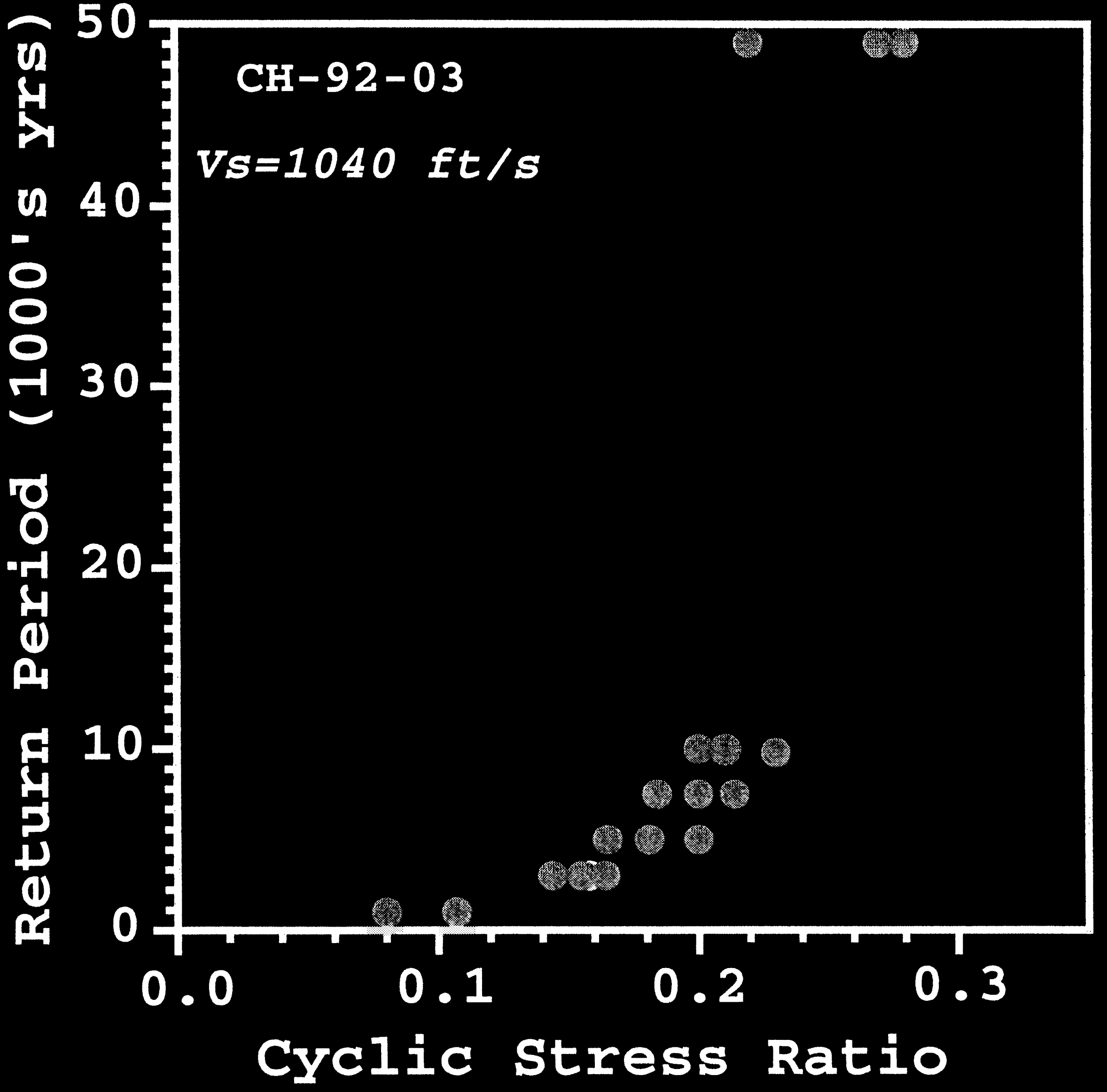
Dilemma:

What are the appropriate loadings for use in dynamic analyses?

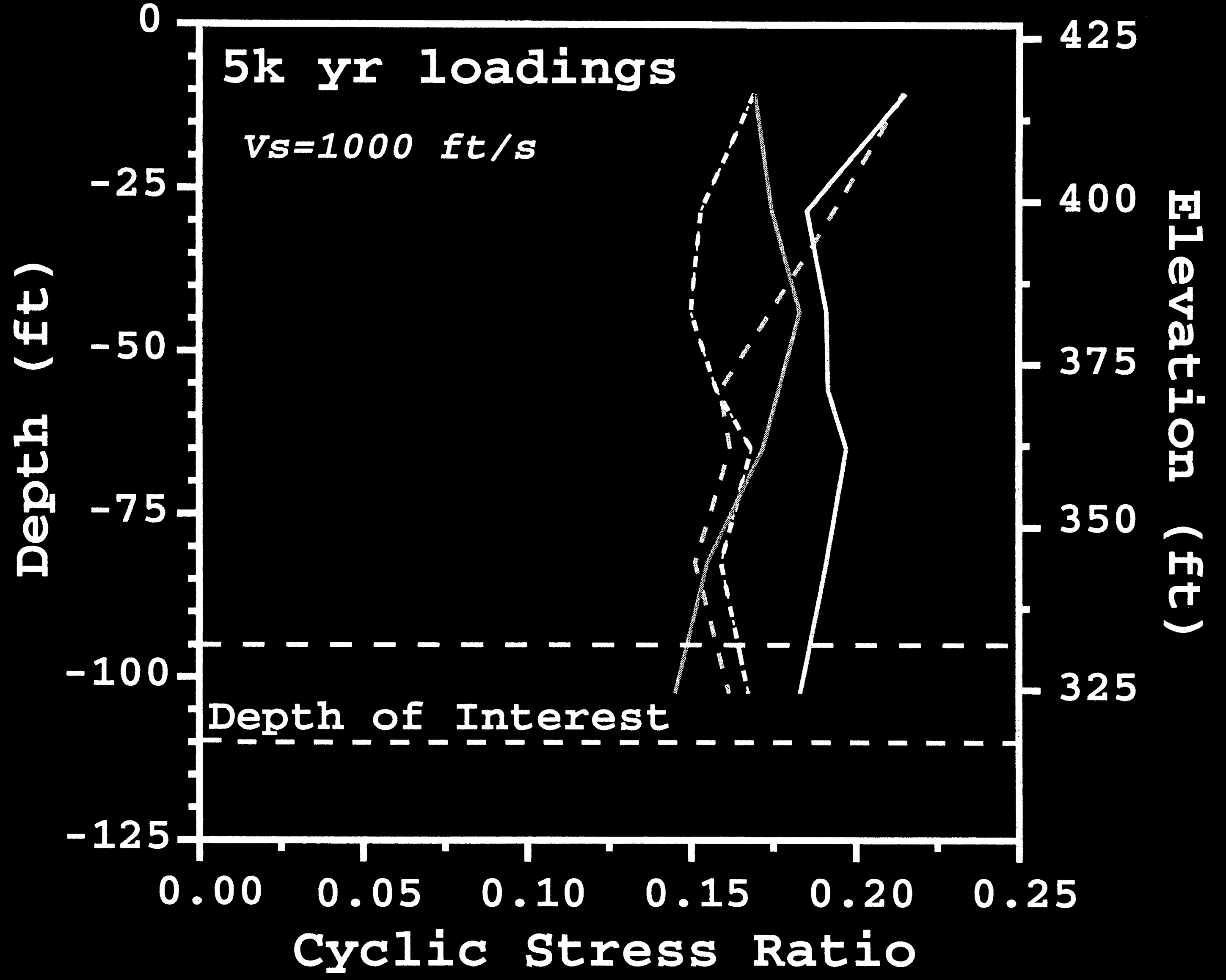
Engineering and fiscal resources require a finite number of recordings for use in analysis of the dam. What should we focus on to define the loading function(s):

Peak Accelerations?
Peak Velocities?
Time Series?

CSR vs Return Period-Section 1



CSR vs Depth-Section 2 (CH-92-02)



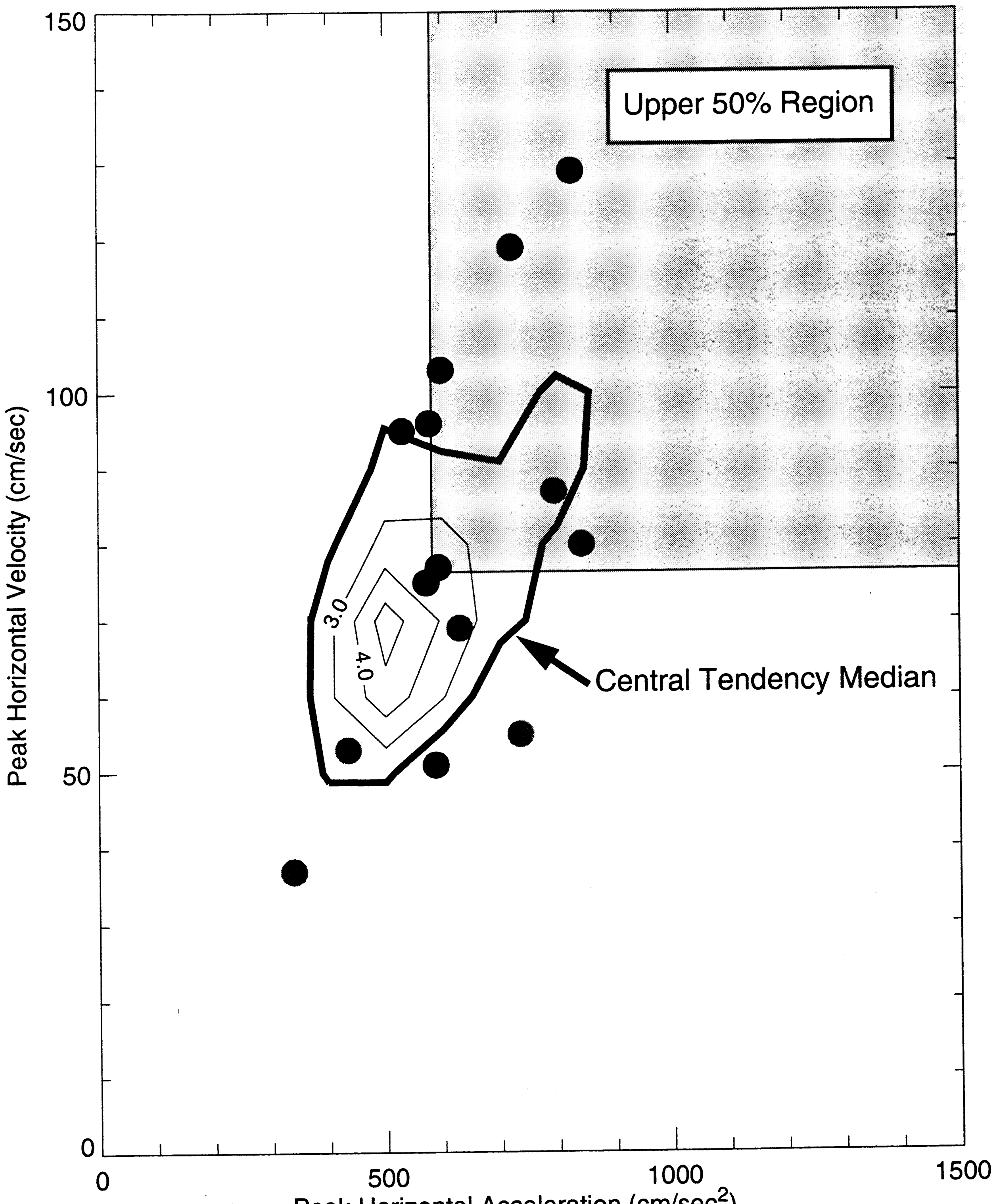
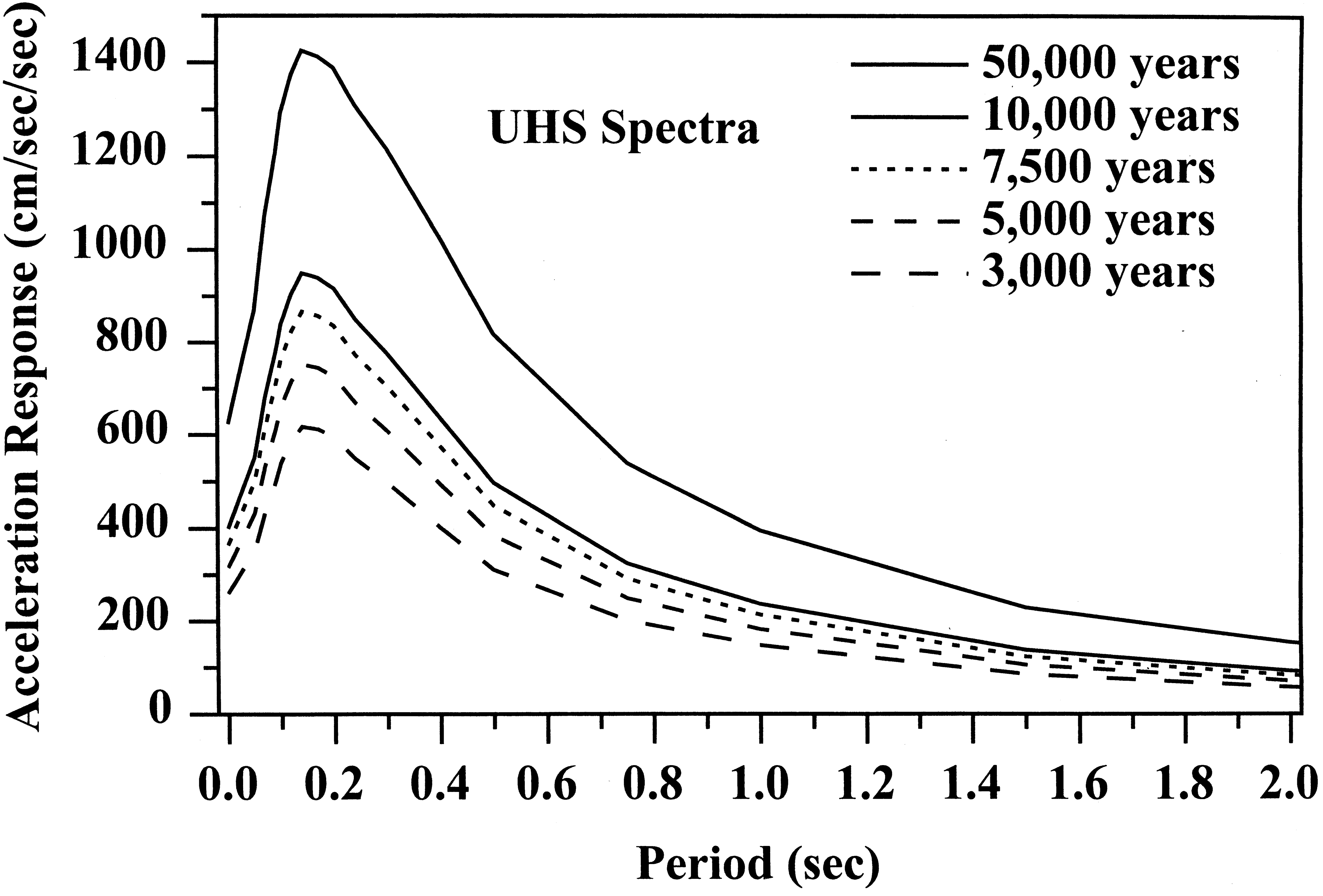
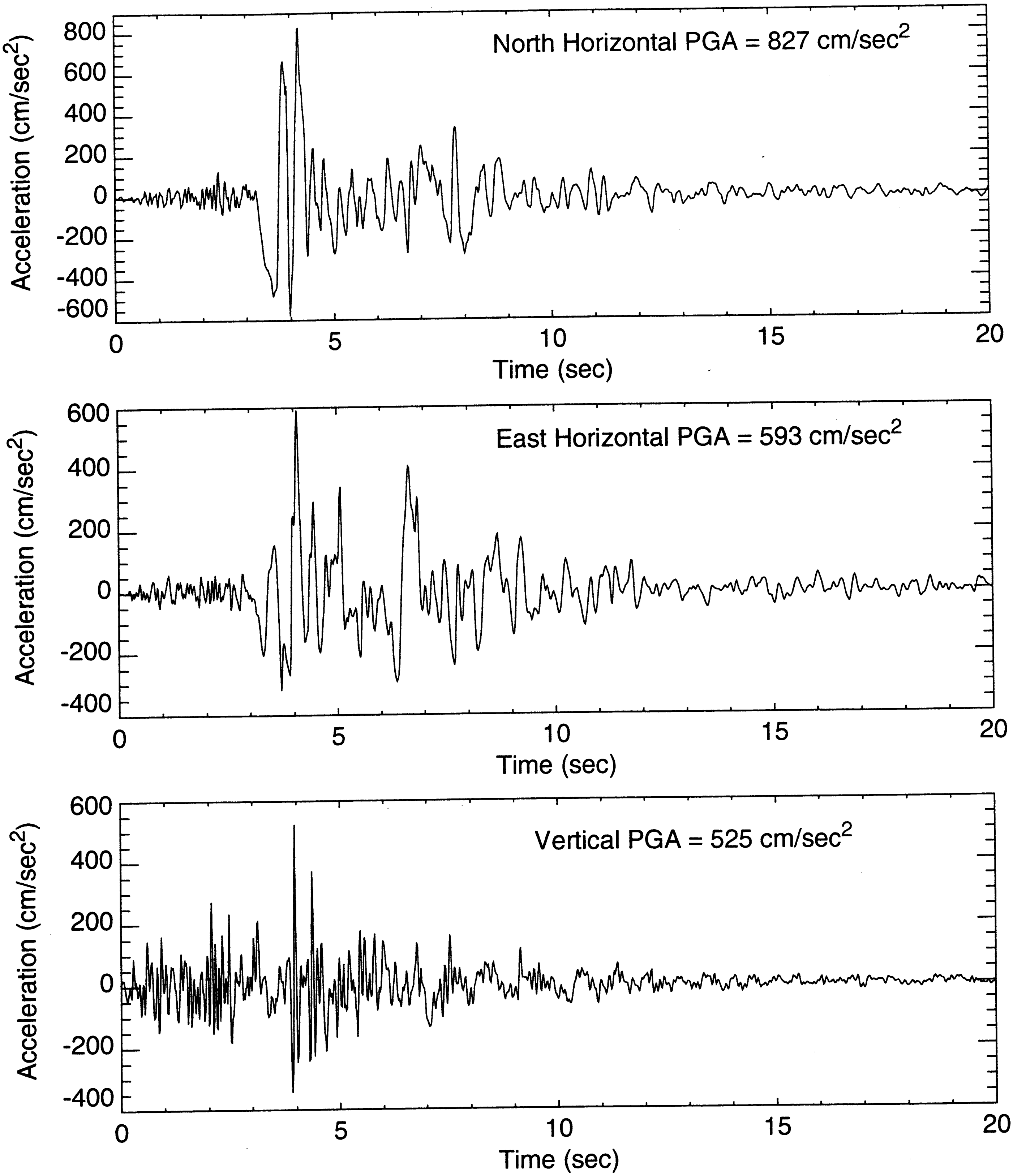


Figure 6-2. Percentage contours (thin) and central tendency median contour (thick) of joint PHA-PHV occurrences from the 1920 rupture simulations of a M 6.9 earthquake on the Red Mountain Fault. The "Upper 50% Region" shaded zone show the region with 50% of the total joint population and the largest loadings. The black filled circles are PHA-PHV values from recommended empirical ground motions and the shaded circles are PHA-PHV values from recommended synthetic ground motions.


UHS Spectra
50,000 years
10,000 years
7,500 years
5,000 years
3,000 years
Acceleration Response (cm/sec/sec)
1400
1200
1000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Period (sec)


North Horizontal PGA = 827 cm/sec^2
Acceleration (cm/sec^2)
800
600
400
200
0
-200
-400
-600
0
5
10
15
20
Time (sec)
East Horizontal PGA = 593 cm/sec^2
Acceleration (cm/sec^2)
600
400
200
0
-200
-400
0
5
10
15
20
Time (sec)
Vertical PGA = 525 cm/sec^2
Acceleration (cm/sec^2)
600
400
200
0
-200
-400
0
5
10
15
20
Time (sec)

SYLMAR

The Future

Source Characterization:

Slip Rates

Recurrence Models

Other Types of Unrecognized Faults?

Ground Motions:

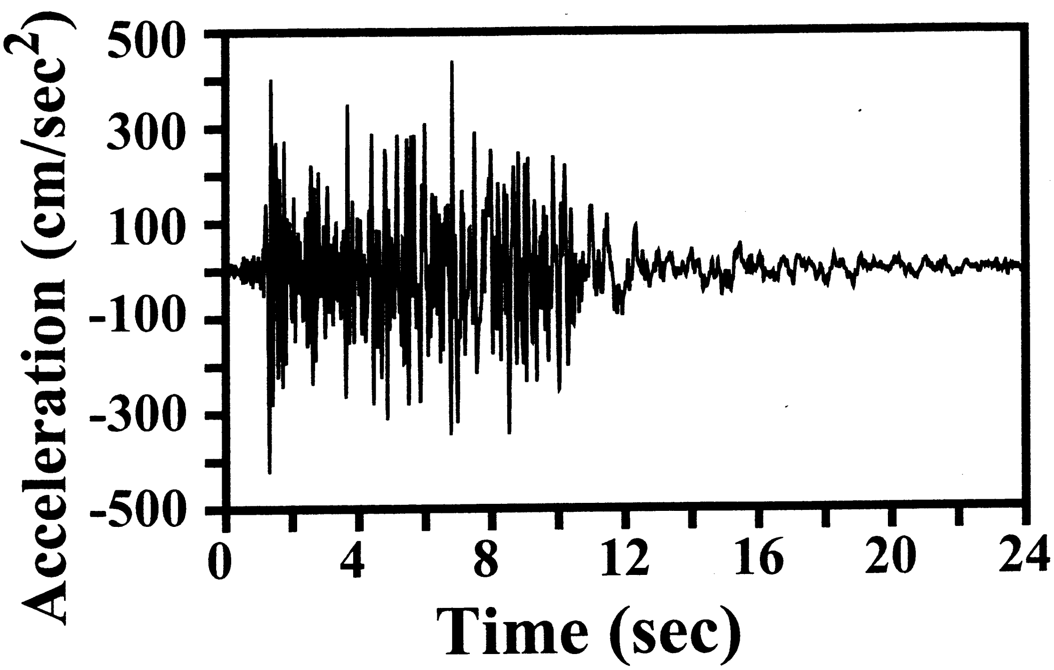
Site Response (neccessary for small AFE)

3-D Effects

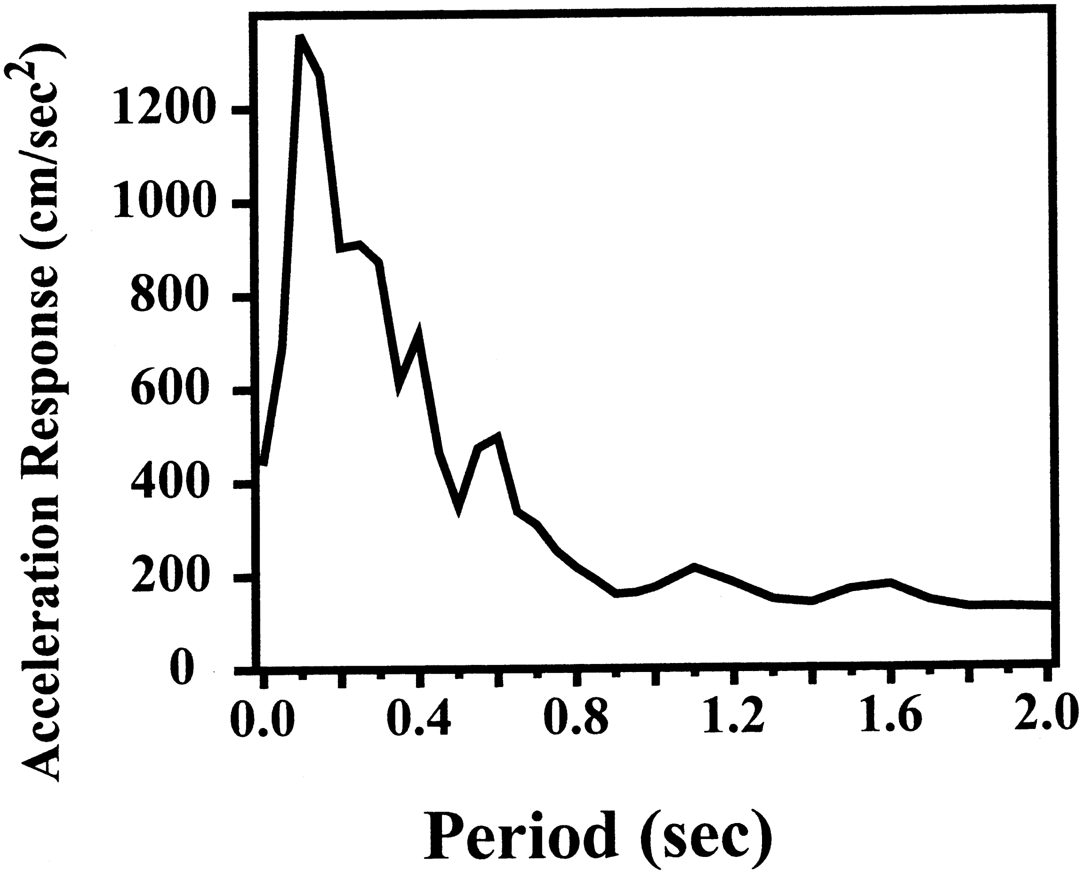
Rupture Dynamics

Integration w/ Engineering Analyses

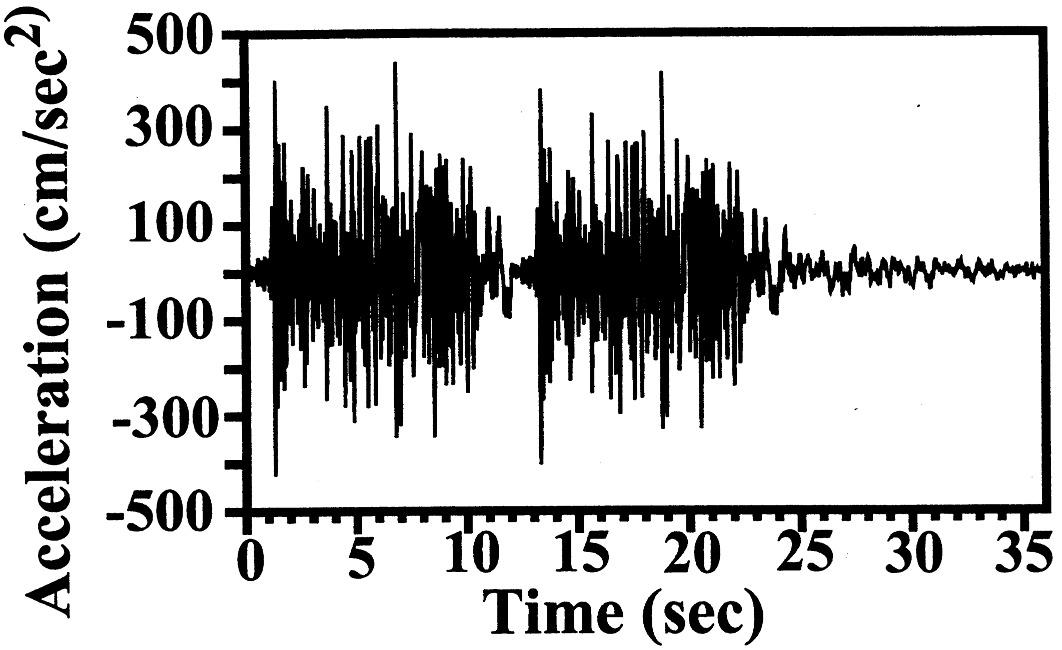
Time Histories

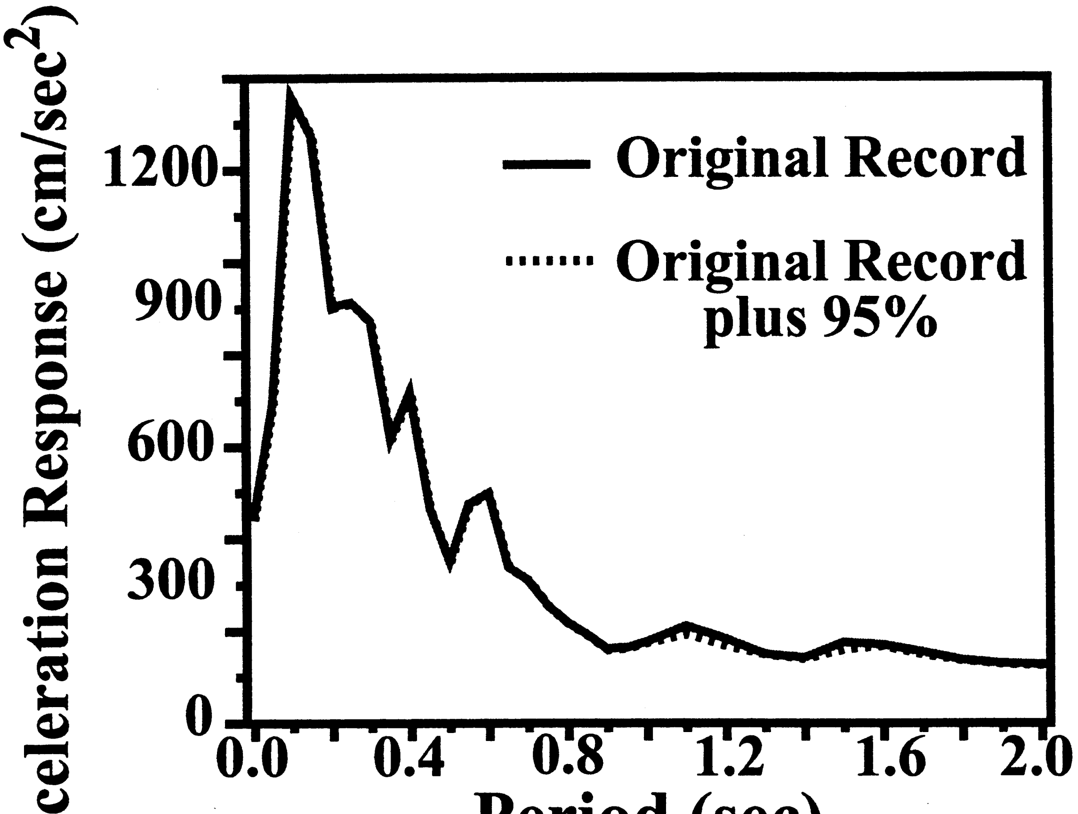


Acceleration (cm/sec^2)
500
300
100
-100
-300
-500
0
4
8
12
16
20
24
Time (sec)



Acceleration Response (cm/sec^2)
1200
1000
800
600
400
200
0
0.0
0.4
0.8
1.2
1.6
2.0
Period (sec)


Acceleration (cm/sec^2)
500
300
100
-100
-300
-500
0
5
10
15
20
25
30
35
Time (sec)


Acceleration Response (cm/sec^2)
1200
900
600
300
0
0.0
0.4
0.8
1.2
1.6
2.0
Period (sec)
Original Record
Original Record plus 95%

PSHA
Potential Derived Quantities

Arias Intensity:

$$I_h = I_{xx} + I_{yy} = \frac{\pi}{2 \cdot g} \cdot \left(\int_0^t (a_x^2(t))dt + \int_0^t (a_y^2(t))dt \right)$$

Total Cumulative Energy:

$$E_{tot} = E_{NS} + E_{EW} + E_V = \frac{1}{2} \cdot \rho(x, y) \cdot \int_0^T \dot{u}^2(x, y, t)dt$$

Acceleration Spectrum Intensity:

$$ASI = \int_{0.1}^{0.5} SA(T)dT$$

Velocity Spectrum Intensity:

$$VSI = \int_{0.1}^{2.5} SV(T)dT$$

Conclusions

(1) For most sites in the Intermountain West- even in areas where Quaternary faults have been identified- the background or random source is an important factor in hazard assessment.

(2) Additional site specific fault investigations are required in areas where the need exists to produce design ground motions with low AFE.

(3) Developing robust estimates of loading functions at sites dominated background seismicity is a challenging task.

(4) Traditional PSHA methods- representative magnitude/distance criteria for time series selection. Result is highly insensitive to duration and phasing.

(5) Ideally we desire a direct link between time histories and annual frequency.

(6) Alternative representation of ground motions, may require multidimensional pdf’s.

ASDSO/FEMA SPECIALTY WORKSHOP

RISK ASSESSMENT FOR DAMS

Utah State University, Logan
March 7-9, 2000

QUANTITATIVE RISK ASSESSMENT OF DAMS

ESTIMATION OF PROBABILITIES OF FAILURE

Robin Fell
School of Civil and Environmental Engineering
University of New South Wales
Sydney, Australia, 2052

1. INTRODUCTION

This paper presents a review of the state-of-the-practice of the estimation of the probability of failure of embankment and concrete dams for use in Quantitative Risk Assessment (QRA).

Probabilities of failure are estimated by a number of methods:

- Historic performance
- Event Tree
- Fault Tree

These are supported by deterministic analysis, stochastic analyses such as Monte Carlo methods, and judgement. Judgement is woven into the fabric of all dam safety investigations and analyses, whether they are performed under a traditional deterministic framework, or in a risk-based framework. It is also the basis for combining information from the different categories.

The emphasis of this paper will be on historic performance methods, and the estimation of structural response to loadings, which are used in event and fault trees. The paper is based on the author's experience in practise and as a researcher, and incorporates the author's knowledge of what is practised in Australia and North America. Much of the text is common to the paper Fell, Bowles, Anderson and Bell (2000), "The status of methods for estimation of the probability of failure of dams for use in Quantitative Risk Assessment", which is to be published in the ICOLD congress in Beijing.

In this paper the probability terms are used in the future, predictive sense: frequency in the past or historic sense.

2. HISTORIC PERFORMANCE METHODS

These methods use the historic performance of dams similar to the dam being analysed to assess a historic failure frequency, and assume that the future performance of such dams will be similar. In some cases, the performance of dams during first filling, or in the first 5 years, is separated from later performance. These methods do not directly account for the reservoir loading, including normal operating loads or floods, nor do they allow for the detailed characteristics of the dam or for the ability of those responsible for the operation of the dam to detect a problem developing and to intervene. Generally speaking, these methods are only applicable for initial or portfolio risk assessments, and for checking more detailed event tree methods, and should not be used alone for detailed assessments.

They are used for estimating the probability of failure of embankment dams by slope instability and piping, and of concrete and masonry gravity dams under normal operating and flood loadings.

2.1 Embankment Dams

2.1.1 Slope Instability

Table 1 summarises the statistics of failures and accidents for large dams up to 1986 (Foster et al 1998, 1999).

Table 1 Statistics of embankment dam slope instability incidents

Year of Operation	**Average Annual Frequency x 10^{-5}**			
	Upstream Instability		Downstream Instability	
	Accident	Failure	Accident	Failure
All Years	15	0.3	18	2
First 5 Years	42		47	4
After 5 Years	9		11	1.5

In all, Foster et al found only six failures of large dams due to downstream slope instability, and one due to upstream slope instability (and that one also involved piping). Only 4% of all failures are due to slope instability. This is because most instability becomes apparent before collapse occurs, with the dam settling or cracking, so intervention to lower the reservoir and/or improve stability can be implemented before the dam breaches.

The annual frequency of failure can be assessed using Table 1, consideration of zoning of the dam (as is done in Foster et al 1998, 1999) the results of stability analyses (including those using peak strength, residual strength), the freeboard, deformation and seepage observations and engineering judgement.

Appendix A includes tables with more detailed statistics of failures and accidents.

It should be noted that it is the probability of breaching which is being considered, so even if a dam is moving, but has significant freeboard, and materials which are not very susceptible to strain weakening, it may have a relatively low probability of failure.

2.1.2 Internal Erosion and Piping

The statistics of failure of embankment dams by piping have been summarized by Foster et al (1998, 1999). Piping accounts for 43% of all embankment dam failures, 54% for dams constructed after 1950. Of these, 65% occur in the embankment, 30% in the foundation, and 5% from the embankment to the foundation.

Foster et al (1998), and Foster and Fell (1999(a)) have proposed a method for estimating the relative likelihood of failure by piping, using these statistics, and allowing for the zoning, embankment construction materials, compaction, the presence of conduits through the dam, foundation geology and treatment during construction, and monitoring and surveillance.

As an example, to estimate the annual probability of failure by piping through the embankment:

(a) Determine the average annual probabilities of failure from Table 2 for piping through the embankment, allowing for the age of the dam, i.e. whether less than or older than 5 years (about 2/3 of piping failures occur on first filling or in the first 5 years of operation).

(b) Calculate the weighting factors w_E, w_F and w_{EF} from Table 3 to take account of the characteristics of the dam, such as core properties, compaction and foundation geology, and to take account of the past performance of the dam. The weighting factors are obtained by multiplying the individual weighting factors from the relevant table. So, for example, $w_E = w_{E(filt)} \times w_{E(cgo)} \times w_{E(cst)} \times w_{E(cc)} \times w_{E(con)} \times w_{E(ft)} \times w_{E(obs)} \times w_{E(mon)}$.

(c) Obtain the annual probability of failure by piping through the embankment from $w_E P_e$. The overall annual probability of failure by piping (P_p) would be obtained by summing the weighted probabilities for piping through the embankment, foundation, and embankment into the foundation:

$$\text{so } P_p = w_E P_e + w_F P_f + w_{EF} P_{ef} \,.$$

If the probabilities are high, allowance must be made for the union of events in this calculation.

Table 2: Average frequency of failure of embankment dams by mode of piping and dam zoning.

ZONING CATEGORY	EMBANKMENT			FOUNDATION			EMBANKMENT INTO FOUNDATION		
	AVERAGE. P_{Te} ($x10^{-3}$)	AVERAGE ANNUAL P_e ($x\ 10^{-6}$)		AVERAGE. P_{Tf} ($x10^{-3}$)	AVERAGE ANNUAL P_f ($x\ 10^{-6}$)		AVER-AGE. P_{Tef} ($x10^{-3}$)	AVERAGE ANNUAL P_{ef} ($x\ 10^{-6}$)	
		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation
Homogeneous earthfill	16	2080	190	1.7	255	19	0.18	19	4
Earthfill with filter	1.5	190	37						
Earthfill with rock toe	8.9	1160	160						
Zoned earthfill	1.2	160	25						
Zoned earth and rockfill	1.2	150	24						
Central core earth and rockfill	(<1.1)	(<140)	(<34)						
Concrete face earthfill	5.3	690	75						
Concrete face rockfill	(<1)	(<130)	(<17)						
Puddle core earthfill	9.3	1200	38						
Earthfill with corewall	(<1)	(<130)	(<8)						
Rockfill with corewall	(<1)	(<130)	(<13)						
Hydraulic fill	(<1)	(<130)	(<5)						
ALL DAMS	**3.5**	**450**	**56**	**1.7**	**255**	**19**	**0.18**	**19**	**4**

Notes: (1) P_{Te}, P_{Tf} and P_{Tef} are the average probabilities of failure over the life of the dam.

(2) P_e, P_f and P_{ef} are the average annual probabilities of failure.

We prefer to use the term relative likelihood, rather than probability to reflect the approximate nature of the approach, which while based on an analysis of the statistics of failure and accidents, and the statistics of the dam characteristics, does not have a rigorous statistical basis, and includes a lot of engineering judgement, particularly for the weighting factors for foundation treatment, observation of seepage, monitoring and surveillance and the effect of filters.

The method is being used for preliminary and portfolio risk assessments in Australia, and is used by USBR as a check on event tree methods.

2.2 Concrete and Masonry Dams

Table 4 summarises the historic performance of concrete and masonry gravity dams for all failure modes including overtopping (Douglas et al 1999).

Table 3: Summary of the weighting factors for piping through the embankment

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 11.1 for the average annual probabilities of failure by piping through the embankment depending on zoning type				
EMBANKMENT FILTERS $w_{E(filt)}$		No embankment filter (for dams which usually have filters (refer to text) [2]	Other dam types [1]	Embankment filter present - poor quality [0.2]	Embankment filter present - well designed and constructed [0.02]
CORE GEOLOGICAL ORIGIN $w_{E(cgo)}$	Alluvial [1.5]	Aeolian, Colluvial [1.25]	Residual, Lacustrine, Marine, Volcanic [1.0]		Glacial [0.5]
CORE SOIL TYPE $w_{E(cst)}$	Dispersive clays [5] Low plasticity silts (ML) [2.5] Poorly and well graded sands (SP, SW) [2]	Clayey and silty sands (SC, SM) [1.2]	Well graded and poorly graded gravels (GW, GP) [1.0] High plasticity silts (MH) [1.0]	Clayey and silty gravels (GC, GM) [0.8] Low plasticity clays (CL) [0.8]	High plasticity clays (CH) [0.3]
COMPACTION $w_{E(cc)}$	No formal compaction [5]	Rolled, modest control [1.2]	Puddle, Hydraulic fill [1.0]		Rolled, good control [0.5]
CONDUITS $w_{E(con)}$	Conduit through the embankment - many poor details [5]	Conduit through the embankment - some poor details [2]	Conduit through embankment - typical USBR practice [1.0]	Conduit through embankment - including downstream filters [0.8]	No conduit through the embankment [0.5]
FOUNDATION TREATMENT $w_{E(ft)}$	Untreated vertical faces or overhangs in core foundation [2]	Irregularities in foundation or abutment, Steep abutments [1.2]		Careful slope modification by cutting, filling with concrete [0.9]	
OBSERVATIONS OF SEEPAGE $w_{E(obs)}$	Muddy leakage Sudden increases in leakage **[up to 10]**	Leakage gradually increasing, clear, Sinkholes, Seepage emerging on downstream slope [2]	Leakage steady, clear or not observed [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5]
MONITORING AND SURVEILLANCE $w_{E(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

Table 4 Historic annual frequency of failure of concrete and masonry gravity dams

Year Commissioned	Frequency of Failure x 10^{-5}					
	Concrete Gravity			Masonry Gravity		
	Overall	First 5 years	After 5 years	Overall	First 5 Years	After 5 Years
1700-1929	15	100	9	54	520	34
1929-1992	3.5	14	1.4	42	160	24

Using the historic performance does give a starting point to estimating probabilities of failure, and the author has been involved in doing preliminary risk analyses using the figures in Table 4, coupled with judgement, taking account the dam geometry, geology and calculated factor of safety for known flood probabilities.

The fundamental limitation of historic performance methods in this case is that failure is load (reservoir water level) driven, and this is not included in the base statistics. In embankment dam stability and piping, the reservoir level has some influence, but it is not so important.

3. EVENT TREE METHODS

Figure 1 shows an example of an event tree for earthquake induced liquefaction failure of embankment dam. The points to note are:

- The start point is the bedrock peak ground acceleration, which influences the probability of liquefaction being initiated, leading to post earthquake instability, loss of freeboard and breaching of the dam.
  The finish point is the breach of the dam, that is, the release of the reservoir water. A dam has not "failed", until this breach occurs. The fact that liquefaction has occurred, does not by itself represent failure.
- The reservoir water level affects the probability of breaching, and the consequences of failure.
- The probability of failure is the sum of all the "breach" probabilities.

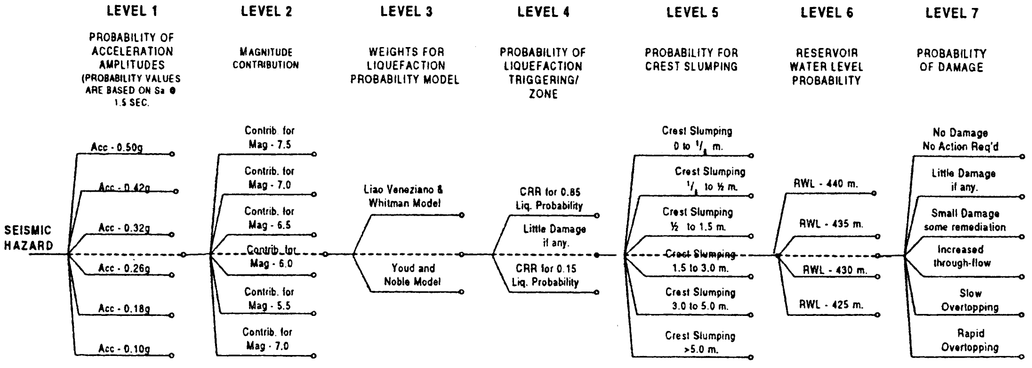


Figure 1 Example of an event tree for liquefaction failure of a dam embankment (Lee et al 1998)

Event trees, some much simpler than that shown in figure 1, can be developed for all modes of failure.

Event tree methods have the advantage that the mechanics of the failure, from initiation to breach can be modelled; as can the reservoir level, the details of the dam and its foundation and the ability to intervene to prevent breaching. However, as discussed below, sometimes there is little objective basis for estimation of the conditional probabilities within the event tree and much subjective judgement is needed. It may therefore be necessary to relate back to historic performance data as a "credibility check" on the answers.

3.1 Embankment Dams

3.1.1 Flood

Failure due to flood can occur by overtopping of the embankment, scour of the spillway chute or energy dissipater (leading to undercutting of the embankment), or overtopping the spillway chute walls, leading to scour and undercutting of the embankment. If the spillway is gated, failure of the gates to operate satisfactorily may lead to overtopping of the dam by a much higher frequency flood than would otherwise be the case. The spillway may also be blocked by floating vegetation, snow/ice, or by instability of the slopes adjacent. The probability of failure for these scenarios is usually estimated as follows:

(a) Embankment overtopping

Peak reservoir water level Vs AEP is calculated. Allowance for wind set-up, or waves is seldom allowed for. The Hume Dam risk study (NSW Dept. Public Works and Services (1998) and McDonald and Wan (1999)) showed that these had little effect on analysis failure probabilities, and including them increased the work significantly.

The probability of failure is calculated from the reservoir level AEP, and a system response curve, that is, probability of failure vs depth of water over the dam crest, which is developed for that dam. Selection of the response relationship is subjective, with factors such as material type, compaction and inherent susceptibility to erosion influencing the choice. Guidance on the depths and duration of water flow over dam crests which lead to failure can be obtained from Dewey and Oaks (1990), Powledge et al (1989) and Allen (1994).

There is no definitive publication which puts this into a probabilistic framework. Most studies seem to accept that the probability of failure approaches 1.0 when the depth of water overtopping the dam is between 0.5m and 1m for modern compacted rockfill, but near zero for poorly compacted earthfill.

(b) Spillway and spillway energy dissipation scour.

Salmon et al (1996) describes a study in which spillway scour is considered. The rate and extent of scour can be based on calculation or hydraulic models, coupled with judgement.

(c) Overtopping of spillway chute walls

The authors' experience is that spillway chute walls are often likely to overtop at floods less than the flood to overtop the dam. If the chute is adjacent the embankment, the overtopping can scour the dam and lead to failure. The AEP of overtopping of the walls can be estimated from calculation or from physical hydraulic scale models. The scour estimates are usually judgmental. Intuitively one would tolerate periodic overtopping by waves in the spillway. Perhaps a steady 0.5m to 1m overtopping would warrant a conditional probability of 1.0.

3.1.2 Slope Instability

Modelling the likelihood of failure of an embankment dam by slope instability in event tree methods requires the modelling of the reservoir level, probability of instability using formal probabilistic methods, estimating the deformation of the dam (loss of level of the crest) and hence whether the reservoir will be higher than the dam crest after failure.

Formal probabilistic methods of stability analysis are well developed and can be used to assess the probability of failure. Mostyn and Fell (1998) review the methods available and their limitations. There are several problems with using these methods:

- The analyses require estimates of means and standard deviations for strength parameters. The latter are usually estimated, based on limited published data, and require an estimate of vertical and horizontal correlation distance for which there are few data available. Anderson et al (1981 and 1982) and Sharp et al (1981) discuss these issues.
- Pore pressures, and their annual probability, need to be modelled to allow annual estimates of probability of failure. These are often difficult to predict.
- Most instability problems arise because of weak zones in the foundation or the dam such as a bedding surface shear in the foundation, or poorly compacted softened zone in the dam. These are often unknown or not recognised so are not modelled in the analysis.
- Model bias can occur. For example the use of cone penetration test to estimate undrained strengths may introduce a bias, unless the uncertainty in the relationship between cone resistance and undrained shear strength is properly modelled.
- The model must use the correct mechanics. To illustrate, some stability analyses must be carried out using undrained strengths, because effective stress analyses can over-estimate the available strength. (see Cooper et al (1997)). For existing dams it is also critical that cracking and crack water pressures are modelled.
- The deformation of the dam after reaching a factor of safety of 1.0 must be modelled, and compared to the freeboard. This can be done using simplified methods, such as, Khalili et al (1997), or using numerical modelling.

McDonald and Wan (1999) describes the use of probabilistic analyses for Hume dam and raises issues relating to length effects and retrospective versus prospective probabilities. The inclusion of length effects seems to be an unnecessary refinement except for very long dams. The retrospective versus prospective probabilities issue is an interesting one, but given that most instability will occur during construction, or first filling, or be due to a deterioration in the dam strength due to seepage or cracking, it does not seem to be a significant issue.

Overall the author is of the opinion that given the low historic probability of failure by slope instability, and the difficulties described above, the use of formal probabilistic methods is typically not warranted, even in the most detailed risk analyses.

3.1.3 Internal Erosion and Piping

A number of organisations have used event trees coupled with expert judgement to assess the probability of piping. Examples are the Coursier Dam study done by BC Hydro (1995), the study of Prospect Dam (Landon-Jones et al, 1996), and a study of three central core earth and rockfill dams in Norway (Johansen et al, 1997). In these studies, the event tree is set up to model initiation, progression, possible intervention, and breaching. Tables 5 and 6 (Foster 1999) show generic failure paths and event trees. The probabilities in the event tree are estimated by a panel of "experts" based on their experience, data supplied to them regarding the design and construction of the dam, and selected reading of papers relevant to the topic.

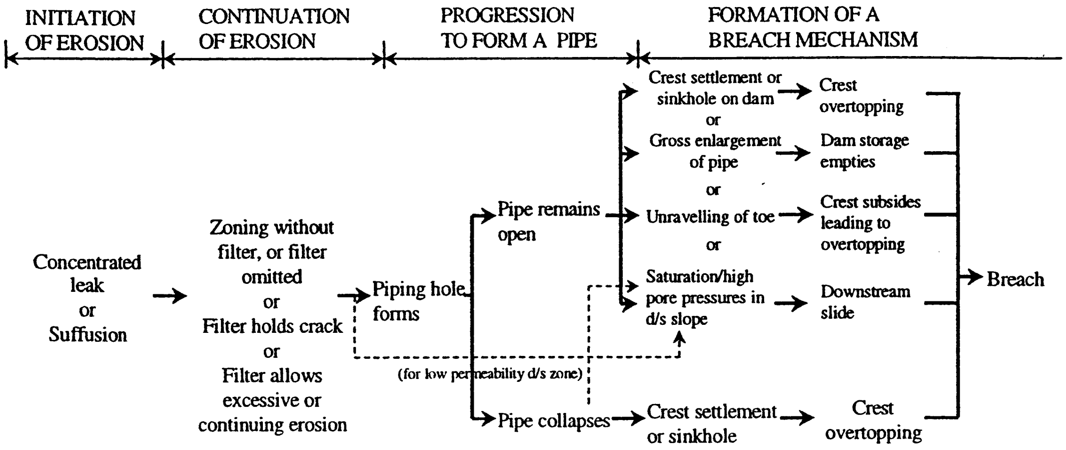


Table 5: Failure path diagram for failure by piping through the embankment

The approach has some advantages compared with the historic performance data approach:

- There is more emphasis on the design, construction and performance of the dam in question
- The problem is broken down into smaller components as shown in figures 2 and 3 (Foster 1999) which usually makes estimation of probability easier
- Consideration of design details, such as compliance with filter criteria is possible.

However, there are some problems including:

- There is little objective basis upon which the expert panel can estimate probabilities for progression and breaching, and it is only marginally better for initiation of piping. Hence, the outcome is very dependent on the judgement of the panel members and hard to document other than as "expert judgement"
- The data provided for the expert panel is likely to be biased towards failures, and as a result, probabilities of piping may be overestimated.

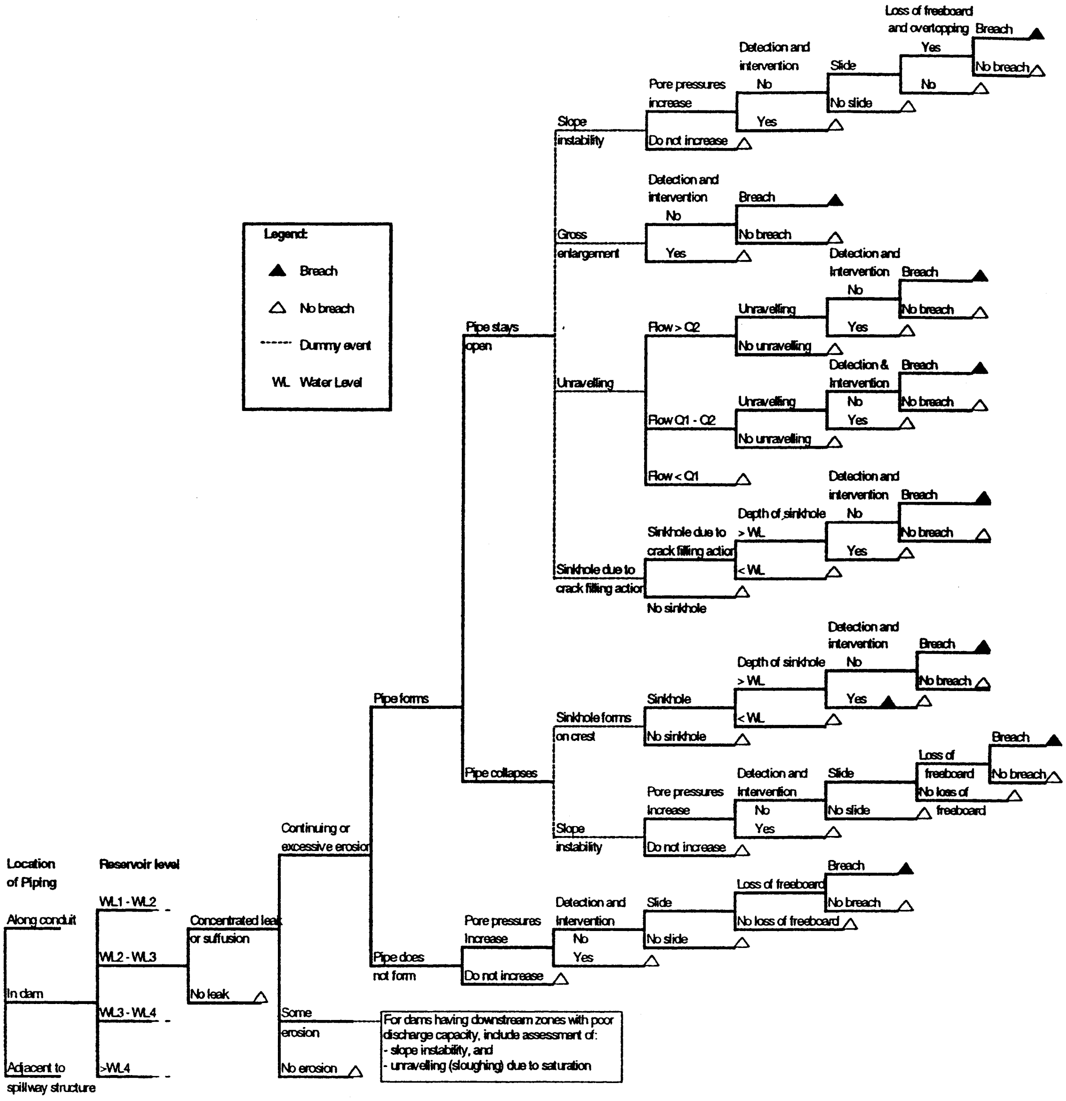


Table 6 Event tree for piping through the embankment

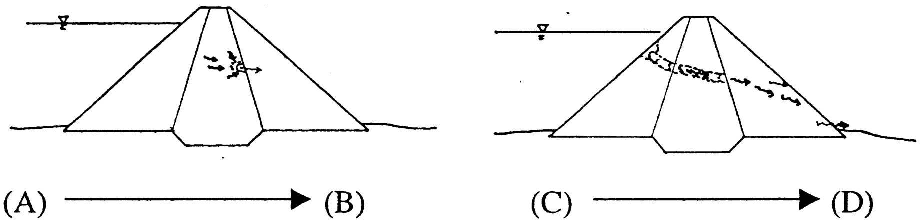


Figure 2 Backward erosion piping

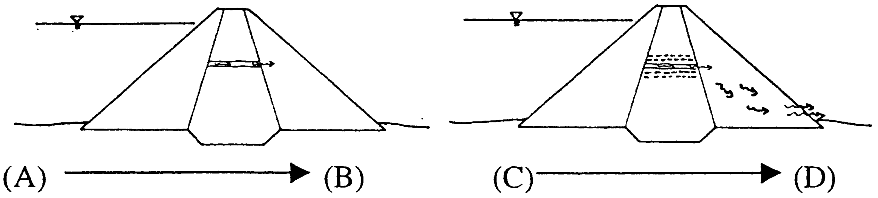


Figure 3; Concentrated leak piping

ZONING CATEGORY	NO. OF FAILURES	NO. OF ACCIDENTS	% OF INCIDENTS (accidents & failures (b)	% DAMS IN POPULATION (a)	AVERAGE PROBABILITY OF FAILURE (x 10^{-3})	AVERAGE PROBABILITY OF INCIDENT (x 10^{-3})	AVERAGE AGE (up to 1986)	AVERAGE ANNUAL PROBABILITIES OF INITIATION OF SLIDING (accidents and failures combined) (x 10^{-6}) (c) (d)		
								All Years of Operation	First 5 Years of Operation	After 5 Years of Operation
Homogeneous earthfill		12	26.1	9.5		12	34.9	331	1176	189
Earthfill with filter		4	8.7	15		2.4	18.8	130	248	86
Earthfill with rock toe		3	6.5	6.1		4.5	24.8	181	458	111
Zoned earthfill		9	19.6	35.9		2.3	21.8	105	233	67
Zoned earth and rockfill		0	0.0	9.3			22.2			
Central core earth and rockfill		2	4.3	8.4		2.2	16.2	135	222	95
Concrete (or other) face earthfill		3	6.5	4.1		6.7	29.7	225	681	132
Concrete (or other) face rockfill		0	0.0	2.8			26.0			
Puddle core earthfill		4	8.7	4.7		7.8	91.5	85	792	44
Concrete corewall, earthfill	1	2	6.5	2.4	3.7	11	48.6	235	1164	128
Concrete corewall, rockfill		1	2.2	0.9		10	32.5	313	1035	181
Hydraulic fill		5	10.9	0.9		51	69.0	735	5173	388
Other zoning type		0	0.0	-	-					
Zoning type unknown		1								
ALL DAMS	**1**	**46**	**100**	**100**	**0.09**	**4.2**	**26.8**	**156**	**412**	**98**

NOTES:
(a) Embankment dam population of 11192 dams excluding all dams constructed in China and dams constructed in Japan before 1930
(b) Percentage of cases where zoning type is known
(c) The percentage of accidents and failures by this mode of sliding occurring at the different times after construction are:

During construction	21%
During first filling	2%
During first five years operation	28%
After five years operation	49%

(d) Calculations of annual probabilities of initiation of sliding are made as follows:
Annual Prob. of Initiation (All Years) = Ave. Prob. of Incidents / Average Age
Annual Prob. of Initiation (First Five Years) = Ave. Prob. of Incidents x 0.51 / 5
Annual Prob. of Initiation (After Five Years) = Ave. Prob. of Incidents x 0.49 / (Average Age - 5)
(e) **The average annual probability of failure by upstream slides is:**

All years of operation: 3 x 10^{-6}

APPENDIX A: Detailed Statistics of Failures and Accidents – from Foster, Fell and Spannagle (1998)

ZONING CATEGORY	NO. OF FAILURES		NO. OF ACCIDENTS		% OF INCIDENTS (accidents & failures) (b)	% DAMS IN POPULATION (a)	AVERAGE PROBABILITY OF FAILURE (x 10^{-3})	AVERAGE PROBABILITY OF INCIDENT (x 10^{-3})	AVERAGE AGE (up to 1986)	AVERAGE ANNUAL PROBABILITIES OF INITIATION OF SLIDING (accidents and failures combined) (x 10^{-6}) (c) (d)		
	Large Dams only	(All Dams)	Large Dams only	(All Dams)						All Years of Operation	First 5 Years of Operation	After 5 Years of Operation
Homogeneous earthfill		(4)	19	(22)	36.5	9.5		20	34.9	582	1987	346
Earthfill with filter			7	(9)	13.5	15		4.7	18.8	252	464	175
Earthfill with rock toe			4	(4)	7.7	6.1		6.6	24.8	268	651	171
Zoned earthfill			6	(6)	11.5	35.9		1.7	21.8	78	166	51
Zoned earth and rockfill	1	(1)	0	(0)	1.9	9.3	1.4	1.1	22.2	49	107	32
Central core earth and rockfill	1	(1)	1	(2)	3.8	8.4	1.6	2.4	16.2	149	237	110
Concrete (or other) face earthfill			0	(0)	0.0	4.1			29.7			
Concrete (or other) face rockfill			0	(0)	0.0	2.8			26.0			
Puddle core earthfill			1	(4)	1.9	4.7		2.2	91.5	24	211	13
Concrete corewall, earthfill			5	(5)	9.6	2.4		21	48.6	435	2070	247
Concrete corewall, rockfill			0	(0)	0.0	0.9			32.5			
Hydraulic fill	2	(2)	4	(4)	11.5	0.9	29.8		69.0			
Other zoning type		(1)	1	(1)	1.9	-	-					
Zoning type unknown	2	(2)	5	(5)								
ALL DAMS	**6**	**(11)**	**53**	**(62)**	**100**	**100**	**0.54**	**5.3**	**26.8**	**196**	**517**	**123**

NOTES:

(a) Embankment dam population of 11192 dams excluding all dams constructed in China and dams constructed in Japan before 1930

(b) Percentage of cases where zoning type is known

(c) The percentage of accidents and failures by this mode of sliding occurring at the different times after construction are:

During construction	15%
During first filling	13%
During first five years operation	21%
After five years operation	51%

(d) Calculations of annual probabilities of initiation of sliding are made as follows:

Annual Prob. of Initiation (All Years) = Ave. Prob. of Incidents / Average Age
Annual Prob. of Initiation (First Five Years) = Ave. Prob. of Incidents x 0.49 / 5
Annual Prob. of Initiation (After Five Years) = Ave. Prob. of Incidents x 0.51 / (Average Age - 5)

(e) **The average annual probabilities of failure by downstream slides are:**

All years of operation:	**2 x 10^{-5}**
First five years of operation	**4 x 10^{-5}**
After five years of operation	**1.5 x 10^{-5}**

APPENDIX A

Detailed Statistics of Failures and Accidents – From Foster, Fell and Spannagle (1998)

Youd, T.L. and Noble, S.K. (1998). Liquefaction criteria based on statistical and probabilistic analyses. Proc. NCEER Workshop on Liquefaction Resistance of Soils.

account the annual probability of the flood loading, the geometry and geology of the foundation, and any available results from similar situations.

Overtopping a concrete dam can also lead to a stability failure of the dam, and care must be taken in selecting the critical section for analysis. Once a dam is overtopped the force distribution changes and the maximum section may no longer be the critical section.

3.2.4 Piping of the Foundation

Piping of the foundation should be considered, particularly for dams on soil foundation. There has been no recorded case of failure by piping on a rock foundation, but several accidents have occurred (Douglas et al 1998). Usually a judgemental probability is assigned, at least for preliminary studies, although in some cases this failure mode may be considered to be implausible.

4. SUMMARY AND CONCLUSION

The methods available for estimating the probability of failure are in varying stages of development. Some failure modes, such as flood-induced overtopping of embankment dams and liquefaction, lend themselves to analysis. Others, such as piping, are not so readily amenable to an analytical approach, so historic performance, and event tree methods using judgemental conditional probabilities must be used. This should not however be taken as an excuse for not including these failure modes in the risk analysis or for that matter, in a deterministic approach to dam safety management. It must always be remembered that dam owners, and the affected public, are concerned with overall dam safety, not only safety related to certain, readily quantified hazards. Analyses should reflect the uncertainty in the risk estimates, as should comparisons with risk criteria.

What should be clear from the foregoing is that judgement and good dams engineering will play a large role in any estimate of the probability of failure of a dam, as it does in traditional dam safety engineering. In fact, apparently objective analysis procedures require judgement to estimate their inputs and to interpret their results. Even the apparently "accurate" and objective flood and earthquake loads have significant judgemental factors involved in their derivation.

Analytical complexity does not necessarily lead to improved estimates of risk. Care must be taken in quoting probabilities which are so low as to be beyond what we can confidently claim to be achievable with modern day engineering.

The current state of QRA practice is better able to estimate relative likelihoods of failure, than absolute probabilities, and is therefore well suited for portfolio applications in which investigations and risk reduction measures are prioritised. It should therefore be used in conjunction with deterministic approaches for decision making on dam safety.

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Allen, P.J. (1994). Dam Break Breach Mechanisms, ANCOLD Bulletin No.97, Australian National Committee on Large Dams.

ANCOLD (1994). Guidelines on Risk Assessment. Australian National Committee on Large Dams.

available to estimate strength. All that can be done is to rely on the judgement of an experienced engineering geologist and rock mechanics specialist to estimate the strengths.

- The uplift pressures are uncertain, and may vary non-linearly with reservoir level and with seasons. Neither De Rham and Salmon (1997) or McDonald and Wan (1999) appear to allow for this uncertainty.
- Three dimensional effects are usually ignored, but may be significant.

As for embankment dam, the main potential shortcoming of the method is that a major weakness in the dam or its foundation may not be identified. The failures of St. Francis and Malpasset dams were both attributable to failures through the foundations on unforeseen weak zones.

3.2.2 Earthquake Stability

Earthquake stability has been allowed for in two different ways:

(a) BC Hydro (De Rham and Salmon, 1997)

In this analysis, pseudostatic calculations were carried out as for static loading, but adding the vertical and horizontal acceleration due to the earthquake. They analysed the records of 34 North American earthquakes, and found that simultaneous occurrence of peak vertical and horizontal acceleration was rare, and modelled this frequency of load combinations in the analysis. Their analysis took account of the fact that these (part) pulses of the earthquake were very short, so they considered 3 failure criteria, which are a de facto allowance for the fact that "failure" may not result in large displacements of the dam.

(b) New South Wales Department Public Works and Services (McDonald and Wan, 1999) and New South Wales Department of Public Works and Services (1998).

In this approach, which has been used on several dams, a Newmark (1965) type analysis which sums the accumulated displacements when the earthquake loads cause the available strength in the dam or its foundation to be exceeded is applied, modelling the uncertainty in tensile and shear strength and unit weight, and allowing for crack propagation. Total dam displacements are calculated, and the post earthquake stability calculated, allowing for any change in uplift pressure due to cracking or dilation of failure surfaces if drains are likely to be sheared, possible loss of post tensioning loads, and change in available tensile and shear strength.

Neither of these methods completely simulates the dam behaviour, which is complex and not readily modelled where a range of variable uncertainties is under consideration. The author favours (in principle) the displacement type approach, but more work is needed to compare the results of these Newmark type analyses to more correct analysis, as has been done for embankment dams.

3.2.3 Scour of the Foundation Due to Overtopping

Floods overtopping the dam may cause scouring leading to undermining of the dam. In some cases, such as concrete weirs on an alluvial foundation, flow through the spillway may scour the foundation. The probability of failure is usually estimated by judgement, taking into

The greatest uncertainty lies in the estimation of residual undrained strengths, and the author recommends that the latest literature in this topic be sought if a study is to be undertaken. Simply to use the Stark and Mesri (1992) method, not allowing for the unexplained variance in the data, probably brings in a conservative bias to the answer. These methods can be used for preliminary analyses by not modelling the uncertainty in loading, the probability of liquefaction (e.g. simply use the Seed and de Alba (1986) method), residual undrained strength (e.g. Use Stark and Mesri (1992)) and omit the calculation of post liquefaction deformation (or use Khalili et al 1997.

(2) Seepage erosion and piping through earthquake induced cracking

Earthquakes commonly induce settlement and cracking of the dam. Most of the cracking is longitudinal, so apparently does not present a potential concentrated seepage path for piping to develop. However transverse cracking may be induced as happened adjacent the spillway walls at Austin dam, (Forster and MacDonald 1998). The longitudinal cracks may also represent scarps of slide surfaces through the dam which may become paths for concentrated leaks.

It is recommended that this be allowed for by reviewing the available literature on cracking of dams during earthquakes, relating the cracking to the probability of the earthquake loading and subjectively estimating the probability of failure, taking account of the dam zoning (particularly the presence of filters), freeboard, foundation profile and abutments of the dam against concrete walls.

Deformation by earthquake can interrupt the integrity of internal filters. The estimated displacements may be related to the probability of failure from seepage erosion through cracks, allowing for the thickness of filters, estimated displacements, and self healing characteristics of the filters.

3.2 Concrete and Masonry Dams

3.2.1 Static Stability

The probability of failure of a gravity dam can be analysed using a probabilistic approach, where the uncertainty in the input parameters are modelled. These include the geometry, reservoir and tailwater loading, unit weight, uplift pressures, shear and tensile strength of the dam and its foundation. Analysis of sliding and overturning, in the dam and foundation should be carried out, this is best done using Monte Carlo simulations. De Rham and Salmon (1997) and McDonald and Wan (1999) discuss the procedure. The procedure is relatively straight-forward but there are the following inherent problems, which are also common to deterministic analysis:

- The distribution of tensile strength of concrete is difficult to predict. Laboratory tests can be carried out on cores from the dam, but uncertainty exists as to their meaning in that the continuity of strong/weak surfaces in the horizontal and vertical direction is not modelled. There are also potential model biases; for example, it is important that direct tensile tests are used, not splitting tensile strengths. As pointed out by EPRI (1992) the latter give much greater strengths. Structural concrete codes tend to be based on the splitting tests.
- The shear strength of the rock foundations is difficult to assess and there are no formal methods for assessing the uncertainty. There is an un-defined bias in the various methods

3.1.4 Earthquake

(1) Loss in freeboard for dams not subject to liquefaction

The probability of loss in freeboard for dams which are not subject to liquefaction can be estimated by modelling:

(a) The probability of reservoir level
(b) The probability of the earthquake ground motion
(c) Dam deformation for the earthquake ground motions. For preliminary studies, deformation may be estimated based on simplified analyses such as Newmark (1965) type approaches, including Makdesi and Seed (1978).
(d) For portfolio studies empirical methods such as those by Swaisgood (1995) and Swaisgood (1998) may be used to estimate the loss of crest elevation.

For more detailed studies, varying degrees of sophistication of numerical methods may be used. However for most dams with generous freeboard, the added time and sophistication of these analyses is not warranted.

It should be noted that if the dam or its foundations are susceptible to significant strain weakening, this must be taken into account. The simplified methods do not allow for more than 20% strength reduction.

(2) Loss of freeboard for dams subject to liquefaction

The probability of loss of freeboard for dams which are subject to liquefaction can be estimated by modelling:

(a) The probability of the reservoir level
(b) The probability of the earthquake ground motion
(c) Calculation of the probability or occurrence and extent of liquefied zones, given the earthquake loading, and the residual undrained strength of the liquefied zones. eg. Dewey et al 1998.
(d) Calculation of the post liquefaction factor of safety, and/or deformations.
(e) Comparison of the deformations and freeboard to see how much freeboard is lost.

BC Hydro (1996), Lee et al (1998), Cattanagh and Lum (1998) and Hartford et al (1997) describe the analysis by BC Hydro for Keenleyside dam. As shown in Figure 1 this allowed for the uncertainty in the earthquake loading, and for the model uncertainty in the probability of liquefaction (using both the Liao et al (1988), and Youd and Noble (1996) methods, weighted for model uncertainty). They also allowed for the uncertainty in the modelling of the extent of the liquefied zone, and used a judgemental distribution of the residual undrained strength, which was estimated using the data from Stark and Mesri (1992), Ishihara (1993) and laboratory testing. They did not model the post liquefaction deformations. The Hume Dam study (McDonald and Wan, 1999), used a similar approach, but was based on Liao et al (1988) and Stark and Mesri (1992).

Research at the University of New South Wales is addressing these problems. This has included consideration of whether erosion will continue or eventually seal in filters which are coarser than current design criteria (Foster and Fell 1999a), and an initial assessment of the factors which influence initiation continuation and progression of erosion and breaching (Foster and Fell 1999c, 2000). Tables 7 and 8 gives an example of the aids to expert judgement given in these references.

The author strongly recommends the use of event tree methods because of the ability to model the particular features of each dam and in many cases it can be seen that either piping will not continue or that a breach mechanism is very unlikely to develop. However the answers must be checked against the historic performance method; and if very different, the reason for the difference resolved.

Table 7 Influence of factors on likelihood of cracking or wetting induced collapse-susceptibility of core materials

Factor	Influence on Likelihood of Cracking or Collapse		
	More Likely	**Neutral**	**Less Likely**
Compaction density ratio (1)	Poorly compacted, <95% standard compaction density ratio (2)	95-98% standard compaction density ratio	Well compacted, ≥98% standard compaction density ratio
Compaction water content	Dry of standard optimum water content (approx. OWC – 3%)	Approx OWC–1% to OWC-2%	Optimum or wet of standard optimum water content
Soil types (3)	Low plasticity clay fines	Medium plasticity clay fines	High plasticity clay fines Cohesionless silty fines

Notes: (1) For cracking, compaction density ratio is not a major factor. It is more important for wetting induced collapse.
(2) <93% Standard compaction, dry of OWC, much more likely.
(3) Soil type is not as important as compaction density and water content.

Table 8 Influence of factors in the likelihood of cracking or hydraulic fracturing – features giving low stress conditions

Factor	Influence on Likelihood of Cracking or Hydraulic Fracture		
	More Likely	**Neutral**	**Less Likely**
Overall abutment profile	Deep and narrow valley. Abrupt changes in abutment profile, continuous across core. Near vertical abutment slopes	Reasonably uniform slopes and moderate steepness, eg. 0.25H:1V to 0.5H:1V	Uniform abutment profile, or large scale slope modification. Flat abutment slopes (>0.5H:1V)
Small scale irregularities in abutment profile	Steps, benches, depressions in rock foundation, particularly if continuous across width of core (examples: haul road, grouting platforms during construction, river channel)	Irregularities present, but not continuous across width of the core	Careful slope modification or smooth profile
Differential foundation settlement	Deep soil foundation adjacent to rock abutments. Variable depth of foundation soils. Variation in compressibility of foundation soils	Soil foundation, gradual variation in depth	Low compressibility soil foundation. No soil in foundation
Core characteristics	Narrow core, H/W>2, particularly core with vertical sides	Average core width, 2<H/W<1	Wide core H/W<1
	Core material less stiff than shell material	Core and shell materials equivalent stiffness	Core material stiffer than shell material
	Central core		Upstream sloping core
Closure section (during construction)	River diversion through closure section in dam, or new fill placed a long time after original construction		No closure section (river diversion through outlet conduit or tunnel)

Steve Vick

Structural Response and Role of Subjective Probability

What is response probability?

risk = p[failure] x consequences

$$\Downarrow$$

p[failure] = ∑ p[initiator] p[*response*]

Why use numerical (quantitative) probability at all?

- **constituent components of uncertainty are more readily evaluated than aggregated uncertainties**

- **numerical probability statements allow for unambiguous aggregation of component occurrence likelihoods**

  [high] [low] [moderate] = ?
  [likely] [negligible] [equally likely] = ?

Why is subjective probability so important?

- **Safety is not a physically measurable quantity**
  ∴ Safety is not a property of the dam, it is a property of the observer

- **Safety involves inductive interpretation**
  ∴ Safety involves belief; and belief is subjective

Probability Interpretations and Properties

relative frequency:	**the probability of an uncertain event is the proportion of times it occurs in repeated trials or experimental sampling of the outcome**
subjective, degree-of-belief:	**the probability of an uncertain event is the quantified measure of one's degree of belief or confidence in the outcome**

attribute	relative frequency	subjective
applies to	repeatable occurrences	single-event or repeatable occurrences
based on	data statistics	state of knowledge
measure of	stable long-run frequency as trials → ∞	belief or confidence (engineering judgment)
property of	the event	the observer
reasoning used	deductive	inductive
information incorporated	measured data	data, interpretation, and judgment
subjective factors	implicit or external	explicit
criteria for validity	statistical rules	coherence with axioms and person's unbiased beliefs
uniqueness	singular value exists in principle	singular value does not exist

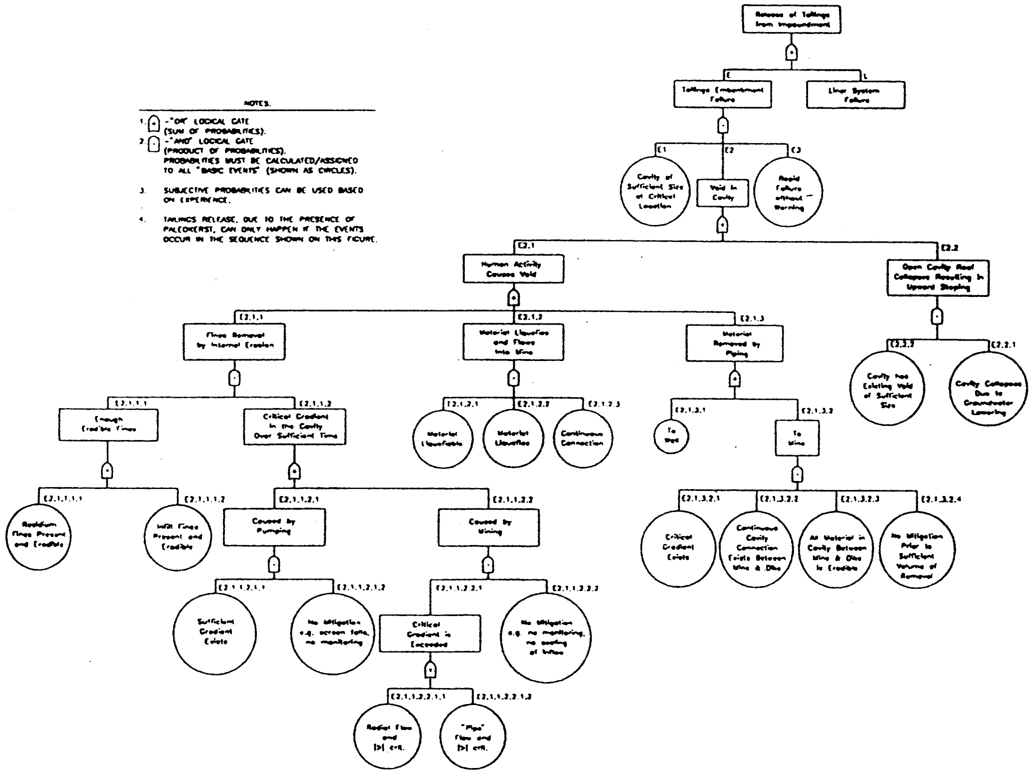
So What Good Is Probability?

1) to identify sources of uncertainty and their relative importance

2) to inform decisionmaking, but not to make the decision or prove its correctness

3) to communicate uncertainty judgments/beliefs

4) to allow others to independently evaluate uncertainty judgments



What Can Subjective Probability Sensibly Do?

Application	Question	Capability
Decisionmaking	**"Is this dam adequately safe?"**	**communicate belief in degree of safety to decisionmakers**
Portfolio	**"Which dams most need to be made safer and why?"**	**prioritize safety needs among dams**
Diagnostic	**"How could this dam be made safer most efficiently and effectively?"**	**investigation tool to identify and rank safety vulnerabilities and mitigation strategies**

Probabilistic Methods for Response Probabilities

Frequency

- **reliability methods**
  - parameter uncertainty in deterministic model
  - yields p[FS<1]
- **binary (logistic) regression**
  - p[liquefaction]
  - p[filter failure]
  - many other possibilities
- **(stochastic models)**
  - component failure rates
  - Markov models
  - limited application for response probability (mainly initiators)
- **(neural nets)**
  - inductive algorithm (enumeration)
  - future potential

Subjective

- **normalized frequency**
  - subjective adjustment of base-rate frequency data
- **subjective algorithm**
  - codified subjective adjustment of subpopulation frequency estimates
  - "benchmarking"
  - motivational bias
- **direct subjective assessment**
  - group assessment (interactions)
  - common decomposition structure (event tree)
  - in-house assessors
  - varied substantive expertise
  - verbal/numerical transformations
  - limited awareness of heuristics and biases
  - limited application of "debiasing" techniques
  - limited probability training

Implications (cont.)

1) There is often a mismatch between expectations of probability and what probability can deliver

2) A probability that does not incorporate subjective uncertainty will always understate global uncertainty

3) A comprehensive probability that incorporates subjective uncertainty cannot be deductively proven to be "true"

4) probability cannot be responsibly used for public persuasion or realistically used to demonstrate strict compliance with prescriptive regulatory criteria

R&D Needs in Subjective Probability Areas

Immediate

- **develop an improved understanding of probability interpretations and corresponding expectations of those using, interpreting, or considering quantitative methods**

- **develop better ways for adapting criteria to probability (rather than vice-versa) and operating within its capabilities**

Intermediate-term

- **education and training of probability assessors in cognitive processes, heuristics and biases**

- **development and application of de-biasing techniques adapted in positive ways to how people think and how they conceptualize subjective uncertainty judgments**

- **education and training in *basic* probability theory (axioms, etc.)**

Longer-term

- **improve judgment of probability assessors**

    - **what is judgment?**
    - **how does substantive expertise differ from normative expertise?**
    - **role of inductive vs. deductive reasoning strategies**
    - **how is judgment enhanced?**

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Considerations for Estimating Structural Response Probabilities in Dam Safety Risk Analysis

By Steven G. Vick

Abstract

The U.S. Bureau of Reclamation has instituted a program for probabilistic risk analysis in its dam safety activities. By acknowledging and explicitly addressing the various uncertainties inherent in the evaluation of dam safety, the objective is to improve the understanding of dam behavior and aid in directing dam safety resources toward those areas where greatest risk reduction benefits can be achieved.

Reclamation's risk analysis activities and its implementation of related technology have proceeded incrementally, expanding and refining the procedures according to perceived needs and outcomes from progressive applications. Its Dam Safety Risk Analysis Methodology document describes the current status of these efforts. Among the elements it incorporates are structural response probabilities that express the conditional likelihood of dam performance given the loadings imposed, and Reclamation's procedures for obtaining them. This report has been prepared to address these and related topics in support of the Methodology document.

The report treats various methods and procedural techniques for estimating structural response probabilities in the context of current Reclamation practice. Many of these methods have already been adopted, but their technical underpinnings may not be universally appreciated or commonly understood by the technical specialists who apply them and the dam safety decisionmakers who use them. One purpose of this work is to enhance this understanding. Inasmuch as engineering judgment is a prerequisite for any dam safety assessment, risk-based or not, its quantification as subjective, degree-of-belief probability receives special emphasis. This aspect of probability is seldom treated in its engineering literature, residing instead in such diverse fields as cognitive and experimental psychology, business management, decision theory, and artificial intelligence. Corresponding emphasis is placed on these cognitive, behavioral and judgmental aspects as they pertain to dam safety risk analysis, with key references to work in these fields.

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1.0 Probability Concepts

Given that a dam experiences some type and magnitude of loading, certain features and components it contains may respond in various ways. Like the loads themselves, these responses are almost always uncertain to one degree or another because of unknown conditions or imperfect understanding of mechanisms. Structural response probabilities are used to quantify this uncertainty. In the context of Reclamation's risk assessment process, neither these probabilities nor the procedures used to estimate them are seen as ends in themselves, but rather as aids to support improved dam safety decisions.

Load probabilities ordinarily incorporate a strong statistical component in records of past earthquakes, floods, or reservoir levels. This is often not so for structural response probabilities which, like any assessment of dam behavior, must incorporate judgment. This may seem to violate some fundamental precept of probability almost as if it were used in two distinct senses, one correct and the other if not incorrect then at least somewhat suspect. In fact, there are two interpretations of probability at work, both equally legitimate, both with rich heritage, and both used in response probability formulation in complementary ways.

1.1 Probability interpretations

Probability is the quantified likelihood of an uncertain outcome of an "event," which can be some process or mechanism, the value of some parameter, or the existence of some unknown condition or *state of nature.* Different probability interpretations arise from different kinds of events and information about them. The mathematics of probability requires only conformance with its basic axioms, for example that the probabilities of any set of mutually exclusive and collectively exhaustive events must sum to unity. But neither the axioms nor the mathematics that express them depend in any way on which interpretation is adopted. These interpretations are, however, fundamental to how probability is used and how its values are obtained.

1.1.1 Relative frequency

The best-known interpretation of probability is the *relative frequency* approach which derives from repeated sampling of a statistically homogeneous population or repeated trials of a probabilistically stationary process. Given a sufficient number of trials or observations, the frequency of occurrence will eventually converge to some stable and constant value. Relative frequency approaches for response probability estimation can include liquefaction probability from repeated field observations, or failure rates of electrical or mechanical components from repeated occurrences based on maintenance records. Statistical characterization of input data in reliability methods also adopts this approach for things like concrete strength or soil properties where sufficient and representative data exist.

The attractiveness of the relative frequency approach is that a probability so derived is scientifically verifiable from the standpoint of repeatability. Given the same sample population and the same statistical procedures, any two estimates will yield the same probability value. Useful as it may be under applicable circumstances, the relative frequency interpretation cannot capture the full range of important uncertainties because it does not allow a probability to be associated with a state of nature. It becomes meaningless to assign a probability to the existence of a geologic defect such as a fault because repeated sampling cannot be performed: either the fault will exist on every trial or it will not, and the frequency interpretation does not pertain to such single-event occurrences. This approach can also be limited because the uniqueness of dams usually fails to provide the kind of homogeneous population that valid statistical sampling requires. Internal erosion frequency over a group of dams, for example, is almost always affected by a host of dissimilar features and conditions.

1.1.2 Subjective, degree-of-belief

Under the subjective, degree-of-belief interpretation, probability is a measure of one's degree of belief or confidence in the outcome of an event. In this approach, all kinds of information and judgments are admissible in formulating a probability value whether based on repeated trials or not, and it therefore becomes of considerable value in assigning likelihoods to a state of nature, processes not readily sampled, and non-repeatable single-event occurrences in general. To the extent that the degree-of-belief approach relies on individual judgment, it is subjective in the same sense as the subjective judgment required for interpreting the input and results of any deterministic analysis.

Central to the degree-of-belief interpretation is that uncertainty derives from one's state of knowledge, and as knowledge, information, or the estimator varies so too will the assessed probability. Here, probability is viewed not as some intrinsic property of the event that could be determined with scientific validity if only sufficient data were available, but as a property of the information available, state of technology, and judgment of the estimator. In a degree-of-belief framework, there is no singular or unique "correct" probability, only one that accurately reflects the belief of the estimator using all of the knowledge and information at hand (*internal validity*) and that conforms to the probability axioms (*coherence*). Accordingly, degree-of-belief interpretations have also been termed *personal, judgmental, subjective* and *Bayesian* probability approaches.

1.2 Probability in everyday use

Both relative frequency and subjective, degree-of-belief interpretations are familiar in the ordinary use of probability for expressing uncertainty, including degree-of-belief approaches that incorporate frequency information. Weather forecasting is a common example. One way to estimate the probability of rain would be to compile the frequency of rain on the date of interest, and such readily-available climatology statistics can yield surprisingly accurate predictions. However, forecasters also have other information and personal experience that includes such things as isobaric patterns, moisture movement, winds aloft, reports from nearby stations, and simple common sense - a glance out the window. All of these elements are judgmentally integrated with climatology statistics (called a *base-rate frequency*) to derive the forecaster's subjective probability of rain. In fact, weather forecasters become remarkably *well-calibrated* (i.e., forecasted rain probabilities of 0.6 correspond to rain about 60% of the time over the long run) due to the prompt and unambiguous feedback they receive, making them popular subjects for research (Murphy and Winkler, 1974).

1.3 Historical development

The distinction between probability as a measure of stable frequency on one hand and as an expression of belief or confidence on the other is at least as old as the mathematics of probability itself. In 1654 the eclectic prodigy Blaise Pascal and the brilliant mathematician Pierre de Fermat devised the combinatorial mathematics of probability in relation to a gambling problem posed by the Chevalier de Méré, a French baron. The probability axioms as we know them today would wait to be formulated by Kolmogorov in 1933 using set theory, but neither the mathematics nor the axioms ever spoke to what probability should be taken to mean.

Between about 1650 the mid-1700's, Classical probabilists and mathematicians such as Pascal, Leibniz, and Jacob Bernoulli used probability in two distinct but complementary senses, one being *aleatory* or literally dealing with frequencies in games of chance, and the other *epistemic* in relation to one's state of knowledge. In this age of the Enlightenment, the Classical probabilists were basically determinists at heart, believing that all uncertainty was fundamentally produced by lack of knowledge that the "rational man" of the day would eventually overcome through the astonishing breakthroughs in scientific understanding then emerging. Hacking (1975) calls this duality the "Janus face" of probability, and the Classical probabilists accepted both concepts, moving easily back and forth between them (Gigerenzer, et. al., 1989). Philosophers John Locke, David Hartley and David Hume rationalized this duality, going so far as to theorize that the brain contained a kind of counting device which recorded and mapped event frequencies onto belief about their likelihood (Gigerenzer, 1994).

During this same period John Graunt began to compile mortality data in London, de Witt and Hudde used it for pricing of annuities, and Adolphe Quetelet extended demographics to social and even moral behavior. Thus began the rise of frequency-based statistics, which came to eclipse both the co-existing duality of the Classical probabilists and its degree-of-belief associations. Gigerenzer, et. al. (1989) attribute this emphasis on the statistics of mass phenomena to the ascendance of the "average man" over the elite "rational man" that accompanied the French revolution and the societal forces surrounding it.

So the situation remained with relative frequency and statistics dominating the experimental sciences until subjective, degree-of-belief concepts re-emerged in the twentieth century through the work of de Finetti (1937), Ramsey (1931) and Savage (1954). Today, degree-of-belief concepts have become the basis for probability use in decision theory, artificial intelligence, and branches of economics and business management, with relative frequency interpretations dominating in physics and other experimental sciences.

1.4 Risk analysis implications

Both relative-frequency and degree-of-belief concepts have their place in dam safety risk analysis, and neither need be adopted to the exclusion of the other. They are in many ways complementary and are often combined, with frequency approaches suited to repeatable processes where applicable data are available, and degree-of-belief approaches to single-event occurrences where experience and engineering judgment prevail. The varied nature of the uncertainties inherent in the evaluation of dam safety prevent it from becoming a purely objective exercise. Engineering judgment, which is by definition subjective, cannot be eliminated, nor would it ever be desirable to do so. Both statistically-characterized data and subjective judgment can be incorporated using these two equally legitimate probability interpretations without violating any mathematical precept of probability itself. This dual application emulates the Classical probabilists, and it provides the basis for understanding the various methods for structural-response probability estimation.

This has several implications for dam safety probability estimators and decisionmakers alike. Even though a failure probability may be expressed as a single number, there can be no singularly valid or uniquely correct value. Such a "credible and defensible" probability would be a sole construct of the relative frequency interpretation with the scientific repeatability and deductive validation that stable frequency implies. By contrast, when degree-of-belief approaches are incorporated, a failure probability becomes an inductive statement of belief about the safety of the dam, including the confidence in all of the measures used in its assessment (Fanelli, 1997). As for any conventional dam safety evaluation, failure probability depends on the judgment exercised, and it can be no better or worse than this judgment itself. Judgment varies with time, knowledge, information, and those who exercise it, and since judgment is not necessarily reproducible in these respects neither is the probability that incorporates it. In this context, a more applicable goal is the sensible and responsible use of such a probability: sensible by applying it with an understanding of the factors that affect it, and responsible by expressing it with due recognition of its intrinsically non-unique character.

2.0 Response Probability Estimation Techniques

There are several alternative techniques that can be used for estimating structural response probabilities.

Broadly grouped, these can be classed as normalized frequency and decomposition methods.

2.1 Normalized frequency

The normalized frequency technique assigns a probability to a particular failure mode by normalizing or adjusting the value relative to a base-rate annual frequency for that same failure mode. Failure frequency data compiled by Reclamation and others can be used for this purpose, typically in a format that allows base-rate frequencies to be determined for various failure modes subdivided according to dam type, height, and age, provided that there are statistically significant numbers of failures and years of dam operation in the subcategory of interest. The normalized frequency technique is not applicable to flood or earthquake initiators because the database cannot reflect the flood or earthquake hazard specific to any particular damsite.

The first step is to identify some base-rate frequency category that best applies to the dam and failure mode being considered. Next, all of the available information relevant to that failure mode for the particular dam is compiled and reviewed. This can include information from site inspections, construction photographs, design and construction records, and all relevant analyses that have been performed. Often these factors are initially synthesized in a way that allows an initial judgment on whether the assessed probability should be either higher or lower than the base-rate frequency (i.e., whether the dam is "better" or "worse" than the "average" dam reflected in the database category). Additional assessments are then required to quantify the degree to which the particular dam departs from typical conditions, and therefore what the failure mode probability estimate should be. In this respect, the normalized frequency method can be seen as a degree-of-belief probability that incorporates statistical information on dam failure frequencies. Figure 1 provides an example format used by Reclamation for normalized frequency estimates of static failure probability of concrete dams.

In practice, this involves several complicating factors. First, the specific conditions or features associated with the "typical" dam in the database are undefined, and even the concept of a typical dam may be hard to envision since each one in the database is unique. Although this may be less important if the particular dam has either serious deficiencies on one hand or a complete absence of symptoms on the other, it can still be difficult to quantify the extent to which the assigned probability should depart from the base-rate frequency. And finally, a normalized frequency cannot easily quantify the relative contribution of specific features or conditions of the dam that influence the probability assigned, making it harder to prioritize factors that may require further analysis or investigation. In this respect, Foster, et. al. (1998) provide estimated failure frequencies for subpopulations of embankment dams according to various features and foundation conditions, and a codified algorithm for judgmental normalization to enhance consistency.

In principle, normalization can be improved by the application of Bayes' Theorem, which provides a formal means for updating probabilities as additional information is obtained or additional factors are invoked.[1] Here the base-rate failure frequency becomes the *prior* probability, the Bayesian estimator is some indicator probability (such as sand boils, cloudy seepage, or inadequate filters for internal erosion), and the updated failure probability incorporating this information is the *posterior* probability. Bayes' Theorem has the potential to considerably enhance the normalized frequency method by isolating and evaluating the contributions of any number of separate indicators. However, it requires that the reliability of the indicator be known in terms of

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[1] The formal application of Bayes' Theorem should not be confused with the "Bayesian" probability approach, as degree-of-belief interpretations are sometimes called. This terminology results from the idea embodied in Bayes' Theorem that probability varies according to the information available, but it does not necessarily imply formal application of the theorem itself.

both its false-positive and accuracy rates. This, in turn, requires experiments or observations under uniform conditions for indicator reliability to be determined on a relative-frequency basis. This information is seldom available for the kinds of subtle, complex, and interrelated indicators important to dam safety assessment. Alternatively, indicator probabilities can be estimated using degree-of-belief approaches, but this can involve similar issues as informal normalized frequency methods.

2.2 Decomposition

The decomposition approach relies on disaggregating each failure sequence into the smallest tractable component events that can realistically be defined. It mimics conventional engineering problem solving methods which recognize that it is easier to address then combine smaller components of a problem than to directly attack a large, complex one. The decomposition approach to estimating response probabilities follows logically from the event-tree structure that defines the component events for each failure sequence, and it can reduce error in the aggregated result provided that component probabilities can be estimated more reliability than target value, which is usually the case (Ravinder, et. al., 1988). The decomposition approach is applicable generally to any failure mode involving flood, earthquake, or static initiators that can be understood at a sufficient level for component events to be defined. The choice among various methods for estimating these individual component event probabilities depends on the type of event being considered; the level and nature of information about it; the availability of techniques to address it; and the capability of team members to implement the approach adopted. Several of these methods are described below.

2.2.1 Statistical methods

Some component event probabilities can be characterized directly by statistical data using the relative-frequency interpretation previously described. Examples could include reservoir level probability, and failure frequency for certain electrical or mechanical components associated with gate operation. In directly applying statistical data on past processes to their future operation, it is important to account for any changes that might have come about since the data were compiled (for instance modifications to reservoir operating rules), and limitations imposed by the size of the statistical sample the data represent.

2.2.2 Degree of belief approaches

Many if not most component probabilities are estimated according to a degree-of-belief interpretation that incorporates all of the data, information, and analyses at hand. However, the cognitive processes used in estimating these probabilities need to be recognized and accommodated. People have limited ability for cognitive discrimination at the extreme ends of the probability scale. For example, in the absence of any underlying base-rate information few are able to articulate an underlying rationale for why a degree-of-belief probability should be 10^{-4} as opposed to, say, 10^{-5} or 10^{-6}. Moreover, such extreme probabilities are often the result of overconfidence bias. As explained subsequently, this is a tendency for people to be much more confident than they should about uncertain events, which can further limit the internal validity of extremely high or extremely low degree-of-belief probability values.

2.2.3 Reliability techniques

For certain component events, input parameters to ordinary deterministic analysis procedures can be specified probabilistically where applicable analytical models and sufficient data for statistical characterization are available. These *reliability* methods apply a probabilistic overlay to input parameters in otherwise conventional analysis techniques. Probability distributions assigned to the input parameters yield the probability that the computed factor of safety is less than 1.0, and first-order second-moment (FOSM), point-estimate methods, or Monte Carlo simulation are used to derive approximate solutions. In practice, judgment usually provides the basis for selecting the form of the parameter distributions, and results can be sensitive to this factor when values on the tail of the distribution are involved. These procedures are most useful for evaluating parameter uncertainty related to material properties, and can account for the effects of systematic error and data scatter, including spatial variability. Long, low dike structures can be especially amenable to such treatment (Vanmarke, 1977). Degree-of-belief probabilities can be incorporated for judgmental weighting of alternative models or properties, for example various time histories that might be used in dynamic response analyses.

Implicit in the application of reliability techniques is that a computed probability for FS<1 corresponds to the probability of event occurrence. This neglects uncertainty associated with the model itself, which goes beyond numerical approximations and simplifications to conceptualization of the process and the variables used to represent it. Factors related to model uncertainty can be among the most controversial and uncertain issues in contemporary practice, and the history of dam engineering contains many examples of analytical models later found to poorly represent the processes involved. Also, many well-accepted models have been developed for design purposes where it is sufficient that they conservatively predict conditions required to avoid failure. Their ability to accurately predict conditions where failure will occur, a fundamental requirement for response probability estimation, can be more in doubt.

2.2.4 Regression techniques

Relationships based on observational data are sometimes available for predicting the occurrence or non-occurrence of a process according to some related parameter. Usually expressed as a deterministic boundary between these binary states, a frequency-based occurrence probability can also be determined directly using statistical binary or logistic regression techniques without the need for algorithms or numerical models of the process. Examples include level-ground liquefaction (Liao, et. al., 1988; Youd and Noble, 1997) and filter performance in laboratory tests (Honjo and Veneziano, 1989) as illustrated on Figure 2. These methods are influenced by the size and interpretation of the available database, and they may require other adjustments to reflect field conditions. Nevertheless, logistic regression techniques are among the most powerful methods for relating field or laboratory observations to response probability. Available data for other binary-outcome processes such as spillway erosion could readily be evaluated probabilistically in this way.

2.3 Applicability

Of the two basic classes of techniques for response probability estimation, decomposition approaches are more general. They provide the only method universally applicable to static, flood and earthquake conditions, and they offer the ability to more specifically identify how particular events, conditions, and features contribute to the response probability derived. However, decomposition techniques can be difficult under two conditions. The first is where lack of field performance experience and inadequate knowledge of mechanisms precludes conceptualizing the failure sequence, as can be the case for processes like nonlinear, post-cracking behavior of concrete dams. Secondly, it can be difficult to realistically define or decompose failure sequences for well-designed and constructed dams that present no evident symptoms of inadequate performance. For static failure modes, normalized frequency methods provide an alternative means for response probability estimation, allowing decomposition and normalized-frequency techniques to be used together for estimating bounding ranges on response probability, or to check one approach against the other for reasonableness.

3.0 Cognitive Processes in Subjective, Degree-of-Belief Probability Estimation

It is clear by now that the degree-of-belief interpretation plays a key role in both normalized frequency and decomposition approaches, but beyond this it requires an understanding by the probability estimator and the facilitator of some of the cognitive processes that people use in developing these estimates. Everyone must confront uncertainty in everyday life, and in general people are remarkably successful in doing so.

Nevertheless, limitations on capacity for processing information make people ill-equipped in many ways for dealing with and expressing uncertainty with the kind of mathematical consistency that the probability axioms require (Hogarth, 1975). Instead, *heuristics*, or simple aids, strategies, and rules-of-thumb are adopted from situational experiences involving predictions of uncertain events (Tversky and Kahneman, 1974).

The problem can be that there are few opportunities to systematically obtain or evaluate feedback from the outcomes of these predictions, and those that do arise may provide anecdotal reinforcement for heuristic rules that are mathematically inconsistent. The divergence between heuristic and mathematical reasoning is termed *bias*. Technical experts, even those with formal probability backgrounds, are no less susceptible than others to various forms of bias, so it falls upon both the facilitator and the probability estimator to recognize and reduce their effects. There are many types and sources of bias, and one, *motivational bias,* has been explained in Section III.B.4 of the text. Some of the more important sources of *cognitive bias* are summarized in Table 1 and further explained below, along with ways to counteract them in risk analysis settings.

3.1 Anchoring and Adjustment

Often an estimator will begin with an initial "best estimate" probability value, then adjust it upward or downward in light of specific information or context. The magnitude of this adjustment is typically insufficient and biased toward the initial value. Known as *anchoring bias*, this can affect normalized-frequency estimates starting from and anchored to some base-rate failure frequency. One way to reduce it can be to start by considering extreme probability scenarios, working "backward" toward the base-rate frequency. Another type of anchoring bias results from *conjunctive distortions* when there are several occurrences that contribute to an outcome. Here, the tendency is to anchor on the probability of only one of these events, with insufficient adjustment to account for their joint probability. A solution is to consider each event individually, then aggregate the component probabilities. This will be recognized as simply another version of the decomposition approach, and it is useful even if performed externally from the event tree.

3.2 Availability

The ease with which specific instances of an occurrence come to mind is termed *availability*, and a related factor is the *salience*, or vividness, with which they are visualized. Probability estimates for events that are available or especially salient tend to be higher than those less readily recalled, which is termed *availability bias*. An investigator of the Teton failure, for example, could be subject to availability bias in estimating probabilities for internal erosion of jointed rock foundations, or a laboratory researcher might be similarly affected in estimating the probability of some behavior from new test procedures just devised.

It can be important to guard against availability bias introduced by review of failure case histories, especially those that are especially well-documented and hence salient. Case history information is fundamental to many aspects of risk analysis, and its importance cannot be overstated. However, when used in probability estimation, it is useful to keep in mind that few dams, even those with adverse conditions, ever actually fail. The potential for availability bias from review of failure case histories can be countered by also including various non-failure incidents that serve to highlight those circumstances or conditions which truncated the failure process. A final source of availability bias can arise simply from disproportionate representation of a particular phenomenon or process in the technical literature or in the research attention it receives. A probability for embankment dam slope instability, for example, might be considerably misjudged in this way.

3.3 Representativeness

The representativeness heuristic is a form of stereotyping by which people tend to emphasize some particular similarity or piece of information rather than integrating and synthesizing information from all sources. In general, *representativeness bias* comes about from the corresponding tendency to undervalue or discard other evidence, especially that based on experience or more general information (Kahneman and Tversky, 1982a,b; Bar-Hillel, 1982). For example, if one were asked to assign a probability to the presence of open joints in the foundation of a dam with no design, construction, or subsurface information, a 50/50 chance might be specified to reflect probabilistic indifference on the two possible outcomes. However, only some dams are founded on rock in the first place, some smaller subset are on jointed rock, and even fewer contain open joints - all forms of general information that would support some lower probability value. This illustrates *base-rate neglect*, or the tendency to give insufficient consideration to underlying base-rate frequency information.

Representativeness bias can also come about through emphasis on more rigorous or complex analysis results, at the expense of simpler techniques or other information external to the analysis altogether. For example, a liquefaction flowslide probability assigned using a complex post-liquefaction deformation analysis might fail to account for field performance experience in some similar situation. A corollary effect is the failure to adequately account for *predictability* of the event according to the quantity and quality of information about it, for instance basing the probability of liquefaction on a single low $(N_1)_{60}$ value without considering the variability inherent in the Standard Penetration Test or the limited statistical sample size.

Representativeness bias can be counteracted by conscious attempts to include all pertinent information in the probability assessment. Each supporting rationale, analysis, or piece of information tells something but is also incomplete in itself, supporting the use of as broad a range of techniques and perspectives as possible. No prior source of information should be discarded as new or more "accurate" information becomes available, but instead the reliability of each separate source should be considered. Once again, simple decomposition incorporating multiple evidence or information sources can aid these efforts.

3.4 Overconfidence

If degree-of-belief probability is an expression of one's level of confidence, then *overconfidence*, or the tendency to be more confident than the evidence warrants, may well be the most important bias affecting its assessment. *Overconfidence bias* is manifested by a tendency to discount outliers, to assign probability distributions on parameters that are too narrow about the mean, or to assign probabilities at the high or low ends of the probability scale that are more extreme than they should be. Overconfidence bias has been shown to be pervasive among the general population and technical experts alike, and its effects can be hard to defeat. The heuristic at work is for people to exaggerate the extent to which what they know is correct. In effect, they are wrong too often when they are certain they're right.

Overconfidence bias is shown consistently in studies where subjects are asked to provide the answers to general-knowledge questions along with the probability that their answers are correct. Over many such subjects and many questions, people are said to be *well calibrated* if their judgments about the probability of being right or wrong correspond to the frequency that they actually are. For example, Figure 3 plots experimental data from several groups of subjects studied by Fischhoff, et. al. (1977). The estimated error probabilities are reasonably well-calibrated with respect to actual error frequencies only within a limited range for probabilities no smaller than about 0.1. Their overconfidence bias - expressed as the difference between actual and judged error probabilities - increased dramatically for more extreme probability estimates with estimated error probability of 1:1,000,000 corresponding to actual error frequency of about 1:10, a ratio of some five orders of magnitude. Moreover, the subjects showed little cognitive discrimination among extreme probability values, with estimated probabilities ranging all the way from 10^{-2} to 10^{-6} for essentially constant error frequency.

The extent to which people are well-calibrated depends heavily on outcome feedback. Weather forecasters become quite well calibrated over the limited probability ranges they use, apparently because the uncertain events they assess (precipitation and temperature) are repetitive in nature and feedback occurs every day (Murphy and Winkler, 1974). Physicians, on the other hand, are often poorly calibrated, possibly because their diagnoses consider a much wider array of dissimilar possibilities and feedback opportunities are limited by lack of followup and patient referrals (Poses, et. al., 1985). Here, the parallels to dam safety questions are evident.

The degree of difficulty about a problem is related to the amount of information and general knowledge about it. Surprisingly, overconfidence bias is both more pervasive and more severe for "hard" questions than for "easy" ones, with some of the most extreme overconfidence observed for tasks about which the assessors have no knowledge whatsoever (Lichtenstein, et. al., 1982). Accordingly, it might be expected that technical experts or specialists would find problems within their knowledge domain easier and therefore less affected by overconfidence, but this appears not to be the case. For example, Figure 4 shows the results of predictions by seven internationally-recognized geotechnical engineers for the height at failure of a test embankment on soft clay, along with error bars providing the 50% confidence ranges they specified for their predictions (Hynes and Vanmarke, 1976). Had they been well-calibrated as a group, half of their ranges should have encompassed the actual failure height. None did. Such studies demonstrate that expert specialists are at least as prone to overconfidence as their less-experienced colleagues of similar training and sometimes even more so, perhaps because the latter are more candid in recognizing the limitations of their knowledge. The best probability assessors can therefore be those having both *substantive* expertise derived from skills, education, and experience in their knowledge domain, and *normative* ability to express judgments in an unbiased way. These studies make it clear that substantive expertise has little influence on normative abilities.

Correcting, compensating, or limiting the effects of overconfidence in degree-of-belief probability assessment can be difficult, but not as hopeless as it might appear. A number of techniques for *debiasing* exist, and some of those useful in the context of Reclamation's efforts are described below.

3.4.1 Training

Training of probability estimators uses the kind of outcome feedback that benefits weather forecasters. Training is an essential component of formal probability elicitation schemes (Keeney and von Winterfeldt, 1991), and it often includes presenting the assessor with a list of general-knowledge questions selected from an almanac (How long is the Amazon River? What is the population of Madagascar?) and requesting 90% confidence limits on each quantity. Using a dozen or so questions, overconfidence bias is easily demonstrated on a personal level when the actual frequency of correct answers is compared to the number inferred from confidence limits. Revealing personal overconfidence bias in this way may help the estimator compensate for it in subsequent probability assessments by more clearly recognizing limitations in knowledge. However, experimental attempts to verify this effect have shown mixed results, with some studies showing improvement and others (Alpert and Raiffa, 1982) showing estimators to be nearly impervious to repeated training and feedback attempts. Still other studies, however, suggest that one of the most effective ways to reduce overconfidence bias can be to educate estimators about the kinds of cognitive processes that can influence probability estimates, an end which the discussions provided here can help serve.

3.4.2 Interrogation

Skilled interrogation can help reduce overconfidence bias by asking the estimator to consider, and even list, the reasons why an assessed probability value might be wrong (Koriat, et. al., 1980). People can be insufficiently critical or intent on justifying their initial response, and they tend to detect inconsistencies only when specifically prompted to look for them. Probing questions by a skilled facilitator to prompt for disconfirming evidence and counterarguments can be among the most effective ways to reduce overconfidence, especially for extreme probability values where its effects are likely to be most severe. One technique asks the estimator to imagine that an outcome contrary to an extreme probability has actually happened, and to provide in hypothetical hindsight some possible reasons why.

3.4.3 Restructuring

Overconfidence bias can be reduced if a "hard" question can be made easier, and one way to do so is to use the familiar methods of decomposition for disaggregating a general question into more specific component parts. The opportunity to do so comes as early as the event-tree construction stage, where bias can be reduced by defining component events to a level of detail such that individual degree-of-belief event probabilities are more likely to reside within the well-calibrated range. Even when complexity imposes practical limits on the desired degree of decomposition within the event tree itself, decomposition can still be undertaken during probability estimation if the resulting events are captured in "sub-tree" form and preserved for documentation.

3.4.4 Constraints

The effects of overconfidence bias can be limited in a more systematic way by constraining degree-of-belief probabilities to values expected to lie within or not far beyond the well-calibrated range. Accompanied by good event decomposition, degree-of-belief probability constraints are sometimes taken as about 0.01 to 0.99, with exceptions for more extreme values in special cases such as those having some underlying base-rate frequency information to support them. While overconfidence bias is not eliminated, this better assures that its effects are not dominant. Incorporating probability constraints into the structure of the probability estimation process itself can also help achieve greater consistency in debiasing effects from one risk analysis to another, making results less dependent on the particular facilitator, estimator, or application.

3.5 Verbal and Numerical Correspondences

Both everyday experience and research suggest that most people express and communicate uncertainty more readily using words than numbers (Zimmer, 1983). This becomes an important consideration in Reclamation's risk analysis procedures that emphasize the synergies arising from group discussions as fundamental to achieving an improved understanding of dam behavior and the uncertainties that affect it. To promote these interactions in a way adapted to how people express uncertainty, Reclamation has adopted the conventions for mapping verbal descriptors of uncertainty into numerical degree-of-belief probability statements provided in the text (Section IV. D. Step 3). These conventions serve to reduce ambiguity in the use of verbal descriptors during group discussions and to enhance consistency in probability estimates from one risk analysis to another.

The role of verbal to numerical transformations is best understood in the context of how people formulate and quantify uncertainty judgments. Several representations of this cognitive process have been proposed that separate it into multiple stages (Beach, 1992; Bolger and Wright, 1992; McClelland and Bolger, 1994; Curley and Benson, 1994). In general, some plausible account or scenario of the operative mechanism or condition in question is first developed. This is then tested against supporting and conflicting evidence, accounting for both its perceived strength and validity, to form a judgment about the uncertainty associated with the scenario and one's strength of belief about it. The final stage expresses the uncertainty judgment as a numerical probability value. In doing so, people sometimes adopt an intermediate step involving word-to-number equivalences such as those shown on Table 2 (Reagan, et. al., 1989), and Reclamation's transformation conventions adopt this concept.

Reclamation's risk analysis procedures place major emphasis on the first two of these stages involving interactive scenario formulation and testing of uncertainty judgments, because this is where mutual understanding of relevant uncertainties comes about. The conventions for translating these judgments into numerical probability statements are introduced primarily in the final stage, where they represent the expression of these judgments but not the judgment-forming process itself. As a device for communicating, both internally among team members and externally to decisionmakers, Reclamation's conventions become an integral part of its risk analysis procedures. As such, they must be recognized and accounted for when interpreting and using the risk analysis results.

3.6 Facilitator Role

Degree-of-belief probability approaches are central to Reclamation's risk assessment methodology. Their use requires an understanding of the cognitive processes that people adopt in estimating them, the forms of bias that can result, and ways to reduce or limit its effects. One of the key roles of the facilitator is to ensure that the risk assessment team applies the following principles:

- Team members need to understand the importance of recognizing and dealing with various forms of bias.
- The information, data, and analyses that contribute to an assessed degree-of-belief probability need to be considered in a balanced and comprehensive way that accounts for the reliability of each source of evidence without discarding or overlooking generalized information or simplified evaluations.
- Decomposition of events into their smallest realistic components can help reduce several forms of bias. This is a logical outgrowth of the event-tree approach.
- The potential for overconfidence bias is greatest for extreme degree-of-belief probability values that fall outside most people's well-calibrated range. Except where there is some underlying base-rate frequency information to support them, such extreme values should be questioned and measures adopted to reduce the effects of overconfidence bias they are likely to incorporate.

4.0 Skills and Expertise for Response Probability Estimation

Risk analysis has been called the systematic application of engineering judgment. Dam safety assessment requires judgment when deciding whether to perform additional analysis or field exploration, when deciding whether a particular dam is safe, or when choosing the best modification alternative for a deficient dam. Structural response assessments, load estimates, and consequence evaluations each have significant associated uncertainties. To characterize them Reclamation typically uses expert opinion methods to obtain judgment-based subjective probabilities as a supplement to relative-frequency derived values. Understanding and enhancing expertise and judgment can help improve not only risk analysis but also other Reclamation activities.

4.1 Characteristics of Expertise

Mastery of subject matter or possession of a repertoire of facts within one's knowledge domain may be necessary, but they are not sufficient for the kinds of expertise that subjective probability estimation requires. Whereas novices operate according to rule-based procedures, experts not only have an enhanced state of knowledge but they navigate a problem space in different ways (Ayton, 1992). The characteristics that distinguish experts from novices are revealed by studies of people routinely responsible for evaluation-based decisions, especially those under great pressure like fighter pilots, airline captains, and nurses (Shanteau, 1992; Klein, 1998). Some of these characteristics are:

- ability to recognize patterns in data, behavior, or case-history experience
- ability to detect anomalies or deviations from these patterns
- a sense of "situation awareness," or the "big picture;" specifically, an ability to track all important information, draw inferences from it, and project it forward in time.
- use of mental simulation to interpret the anticipated operation of a process
- ability to make fine discriminations and detect subtle differences
- awareness of their own limitations

In many ways these characteristics capture the essence of judgment, or some might say simple common sense, and it is easily recognized that all of them are related to processes used in formulating subjective probability estimates. Table 3 shows some of these parallels that illustrate how developing these characteristics of expertise goes hand-in-hand with developing the cognitive skills needed for unbiased probability estimation.

4.2 Group Processes

The skills and characteristics of expertise require continual feedback and practice, and it is rare to find them all in any one person. For this and other reasons, probability estimation carried out in a group setting can have advantages over individual estimates combined externally to the estimation process. This *behavioral aggregation* involves a largely unstructured process in which group members communicate among themselves to arrive at some consensus probability judgment. These interactions can sometimes allow group performance to achieve the level of its best member, but this is often impeded by the following factors (Rowe, 1992):

- social pressure that forces conformity to majority opinion
- overinfluence of more verbal or strident individuals
- changing motives to reach premature consensus
- the need for competitive individuals to "win" and not lose face
- reinforcement of mutual biases, especially if group members share the same training and background

These factors can cloud the ability of groups to select the most appropriate opinion-combining strategy or to arrive at the most appropriate weighting for their members. The role of group member selection and that of the facilitator are evident in controlling these effects.

4.3 Skills and Abilities in Reclamation Risk Analyses

The ideal probability estimator in a Reclamation risk analysis is one whose opinion blends an intimate knowledge of the dam and its historical performance; a solid background in the engineering principles relative to the failure mode component under consideration; and a thorough understanding of basic tenets of probability theory and decision analysis. Moreover, a person whose experience includes evaluating dam failure case histories might often be preferable to one with exclusively design experience. The desirable quality is an ability to adopt a broad but skeptical viewpoint. A good designer accustomed to eliminating uncertainty may be less comfortable dealing with it, a perspective that can lead to overconfidence and/or motivational bias.

An intimate knowledge of the dam and its performance history is important to ensure that all possible failure modes have been identified; that the explorations, test programs, and analyses are consistent with performance history and construction information; and that estimated probabilities realistically address the dam's overall condition and behavior. Selection of team members need not hinge on this qualification, but a member chosen for technical competence rather than knowledge of the dam must be allocated the time necessary for review of the SEED Data Books and other related information.

A thorough understanding of relevant engineering principles is important because good judgment is formed by processing both theoretical and empirical information. Necessary technical background includes field explorations, laboratory testing, and analytical methods. Each laboratory test, each sampling method, and each analytical model has various associated parameter and model uncertainties. Understanding the pitfalls in sampling, the strengths and weaknesses of the testing, and the limitations of the analytical procedures can only come with experience obtained when knowledge of theory is combined with an understanding of how well the theory conforms to actual behavior of real structures.

Knowledge of the basic tenets of probability theory and decision analysis is important for determining when an answer that seems intuitively obvious may be incorrect. It is important to develop a sense for the significance of probabilities of combined events, and to know how updated information can be combined with prior probability estimates. Recognizing when a sequence of events has been sufficiently decomposed requires experience in developing event trees that are neither so detailed that event relationships are obscured nor so simplified that event probabilities cannot be conceptualized. An expert facilitator can, to some degree, compensate for limited knowledge in this area, but the quality of the risk analysis can be materially improved if all team members are well versed in probability and decision theory.

Identifying and developing failure modes may be best accomplished by an interdisciplinary group, but once the event tree has been established the probabilities assigned to each event need to reflect the best available judgement of a team of estimators within the applicable discipline. The best risk analysis team member candidates at Reclamation might be the team leader or Principal Engineer, the most recent Performance Parameter TM author, the senior engineer for the dam, or the technical staff most familiar with the analyses conducted to date on the dam. These persons would have both the intimate knowledge of the dam's historical performance and the technical knowledge required. The next best choice would be those with outstanding technical expertise in the desired field, but having less detailed familiarity with the dam. In either case, team members need to be allowed to decline to estimate if they feel they are not sufficiently qualified to render a knowledgeable or unbiased assessment.

These attributes of Reclamation team members may result in a collection of people prone to motivational and/or cognitive bias. Training of team members and interrogation techniques on the part of the facilitator can reduce the effects of bias, but not eliminate them. Therefore, it is important that DSO decisionmakers have an understanding of these effects so that response probability estimates and risk analysis results derived from them can be used sensibly and responsibly within the context of how they are obtained.

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TABLE 1. Summary of Heuristics and Biases

Heuristic or bias	Description
1) Overconfidence bias	tendency to be more confident than warranted in estimating probabilities that are too extreme or distributions too narrow about the mean
2) Representativeness heuristic	overemphasis on a particular correlation, similarity, or type of information, with insufficient consideration of other information
a) Base-rate neglect	overemphasis on specific similarities with insufficient consideration of base-rate frequencies
b) Insensitivity to sample size	overestimating the significance of limited data
3) Availability heuristic	overemphasis on specific instances more easily or vividly recalled
4) Anchoring and adjustment heuristic	development of an initial probability value which is then modified to yield the final result
a) insufficient adjustment	insufficient modification of the initial probability
b) conjunctive distortion	overestimation of joint probability compared to aggregated component probabilities

TABLE 2. Numerical responses and ranges for 18 probability expressions (after Reagan, et. al., 1989)

Expression	Single-number probability equivalent, % (median of responses)	Specified range, % (median upper and lower bounds)
Almost impossible	2	0 to 5
Very improbable	5	1 to 15
Very unlikely	10	2 to 15
Very low chance	10	5 to 15
Improbable	15	5 to 20
Unlikely	15	10 to 25
Low chance	20	10 to 20
Possible	40	40 to 70
Medium chance	50	40 to 60
Even chance	50	45 to 55
Probable	70	60 to 75
Likely	70	65 to 85
Very possible	80	70 to 87.5
Very probable	80	75 to 92
High chance	80	80 to 92
Very likely	85	75 to 90
Very high chance	90	85 to 99
Almost certain	90	90 to 99.5

TABLE 3. Expertise and subjective probability estimation

Characteristic of experts	Corresponding subjective probability skill	Heuristic affected/ bias reduced
Pattern recognition	emphasizes content of broader information from data and case histories	representativeness
Anomaly detection	appropriate attention to outliers	overconfidence
Situation awareness	use of all applicable information	representativeness
Mental simulation	decomposition of processes and failure sequences	overconfidence, conjunctive distortion
Discrimination ability	recognition of misleading generalizations	representativeness, anchoring and adjustment
Awareness of limitations	realistic appraisal of what is not known	overconfidence

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Hydraulic Water Control Structures for Dams – How Reliable?

Professor Jack Lewin (Hon) D. Eng. FICE

In the last decades, dam safety has been re-examined and extensive technical literature exists on the subject. Statistics of dam failures have been collected and analysed (ICOLD, 1995). Corresponding investigations into the hazard and reliability of reservoir appurtenances are more recent. There is a greater awareness that the integrity of a dam installation includes the reliability of gates controlling flood release and the facility to empty a reservoir if a fault develops.

In an analysis of causes of embankment incidents and failures, according to USCOLD (US NRC, 1983), 2% of 240 dams experienced malfunction of gates. Since the publication of this analysis a few catastrophic events have been recorded involving spillway gates and a number which involved risk.

EVENTS AT SPILLWAY GATE INSTALLATIONS

In 1967 a spillway gate on the Washi Dam in Japan collapsed suddenly (Yano, 1968). The gate was 12 m high and 9 m wide. It was swept down-stream. The cause was dynamic instability induced by eccentricity of the trunnion bearings (Ishii et al, 1977 & 1979).

Eccentricity of trunnion bearings is deliberately introduced on some large Tainter gates to reduce the hoisting effort. When this is practised. do engineers check that the damping forces compensate for the possible dynamic instability effects? When the writer surveyed the large Tainter gates at the bottom outlet of the Tarbela dam on the river Indus in Pakistan, one of them, which was in operation, vibrated alarmingly. The gate had trunnions mounted on eccentrics operated by hydraulic cylinders. The purpose was to advance the gate towards the tunnel outlet to increase the pressure on the seals.

The collapse of spillway gate 3 of the Folsom Dam (Bureau of Reclamation, 1966) has alerted engineers to the possibility of a similar occurrence due to the design of the trunnions and their system of lubrication.

The possibility of failure had existed for a long time and could have been predicted; however this was the first case. Were there engineers who recognised that the design and choice of materials of the bearings were vulnerable but were dissuaded from altering it by the numerous installations which had operated apparently satisfactorily.

I objected to the design of the trunnions of the Yuvacik Dam at Izmit in Turkey, which followed the arrangement of the trunnions at the Folsom Dam. The Turkish design organisation responded– "we never had any problems at other dams in Turkey". They added, for good measure, "we have more dams in Turkey than you have in England". This occurred three years after the event at the Folsom Dam.

A spillway gate of a Swedish dam collapsed due to debris accumulation.

Also in Sweden, a serious breakdown occurred during the remote control of a sector gate (Lagerholm, 1996) due to the gate passing the upper limit switch. The bolts on the gate bearings sheared, causing the gate to break loose and to move down the spillway.

A spillway gate malfunctioned in 1992 at the Tarbela Dam Pakistan (Khan, 1994) when it became stuck during a lowering operation. It fell down, breaking two hoist ropes, damaging the gate and the weir. The gate was 28.6 m high and 15.2 m wide. Over a long period, the clearance between the side sealing plates on the piers (the seal contact plates) and the clamping bar securing the rubber seal on the gate had deteriorated. The cause of the dimensional change was not reliably established.

One instance of failure of a dam due to inability to open the spillway gates occurred in Spain.

The collapse of the gate of the Washi Dam is the only recorded case of complete failure of a gate due to vibration. There can be a number of different causes, the design of the gate lip, eddy shedding from the lip of a gate, seal leakage, unfavourable approach flow. At a large multigate sluice installation, self-exciting wave oscillations occurred in the upstream basin when six openings discharged while four others were closed by gates (Novak, 1984).

An example of serious gate vibration occurred at one of the spillway gates at Dundreggan near Loch Ness in Scotland (Noble et al, 2000). Vibration at low gate opening caused numerous fatigue cracks at stress concentrations. The cause was flow re-attachment at the gate lip. The gate had been installed during the 1950s and had previously been operated at larger gate openings.

It should be a matter of course on changing operational procedures that the possible technical consequences are investigated, also that gate vibration should be reported as soon as it is noticed, even if it is confined to a limited range.

INCIDENTS AND FAILURES OF BOTTOM OUTLETS

There are a number of research papers of hydrodynamic problems which have occurred at bottom outlets. Because high velocity flow is experienced at bottom outlets compared with spillway gates, hydrodynamic problems are more frequent.

Bottom outlets have failed to open due to silting. At the Barasona reservoir in Spain (Romeo, 1996), the silt had extended to a depth of 20 m adjacent to the dam and had completely blocked the outlet. The problem became dangerous following a major storm in 1993.

A number of bottom outlets are never, or rarely, exercised. A recent survey of reservoir appurtenances at dams in Indonesia identified a number of bottom outlets which had not been operated since impounding of the reservoirs. These are not isolated cases. Lagerholm (1996) noted similar failures to exercise bottom outlets in Sweden. Seals under high pressure are subject to contact welding after some time. Gates and bottom outlets which have not been regularly moved may be difficult or impossible to raise.

In 1974, the diversion tunnel of the Tarbela Dam on the river Indus in Pakistan collapsed during the construction state of the dam due to cavitation damage. The cause was sticking of a control gate in a partially open position. This was one of the most destructive failures of a tunnel gate. (Kenn et all 1981).

When the discharge from a tunnel gate does not result in supercritical flow, the possibility of creating highly sheared flow is present and the Tarbela incident illustrated its destructive power.

A comprehensive survey of the operation of bottom outlets at 50 large dams was carried out in Romania (Ionescu et al, 1994). While it may not be representative of experience in other countries, significant deterioration, incidents and failures were recorded. Damage had occurred at 38 gate installations. 60% of the incidents and failures were due to vibration problems, including two structural failures, which occurred after 8 and 20 years operation. Four events of intake clogging made the bottom outlets unavailable and nine vibration problems were classified as 'serious'.

CONTROL SYSTEM FAILURES

Incidents of inadvertent operation of gates under automatic control have occurred. Rajar et al (1994) record the self-induced opening of spillway gates on the Mavcice Dam in Slovenia. Two radial gates 20 m high and 13.5 m wide opened, discharging at a rate of 1192 m^3/s, equivalent to a 50-year return period flood.

Other incidents of uncontrolled gate openings have occurred but have not been recorded because they have not resulted in loss of life or damage.

A number of gate designers and reservoir operators require that automatic gate control systems are backed by hard wired electrical circuits which inhibit the time of operation of gates or the distance travelled following a command to move a gate.

COMMON CAUSE FAILURES

Common cause failures, that is failures which affect the operation of a system, are the most serious risk. They range from failure of the mains supply and the back-up system to fire, explosion, earthquake and failure of central control systems.

In electrical installations associated with spillway gates, redundancy is usually provided for transformers, mains switches and supply cables. Standby generating plant is almost invariably provided, either of the permanent or mobile type. Portable plant forms a second standby at some installations. Surprisingly, double busbars are rare in the distribution of electrical power. The failure of a single busbar can be a common cause fault, or at least affect several gates in a multi-gate installation.

The same degree of redundancy in the electrical mains and distribution equipment is rarely provided at bottom outlets.

In a critical industrial installation the electrical supply switchgear and distribution would be divided between two chambers which are not interconnected, with essential services duplicated. In the event of a fire or explosion, part of the plant and essential services would continue to function. This practice does not appear to be followed at spillway gate control stations

The usual practice where central and automatic control is provided is to site local control systems close to gates. The latter are usually electro-mechanical controls. This satisfies one criterion of reliability of control systems, that there should be duplicate controls and that the two systems should be generically different.

EARTHQUAKES

The performance and safety of dams during earthquakes world-wide has been remarkably good (Charles et al, 1991). Nevertheless the failure of a dam can have such serious consequences that earthquake safety evaluation of existing dams and of new constructions is a general requirement. Following an earthquake, the release of reservoir water can be a critical control function if the dam has been damaged by the seismic motion. Therefore, spillway gate installations and bottom outlets need to remain operational after an earthquake and should be included in the seismic analysis. As a New Zealand engineer expressed it :When the big one hits, the likely scenario is that massive power load will be dropped and spilling will quickly be necessary to prevent dam overtopping and serious damage to generating facilities" (Williams, 1996).

A review of incidents at dams that have been exposed to seismic events (Hinks & Gosschalk, 1993) shows that, while dam performance is, on the whole, fairly good, there are a number of events in which dams have suffered significant structural damage. In some of these cases the dam has subsequently failed entirely, although such failure has rarely occurred at the time of the earthquake; most failures have occurred either after a few hours or up to 24 hours after the earthquake.

Given this history, it is clear that directly after a dam has experienced a significant seismic event there is likely to be an urgent requirement for the water level in the reservoir to be lowered quickly both to reduce the pressure on the potentially damaged and weakened structure and to alleviate the consequences should the dam fail at a later time. Spillway gate and bottom outlets will be used for this purpose, with the spillway gates providing the greater initial capacity for level reduction.

Even in the UK, which most inhabitants do not consider an earthquake zone, there were some 201 earthquakes in 1998 in the British Isles and the surrounding continental shelf areas.

Seismic design of gates is complex, largely as a result of the earthquake inducing acceleration loadings acting in all three orthogonal directions simultaneously. This is particularly important in the sections of the gate which are subject to contact with the reservoir water. The overall effect of water adjacent to a steel element is to add to that element's mass and it is the product of the cumulative mass and the acceleration that generates the forces on the element.

Lateral movement of piers must be expected as a consequence of a seismic tremor. It is possible to design gates so that lateral movement of piers or abutments does not jam them by introducing collapse zones; however, this is rarely practised.

Cranes which operate turbine outlet gates are liable to be derailed due to an earthquake shock. Means to prevent crane wheels from jumping rails are established and are fitted where the risk exists. In military and naval defence applications, where electrical switchgear can be subject to severe shocks, shock absorbent mountings are installed. They do not appear to be used for electrical panels controlling gates in areas of high seismicity. An independent view is that the precautions necessary to ensure functioning of spillway gates and bottom outlet installations following a major seismic shock are mostly inadequate and that many appurtenances are at risk.

Damage and disablement of gates following an earthquake are not the only factors to be considered; blocking of access to an installation due to a landslip or damage to roads can inhibit emergency work.

FREQUENT OPERATIONAL PROBLEMS OR DEFICIENCIES

While reservoir appurtenances have a good operational record overall, there have been cases of failure, some potentially catastrophic, as well as areas where persistent operational problems occur. Specific causes of faults (Lagerholm, 1996) were:

- limit switch function
- ice problems (in Northern Europe, Canada and some states of the USA; presumably this must apply also to Eastern Europe and other parts of the world subject to severe winter weather)

- seal leakage, which in winter can cause freezing of the gates
- failure of heating systems
- trunnion bearing problems (the most frequent source of faults)
- loss of communication links

To these must be added:

- gate vibration
- cavitation at the bottom outlet of high head dams
- silting of the intake to bottom outlets
- lack of regular exercise of bottom outlet (also mentioned by Lagerholm, 1996)
- floating debris in extreme floods
- electrical cable fracture
- clogging of the intake and silting of water operated gates

Of lesser frequency are:

- control system malfunction
- uncontrolled descent due to hoist brake failure (two known cases – one reported by Lagerholm, 1996)

There are also records of problems or breakdown of vertical lift spillway gates, bottom outlet rolling gates, pinrack operated gates, and others.

RISK ASSESSMENT OF GATED STRUCTURES OF A RESERVOIR

There is sufficient evidence of failures and malfunction of reservoir appurtenances for spillway and bottom outlet gates to be included in a risk assessment of a dam. Determination of reliability must include potential liability due to design, operation and maintenance, operator training, inspection and supervision and record-keeping of incidents.

Maintenance can be deficient, variable at different stations of the same authority, or completely absent because there is no maintenance budget or authority to order spares. The latter was the case at hydropower plants in a tropical country.

METHODS OF RISK ANALYSIS

A number of detailed hazard and reliability assessments of barrages have been carried out. A barrage is constructed specifically to deal with the hazard of flooding, while the function of a reservoir may be electricity generation, water supply or flood storage and the hazard is perceived as a consequential risk. This may explain why, until recently, more detailed assessments of reliability were carried out on barrages than reservoir flood control structures.

There are a number of definitions of risk. The simplest one is "The likelihood of occurrence of adverse consequences" (McCann et al, 1985). For the purpose of quantifying risk, the definition by BC Hydro (1993) is more useful: "A measure of the probability and severity of an adverse effect to health, property, or the environment. Risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (i.e. the product of 'probability x consequence')."

Risk analysis must by definition include probabilistic events, although they may sometimes be implicit. Risk assessment is a combination of art, judgement and science (in that order) constrained in a formalised process (Bivins, 1984).

The most detailed methods used in risk analysis are fault trees and event trees. Fault trees allow the diagrammatic presentation of components that may lead to failure in a system element. A general failure event – the event to be analysed – is at the top of the fault tree, the remainder of which is formed by specific events which can potentially lead to the failure. Analysis of the fault tree results in determination of minimal cut sets, which are the minimal combination of events which cannot be reduced in number and whose occurrence cause the top event. Calculation of the probability of occurrence for each minimal cut set is carried out from the probabilities of the basic events.

An event tree represents all the possible sequences of events which could result from a given initiating event. Unlike a fault tree, it works from the specific to the general. It therefore traces how failure sequences propagate. Branching is limited to 'yes' or 'no' at each system response. There are similarities with operational logic diagrams.

For analysing complex systems, computer programmes have been developed for the calculation of elaborate schematic structures. The one best known in the UK is AEA Technology's programme Fault Tree Manager. A previous version 'Orchard' was used in a reliability assessment of the Thames Tidal Defences and the barrages for the flood prevention of the City of Venice. Hoyland et al (1994) discuss other programmes.

Other techniques which are used to identify different failure modes of appurtenant works consist of structured questions which help to analyse the system. Examples are failure modes and effects analysis (FMEA) and failure modes, effects and criticality analyses (FMECA). BS 5760: Part 5: 1991 describes these as methods of reliability analysis intended to identify failures which have consequences affecting the functioning of a system within the limits of a given application, thus enabling priorities for action to be set. Hazard and operability study (HAZOP) is another analytical tool which concentrates on identifying deviations from design and operating conditions. These techniques use worksheets which are filled out during analysis of a system to document a qualitative assessment.

In dam engineering, a probabilistic risk analysis (PRA) is used as a basis for making decisions when selecting among different remedial actions, and to determine priorities. It is helpful when carrying out PRA if there is a collection of statistics, but this is not essential. When assessing gates and valves, an analysis of service records is a useful guide. This is also used when assigning failure probabilities to fault and event tree branches.

Reliability assessments based on fault trees of the Thames, Barking Creek and other storm surge barriers comprising the Thames Tidal Defences were carried out (UKAEA, 1987 & Duke, 1990), and two reliability assessments of the design of the barrages for the flood defence of the City of Venice (AEA Technology, 1989 & Lewin, 1993).

The Rykswaterstaat in the Netherlands has carried out similar assessments on barriers for flood protection of the Netherlands. Some results of a risk assessment of the New Waterway storm surge gate were given in the papers by Ieperen (1994) and Janssen (1994). At spillway gate installations a fault tree reliability assessment was carried out as part of the deficiency investigations for the Seven Mile Dam in British Columbia (Klohn, 1996). This was a major undertaking – the documentation of the investigation of reliability for normal conditions is extensive, comprising three volumes.

Lagerholm (1996) mentions in his paper on 'Safety and reliability of spillway gates' that fault tree analysis has been performed in Sweden on different types of spillway gate functions. The wording suggests that these were not total system assessments.

The construction of fault and/or event trees and the production of minimal cut sets, together with the computational work required, involves considerable man hours. This type of analysis is considered necessary in special cases such as the Seven Mile Dam, where the operation and reliability of the spillway and drainage systems are crucial to the safety of the dam, or the Folsom Dam where collapse of a spillway gate has resulted in consideration of a fault tree assessment of the spillway system.

In most spillway systems there should be adequate redundancy, so that the malfunction of a gate does not result in a serious risk. If redundancy is provided the overall system reliability depends more on common cause failures, that is, on an event which affects the total installation, such as loss of power supply, a fire or an earthquake. However, redundancy of gates is rarely provided for an extreme event.

Even failure modes, effects and criticality analyses (FMECA) and hazard and operability studies (HAZOP) can involve much technical manpower. They are usually carried out by a team of engineers and technicians familiar with an installation, and can result in lengthy evaluation of specific elements of the control structures.

Where the operator of several dams requires an initial hazard assessment of a number of reservoir appurtenances of different design and age, methods of assessment based on the systematic application of engineering judgement are sometimes used. In Norway, a simplified risk analysis is being applied to dam safety. Scottish and Southern Energy uses a similar approach to determine priorities for maintenance and improvement of spillway gate and reservoir bottom outlet structures. The analyses could be more appropriately called 'systematic application of engineering judgement'.

Fault trees and minimal cut sets are important tools to assess the reliability of a total installation and for quantifying the contribution of sub-systems and major components to the failure of the top event. They are not, as a rule, extended to include details such as limit switches, an important vulnerable element of gate hoists, local leakages of seals which can cause gate vibration and freezing up of side seals at spillway gates in winter, and others. Unless data of operational problems over an extended period of time are available, it is difficult to assign failure probabilities to these and similar elements. This does not apply to the electrical supply and distribution systems of spillway gate and bottom outlets. General and detailed statistical information is available to assign a failure probability to each element and the result will more accurately reflect the failure probability than the parallel assessment of gates and their mechanical features.

Fault tree reliability assessments are a valuable tool to determine the overall integrity of an installation in relation to the risk of the dam and reservoir. The inclusion in the risk assessment of management, operator training, operational procedures, communication, possible malicious action and failure of advance warning systems results in a comprehensive assessment. In barrages, ship collision is an important risk factor and, more remotely, an aircraft crash.

Operationally, engineering assessments are required when the main objective is to determine the adequacy of maintenance, elimination or improvement of features or elements which are vulnerable, and the reduction in the probability of failures which can put a gate out of operation. A structured assessment system based on engineering judgement is probably the best means of achieving this.

A reasonable record of experience is available of design features of gates and valve systems which are likely to result in operational problems, or are indicators of risk. Instead of structured generalised questions which are the basis of HAZOP, more specific charts should be available for carrying out reliability assessments. They could take the form of diagrams and description of design features or the condition of a component and assign a number. The sum of the numbers would be an index of priorities and individual high numbers would draw attention to areas of urgent action. It would not form a probabilistic index, but if well constructed could be part of a risk assessment.

Reservoir control appurtenances are designed for extreme events and few have been subjected to exceptional loading. However, hydraulic conditions which cause gate vibration, while not necessarily extreme events, may not occur for years after commissioning. Hydraulic conditions, combined with structural mechanical and electrical deterioration, can cause a risk and hazard because they are the coincident event of a number of probabilities. In a formal probabilistic investigation they may not show up, because it assumes that at each demand, the term used in reliability assessment for a gate movement, the structural mechanical and electrical condition is assumed to be the same and that no deterioration has occurred. To factor wear and deterioration is difficult and quantifying it depends on judgement, subject to wide latitude.

RELIABILITY INDICES

The probabilistic reliability derived from a fault tree analysis can be expressed as failure per demand. In the case of a spillway gate, this would be the opening of the gate.

For the Thames Barrier, this was 1.55×10^{-4} per gate per demand (AKAEA, 1987). Expressed differently, there is a chance that a single gate will fail to close on one on 560 closure demands, and that two of the ten gates will fail to close on one full closure in approximately 6000 closure demands.

In the hazard and reliability study of the Flood Prevention Scheme for the City of Venice, failure was defined as flooding of Venice more than 280 mm above Venice datum. The design resulted in 1 event in 800 years (Lewin, 1993).

For the New Waterway storm surge barrier in the Netherlands, the derived reliability targets were:

- Probability of not closing due to human or technical errors less than 10^{-3} on demand
- Probability of collapse less than 10^{-6} in any year
- Probability of not opening due to human or technical errors less than 10^{-4} on demand

For the Seven Mile Dam in British Columbia the reliability analysis (Klohn, 1996) resulted in:

- Probability of failure of spillway gates to open due to environmental hazards 9.68×10^{-6}
- Probability of failure of spillway gates to open due to electrical or

mechanical failures 2.07 x 10^{-7}

- Probability of power supply unavailability to the spillway gates 2.07 x 10^{-7}

A good industrial system standard is one failure in 10^{-4} per demand. The reliability of a spillway gate installation depends on whether all the gates can pass the probable maximum flood (PMF) or the half PMF. The usual practice in a multi-gate spillway system is that a thousand year return period flood can be passed with one gate out of operation. A failure rate of 10^{-4} per gate per demand would appear to be an adequate assurance under these conditions. If the gates cannot pass the PMF a lower failure rate would be appropriate. This would depend on the hazard resulting from a gate failing to open under flood conditions. Some spillway gates, especially older ones, would not qualify for a failure rate of 10^{-4} per demand or a more severe criterion.

Bottom outlets consist more frequently of a single operating gate with a back-up gate or a discharge valve backed by a butterfly valve or a gate. Two or more parallel fluidways are less frequent. It is suggested that a failure rate of the order of 10^{-5} would be appropriate where only one gate with a back-up gate is provided. Whether a higher reliability is required than that of a spillway gate installation depends on the risk associated with failure of the bottom outlet.

Failure probability rating for electrical services, both for details and systems, are available and are statistically valid. This includes standby generating plant.

For spillway gates, their hoisting machinery and control systems, failure probabilities have to be assessed from service records, known incidents or structural and mechanical plant which have some similarity. The available data will probably be of low statistic validity. The selection of a failure probability for each item of a fault tree branch will therefore involve a significant element of engineering judgement. Such judgement, whether exercised by an individual or collectively, depends on experience.

The problems encountered with bottom outlets are more frequently the interaction of structural and mechanical aspects with hydrodynamics. Assignment of failure probabilities to fault tree branches when investigating bottom outlets is therefore even more dependent on judgement and knowledge of theory and practice.

When gate vibration is taken into account, the problem is compounded. ICOLD Bulletin No. 102 gives guidance on gate vibration, although it is difficult to relate it to practical problems. Other publications (Naudascher et al, 1994, Kolkman, 1979 & 1984, Lewin, 1995) and many research papers are helpful but require knowledgeable interpretation.

A number of recent technical papers show that dam engineers are accumulating records of component and system failures of hydraulic equipment, and that these are being systematically analysed. For maximum results these should be carried out on a wide scale, and preferably on an international basis.

Some technical papers recorded failure events which resulted in serious hazards. This would not have been highlighted in a conventionally constructed fault tree and would have resulted in a low failure probability. Integrating experience and knowledge on a wide scale may identify areas where reliability and hazard resulting from a rare combination of factors would result in a different construction of a fault tree, or simply indicate the need for remedial action. A fundamental difficulty is to factor wear, deterioration and corrosion into any reliability assessment.

CONCLUSIONS

Spillway gate installations and bottom outlets control the flow of water. The design of control structures should therefore start with an understanding of the medium to be controlled, water. This is not always the case. Hydrodynamic problems appear to be a frequent cause of malfunction of gates and valves. The identification of actual or potential problems of gate vibration and cavitation requires specialist knowledge and experience. Many research papers have been published. They are often difficult to relate to cases which occur in practice. Guidelines have been formulated in a chapter of a book on Hydraulic Gates and Valves (Lewin, 1995).

Structural problems can be identified by conventional static analysis. The methodology is established (US Corps of Engineers, 1997: DIN 19704-2) At least one computer program is available for the design or checking of Tainter gates. Dynamic response problems, such as earthquakes, can be approximated by using a pseudo-static analysis or, if more accurate results are required, a finite element analysis is required.

The investigation of electrical, mechanical and control problems can be systematised by using Data Collection Sheets in conjunction with Failure Mode, Effect and Criticality Analysis (FMECA). This is successfully practised by Scottish and Southern Energy (Sandilands et al 1998). A Library of such Data Collection Sheets, accessible via the internet and continually updated, would be an asset to engineers and supervisory agencies.

Human factors and common cause failures should become apparent by construction of high level fault trees.

Spillway gate installations are part of a system, comprising the dam, the reservoir, the bottom outlet, power generation or water abstraction. The operation of the system is determined by the reservoir inflow characteristics, the hydrology of the outflow, the potential of upstream and downstream risks and common cause events. To arrive at a hazard and reliability assessment, the total system should be considered.

Technical and organisational improvements depend on the identification of deficiencies. The importance and urgency of carrying out technical improvements in design and reliability is influenced by statistical data. For moving water control structures, few organisations are likely to gather sufficient internal data to determine priorities. This requires international co-operation on a systematic basis, especially since equipment is designed to function during an extreme event. The methodologies for identifying and quantifying hazard and reliability are a valuable tool in effecting improvements.

FOOTNOTE:

The paper is a personal view of the author based on information available to him and his experience of work in the United Kingdom and other parts of the world. The practice of design, attainment and maintenance of reliability and the supervisory function varies appreciably for different countries.

In the UK, reservoir owners and operators have specific responsibilities for their dams and need to formulate safety management procedures within the context of the Reservoirs Act 1975. Engineers are appointed to a panel which qualifies them to carry out regular statutory inspection of dams and reservoirs.

Membership of a particular section of the panel permits an engineer to design and supervise the construction of a dam and reservoir. Reservoir and dam work is the only statutory restricted function of engineers in the UK. Panel engineers advise reservoir owners and operators of the work necessary to comply with the safety requirements of the Act. Appointment to any section of the panel is by stringent peer selection administered by the UK Institution of Civil Engineers.

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Lewin, J. "Hazard and Reliability of Hydraulic Equipment for Dams"

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DAMAGE ASSESSMENT

T. F. GLOVER

ADDITIONAL MOTIVATIONS FOR ESTIMATING DAMAGES

- **DETERMINE THE VALUE OF INFORMATION**

- **INFORMATION HAS VALUE IN PERMITING US TO REVISE OUR CHOICES OF WEALTH IN NORMAL OPERATING STATES RELATIVE TO STATES IN WHICH LOSS OCCURS**

DAMAGE INFORMATION
&
OPERATING REVENUES
&
ASSET VALUE

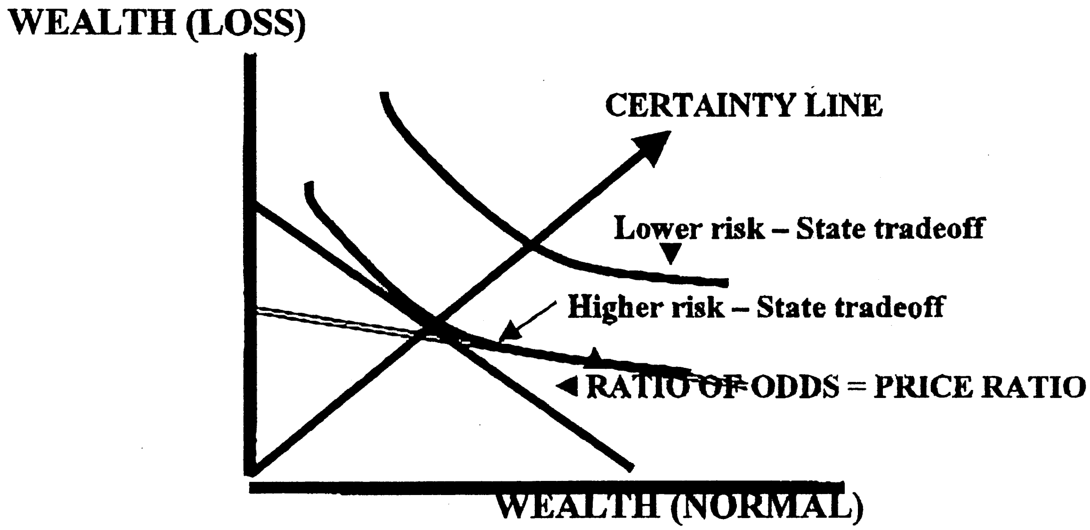
⇓

IDENTIFY THE TRADEOFF
CONDITIONS BETWEEN
STATES OF LOSS AND NORMAL OPERATIONS

- **INFORMATION ABOUT PROBABILITIES ALLOWS US TO REVISE THE PROBABILITIES ABOUT THE TWO STATES**

- **INFORMATION ON THE RISK OF DAMAGE ENABLES US TO REVISE OUR CHOICES OF THE TRADEOFFS BETWEEN NORMAL AND LOSS STATES TO ATTEMPT TO INCREASE EXPECTED UTILITY OF WEALTH**

WEALTH TRADEOFF BETWEEN STATES OF NORMAL CONDITIONS AND CONDITIONS OF LOSS



TRADEOFF INFORMATION AND ODDS ARE USED IN:

1. **INSURANCE DECISIONS**
2. **SETTING SAFETY STANDARDS AND THE COSTS OF SUCH STANDARDS**
3. **DECISIONS ABOUT BUSINESS RISK**
4. **INVESTMENT DECISIONS TO MODIFY RISK**
5. **RESOLVE ISSUES OF MORAL HAZARD AND ADVERSE SELECTION (POOLING RISK VS SEPARATING RISK)**
6. **DETERMINING THE RISK OF CAPITAL AND THE COST OF CAPITAL USED TO DEVELOP INFORMATION ABOUT NEW INVESTMENTS**

BUSINESS RISK

BUSINESS RISK IS GENERALLY REFERRED TO AS THE RISK INHERENT IN THE FIRM (OR INDUSTRY) - INDEPENDENT OF THE METHOD OF FINANCING

BUSINESS RISK IS REFLECTED IN THE VARIABILITY OF NET OPERATING INCOME OR CASH FLOWS

BUSINESS RISK IS REFLECTED IN THE PROBABILITY DISTRIBUTION OF NET CASH FLOW

PRICE EFFECTS RISK

TECHNOLOGY AND PRODUCTION HAVE EFFECTS ON BUSINESS RISK

FINANCIAL RISK IS THE ADDED VARIABILITY OF THE NET CASH FLOWS OF THE OWNER'S EQUITY THAT RESULTS FROM THE FIXED FINANCIAL OBLIGATION ASSOCIATED WITH DEBT FINANCING AND/OR CASH LEASING

DYNAMIC OPTIMAL ALLOCATION OF RESOURCES IN INVESTMENT IS DERIVED WHEN WE MAXIMIZE THE NET PRESENT VALUE OF THE PROJECTED INVESTMENT: MARGINAL BENEFITS = MARGINAL COST

$$NPV = \sum_t \frac{\text{(NET EARNINGS)}}{(1+R)^t} - \text{INVESTMENT COST}$$

R IS THE DISCOUNT RATE OR COST OF CAPITAL WHICH REFLECTS RISK - VARIABILITY IN NET EARNINGS ALSO REFLECTS RISK

OPTIMAL ALLOCATION OF RESOURCES IN INVESTMENT UNDER RISK CONDITIONS: MAXIMIZE THE EXPECTED PRESENT VALUE OF NET BENEFITS OVER INVESTMENT ALTERNATIVES = THE SUMATION OF PROBABILITIES OF EVENTS X PRESENT VALUE OF NET BENEFITS

MAY ONLY BE ABLE TO PROVIDE CONDITIONS IN INVESTMENT WHERE BENEFITS GENERATED EXCEED COSTS IMPOSED: BENEFIT-COST RATIO

$$[\sum_t \text{BENEFITS}/(1+R)^t] / [\sum_t \text{COSTS}/(1+R)^t] > 1$$

MAY ONLY BE ABLE TO MINIMIZE COST SUBJECT TO A SAFETY TARGET IN RISK ASSESSMENT -- COST EFFECTIVENESS ANALYSIS OR MINIMIZE LIFE CYCLE COSTS OF AN INVESTMENT [VARIATION IN BENEFITS AND COSTS ARE INVOLVED IN EACH]

THE PRACTICE OF DAMAGE ESTIMATION

DIFFERENT DEFINITIONS/ACCOUNTING FOR DAMAGES

♣AVOIDED DAMAGES

- COSTS OF DAMAGES THAT CAN BE AVOIDED BY INVESTMENT TO MODIFY THE RISK OF AND OCCURANCE OF FAILURES THAT CAUSE DAMAGE
- AVOIDED COSTS
- INCOME ACCOUNTING – ACCOUNTING FOR LOSSES IN INCOME, TRUNCATION OF ACTIVITIES THAT PRODUCE A GROSS MARGIN
- DAMAGES TO DOWNSTREAM STRUCTURES
- DAMAGE TO THE HEADWORKS STRUCTURES
- ALTERNATIVE COST OF RESOURCES – OPPORTUNITY COST CONCEPT

♣SUSTAINED DAMAGES

- ALL DAMAGES INCLUDING SHORT TERM COSTS INDUCED BY A CATASTROPHIC EVENT
- USUALLY USED TO ACCOUNT FOR THE EXTREMITY OF AN EVENT AND TO ACCOUNT FOR ALL HARM
- GOVERNMENTAL SUBSIDY AND LOAN PROGRAMS ARE TRIGGERED FROM THESE DAMAGE ESTIMATES

♣ SECONDARY IMPACT COSTS

- CHANGES IN BUSINESS ACTIVITY
- LONG TERM RELOCATION COSTS AND ADJUSTMENT COSTS
- PRODUCTION AND TRANSPORTATION CHANGES
- MAY INVOLVE LONG-TERM CHANGES IN RESOURCE COSTS
- ADJUSTMENT COSTS OF DOING WITHOUT A RESOURCE AND A RESOURCE DELIVERY SYSTEM
- INVOLVES SIMULATION OF LONG-RUN IMPACTS VIA SIMULATION, INPUT-OUTPUT-IMPACT, STATISTICAL, AND MATHEMATICAL PROGRAMMING MODELS
- INVOLVES ESTIMATION OF CHANGES IN RESOURCE VALUATION VIA COMPARISONS OF SHADOW VALUES AND/OR THE CHANGE IN THE VALUATION OF A DELIVERY SYSTEM

♣ ENVIRONMENTAL DAMAGES

- GENERALLY VIEWED AS A SEPARATE DAMAGE ISSUE BECAUSE OF MEASUREMENT AND VALUATION PROBLEMS
- DAMAGES TO HABITAT
- DAMAGES TO CULTURAL RESOURCES
- EVALUATION OF TEMPORAY LOSSES VS LONG-TERM ALTERATION OF ENVIRONMENTAL RESOURCES
- LONG-TERM LOSSES DEPEND ON SPECIES RESILIANCY AND/OR RECOVERY, DEVELOPMENT OF NEW ECOLOGIES VIA INVESTMENT AND/OR THE DAMAGING EVENT
- TECHNIQUES USED TO VALUE RESOURCE THAT ARE NOT VALUED IN THE MARKET PLACE ARE USED, BUT THERE IS CONSIDERABLE DEBATE ON THE APPROPRIATENESS OF THEIR USE – NEW TECHNIQUES ARE BEING EVALUATED AND HOLD PROMISE

MORE ON ENVIRONMENTAL DAMAGES

- RISK BENEFIT ANALYSIS HAS BEEN ONGOING IN THIS AREA BY VARIOUS AGENCIES SUCH AS THE U.S. EPA AND U.S. DOE, BUT ANALYSES IN RISK ASSESSMENTS OF LARGE DAMS HAS BEEN WEAK AT BEST

- TWO TYPES OF RISKY "COMMODITIES" OR RESOURCES
  .... NATIONAL TREASURES WHICH, IF DESTROYED, NO AMOUNT OF MONEY CAN RESTORE – THE RESOURCE BASE IS ALTERED – THE CONSUMER FACES A "CONSUMPTION UNCERTAINTY" ABOUT THIS TYPE OF RISKY "COMMODITY"
  .... COMMODITIES SUBJECT TO PRICE RISK

  WILLINGNESS TO PAY FOR RISK REDUCTION IS DIFFERENT BETWEEN THE TWO COMMODITIES AND PRESENTS A VALUATION PROBLEM

- RANKING OF PRIORITIES RELATIVE TO PROJECTED DAMAGES PROBABLY NEEDS TO BE COMPLETED TO ASSESS DAMAGE AND RISK REDUCTION ALTERNATIVES AND THE COSTS ASSOCIATED WITH THESE ALTERNATIVES

ALTERNATIVE DAMAGE MEASUREMENT ISSUES

IN PRACTICE THE ISSUES HAVE DEPENDED ON STRUCTURE OWNERSHIP

PUBLIC OWNERSHIP – FLOOD CONTROL PROJECTS

- **DAMAGES ARE MEASURED AS AVOIDED DAMAGES**
- **DAMAGES ARE BASED ON THE OPPORTUNITY COST OF RESOURCES CONCEPT**
- **DAM FAILURES TRUNCATE THE FLOOD CONTROL SERVICE CAPABILITY OF THE DAM – THE VALUE OF THE FLOOD CONTROL STRUCTURES = THE VALUE OF THE DOWNSTREAM STRUCTURES BEING PROTECTED**
- **IF THE FAILURE IS PROJECTED TO CHANGE RESOURCE COSTS, THEN THE RESOURCE COSTS ARE THE OPPORTUNITY COST OF THE RESOURCES – THE ALTERNATIVE COST OF GETTING THE RESOURCES TO RESTORE NORMAL SERVICE DELIVERY – MAY INVOLVE CONTINGENCY COSTS**
- **IF, FOR EXAMPLE, HYDRO-ELECTRIC POWER IS LOST FROM THE DAMAGED FACILITY, BUT CAN BE OBTAINED FROM THE POWER GRID NETWORK AT THE SAME PRICE, THERE IS NO CHANGE IN RESOURCE COST- THERE IS JUST A REDISTRIBUTION**

- AGRICULTURAL LOSSES MAY BE PICKED UP IN OTHER REGIONS AND WITHOUT PRICE CHANGES– THERE IS A REGIONAL DISTRIBUTION – BUT IF IRRIGATION WATER HAS TO BE OBTAINED FROM ANOTHER SOURCE AT HIGHER COST, THEN THERE IS AN ALTERNATIVE RESOURCE COST THAT HAS TO BE COUNTED

- MINIMAL INCOME ACCOUNTING MEASURES OF DAMAGE

- DAMAGES ARE ASSOCIATED WITH REDUCTIONS IN THE NATIONAL ECONOMIC DEVELOPMENT ACCOUNT – CHANGES IN GNP OR GDP CAUSED BY CHANGES IN COSTS AS A RESULT OF THE PROJECTED FAILURE EVENT – THESE ARE THE DAMAGES TO BE AVOIDED

- SOME ALLOWANCE FOR AVOIDED COSTS WHICH ARE MAINLY CONTINGENCY COSTS

- ACCOUNTS FOR NATIONAL ECONOMIC WELFARE CHANGES AND LIABILITY FOR DOWNSTREAM LOSSES

- IN SOME CASES SECONDARY IMPACT DAMAGES ARE REVIEWED – THIS IS AN ATTEMPT TO LOOK AT LONG-TERM RESOURCE COST INCREASES DUE TO FAILURE OF A DELIVERY SYSTEM OR A MULTI-PURPOSE STRUCTURE AND ASSOCIATED ADJUSTMENT COSTS

PRIVATE OWNERSHIP – LIABILITY FOR DOWNSTREAM DAMAGES

- SEPARATION OF DAMAGES ACCRUING TO OWNER/OPERATOR RELATIVE DAMAGES ACCRUING TO DOWNSTREAM THIRD PARTIES
- FOR OWNER/OPERATOR STRUCTURES – DAMAGES ARE ACCOUNTED AS LOSSES IN THE BOOK VALUE OR REPLACEMENT VALUE
- INCOME ACCOUNTING OF LOSSED REVENUES OF SERVICES OF THE STRUCTURES
- THIRD PARTY DAMAGES INCLUDE DAMAGED VALUE OF STRUCTURES AND INFRASTRUCTURE
- INCOME ACCOUNTING FOR LOSSES IN INCOME, LOSS IN GROSS MARGIN OF VARIOUS DOWNSTREAM ACTIVITIES
- CHANGES IN RESOURCE COSTS ARE ACCOUNTED AS DAMAGES AND CAN BE SHORT RUN AND LONG RUN CHANGES IN RESOURCE COSTS
- DEPENDING ON THE IMPACTS OF THE FAILURE EVENT, SECONDARY IMPACT COSTS MAY BE INCLUDED IN DAMAGES OR AT LEAST EVALUATED
- ENVIRONMENTAL DAMAGE – QUANTITATIVE OR QUALITATIVE IN NATURE DEPENDING ON INFORMATION AND DATA

DAMAGE INPUTS TO THE RISK ASSESSMENT

DAMAGES ESTIMATES AND INPUTS ARE DEVELOPED ON A PER EVENT BASIS

CONVERTED TO RISK COST IN THE RISK ASSESSMENT

PATHWAY PROBABILITY APPLIED TO THE DAMAGES

THE DAMAGES OF INTEREST ARE THE INCREMENTAL DAMAGES

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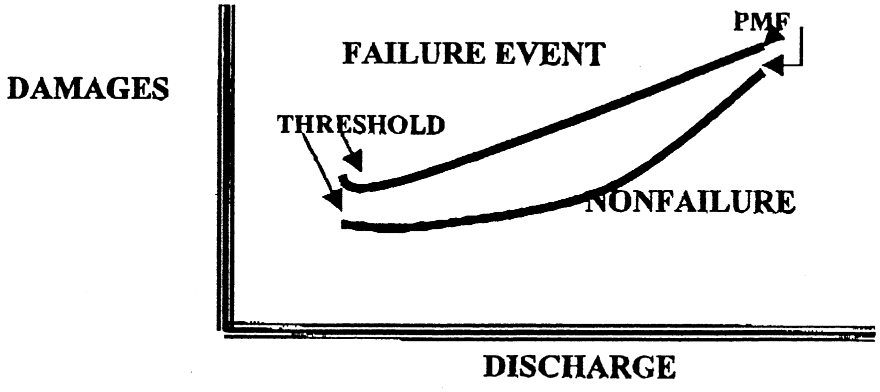
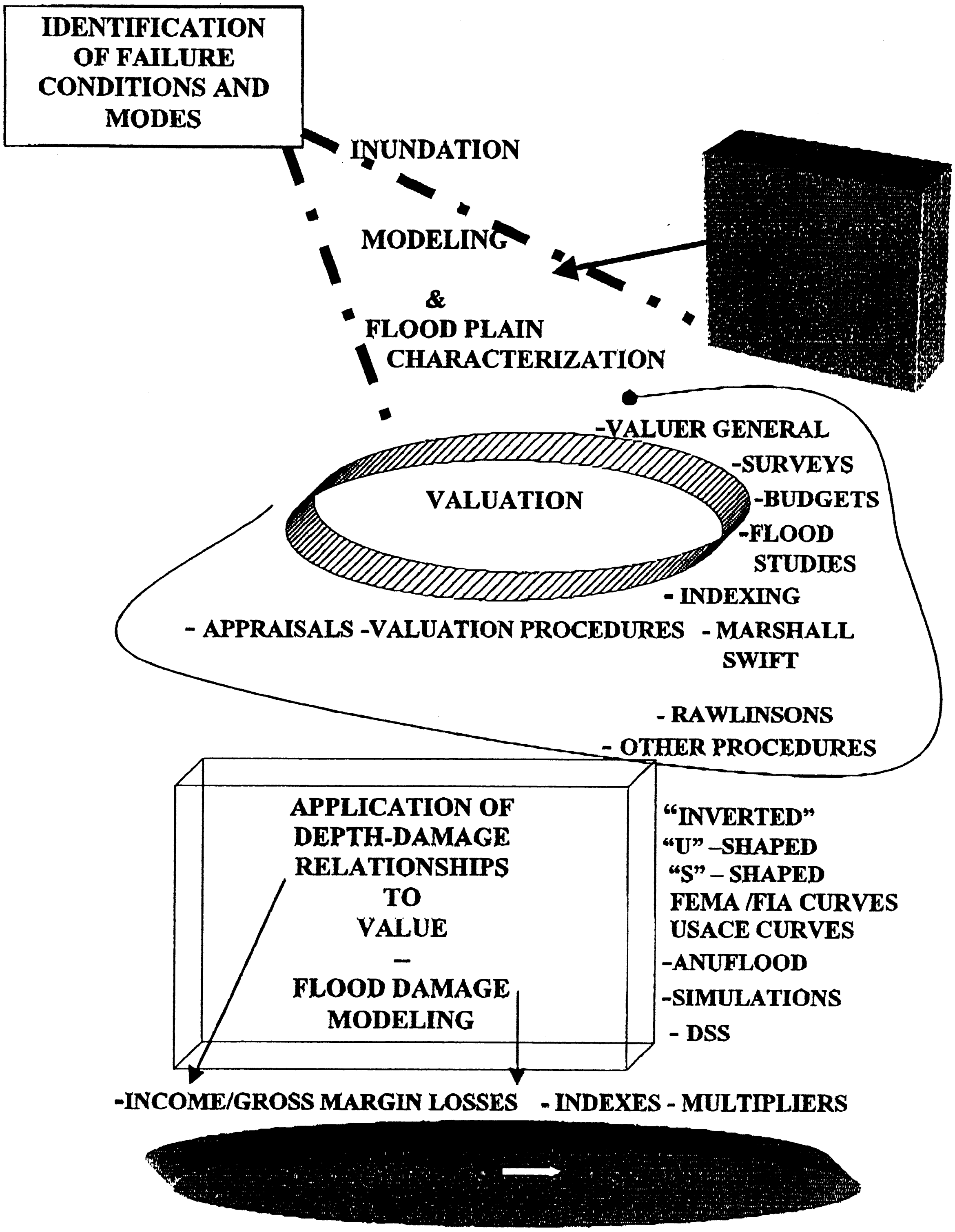
THE DIFFERENCE BETWEEN DAMAGES DUE TO FAILURE EVENTS AND DAMAGES ASSOCIATED WITH NO FAILURE



CURRENT GENERAL APPROACH TO ESTIMATION



IDENTIFICATION OF FAILURE CONDITIONS AND MODES

INUNDATION

MODELING

&

FLOOD PLAIN CHARACTERIZATION

VALUATION

- **-VALUER GENERAL**
- **-SURVEYS**
- **-BUDGETS**
- **-FLOOD STUDIES**
- **- INDEXING**
- **- APPRAISALS**
- **-VALUATION PROCEDURES**
- **- MARSHALL SWIFT**
- **- RAWLINSONS**
- **- OTHER PROCEDURES**

APPLICATION OF DEPTH-DAMAGE RELATIONSHIPS TO VALUE

–

FLOOD DAMAGE MODELING

"INVERTED"
"U" –SHAPED
"S" – SHAPED
FEMA /FIA CURVES
USACE CURVES
-ANUFLOOD
-SIMULATIONS
- DSS

-INCOME/GROSS MARGIN LOSSES - INDEXES - MULTIPLIERS

COST EFFECTIVENESS APPROACH TO ENVIRONMENTAL EVALUATION
(PARTIAL QUANTIFICATION)

VALUATION PROBLEM: UNABLE TO ELICIT WILLINGNES TO PAY FOR ENVIRONMENTAL RESOURCES NOT EXCHANGED IN THE MARKET

THEN OBTAIN INFORMATION ON VOTING, EMOTIONAL OR POLITICAL "VALUE" - OR SCIENTIFIC EVIDENCE OF VALUE (SUCH AS EXPRESSED IN BIODIVERSITY DEBATES)

DETERMINE DISTINCTIVENESS = D = HOW UNIQUE OR DIFFERENT IS THE SITE, ECOLOGY, CAPABILITY OF BOARDING THE SPECIES

DETERMINE UTILITY = U = HOW MUCH DO WE LIKE OR PLACE POLITICAL "VALUE" ON , OR VOTE THAT WE LIKE THE SITE, ECOLOGY, SPECIES, BOARDING CAPACITY

DETERMINE BY HOW MUCH THE "SURVIVABILITY" OF A SPECIES, SITE OR ECOLOGY CAN ACTUALLY BE IMPROVED BY A RISK REDUCTION ALTERNATIVE = ΔP = THE NOTION OF CHANGE OF PROBABILITY

DETERMINE HOW MUCH IT COSTS TO IMPROVE ON ΔP

R = RANKING = $[D + U](\Delta P)$ = RANKING OF PROJECTS TO MODIFY RISK

//////////////

PROBABILITY OF SURVIVABILITY, P, IS SUCH THAT $\Delta P \equiv P^O - P_O$ IS RELATIVELY SMALL AND $0 \leq P_O \leq P^O \leq 1$, WHERE $P = P_O$ INDICATES THERE IS NO SPECIES BOARDED BY THE ECOLOGY OR ENVIRONMENT IN QUESTION, AND WHERE $P = P^O$ INDICATES THE "DESIRED" SPECIES IS BOARDED BY THE ECOLOGY.

NEED INFORMATION ON INCREMENTAL EFFECTS ON SURVIBABILITY INITIATED BY THE FAILURE EVENT RELATIVE TO THE NONFAILURE EVENT

THIS QUALITATIVE COST EFFECTIVENESS APPROACH APPROXIMATES AND OPTIMIZATION PROBLEM WHEREBY EXPECTED DIVERSITY OF ECOLOGIES + SPECIES BOARDING CAPACITY ARE MAXIMIZED SUBJECT COST AND PROBABILITY CONDITIONS

MAXIMIZE $_{\text{OVER } \{P\}}$

$$[W(\{P_n\}) + U(\{P_n\})]$$

SUBJECT TO:

n INDIVIDUAL PROBABILITY CONSTRAINTS

$$P_{no} \leq P_n \leq P_n^o \qquad \forall n$$

&

THE OVERALL BUDGET CONSTRAINT

$$\Sigma C_n \{(P_n - P_n^o)/(P_n^o - P_{n0})\} = B$$

WHERE W(P) IS THE EXPECTED DIVERSITY FUNCTION

U(P) IS THE HOLDINGS OF THE BOARDING CAPIBILITY

IF WE CAN GET INFORMATION ON EACH OF THESE FROM SECONDARY DATA FROM PREVIOUS INVESTIGATION THEN WE APPLY THE ABOVE MATHEMATICAL PROGRAMMING MODEL TO GET AN INTERIOR SOLUTION FOR P_n

ONE OF THESE VALUES THAT SATISFIES

$$P_{no} \leq P_n \leq P_n^o$$

CORRESPONDS TO PARTIAL PROTECTION OR FRACTIONAL BOARDING OF A SPECIES OR HOLDINGS OF A SPECIES

THIS MIGHT BE GIVEN THE PHYSICAL INTERPRETATION OF BOARDING ONLY SOME FRACTION OF A REPRODUCTIVELY VIABLE POPULATION SIZE

SO A SURVIVAL PROBABILITY OF P_n FOR A SPECIES OR HOLDING COMES AT A BUDGET COST OF

$$C_n \{(P_n - P_n^o)/(P_n^o - P_{n0})\}$$

ECONOMIC FEASIBILITY INVESTMENT CRITERIA

- EFFICIENCY IN RESOURCE ALLOCATION IS ACHIEVED WHEN NET BENEFITS ARE MAXIMISED
  - WHERE MARGINAL BENEFITS = MARGINAL COST
- THE EFFICIENT ALLOCATION IS EMPIRICALLY ACHIEVED DYNAMICALLY BY MAXIMISING THE PRESENT VALUE OF NET BENEFITS
- UNDER RISK CONDITIONS THE EXPECTED VALUE OF NET BENEFITS IS MAXIMISED OR SOME PERCENTILE IS USED

OTHER CRITERIA USED IN PRACTICE

- POSITIVE NET PRESENT VALUE
- ANNUALISED BENEFIT/COST RATIO > 1
- DISCOUNTED BENEFIT/COST RATIO > 1
- INTERNAL RATE OF RETURN
- // THESE CRITERIA GUARANTEE NO ACTIVITY CONFERS MORE COST ON SOCIETY THAN BENEFITS. THEY DO NOT GUARANTEE THE EFFICIENT ALLOCATION OF RESOURCES
- B/C = 1 IMPLIES AVE BENEFITS= AVE. COSTS//

COST EFFECTIVENESS

- INVOLVES MINIMISING THE COST OF ACHIEVING A SPECIFIED OUTCOME
- EXAMPLES
  - MINIMISE THE COST TO SAVE A LIFE
  - LIFE CYCLE COSTING (MINIMIZING CAPITAL AND OPERATION COSTS OF ACHIEVING AN OUTCOME
  - MINIMISING THE COST TO MAINTAIN SUPPLY

- B/C > 1 GUARANTEES COSTS IMPOSED ARE NOT MORE THAN BENEFITS
- INTERNAL RATE OF RETURN > BORROWING RATE
- COST EFFECTIVENESS: CHEAPEST FOR A TARGET
- MAX NET PRESENT VALUE - GUARANTEES THE EFFICIENT POINT

OTHER COST EFFECTIVENESS EXAMPLES

- MINIMISE THE SUM OF THE COST TO SAVE A LIFE AND REMEDIATION COSTS
- UNCERTAINTY ADJUSTED COST-BENEFIT
  - INCORPORATES RISK UNCERTAINTY
  - MIN [CSL*R(Z)*PAR+C(Z)] OVER ALTERNATIVES , Z

  - …. FOR CSL= COST TO SAVE A LIFE, Z= CHOICE OF REMEDIAL ACTION, R = SOME M UPPER CONFIDENCE LEVEL ON RISK (95TH PERCENTILE), AND C = COST OF THE REMEDIAL ACTION
  - INCORPORATES RISK UNCERTAINTY OF AN UPPER CONFIDENCE LEVEL , NOT EXPECTED VALUE

THRESHOLD UNCERTAINTY ADJUSTED COST BENEFIT

- **MIN [CSL*Σ j R(Z)*PAR + C(Z)]**
  S.T *PROB* (R <= S) >= 1 - a
  - **.... WHERE , a , DEFINES THE MARGIN OF SAFETY AND S IS THE THRESHOLD DEFINING MAXIMUM ACCEPTABLE RISK**
- **THE IMPLICATION IS THAT THE OBJECTIVE FUNCTION WILL LEAD TO REMEDIATION EVEN WHEN THE CSL EXCEEDS VALUES GENERALLY ACCEPTABLE**

ASDSO/FEMA Specialty Workshop on
Risk Assessment for Dams

Session 3.1 – Quantitative Approaches – State of the Practice:

Life Loss Estimation

March 8, 2000

David S. Bowles
Utah State University and RAC Engineers & Economists

Life Loss Estimates needed for ...

- Evaluation of dams against risk criteria
- Assessment of life safety benefits (risk reductions) of risk reduction measures
  - effectiveness of emergency planning
- Estimates of cost effectiveness of life safety risk reduction for:
  - *justifying* fixes
  - *prioritising* fixes and investigations

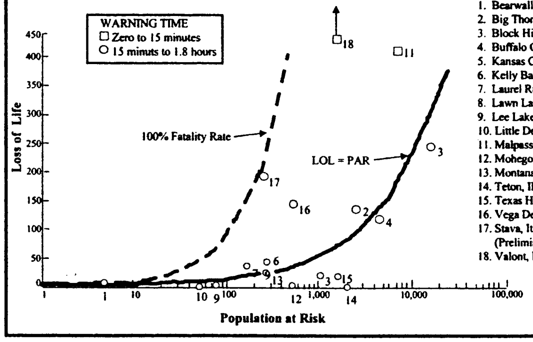
Existing Approaches

- Empirical
  - Brown-Graham (1988)
  - Dekay-McClelland (1993)
  - Site-specific uncertainty adaptation of D-M (USU-RAC 1998)
  - USBR/Graham (1999)
- Simulation
  - BC Hydro

Brown and Graham

- PAR < 25,000
- Low WT < 1.5 hours
  - $LOL = (PAR)^{0.6}$
- High WT > 1.5 hours
  - $LOL = 0.0002\ (PAR)$

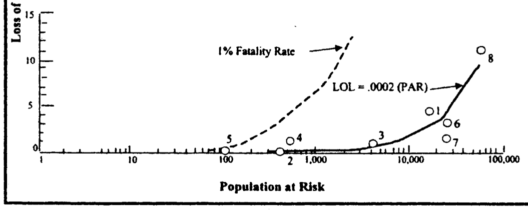
Loss of Life
- Low Warning and Zero Warning



Historic Cases
1. Bearwallow, NC
2. Big Thompson, CO
3. Block Hills, SD
4. Buffalo Creek, KY
5. Kansas City, MO
6. Kelly Barnes, CA
7. Laurel Run, PA
8. Lawn Lake, CO
9. Lee Lake, MA
10. Little Deer Creek, UT
11. Malpasset, France
12. Mohegon Park, CT
13. Montana
14. Teton, ID (Upper)
15. Texas Hill Country
16. Vega De Tera, Spain
17. Stava, Italy (Preliminary)
18. Valont, Italy

Loss of Life
- High Warning Cases

Historic Cases
1. Baldwin Hills, CA
2. Bushy Hill Pont, CT
3. Denver, CO
4. DWAD, UT
5. Kansas River, KS
6. Prospect Dam, CO
7. Northern New Jersey
8. Teton, ID (Lower)



Dekay and McClelland

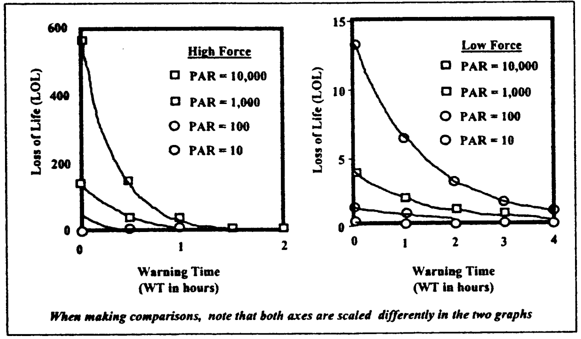
- **High Force (e.g. V*d > 4.5 ft²/sec)**

$$LOL = \frac{PAR}{1+13.277(PAR^{0.440})\exp(2.982(WT) - 3.790)}$$

- **Low Force (e.g. V*d < 4.5 ft²/sec)**

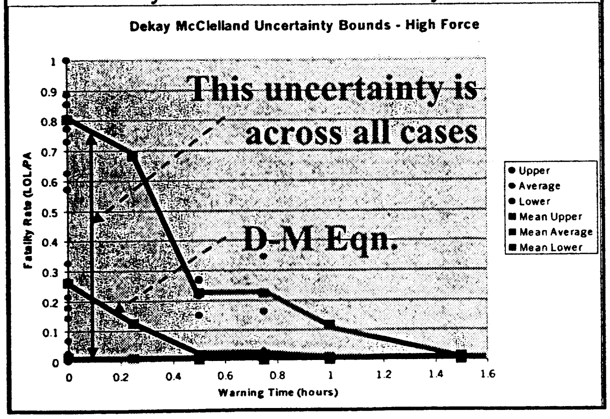
$$LOL = \frac{PAR}{1+13.277(PAR^{0.440})\exp(0.759(WT))}$$

Predicted LOL for High- and Low-Force Conditions over a Range of PARs



When making comparisons, note that both axes are scaled differently in the two graphs

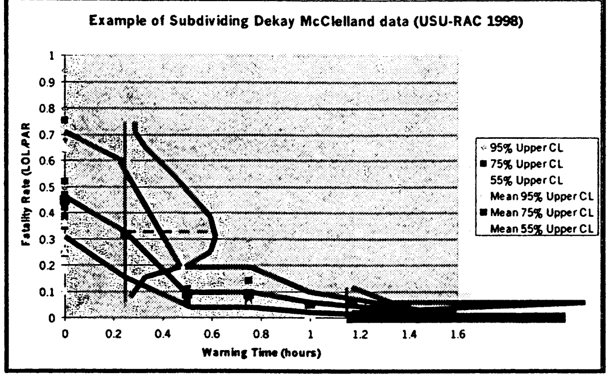
Dekay McClelland Uncertainty Bounds



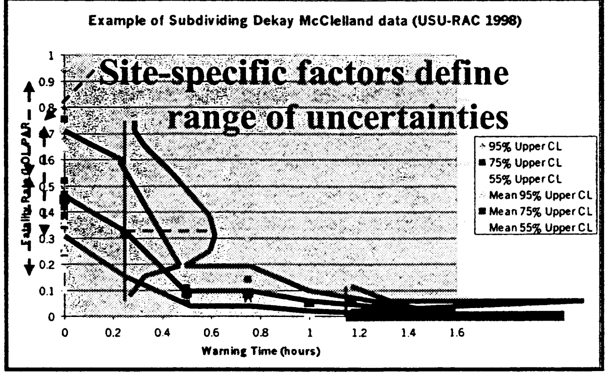
This uncertainty is across all cases

D-M Eqn.

Example of site-specific uncertainty (USU-RAC 1998)


Example of Subdividing Dekay McClelland data (USU-RAC 1998)

Example of site-specific uncertainty (USU-RAC 1998)

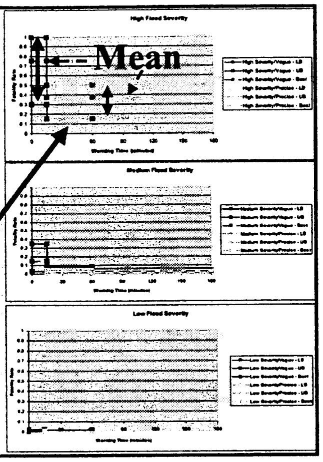

Example of Subdividing Dekay McClelland data (USU-RAC 1998)

Site-specific factors define range of uncertainties

USBR (Graham 1999) Fatality rate is a function of site-specific factors:

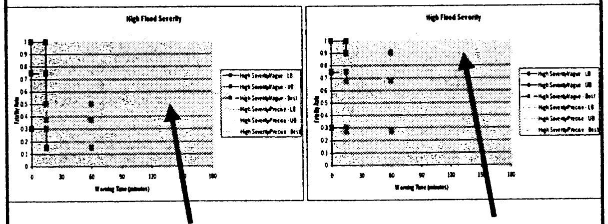
- Flood severity
  - damage to structures
  - low, medium, high
- Warning time
  - 0 - 15, 15 - 60, > 60 minutes
- Flood severity understanding
  - vague, precise

USBR (Graham 1999)
Fatality rate vs. Warning time:
High, Medium and Low Flood Severities



- 50% evacuation rate for high flood severity
- ***Vague understanding***
- ***Precise understanding***

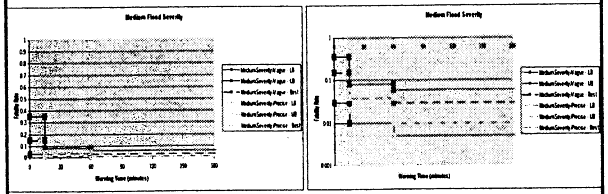
USBR (Graham 1999)
Fatality rate vs. Warning time
- <u>High</u> Flood Severity



- 50% evacuation rate
- 50% remaining PAR

10% evacuation rate
90% remaining PAR

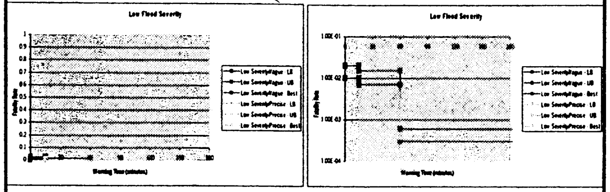
USBR (Graham 1999)
Fatality rate vs. Warning time
- <u>Medium</u> Flood Severity



- Arithmetic scale

Logarithmic scale

USBR (Graham 1999)
Fatality rate vs. Warning time
- <u>Low</u> Flood Severity



- Arithmetic scale

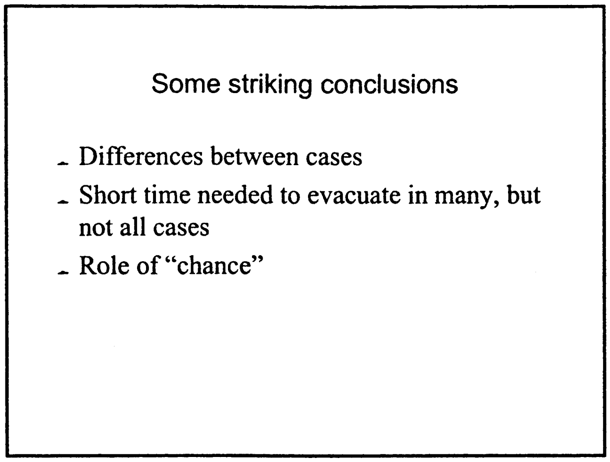
Logarithmic scale

Utah State University Life Loss Research Institute for Dam Safety Risk Management, (1998 - 2001)

- Sponsors:
  - USBR, Corps, ANCOLD, Victoria, Queensland
- Goal:
  - **development of a practical and improved life loss estimation approach for use in RA and emergency planning**

USU Project Approach/Status

- Phase 1:
  - 180 case historical flooding events collected
  - 163 homogeneous subPAR characterized from 38 events
  - exploratory data analysis
  - preliminary findings from characterization - ANCOLD 1999 paper
    - **NOT A MODEL YET!!!**
  - model formulation and validation
- Phase 2
  - software development with Corps HEC



Some striking conclusions

- Differences between cases
- Short time needed to evacuate in many, but not all cases
- Role of "chance"

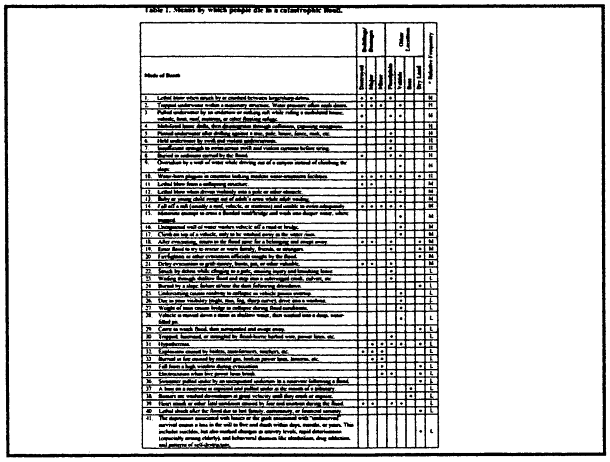


Table 1. Means by which people die in a catastrophic flood.

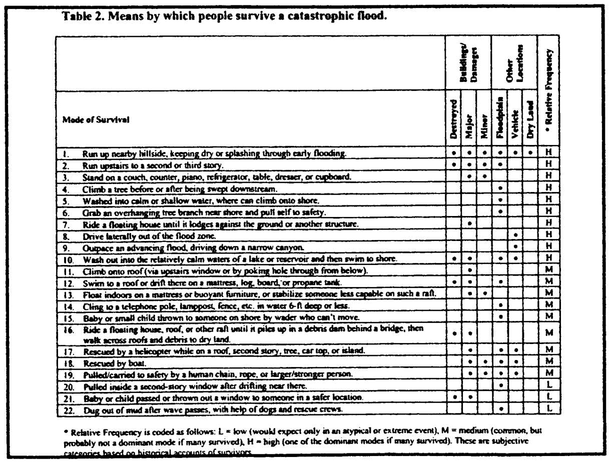


Table 2. Means by which people survive a catastrophic flood.

	Buildings/ Damages			Other Locations			
Mode of Survival	**Destroyed**	**Major**	**Minor**	**Floodplain**	**Vehicle**	**Dry Land**	*** Relative Frequency**
1. Run up nearby hillside, keeping dry or splashing through early flooding.	•	•	•	•	•	•	H
2. Run upstairs to a second or third story.	•	•	•	•			H
3. Stand on a couch, counter, piano, refrigerator, table, dresser, or cupboard.		•	•				H
4. Climb a tree before or after being swept downstream.				•			H
5. Washed into calm or shallow water, where can climb onto shore.				•			H
6. Grab an overhanging tree branch near shore and pull self to safety.				•			H
7. Ride a floating house until it lodges against the ground or another structure.		•					H
8. Drive laterally out of the flood zone.					•		H
9. Outpace an advancing flood, driving down a narrow canyon.					•		H
10. Wash out into the relatively calm waters of a lake or reservoir and then swim to shore.	•	•		•	•		H
11. Climb onto roof (via upstairs window or by poking hole through from below).		•					M
12. Swim to a roof or drift there on a mattress, log, board, or propane tank.	•	•		•			M
13. Float indoors on a mattress or buoyant furniture, or stabilize someone less capable on such a raft.		•	•				M
14. Cling to a telephone pole, lamppost, fence, etc. in water 6-ft deep or less.				•			M
15. Baby or small child thrown to someone on shore by wader who can't move.				•			M
16. Ride a floating house, roof, or other raft until it piles up in a debris dam behind a bridge, then walk across roofs and debris to dry land.	•	•					M
17. Rescued by a helicopter while on a roof, second story, tree, car top, or island.		•		•	•		M
18. Rescued by boat.		•	•	•	•		M
19. Pulled/carried to safety by a human chain, rope, or larger/stronger person.		•	•	•	•		M
20. Pulled inside a second-story window after drifting near there.				•			L
21. Baby or child passed or thrown out a window to someone in a safer location.	•	•					L
22. Dug out of mud after wave passes, with help of dogs and rescue crews.				•			L

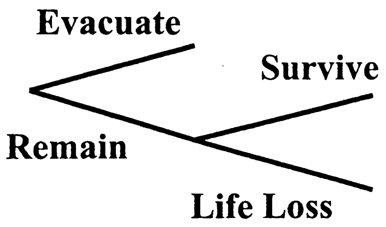
* Relative Frequency is coded as follows: L = low (would expect only in an atypical or extreme event), M = medium (common, but probably not a dominant mode if many survived), H = high (one of the dominant modes if many survived). These are subjective categories based on historical accounts of survivors.

CHARACTERISATION OVERVIEW

- Pieces of the Life Loss Puzzle
  - 100 *characterising* variables
  - NOT *predictive* variables for a model
  - grouped into 16 categories
- Homogeneous SubPar
  - (Par_i, $Tpar_i$, L_i, P_i, $Ptpar_i$, Pr(zone), HBU)

EVACUATION → LIFE LOSS

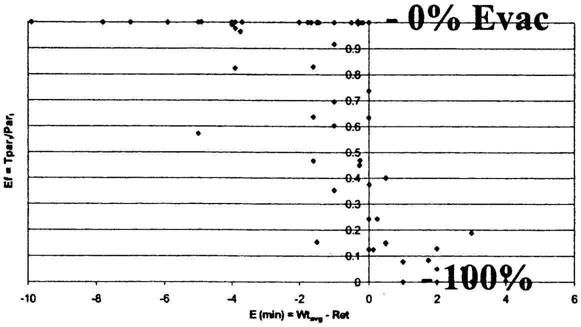
EVACUATION → LIFE LOSS



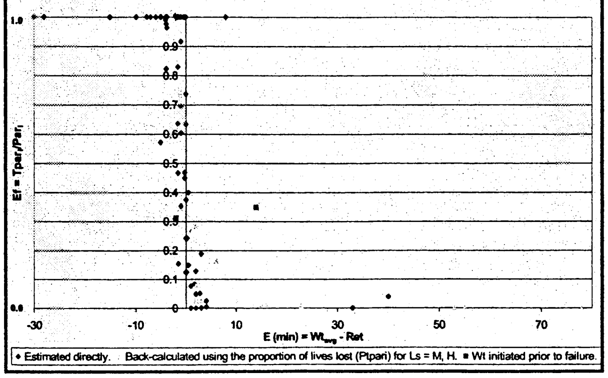
EVACUATION

- Failure Mode (Fm)
- Detectability (Det)
- Warning Times and Effectiveness (Wt, Wt_{avg}, Sc)
- Representative Evacuation Time (Ret)
- Excess Evacuation Time (E, Ef)

Evacuation Nonsuccess Factor (Ef) vs. Excess Evacuation Time (E) *(mins.)*



Evacuation Nonsuccess Factor (Ef) vs. Excess Evacuation Time (E) *(mins.)*



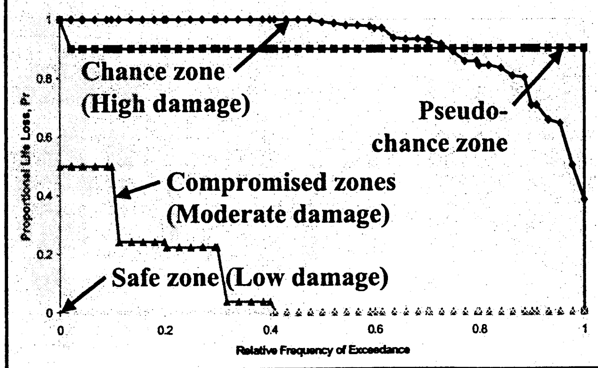
EXPOSURE TO LIFE LOSS

- Par Type and Evacuation Modes (Pt)
- Flood Dynamics
- Loss of Shelter (Ls = L, M, H)
- Havens (Sh, Ch, Psh, Ah, Coh)
- Flood Zones and Zone Densities (Sz, Cz, Pcz, Coz, Szd, Czd, Pczd, Cozd)

RATES OF LIFE LOSS

- Lethality Rates in Flood Zones (Lsz, Lcoz, Lpcz, Lcz; Prsz, Prcoz, Prpcz, Prcz)
- Lethality Rate Outside of Flood Zones
- Life-Saving Interventions (Rr)
- Complications or Aberrations
- Post-flood Psychological Trauma

Relative frequencies of proportion of lives lost in historic flood zones

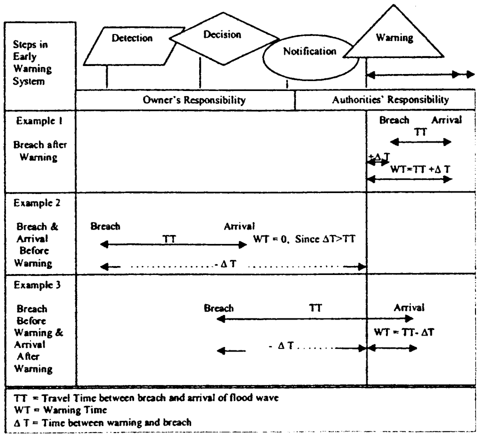


TOWARDS AN IMPROVED PREDICTIVE MODEL

- Consider different subPar's not global PAR
- Consider subPAR types separately
  - Motorists
- Formulated, calibrated and validated using case histories
- Include as many explanatory (predictive) variables as practical
  - use GIS for spatially distributed variables
  - linked to dynamic flood routing model
- Output: distribution of estimated life loss
  - accounting for intrinsic variability and
  - model simplifications

Populations at Risk (PAR)

- Location and centers
- Densities
- Special populations (institutionalized, cultural)
- Critical individual
- Future growth

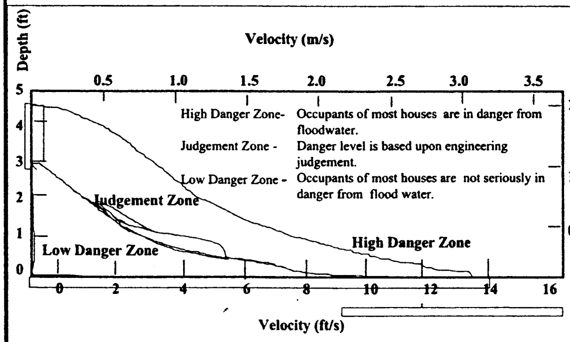


TT = Travel Time between breach and arrival of flood wave
WT = Warning Time
Δ T = Time between warning and breach

Warning Time Adjustments - Alamo Dam
WT = Adjustment + Travel Time

Load Type	Failure Mode	Week-day		Week-end	
		Day	Night	Day	Night
Blue Sky	Piping	4	2	3	2
	Slope Stability	4	2	3	2
	Earthquake	1	-1	-1	-1
Flood	Threshold Overtopping	6	6	6	6
	PMF/PMF+SPF Overtopping	6	6	6	6
	Toe Erosion	6	6	6	6
	Wave Action	0	0	0	0

Depth-Velocity Flood Danger Level Relationship for Adults



High Danger Zone- Occupants of most houses are in danger from floodwater.

Judgement Zone - Danger level is based upon engineering judgement.

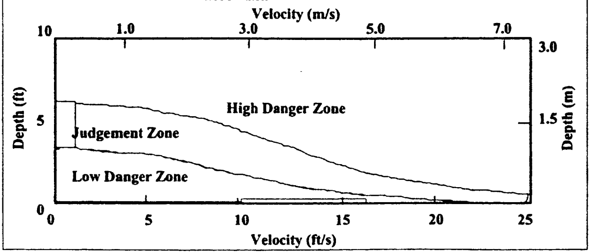
Low Danger Zone - Occupants of most houses are not seriously in danger from flood water.

Depth-Velocity Flood Danger Level Relationship for Houses Built on Foundations

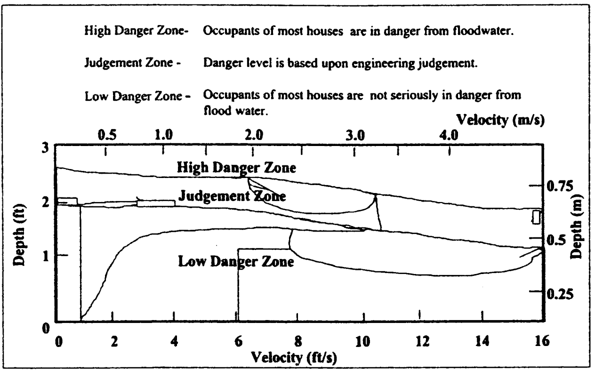
High Danger Zone- Occupants of most houses are in danger from floodwater.

Judgement Zone - Danger level is based upon engineering judgement.

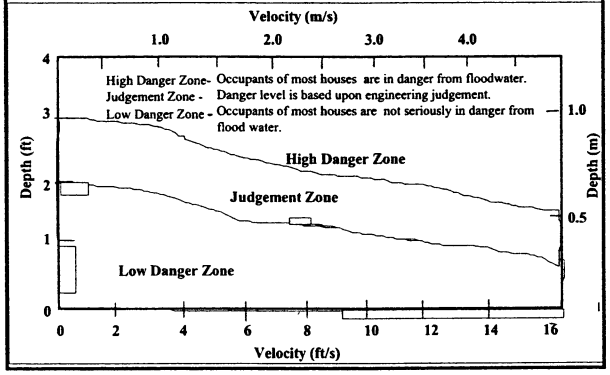
Low Danger Zone - Occupants of most houses are not seriously in danger from flood water.



Depth-Velocity Flood Danger Level Relationship for Mobile Homes

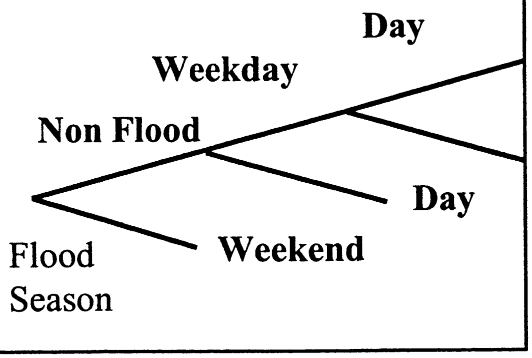


Depth-Velocity Flood Danger Level Relationship for Passenger Vehicles



Exposure factors:

- Day/night
- Seasonal/temporary locations
- Weekday/weekend - employment/school patterns



Day

Weekday

Non Flood

Day

Flood Season

Weekend

PAR Exposure Factors
An Example

Exposure Period	Duration (Hours)	Exposure Factors as Fraction of a Year		
		Flood Events	Sunny Day Events	
		Season 1 November - March	Season 1 November - March	Season 2 April - Octobe
Week Day	14	0.41667	0.17361	0.24306
Week Night	10	0.29762	0.12401	0.17361
Weekend Day	14	0.16667	0.06944	0.09722
Weekend Night	10	0.11905	0.04960	0.06944

Proceedings of the Australian Committee on Large Dams (ANCOLD) Annual Meeting, Jindabyne, New South Wales, Australia, November 1999

LIFE-LOSS ESTIMATION: WHAT CAN WE LEARN FROM CASE HISTORIES?

by Duane M. McClelland[1] and David S. Bowles[2]

ABSTRACT

There is a growing concern about the limitations of the approaches to life-loss estimation that are currently used in dam safety risk assessment. This paper summarises insights into factors that affect evacuation effectiveness, loss of life, and survival, based on a detailed review of historical dam breaks and other types of floods. The understanding and empirical characterisation of life loss dynamics being developed from these case histories are intended to provide the foundation for an improved practical life-loss estimation model.

BACKGROUND

In order to reduce risks of life loss associated with dams in the most effective and expeditious manner, life-loss estimates are needed in dam safety risk assessment for the following purposes:

- To evaluate the risks of existing dams against life safety risk criteria.
- To assess the life safety benefits (i.e. risk reductions) of structural and non-structural risk reduction measures.
- To estimate the cost effectiveness of life safety risk reduction as a means of justifying or prioritising such risk reduction measures.

In addition, an improved understanding of life loss dynamics associated with floods should be valuable for strengthening emergency management planning.

Research into life-loss estimation has been underway at Utah State University's Institute for Dam Safety Risk Management since early 1998 with funding from the U.S. Bureau of Reclamation (USBR), U.S. Army Corps of Engineers (USACE), and Utah State University (USU). The overall goal of our work is to develop an improved practical life-loss estimation model for use in dam safety risk assessment. The foundation for the new model will be historic life-loss dynamics captured through detailed characterisation of the events surrounding historic flood waves. This paper summarises our initial findings after reviewing the first group of case histories. The paper begins with an important statement to clarify that this paper is about case histories and not about proposing a new model. A summary of our overall approach and a conceptual overview of our work follow. The remainder of the paper is divided into sections on evacuation, exposure, and rates of life loss. We close with some brief thoughts on developing an improved life-loss model.

AN IMPORTANT STATEMENT:THIS IS NOT A MODEL

It is important for the reader to understand that we are not describing a new model in this paper; rather, we are describing what we have learnt from reviewing case histories. There is a danger that the reader will assume that the characterizing variables that we use to represent these case histories will become the predictive variables in the model that we are developing. This is not necessarily the case. Our goal is a practical model that will be realistic in terms of input data requirements, but we believe that such a model can only be developed once the details of the underlying life loss dynamics are better understood. We are seeking simplification in model structure based on empirical evidence and not presumption about the underlying processes that determine life loss.

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[1] Engineer, GEI Consultants and formerly Research Assistant, Utah State University.

[2] Professor of Civil and Environmental Engineering and Director, Institute for Dam Safety Risk Management, Utah State University; and Principal, RAC Engineers & Economists.

APPROACH

Phase 1 of our work is focusing on the collection and detailed review of case histories and development of a model to predict life-loss. In Phase 2 we plan to incorporate the model into computer software that will link it to inundation modelling and GIS databases. These will provide critical spatial, temporal, and structural inputs.

To date, we have identified about 180 flood events that have caused loss of life. Most of these involved failure of a dam, but some were dyke failures, flash floods, expansive floods, or other types of floods. The characterisation of each event entails dividing the population at risk (see below) into subpopulations at risk (subPar), assigning values to nearly 100 quantitative or categorical variables for each subPar, and documenting insights into life-loss dynamics. So far, 38 events have been characterised, yielding 163 non-overlapping subPar, including many cases for which life loss was zero.

We have begun exploratory data analysis on the first group of case histories to identify those characterising variables that may be useful as prediction variables for estimating the fraction of people that evacuate and the proportion of lives lost in the fraction of people that fail to evacuate. Additional case histories are being collected and added to those that have not yet been characterised. This second group will be characterised with special focus on those areas that are identified as being important for model development. The model will be formulated and tested based on the results obtained from additional analyses, and guidance will be developed for the estimation of prediction variables.

CONCEPTUAL OVERVIEW

Pieces of the Life Loss Puzzle

Deaths have historically occurred in the overlapping contexts presented in Table 1. People have survived catastrophic floods through the means presented in Table 2. To develop a realistic model for calculating how many people are likely to perish or survive, it is helpful to understand the many pieces to the life-loss puzzle. Just as one might sort puzzle pieces by shape or color, the life-loss pieces can generally be placed within one of 16 categories. While there is not space here to piece the entire puzzle together, the most prominent pieces within each category are summarized in this section.

Homogeneity of SubPar (Par_i, $Tpar_i$, L_i, P_i, $Ptpar_i$, Pr(zone), HBU)[3]

Population at risk (Par) quantifies the number of people who, without evacuating, would remain within those regions of the flood's imprint that exceed some minimum criteria of depth and velocity. SubPar (Par_i) are any subsets of Par. The threatened population (Tpar) quantifies members of Par that remain in the flood zone when flooding exceeds the aforementioned minimum criteria of depth and velocity.

For descriptive or predictive purposes, it would be of questionable value to derive a statistical function or distribution from a small set of Par that are heterogeneous with respect to a very large number of interdependent variables. Homogeneous subPar provide the means by which this problem can be overcome. Not only do Par_i greatly increase the number of data points that can be analyzed, but if they are thoroughly characterized, they can be grouped into bins according to statistical populations.

If subPar are truly homogeneous in every respect, they are called homogeneous base units (HBU). HBUs are an ideal construct which can only be approximated, but which are useful for descriptive purposes. They are analogous to subatomic particles. Protons, neutrons, and electrons fall into three separate populations, but within a population, they are consistent across substances, no matter how different those substances appear on a macroscale. In the same way, HBUs have predictable life loss distributions, with variance governed largely by chance, but a small number of HBUs can be aggregated in numerous ways to create any historic, future, or hypothetical flood event.

---

[3] Par, and many other variables, are singular or plural based on context.

Table 1. Means by which people die in a catastrophic flood.

	Buildings/ Damages			Other Locations				* Relative Frequency
Mode of Death	**Destroyed**	**Major**	**Minor**	**Floodplain**	**Vehicle**	**Boat**	**Dry Land**	
1. Lethal blow when struck by or crushed between large/sharp debris.	•	•		•				H
2. Trapped underwater within a stationary structure. Water pressure often seals doors.	•	•	•		•			H
3. Pulled underwater by an undertow or sinking raft while riding a mobilized house, vehicle, boat, roof, mattress, or other floating refuge.	•			•	•			H
4. Mobilized home drifts, then disintegrates through collisions, exposing occupants.	•							H
5. Pinned underwater after drifting against a tree, pole, house, fence, rock, etc.				•				H
6. Held underwater by swift and violent undercurrents.				•				H
7. Insufficient strength to swim across swift and violent currents before tiring.				•				H
8. Buried in sediment carried by the flood.	•			•	•			H
9. Overtaken by a wall of water while driving out of a canyon instead of climbing the slope.					•			H
10. Water-born plagues in countries lacking modern water-treatment facilities.	•	•	•	•	•		•	H
11. Lethal blow from a collapsing structure.	•	•						M
12. Lethal blow when driven violently into a pole or other obstacle.				•	•			M
13. Baby or young child swept out of adult's arms while adult wading.								M
14. Fall off a raft (usually a roof, vehicle, or mattress) and unable to swim adequately.	•	•	•	•	•			M
15. Motorists attempt to cross a flooded road/bridge and wash into deeper water, where trapped.					•			M
16. Unexpected wall of water washes vehicle off a road or bridge.					•			M
17. Climb on top of a vehicle, only to be washed away as the water rises.					•			M
18. After evacuating, return to the flood zone for a belonging and swept away.	•	•		•			•	M
19. Enter flood to try to rescue or warn family, friends, or strangers.				•			•	M
20. Firefighters or other evacuation officials caught by the flood.							•	M
21. Delay evacuation to grab money, boots, pet, or other valuable.	•	•		•				M
22. Struck by debris while clinging to a pole, causing injury and knocking loose.				•				L
23. Wading through shallow flood and step into a submerged creek, culvert, etc.				•				L
24. Buried by a slope failure at/near the dam following drawdown.							•	L
25. Undercutting causes roadway to collapse as vehicle passes overtop.					•			L
26. Due to poor visibility (night, rain, fog, sharp curve), drive into a washout.					•			L
27. Weight of train causes bridge to collapse during flood conditions.					•			L
28. Vehicle is moved down a street in shallow water, then washed into a deep, water-filled pit.					•			L
29. Come to watch flood, then surrounded and swept away.							•	L
30. Trapped, lacerated, or strangled by flood-borne barbed wire, power lines, etc.				•				L
31. Hypothermia.		•	•	•	•		•	L
32. Explosions caused by boilers, transformers, smelters, etc.	•	•	•					L
33. Burned in fire caused by natural gas, broken power lines, lanterns, etc.		•	•					L
34. Fall from a high window during evacuation.			•				•	L
35. Electrocution when live power lines break.			•	•			•	L
36. Swimmer pulled under by an unexpected undertow in a reservoir following a flood.							•	L
37. A boat on a reservoir is capsized and pulled under at the mouth of a tributary.						•		L
38. Boaters are washed downstream at great velocity until they crash or capsize.						•		L
39. Heart attack or other fatal condition caused by fear and exertion during the flood.	•	•		•	•			L
40. Lethal shock after the flood due to lost family, community, or financial security.							•	L
41. The depression associated with losses or the guilt associated with "undeserved" survival causes a loss in the will to live and death within days, months, or years. This includes suicides, but also marked changes in activity levels, rapid deterioration (especially among elderly), and behavioral diseases like alcoholism, drug addiction, and patterns of self-destruction.							•	L

* Relative Frequency is coded as follows: L = low (would expect only in an atypical or extreme event), M = medium (common, but probably not a dominant mode if many died), H = high (one of the dominant modes if many died). These are subjective categories based on historical accounts of fatalities.

Table 2. Means by which people survive a catastrophic flood.

	Buildings/ Damages			Other Locations			* Relative Frequency
Mode of Survival	**Destroyed**	**Major**	**Minor**	**Floodplain**	**Vehicle**	**Dry Land**	
1. Run up nearby hillside, keeping dry or splashing through early flooding.	•	•	•	•	•	•	H
2. Run upstairs to a second or third story.	•	•	•	•			H
3. Stand on a couch, counter, piano, refrigerator, table, dresser, or cupboard.		•	•				H
4. Climb a tree before or after being swept downstream.				•			H
5. Washed into calm or shallow water, where can climb onto shore.				•			H
6. Grab an overhanging tree branch near shore and pull self to safety.				•			H
7. Ride a floating house until it lodges against the ground or another structure.		•					H
8. Drive laterally out of the flood zone.					•		H
9. Outpace an advancing flood, driving down a narrow canyon.					•		H
10. Wash out into the relatively calm waters of a lake or reservoir and then swim to shore.	•	•		•	•		H
11. Climb onto roof (via upstairs window or by poking hole through from below).		•					M
12. Swim to a roof or drift there on a mattress, log, board, or propane tank.	•	•		•			M
13. Float indoors on a mattress or buoyant furniture, or stabilize someone less capable on such a raft.		•	•				M
14. Cling to a telephone pole, lamppost, fence, etc. in water 6-ft deep or less.				•			M
15. Baby or small child thrown to someone on shore by wader who can't move.				•			M
16. Ride a floating house, roof, or other raft until it piles up in a debris dam behind a bridge, then walk across roofs and debris to dry land.	•	•					M
17. Rescued by a helicopter while on a roof, second story, tree, car top, or island.		•		•	•		M
18. Rescued by boat.		•	•	•	•		M
19. Pulled/carried to safety by a human chain, rope, or larger/stronger person.		•	•	•	•		M
20. Pulled inside a second-story window after drifting near there.				•			L
21. Baby or child passed or thrown out a window to someone in a safer location.	•	•					L
22. Dug out of mud after wave passes, with help of dogs and rescue crews.				•			L

* Relative Frequency is coded as follows: L = low (would expect only in an atypical or extreme event), M = medium (common, but probably not a dominant mode if many survived), H = high (one of the dominant modes if many survived). These are subjective categories based on historical accounts of survivors.

To explore how an analyst might approximate an HBU, it is helpful to present a few preliminary definitions. *Par type* (Pt) refers to the unique physical *environment* surrounding members of a subPar. For example, the environment surrounding waders is typically the river, the open floodplain, and trees while the environment surrounding residents is characterized by houses and streets. *Excess evacuation time* (E) is the difference between two averages: the *average warning time* (Wt_{avg}) minus the *representative evacuation time* (Ret). Wt_{avg} is the average value of the *individual warning time* (Wt_i)—the time an individual has to evacuate after becoming aware of an approaching flood and before the flood arrives. Ret is the average time each person requires to clear the flood imprint associated with Par. Although one could refer to the flood imprint as the flood zone, the term *flood zone* carries a different technical meaning. Flood zones are spatially discontinuous regions in the flood that have similar exposure characteristics and hence similar proportional life loss distributions. *Life loss* (L) refers to the number of fatalities that are directly or indirectly caused by the flood in question. Drowning would be a direct cause while a heart attack due to grief would be an indirect cause. The *proportional life loss* is the fraction of lives lost: (lives lost)/(population present). It can be defined as the *proportion of Par* (P = L/Par), the *proportion of Tpar* (Ptpar = L/Tpar), or the proportion of their subdivisions. With respect to flood zones, Pr(zone) is the proportion of lives lost within the specified zone.

Analysts can approximate HBUs by noting the following: 1) isolating Par_i by location promotes homogeneity on all levels, 2) distinguishing Par_i by Par type minimizes differences in the physical environment, 3) distinguishing Par_i by magnitude of E and reducing Par_i to $Tpar_i$ minimizes differences in temporal-spatial dynamics. At the level of $Tpar_i$, an analyst can approximate HBUs by identifying flood zones. It is important that these zones are three-dimensional, since, in terms of proportional life loss, the HBU on the second or third story of a building might be the same HBU as shallow flooding near shore.

Detailed historical research is critical to verify that a given flood zone truly does approximate an HBU. It also provides important insights into how to divide a Par into homogeneous Par_i, how to quantify E and use it to reduce Par_i to $Tpar_i$, and how to approximate the life-loss distributions that characterize each flood zone. Relevant insights are presented in the sections that follow.

EVACUATION

Failure Mode (Fm)

The following broad causes of dam failures have all lead to deaths: high water, internal weaknesses, gates that are quickly opened, slope failure following drawdown, displacement of the reservoir by an upstream landslide, and sabotage or war-time bombing. Although an earthquake-induced failure is often considered to be the greatest hazard, there are currently no well-documented examples of flood-related life loss following an earthquake.

The cause of a failure affects life loss only in-so-far as it affects the detection time and thus the warning time, the local conditions that govern evacuation dynamics, the size and nature of the population at risk (thunderstorms follow diurnal and season patterns), and the hydraulic characteristics of the flood. The exception is slope failures, which can kill without water.

Detectability (Det)

When a safety concern has been detected, there has often been a reluctance to issue a warning until failure is imminent or has been confirmed. For example, during the Allegheny County flash flood[4], weather radar operators dismissed radar readings as false anomalies. Prior to the Buffalo Creek dam failure and the failure of Canyon Lake Dam in the Black Hills, company or civic officials actively tried to prevent public warnings. Following the Mill River dam failure, the owner delayed warning dissemination by arguing with an eyewitness over which part of the dam had failed.

Warning Times and Effectiveness (Wt, Wt_{avg}, Sc)

The initial warning time (Wt), whether restricted to official sources or defined to include any human source, captures nothing about the percentage of people warned, the urgency or effectiveness of the warning, the rate of warning propagation, the variety of times available for evacuation, or the time needed to evacuate. As such, it is informative regarding the response rate of officials, but it provides little information about evacuation. As an extreme example, Wt for the Bangladesh storm surge of 1970 was 3 days, but dissemination of the warning was poor and 225,000 people died. The conclusion is that Wt is not a normalized variable and has limited use when comparing separate events.

A more useful measure of warning dynamics is the average warning time over a subPar. Wt_{avg} is the average individual warning time (Wt_i) and includes all sources of information, human and environmental, formal and informal. Sources include sensory clues, telephone calls, honking motorists who shout warnings, shouts from fleeing neighbors, family or friends who stop by, the radio, the TV, CB radios, officials who use bullhorns or knock on doors, and self-appointed Paul Reveres.

It should be recognized that wired telephone service and power are quickly lost in virtually every catastrophic flood, so widespread warnings using mass media or telephone lines are usually possible only when they precede a failure or when a community is not near the dam. Since wireless communication is one of the fastest growing segments of the economy, cell phones and internet-enabled devices may provide new, rapid means of last-minute warning dissemination.

The average warning time provided by sensory clues (Sc, in minutes) has often made it possible for the majority of people to evacuate when a flood inundation area is narrow. Sources of visible clues have included a wall of water, piled high with debris and houses; a debris-filled, fast-rising flood that precedes a

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[4] See Appendix A for a list of flood events cited in the text. These are only a few of the approximately 180 events that we have reviewed.

wall of water; power lines that swing violently from upstream disturbances; railroad tracks that snake violently; neighbors who move vehicles to high ground or congregate on the hillside; pets that become agitated; and power failures.

Auditory clues can carry several miles. They originate from tumbling waves that roar like thunder; trees and telephone poles that snap in two; logs, trees, and boulders that bounce off a canyon's walls; houses that collide and explode in a shower of splintered boards; a creek that rises with a crescendo; exploding power stations or transformers; severed power lines that buzz; motorists that honk their horns while racing by; and dead phone lines.

Heavy rain, hail, and strong winds can drive people indoors and mask sensory clues. Such was the case during the Eldorado Canyon flash flood and following the Mill River dam failure. Sensory clues can also be muted when a flood rises very quickly rather than crashing downstream as a wall. When this occurs at night, a flood can surround a house without advance detection. This was common during the Dale Dyke Dam failure and the Black Hills flash floods.

It is helpful to visualize how informal warnings propagate. In a long, narrow river valley, when a wall of water progresses slower than people can drive, there will typically be motorists or residents who detect the flood through sensory clues and who flee downstream in an automobile. If they can gain distance, these motorists may stop along the way to warn residents or to pick up family and friends. At the least, they will typically turn on their lights, honk their horns, and possibly shout quick warnings out their windows. Such warnings do not always communicate the approaching danger effectively, but they generate curiosity that alerts other residents to sensory clues or alternate forms of warning. This allows many to run up a nearby hillside or to evacuate by automobile. Such actions generate a chain reaction as more vehicles evacuate, people warn their neighbors, and people notice the swarm of unusual activity outside their windows. This contagious process can mobilize the better part of a community, saving countless lives, even in the absence of warnings by public officials. However, it is by nature fairly random, so if many houses are rapidly destroyed, chances are high that at least some people will remain ignorant of the approaching danger and fall victim to the flood. People recounting the Buffalo Creek dam failure provide excellent insights into this process as it worked itself out over 15 miles (Deitz and Mowery, 1992).

Although Wt_{avg} captures many characteristics of a warning, it does not characterize those with the shortest Wt_i. The significance of this grows when subPar are heterogeneous. Those who are hardest to reach include motorists and people in isolated campsites, who may also be the most vulnerable. The inability of officials to warn campers contributed significantly to life loss during the Black Hills flash floods. Despite widespread warnings, motorists perished on 6 different creeks during the Austin, Texas, flash floods.

Another limitation to Wt_{avg} is that it does not characterize a warning's urgency, credibility, or the extent to which those delivering the warning seek to ensure or enforce an evacuation.. When warnings precede a failure and thus reflect only the possibility of a flood, large segments of a population may postpone evacuation to "wait and see." Rumors of an impending failure were rampant prior to the failure at Buffalo Creek, but many people reported that they ignored these warnings as the next link in a chain of false alarms. State police attempted to enforce an evacuation around Vaiont Lake, Italy, for 30 hours, but enough people slipped back through the patrols that 158 people died when the mountainside slipped and generated a huge wave. Sixty people died in buildings above the dam itself, many of whom were monitoring the slope movement and had provided the evidence on which the evacuation was based. Downstream, nearly 2,000 people died. A few areas received advance warnings, but the warnings did not indicate the magnitude of the ensuing event and they were not widely disseminated. These miscalculations indicate that warnings may be narrowly targeted and that the areas that should be evacuated may not be correctly assessed. When the worst flooding in memory has posed little threat to life, even a confirmed flood wave can be treated lightly. There was evidence of this as people awaited the Big Thompson flash flood, the Eldorado Canyon flash flood, the Rapid Creek flash flood, and the flood waves from failure of the Buffalo Creek and Mill River dams. Overall, the likelihood that people will evacuate increases with the number of warnings they receive and the number of different sources from which they receive them. The least effective form of warning appear to have been National Weather Service announcements in the form of a "crawl" at the bottom of the TV screen.

Representative Evacuation Time (Ret)

When a flood is not more than 1000 ft wide, most houses have a back door within 300 ft of safety. If the danger is clearly understood, it generally takes 0.5-3 min for a family to evacuate during the day, and 1-6 min at night, depending on how many people must be gathered, how quickly they expect the flood to arrive, how extreme the weather is outside, and whether they linger to get dressed, grab possessions, or warn neighbors. If the warning is slow to register, these ranges must be extended. The representative evacuation times (Ret) are on the order of 1-2 min during the day and 2-4 min at night. During the day, a wall of water can provide a Wt_{avg} of 1-4 min based on sensory clues, explaining why some very destructive floods have killed a small percentage of Par when Wt = 0 min (i.e., the Shadyside and Eldorado Canyon flash floods).

When E is large, people may delay evacuation to put their households in order. When E is short, however, people generally warn those immediately around them and take the quickest route to safety. There are, however, important exceptions. People often slow their evacuation to help others—a spouse, children, aged parents, a disabled relative, neighbors, and even strangers. This, combined with the fact that members of households generally receive a warning about the same time, often results in families evacuating together or perishing together. A small fraction of people will delay or turn back to grab a purse or wallet, pair of boots, coat, clean clothes for a child, or some other item of relatively minor importance. People also delay to grab a pet or to release livestock. Many working spouses died following the Mill River dam failure because, rather than evacuating the mills to safety, they tried to reach their families at home and were swept away.

There can be structural or topographic barriers to evacuation. Following the failure of the Austin Bayless Pulp & Paper Company Dam, elderly adults threw children over fences, but were themselves swept away. Following the Kelly Barnes Dam failure, one person nearly waded to safety, only to disappear when he stepped into a submerged creek.

While rare, evacuees can also panic. During the Buffalo Creek failure, one woman stood numbly in her tracks while others called to her. During the Dale Dyke failure, a man suffered fatal injuries after leaping from a second-story window into water so shallow it was nothing but mud. During the Kelly Barnes failure, one family ran parallel to the creek, never thinking to run laterally up the mountain. During the Mill River failure, groups of panicked workers ignored the safe hillside just behind them and chose to cross a bridge to try and reach the other side.

Evacuation by automobile deserves special consideration. People often choose to use vehicles when it would be safer, a shorter distance, and quicker to run up a hillside. There are several reasons for this. First, a vehicle has great monetary value, so there is a desire to remove the vehicle from the flood zone. This desire is most apparent when people risk their lives to drive a car a few hundred feet to safety, or when they refuse to abandon a stalled vehicle while it is still safe to wade. Second, a vehicle is associated with speed, which is desirable during an evacuation. Third, a vehicle provides a means by which a family can reach food and shelter once their house is flooded. Fourth, many people are conditioned by habit to drive rather than to run. Fifth, a vehicle helps transport those with limited mobility.

Excess Evacuation Time (E, Ef)

In its simplest form, $E = Wt_{avg} - Ret$. Wt, Wt_{avg}, and Sc say something about the time available for evacuation and Ret describes the time needed to evacuate, but only E relates the two. As such, E helps normalize the evacuation dynamics across events with different warning times and evacuation requirements.

Ef is the evacuation nonsuccess factor, equal to $Tpar_i/Par_i$. Values of E from 113 historic subPar for which $Tpar_i$ was known, or could be reasonably estimated, were plotted against Ef. The central portion of the graph is shown in Figure 1a and the entire plot is shown in Figure 1b.

The triangular symbols in Figure 1b were back calculated from an additional 14 subPar using average values from distributions like those in Figure 2. In this case, since Ls was known, the distributions reflected the proportion of lives lost when Ls = M and when Ls = H. Although merely suggestive, these extra data points add credence to the general trend evident among smaller values for E. Not shown in Figure 1b are points at (E = -1380, Ef = 1) and (E = 352.5 and Ef = 0). The rectangular symbols indicate that the first warning was initiated prior to failure.

Figures 1a and 1b indicate that for negative values of E, Ef asymptotically approaches 1.0, and for positive values of E, Ef asymptotically approaches zero. Intuitively one would expect this, but the empirical data also provide a way to estimate the variability in Ef at different values of E. The skewness in this distribution shifts from positive to negative as E changes from negative to positive values. It is clear that any prediction of life loss that intends to capture real-world evacuation dynamics needs to incorporate this intrinsic variability.

E says a great deal about the likely size of Tpar$_i$, but it says nothing about the ability of people to reach a safe zone within the flood imprint or to evacuate after the flood arrives.

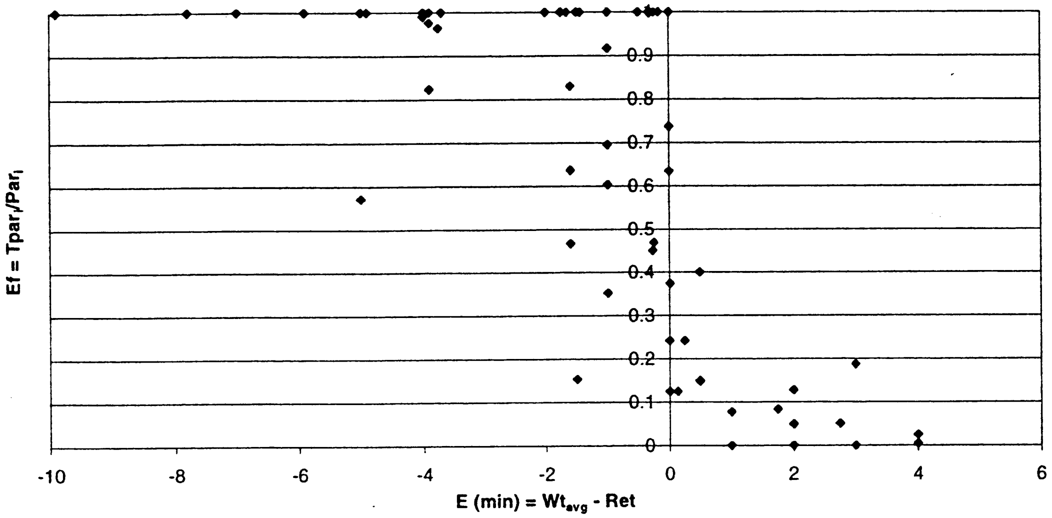

Figure 1a. Scatter plot of the excess evacuation time (E) vs. the evacuation nonsuccess factor (Ef) when absolute value of E is small.

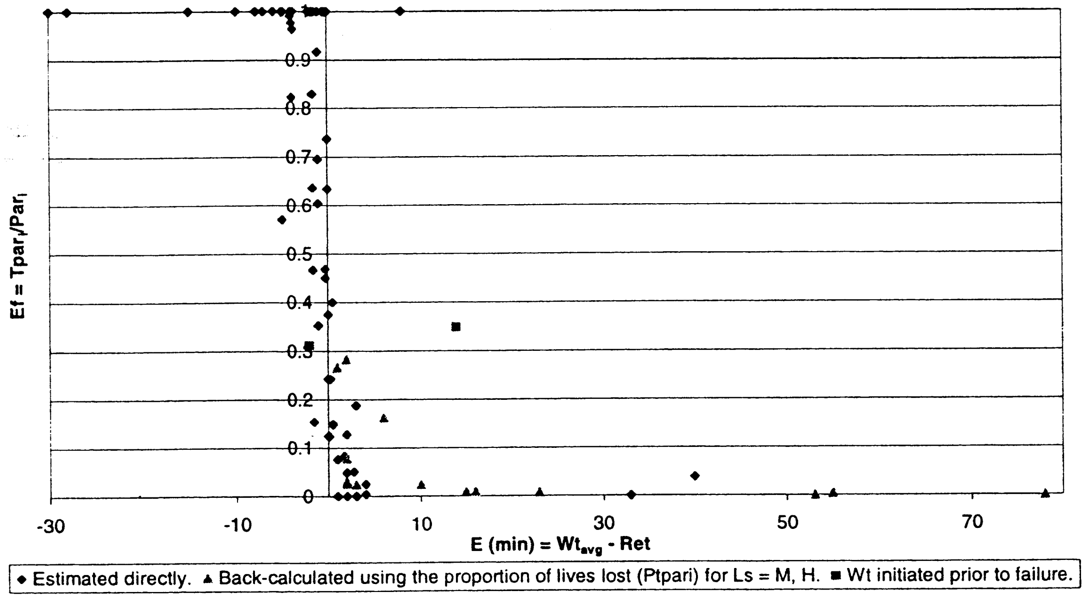

Figure 1b. Scatter plot of the excess evacuation time (E) vs. the evacuation nonsuccess factor (Ef). Where indicated, values were back-calculated using average values from a distribution like that in Figure 2, only based on Ls instead of flood zones.

EXPOSURE

Par Type and Evacuation Modes (Pt)

Wt_{avg}, Ret, E, and thus Ef all vary depending on the environment in which people are located. This environment also has a profound impact on the flood dynamics to which members of $Tpar_i$ will be exposed. Distinct environments define the most common Par types (Pt): campers and recreationists near the river (C), waders and swimmers in the river (W), boaters on the river (B), recreationists on a lake (L), motorists (Af), train passengers (T), and those in or near buildings (D)[5].

Temporal considerations are especially relevant to quantifying each type of subPar. Whether people are at work, in school, commuting, at home, or asleep; and whether or not it is a tourist season; profoundly influences the quantification of each type of subPar. Weather conditions are also very important.

Flood Dynamics

Catastrophic floods are violently turbulent, making swimming difficult or impossible. Most frequently, people die because they are tossed about or pinned underwater, struck by debris, driven into a stationary object, or buried in sediment (Table 1).

If people know how to swim, velocity is the killer and depth is the accomplice. For example, 58% of the campers died when 3 ft of water raced across the Arás alluvial fan (Gutiérrez et al. 1998), but those who washed into the deep, calm waters of Lake Mohave below Eldorado Canyon remarked on how easy it was to swim to shore (National Park Service file; see note in References). Depth of the flood wave is principally important as it contributes to turning moment and traps people underwater by crashing down on them.

A large debris load characterizes catastrophic floods, consisting of earth, rocks, forest litter, felled trees, telephone poles, roofs and boards from shattered buildings, floating homes, vehicles, barbed wire, fences, propane tanks, railroad cars, railroad ties, furniture, and other objects. The leading edge of the Eldorado Canyon flash flood resembled freshly mixed concrete (Glancy and Harmsen 1975). The Mill River Dam failure was typical of a wall of water passing through forests and communities:

> *A great mass of brush, trees, and trash was rolling rapidly toward me. I have tried many times to describe how this appeared; perhaps the best simile is that of hay rolling over and over as a hayrake moves along the field, only this roll seemed twenty feet high, and the spears of grass in the hayrake enlarged to limbs and trunks of trees mixed with boards and timbers; at this time I saw no water. (Sharpe 1995, p. 97, recording a quote from a young boy)*

If the flood is not slow rising and it passes through a canyon or narrow valley, debris tends to concentrate at the leading edge of the flood, slowing the wave and causing it to pile up as a wall behind a loose, mobile debris dam. This wall will tend to ride a winding canyon like a bobsled, sloshing up one side and then another. Superelevation differences of 10-20 ft have been observed, representing roughly 30% - 80% of the flood's peak depth. Because a wave must generally be slowed to pile up into a wall of water and debris, such a wall may sweep a fast-rising, debris-filled flood before it as the mobile wall leaks and sections break away to travel more rapidly. This can provide an important sensory clue, giving residents precious seconds or minutes to wade to safety.

Related to this, floods often rise in progressive surges. This contributes to survival by prolonging the time over which people can struggle toward a haven, but it contributes to fatalities when unexpected waves topple waders and those on rooftops into the flood.

Debris dams tend to form behind bridges, reversing attenuation and causing a wave to rise in height. If the bridge or debris dam fails suddenly, the renewed wall of water will be higher and the peak flow rate will be greater than if the temporary dam had not formed. As debris dams form and fail, a flood wave can be

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[5] Af and D were symbols derived from another category called fatality type (Ft). In that context, Af stands for automotive fatalities and D stands for general drowning deaths in town.

slowed and renewed over and over as it moves through many miles of canyon or narrow valley, as was the case in the Buffalo Creek flood.

Debris can kill by piercing, crushing, or toppling people, but it can also save lives by providing a floatation aid. If they are not destroyed, homes can become mobilized rafts. Many people were seen walking to shore across the debris dams that formed at bridges along Buffalo Creek after their houses lodged in the mass. As for the sediment load, it increases the density of a flood, and generally its momentum. Combined, this makes people and buildings more buoyant and easier to topple than if they were located in clear water with the same depth and velocity.

Given identical volumes and no warning, an expansive flood is safer than a narrow flood because slopes diminish, velocities and depths drop, walls of water collapse, each successive row of houses buffers the next row, and structural damages reduce, leaving behind more havens.

Loss of Shelter (Ls = L, M, H)

Unless an occupant is trapped underwater or a structure is destroyed, a building offers shelter from a flood. The degree of shelter depends on the structural damage that occurs and the elevation of the top accessible level in relation to the peak flood level. *Loss of shelter* (Ls) seeks to describe the extent to which shelter is lost within a building and is distinct from economic damages and other traditional damage categories.

Ls depends, in part, on the concept of havens, presented below. When Ls is Low (L), it implies relatively safe havens on every floor. When Ls is major (M), it implies the loss of a safe haven on the first floor. When Ls is high (H), it implies complete loss of all reliable havens because the building has been submerged or destroyed. A building that drifts a few hundred feet and comes to rest without sinking or disintegrating has major loss of shelter since some level of shelter remains.

Historic accounts by survivors suggest more detailed distinctions, but there is space to present only one. Almost every room in a home has a counter, desk, couch, table, chair, bookcase, bed, dresser, piano, or other piece of furniture that can provide an elevated platform or a floatation device during a flood. When a flood is relatively quiescent, with few exceptions, these objects and a little swimming allow people to keep their heads above the water surface even when the flood nears the ceiling. While elevated ceilings pose a special problem, a flood reaching such depths without causing major damage is necessarily very calm, making it easier to cling to floating furniture, tread water, or hang onto roof rafters. The Dale Dyke failure provides several examples of people who survived these conditions, but no examples of fatalities under such conditions have been found so far in our work. Thus, Ls = L when there is minor structural damage and the flood does not encroach within headroom—say a foot of the first-floor ceiling. This form of shelter would obviously be compromised if the peak depths lasted more than 20-30 min or if the water was very cold, and survival would depend on the age and mobility of a room's occupants.

Havens (Sh, Ch, Psh, Ah, Coh)

When E is small or negative, members of $Tpar_i$ can still survive a flood if they reach some form of haven. Four categories of havens can be identified: safe havens (Sh), pseudo-safe havens (Psh), aerated havens (Ah), and chance havens (Ch). Compromised havens (Ch) are the combined total of Psh and Ah because the shelter has been compromised in both cases. Havens are informed by Ls, but they transcend Ls and buildings.

Levels of flood exposure for which historic rates of life loss approach zero characterize a safe haven. Examples include the first floor when Ls = L, upper stories with quiescent flooding characteristic of Ls = L; flooding with higher velocities that have insufficient depths to sweep people out of windows, doors, or holes in the wall (i.e., flood depths less than about 3 ft above the floor); accessible rooftops and attics, calm or shallow waters in which people can wade, sturdy treetops that are easy to reach and sit in for hours, and hillsides after the flood arrives.

Pseudo-safe havens begin as safe havens but become mobile. They only exist among a subset of buildings with major damage (Ls = M). When a house drifts more than a short distance, most occupants die because the house either sinks or breaks apart. As such, Psh are limited to buildings that float only a few feet off the bottom and come to rest again within 300 ft. This is most common with mobile homes (caravans).

An aerated haven is another subset of Ls = M. When part of a stationary building is torn away and the flood does not rise more than a few feet above the remaining floor or highest counter, occupants can survive by clinging to what remains. Damage on this scale results when buildings collide, a tree crashes through a wall, a house at the edge of a flood is cut in half by a wall of water, a well-anchored house is broken apart by successive waves, or a central chimney or structural anchor supports a small platform. In the open, if a person must cling to an object like a lamppost, tree, or fence to remain stationary, that is also an aerated haven.

Chance havens are reached primarily by chance through the whims of the current. Severed rooftops, mattresses, propane tanks, and logs are the most common floating Ch. People can also be washed to stationary rooftops, open windows, debris piles, overhanging branches, treetops, quiescent lakes or backwaters, and the shore itself. Pseudo-safe havens become chance havens once a building is swept far downstream in the open current. Significantly, because there is a velocity differential between victims and chance havens, Ch have the potential to kill as well as to save.

Flood Zones and Zone Densities (Sz, Cz, Pcz, Coz, Szd, Czd, Pczd, Cozd)

Flood zones are informed by Ls and havens, but they are not synonymous with either and they include the open flood. They are one step closer to HBUs than categories of Ls, they transcend buildings, and the historic proportion of lives lost within each zone varies primarily by chance. However, extreme depths, velocities, temperatures, or other conditions can limit the range of the distributions of proportional life loss that apply in a specific case.

Safe zones (Sz) include all safe havens and mildly compromised havens. A compromised haven (Ch = Psh or Ah) is mildly compromised when exposure levels within the haven are comparable to those in a safe haven. As such, safe zones form a single statistical population with respect to their proportional life loss distribution, comparable to that for Ls = L.

Chance zones (Cz) are places where people are submerged or face the open flood, including all chance havens that might be reached while drifting. Common settings would be campgrounds, the open floodplain, and where Ls = H, which appears to have a nearly identical proportional life-loss distribution.

Pseudo-chance zones (Pcz) encompass that narrow range of flow conditions for which it is unclear whether a building is likely to be destroyed, float far downstream, or maintain a compromised haven. As such, the Pcz is defined because it may be useful for future life-loss prediction. To approximate the proportional life-loss distribution in this zone, one might combine the relevant tails from proportional life-loss distributions for Ls = H and Ls = M to capture the range of possible values and to make the uncertainty explicit.

Compromised zones (Coz) include that intermediate range of compromised havens that intentionally have not been classified as safe zones or pseudo-chance zones. The proportional life-loss distribution should closely resemble that when the severity of structural damage for Ls = M is in the central 60% - 80%.

Zone densities (Zd = Szd, Czd, Pczd, and Cozd) represent the distribution of $Tpar_i$ among flood zones based on the accessibility of havens. The word "density" refers to the number of people who reach a particular zone category (Zd = people/zone), with the chance zone populated only by those who can't first reach another zone. Access to a zone includes the physical ability to move to the zone location and sufficient time to get there. When people are outdoors, this time is on the order of Sc. When they are indoors, this time is usually at least 30 seconds. History suggests that most members of $Tpar_i$ reach the safest haven to which they have access, but under a narrow set of circumstances they may forsake an upstairs refuge only to encounter the flood in the open while attempting to evacuate.

RATES OF LIFE LOSS

Lethality Rates in Flood Zones (Lsz, Lcoz, Lpcz, Lcz; Prsz, Prcoz, Prpcz, Prcz)

The symbols L(zone) pertain to the number of lives lost in the designated zone. Pr(zone) indicates the proportion of lives lost in the zone. Historical values for Pr(zone) are presented in Figure 2 in the form of relative frequency diagrams. Theoretically, proportional life loss increases across zones in the order Prsz, Prcoz, Prpcz, and Prcz. Figure 2 indicates that this is indeed the case, although Prcz is not consistently higher than Prpcz. This can be explained by the fact that Prpcz applies more narrowly in historical contexts than in predictive contexts - if a haven survived, this is usually known. As such, only three data points fit the Prpcz category. In each case, local structural damages were so severe they resembled Ls = H, but without certainty. The conclusion is that Prpcz is more likely to resemble Ls = H and Prcz in historical contexts than in predictive contexts because the range of uncertainty in historical contexts is skewed toward greater damages. Ignoring Prpcz, the most dramatic jump in proportional life loss is between Coz and Cz, indicating a significant shortcoming in the definition of flood forcefulness used by DeKay and McClelland (1993): their definition treats Ls = M and Ls = H as identical.

As long as people can keep their heads above water by wading or treading water and they are sheltered from high velocities and violent impacts from debris, deaths are unusual. Hence, out of 47 historical safety zones that we have examined so far, people died in only two and these deaths were in atypical circumstances.

In the chance zone, survival depends on being swept to a chance haven that lasts until the flood passes or one can reach shore. As such, it is common for everyone to perish and quite uncommon for more then 20% to survive. For a particular setting, some of the variability in this distribution depends on the water depths, velocities, and temperatures; the availability of chance havens; and the absence of lethal obstacles and debris. However, as the zone name implies, much of the variability evident in this distribution can be attributed to chance.

As would be expected, the proportion of lives lost in compromised zones ranges between that in safe zones and that at the extreme lower tail of the chance zone. This gives credence to the notion that these three zones can be treated as distinct populations that approximate HBUs and can be used to reconstruct historic events, and to predict future or hypothetical life loss events once zone densities are known. Furthermore, Figure 2 presents preliminary empirical distributions reflecting the anticipated variance in life loss within each zone based on chance or factors that may be beyond our ability to predict.

While exploring potential predictive variables that might give guidance as to cases for which only a portion of a given distribution might apply, the random patterns found in scatter diagrams suggest that chance is the dominant determinant of variability in the center of each distribution. However, when flood depths and velocities are unusually high or unusually low, proportional life loss has historically been limited to the corresponding tails of the distributions in the cases we have examined. With ongoing research, we hope to reduce uncertainty by identifying those ranges of key predictive variables that limit the proportional life loss to a particular band within a given distribution in Figure 2.

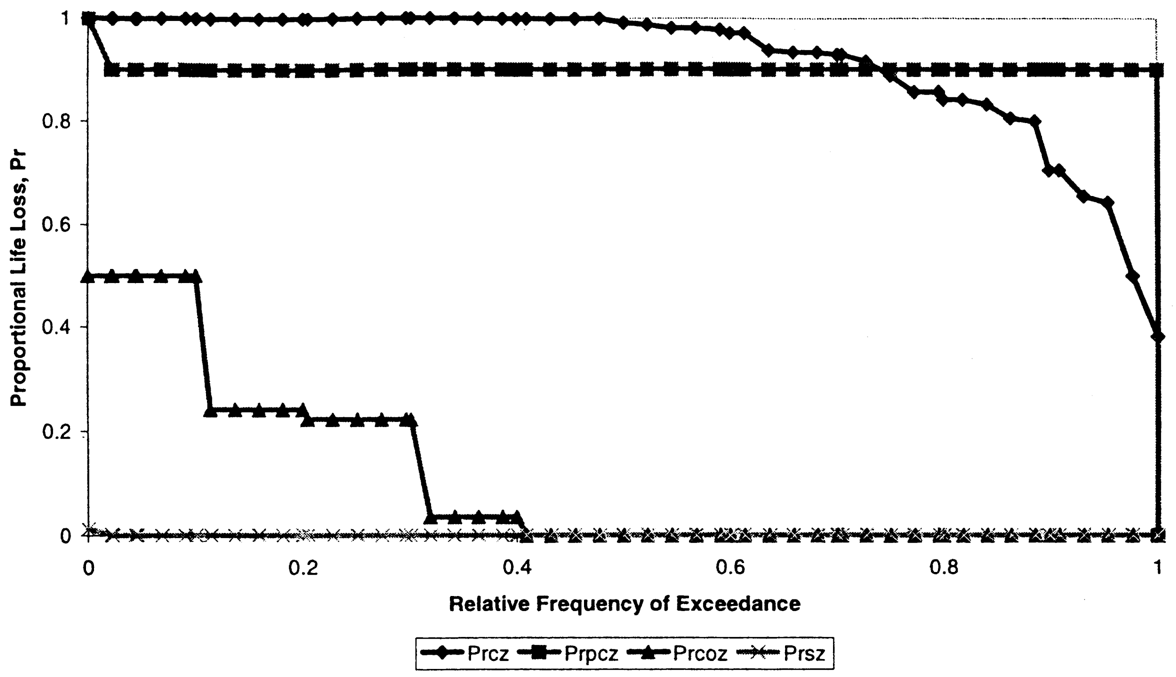

Figure 2. Relative frequencies of the proportion of lives lost in historic flood zones.

Figure 2 was developed exclusively using subPar with Pt = D (residential or commercial districts), but the zone environments to which people fled included regions inside and outside of buildings. This is consistent with the definition of zones. Although other Pt were not included in Figure 2, when zones could be identified within them, the proportion of life loss within those zones fell within the ranges shown in Figure 2. Nevertheless, it is helpful to highlight issues that affect life loss in other Pt.

People in any Pt can eventually find themselves attempting to wade to safety. Waders in catastrophic floods are much more likely to be swept away than waders in a laboratory channel exposed to the same average depth/velocity combination. Walls of water, surges, waves, hidden obstacles, dense sediment, large debris, unpredictable turbulence, slick surfaces, the need to carry infants and children, and other factors all increase the chances that a wader will be swept away. As such, the ranges of depth and velocity that fall between the safe zone and the chance zone may be too narrow to accurately predict with existing flood routing models.

Motorists face a situation similar to those who become trapped in a room by external water pressure. If a flood sweeps a passenger vehicle into water more than 4 ft deep, those inside the vehicle are almost guaranteed to drown unless they are rescued while the vehicle is still floating. There were no survivors in the historical record that was examined.

Motorists could readily be subdivided based on the contexts in which they can die. Motorists have historically perished when: 1) a flood undermined a section of road, 2) they drove onto a flooded bridge before seeing the danger under conditions of poor visibility, 3) a dam bearing a road washed away leaving a gapping hole over which motorists could plunge, 4) they attempted to evacuate down a long canyon instead of climbing the hillside, 5) they were overtaken by a wall of water, 6) they refused to abandon their vehicles after stalling in a rising flood, 7) a sudden surge of water sideswiped the vehicle, 8) they attempted to cross a low-water crossing, 9) they were swept into a canal, gully, excavation, or drainage ditch, and 10) an expanse of city streets was inundated. Historic close calls included many who quickly moved a vehicle out of harms way and employees who were driving on a dam just before failure to examine it or to attempt repairs.

Water through which people can wade is often capable of washing a vehicle downstream. As sediment coats a road surface and the weight of a vehicle is reduced through buoyancy, friction between the tires and the road is reduced considerably. For example, one woman drowned following the failure of Baldwin Hills Dam when her vehicle was swept down a street by slow currents about 3 ft deep. While rescue workers waded beside her car, it plunged into a deep pit. Excavations, ditches, canals, gullies, and other topographic depressions can turn an otherwise shallow flood into a death trap.

Many automotive fatalities are a result of motorists choosing to cross a flooded bridge or roadway, either because the flood appears shallow or because the motorist does not realize that a combination of relatively minor depths and velocities can carry away a vehicle. Eleven out of 13 deaths during the Austin, Texas, flash floods were of this nature. These types of fatalities are a form of convergence death that inherently limits Par_i to $Tpar_i$. Motorists who see a lead motorist get into trouble will generally have time to stay clear themselves.

Trains are similar to automobiles if they are moving. When the railroad bridge collapsed during the Dry Creek flash flood, Many passengers died due to the impact of the train crash, apart from drowning. When stationary, however, as the trains were following the failure of the South Fork Dam in 1889, trains most closely resemble mobile homes with limited buoyancy.

Campgrounds offer few havens except trees, hills, and an occasional outbuilding, and the trees and buildings enter the chance zone if they topple. Moreover, campsites are often located near a river where valleys are steep and narrow so recreationists can readily be exposed to high velocities, great depths, and a wall of water.

Boaters have an advantage if wearing life jackets, but boaters also face increased risks since they are hard to warn and their evacuation time tends to be higher than for those on land. In the US, the popularity of guided fishing trips, river rafting, kayaking, and personal drift boats has increased dramatically over time. Many rivers now experience boats year-round. As such, this type of subPar is more relevant to future failures than to historic ones.

Lethality Rate Outside of Flood Zones

Deaths that have little or no relationship to flood zones fall into at least four categories: 1) those who die of a heart attack, stroke, or other medical condition brought on by fear for their personal safety, 2) those who die of a heart attack, stroke, or other medical condition shortly after learning that their loved ones have perished, 3) those who actively commit suicide during or after the flood, and 4) those who lose the will to live or develop self-destructive behavioral patterns. These deaths are typically omitted from the official lists of flood-related fatalities. In some cases, the individuals may have never come near the flood.

Since such deaths are not officially tallied, they are difficult to quantify, but overall they appear to be a tiny fraction of total deaths and they are most likely when life loss is large, making their relative contribution proportionately small.

Life-Saving Interventions (Rr)

Heroic rescues by family members, neighbors, and those giving warnings have helped to reduce life loss in the first seconds or minutes of a flood, but the floods with the greatest life loss have generally claimed their victims before professional rescuers were able to arrive. Once people are submerged or swept away, rescues are primarily a matter of chance. When people can reach treetops, housetops that are not moving, or islands, hundreds or thousands of people can be rescued by helicopter or boat over several hours, as was the case following the Baldwin Hills failure, but in such cases most of the individuals are not at high risk of drowning and could safely wait for the flood to pass. Overall, then, on a mass scale, modern rescue resources (Rr) reduce life loss primarily by helping to shuttle people to modern hospitals or by providing advanced medical care in the field to those who are injured.

Complications or Aberrations

Due to their striking uniqueness, every flood wave has the potential to cause life loss through rare or unexpected means. The nature and concentration of a debris load influences the likelihood that someone can drift to safety while avoiding being crushed or pierced. Fires were started by the Big Thompson, Black Hills, Dale Dyke, and South Fork floods. Some have been electrocuted before the power company shut off power to an inundated region. Lives can be lost in hospitals when flooding prevents essential medical professionals from reaching the building or interrupts a critical power supply. Persons with limited mobility are in greater danger and can endanger those who try to help them. Floods can sweep poisonous snakes out of riverside haunts, adding them to the hazards in the water and leaving them behind in inhabited areas. Prolonged floods or floods in winter can cause fatal hypothermia. Convergence deaths result when onlookers come to watch the flood or render assistance, and inadvertently become trapped and swept away.

Post-flood Psychological Trauma

When homes and life-investments are obliterated; people see naked, muddied, and mutilated corpses; families are relocated; and people's sense of security is cast asunder, it destroys social networks and a highly valued sense of community and belonging. Since large segments of families often perish together, survivors often face multiple losses. As an extreme example, one woman lost 55 members of her family during the Vaiont flood. Emotional and financial losses continue as there is almost always widespread looting following a destructive flood.

Combined, flood-induced trauma can cause extreme, debilitating, and even fatal psychological scaring. Symptoms observed following the Buffalo Creek disaster include an extreme fear of storms, even when relocated far above a river; recurring nightmares; a desire to withdraw from social contact; an inability to return to work; lethargy; drug or alcohol abuse; suicidal tendencies; chronic depression and apathy; marital conflict or divorce, including blame for warning one set of relatives over another, or failure to save a child; guilt for surviving when others died; guilt for failing to save others, or viewing oneself as a coward; and early death after giving up the will to live (Deitz and Mowery 1992; Erikson 1976). While not part of life-loss statistics, it is important to realize that traumatic flood events that destroy lives and property can continue to shorten lives long after the event.

The resiliency of the students at Toccoa Falls Bible College following the Kelly Barnes failure suggest that a strong faith in God, His sovereignty, and in heaven, can help people cope with the death of loved ones and move forward with healthy living patterns (Foster and Mills 1978).

TOWARDS AN IMPROVED PREDICTIVE MODEL

On a macroscale, flood events are sufficiently unique to make it difficult or impossible to produce credible life loss estimates based on a lumped model using a single global Par. The variability in life-loss dynamics between different Par types alone makes a global comparison between events incongruent. To sustain credibility, a model should be grounded in, calibrated with, and validated using historically verifiable life-loss patterns. To improve the confidence of users, a model should explore these patterns on a level for which variation in proportional life loss varies largely by chance rather than dominant factors that are neglected through oversimplification of the model itself. However, to the extent that a practical model must exclude some factors that are too costly or too poorly understood to include, the resulting uncertainty in model predictions should account for both the variability in life loss that is inherent to real-world flood events and that which is introduced through model simplification.

As such, we believe that an improved practical approach must be founded on case histories at the level of subPar, flood zones, or other approximations to HBUs. We are therefore formulating an empirically grounded conceptual model with this in mind. The model needs to be refined, tested, and reviewed before it can be formally presented, but the model currently shows great promise.

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APPENDIX A. LIST OF FLOOD EVENTS CITED IN THE TEXT

- Allegheny County flash floods (especially Little Pine Creek), Pennsylvania, USA, May 30, 1986, L = 9.
- Arás alluvial fan flash flood, central Pyrenees, Spain, August 7, 1996, L = 87.
- Austin Bayless Pulp & Paper Company Dam failure, Austin, Pennsylvania, USA, Sept. 30, 1911, L = 88.
- Austin, Texas, flash floods, USA, May 24f, 1981, L = 13.
- Baldwin Hills Dam failure, California, USA, December 14, 1963, L = 5.
- Bangladesh storm surge, coast of Bangladesh, November 12, 1970, L = 225,000.
- Big Thompson flash flood, Colorado, USA, July 31, 1976, L = 145.
- Black Hills flash floods and failure of Canyon Lake Dam, South Dakota, USA, June 9f, 1972, L = 237.
- Buffalo Creek coal waste dam failures, West Virginia, USA, September 26, 1972, L = 139.
- Canyon Lake Dam failure in Rapid City, South Dakota, USA, June 9, 1972 (see Black Hills).
- Dale Dyke Dam failure, Sheffield, England, March 11, 1964, L = 263.
- Dry Creek flash flood resulting in a train wreck, Colorado, USA, August 7, 1904, L = 96.
- Eldorado Canyon flash flood, Nevada, USA, September 14, 1974, L = 10.
- Kelly Barnes Dam failure, Toccoa Falls, Georgia, USA, November 6, 1977, L = 39.
- Mill River dam failure near Williamsburg, Massachusetts, USA, 1874, L = 151.
- Rapid Creek flash flood (see Canyon Lake Dam failure and Black Hills flash flood), L = 207.
- Shadyside flash floods (Wegee and Pipe Creeks), near Shadyside, Ohio, USA, June 14, 1990, L = 24.
- South Fork Dam failure near Johnstown, Pennsylvania, USA, May 31, 1889, L = 2,209.
- Vaiont Dam overtopping generated by a massive landslide in the reservoir, Italy, October 9, 1963, L = 2,056 (or more).

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A Procedure for Estimating Loss of Life Caused by Dam Failure

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DSO
DAM SAFETY OFFICE

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by
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U.S. Department of Interior
Bureau of Reclamation
Dam Safety Office
Denver, Colorado

September 1999

A Procedure for
Estimating Loss of Life Caused by Dam Failure

Wayne J. Graham, P.E.[1]

ABSTRACT

Risk assessments and other dam safety studies often require that an estimate be made of the number of fatalities that would result from dam failure. To assist in this effort, an extensive evaluation of dam failures and the factors that contributed to loss of life was conducted.

Every U.S. dam failure that resulted in more than 50 fatalities and every dam failure that occurred after 1960 resulting in any fatalities was investigated with regard to warning, population at risk (PAR) and number of fatalities. These dam failure data are used to provide a historical perspective of the risk associated with the U.S. dam inventory.

Loss of life resulting from dam failure is highly influenced by three factors: 1)The number of people occupying the dam failure flood plain, 2)The amount of warning that is provided to the people exposed to dangerous flooding and 3)The severity of the flooding.

The procedure for estimating loss of life due to dam failure relies heavily on data obtained from U.S. dam failures. The procedure is composed of 7 steps:

1) Determine dam failure scenarios to evaluate.
2) Determine time categories for which loss of life estimates are needed.
3) Determine when dam failure warnings would be initiated.
4) Determine area flooded for each dam failure scenario.
5) Estimate the number of people at risk for each dam failure scenario and time category.
6) Apply empirically-based equations or methods for estimating the number of fatalities.
7) Evaluate uncertainty.

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INTRODUCTION

Evaluating the consequences resulting from a dam failure is an important and integral part of any dam safety study or risk analysis. Some dam failures would cause only minimal impacts to the dam owner and others, while large dams directly above large population centers are capable of causing catastrophic losses. Dam failure can cause loss of life, property damage, cultural and historic losses, environmental losses as well as social impacts. This paper focuses on the loss of life that results from dam failure. Included is a procedure for <u>estimating</u> the loss of life that would result from dam failure. No currently available procedure is capable of predicting the exact number of fatalities that would result from dam failure.

SOME SIGNIFICANT DAM FAILURES

The world's most catastrophic dam failures occurred in August 1975 in the Zhumadian Prefecture of Henan Province in central China. A typhoon struck, causing reservoirs to swell. Banqiao Dam, 387 ft (118 meters) high, and Shimantan Dam collapsed as did dozens of smaller dams. Millions of people lost their homes. The death toll estimates for these failures varied widely. Approximately 26,000 deaths occurred from drowning in the immediate aftermath of the dam collapses. There were as many as 230,000 deaths if those who died of consequent health epidemics and famine are included.

Europe's most catastrophic event associated with a dam occurred at about 2240 hours on October 9, 1963. The event occurred 3 years after the completion of Vajont Dam which is located in northern Italy. A 350 million cu. yard (268 million cu. m.) landslide fell within 20 to 30 seconds into the reservoir formed behind the dam. The dam, at the time the world's second highest, did not fail. However, the effect of this huge mass of material that slid into the reservoir, which was almost at the maximum water level, was a gigantic wave of 40,500 acre-ft (50,000,000 cu. m.) of water that, after rising for 820 ft (250 m) in height, poured both towards the village of Longarone, 1.2 miles (2 km) downstream from the dam, and upstream along the reservoir, flooding the towns of Erto and Casso which were located on the hillsides surrounding the reservoir. About 2,000 people died as a result of this event, with about 1,269 of these occurring in Longarone where the fatality rate was about 94%. At Belluno, about 10 miles (16 km) downstream from Longarone, there was damage to more than 150 houses; luckily, the river dikes in most places prevented spillage into built-up areas. In the downstream valley area, there were few fatalities, even where there was substantial property damage.

More recently, Stava Dam, located in northern Italy, failed at about 1220 hours on July 19, 1985. The failure of this mine waste tailings dam resulted in the death of about 90% of the 300 people at risk in the community of Stava which was located about 0.6 mile (1 km) downstream from the dam.

The United States has also had major dam failures. Data for failures occurring in the United States are provided in more detail to provide the reader with an enhanced understanding of the relationships between dam failure, flooding, population at risk, warning and loss of life. The dam failure data are then analyzed to show trends and patterns.

History shows that the loss of life from dam failure in the United States has diminished with the passage of time. In the late 1800's and early 1900's, there were several dam failures with considerable loss of life. The loss of life resulting from dam failure during the 1980's and 1990's has been very low. The following is a summary of every dam failure in the United States that caused more than 50 fatalities:

Williamsburg Dam, also known as the Mill River Dam, Massachusetts, failed at about 0720 hours on Saturday May 16, 1874. The dam was 9 years old when it failed. The dam was earthfill with a masonry core wall. The dam was about 43 ft (13.1 m) high and contained about 307 acre-ft (379,000 cubic meters) of water at the time of failure. The reservoir was about 4 ft (1.2 m) below the dam crest at the time of failure. The failure was caused by seepage which carried away fill leading to embankment sliding and then collapse of the core wall. The failure resulted in about 138 fatalities and about 750 people were homeless. All of the fatalities occurred within the first 7 mi (11 km) downstream from the dam. After observing the dam failure, the dam tender traveled by horseback and began warning people downstream.

South Fork Dam, also known as the Johnstown Dam, Pennsylvania, failed at about 1510 hours on May 31, 1889. The dam was 36 years old when it failed. The earthfill dam was 72 ft (21.9 m) high and contained about 11,500 acre-ft (14.2 million cubic meters) of water. The dam failed as a result of overtopping that occurred during a flood caused by a 25-year frequency storm. The failure resulted in about 2,209 deaths, the largest loss of life from any U.S. dam failure. Nearly all of the fatalities occurred within the first 14 mi (22.4 km) downstream from the dam, with most in the town of Johnstown which was 14 mi (22.4 km) downstream from the dam. The number of fatalities was high because portions of the floodplain were densely populated, the flooding destroyed the majority of buildings in downtown Johnstown, and flooding in Johnstown preceding the arrival of dam failure flooding made it difficult for people to respond to the limited dam failure warnings that were issued. The dam tender traveled by horseback to a nearby community about 3 hours before dam failure and a message was then telegraphed to Johnstown describing the danger, but the warning was largely ignored.

Less than a year later, Walnut Grove Dam, Arizona, failed at about 0200 hours on February 22, 1890. The dam was 2 years old when it failed. The timber-faced rockfill dam was 110 ft (33.5 m) high and stored 50,000 acre-ft (62 million cubic meters) of water. During the flood, the dam withstood up to 3 ft (0.9 m) of overtopping for up to 6 hours before the dam failed. The failure resulted in between 70 and 100 fatalities. Many of the people who died were located at a construction camp for a lower dam which was about 15 mi (24 km) downstream from Walnut Grove Dam. Attempts were made to reach and warn people at the downstream construction camp. The distance to the construction camp, as well as the adverse weather, prevented the messenger on horseback from reaching the camp before the dam failure flood wave arrived.

Austin Dam, Pennsylvania, failed at about 1420 hours on September 30, 1911. The dam was 2 years old when it failed. The dam was variously described as being either 43 ft (13.1 m) or 50 ft (15.2 m) high and the reservoir contained either 550 acre-ft (678,000 cubic meters) or 850 acre-ft (1.05 million cubic meters) of water. The concrete gravity dam failed during normal weather conditions as a result of a weakness in the foundation or in the bond between the foundation and concrete. The failure resulted in at least 78 fatalities all of which occurred in the first 2 mi (3.2 km) downstream from the dam. A person living near the dam, after observing the sudden failure, phoned telephone operators in the community of Austin which was 1.4 mi (2.4 km) downstream from the dam.

Saint Francis Dam, California, failed at 2357 hours (about midnight) on March 12-13, 1928. The dam was 2 years old when it failed. The dam was 188 ft (57.3 m high) and the reservoir contained about 38,000 acre-ft (46.9 million cubic meters) of water. The concrete gravity dam failed as a result of structural defects. Weather was normal at the time of the dam failure. The failure resulted in about 420 fatalities. Unlike most of the other U.S. dam failure cases, loss of life did extend for quite some distance downstream from the dam. This perhaps is expected due to the severity of flooding, the larger population centers being quite some distance from the dam, and the darkness and difficulties in warning during the early morning hours. The highest fatality rates, however, were in areas that were close to the dam. For example, at Powerhouse No. 2, located about 1.6 mi (2.6 km) downstream from the dam, the dam failure claimed all of its occupants. In this same area lived the dam tender who also perished in the flood. At the California Edison Construction Camp, located about 17 mi (27 km) downstream from the dam, 89 of the 150 who had been there perished. This is a fatality rate of about 60%. Efforts to warn and evacuate people did not begin until a few hours after the dam failed.

The Buffalo Coal Waste Structure, West Virginia, failed at about 0800 hours on February 26, 1972. The structure did not receive the engineering, design, construction and care of a typical dam and is therefore called a structure and not a dam. The structure, begun in 1970, was continually being modified and enlarged as it was a waste pile used to dispose of material extracted during coal mining. The structure was about 46 ft (14.0 m) high and the failure released about 404 acre-ft (498,000 cubic meters) of water. This coal waste pile structure failed as a result of slumping of the structure face during a 2-year frequency rainfall event. There were 125 fatalities, all occurring in the first 15 mi (24 km) downstream. Warning of people exposed to the flooding began after the structure failed; reaction to the warnings was meager because there had been at least 4 previous false alarms.

Canyon Lake Dam, South Dakota, failed at about 2245 hours on June 9, 1972. The dam was 39 years old when it failed. The dam was about 20 ft (6.1 m) high and about 700 acre-ft (863,000 cubic meters) of water was released during the dam failure. The dam failed as a result of overtopping experienced during the Black Hills Flash Flood. The peak inflow to the reservoir was about 43,000 ft^3/s (1220 m^3/s) and the peak outflow was about 50,000 ft^3/s (1420 m^3/s). Some warning was issued to floodplain residents but those issuing the warnings did not initially comprehend the magnitude of the imminent flooding, nor was there a general awareness that the dam was going to fail. It is sometimes reported that all of the people that died during the Black Hills Flash Flood were victims of the dam failure. This is not correct. Of the 236 people who died, 35 died in the first 3 mi (4.8 km) upstream from the dam and 36 died in other basins not impacted by the dam failure. Approximately 165 of the fatalities occurred downstream from Canyon Lake Dam. Many of these people would have died even if the dam had not failed (or had not existed) due to the catastrophic nature of the flooding. Major flooding in Rapid City would have occurred without dam failure. The exact number of people who died as a direct result of the failure of Canyon

Lake Dam, i.e, the incremental loss of life, will never be known. It is estimated that the failure of Canyon Lake Dam resulted in 33 fatalities. This estimate is based on the assumption that the incremental loss of life downstream from Canyon Lake Dam caused by dam failure was 20% of the total loss of life downstream from the dam caused by the flood.

Table 1, "Dam Failures in the United States Resulting in Fatalities - 1960 through 1998," lists all dam failures in the United States that resulted in 1 or more fatalities during this 39-year time period.

Table 1
Dam Failures in the United States Resulting in Fatalities
1960-1998

Dam	Location	Date of Failure	Age of Dam	Cause of Failure	Dam Height (m)	Volume Released ($10^6 m^3$)	Warning Time (Hours)	People at Risk	Loss of Life
Electric Light Pond	Eagleville, New York	1960	n/a	n/a	7.9	unknown	unknown	unknown	1
Mohegan Park	Norwich, Connecticut	March 6, 1963 9:30 p.m.	110	Piping during elevated level caused by rain.	6.1	0.170	0	500	6
Little Deer Creek	near Hanna, Utah	June 16, 1963 6:13 a.m.	1	Piping during normal weather.	26.2	1.419	0	50	1
Baldwin Hills	Los Angeles, CA	December 14, 1963 3:38 p.m.	12	Piping during normal weather.	20.1	0.863	1 hour and 18 minutes	16,500	5
Swift	northwest Montana	June 8, 1964 10 a.m.	49	Overtopping during major flood event.	47.9	42.31	unknown	unknown	19
Lower Two Medicine	northwest Montana	June 8, 1964 3:30 p.m.	51	Embankment washed out next to concrete spillway walls.	11.0	25.82	unknown	unknown	9
Lee Lake	near East Lee, MA	March 24, 1968 1:25 p.m.	3	Piping.	7.6	0.370	0	80	2
Buffalo Creek Coal Waste	Logan County, West Virginia	February 26, 1972 8:00 a.m.	0	Slumping of dam face during 2-year rain event.	14.0	0.498	0	4,000	125

Dam	Location	Date of Failure	Age of Dam	Cause of Failure	Dam Height (m)	Volume Released ($10^6 m^3$)	Warning Time (Hours)	People at Risk	Loss of Life
Lake "O" Hills	Alaska	April 1972	n/a	Unknown.	4.6	0.059	unknown	unknown	1
Canyon Lake	Rapid City, South Dakota	June 9, 1972 10:45 p.m.	39	Overtopping during catastrophic flood; 245 total deaths from all flooding.	11.3	0.863	0	very large but unknown	33
Bear Wallow	Buncombe County, NC	February 22, 1976 2:30 a.m.	n/a	Rainfall; probable overtopping.	11.0	0.037	0	8	4
Teton	near Wilford, Idaho	June 5, 1976 11:57 a.m.	0	Piping of dam core in foundation key trench during initial filling.	93.0	308.4	1 hour 15 minutes	25,000	11
Laurel Run	near Johnstown, PA	July 20, 1977 2:35 a.m.	16	Overtopped.	12.8	0.555	0	150	40
Sandy Run	near Johnstown, PA	July 20, 1977	63	Overtopped.	8.5	0.057+	0	unknown	5
Kelly Barnes	near Toccoa Falls, GA	November 6, 1977 1:30 a.m.	78	Slope failure. during 10-year flood.	12.2	0.777	0	250	39
Lawn Lake and then Cascade Lake	near Estes Park, CO	July 15, 1982 5:30 a.m./ 7:42 a.m.	79/ 74	Lawn Lake piping during normal weather/ Cascade from overtopping.	7.9/ 5.2	0.831/ 0.031	0	5000	3
D.M.A.D.	near Delta, Utah	June 23, 1983 1:00 p.m.	24	Backcutting caused by collapse of downstream diversion dam	8.8	19.74	1+	500	1

Dam	Location	Date of Failure	Age of Dam	Cause of Failure	Dam Height (m)	Volume Released ($10^6 m^3$)	Warning Time (Hours)	People at Risk	Loss of Life
Nix Lake	near Henderson, Texas	March 29, 1989	55	Overtopping.	7.0	1.030	0	6	1
Evans and then Lockwood	Fayetteville, NC	September 15, 1989 9:30 p.m./ 10:00 p.m.	23/ 30	Each dam failed from overtopping.	5.5/ 4.3	0.089/ 0.039	0?	unknown but large	2
Kendall Lake	Camden, S. Carolina	October 10, 1990 7:00 p.m.	90	Overtopping.	5.5	0.851	0	unknown but large	4
Georgia Dams	217 dams failed throughout state	July 1994	n/a	unknown	unknown	unknown	unknown	unknown	3?
Timber Lake	near Lynchburg, VA	June 22, 1995 11:00 p.m.	69	Overtopping.	10.1	1.787	0	4 lane highway	2
Bergeron Pond	Alton, NH	March 13, 1996 6:50 p.m.	2	Failure occurred in the area of the concrete spillway. Dam not overtopped.	11.0	0.238	0	50	1

Note:

"Warning Time" is defined as the amount of time between the initiation of the dissemination of dam failure warnings and the initiation of dam failure. Many of the entries in this column are zero, indicating that dam failure warnings were not issued prior to dam failure.

"People at Risk" is defined as the number of people in the dam failure floodplain prior to the issuance of any flood or dam failure warnings.

"n/a" indicates that data is unknown or unavailable.

OBSERVATIONS ON DAMS AND DAM FAILURES

In the mid 1980's there were about 5,459 dams in the United States higher than 49 feet (15 meters) and more than 10 times as many, 71,000, that were more than 25 ft (7.6 meters) high. During the period 1960 through 1998, there were more than 300 fatalities resulting from dam failures in the United States. Failure of dams less than 15 meters high (dams too small to be included in the International Commission on Large Dams (ICOLD) Register of Dams) caused 88% of the total number of deaths occurring during this time period. There are certain types of dam failures that have occurred infrequently and thus information on these types of failures and the consequences that would result from these failures is deficient. These failures would include concrete dams, high embankment dams or any type of dam failing as a result of an earthquake.

Surprising as it may seem, most dam failures in the United States have not resulted in fatalities. During the 9-year period from late 1985 to late 1994 there were more than 400 dam failures in the United States. Most of these dams were small and many were unregulated. These dam failures resulted in only 10 fatalities. There were no fatalities from more than 98% of the dams that failed during this time period. It should be noted that many of the 400 dams were small, probably not large enough to be included in the National Inventory of Dams data base. In addition, many of these dams were probably either not classified with regard to hazard potential or classified as low or significant hazard potential dams. Less stringent safety standards usually apply to low and significant hazard dams.

Some interesting and relevant observations were developed from the 1960-1998 dam failure data shown in Table 1:

- Failure of dams less than 20 ft (6.1 m) high caused 2% of the deaths.
- Failure of dams between 20 ft (6.1 m) and 49 ft (15 m) high caused 86% of the deaths.
- Failure of dams less than 49 ft (15 m) high caused 88% of the deaths. These dams are not high enough to be included in the ICOLD inventory.

- There were 5 or less fatalities in 65% of the dam failure events that had fatalities.

- Failure of dams with drainage areas less than 2 sq mi (5.2 sq km) caused 47% of the deaths.
- Failure of dams with drainage areas less than 10 sq mi (26 sq km) caused 75% of the deaths.

Based on knowledge of the location of victims in 16 of the 23 dam failures (representing 87% of the fatalities) that occurred during the 39-year period from 1960-1998:

- 50% of the fatalities occurred 3 mi (4.8 km) or less from a dam that failed.
- More than 99% of the fatalities occurred 15 mi (24 km) or less from a dam that failed.

PREDICTING CONSEQUENCES OF DAM FAILURE

Loss of life sometimes results from dam failure. Loss of life is likely if a dam fails without warning and the failure produces flooding that destroys residential structures. Procedures for estimating loss of life have appeared in several documents. A good summary of these procedures is found in "Predicting Loss of Life in Cases of Dam Failure and Flash Flood," by DeKay and McClelland, 1993. Reclamation has prepared procedures for estimating loss of life and these are contained in "Guidelines to Decision Analysis," published in 1986 and in "Policy and Procedures for Dam Safety Modification Decisionmaking," published in 1989. The procedure presented herein, which includes an explicit procedure for estimating when a dam failure warning would be initiated, incorporates information from the two Reclamation documents as well as, "A Procedure for Estimating Loss of Life Due to Dam Failure," presented at the 1997 (U.S) Association of State Dam Safety Officials Annual Conference.

Procedures for estimating loss of life have also been developed by personnel at British Columbia Hydropower. The procedure is documented in a December 1996 Risk Assessment Report for Hugh Keenleyside Dam. The procedure evaluates the spacial and temporal location of flooding caused by dam failure, the number of people at risk at different locations and times, the time required for warning to be issued and spread to those at risk, the time required for people to begin taking action, the time required for people to escape and the probability that a person caught by the flood water would become a fatality. This procedure is logically sound, but at this time, there are not sufficient data to establish values of the various parameters and their relationship to one another.

It is important to determine the incremental consequence of dam failure. The incremental consequence of dam failure is the additional loss or damage caused by dam failure compared to the event occurring without dam failure. For a dam failure occurring from an earthquake, the incremental consequence would be the additional loss caused by flooding over and above the loss caused by the earthquake. For a dam failure caused by a major flood, the incremental consequence would be the additional loss caused by the dam failure over and above the loss that would have occurred if the dam and reservoir had passed the reservoir inflow without failing.

Factors Influencing Loss of Life Resulting from Dam Failure

Several factors will determine the number of fatalities resulting from dam failure. Included among these are the:

- Cause and type of dam failure.
- Number of people at risk.
- Timeliness of dam failure warnings.
- Flood depths and velocities in the downstream floodplain prior to dam failure.
- Flood depths and velocities resulting from dam failure.
- Availability of sensory clues (sight of floodwater or sounds created by rushing floodwater) to the people at risk.
- Time of day, day of week and time of year of failure.
- Weather, including air and water temperature.
- Activity in which people are engaged.
- General health of people threatened by floodwater.
- Type of structure in which people are located.
- Ease of evacuation.

The number of fatalities resulting from dam failure is most influenced by three of the factors described above. These factors are: 1)The number of people occupying the dam failure flood plain, 2)The amount of warning provided to the people exposed to dangerous flooding, and 3)The severity of the flooding. Without exception, dam failures that have caused high fatality rates were those in which residences were destroyed and timely dam failure warnings were not issued.

Two examples that show the importance of timely dam failure warning are as follows:

Teton Dam, located near Wilford, Idaho, failed at about noon on June 5, 1976. At the time of the failure, the sky was sunny or partly cloudy and the air temperature was a survivable 81 degrees F (27 degrees C). More than 3,000 homes were damaged and more than 700 homes were destroyed. Failure of the dam resulted in flood related injuries to more than 800 people and the death of 11 of the 25,000 people at risk. Failure occurred during the day, warnings to downstream areas commenced about 1 hour and 15 minutes prior to dam failure, and most people were able to evacuate before the house-destroying flood water arrived. The number of fatalities with less warning would have been much higher. For instance, failure of this dam at 3 a.m. probably would have been accompanied by no dam failure warnings and would have resulted in the loss of hundreds of lives.

Laurel Run Dam, located near Johnstown, Pennsylvania, failed in 1977. (Western Pennsylvania has seen 3 major dam failure events: South Fork Dam Failure, Austin Dam Failure and Laurel Run Dam Failure). Failure of this 42 ft (12.8 m) high dam claimed the lives of 40 of the 150 people at risk. Failure occurred at night when most people were asleep and dam failure warnings were not issued in the narrow 3 mi (4.8 km) long valley downstream from the dam. In addition, escape was surely hampered by the rain, lightning and darkness that accompanied the arrival of dam failure flooding. The number of fatalities probably would have been near zero if warnings had been issued to the people in the valley prior to dam failure.

A dam failure during the day will likely cause fewer fatalities than one occurring at night, all other things being equal. The daytime failure will probably be discovered earlier in the failure process and dam failure warnings would likely be issued earlier than if the failure occurred at night. In addition, during the day, news media and public safety agencies are staffed at higher levels, people are awake and people can see or hear the approaching flood water which in itself is a warning or warning confirmation.

Sources of Uncertainty

It is difficult to give a precise estimate of the loss of life that would occur from a dam failure for the following reasons:

- The time of dam failure (day, week, season), conditions existing at the time of failure (clear, rain, snow, darkness) and the number of people at risk at the time of dam failure (seasonal recreational usage, special events) are either unknown or can only be estimated.

- It is not known exactly when a dam failure warning message would be given. Experience indicates that there is sometimes a reluctance to issue dam failure warnings. Examples include the failure to issue warnings before the Buffalo Creek Coal Waste Structure failure in West Virginia, as well as the delay in initiating the dam failure warnings at Teton Dam in Idaho. The operating procedures or emergency plans that may be available for a dam should provide some guidance regarding when a warning would be issued. There is no assurance, however, that a warning would be initiated as directed in a plan. A study investigating loss of life from dam failure can be used to highlight weaknesses in the dam failure warning process and provide some guidance on how improvements in the process would reduce the loss of life.

•The procedure for estimating loss of life is not precise. Even if the time of the failure, conditions existing at the time of failure, number of people at risk, and the time at which warnings are initiated are known with certainty, there will be error in the loss of life estimate.

PROCEDURE FOR ESTIMATING LOSS OF LIFE

The procedure for estimating loss of life can be broken into various steps. Briefly, the steps are as follows:

Step 1: Determine dam failure scenarios to evaluate.
Step 2: Determine time categories for which loss of life estimates are needed.
Step 3: Determine when dam failure warnings would be initiated.
Step 4: Determine area flooded for each dam failure scenario.
Step 5: Estimate the number of people at risk for each failure scenario and time category.
Step 6: Apply empirically based equations or method for estimating fatalities.
Step 7: Evaluate uncertainty.

The steps are now given in more detail.

Step 1: Determine Dam Failure Scenarios to Evaluate

A determination needs to be made regarding the failure modes to evaluate. For example, loss of life estimates may be needed for two scenarios - failure of the dam with a full reservoir during normal weather conditions and failure of the dam during a large flood that overtops the dam.

Step 2: Determine Time Categories For Which Loss of Life Estimates Are Needed

The number of people at risk downstream from some dams is influenced by seasonality or day of week factors. For instance, campgrounds may be unused in the winter and heavily used in the summer, especially summer weekends. The number of time categories (season, day of week, etc.) evaluated should display the varying usage of the floodplain and corresponding number of people at risk. Since time of day can influence both when a warning is initiated as well as the number of people at risk, each study should include a day category and a night category for each dam failure scenario evaluated.

Step 3: Determine When Dam Failure Warnings Would be Initiated

Determining when dam failure warnings would be initiated is probably the most important part of estimating the loss of life that would result from dam failure. Table 2, "Guidance for Estimating When Dam Failure Warnings Would be Initiated," was prepared using data from U.S. dam failures occurring since 1960 as well as other events such as Vajont Dam in Italy, Malpasset Dam in France and Saint Francis Dam in California. An evaluation of these dam failure data indicated that timely dam failure warnings were more likely when the dam failure occurred during daylight, in the presence of a dam tender or others and where the drainage area above the dam was large or the reservoir had space for flood storage. Timely dam failure warnings were less likely when failure occurred at night or outside the presence of a dam tender or casual observers. Dam failure warnings were also less likely where the drainage area was small or the reservoir had little or no space for flood storage, i.e, when the reservoir was able to quickly fill and overtop the dam. Although empirical data are limited, it appears that timely warning is less likely for the failure of a concrete dam. Although dam failure warnings are frequently initiated before dam failure for earthfill dams, this is not the case for the failure of concrete dams.

Table 2, "Guidance for Estimating When Dam Failure Warnings Would be Initiated (Earthfill Dam)," provides a means for deriving an initial estimate of when a dam failure warning would likely be initiated. Guidance has not been provided for the failure of a concrete dam. Estimates for concrete dams must be developed on a case-by-case basis. The use of Table 2, combined with information obtained from any operating or emergency procedure for the dam, should answer the question, "When will a dam failure warning be initiated?" It is easily seen using Table 2 that the amount of dam failure warning for a particular dam will be different based on cause of failure and time at which the failure occurs.

The availability of emergency action plans, upstream or dam-site instrumentation, or the requirement for on-site monitoring during threatening events influences when a dam failure warning would be initiated. Assumptions regarding when a warning is initiated should take these and other risk-reduction actions and programs into account.

Table 2

Guidance for Estimating When Dam Failure Warnings Would be Initiated (Earthfill Dam)

Dam Type	Cause of Failure	Special Considerations	Time of Failure	When Would Dam Failure Warning be Initiated?	
				Many Observers at Dam	No Observers at Dam
Earthfill	Overtopping	Drainage area at dam less than 100 mi^2 (260 km^2)	Day	0.25 hrs. before dam failure	0.25 hrs. after fw reaches populated area
		Drainage area at dam less than 100 mi^2 (260 km^2)	Night	0.25 hrs. after dam failure	1.0 hrs. after fw reaches populated area
		Drainage area at dam more than 100 mi^2 (260 km^2)	Day	2 hrs. before dam failure	1 hr. before dam failure
		Drainage area at dam more than 100 mi^2 (260 km^2)	Night	1 to 2 hr. before dam failure	0 to 1 hr. before dam failure
	Piping (full reservoir, normal weather)		Day	1 hr. before dam failure	0.25 hrs. after fw reaches populated area
			Night	0.5 hr. after dam failure	1.0 hr. after fw reaches populated area
	Seismic	Immediate Failure	Day	0.25 hr. after dam failure	0.25 hr. after fw reaches populated area
			Night	0.50 hr. after dam failure	1.0 hrs. after fw reaches populated area
		Delayed Failure	Day	2 hrs. before dam failure	0.5 hrs. before fw reaches populated area
			Night	2 hrs. before dam failure	0.5 hrs. before fw reaches populated area

Notes: "Many Observers at Dam" means that a dam tender lives on high ground and within site of the dam or the dam is visible from the homes of many people or the dam crest serves as a heavily used roadway. These dams are typically in urban areas. "No Observers at Dam" means that there is no dam tender at the dam, the dam is out of site of nearly all homes and there is no roadway on the dam crest. These dams are usually in remote areas. The abbreviation "fw" stands for floodwater.

Step 4: Determine Area Flooded for Each Dam Failure Scenario

In order to estimate the number of people at risk, a map or some other description of the flooded area must be available for each dam failure scenario. In some cases, new dam-break studies may need to be prepared. However, existing maps should be used as much as possible to reduce study costs. Judgements will have to be made whether currently published or draft inundation maps reflect the flooding from the various failure scenarios for which loss of life estimates are needed. For instance, a dam failure inundation map based on a failure caused by dam overtopping may not accurately depict the flooding caused by a piping failure with a much lower reservoir level.

Analyses based on the use of dam failure inundation studies and maps leads to uncertainty. Dam break modeling requires the estimation of: 1) The time for the breach to form, 2) Breach shape and width and 3) Downstream hydraulic parameters. Variations in estimates of these parameters can result in changes in flood width, flood depth and flood wave travel time. This can lead to uncertainty in the: 1) Population at risk, 2) Warning time and 3) Flood severity.

Step 5: Estimate the Number of People at Risk for Each Failure Scenario and Time Category

For each failure scenario and time category, determine the number of people at risk. Population at risk (PAR) is defined as the number of people occupying the dam failure floodplain prior to the issuance of any warning. A general guideline it to: "Take a snapshot and count the people." The number of people at risk varies throughout the day.

The PAR will likely vary depending upon the time of year, day of week and time of day during which the failure occurs. Utilize census data, field trips, aerial photographs, telephone interviews, topographic maps and any other sources that would provide a realistic estimate of floodplain occupancy and usage.

Within the Bureau of Reclamation, the Remote Sensing and Geographic Information Group (GIS) can provide products that assist with the estimation of the population at risk. The GIS Group has the capability of estimating population using 1990 population and employment census information in combination with available inundation maps. Caution must be exercised because the 1990 data may not reflect current conditions. In using products from the GIS Group one must recognize that recreationists, campers and other non-permanent occupants are not counted in population census data. Similarly, it is important that double counting not take place. Centers of employment fill as housing units empty and vice versa. It is important to understand the methods used by the GIS Group to mesh flood boundaries with census block data. There is uncertainty in the methods and hence in the population at risk estimates.

Step 6: Apply Empirically-Based Equations or Method for Estimating the Number of Fatalities

Various methods have been suggested for estimating loss of life based on measures of population at risk, warning time and other factors. For background purposes, the Brown and Graham as well as the DeKay and McClelland methods are described. It is recommended that these methods be abandoned and replaced with a new flood severity based method for estimating loss of life. This new method is described in detail.

Knowledge gained in the 1980's and 1990's regarding the interrelationship between warning, flood lethality and the number of people at risk allowed the development of procedures to estimate the loss of life resulting from dam failure. It was found that loss of life is highly related to the warning issued to the people at risk. The lethality of flooding (which is a function of flood depth and velocity) is also a major factor, especially in those cases where warnings are not issued or when people are warned but fail to evacuate.

Two different papers were prepared that provided procedures for estimating loss of life from dam failure. In 1988, Brown and Graham published, "Assessing Threat to Life from Dam Failure." In 1993, DeKay and McClelland published, "Predicting Loss of Life in Cases of Dam Failures and Flash Floods." A summary of the procedures, and loss of life estimating equations presented by each pair of authors is presented below.

The Brown and Graham procedure uses equations that were derived from the analysis of 24 dam failures and major flash floods, shown in Table 3. The concepts contained in the Brown and Graham paper were incorporated into Reclamation's "Policy and Procedures for Dam Safety Modification Decisionmaking" (1989) and equations from this document are presented below.

Warning time used in the equations is defined as the elapsed time between the initiation of an official evacuation warning to the public and the arrival of dangerous flooding at the population at risk. Warning time must therefore consider the time it takes for flood water to reach the community or group of people at risk.

When warning time is less than 15 minutes:
Loss of Life = .5(PAR)

When warning time is between 15 and 90 minutes:
Loss of Life = $PAR^{.6}$

When warning time is more than 90 minutes:
Loss of Life = .0002(PAR)

It can easily be seen that the loss of life estimated using these relationships will vary widely depending upon the warning. With 5000 people at risk, loss of life from dam failure could be as much as 2500 people if these people are located in an area that receives less than 15 minutes of warning. The loss of life would only be 1 if the people are located in an area that receives more than 90 minutes of warning.

Table 3
Dam failures and Floods used by Brown and Graham

TABLE 1. Dam Failure and Flash Flood Cases.

Location	Population at Risk	Loss of Life	Hours Warning
Baldwin Hills, California, 1963	16,500	5	1.5
Bearwallow, North Carolina, 1976	4	4	0
Big Thompson, Colorado, 1976	2,500	139	<1.0
Black Hills, South Dakota, 1972	17,000	245	<1.0
Buffalo Creek, West Virginia, 1972	4,000	125	<1.0
Bushy Hill Pond, Connecticut, 1982	400	0	2-3
Denver, Colorado, 1965	3,000	1	3
DMAD, Utah, 1983	500	1	1-12
Kansas City, Missouri, 1977	1,000	25	<1.0
Kansas River, Kansas, 1951	58,000	11	>1.5
Kelly Barnes, Georgia, 1977	250	39	<0.5
Laurel Run, Pennsylvania, 1977	150	40	0
Lawn Lake, Colorado, 1982	5,000	3	<1.5
Lee Lake, Massachusetts, 1968	80	2	<1.0
Little Deer Creek, Utah, 1963	50	1	<1.0
Malpasset, France, 1959	6,000	421	0
Mohegan Park, Connecticut, 1963	500	6	0
Montana, 1964 (Swift and Two Medicine Dams)	250	27	<1.5
Northern New Jersey, 1984	25,000	2	>2
Prospect Dam, Colorado, 1980	100	0	>5
Teton, Idaho, 1976 (Dam through Wilford)	2,000	7	<1.5
Teton, Idaho, 1976 (Rexburg to American Falls)	23,000	4	>1.5
Texas Hill Country, 1978	1,500	25	<1.5
Vega De Tera, Spain, 1959	500	150	0

Source: "Assessing the Threat to Life from Dam Failure," published in <u>Water Resources Bulletin</u>, Vol. 24, No. 6, December, 1988.

DeKay and McClelland, supported by funding received from the Bureau of Reclamation, expanded on the work begun by Brown and Graham. They submitted the report entitled "Setting Decision Thresholds for Dam Failure Warnings: A Practical Theory-Based Approach" to Reclamation on December 31, 1991. In 1993 they published "Predicting Loss of Life in Cases of Dam Failure and Flash Flood" in the publication Risk Analysis. The events used by DeKay and McClelland, shown in Table 4, are the same as those used by Brown and Graham. DeKay and McClelland also included a few events that were not used by Brown and Graham. The DeKay and McClelland procedure demonstrated that loss of life is related to the number of people at risk in a nonlinear fashion. They also found that loss of life is greater in situations where the flood waters are deep and swift. DeKay and McClelland have a separate equation for high and low force conditions. Their equation, as it appears in Risk Analysis, for high force conditions, i.e., where 20% or more of flooded residences are either destroyed or heavily damaged is:

$$\text{Deaths} = \frac{\text{PAR}}{1 + 13.277(\text{PAR}^{0.440})e^{[2.982(\text{WT}) - 3.790]}}$$

Their equation for low lethality conditions, i.e., where less than 20% of flooded residences are either destroyed or heavily damaged is:

$$\text{Deaths} = \frac{\text{PAR}}{1 + 13.277(\text{PAR}^{0.440})e^{[0.759(\text{WT})]}}$$

where PAR is the number of people at risk and WT is warning time in hours. Warning time (WT), as used by Dekay and McClelland, is the time in hours from the initiation of dam failure warning until the dam failure floodwater reaches a community or other group of people. Warning time must therefore consider the time it takes for flood water to reach the community or group of people. When dam failure warnings do not precede the arrival of dam failure flooding in an area, WT would be zero. A negative warning time should not be used in these equations.

A major difference between the procedure developed by DeKay and McClelland and that of Brown and Graham is that warning time is treated as a continuous variable by DeKay and McClelland; whereas Brown and Graham utilized discrete bins and placed warning time into 2 or 3 categories.

DeKay and McClelland cautioned against using their equations for dams that fail without warning above areas with very large populations at risk. They also stated that their equations should not be applied to cases like Vajont, in which a massive landslide displaced nearly the entire contents of a reservoir. The Brown and Graham procedure as well as the DeKay and McClelland procedure both conclude that loss of life is much greater in those areas that receive little warning compared to those areas that receive more than an hour or so of warning. The value of adequate dam failure warning in reducing loss of life from dam failure can not be overemphasized.

Table 4
Dam Failures and Floods used by DeKay and McClelland

Table I. Dam Failure and Flash Flood Events[a]

Location	Population at risk (PAR)	Hours warning (WT)	Hours warning (WT) dichotomous	Hours warning (WT) continuous	Flooding forcefulness (Force)	Actual loss of life (LOL)	Predicted loss of life [Eq. (11), LOL]
Allegheny County, PA, 1986[b]	2200	—	0	0.00	0	9	6
Austin, TX, 1981[b]	1180	—	0	1.00	1	13	9
Baldwin Hills, CA 1963	16,500	1.5	1	1.50	1	5	9
Bearwallow, NC, 1976	8[c]	0.0	0	0.00	1	4	5
Big Thompson, CO, 1976	2500	<1.0	0	0.50	1	144[c]	59
Black Hills, SD, 1972	17,000	<1.0	0	0.50	1	245	174
Buffalo Creek, WV, 1972	5000[c]	<1.0	0	0.50	1	125	87
Bushy Hill Pond, CT, 1982	400	2–3	1	2.50	0	0	0
Centralia, WA, 1991[b]	150	—	0	0.00	0	0	1
Denver, CO, 1965	10,000[c]	2.33–4.0[c]	1	3.17	0	1	1
DMAD, UT, 1983	500	1–12	1	6.50	0	1	0[d]
Kansas City, MO, 1977	2380[c]	<1.0	0	0.50	1	20[c]	57
Kansas River, KS, 1951	58,000	>2.0[c]	1	3.00	1	11	0[d]
Kelley Barnes, GA, 1977	250	<0.5	0	0.25	1	39	31
Laurel Run, PA, 1977	150	0.0	0	0.00	1	40	40
Lawn Lake, CO, 1982	5000	0.0–1.0[c]	0	0.50	0	3	5
Lee Lake, MA, 1968	80	0.0[c]	0	0.00	1	2	26
Little Deer Creek, UT, 1963	50	0.0[c]	0	0.00	0	1	1
Malpasset, France, 1959	6000	0.0	0	0.00	1	421	406
Mohegan Park, CT, 1963	1000[c]	0.0	0	0.00	0	6	4
Northern NJ, 1984	25,000	>2.0	1	3.00	0	2	2
Prospect Dam, CO, 1980	100	>5.0	1	7.50	0	0	0[d]
Shadyside, OH, 1990[b]	884	—	0	0.00	1	24	127
Stava, Italy, 1985[b]	300	—	0	0.00	1	270	64
Swift and Two Medicine Dams, MT, 1964	250	<1.5	0	0.75	1	28[c]	8
Teton, ID, 1976 (Dam through Wilford)	2000	<1.5	0	0.75	1	7	25
Teton, ID, 1976 (Rexburg to American Falls)	23,000	>1.5	1	2.25	0	4	4
Texas Hill Country, 1978	2070[c]	<1.5	0	0.75	1	25[c]	25
Vega De Tera, Spain, 1959	500	0.0	0	0.00	1	150	89

[a] Original data (PAR, WT, and actual LOL) are from Ref. 2, except as noted.
[b] New case. See footnote 8.
[c] Value has been revised. See footnote 8.
[d] This case not used to derive Eq. (11).

Source: "Predicting Loss of Life in Cases of Dam Failure and Flash Flood," published in Risk Analysis, Vol. 13, No. 2, 1993.

Limitations of Loss of Life Estimating Equations

The empirical data set used by Brown and Graham, and DeKay and McClelland, in developing the loss of life estimating equations did not include some types of events and warning scenarios. Most of the dams in the data set were smaller structures. Only 7 of the dams used in developing the equations were more than 49 ft (15 m) high. The data set included many more earthfill dams than concrete dams. The data set included no dams that failed due to an earthquake. The equations may not be applicable for use with dam sizes, dam types, failure causes, flood severity and warning scenarios not reflected in the data set.

Most notably under represented in the empirical data set used by Brown and Graham, and DeKay and McClelland, were events that caused severe flooding, either with or without warning. As a result, the equation for high lethality is deficient when used to predict life loss for dam failures that result in truly catastrophic flooding. The following example explains this problem in more detail: St. Francis Dam, a concrete structure located north of Los Angeles, failed at about midnight, March 12-13, 1928. Warnings did NOT precede dam failure. Within a period of just a few minutes, the area immediately downstream from the dam changed from one of no flooding to one where the flood covered the valley floor to a depth of nearly 100 ft (30 m). Imagine rapidly moving water, with a depth as high as a ten story tall building, battering a typical campsite, mobile home or single family house! There were not many people living immediately downstream from the dam; if there had been, the loss of life from this dam failure would have been much greater. Assume for a moment that there had been 10,000 people living near the river in the first few miles downstream from the dam. The DeKay and McClelland equation for high lethality and a warning time of zero predicts a life loss of about 550 people, which is a fatality rate of slightly less than 6%. This seems far too low for this situation. A fatality rate of 80 to 100% would be more appropriate for flooding of this type, a rate that is similar to what happened in Longarone, located a short distance downstream from Vajont Dam in Italy. The DeKay and McClelland equation for high lethality and no warning results in a fatality rate of 55% if 10 people are at risk but only 5.5% if 10,000 people are at risk.

A similar problem exists if it is assumed that a warning goes out a few hours before dam failure. Reclamation has generally assumed that the loss of life would be about 1 person for every 5,000 at risk if the warning is issued to the risk area at least 1.5 hours before flooding occurs in the area. Such a small fatality rate probably is not realistic with very catastrophic flooding. The loss of life is going to be directly related to the number of people who do not receive the warning or ignore the warning and remain in the risk area. The same percentage (80 to 100%) of the people remaining would likely become fatalities if exposed to the type and severity of flooding that occurred immediately downstream from St. Francis Dam or Vajont Dam. It may be very difficult to determine how many people will not evacuate. If a warning does not reach people or if people do not believe the warning or if they do not believe that their life is at risk, then these people are more likely to remain in the danger area.

When Brown and Graham originally developed their life loss estimating equations, they thought that it was logical for the fatality rate (the number of fatalities as a fraction of the population at risk) to decrease as the population at risk increased. The assumption was that as the population increased, or became more dense, warning and communication facilities would be more advanced. Probably what was observed, unknowingly, is that as the population at risk increased, the area under consideration was increasing in size and was therefore including areas where the flooding was less lethal. The Brown and Graham as well as the DeKay and McClelland data bases probably contain many cases demonstrating that there is an inverse relation between population at risk and flood lethality. This means that as the population at risk increased, the flood lethality (or flood severity) decreased. Large populations do not fit into narrow canyons - hence larger populations are situated in the flatter areas where the lethality is usually reduced.

Some questions regarding the validity of the equations developed by Brown and Graham as well as Dekay and McClelland remain. Do the equations give accurate results when large numbers of people are exposed to truly catastrophic flooding? Should the fatality rate vary so much for different population sizes? Does adequate warning time result in low fatality rates? - Or is adequate warning most likely to occur for benign floods and these floods are not very lethal, regardless of the warning?

Some Floods are Benign While others are Catastrophic

Dam failure can result in flooding that can be broadly divided into 3 damage categories: low, medium and high. The first would be where homes are flooded but not destroyed. Even without any warning, the fatality rate for dam failures that cause this type of flooding is often 0% and almost always less than 1%. Many of the dam failures that resulted in flooding described by DeKay and McClelland as having a "low force" would fit this category. Many of the more than

400 dams that failed in the United States from 1985 to 1994 would also fit this category.

The second type of flooding resulting from dam failure is that which causes the destruction of homes and businesses. Trees and some homes remain and these trees or rooftops may provide temporary refuge until the flooding recedes. Without warning, the fatality rates for dam failures causing this type of flooding have ranged from a few percent up to about 25% or more. Dam failures that resulted in flooding described by DeKay and McClelland as having a "high force" would fit this category.

The third type of flooding is that which occurs very suddenly and is truly of catastrophic magnitude. The floodplain is swept clean. Houses are crushed, washed away and there is little or no trace of their prior existence when the flood water recedes. The landslide-generated wave at Vajont Dam, Italy caused this type of flooding in Longarone. The failure of Stava Dam in Italy and St. Francis Dam in California also caused this type of flooding immediately downstream from each structure. Mine tailings dams and concrete dams seem to have the capability of producing this type of flooding due to the short failure times for these dams. Without warning, the fatality rates for dam failures causing this type of flooding have ranged from about 50% up to about 100% for areas immediately downstream from the dam.

FLOOD SEVERITY BASED METHOD FOR ESTIMATING LIFE LOSS

Recognizing weaknesses in the Brown and Graham, and the DeKay and McClelland equations, a new method for estimating life loss has been developed. The method still uses results from steps 1-5; only the process for determining the loss of life based on the population at risk has changed. The method developed provides recommended fatality rates based on the flood severity, amount of warning and a measure of whether people understand the severity of the flooding.

This new method was developed using an enlarged data set which totaled approximately 40 floods, many of which were caused by dam failure. The 40 floods include the data used by Brown and Graham, Dekay and McClelland, nearly all U.S. dam failures causing 50 or more fatalities, and other flood events that were selected in an attempt to cover a full range of flood severity, warning and flood severity understanding combinations. The following paragraphs describe the terms and categories that form the basis for this methodology.

Flood Severity along with warning time determines, to a large extent, the fatality rate that would likely occur. The flood severity categories are as follows:

1) Low severity occurs when no buildings are washed off their foundations.

2) Medium severity occurs when homes are destroyed but trees or mangled homes remain for people to seek refuge in or on.
3) High severity occurs when the flood sweeps the area clean and nothing remains. Although rare, this type of flooding occurred below St. Francis Dam and Vajont Dam.

Warning Time is the other factor that is important in determining the fatality rate. The warning time categories are as follows:

1) No warning means that no warning is issued by the media or official sources in the particular area prior to the flood water arrival; only the possible sight or sound of the approaching flooding serves as a warning.

2) Some warning means officials or the media begin warning in the particular area 15 to 60 minutes before flood water arrival. Some people will learn of the flooding indirectly when contacted by friends, neighbors or relatives.

3) Adequate warning means officials or the media begin warning in the particular area more than 60 minutes before the flood water arrives. Some people will learn of the flooding indirectly when contacted by friends, neighbors or relatives.

Flood Severity Understanding is the last factor that has an impact on the fatality rate. The relative understanding of the flood severity is a function of the distance or time from the dam failure or the source and origination of flooding. The farther one is from the source of the flooding, the greater the likelihood that the warning will be precise and accurate. This is because people have seen the flooding in upstream areas, they understand the damage potential of the flooding and the warnings are adjusted to reflect the actual danger. Similarly, the people receiving the warning should obtain a better understanding of the danger to which they are exposed. A warning of potential flooding, before it actually occurs (because a dam has not yet failed or during a flash flood in which the true flood magnitude is often not known until after the event is over), may not be understood by the warning issuers and would therefore be difficult to describe. Recipients of this warning will therefore not get an accurate picture of the flooding about to occur and may not evacuate at all or not as quickly as they should. This factor will come into consideration only when there is some or adequate warning.

The flood severity understanding categories are as follows:

1) Vague Understanding of Flood Severity means that the warning issuers have not yet seen an actual dam failure or do not comprehend the true magnitude of the flooding.

2) Precise Understanding of Flood Severity means that the warning issuers have an excellent understanding of the flooding due to observations of the flooding made by themselves or others.

Summarizing, flood severity can have 3 categories, warning time can have 3 categories, and flood severity understanding can have 2 categories. Flood severity understanding does not apply when there is no warning. There are therefore <u>15</u> different combinations possible.

Table 5 shows the 40 flood events placed in the categories corresponding to the definitions given above. For each flood event evaluated, a determination was made regarding the flood severity category, warning time category and flood severity understanding category that most accurately described the situation at a particular location. Some floods are listed more than once, so from the 40 flood events evaluated, 50 individual entries were made. As an example, Baldwin Hills Dam had approximately 100 people in an area that had medium flood severity, adequate warning and precise flood severity understanding. Baldwin Hills Dam also had 16,400 people in an area that had low flood severity, adequate warning and precise flood severity understanding. Baldwin Hills Dam, therefore, is listed twice in Table 5.

Some categories, such as low severity, adequate warning, have many different entries included in Table 5. This is because there have been many cases where warnings have been issued for benign floods. Some categories, such as high flood severity, some or adequate warning, have no entries. This is because warnings have not been issued prior to the failure of dams like St. Francis or Malpasset, or prior to the non-failure catastrophic flood that originated from the landslide generated wave at Vajont Dam.

Table 6, "Fatality Rates Derived from Case Studies," summarizes data from the case studies evaluated. The table contains the fatality rates for the events presented in Table 5. Values presented include the average of the fatality rates for each category as well as the range. As an example, if there were 3 cases for one particular category, and the fatality rates were 0.01, 0.09 and 0.11, the average was shown as .07 and the range was shown as 0.01 to 0.11.

Table 5

HIGH FLOOD SEVERITY (Area is swept clean, nothing remains)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ (ft$^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
None/Low		Vega De Tera Dam	Spain	1-10-1959	Yes, concrete	125 of 150 buildings destroyed	200	500	3	150	0.30
		Bear Wallow Dam	NC	2-22-1976	Yes	House at bottom of hill buried by debris, soil and rock	n/a	8	1	4	0.5
		St. Francis Dam, Cal. Edison Construction Camp	CA	3-13-1928	Yes, concrete	60 foot flood depth	n/a	150	17	89	0.60
		Armero Lahar	Columbia, South America	12-13-1985	Volcanic eruption caused flooding (mud flow)	Mayor contacted but didn't believe community was at risk. Flood traveled at about 25 mph.	n/a	27,000	37	22,000	0.81
		Stava Dam	Italy	7-19-1985	Yes, mine dam	100 foot flood depth	n/a	300	1	270	0.90
		Vajont Dam	Italy	10-9-1963	No, flood caused by landslide into reservoir	At Longarone, 10 miles farther downstream there were few casualties	n/a	1348	1.5	1269	0.94
		Malpasset Dam	France	12-2-1959	Yes, concrete	100 foot flood depth	n/a	30	0	30	1.00
		St. Francis Dam	CA	3-13-1928	Yes, concrete	How could you survive?	963	n/a	0	n/a	1.00
Some	Vague										
	Precise										
Adequate	Vague										
	Precise										

Table 5 - Continued

MEDIUM FLOOD SEVERITY
(Buildings are destroyed. Trees/crushed houses provide refuge)

WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ (ft$^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
None/Low		Little Deer Dam	Hanna UT	6-16-1963	Yes	Young camper died	n/a	50	?	1	.020
		Buffalo Creek Coal Waste Dam	Man WV	2-26-1972	Yes, coal waste	Informal warnings	20-143	5000	0-14	125	.025
		Shadyside Flood	Shadyside OH	6-14-1990	No	WRI-91-4147 reference	n/a	884	-	24	.027
		Austin Dam	Austin PA	9-30-1911	Yes, concrete	11 to 30 minutes warning	143	2000	1.5	78	.039
		Lawn Lake Dam, Roaring River	Estes Park CO	7-15-1982	Yes	Noise provided alert. Major channel changes.	n/a	25	0-3	1	.040
		Big Thompson Flood	Estes Park CO	7-31-1976	No	Most received no warning	131	2500	-	144	.058
		Malpasset Dam	Frejus, France	12-2-1959	Yes, concrete	10 ft high entering Frejus	n/a	6000	0-7	391	.065
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At Johnstown, major flooding in community before dam failure	100-166	19806	14	1756	.089
		Mill River Dam	Williamsburg MA	5-16-1874	Yes	Some received few minutes warning	25	750	3-7	138	.184
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At Woodvale	166	1247	13	314	.250
		Laurel Run Dam	Johnstown PA	7-20-1977	Yes	Night	200-400	150	0-3	40	.270
		Kelly Barnes Dam	Toccoa GA	11-6-1977	Yes	Night, excludes dorm	96	100	1	36	.360
		Heppner Flood Disaster	Heppner OR	6-14-1903	No	Depth only 5 feet!	72	470	-	200	.430
Some	Vague	Black Hills Flood	Rapid City SD	6-9-1972	No/Yes	3000 injured	42	17000	-	245	.014
	Precise	Teton Dam, Wilford	Idaho	6-5-1976	Yes	The victims had been warned	82	600	8-9	5	.01

Table 5 - Continued

MEDIUM FLOOD SEVERITY (Buildings are destroyed. Trees/crushed houses provide refuge)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ (ft$^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
Adequate	Vague	Arkansas River Flood	Pueblo CO	6-3-1921	No	Floodplain depths up to 15 feet	17.3	2000	-	100	0.05
	Precise	Baldwin Hills Dam, between dam and Sanchez Drive	Los Angeles CA	12-14-1963	Yes	Multiple warnings, day	200	100	0-0.5	0	0.0
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At South Fork	166	200	2	5	.025
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At East Conemaugh	166	2000	11	52	.026
		South Fork Dam	Johnstown PA	5-31-1889	Yes	At Mineral	357	200	7	16	.080

Table 5 - Continued

LOW FLOOD SEVERITY
(Buildings are not washed off foundations)

WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ ($ft^{2/s}$)	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
None/Low		South Davis County Water Imp. Dist. #1 Dam	Bountiful UT	9-24-61	Yes	No warning	16	80	0-1	0	0.0
		Seminary Hill Reservoir	Centralia WA	10-5-91	Yes	No warning	13	150	0-1	0	0.0
		Allegheny County Flood	PA	5-30-86	No	9 homes destroyed, 76 major damage	n/a	2200	-	9	.004
		Mohegan Park Dam	Norwich CT	3-6-63	Yes	5 died in mill collapse	n/a	1000	0-2	7	.007
		Lee Lake Dam	East Lee MA	3-24-68	Yes	6 houses destroyed; 20 damaged	n/a	80	0-5	2	.025
Some	Vague	Lawn Lake Dam, Aspenglen Campground	Estes Park CO	7-15-82	Yes	Victims warned, but not of dam failure	n/a	275	7	2	.007
		Brush Creek Flood	Kansas City KS	9-12-77	No	17 deaths were automobile related	25	2380	-	20	.008
		Austin Flood	Austin TX	5-24&25-81	No	11 deaths were automobile related	n/a	1180	-	13	.011
		Texas Hill Country Flood	TX	8-2-78	No	Nearly placed in medium severity	n/a	2070	-	25	.012
	Precise	Quail Creek Dike (Dam)	St. George UT	1-1-89	Yes	No buildings destroyed?	31	1500	17	0	0.0

Table 5 - Continued

LOW FLOOD SEVERITY (Buildings are not washed off foundations)											
WARNING TIME	FLOOD SEVERITY UNDERSTANDING	EVENT	GENERAL LOCATION	DATE	DAM FAILURE?	COMMENTS	$\frac{Q-Q_{2.33}}{\text{FLOOD WIDTH}}$ $(\text{ft}^{2/s})$	NUMBER OF PEOPLE AT RISK	MILES FROM DAM FOR PEOPLE AT RISK	DEATHS	FATALITY RATE
Adequate	Vague										
	Precise	Phoenix Area Flood	Phoenix AZ	2-80	No	11 of 13 bridges destroyed	n/a	6,000	-	0	0.0
		Bushy Hill Pond Dam	Essex CT	6-6-82	Yes	Night	n/a	300	0-2	0	0.0
		Lawn Lake Dam, downstream from National Park	Estes Park CO	7-15-82	Yes	Good warning	n/a	4,000	8-14	0	0.0
		Prospect Dam	CO	2-10-80	Yes	Not much damage	4	100	?	0	0.0
		South Platte River Flood	Denver CO	6-16-65	No	Up to 4 hours warning	19	10,000	-	1	.0001
		Passaic River Basin Flood	Northern NJ	4-84	No	Sluggish flood	n/a	25,000	-	2	.0001
		Flooding from Hurricane Agnes	PA only	6-92	No	>3500 dwellings or mobile homes destroyed. Water rose much slower than in many dambreak floods	n/a	250,000	-	48	.0002
		Kansas River	Eastern Kansas	7-51	No	Sluggish major flood, up to 30 feet deep	25-56	58,010	-	11	.0002
		Teton Dam (Rexburg to Amn. Falls)	ID	6-5-76	Yes	Some homes destroyed	n/a	23,000	15-156	5	.0002
		Great flood of 1993	Midwest US	1993	No	Sluggish flood	n/a	150,000	-	38	.0003
		Baldwin Hills Dam, between Sanchez Drive and Coliseum	Los Angeles CA	12-14-63	Yes	Multiple warnings, day	67	16,400	0.5-1.0	5	.0003
		DMAD Dam	Delta UT	6-23-83	Yes	Benign flooding, transient died	n/a	500	15	1	.0020

Table 6
Fatality Rates Derived from Case Studies
(Use Table 7 for selecting fatality rates)

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk that died)	
			Average	Range
HIGH	no warning	not applicable	0.76	0.3 to 1.00
	15 to 60	vague	No case fit this category.	
		precise	No case fit this category.	
	more than 60	vague	No case fit this category.	
		precise	No case fit this category.	
MEDIUM	no warning	not applicable	0.14	0.02 to 0.43
	15 to 60	vague	0.014	only one case
		precise	0.01	only one case
	more than 60	vague	0.05	only one case
		precise	0.035	0.0 to 0.080
LOW	no warning	not applicable	0.007	0.0 to 0.025
	15 to 60	vague	0.0095	0.007 to 0.012
		precise	0.0	only one case
	more than 60	vague	No case fit this category	
		precise	0.0003	0.0 to .002

GUIDANCE ON USING THE FLOOD SEVERITY BASED METHOD FOR ESTIMATING LIFE LOSS

Table 7, "Recommended Fatality Rates for Estimating Loss of Life Resulting from Dam Failure," contains recommended fatality rates for each of the 15 different combinations of flood severity, warning time and flood severity understanding. The fatality rates shown in Table 7 were derived from those shown in Table 6. Some changes were made in preparing Table 7 from Table 6 so that there was a consistent pattern in the fatality rates. The changes were based on judgement rather than any statistical analysis of the data. The suggested fatality rate range shown in Table 7 does not always capture the full range shown in Table 6. For those categories in which there were few or no cases, judgement was used in estimating a fatality rate and in developing a suggested range. In determining whether the flood severity is low, medium or high, use the following guidance:

1) Use low severity for locations where no buildings are washed off their foundation.

2) Use medium severity for locations where homes are destroyed but trees or mangled homes remain for people to seek refuge in or on.

3) Use high flood severity only for locations flooded by the near instantaneous failure of a concrete dam, or an earthfill dam that turns into "jello" and goes out in seconds rather than minutes or hours. In addition, the flooding caused by the dam failure should sweep the area clean and little or no evidence of the prior human habitation remains after the floodwater recedes. Nearly all of the events used in defining this category caused very deep floodwater that reached its ultimate height in just a few minutes. The flood severity will usually change to medium and then low as the floodwater travels farther downstream.

4) In determining whether flooding is low severity or medium severity, use low severity if most of the structures will be exposed to depths of less than 10 feet and medium severity if most of the structures will be exposed to depths of 10 feet or more. (Note that low severity flooding can be quite deadly to people attempting to drive vehicles).

Another method that can be used to separate low severity flooding from medium severity flooding is to use the parameter DV where:

$$DV = \frac{Q_{df} - Q_{2.33}}{W_{df}}$$

And:

Q_{df} is the discharge at a particular site caused by dam failure.

$Q_{2.33}$ is the mean annual discharge at the same site. This discharge can be easily estimated and it is an indicator of the safe channel capacity. As discharges increase above this value, there is a greater chance that it will cause overbank flooding.

W_{df} is the maximum width of flooding caused by dam failure at the same site.

The units of DV is d^2/s or depth times velocity, thus the term DV. Although the parameter DV is not representative of the depth and velocity at any particular structure, it is representative of the general level of destructiveness that would be caused by the flooding. The parameter DV should provide a good indication of the severity (potential lethality) of the flooding. As the peak discharge from dam failure increases, the value of DV increases. As the width of the area flooding narrows, the value of DV again increases.

Low flood severity should be assumed, in general, when DV is less than 50 ft^2/s (4.6 m^2/s). Medium flood severity should be assumed, in general, when DV is more than this value.

The warning time for a particular area downstream from a dam should be based on when a dam failure warning is initiated and the flood travel time. For instance, assume a dam with a campground immediately downstream and a town where flooding begins 4 hours after the initiation of dam failure. If a dam failure warning is initiated 1 hour after dam failure, the warning time at the campground is zero and the warning time at the town is 3 hours.

The preponderance of dam failure data indicates that a high percentage of life loss resulting from dam failure occurs in the first 15 mi (25 km) downstream from a dam that has failed. For smaller dams this distance is considerably less than 15 mi (25 km). Loss of life, as a percentage of people at risk, becomes very small more than 15 mi (25 km) downstream from a dam for two main reasons. First, these downstream areas receive warning that usually is much better than the warning, if any, issued in areas nearer the dam; and second, the energy exhibited by the flood is lessened, the flood rises at a slower rate and the leading edge of the flooding usually moves at a slower rate in these downstream areas. Based on these empirical data and recognizing that the failure of some large dams could result in loss of life patterns or characteristics that are not observable with this same data base, loss of life studies should extend downstream from a dam for 30 mi (50 km). There may be some very high dams, or those storing very large quantities of water, where severe flooding could extend for 100 miles (161 km) or more downstream from the dam. In these cases, loss of life studies may be extended more than 30 mi (50 km) downstream from the dam. In general, however, life loss more than 30 mi (50 km) downstream from a dam should be very small compared to the life loss estimated for the areas nearer the dam. It is not anticipated that the life loss downstream from mile 30 (50 km) would change the results of a dam safety recommendation.

Table 7
Recommended Fatality Rates for Estimating Loss of Life Resulting from Dam Failure

Flood Severity	Warning Time (minutes)	Flood Severity Understanding	Fatality Rate (Fraction of people at risk expected to die)	
			Suggested	Suggested Range
HIGH	no warning	not applicable	0.75	0.30 to 1.00
	15 to 60	vague	Use the values shown above and apply to the number of people who remain in the dam failure floodplain after warnings are issued. No guidance is provided on how many people will remain in the floodplain.	
		precise		
	more than 60	vague		
		precise		
MEDIUM	no warning	not applicable	0.15	0.03 to 0.35
	15 to 60	vague	0.04	0.01 to 0.08
		precise	0.02	0.005 to 0.04
	more than 60	vague	0.03	0.005 to 0.06
		precise	0.01	0.002 to 0.02
LOW	no warning	not applicable	0.01	0.0 to 0.02
	15 to 60	vague	0.007	0.0 to 0.015
		precise	0.002	0.0 to 0.004
	more than 60	vague	0.0003	0.0 to 0.0006
		precise	0.0002	0.0 to 0.0004

Closing Comments on the Flood Severity Based Method

High Severity flooding is not well represented in the data base. In order to estimate loss of life for these events, there is a need to determine the number of people who will remain in the dam failure floodplain after warnings are issued. At this time, no guidance is being provided on this topic.

Medium Severity flooding results in a wide range of fatality rates, especially when there is no warning. Factors that influence this range would include: do some people evacuate in response to environmental clues, are people awake, is it night and is it raining? Laurel Run and Kelly Barnes dam failures both had high fatality rates and in each case the events occurred at night and no knowledge of impending dam failure was available to people at risk. The Heppner, Oregon Disaster, with the highest fatality rate, was a very unusual case. A USGS Water Supply Paper stated, "It seems almost incredible that a flood of a depth of only 5 feet above the general level of the town should cause such a loss of life....Nearly all of the houses simply rested on posts or open foundations of stone....So they lifted off their foundations and floated away like boats." The USGS learned that "No building that can be lifted from its foundation and swept away should be allowed in the area of a possible flood." - The beginnings of floodplain management concepts, nearly 100 years ago!

Low Severity flooding results in low fatality rates, regardless of the quantity and quality of warnings. The people writing about these floods at the time frequently commented on the low fatality rates. Examples include: Kansas River Flood of 1951: "And the wonder is that the death list was not longer." Hurricane Agnes flooding of 1972: "The death toll of 117 was light considering the severity of the widespread floods." Phoenix area flooding of 1980: "Three people died in Arizona, a surprisingly low number considering the magnitude of the damage."

Using the recommended fatality rates based on the flood severity, warning time and flood severity understanding, can produce results much different than the results obtained with the Brown and Graham or DeKay and McClelland equations. For instance, take a community of 10,000 people exposed to medium severity flooding with 1.5 hours of warning. The Brown and Graham equations predicts 2 fatalities and the DeKay and McClelland equation for high lethality predicts about 7 fatalities. The fatality rate in Table 7 for precise warning issued more than 60 minutes before flood arrival results in a predicted 100 fatalities.

The fatality rate in areas with medium severity flooding should drop below that recommended in Table 7 as the warning time increases well beyond one hour. Repeated dam failure warnings, confirmed by visual images on television showing massive destruction in upstream areas, should provide convincing evidence to people that a truly dangerous situation exists and of their need to evacuate. This should result in higher evacuation rates in downstream areas and in a lowering of the fatality rate.

Step 7: Evaluate Uncertainty

Estimating loss of life from dam failure is an art as much as it is a science. There may never be a procedure available that will provide precise and accurate estimates of the loss of life that results from failure.

There are various types of uncertainty that can influence loss of life estimates. One type of uncertainty deals with the cause of dam failure. Step 1 of this procedure suggests that separate loss of life estimates be developed for each failure cause of interest. Various causes of dam failure will result in differences in downstream flooding and therefore result in differences in the number of people at risk as well as the severity of the flooding. Dam failure modeling, which serves as a basis for developing dam failure flood boundaries, flood severity and flood wave travel times, is also fraught with many types of estimates and uncertainty. Another type of uncertainty, generally random in nature, is the time of day, time of week and time of year that failure occurs. Step 2 of this procedure suggests once again that separate loss of life estimates be developed for various possible combinations. The time at which warning is initiated and the number of people at risk may depend upon the time at which failure occurs.

Additional uncertainty is associated with when warnings would be initiated. Step 3 and Table 2 provide guidance on when warnings would be initiated. Other warning scenarios may be equally or more likely. Uncertainty associated with warning initiation can be evaluated by varying the assumption regarding when a warning would be initiated.

The last type of uncertainty is associated with the inability to precisely determine the fatality rate. There was uncertainty associated with categorizing some of the flood events that are included in Table 5. Similarly, some of the factors that contribute to life loss are not captured in the categories shown in Tables 6 and 7. This type of uncertainty can introduce significant, but unknown, errors into the loss of life estimates. Some possible ways of handling this uncertainty would be to 1) use the range of fatality rates shown in Table 7, 2) when the flooding at a particular area falls between two categories (it is unclear if the flood severity would be medium or low, for example) the loss of life estimates can be developed using the fatality rate and range of rates from all categories touched by the event and 3) the events cataloged in table 5 can be evaluated to see if there are any that closely match the situation at the site under study.

SUMMARY

The procedure described herein provides a method for estimating the loss of life resulting from dam failure. The procedure was developed using data from about 40 floods, many of which were caused by dam failure. The procedure suggests that fatality estimates be developed for different failure causes and for different times of the day, week or year. The procedure contains guidance on when a dam failure warning would be issued and this warning initiation is based on the drainage area at the dam, the number of formal and informal dam observers, and the time of day (or night) when failure occurs. The procedure then provides fatality rates for converting population at risk to probable life loss. The fatality rates are a function of flood severity, warning time for each group of people at risk, and flood severity understanding. This last factor will influence the quality and accuracy of the warning messages and will influence the response taken by people at risk. The procedure provides a discussion of uncertainty and how it can be evaluated.

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ASDSO/FEMA Specialty Workshop on
Risk Assessment for Dams

Session 3.1 – Quantitative Approaches – State of the Practice:

Tolerable Risk Criteria/ Public Protection Guidelines

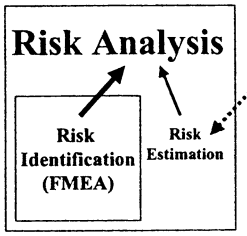
March 8, 2000

David S. Bowles
Utah State University and RAC Engineers & Economists

The process of determining a) what can go wrong, why and how, and b) its (project) effects and consequences

Risk Identification (FMEA)

The process of quantifying risk - probability and consequences



Risk Analysis

Risk Identification (FMEA)

Risk Estimation

ORGANISATIONAL CONTEXT FOR RISK MANAGEMENT

Risk management takes place in the *context* of *wider goals*, *objectives* and *strategies* of the organisation.

Organisational policy and goals help define the *criteria* by which it is decided whether a risk is *acceptable* or not, and form the basis for options for *treatment.*

AS/NZS 4360:1995

Defining the Decision Framework

- Decision process
- Decision makers & Stakeholders
  - in-house
  - regulator
  - community
  - interest groups
- Decision criteria
  - external - regulation, guidelines, practice
  - internal - business, role, public trust, reputation
- Information needs from RA

ACCEPTABLE RISK

... the determination of acceptable risk levels depends fundamentally and inescapably on *value judgments* which cannot be standardized or quantified.

... there are *no independent variables or physical constants* in the process of risk acceptance.

Therefore, from a societal point of view, *quantitative methods must be contained and controlled within decision-making processes* that can be depended upon to take account of societal values.

...acceptable risks can be determined only through *acceptable (decision) processes*;

... it is not necessary to agree with the decision to find it acceptable.

Reid (1992)

Tolerable Risk

- “Risk is *not regarded as negligible* or something that can be ignored, but *must be kept under review and reduced further still!*”

Health and Safety Executive, UK, 1998

QUANTITATIVE CRITERIA serve a useful role in the risk evaluation process, but dam safety *decisions should be made by those responsible for ensuring dam safety* after all the relevant factors are assessed and weighed; *they should not be the automatic result of applying a criterion* to the results of a risk analysis.

Bowles 1998

Life safety criteria

One organisation's criteria may not be appropriate for another organisation

- Individual:
  - ANCOLD (1994)
- Societal:
  - USBR (1997) Public Protection Guidelines
  - B.C. Hydro (1993)
  - ANCOLD (1998)

INDIVIDUAL RISK

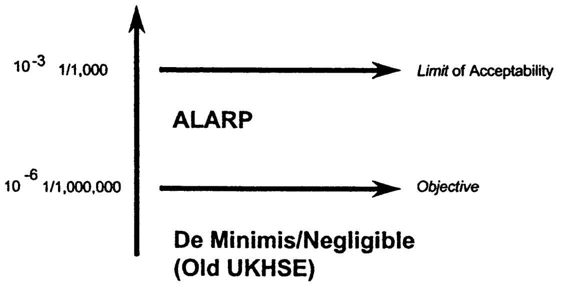
- is negligible (i.e. tolerably low) if it is similar to the risk of life loss due to natural hazards

  ... about 1 in 1 million years or 10^{-6} per annum

- is excessive (i.e. unacceptably high) if it is similar to the risk of life loss due to disease

  ... about 1 in 1 thousand years or 10^{-3} per annum

Individual Risk



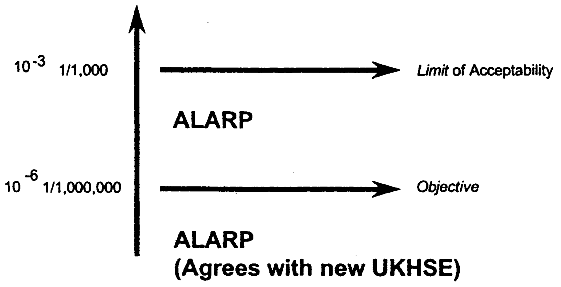
10^{-3} 1/1,000 → *Limit* of Acceptability

ALARP

10^{-6} 1/1,000,000 → *Objective*

De Minimis/Negligible
(Old UKHSE)

Individual Risk



10^{-3} 1/1,000 → *Limit* of Acceptability

ALARP

10^{-6} 1/1,000,000 → *Objective*

ALARP
(Agrees with new UKHSE)

ANCOLD (1994) *individual* risk criteria

- Objective: for upgrading existing dams
  - 1×10^{-6} per exposed person per year *averaged over Population at Risk (PAR)*
  - 1×10^{-5} per year for the *person at greatest risk*
- Limit: up to 10 times Objective might be tolerable for existing dams subject to ALARP

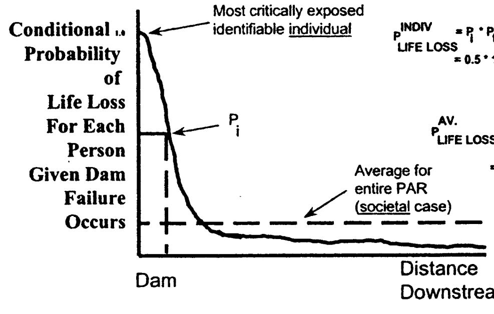
Individual Risk - Identifiable Individual (Bowles 1996)

BENCHMARKS		COMPARISON OF STANDARDS			
Natural Events	Man-Caused Events	Per Year Probability	Dams	Hazardous Industry	Nuclear Power Plants
		10^{-3}			
Disease - 30 Yr. Old	Motor Vehicles	10^{-4}	L-ANCOLD (existing) L-BC HYDRO	L-NEW (existing) L-Netherland	L-UKHSE
		10^{-5}	O-ANCOLD (existing) L-ANCOLD (new/upgrade)	L-WA (new) L-Hong Kong (new) L-UKHSE	
All Nat. Hazs	Air Travel	10^{-6}	O-ANCOLD (new/upgrade)	L-Netherland (new) WA (new) O-UKHSE	O-UKHSE
Lightning					O-USNRC
Hurricanes		10^{-7}			

UKHSE - United Kingdom Health & Safety Executive
NSW - New South Wales
WA - Western Australia
USNRC - United States Nuclear Regulatory Commission

L = Limit Standard
O = Objective Standard

Relationship Between Individual and Average (Societal) Probability of Life Loss



$P^{INDIV}_{LIFE\ LOSS} = P_i \cdot P_f = 0.5 \cdot 10^{-4}$ per year

$P^{AV.}_{LIFE\ LOSS} = \frac{N}{PAR} \cdot P_f = \frac{10}{1{,}000} \cdot 10^{-4} = 1 \times 10^{-7}$ per year

Life safety criteria

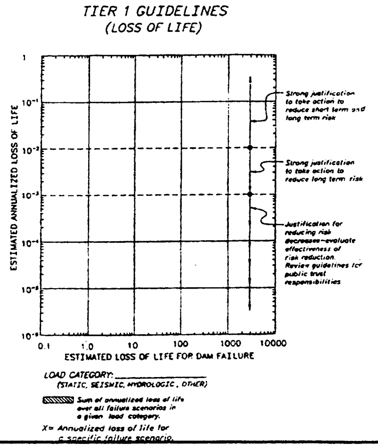
One organisation's criteria may not be appropriate for another organisation

- Individual:
  - ANCOLD (1994)
- Societal:
  - USBR (1997) Public Protection Guidelines
  - B.C. Hydro (1993)
  - ANCOLD (1998)

USBR Public Protection Guidelines

Tier 1 - Expected incremental life loss

- For each loading type (floods, earthquakes, static):
- **> 0.01 lives/yr = STRONG JUSTIFICATION** for *short and long term* measures
- **< 0.01 & > 0.001 lives/yr = STRONG JUSTIFICATION** for *long term* measures
- **< 0.001 lives/yr = DIMINISHED JUSTIFICATION** for *long term* measures
  - evaluate (cost) effectiveness (ALARP) and
  - public trust responsibilities

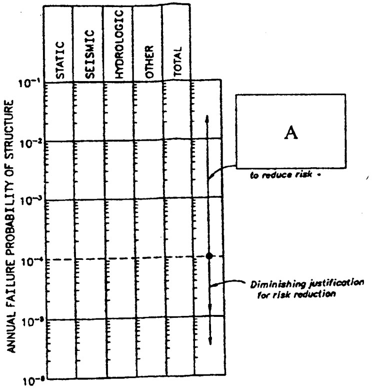


USBR Public Protection Guidelines

Tier 2 - Probability of failure

- Totaled over all loading types:
- **> 1 in 10,000/yr = INCREASING JUSTIFICATION** for reducing probability of failure
- **< 1 in 10,000/yr = DIMINISHING JUSTIFICATION** for reducing probability of failure

TIER 2 GUIDELINES
(FAILURE EVENT PROBABILITY)

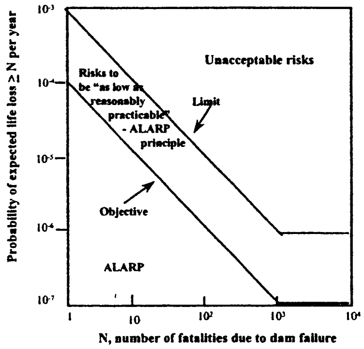


BC Hydro Interim Criteria

- For total risk over all loading types:
  - Expected incremental life loss < 0.001 lives/year
  - Incremental risk cost < C$10,000/year
  - ALARP principle
- *BC Hydro has completed standards-level fixes at most dams*
  - *now focusing on consequences to manage dam safety*

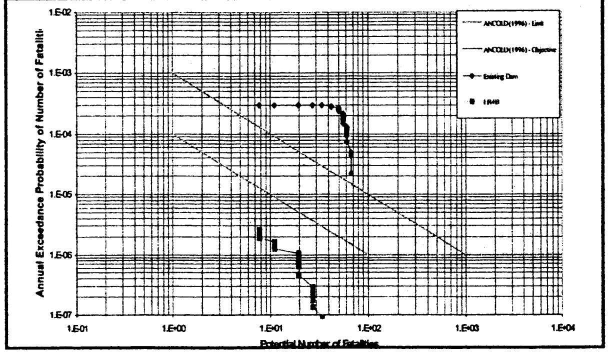
Build F-N

ANCOLD (1998) revised interim *Societal* Risk Criteria



Existing Dam *vs.* 300 m long Fuse Plug in Low Embankment - Lake Buffalo Dam

ANCOLD Interim Societal Risk Criteria (F-N)



Annualized Risk Reduction - Benefits

$\text{Ann. Risk}_{\text{Existing Dam}} - \text{Ann. Risk}_{\text{Fix}}$

1) Life Safety Ann. Risk
   = Life loss * Prob. of life loss in lives/year
2) Economic Risk Cost
   = Economic Loss * Prob. of failure in $/year
3) Prob. of failure in /year

ALARP Principle

"as low as reasonably practicable"

- Risks are "acceptable only if reasonable practical measures have been taken to reduce risks" (IAEA 1992)
- Economic basis for ALARP (Rowe 1977):
  - Cost-per-life-saved
  - Diminishing economic returns
- ALARP should be applied below objective as well as between limit and objective criteria

Cost-per-statistical-life-saved (CPSLS)
AIR BAGS - HYPOTHETICAL

- $500 per air bag
- 10 million new cars per year
- $5B COST per year
- 50,000 deaths per year
- Say 5,000 lives saved per year by air bags
- Then $5B COST per year SAVES 5,000 lives per year
- CPSLS = $5B/5,000 lives
  = $1M per statistical life saved

Cost Per Life Saved

$$\frac{\text{Cost of Fix} \quad - \quad \text{Economic Benefits}}{\text{Life Loss}_{\text{existing}} \qquad \text{Life Loss}_{\text{fix}}}$$

$$\frac{\$/\text{Year}}{\text{Lives/Year}} = \frac{\$}{\text{Lives}}$$

COST-PER-(STATISTICAL) LIFE-SAVED

EXAMPLE: Existing dam consequences: 1 in 100 /yr, 30 lives

a) Level 1 Rehab: Cost = \$3.2 M/yr, Benefits = \$0.2 M/yr
Consequences: 1 in 10,000 /yr, 100 lives

$$\text{Cost-per-life-saved} = \frac{\text{Rehab. cost} \quad - \quad \text{Rehab. benefit}}{\text{Prob*Lives}_{\text{exist}} - \text{Prob*Lives}_{\text{rehab}}}$$

$$= \frac{\$3.2 - 0.2}{1/100 \times 30 - 1/10{,}000 \times 100} = \frac{3.0}{0.3}$$

$$= \mathbf{\$10\ M/life\ saved}$$

b) Level 2 Rehab: Cost: \$3.01 M/yr, Benefits: \$0.01 M/yr
Consequences: 1 in 1,000,000 /yr, 100 lives

$$\text{Cost-per-life-saved} = \frac{\$3.01 - 0.01}{1/10{,}000 \times 100 - 1/1{,}000{,}000 \times 100} = \frac{3.0}{0.001}$$

$$= \mathbf{\$3\ B/life\ saved}$$

CPLS DOES NOT INVOLVE PLACING A VALUE ON HUMAN LIFE

If *individual or population (societal) risk* alone is used in setting program priorities, there is no guarantee that the programs selected are reducing risk sensibly. Large individual or population risks, that are very expensive to reduce, may not be *cost effective*. Only by considering both the *benefits* and the *costs* of risk reduction can sensible decisions be made.

- U.S. Federal Budget, 1992

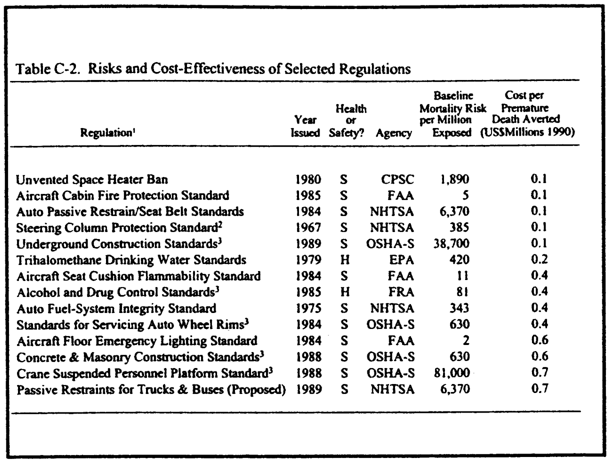


Table C-2. Risks and Cost-Effectiveness of Selected Regulations

Regulation[1]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted (US$Millions 1990)
Unvented Space Heater Ban	1980	S	CPSC	1,890	0.1
Aircraft Cabin Fire Protection Standard	1985	S	FAA	5	0.1
Auto Passive Restrain/Seat Belt Standards	1984	S	NHTSA	6,370	0.1
Steering Column Protection Standard[2]	1967	S	NHTSA	385	0.1
Underground Construction Standards[3]	1989	S	OSHA-S	38,700	0.1
Trihalomethane Drinking Water Standards	1979	H	EPA	420	0.2
Aircraft Seat Cushion Flammability Standard	1984	S	FAA	11	0.4
Alcohol and Drug Control Standards[3]	1985	H	FRA	81	0.4
Auto Fuel-System Integrity Standard	1975	S	NHTSA	343	0.4
Standards for Servicing Auto Wheel Rims[3]	1984	S	OSHA-S	630	0.4
Aircraft Floor Emergency Lighting Standard	1984	S	FAA	2	0.6
Concrete & Masonry Construction Standards[3]	1988	S	OSHA-S	630	0.6
Crane Suspended Personnel Platform Standard[3]	1988	S	OSHA-S	81,000	0.7
Passive Restraints for Trucks & Buses (Proposed)	1989	S	NHTSA	6,370	0.7

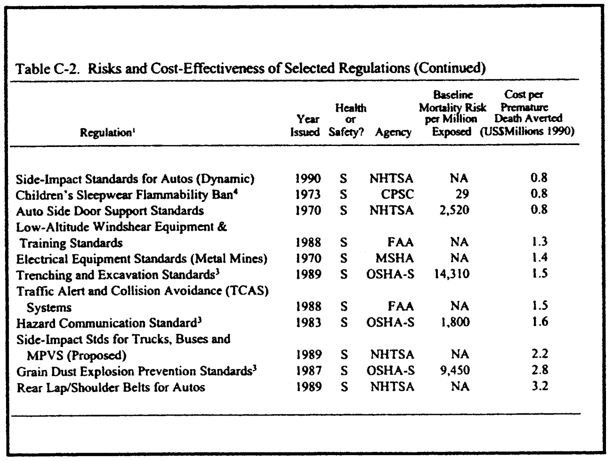


Table C-2. Risks and Cost-Effectiveness of Selected Regulations (Continued)

Regulation[1]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted (US$Millions 1990)
Side-Impact Standards for Autos (Dynamic)	1990	S	NHTSA	NA	0.8
Children's Sleepwear Flammability Ban[4]	1973	S	CPSC	29	0.8
Auto Side Door Support Standards	1970	S	NHTSA	2,520	0.8
Low-Altitude Windshear Equipment & Training Standards	1988	S	FAA	NA	1.3
Electrical Equipment Standards (Metal Mines)	1970	S	MSHA	NA	1.4
Trenching and Excavation Standards[3]	1989	S	OSHA-S	14,310	1.5
Traffic Alert and Collision Avoidance (TCAS) Systems	1988	S	FAA	NA	1.5
Hazard Communication Standard[3]	1983	S	OSHA-S	1,800	1.6
Side-Impact Stds for Trucks, Buses and MPVS (Proposed)	1989	S	NHTSA	NA	2.2
Grain Dust Explosion Prevention Standards[3]	1987	S	OSHA-S	9,450	2.8
Rear Lap/Shoulder Belts for Autos	1989	S	NHTSA	NA	3.2

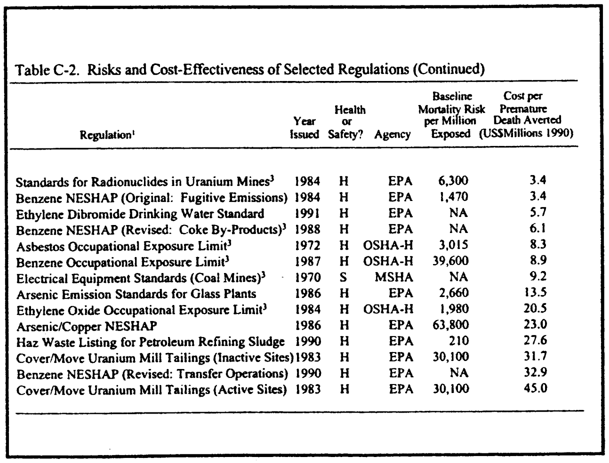


Table C-2. Risks and Cost-Effectiveness of Selected Regulations (Continued)

Regulation[1]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted (US$Millions 1990)
Standards for Radionuclides in Uranium Mines[3]	1984	H	EPA	6,300	3.4
Benzene NESHAP (Original: Fugitive Emissions)	1984	H	EPA	1,470	3.4
Ethylene Dibromide Drinking Water Standard	1991	H	EPA	NA	5.7
Benzene NESHAP (Revised: Coke By-Products)[3]	1988	H	EPA	NA	6.1
Asbestos Occupational Exposure Limit[3]	1972	H	OSHA-H	3,015	8.3
Benzene Occupational Exposure Limit[3]	1987	H	OSHA-H	39,600	8.9
Electrical Equipment Standards (Coal Mines)[3]	1970	S	MSHA	NA	9.2
Arsenic Emission Standards for Glass Plants	1986	H	EPA	2,660	13.5
Ethylene Oxide Occupational Exposure Limit[3]	1984	H	OSHA-H	1,980	20.5
Arsenic/Copper NESHAP	1986	H	EPA	63,800	23.0
Haz Waste Listing for Petroleum Refining Sludge	1990	H	EPA	210	27.6
Cover/Move Uranium Mill Tailings (Inactive Sites)	1983	H	EPA	30,100	31.7
Benzene NESHAP (Revised: Transfer Operations)	1990	H	EPA	NA	32.9
Cover/Move Uranium Mill Tailings (Active Sites)	1983	H	EPA	30,100	45.0

Table C-2. Risks and Cost-Effectiveness of Selected Regulations (Continued)

Regulation[1]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted (US$Millions 1990)
Acrylonitrile Occupational Exposure Limit[3]	1978	H	OSHA-H	42,300	51.5
Coke Ovens Occupational Exposure Limit[3]	1976	H	OSHA-H	7,200	63.5
Lockout/Tagout[3]	1989	S	OSHA-S	4	70.9
Asbestos Occupational Exposure Limit[3]	1986	H	OSHA-H	3,015	74.0
Arsenic Occupational Exposure Limit[3]	1978	H	OSHA-H	14,800	106.9
Asbestos Ban	1989	H	EPA	NA	110.7
Diethylstilbestrol (DES) Cattlefeed Ban	1979	H	FDA	22	124.8
Benzene NESHAP (Revised: Waste Operations)	1990	H	EPA	NA	168.2
1,2-Dichloropropane Drinking Water Standard	1991	H	EPA	NA	653.0
Haz Waste Land Disposal Ban (1st 3rd)	1988	H	EPA	2	4,190.4
Municipal Solid Waste Landfill Standards (Proposed)	1988	H	EPA	<1	19,107.0
Formaldehyde Occupational Exposure Limit[3]	1987	H	OSHA-H	31	86,201.8

Table C-2. Risks and Cost-Effectiveness of Selected Regulations (Continued)

Regulation[1]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted (US$Millions 1990)
Atrazine/Alachlor Drinking Water Standard	1991	H	EPA	NA	92,069.7
Haz Waste Listing for Wood Preserving Chem.	1990	H	EPA	<1	5,700,000.0

[1] 70-year lifetime exposure assumed unless otherwise specified
[2] 50-year lifetime exposure
[3] 45-year lifetime exposure
[4] 12-year exposure period
NA=Not available
Agency Abbreviations--CPSC: Consumer Product Safety Commission; MSHA: Mine Safety and Health Administration; EPA: Environmental Protection Agency; NHTSA: National Highway Traffic Safety Administration; FAA: Federal Aviation Administration; FRA: Federal Railroad Administration; FDA: Food and Drug Administration; OSHA-H: Occupational Safety and Health Administration, Health Standards; OSHA-S: Occupational Safety and Health Administration, Safety Standards.
Source: John F. Morrll, III, "A Review of the Record." *Regulation*, Vol. 10, No. 2 (1986), p. 30. Updated by the Author, et al.

ALARP Justification - CPLS

(Viscusi 1998) ~ $ are per statistical life saved

- U.S. Federal government practice
  - USDOT: refuses > **US$3M**
  - OMB: **US$140M**
- If entire US GDP spent on prevention of accidental death: **US$55M**
- Implicit accident prevention *spending* values: **US$5M ($3M - $7M)**
  - approximately 10x greater than accident victim *compensation* from product liability suits (Ford Pinto)
  - serves a *deterrent purpose* to determine level of spending (investment) in safety
- Dams that we have assessed: **US$0 - $10**

ALARP Justification

Based on U.S. Federal government practice

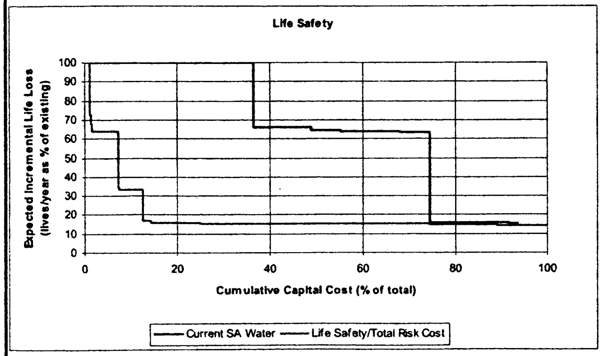
(USDOT has refused > $3M - OMB max. used: $140M)

Cost Effectiveness of Risk Reduction

(e.g. Cost per Statistical Life Saved)

- 1) Used for evaluating ALARP
  - legal obligation
- 2) Used for maximising rate of risk reduction
  - cost effectiveness = "bang for the buck"

PRA Prioritization vs. Current SA Water Program Life Loss Risk Reduction



DE MINIMIS RISK

"de minimis non curat lex" meaning the law does not concern itself with trifles

Shortreed et all (1995)

so low that it does not concern people

Whipple (1986)

DE MINIMIS RISK

A dam owner may have a legal obligation to implement a relatively low cost fix even if it is not cost effective

Bowles 1998

De Minimis Risk Justification

An example

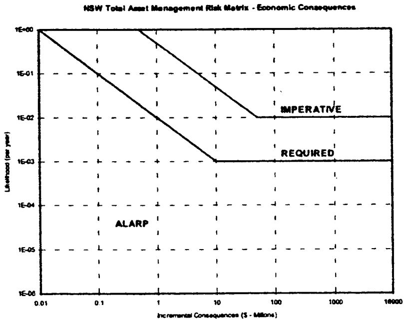
Economic criteria

One organisation's criteria may not be appropriate for another organisation

- NSW (1993) Total Asset Management risk matrix for economic consequences

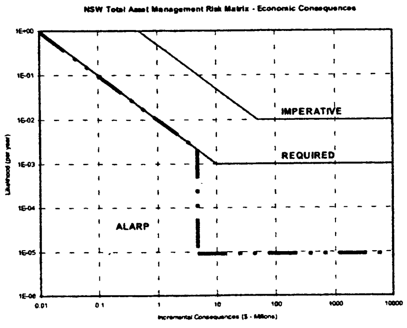
NSW Total Asset Management

EXAMPLE Risk Matrix - Financial Consequences



NSW Total Asset Management

EXAMPLE Risk Matrix - Financial Consequences



Economic criteria

One organisation's criteria may not be appropriate for another organisation

- NSW (1993) Total Asset Management risk matrix for economic consequences
- Cost-per-(statistical) life-saved
- Other economic criteria
  - Benefit:cost Ratio
  - Net Present Value
  - Internal Rate of Return
  - Total Economic Cost

Incorporating Uncertainty in Risk Evaluation

Rating for Engineering Assessment Summary based on Current Practice, Standards and Guidelines			Additional Investigations Needed?	Formulate Risk Reduction Measure for Evaluation in RA?
Rating Symbol	**Definition**	**Interpretation**		
P	Pass	Has been signed off as a "P" against current practice	None	No
AP	Apparent Pass	Has NOT been signed off against current practice - best judgement is that will "P" after additional investigations are completed	Yes to establish if a P or NP.	No
ANP	Apparent No Pass	Has NOT been signed off against current practice - best judgement is that will be a "No Pass" after additional investigations are completed	Yes to establish if a P or NP	Yes. For "state-of-the-art" issues may decide to continue monitoring performance
NP	No Pass	Has been signed off as a "NP" against current practice	None to establish NP, but some may be needed for design of fix	Yes
?		Insufficient information available to make a judgement. TRY TO AVOID THIS RATING IF POSSIBLE.	Yes	Yes, but flag the higher uncertainty associated with whether or not the measure will be needed.
(__)		Indicates that a "NP" or "ANP" rating is not considered to be associated with a plausible failure (breach) mode		

NOTES:

1) Ratings can be applied to individual assessments, or groups of assessments for loading (flood, earthquake, normal operating) - subsystems for a dam

2) When determining a rating across a groups of assessments, the lowest level of rating (P, AP, ANP, P from highest to lowest) is assigned for ratings without and with parentheses (brackets), e.g. AP(ANP)

3) For assessments that are set up with increasing levels of detail (e.g. ANCOLD 1998 Earthquake Guidelines), a P can be assigned at a low level of detail if it is current acceptable practice to "Pass" a dam based on this level of detail. However, if a dam does "Not Pass" at the low level of detail, it should be rated as "AP" or "ANP" based on best judgement of the outcome of more detailed levels of assessment.

David S. Bowles: 22 November 1999

XYZ DAM - Engineering Assessment Summary based on Current Practice, Standards and Guidelines

Flood	Rating		Earthquake	Rating		Normal Operating	Rating	
CONCRETE GRAVITY DAM			**CONCRETE GRAVITY DAM**			**CONCRETE DAM**		
ANCOLD 1991		P	ANCOLD 1991		P	ANCOLD 1991		NP
Foundation piping		AP 1)	ANCOLD 1998		AP	Piers		**P**
Stilling basin undermining		P	Piers		P	Gate		**P**
Drains		ANP	Gates		ANP			
SPILLWAY			**SPILLWAY**			**SPILLWAY**		
Spillway capacity		P	Piers - ANCOLD 1991		AP			
Spillway training walls - structural stability		ANP	Gates - ANCOLD 1998		AP			
Spillway training walls - hydraulic adequacy		AP	Spillway Walls		ANP			
Gates		P						
Structural (spillway training walls)								
EMBANKMENT DAMS	**Right**	**Left**	**EMBANKMENT DAMS**	**Right**	**Left**	**EMBANKMENT DAMS**	**Right**	**Left**
Toe erosion	N/A	N/A	**Embankment**			Embankment	P	P
Wave action	ANP	ANP	Liquefaction	P	P	Piping	NP	AP
Outlet works	N/A	N/A	stability	P	P	filters	NP	NP
			Piping	NP	NP	Slope stability	P	P
			Foundation			Foundation	P	P
			Liquefaction	P	P			
			stability	P	P			
						Reservoir rim stability	P	P
OVERALL RATINGS		**ANP**			**NP**			**NP**

Further investigations need to reach final assessment: LIST USING FOOTNOTES FOR ALL AP'S OR ANP'S

1) ....

Prepared by David S. Bowles 3/8/00

Table I.1-1. Summary of risk evaluation ratings.

Risk Evaluation Type			Rating Code	Explanation
Life Safety-Societal Risk	ANCOLD (1998) Interim Amended Societal Risk Criteria *(for all failure modes combined)*	Limit	N	Does not meet limit criterion - F-N plots above limit criterion
			Y	Meets limit criterion - F-N plots below limit criterion
		Objective	N	Does not meet objective criterion - F-N plots above objective criterion
			Y-ALARP?	Meets objective criterion, but ALARP must be evaluated - F-N plots below objective criterion
	USBR (1997) Interim Tier 1 Public Protection Guidelines *(for flood, earthquake and static failure modes separately)*		N-StrongL&S	Strong justification for long- and short-term risk reduction measures - Expected incremental loss of life exceeds 0.01 lives/year
			N-StrongL	Strong justification for long-term risk reduction measures - Expected incremental loss of life between 0.01 and 0.001 lives/year
			Y-ALARP?	Diminished justification for long-term risk reduction measures (i.e. ALARP must be evaluated) – Expected incremental loss of life less than 0.001 lives/year
	USBR (1997) Interim Tier 2 Public Protection Guidelines *(for total of failure modes)*		N	Increasing justification to reduce probability of failure - Probability of failure exceeds 1 x 10^{-4} /year
			Y-ALARP?	Decreasing justification to reduce probability of failure (i.e. ALARP must be evaluated) - Probability of failure less than 1 x 10^{-4} /year
	BC Hydro (1993) Interim Societal Risk Criteria *(for total of failure modes)*		N	Does not meet criterion - Expected incremental loss of life exceeds 0.001 lives/year
			Y-ALARP?	Meets criterion, but ALARP must be evaluated - Expected incremental loss of life less than 0.001 lives/year
Life Safety–Individual Risk	ANCOLD (1994) Average over PAR *(for total of all failure modes)*	Limit	N	Does not meet limit criterion – Incremental probability exceeds 1 x 10^{-5}
			Y	Meets limit criterion - Incremental probability less than 1 x 10^{-5}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1 x 10^{-6}
			Y-ALARP?	Meets objective criterion - Incremental probability less than 1 x 10^{-6}, but ALARP must be evaluated
	ANCOLD (1994) Person at most risk *(for total of failure modes)*	Limit	N	Does not meet limit criterion - Incremental probability exceeds 1 x 10^{-4}
			Y	Meets limit criterion - Incremental probability less than 1 x 10^{-4}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1 x 10^{-5}
			Y-ALARP?	Meets objective criterion - Incremental probability less than 1 x 10^{-5}, but ALARP must be evaluated
	BC Hydro (1993) Interim Person at most risk *(for total of failure modes)*		N	Does not meet criterion - Incremental probability exceeds 1 x 10^{-4}
			Y-ALARP?	Meets criterion - Incremental probability less than 1 x 10^{-4}, but ALARP must be evaluated
Economic/ Financial	NSW Total Asset Management Risk Example Guidelines *(for flood, earthquake and static failure modes separately)*		N-Major	Major risk - Imperative that risk reduction be implemented
			N-Medium	Medium risk - Risk reduction required in a reasonable time
			Y-ALARP?	Low risk - Risk reduction to be ALARP

ALARP Justification rating: EXAMPLE ONLY

ALARP Justification Rating	Range of Cost-per-statistical-life saved (US$M/life)	
	Greater than or equal to	Less than
Very Strong		3
Strong	3	30
Moderate	30	140
Poor	140	

De Minimis Justification rating: EXAMPLE ONLY - VARIES WITH OWNER

De Minimis Justification Rating	Range of Risk Reduction Measure Cost (US$M)	
	Greater than or equal to	Less than
Strong		2
Moderate	2	5
Poor	5	10
Weak	10	

Options Justification and Summary of Engineering/Current Practice and Risk-based Ratings

DAM			COST	ENGINEERING RATINGS			LIFE SAFETY RATINGS							FINANCIAL RATING	JUSTIFICATION RATING		
							ANCOLD Societal		USBR				BC Hydro				
									Tier 1			Tier 2					
Name	No.	Option Description		Flood	Earthquake	Normal	Limit	Objective	Flood	Earthquake	Normal				B:C Ratio	ALARP	De Minims
A		Do Nothing	$ -	NP	AP	AP	No	No	N-Long	Y-ALARP?	Y-ALARP?	No	No	N-Major	-	-	-
	1	1:50,000 spillway	$ 8.00 M	NP	P	P	Y-ALARP?	No	Y-ALARP?	Y-ALARP?	Y-ALARP?	Y-ALARP?	Y-ALARP?	N-Medium	No	Poor	Weak
	2	1:100,000 spillway	$ 10.00 M	NP	P	P	Y	Y	Y	Y	Y	Y	Y	Y-ALARP?	No	Weak	Weak
	3	1:1,000,000 spillway	$ 16.00 M	P	P	P	Y	Y	Y	Y	Y	Y	Y	Y	No	Weak	Weak
B		Do Nothing	$ -	AP	NP	AP	No	No	N-Long	Y-ALARP?	Y-ALARP?	Y-ALARP?	No	N-Medium	-	-	-
	1	Filter & Berm	$ 3.00 M	AP	P	P	Y-ALARP?	No	Y-ALARP?	Y-ALARP?	Y-ALARP?	Y-ALARP?	Y-ALARP?	Y-ALARP?	**Yes**	**Very Strong**	**Strong**
	2																
	3																
C																	
	1																
	2																
	3																

▨ Justification to proceed with a higher level of fix

Justification to proceed with higher level of fix based on ALARP

NOTE:

1) Individual risk evaluations are not included

2) In this example options are listed as alternatives NOT additive staged separable construction upgrade packages

DAM SAFETY RISK BASED DAM SAFETY CRITERIA AND GUIDELINES

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1.0 OVERVIEW

In this section, we present various life safety and economic/financial risk-based criteria that were used in this study. Table I.1-1 is a summary of the definitions of the risk evaluation ratings for each of these risk-based criteria, which were used for displaying the results of each risk assessment of an existing dam or a risk reduction measure. Criteria from other organizations are considered for reference and benchmarking purposes.

It is important to remember that the degree of risk accepted, and the risk criteria established, by one organization may not be appropriate for adoption by another organization. It is, therefore, essential that each dam owner assess the compatibility of the criteria presented in this section with their capital approval process, corporate risk management strategy and position, dam safety decision making process, and legal framework. This assessment should include community consultation and input from other stakeholders.

Quantitative criteria can serve a useful role in the risk evaluation process. When they are used the effects of uncertainties in the risk analysis process should be considered. However, dam safety decisions should be made by those responsible for ensuring dam safety after all the relevant factors have been assessed and weighed; they should not be the automatic result of applying a criterion to the outcomes of a risk analysis. Thus, the use of risk assessment enhances the decision-making process, but does not replace reference to traditional engineering criteria and other relevant factors.

Table I.1-1. Summary of risk evaluation ratings.

Risk Evaluation Type			Rating Code	Explanation
Life Safety-Societal Risk	ANCOLD (1998) Interim Amended Societal Risk Criteria *(for all failure modes combined)*	Limit	N	Does not meet limit criterion - F-N plots above limit criterion
			Y	Meets limit criterion - F-N plots below limit criterion
		Objective	N	Does not meet objective criterion - F-N plots above objective criterion
			Y-ALARP?	Meets objective criterion, but ALARP must be evaluated - F-N plots below objective criterion
	USBR (1997) Interim Tier 1 Public Protection Guidelines *(for flood, earthquake and static failure modes separately)*		N-StrongL&S	Strong justification for long- and short-term risk reduction measures - Expected incremental loss of life exceeds 0.01 lives/year
			N-StrongL	Strong justification for long-term risk reduction measures - Expected incremental loss of life between 0.01 and 0.001 lives/year
			Y-ALARP?	Diminished justification for long-term risk reduction measures (i.e. ALARP must be evaluated) – Expected incremental loss of life less than 0.001 lives/year
	USBR (1997) Interim Tier 2 Public Protection Guidelines *(for total of failure modes)*		N	Increasing justification to reduce probability of failure - Probability of failure exceeds 1×10^{-4}/year
			Y-ALARP?	Decreasing justification to reduce probability of failure (i.e. ALARP must be evaluated) - Probability of failure less than 1×10^{-4}/year
	BC Hydro (1993) Interim Societal Risk Criteria *(for total of failure modes)*		N	Does not meet criterion - Expected incremental loss of life exceeds 0.001 lives/year
			Y-ALARP?	Meets criterion, but ALARP must be evaluated - Expected incremental loss of life less than 0.001 lives/year
Life Safety–Individual Risk	ANCOLD (1994) Average over PAR *(for total of all failure modes)*	Limit	N	Does not meet limit criterion – Incremental probability exceeds 1×10^{-5}
			Y	Meets limit criterion - Incremental probability less than 1×10^{-5}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1×10^{-6}
			Y-ALARP?	Meets objective criterion - Incremental probability less than 1×10^{-6}, but ALARP must be evaluated
	ANCOLD (1994) Person at most risk *(for total of failure modes)*	Limit	N	Does not meet limit criterion - Incremental probability exceeds 1×10^{-4}
			Y	Meets limit criterion - Incremental probability less than 1×10^{-4}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1×10^{-5}
			Y-ALARP?	Meets objective criterion - Incremental probability less than 1×10^{-5}, but ALARP must be evaluated
	BC Hydro (1993) Interim Person at most risk *(for total of failure modes)*		N	Does not meet criterion - Incremental probability exceeds 1×10^{-4}
			Y-ALARP?	Meets criterion - Incremental probability less than 1×10^{-4}, but ALARP must be evaluated
Economic/ Financial	NSW Total Asset Management Risk Example Guidelines *(for flood, earthquake and static failure modes separately)*		N-Major	Major risk - Imperative that risk reduction be implemented
			N-Medium	Medium risk - Risk reduction required in a reasonable time
			Y-ALARP?	Low risk - Risk reduction to be ALARP

2.0 LIFE SAFETY CRITERIA

Five types of life safety criteria or guidelines are summarised below. The first three are societal risk criteria and the last two are individual risk criteria. All criteria used in this study, except for the ANCOLD individual risk criteria, are interim. The ANCOLD criteria are being widely used on a reference basis in Australia with limited examples of dam safety decisions being made that incorporate these criteria as at least a part of their justification. The USBR guidelines are being routinely used as a significant consideration in decision making on both the priority and the level of risk reduction adopted. BC Hydro's criteria were not formally adopted by management, or approved by their regulator. The BC Hydro portfolio of dams is a mature portfolio in the sense that most dams meet engineering standards, and, therefore, current BC Hydro practice has de-emphasized the use of risk-based criteria. However, BC Hydro's former Dam Safety Director, Gary Salmon, indicates that these criteria were used to support several significant dam safety decisions (Salmon, 1999).

2.1 ANCOLD (1998) Amended Interim Societal Risk Criteria

This cumulative probability-incremental loss of life (F-N) chart (Figure I.2-1) includes limit and objective criteria. Life safety risk for a dam is plotted on the F-N chart as a cumulative probability distribution (i.e. AEP) of incremental loss of life, summed across all dam failure modes and population exposure categories. Loss of life risk is considered to be unacceptable when the F-N plot for a dam plots above the "limit" criterion line. Although not part of the ANCOLD criteria, we recommend that the high (upper) confidence limits of the F-N plot should not fall above the "limit" criterion line. The goal should be to reduce best estimates of societal life loss risks to the level of the "objective" criterion line. However, the "as low as reasonably practicable" (ALARP) principle and the "de minimis risk" legal principle should be considered by evaluating the cost-effectiveness of risk reductions down to, and below, the objective criterion level (ANCOLD, 1998).

Ratings are defined in Table I.1-1 for meeting and not meeting both the limit and objective criteria. In the case of meeting the objective criterion, the rating code is "Y-ALARP?" to indicate that even though the objective criterion is met, ALARP should be evaluated.

2.2 USBR (1997) Public Protection Guidelines

The principal condition in the USBR's two-tier public protection (societal risk) guidelines is that expected (i.e. average or annualised) incremental life loss, n, due to dam failure, should be less than 0.001 lives per annum for each loading type (e.g. flood, earthquake, static/internal). Specifically, Reclamation's Tier 1 Guideline is summarised as follows:

$n > 0.01$	"Strong justification for taking actions to reduce risks for both long term and short term *(5 years or less)* continued operations."
$0.01 > n > 0.001$	"Strong justification for taking actions to reduce risks under continued long term operations."
$n < 0.001$	"Justification for reducing risk decreases *(diminishes)* - evaluate *(cost)* effectiveness and public trust responsibilities."

Three ratings are defined in Table I.1-1 for the Tier 1 Guideline, corresponding to the three cases summarised above. For the third case, in which $n < 0.001$, the rating code is "Y-ALARP?" to indicate that ALARP should be evaluated.

Reclamation's Tier 2 Guideline is summarised as follows: "it is recommended that each individual dam have a maximum combined (i.e. totalled over all loading types and failure modes) annual probability of failure of 1 in 10 000 (per year)." For a dam with an estimated probability of failure exceeding 1 in 10 000 per year, there is said to be an "increasing justification" for reducing the probability of failure. Whereas for a dam with a probability of failure less than 1 in 10 000 per year, there is said to be a "diminishing justification" for reducing the probability of failure.

Two ratings are defined in Table I.1-1 for the Tier 2 Guideline, corresponding to the cases of probability of failure exceeding, or less than, 1 in 10 000 per year. For the second case, the rating code is "Y-ALARP?" to indicate that ALARP should be evaluated.

2.3 BC Hydro (1993) Interim Societal Risk Criterion

Expected (i.e. average or annualised) incremental life loss, n, due to dam failure should be less than 0.001 lives per annum summed over all load categories. Two ratings are defined in Table I.1-1, corresponding to the cases of n exceeding, or less than, 0.001 lives per year. For the second case, the rating code is "Y-ALARP?" to indicate that ALARP should be evaluated.

2.4 ANCOLD (1994) Individual Risk Criteria

ANCOLD (1994) proposed objective and limit criteria for two types of individual risk: an average over the (exposed) population at risk and the person at greatest risk. For upgrading existing dams, the following objective values are proposed, based on considering all loading types:

1×10^{-6} per exposed person per annum as an average over the population at risk (PAR)
1×10^{-5} per annum for the person at greatest risk.

ANCOLD (1994) indicated that "Limit values up to 10 times these objective values might be tolerable for existing dams subject to application of the ALARP principle ...". As with the ANCOLD societal risk criteria, we recommend that the cost-effectiveness of risk reduction down to, and below, the objective criterion level should be considered based on the ALARP principle and the "de minimis risk" legal principle.

Ratings are defined in Table I.1-1 for meeting and not meeting both the limit and objective criteria for both types of individual risk. In the case of meeting the objective criterion, the rating code is "Y-ALARP?" to indicate that even though the objective criterion is met, ALARP should be evaluated.

2.5 BC Hydro (1993) Interim Individual Risk Criteria

The person at greatest risk should not be exposed to a probability of life loss due to dam failure of more than 1 x 10^{-4} per annum. Ratings defined in Table I.1-1 are similar to those for ANCOLD individual risk objective criterion.

ANCOLD (1998) revised interim *Societal* Risk Criteria

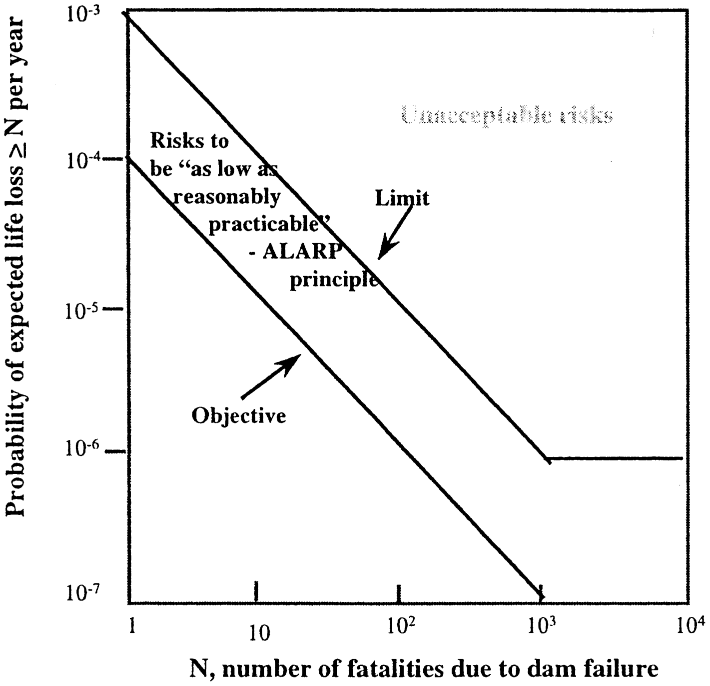

Figure I.2-1. ANCOLD Amended Interim Societal Risk Criteria (ANCOLD, 1998)

3.0 ECONOMIC CRITERIA

Several economic or financial criteria are summarised in this subsection. They are benefit:cost ratio, the cost effectiveness of risk reduction, including cost-per-(statistical) life-saved, and ALARP and de minimis risk considerations.

3.1 Benefit:Cost Ratio

A benefit:cost ratio can be calculated for each risk reduction measure. Costs include the annualised capital cost of the risk reduction measure, recurring costs, and any decreases in annual revenues associated with the measure. Benefits include risk cost reduction and any increases in annual revenues, or decreases in subsidies associated with the measure. If the ratio is greater than one, economic benefits exceed costs and the measure is, therefore, justified on economic grounds without consideration of other benefits such as life safety improvements, and protection of environmental resources or community structure.

3.2 Cost Effectiveness of Risk Reduction

The cost effectiveness of risk reduction is calculated as the annualised cost of the risk reduction measure divided by the risk reduction. The risk reduction can be expressed in various ways, such as probability of failure risk, economic risk cost, or life safety risk. When calculated for life safety risk, the cost effectiveness is also referred to as the cost-per-(statistical) life-saved (CPLS, or cost-to-save-a-life).

Benefit:cost ratios of less than one are common for dam safety risk reduction works. If a risk reduction measure with a benefit:cost ratio of less than one is implemented, the amount by which annualised costs exceed annualised benefits can be assigned as a cost of improving life safety or achieving other non-commensurable benefits. The CPLS can then be calculated by dividing that exceedance amount by the reduction in annualised (expected) incremental life loss attributable to the risk reduction alternative. If the benefit:cost ratio exceeds one, the numerator in this calculation is zero, and hence the CPLS is zero. In this case, the risk reduction measure is justified completely by its economic benefits, and the reduction in life loss risk can be considered to be at zero cost (i.e. it is "free").

Since CPLS is a measure of cost effectiveness of risk reduction, smaller values indicate that a risk reduction alternative is "good value for the money". By comparing CPLS estimates for a specific dam safety risk reduction measure with estimates from other fields, one can make an assessment of how a life-saving investment in dam safety would compare with public safety investments that are being made in other fields. Such comparisons can provide a basis for evaluating whether or not risk reduction is ALARP (see Section 3.3).

CPLS estimates can be an important consideration in selecting amongst risk reduction alternatives. If the same risk reduction effect can be achieved at lower cost, then the lower cost alternative would have a lower CPLS and would be the favoured alternative. If additional life safety risk reduction can be expected from alternatives that have a higher CPLS, then an owner should consider implementing them if their CPLS is not excessively high. This can be judged by reference to CPLS estimates for measures that are being implemented in dam safety or other fields. In addition, it is sometimes useful to assess if a point of diminishing returns has been reached by examining the variation of CPLS with project scale (e.g. spillway capacity in terms of design AEP).

Another use of CPLS is in prioritising risk reduction investments. If measures with the smallest CPLS are implemented first, the rate of life safety risk reduction will be maximised. This consideration is particularly relevant when performing a Portfolio Risk Assessment in which risk reduction measures are being considered at several dams and when these measures may take an extended period of time to obtain funding or complete construction. Similar uses of the cost effectiveness of economic risk reduction or probability of failure risk reduction can also be made.

3.3 ALARP and de minimis Risk Considerations

In addition to using risk-based criteria, there appears to be a persuasive legal basis for including both ALARP (as low as reasonably practicable) and de minimis risk considerations in dam safety decision making. The basis for ALARP is that risks are "acceptable only if reasonable practical measures have been taken to reduce risks" (IAEA, 1992). In practice this is commonly taken to mean that risks have been reduced to the point where it is no longer cost effective to reduce them further. We have developed an illustration of how the cost effectiveness of improving life safety (i.e. cost-per-statistical-life-saved, CPLS) can be used to assess the degree of ALARP justification for a risk reduction measure. We have based this illustration on U.S. Federal Government practice in Table I.3-1 and Viscusi (1998). Table I.3-1 lists CPLS estimates for various activities in the USA which could be considered to be similar to dam safety in that the population at risk has essentially no control over the hazard and may not be a direct beneficiary from the hazardous activity. Four illustrative ALARP justification ratings (very strong, strong, moderate, and poor) are defined in Table I.3-2 in increasing magnitude of CPLS.

The term, de minimis risk, comes from the Latin, "de minimis non curat lex" meaning the law does not concern itself with trifles (Shortreed et al., 1995). A significance of de minimis risk in dam safety decision making is that "a dam owner may have a legal obligation to implement a relatively low cost fix (risk reduction measure), even if it is not cost effective" (Bowles et al., 1998b, p. 322). The de minimis risk concept appears to be related to the concept of what a "reasonable" dam owner would do to reduce risk in a particular situation. It should be remembered, however, that under a common law system there is no guarantee that a safety decision made before an event will be viewed favorably by a court after a dam failure. For illustrative purposes, we have developed de minimis risk justification ratings, which show how the capital costs of risk reduction measures could be used to assess the justification for a measure. Four de minimis risk justification ratings (strong, moderate, poor, and weak) are defined in Table I.3-3 in increasing order of magnitude of capital cost of the risk reduction measures.

ALARP should always be evaluated when limit and objective values of risk-based criteria appear to be met by an existing dam or by a proposed risk reduction measure. De minimis risk should be evaluated when there appears to be no ALARP justification to proceed with a risk reduction measure. The ALARP and de minimis risk justification ratings presented in Tables I.3-2 and I.3-3 should be considered to be illustrative. Each owner should develop their own position on the definition of these ratings and how to interpret them.

3.4 New South Wales Government (1993) Total Asset Management Risk Matrix (Example) for Economic Consequences

This New South Wales Government (1993) example of a likelihood (non-cumulative probability) - incremental economic consequence risk matrix (Figure I.3-1) is divided into three economic/financial risk rating regions: "Major", "Medium", and "Low". Economic consequences for each risk category (i.e. floods, earthquakes and normal operating conditions) are plotted separately on this risk matrix. Risk treatment is recommended for risks falling into each rating region, as follows: "Major Risk - Imperative to suppress risk to lower level"; "Medium Risk - Corrective action required in a reasonable time frame"; and "Low Risk - Corrective action where practicable", implying that ALARP should be evaluated. Each dam owner should consider adapting this type of risk matrix to their own loss-financing situation.

Three ratings are defined in Table I.1-1, corresponding to the three example cases economic/financial regions for the NSW TAM risk matrix example. For the low risk region, the rating code is "Y-ALARP?" to indicate that ALARP should be evaluated.

3.5 Other Economic Criteria

Other criteria, such as net present value (NPV), internal rate of return, or minimised total economic cost (sum of risk cost and annualised cost of risk treatment) can be applied to dam safety decision making. However, although these criteria have been used in the dam safety field, caution should be exercised in applying them in isolation, without consideration of life safety criteria and other factors such as environmental, social and business impacts.

Table I.3-1. Cost-per-(statistical) life-saved estimates for comparison with dam safety estimates (based on Office of Management and Budget, 1992).

Regulation[a)]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted ($US Millions 1990)
Aircraft Cabin Fire Protection Standard	1985	S	FAA	5	0.1
Steering Column Protection Standard[b)]	1967	S	NHTSA	385	0.1
Trihalomethane Drinking Water Standards	1979	H	EPA	420	0.2
Aircraft Seat Cushion Flammability Standard	1984	S	FAA	11	0.4
Auto Fuel-System Integrity Standard	1975	S	NHTSA	343	0.4
Aircraft Floor Emergency Lighting Standard	1984	S	FAA	2	0.6
Side-Impact Standards for Autos (Dynamic)	1990	S	NHTSA	NA	0.8
Auto Side Door Support Standards	1970	S	NHTSA	2,520	0.8
Low-Altitude Windshear Equipment & Training Standards	1988	S	FAA	NA	1.3
Side-Impact Standards for Trucks, Buses, and MPVs	1989 (Proposed)	S	NHTSA	NA	2.2
Rear Lap/Shoulder Belts for Autos	1989	S	NHTSA	NA	3.2
Benzene NESHAP (Original: Fugitive Emissions)	1984	H	EPA	1,470	3.4
Ethylene Dibromide Drinking Water Standard	1991	H	EPA	NA	5.7
Benzene NESHAP (Revised: Coke By-Products)[c)]	1988	H	EPA	NA	6.1
Arsenic Emission Standards for Glass Plants	1986	H	EPA	2,660	13.5
Haz Waste Listing for Petroleum Refining Sludge	1990	H	EPA	210	27.6

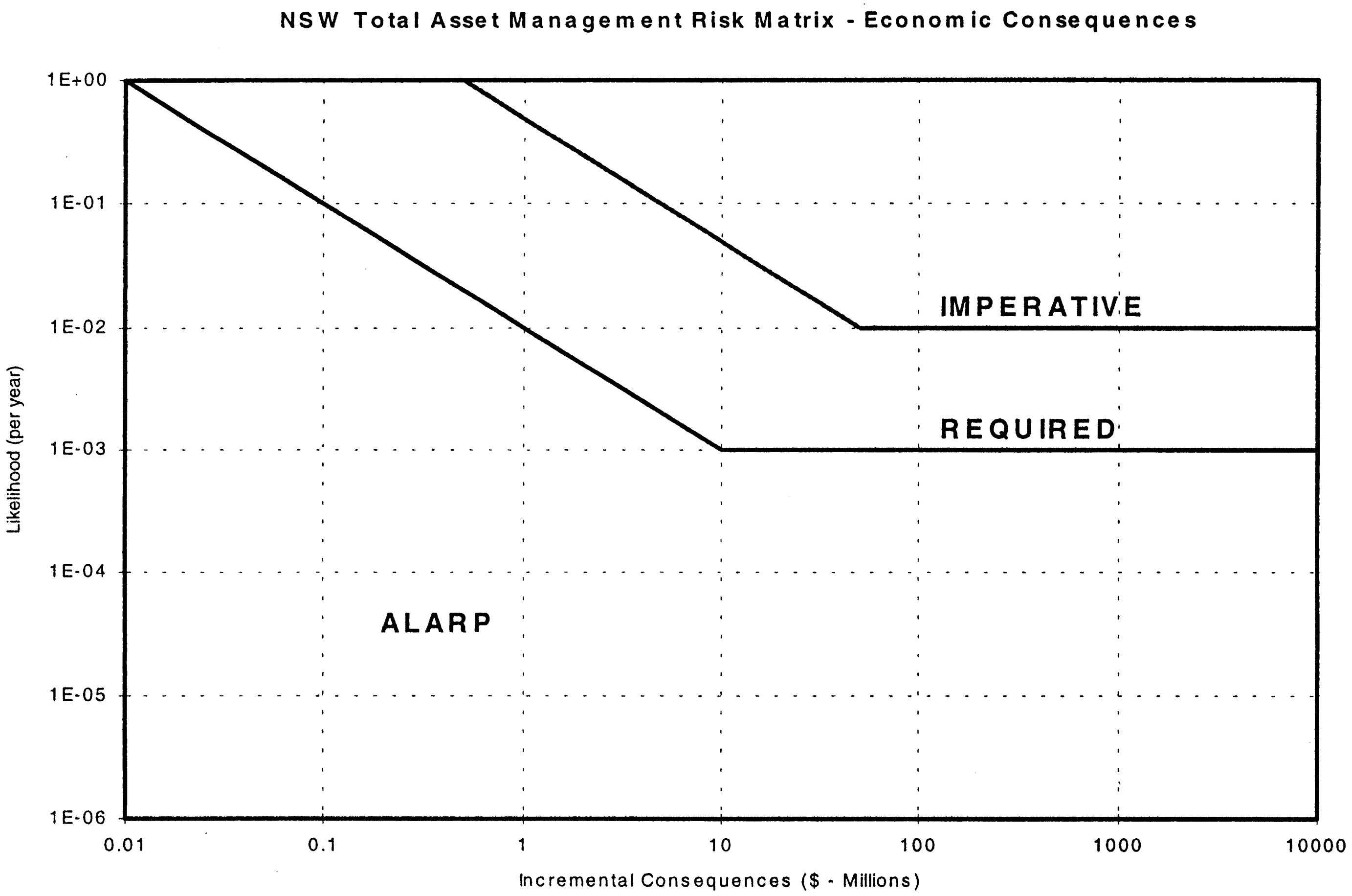

Figure I.3-1. NSW Total Asset Management Risk Matrix (Example) - Economic Consequences in AU$

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GUIDELINES FOR ACHIEVING PUBLIC PROTECTION IN DAM SAFETY DECISION MAKING

UNITED STATES DEPARTMENT OF INTERIOR
Bureau of Reclamation
Denver, Colorado

April 4, 1997

Interim Guidelines
To Be Revised After
1 Year of Use

PREFACE

The Bureau of Reclamation is responsible for over 350 storage dams which form a significant part of the water resources infrastructure of the western United States. As the owner of these dams Reclamation is committed to providing the public and the environment with adequate protection from the risks which are inherent in collecting and storing large volumes of water for later distribution and/or release. This document presents Bureau of Reclamation guidelines for ensuring adequate and consistent levels of public protection in the evaluation and modification of existing dams and appurtenant structures and the design of new structures.

Traditional design and analysis methods have focussed on selecting a level of protection based on loadings from extreme events and conditions which are at the upper bound of those which are considered to be reasonably probable. By designing structures to withstand these events and conditions, it is commonly accepted within the civil engineering profession that the dams meet an acceptable standard of public safety, however, using this approach can result in widely varying levels of risk exposure from one structure to another. In addition to ensuring public safety for large events, Reclamation is also committed to providing public safety for smaller events and loading conditions which occur more frequently. An analysis framework is needed which can address the most cost effective way to provide public protection over the full range of loading conditions.

As a water resources management agency, Reclamation strives to provide decision makers with information which is pertinent to the decisions to be made and is founded upon current or emerging water resources management and public safety practices. For the past decade, there has been an increasing trend in water resources analysis toward the use of probabilistic design methods for evaluating the effectiveness of expending funds for enhancing public safety. There has also been more recognition that utilizing even the most restrictive design standards results in some risk of failure, although the risk may be very small.

This document addresses the incorporation of risk evaluation measures into the Dam Safety decision making process. One key aspect of water resources decision making is that the process almost always requires the evaluation of multiple objectives such as national economic development benefits which can be derived from additional capital investment, public safety, resource protection, and consideration of social concerns. Selecting an appropriate level of public protection is a two stage process in which the need for a risk reduction action is first determined. Once a decision is made to take action, specific alternatives should be considered with respect to the objectives of the agency and the public in an appropriate decision analysis framework. These guidelines have been prepared to assist Reclamation staff in presenting public safety information which will assist decision makers in allocating the available resources.

This document supplements the "Policy and Procedures for Dam Safety Modification Decision Making" (April 1989) by expanding the incremental loss of life concept to consider the likelihood of such consequences and by introducing a public trust component of decision making. The document is divided into two parts. The first part provides general background information on assessing appropriate levels of public protection through the risk assessment process. The second part provides the applicable guidelines for determining an appropriate level of public protection for Reclamation dams.

I. General

The risk assessment procedure is used, as one of several inputs into the Reclamation decision making process, to help portray an overall picture of risks, potential impacts and resulting costs (economic, social and other costs) of different options. The guidelines and procedures contained herein are intended to incorporate results from current analysis methods and supplement decision making processes being used within Reclamation.

One of the key elements of Reclamation's Dam Safety Program is using the data collected or developed for a dam to determine if an adequate level of public protection is provided. In this decision making process, it is important that data, assumptions, and the anticipated performance over the full range of potential loading conditions are evaluated and documented. Organizational guidance on dam safety decision making comes from Reclamation's Dam Safety Program mission which is:

> "To ensure that Reclamation dams do not present unacceptable risk to people, property, and the environment."

Guidance also comes from external sources:

> *Reclamation Safety of Dams Act of 1978*
> "In order to preserve the structural safety of Bureau of Reclamation dams and related facilities, the Secretary of the Interior is authorized to perform such modifications as he determines to be reasonably required." The Reclamation Safety of Dams Act was passed in 1978 as a result of several dam failures in the 1960's and 1970's including Teton Dam, a large Reclamation storage dam.
>
> *Federal Guidelines for Dam* Safety, 1979
> These guidelines are intended to promote prudent and reasonable dam safety practices among federal agencies. With respect to risk assessment, the guidelines state: "The agencies should individually and cooperatively support research and development of risk-based analysis and methodologies as related to the safety of dams. This research should be directed especially to the fields of hydrology, earthquake hazard, and potential for dam failure. Existing agency work in these fields should be continued and expanded more specifically into developing risk concepts useful in evaluating safety issues."

These guidelines provide a framework for collecting and presenting pertinent information from a risk assessment which is necessary for effective decision making with regard to public protection from the risks associated with Reclamation dams. The risk assessment and the information collected and presented therefrom is intended to support justification for corrective actions, to assist in prioritizing the allocation of resources, and to ensure a comprehensive assessment of the risks at a given dam.

A. Risk Assessment

Risk assessment methods provide techniques to organize and plan the data collection and technical studies necessary to evaluate dam safety concerns at a site. Decision making considerations related to the need for corrective actions can also be organized in a fashion which will lead to a combined assessment of several pertinent factors which contribute to providing appropriate protection for the public. To accomplish this, teams must make judgements regarding the response of a dam to each loading condition. Risk assessment provides a framework in which the team can consider a number of possible adverse outcomes to a given loading condition, compute the risk associated with each possible outcome, and then accumulate the risks to arrive at an estimate of overall risk of failure for each loading condition. The procedure for performing risk assessment generally consists of collecting and evaluating data for the following equations for all loading conditions, structure responses, and resulting consequences:

Risk Probability of Load Probability of Structure Response Probability of Adverse Consequences Exposure

[illegible]

The process involves the development of an event tree identifying all of the potential loading events, dam responses, exposure conditions, and consequences. The overall risk from the dam is the accumulation of all risks associated with each of the possible paths through the event tree. Additional information on the methodology for performing risk assessments can be found in "*Risk Based Decision Analysis Methodology.*"

B. Application

Risk assessment can be applied to a variety of factors associated with Dam Safety decision making including economics, loss of life, environmental impacts, social impacts, etc. Application to economics, for example, will yield the expenditures which would be cost effective (either by benefit-cost or rate of return analysis) in reducing the economic risks by given amounts.

These guidelines focus on assessing risks associated with the potential for loss of life. Protection of human life is of primary importance to public agencies constructing, maintaining, or regulating civil works and is the key factor in decisions regarding whether or not a particular dam provides adequate public protection. Economic and/or environmental risk assessment, although not addressed in these guidelines, may be applied on specific projects where the decision making process would be enhanced by presentation of the entire breadth of consequence risks. Economic and/or environmental risk assessment should be performed where the potential loss of life is not present or is so small that it doesn't provide sufficient or appropriate input for a decision regarding modification of a structure. Where a risk reduction action is to be taken, the estimated consequences should take into account expected future changes in land use, population, or other parameters so that a decision regarding the extent of risk reduction will be appropriate as far into the future as can reasonably be foreseen.

C. Risk-Based and Standards-Based Decision Making

While risk-based and standards-based (for instance: design standards, codes or criteria) decision making are frequently seen as competing approaches, they actually complement each other when both are used in a manner which exploits their strengths. Decision making relies on and is made on the basis of judgement (which includes experience and precedent). In most cases the judgement is based on subjectively weighing alternative decisions against the consequences to find a satisfactory solution which the decision maker(s) considers to be "reasonable." Risk assessment formalizes and documents this judgement process and is especially useful for dams since the technical staff must assess the future performance of dams without the benefit of being able to test the structures to failure as is the practice in many other industries. Standards and guidelines generally arise when it becomes apparent that the judgement associated with a particular part of the decision process has a degree of repetition in the outcomes. In these cases, designing to a particular standard can simplify the design data collection and design processes while yielding acceptable designs. However, standards have also been developed in some cases to ensure that conservative assumptions are made due to uncertainties in the potential loading conditions or in the responses of structures to those loading conditions. In these cases, designing to a particular standard may be inefficient and not result in the desired risk reduction.

When using standards, care needs to be taken to ensure that program objectives and desired levels of risk exposure are being adequately met. In the evaluation of public protection for dam safety decisions, standards which are based on loading conditions can lead to significantly different levels of public protection (public risk) at different dams since the standards do not consider the probability of the loading conditions or the expected consequences of the loading conditions. In cases where the combination of loading conditions and the consequences are large, the probability of a structural failure response must be so small that it becomes a significant challenge for the technical staff to reasonably estimate the probabilities. These cases lead to a need for the decision and design processes to focus on methods which will provide an acceptable level of confidence in the performance of the structure. This is frequently accomplished by using commonly accepted loading conditions, employing the best available technologies and providing redundancies in the design to ensure protection of the public.

D. Dealing with Uncertainty

The use of risk assessment methods in determining appropriate levels of public protection for Reclamation dams will allow the technical staff and decision makers to more directly address the uncertainties associated with the variety of potential responses of a dam to a range of loading conditions. Risk assessment provides a quantitative means of considering the parameters which contribute to risk at a site. While consideration of these parameters help in understanding the risks, the parameters are estimated probabilities and consequence values which each have their own estimation uncertainties. Sensitivity analysis allows an understanding of the effects of varying estimates on the results of a risk assessment but do not fulfill the requirements of an uncertainty analysis. The risk values computed in a risk assessment are risk distributions rather than point estimates of risk. The distribution of the computed risk is needed to provide a reasonable representation of the uncertainty associated with the computed risk. Estimates of the risk and its distribution may be computed by Monte Carlo simulation or first order analysis of uncertainty.

E. Application of Results

Risk assessment is a tool which enables designers and decision makers to better understand possible failure mechanisms and the elements of risk involved in the various options related to dam safety. The results of a risk assessment also allow Reclamation to better communicate the risks associated with a structure to the public in general, the downstream population at risk, and water users. As a tool, it is not the only input for decisions, but it is one that provides the overall picture of risks, potential impacts of options, and resulting costs (economic, social and other). The results of risk assessments can contribute to efficient accomplishment of the dam safety program by quantifying engineering judgement that allows for the discrimination of:

- Conditions producing the greatest risk at a given site.
- The sites with the greatest risk.
- Risk reduction effectiveness of alternative courses of action.
- Allocations of dam safety program funding which will contribute the greatest overall risk reductions.

In addition, the use of risk assessment as a tool in decision making provides credible information needed for approval of the selected alternative.

When risk of failure is determined to not justify additional risk reduction, this does not mean that failure and the resulting consequences, cannot or will not occur. Public protection decision processes should also consider other factors including consequences, economics, environmental impacts, social impacts, and other factors pertinent to the dam safety decisions to be made.

II. Public Protection Guidelines

These guidelines for achieving satisfactory public protection are necessary to help Reclamation decision makers understand the relative risk that a particular dam presents and the degree of justification and urgency to take risk reduction actions. Risk level guidelines, as opposed to a specific criteria, permit potentially important and influential, site-specific factors to also be considered in the decision.

Reclamation public protection guidelines consist of two-tiers that are to be considered in the decision process. The first tier deals with loss of life considerations. The second tier deals with agency public trust responsibilities. The latter considers the accumulation of risks from Reclamation's total inventory of dams. If decisions regarding risk reduction actions significantly deviate from these guidelines, the basis for the deviation should be understood and documented by the decision makers. The downstream population at risk should be aware of the reason(s) for the deviation.

A. First Tier Risk Reduction Guidelines - Loss of Life

Storing water above a populated area is not a zero-risk activity. Guidance is provided herein to help determine when additional risk reduction actions should be taken to enhance public safety.

The risk of loss of life is presented as the estimated average annual loss of life due to a specific loading category (seismic, static, hydrologic) at a dam along with the range of the estimate considering the variation in load probability and response probability estimation. The estimated average annual loss of life is the sum of the probability of dam failure multiplied by the annual probability of the loading and the estimated number of lives that would be lost for each dam failure scenario under a particular loading category. The following guidance should be considered when evaluating the justifications to implement risk reduction activities.

For an Estimated Average Annual Loss of Life >. 01	Reclamation considers that there is strong justification for taking actions to reduce risks for both long term and short term continued operations. Short term refers to interim risk reduction activities until permanent risk reduction actions can be designed and implemented. The duration of short term actions is considered to be 5 years or less. Short term actions could include restricting reservoir operations, temporary structural modifications, or reducing the downstream hazard potential.
For an Estimated Average Annual Loss of Life Between .01 and .001	Reclamation considers that there is strong justification for taking actions to reduce risks under continued long term operations. Reduced justification

for implementing risk reduction actions under short term operations provided permanent risk reduction can be implemented within a 2 to 5 year period after a decision is made to pursue long term risk reduction. Public safety is the key factor in decision making.

For an Estimated Average Annual Loss of Life < .001 The justification to implement risk reduction actions diminishes as estimated risks are increasingly smaller than .001 estimated annual life loss probability. Corrective action costs, uncertainties in the risk estimates, scope of consequences, operational and other water resources management issues play an increased role in decision making.

When the probability of a given loading category is relatively high and there is high potential downstream loss of life, even a very low probability of uncontrolled release could indicate action is required under the above guidelines. In some cases, the implied allowable probability of failure given the load may be so small that the response can't be predicted at that level with a reasonable degree of confidence. In such cases, Reclamation must focus on ensuring that there are sufficient protective (defensive design) measures incorporated into the structure which lead to confidence in its ability to withstand the load imposed without uncontrolled releases.

When loss of life estimates are low for a given loading category, a threshold estimated average annual loss of life probability of .001 can potentially expose a small population to failure events with relatively high probabilities. Risk to an individual from dam failure for these cases may be similar to other societal risks such as auto accidents and disease. As a result for the exposed population, dam risks could contribute significantly to the life risks of an individual in the population. This situation is addressed through the Tier 2 considerations identified in the following section.

In addition to estimated average annual loss of life estimates, decision makers are presented with information via the risk assessment depicting the loss of life consequences associated with the loading conditions evaluated. Single events that cause high numbers of lost lives are viewed as national tragedies that are long remembered by the public. There is significant public aversion to single, high consequence events, and the public expects a high degree of protection from such events.

Results from a risk assessment are to be graphically summarized under the Tier 1 heading on figure 1 such that decision makers can identify both the annualized loss of life risk and level of consequences associated with a given load category. An example depicting the plotting of this information is provided beginning on page 12 of this document.

Use of systematic warning (emergency action plans and early warning) has been shown to reduce the potential for loss of life during catastrophic events. While emergency action plans are already

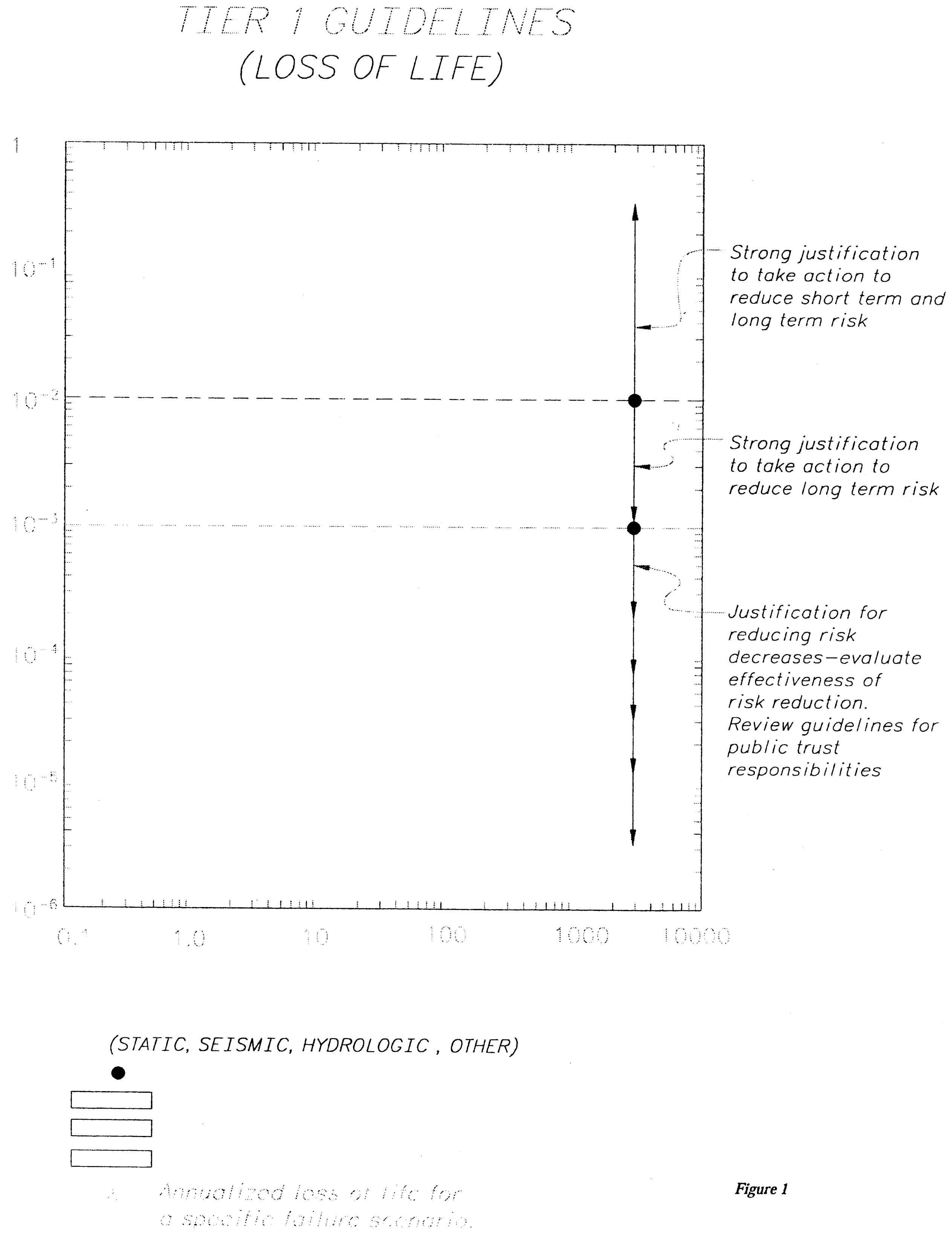

TIER 1 GUIDELINES
(LOSS OF LIFE)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.1
1.0
10
100
1000
10000
Strong justification to take action to reduce short term and long term risk
Strong justification to take action to reduce long term risk
Justification for reducing risk decreases—evaluate effectiveness of risk reduction. Review guidelines for public trust responsibilities
(STATIC, SEISMIC, HYDROLOGIC , OTHER)
●
Annualized loss of life for a specific failure scenario.

Figure 1

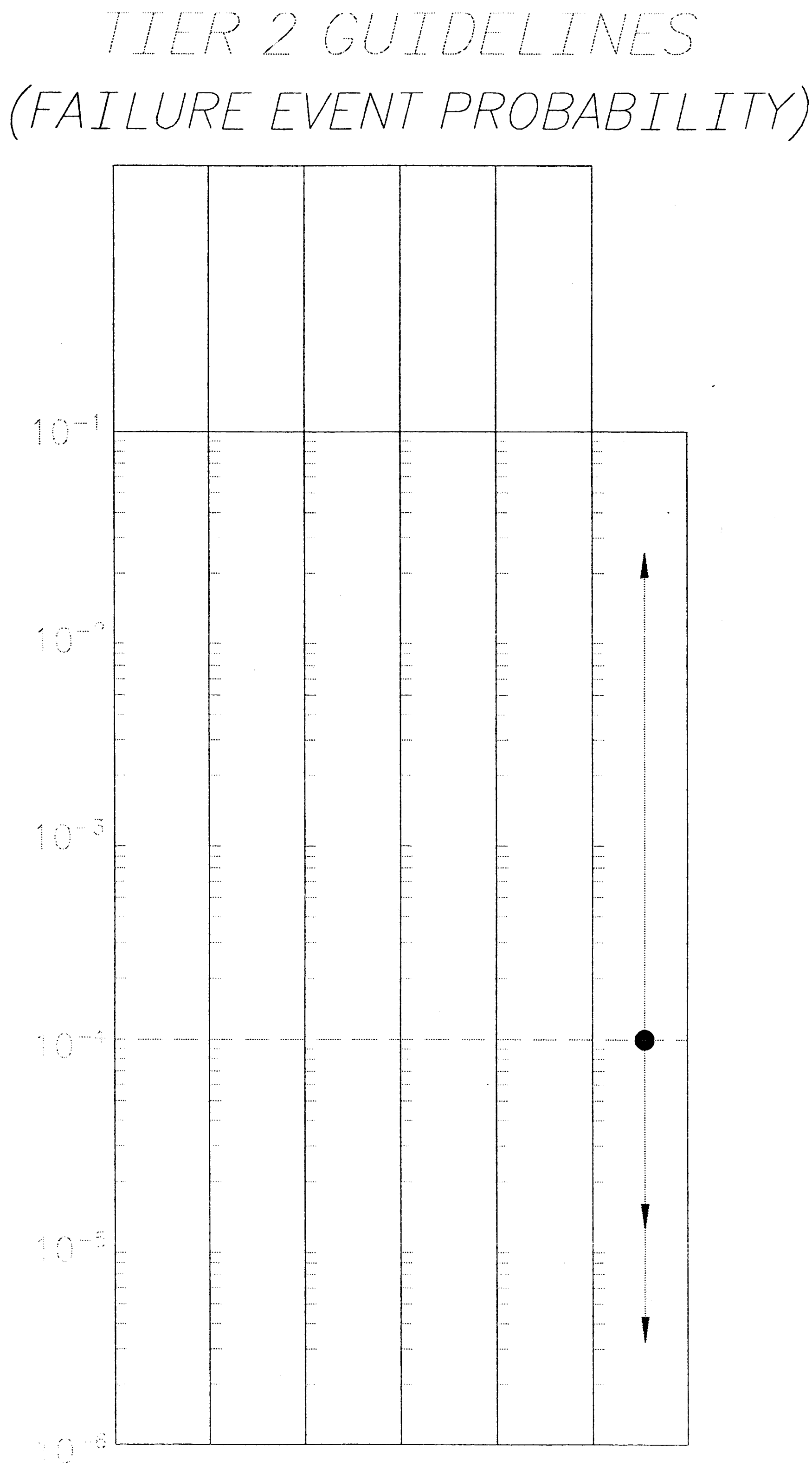

TIER 2 GUIDELINES
(FAILURE EVENT PROBABILITY)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

Figure 2

a standard component of the standing operating procedures for most Reclamation dams, the potential risk reduction benefits of early warning systems (or enhanced methods to detect adverse dam performance) are also investigated by Reclamation for both operational and dam failure scenarios under the Dam Safety program.

B. Second Tier Public Protection Guidelines - Public Trust Responsibilities

Although loss of life risks and consequences may be suitably addressed at a specific dam in accordance with the first tier guidelines, the probability that a structure under the auspices of the Reclamation dam safety program will experience an uncontrolled reservoir release from a dam is the accumulation of the probabilities of such events imposed by each of the individual dams within the Reclamation inventory. The greater the inventory of dams and the time of exposure, the more difficult it becomes to ensure that the agency will not experience a dam failure. To manage an effective dam safety program on behalf of the federal government and to assure the public of the credibility of its public agencies, dam failures and associated large consequences need to be avoided. Once a dam failure occurs, public trust is compromised and more severe and potentially more costly public expectations can be imposed. In addition, a high level of national safety and stewardship of public assets is expected of Reclamation as an agency specifically entrusted to manage a large inventory of dams.

To illustrate the magnitude of this concern, consider Reclamation's inventory of 382 high or significant hazard dams. While no two dams pose the same risk to the public, it is useful to consider an equal, average probability of an uncontrolled reservoir release from any Reclamation dam. As shown in Figure 3, limiting the probability of an uncontrolled reservoir release at one or more dams to less than a 10 percent chance in the next 50 years requires an average annual risk of a failure event at all dams to be less than approximately 1 chance in 200,000 . Considering that there will be a range of probabilities for uncontrolled reservoir release will vary throughout Reclamation's inventory of dams, it is the dams with the less remote probabilities of uncontrolled reservoir release that will contribute the greatest toward the possibility of one or more incidents at Reclamation dams in the next 50 years. Figure 3 also shows that allowing only 10 dams in Reclamation's inventory to have a probability of uncontrolled reservoir release equal to 1 in 1,000 would result in a 40 percent chance of such a release during the next 50 years from just these dams alone. Therefore, it is important that the public protection decision making process for any single dam be performed in the context of how that decision will impact the overall risk to Reclamation and the Federal Government.

To ensure a responsible performance level across the inventory of Reclamation Dams, it is recommended that each individual dam have a maximum combined annual probability of failure of 1 in 10,000. Failure event probabilities according to these guidelines are to be plotted on Figure 2 under the Tier 2 heading.

Meeting Reclamation's public safety and public trust responsibilities would be difficult and expensive to achieve with only passive structural systems. Therefore, an active examination, monitoring, and evaluation program is in place to provide a mechanism for early detection of developing and/or potential problems. This early detection information should be used to assess changes in the perceived risks at individual dams and to prioritize funding for the dam safety program for risk reduction activities.

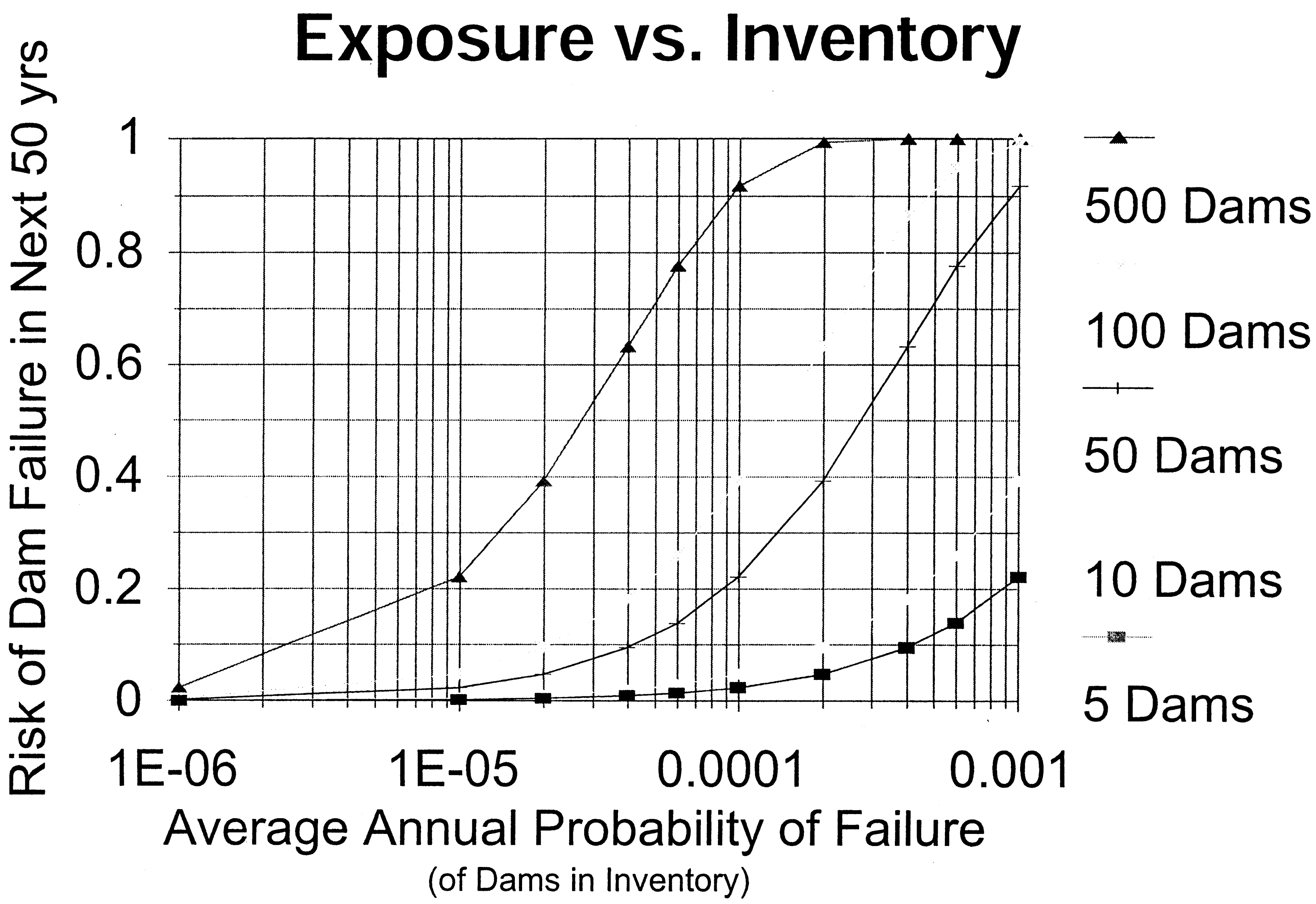

Exposure vs. Inventory
Risk of Dam Failure in Next 50 yrs
1
0.8
0.6
0.4
0.2
0
1E-06
1E-05
0.0001
0.001
Average Annual Probability of Failure
(of Dams in Inventory)
500 Dams
100 Dams
50 Dams
10 Dams
5 Dams

Figure 3

C. Risk Reduction Cost Effectiveness

As part of the decision to reduce risk at a dam, the risk reduction effectiveness of various alternatives needs to be evaluated. The cost for providing additional increments of risk reduction within the framework of the *Loss of Life Guidelines* should be determined and considered when choosing the preferred risk reduction alternative. The following indices should be computed to help determine, on a comparative basis, how effectively a proposed action reduces risk:

Absolute Risk Reduction Index:

$$ARRI = \frac{1000 \cdot \text{Estimated Annualized Loss of Life (No Action} - \text{Alternative)}}{\text{Alternative Cost (millions of \$)}}$$

Relative Risk Reduction Index:

$$RRI = \frac{\left(\dfrac{\text{No Action Estimated Average Annual Loss of Life}}{\text{Alternative Estimated Average Annual Loss of Life}}\right)}{\text{Alternative Cost (millions of \$)}}$$

* Alternative cost is the present worth of all capital and recurring costs

The indices provide a means for comparing alternatives. Initially, these comparisons will be most beneficial for comparisons for reducing risk at a particular dam, an expanding database of risk information will allow for a comparison between dams for the purpose of prioritizing the use of resources available for public protection. <u>Higher values of the indices indicate more effective use of monetary resources in providing public protection</u>. The absolute risk reduction index reflects overall cost effectiveness of expenditures at the evaluated site which can be compared to other sites. The relative risk reduction reflects the degree of improvement achieved at the site being evaluated. Following is an example calculation of the indices:

	Alternative #1	Alternative #2
Present (No action) Estimated Average Annualized Loss of Life	.01	.01
Estimated Average Annual Loss of Life with Alternative Implemented	.001	.0001
Alternative Implementation Cost	$500,000	$2,000,000
Absolute Risk Reduction Index	18	5.0
Relative Risk Reduction Index	20	50

In some cases, there may be substantial reductions in risk costs originating from a reduced chance of uncontrolled reservoir release. The principles of the analysis of these economic benefits has previously been documented in "Policy and Procedures for Dam Safety Modification Decision making" (April 1989) in the section describing the procedures to be used for risk analysis. When there are measurable reductions in risk costs associated with an alternative, it is appropriate to subtract the present value of the economic benefits from the cost of the alternative prior to computing the indices. This reduction of the alternative cost will ensure that the indices are based on the portion of the costs which would have to be allocated to the purpose of public protection. (Note: When the economic benefits of an alternative exceed the cost of that alternative, the indices will be negative and do not need to be reported since the alterative is fully justified by the economic benefits.)

The indices may also be used to evaluate short term risk reduction alternatives when it appears that additional risk reduction measures may be justified. When considering short term measures for public protection, the above indices should be corrected by a factor which relates the duration that the short term measures will be in place to the assumed duration of a long term measure. When the annualized probability of loss of life is less than .01, the adjusted index value is computed as follows:

$$\text{Adjusted index} = \text{index} * \frac{\text{Duration of interim fix}}{\text{Duration of long term fix}}$$

If the adjusted index for the interim fix is equivalent or greater than the index for the long term fix, the interim fix should be recommended to decision makers. When estimated average annual loss of life is greater than .01, the adjustment factor is more accurately calculated by taking the ratio of the total loss of life probability for the interim modification (typically having a life span of 2-5 years) to the total loss of life probability for the long term modification (based on a duration of 50 years*). The total loss of life probability is defined as:

$P_F = 1 - (1 - P)^n$, where

P_F = the total probability of loss of life for the life span of the modification
n = the life span of the modification, in years
P = the estimated average annual loss of life under the modification

As above, the adjusted indices for an interim fix are determined by multiplying the originally calculated indices by the adjustment factor.

** Note: The duration of 50 years has been selected in part due to parallels with economic analysis. If given the choice of eliminating risk in a current year or a future year, it would be expected that decision makers would prefer to eliminate risk in the current year. If we extend the notion of the time value of money to the evaluation of risk, risks more than 50 years in the future are of little significance in comparison to risks over the next 50 years.*

Sample Plotting of Risk Assessment Results

Following are hypothetical results of a risk assessment to illustrate the manner in which results should be depicted on Figures 1 and 2:

> Earthquake load range probability (only a single loading category and load range are considered for simplicity):
>
> > Best estimate: 0.00005
> > Variation of Load range probability: 0.00001 to 0.0001
>
> 2 dam responses, each with a loss of life variation:
>
> > Response 1: Slump
> > Failure probability given load: 0.5 (range 0.2 to 0.8)
> > Loss of life: 100 (range 50 to 300)
> >
> > Response 2: Seepage erosion through cracks
> > Failure probability: 0.1 (range 0.02 to 0.4)
> > Loss of life = 5 (range 1 to 40)

Tier 2 Plotting:

From the above data, the best estimate of the annual probability of an adverse response is computed by the following equation:

$$\begin{pmatrix}\text{Best Estimate of}\\ \text{Annual Adverse}\\ \text{Response}\\ \text{Probability}\end{pmatrix} = \sum_{i=1}^{\text{number of load ranges}} \left(\begin{pmatrix}\text{Best Estimate}\\ \text{of}\\ \text{Load Range}\\ \text{Probability}\end{pmatrix}_i * \sum_{j=1}^{\text{number of adverse responses}} \begin{pmatrix}\text{Best Estimate}\\ \text{of Response}\\ \text{Probability}\end{pmatrix}_j \right)$$

.00005*(.5+.1) = .00003

This value is plotted as a point on the Tier 2 chart for the appropriate loading category. Since it is also desired to provide decision makers with information about the sensitivity/uncertainty of the best estimate, the variations of the parameters of the best estimates must also be evaluated and plotted. In this process, the load range probability and response probability are varied, one at a time, and plotted independently. The upper bounds for each variation are computed by replacing the best estimate parameters with the maximum values of the ranges of those parameters subject to the requirement that the summations of load range probabilities and response probabilities for each load range are less than or equal to 1.0. The lower bounds for each variation are computed by replacing the best estimates parameters with the minimum values of the ranges of those parameters.

Sensitivity due to response probability variation:

> Upper bound estimate of annual adverse responce probability -
>
> > The probabilities must first be normalized since the response probabilities sum to a value greater than 1.0 which indicates that the responses can not be mutually exclusive. As the probabilities of any two independent events becomes larger, the

probability of both events occurring increases thus requiring an adjustment to the computation of the probability of failure from either event.

Probability of Failure = 1 - [1 - P(R1)] * [1 - P(R2)]
where: P(R1) = Probability of response 1
P(R2) = Probability of response 2

Probability of failure for the given data = 1 - (.2)*(.6) = 0.88

Therefore, the adjusted probabilities must sum to 0.88. Additionally, we wish to preserve the ratios between the probabilities such that the adjusted probability of response #1 will continue to be twice the adjusted probability of response #2. If we allow P1 to be the adjusted probability of response #1 and P2 to be the adjusted probability of response #2, we have the following two simultaneous equations for determination of P1 and P2:

$$P1 + P2 = 0.88 \qquad \text{and} \qquad P1/P2 = 0.8/0.4$$

Solving the equations yields values of P1=0.59 and P2=0.29. The upper bound estimate of annual adverse response variation can then be determined as:

.00005*(0.59 + 0.29) = .000044

Lower bound estimate of annual adverse response probability -
.00005*(0.2 + .02) = .000011

The above results are plotted on Figure 5.

Tier 1 Plotting:

The best estimate of the estimated annualized loss of life is computed according to the following equation:

$$\begin{matrix}\text{Estimated}\\ \text{Annualized}\\ \text{Loss of Life}\\ \text{for a given}\end{matrix} = \sum_{i=1}^{\text{number of load ranges}} \left(\begin{matrix}\text{Best Estimate}\\ \text{of}\\ \text{Load Range}\\ \text{Probability}\end{matrix}_i * \sum_{j=1}^{\text{number of responses}} \left(\begin{matrix}\text{Best Estimate}\\ \text{of Response}\\ \text{Probability}\end{matrix}_j * \begin{matrix}\text{Best Estimate}\\ \text{of Response}\\ \text{Consequence}\end{matrix}_j \right)\right)$$

The weighted average of estimated loss of life for all responses of the dam is computed according to the following equation:

$$\begin{matrix}\text{Weighted Average}\\ \text{Loss of Life}\end{matrix} = \frac{\text{Estimated Annualized Loss of Life}}{\text{Annual Adverse Response Probability}}$$

For the given data:

Best Estimate of Estimated Annualized Loss of Life = 0.00005*(0.5*100 + 0.1*5) = 0.00253

Weighted Average Loss of Life = 0.00253/.00003 = 84

This information is plotted on Figure 4 as a point.

To evaluate sensitivity/uncertainty of the best estimate, the variations of the parameters of the best estimates must also be evaluated and plotted. In this process, the load range probability, response probability, and consequence variations are varied, one at a time, and plotted independently. The upper bounds for each variation are computed by replacing the best estimate parameters in the estimated annualized loss of life equation with the maximum values of the ranges of those parameters subject to the requirement that the summations of load range probabilities and response probabilities for each load range are less than or equal to 1.0. The lower bounds for each variation are computed by replacing the best estimates parameters with the minimum values of the ranges of those parameters. The variation in loss of life is shown as a range between the minimum and maximum loss of life values for any adverse response of the dam.

Minimum loss of life for all adverse responses = 1

Maximum loss of life for all adverse responses = 300

Sensitivity due to load probability variation:

Upper bound estimate of estimated annualized loss of life -

.0001*(0.5*100 + .1*5) = .00505

Lower bound estimate of estimated annualized loss of life -

.00001*(0.5*100 + .1*5) = .000505

This information is plotted as a box on the Tier 1 chart and should be labeled "Load Range Probability Variation."

Sensitivity due to response probability variation:

Upper bound estimate of estimated annualized loss of life (using adjusted probabilities from tier 2 computations) -

.00005*(.59*100 + .29*5] = .003

Lower bound estimate of estimated annualized loss of life -

.00005*(0.2*100 + .02*5) = .001

This information is plotted as a box on the Tier 1 chart and should be labeled "Response Probability Variation."

Sensitivity due to response consequence variation:

Upper bound estimate of estimated annualized loss of life -

.00005*(0.5*300 + .1*40) = .0077

Lower bound estimate of estimated annualized loss of life -

.00005*(0.5*50 + .1*1) = .00126

This information is plotted as a box on the Tier 1 chart and should be labeled "Response Consequence Variation."

Individual response/failure mode estimates may also be plotted on the Tier 1 chart to show which responses of the dam contribute most to the overall risk. Each of these scenarios is based on the best estimates and is plotted as an "X" on the chart.

Response #1:	Estimated Annualized Loss of Life	0.00005*0.5*100 = 0.0025
	Loss of Life	100
Response #2:	Estimated Annualized Loss of Life	0.00005*.1*5 = 0.000025
	Loss of Life	5

The above results are plotted in Figure 4.

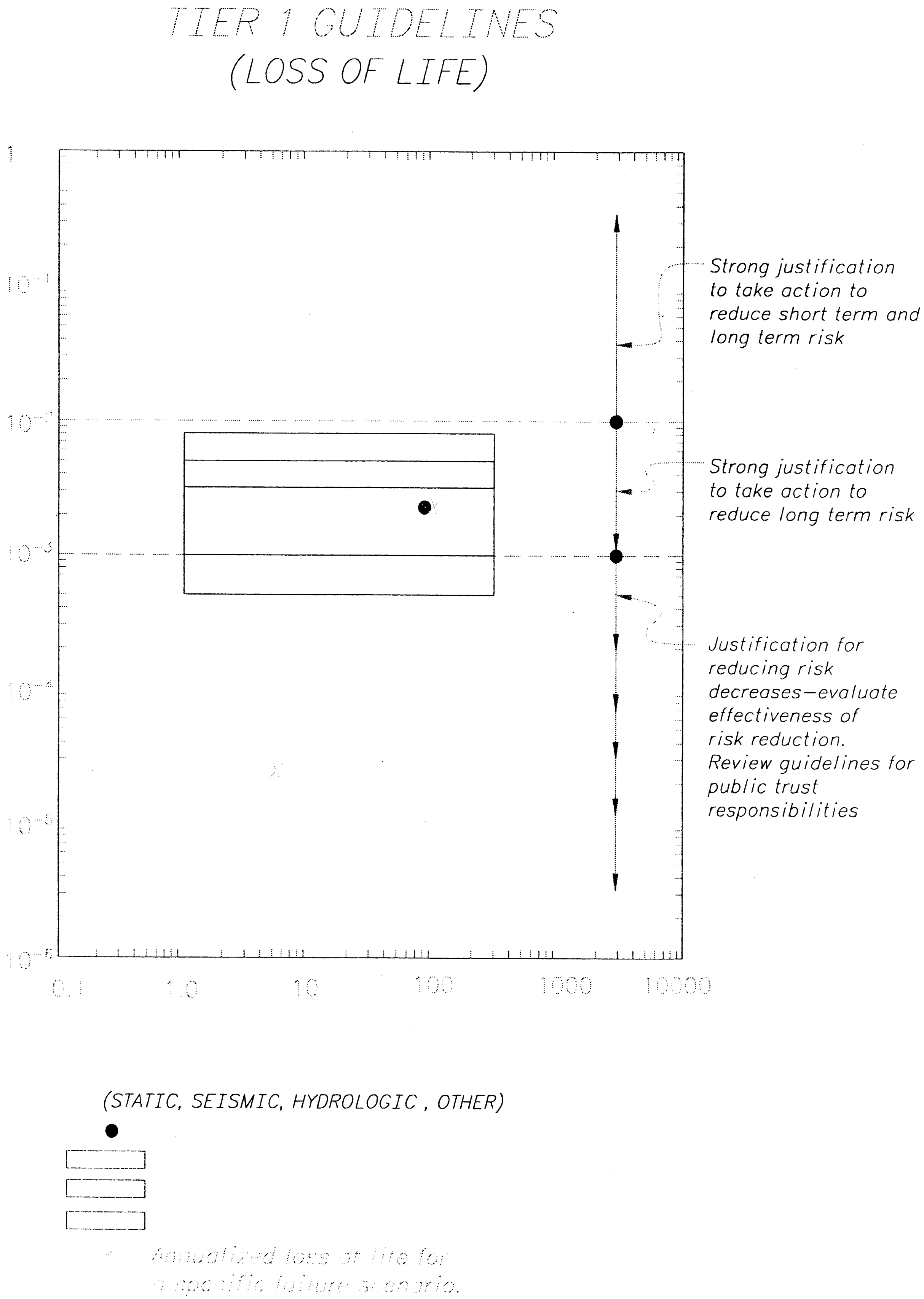

TIER 1 GUIDELINES
(LOSS OF LIFE)
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.1
1.0
10
100
1000
10000
Strong justification to take action to reduce short term and long term risk
Strong justification to take action to reduce long term risk
Justification for reducing risk decreases—evaluate effectiveness of risk reduction. Review guidelines for public trust responsibilities
(STATIC, SEISMIC, HYDROLOGIC , OTHER)
Annualized loss of life for a specific failure scenario.

Figure 4

TIER 2 GUIDELINES
(FAILURE EVENT PROBABILITY)

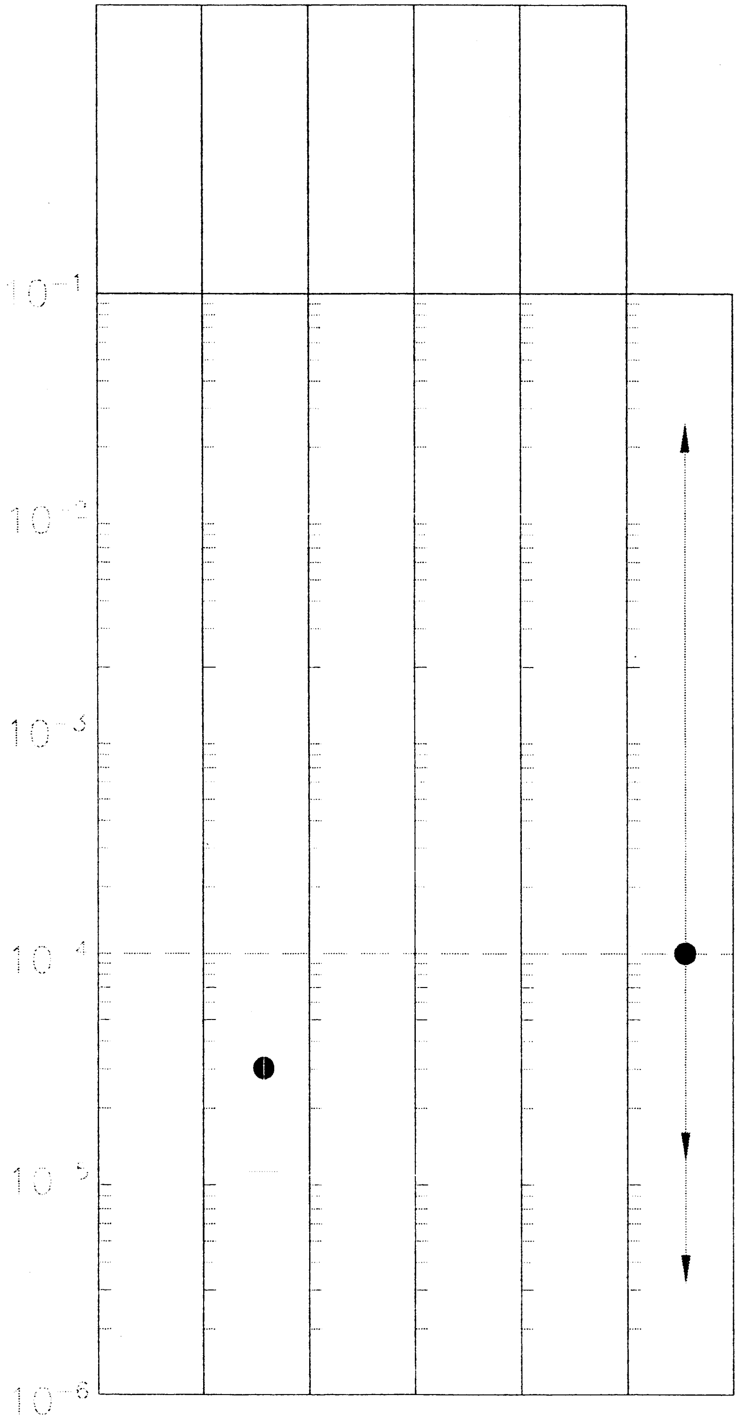


Figure 5

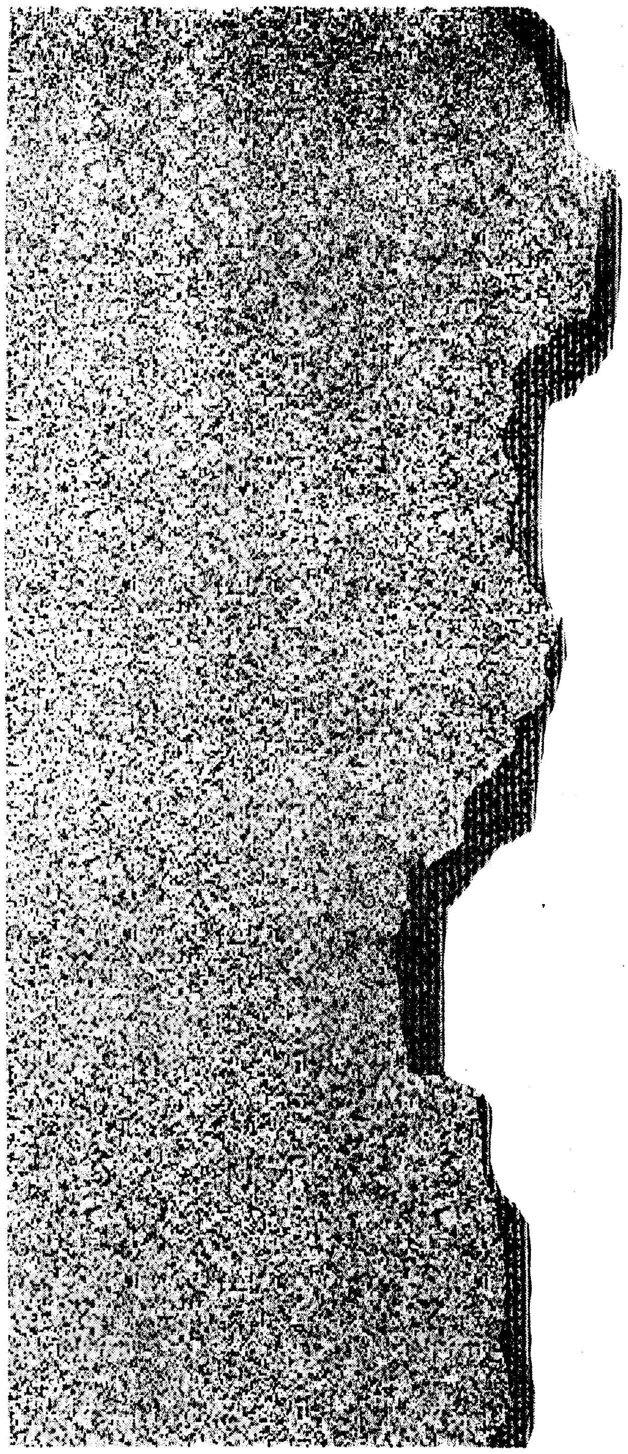
Sample Index Computation for an Interim Action

(Adapted from the Bradbury Dam Spillway Risk Assessment)

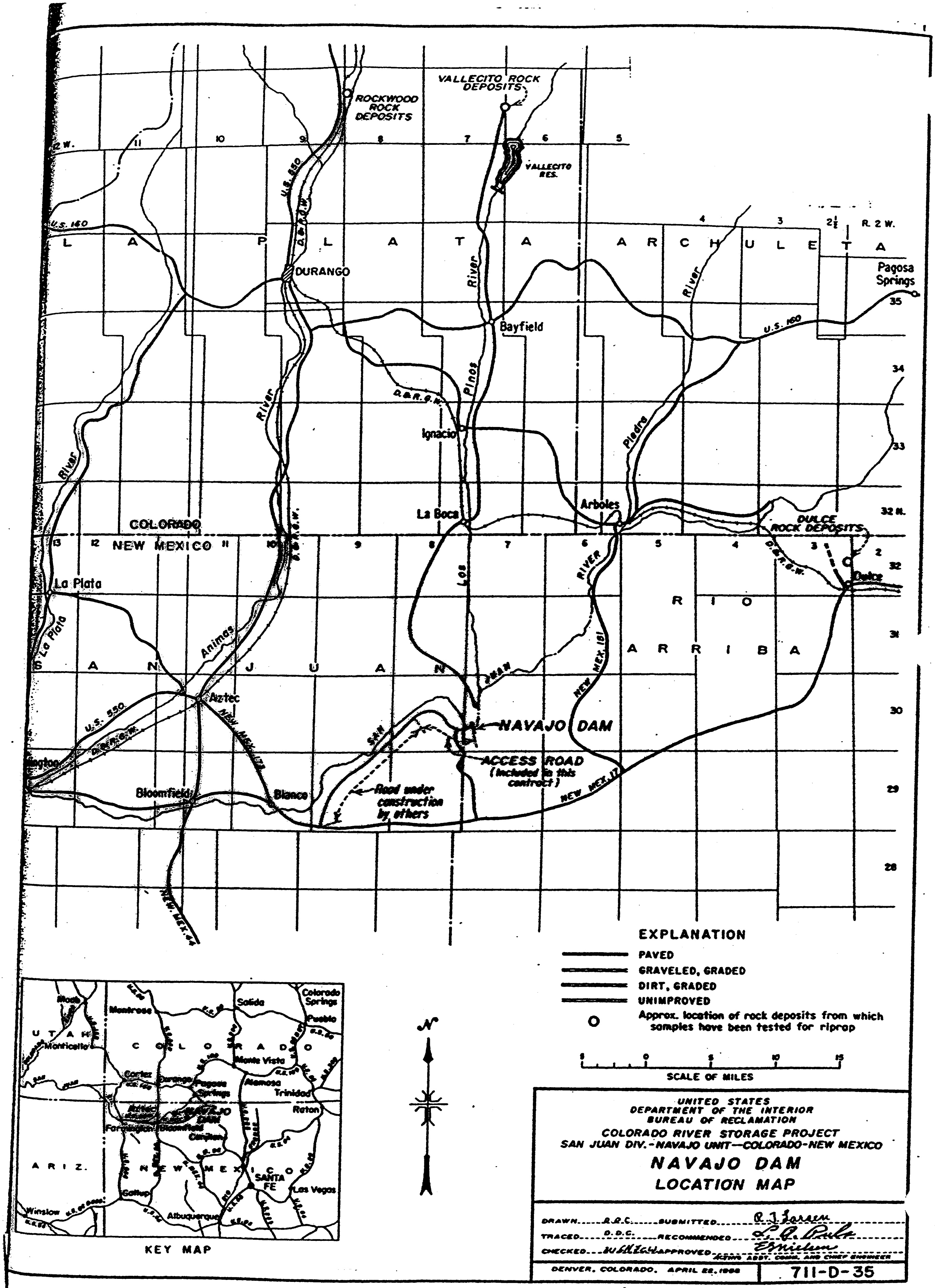
At Bradbury Dam, required spillway modifications to reduce seismic risk could not be performed concurrently with the dam modifications due to construction scheduling considerations. However, two interim measures were considered which would reduce risk until the spillway modifications could be accomplished. One interim alternative was to add structural bracing to the gates for a nominal cost, and the other alternative involved implementing those portions of the selected final corrective action which could be implemented without impacting the dam modification.

	Complete Corrective Action	Interim Action A	Interim Action B
No Action Estimated Average Annualized Loss of Life	.0017	.0017	.0017
Alternative Estimated Average Annualized Loss of Life	.00015	.0006	.0002
Alternative Implementation Cost	$2,500,000	$35,000*	$1,200,000
Evaluated Duration of Corrective Action	50 years	2 years	2 years
Absolute Risk Reduction Index	$.62 = \frac{1000 \cdot (.0017 - .00015)}{2.5}$	$31.4 = \frac{1000 \cdot (.0017 - .0006)}{.035}$	$1.25 = \frac{1000 \cdot (.0017 - .0002)}{1.2}$
Adjusted Absolute Risk Reduction Index		$1.3 = 31.4 \cdot \frac{2}{50}$	$.05 = 1.25 \cdot \frac{2}{50}$
Relative Risk Reduction Index	$4.5 = \frac{.0017 / .00015}{2.5}$	$81 = \frac{.0017 / .0006}{.035}$	$7.08 = \frac{.0017 / .0002}{1.2}$
Adjusted Relative Risk Reduction Index		$3.2 = 81 \cdot \frac{2}{50}$	$.28 = 7.08 \cdot \frac{2}{50}$

* Note: Alternative implementation costs are those costs of interim actions which are not considered to be part of the complete corrective actions.



NAVAJO DAM
RISK ANALYSIS
1998



UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
SAN JUAN DIV.-NAVAJO UNIT—COLORADO-NEW MEXICO

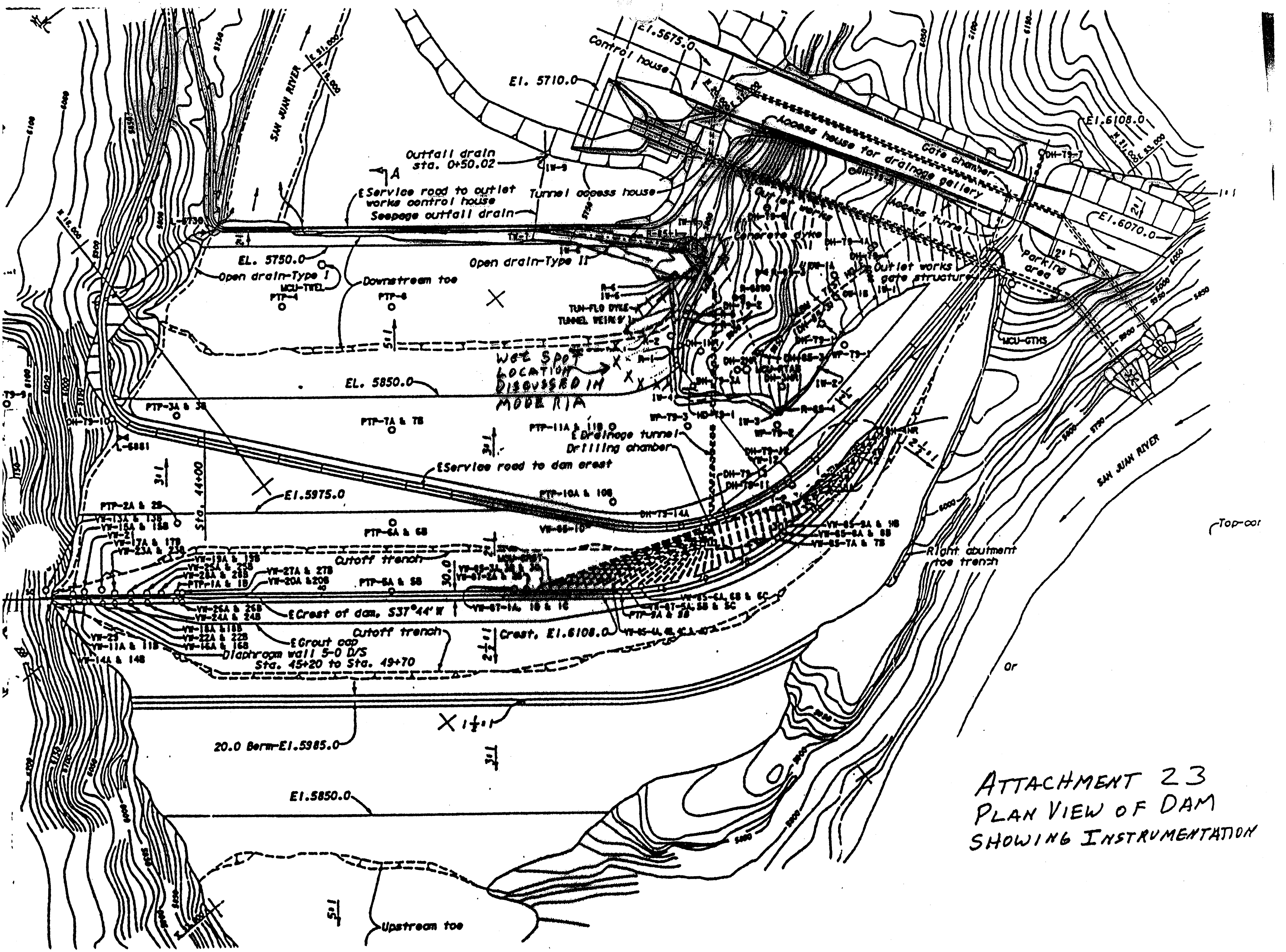
NAVAJO DAM
LOCATION MAP

DRAWN R.R.C. SUBMITTED R. J. Larsen
TRACED D.D.C. RECOMMENDED L. G. Puls
CHECKED W.H.H.G.L. APPROVED E. Nielsen
ACTING ASST. COMM. AND CHIEF ENGINEER

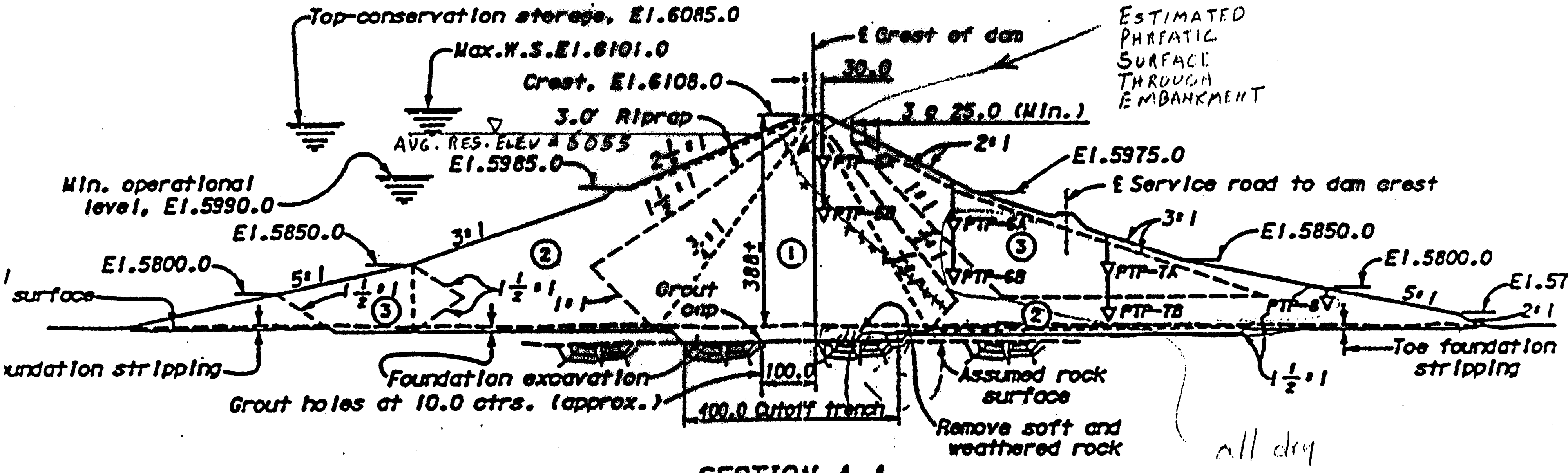
DENVER, COLORADO. APRIL 22, 1958

711-D-35

ATTACHMENT 21
LOCATION OF COMMUNITIES
AND TRIBUTARIES



ATTACHMENT 23
PLAN VIEW OF DAM
SHOWING INSTRUMENTATION



SECTION A-A
STA. 37+60

ATTACHMENT 22
CROSS SECTION OF
NAVAJO DAM

See Sketch 1 for a general representation of these failure modes.
Using the symbols for **R**, **C** and **L** for Right Abutment , Channel, and Left Abutment respectively and the numeric values above for failure mode identifiers yields basic failure mode labels for reference of --- **R1, R2, R3, C1, C2, C3, L1, L2, L3.** Variations of these basic modes would be characterized by an additional letter (e.g., **R2A, R2B).**

For each of these piping and seepage related failure modes the team was asked to use a generic "dam response probability" event tree formulation (shown in Appendix A) with the following four components or steps:

1. Probability of the presence of continuous joints
2. Probability of initiation of piping
3. Probability that piping progresses
4. Probability of breach (including consideration of intervention)

The event tree was not restricted to these four branches in that sub-trees to further define any one component (step) could be used, but to the degree possible the team was asked to use (test) the process of describing the factors that made each of these steps in the "seepage to breach" process more or less likely for each failure mode and then lumping those factors together in making the estimate of the likelihood of that step occurring.

The team agreed to start with the Right Abutment with the hope that some generalizations or approximations based on those results could be applied to the other two areas.

Right Abutment Failure Mode R1

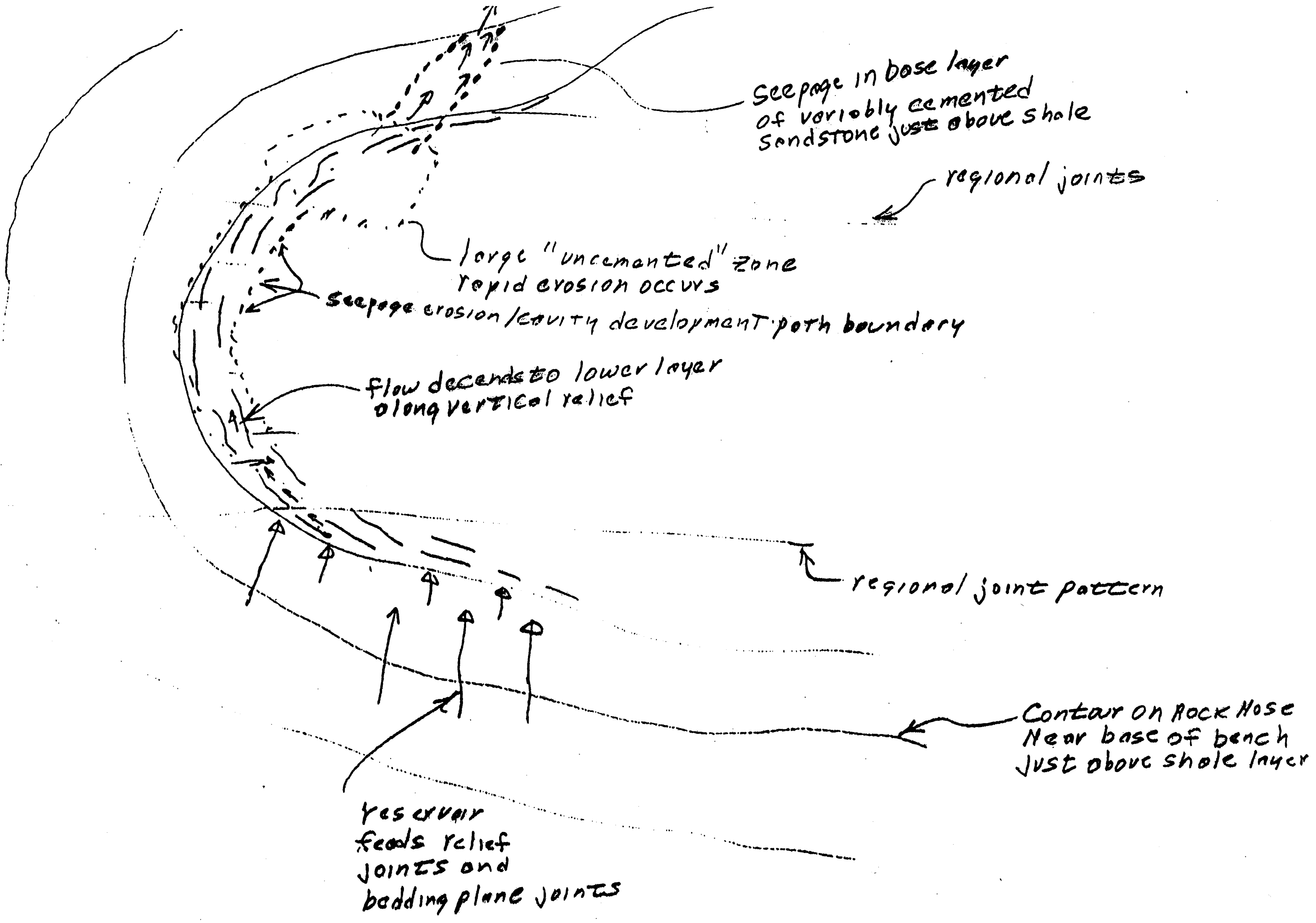
Estimation of the Probability of Failure Mode R1 - Piping Failure Initiated by Flow Through the Right Abutment for Reservoir Elevations above and below Elev. 6085

The team began with the "generic" piping and seepage event tree containing the 4 steps in the "seepage to breach" process identified above for the reservoir below elevation 6085. Routings indicated that this elevation would be exceeded by approximately the 1 in 200 year event given a starting reservoir elevation of about 6,050 (See Item 2) . Thus the load probability for the reservoir being at or below elevation 6085 was estimated as 1- 1/200 = 0.995. (See Event Tree in Appendix A - Failure Mode R1)

The first step in the generic response probability process is - Probability of the presence of continuous joints. Note that when referring to the node number the counting began after the load probability node (as it is not a "generic response" node), however, the load node is shown on the event trees.

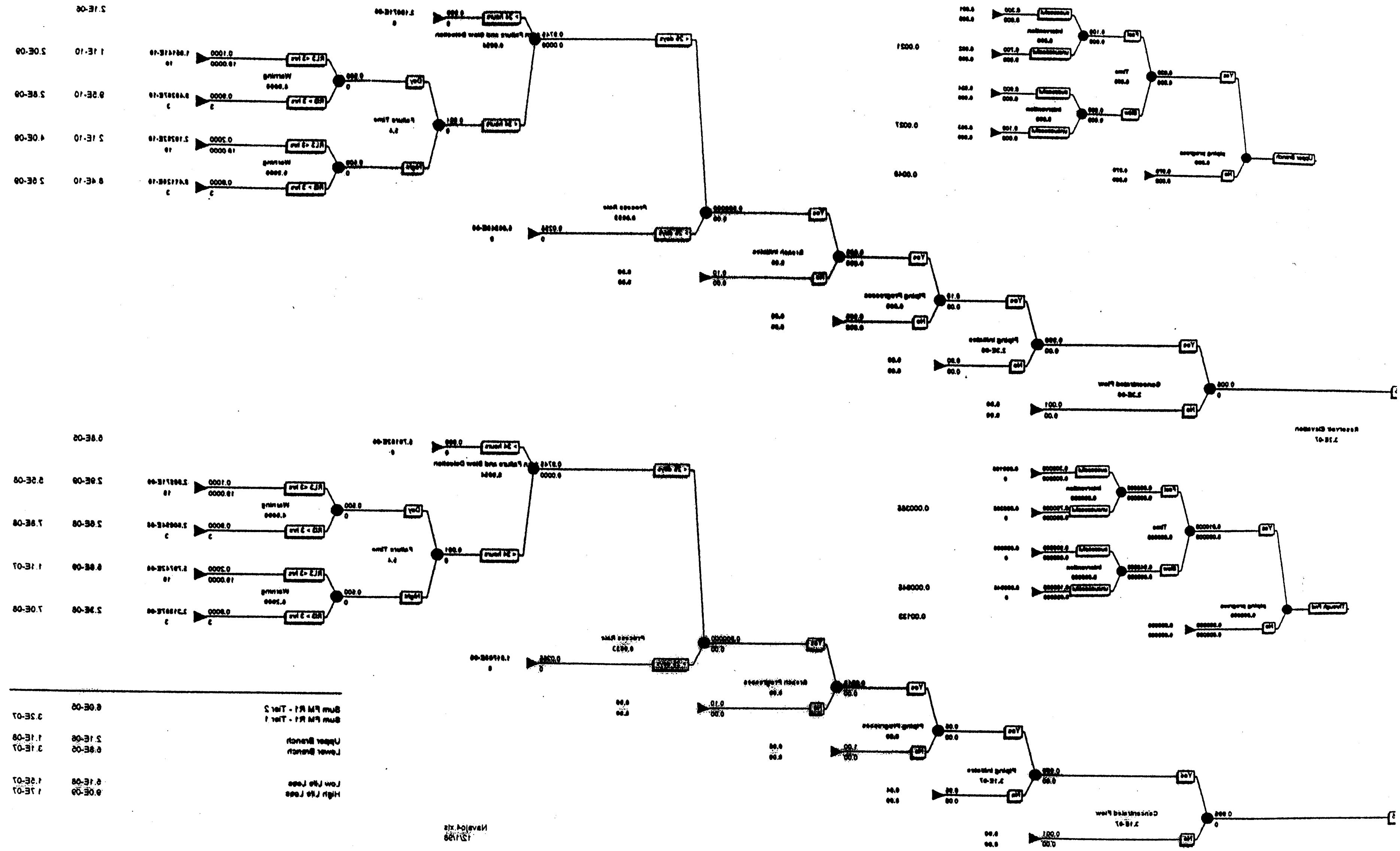
<u>Event tree - First Node</u> - Probability of the presence of a "concentrated flow" -
(See Event Tree in Appendix A - Failure Mode R1)

The team only identified items that would seem to make the presence of a concentrated seepage flow in the right abutment more likely (See Appendix C- Failure Mode R1).



SKETCH 2

RIGHT ABUTMENT FAILURE MODE R1
FLOW THROUGH FOUNDATION
GEOLOGIC MODEL OF PIPING
PROGRESSION



VERBAL DESCRIPTORS

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Failure Mode R1 - Piping through right abutment foundation-

Event Tree Condition - Presence of a concentrated leak

Factors That Make the Condition

MORE LIKELY
Experiences from the drainage tunnel
Experiences from US Bureau of Mines drill hole
Experiences from drill holes HD-1,2, and 3
Flows from natural "holes in the rock"
Joints flowing water
Observed seepage

LESS LIKELY

Event Tree Condition - Piping of foundation material initiates

Factors That Make the Condition

MORE LIKELY
Uncontrolled exits exist
Less seepage reduction above D-Shale
Lower portion of sandstone was more friable
Caving occurred in vertical drill holes
Uncemented sand was logged in drill cores
Evidence some gypsum above "D" layer solutioned--
Less seepage reduction above D shale
Bureau of Mines hole made sand --------
holes made sand ---------
holes made sand ----------
Pre tunnel instrumentation was poor
recent changes in seepage areas along
with decrease in tunnel flows

LESS LIKELY
Depth of "hole in wall" unchanging
Historic seeps clean -no piles of sand
First filling (1963-74) okay - no sand
Seepage observation for 30 years
without piping incident
Gypsum gone from sandstone
no piping observed
Changed seepage pathway seems Horizontal
to be required to cause significant Tunnel
observable particle movement
No completely uncemented discharge Some
faces
Friable materials tend to be med. to
coarse sand sizes
Measured seepage not going up
Most fractures in abutment are not
open much
Existing flowing tunnel drains did not
make sand and are not deteriorating

Uncertainty Evaluation for Navajo Risk Analysis

Uncertainty in what?

1) uncertainty associated with group subjective probability estimates

- **formally expresses group confidence in each estimate**
- **i.e., the "probability of the probability"**

2) uncertainty associated with loss of life estimates

Terminology: "uncertainty" used in two senses

1) uncertainty in the *event*

- **single-valued "best estimate" probability by group consensus**

2) uncertainty in the *estimate*

- **subjectively-assigned probability distributions on event occurrence**

Why is there variability in the subjective probability value?

- SP is not unique
- SP depends on one's personal state of knowledge and judgment
- SP varies according to:
  - time: status and understanding of technology
  - information available
  - individual differences in interpretation of information

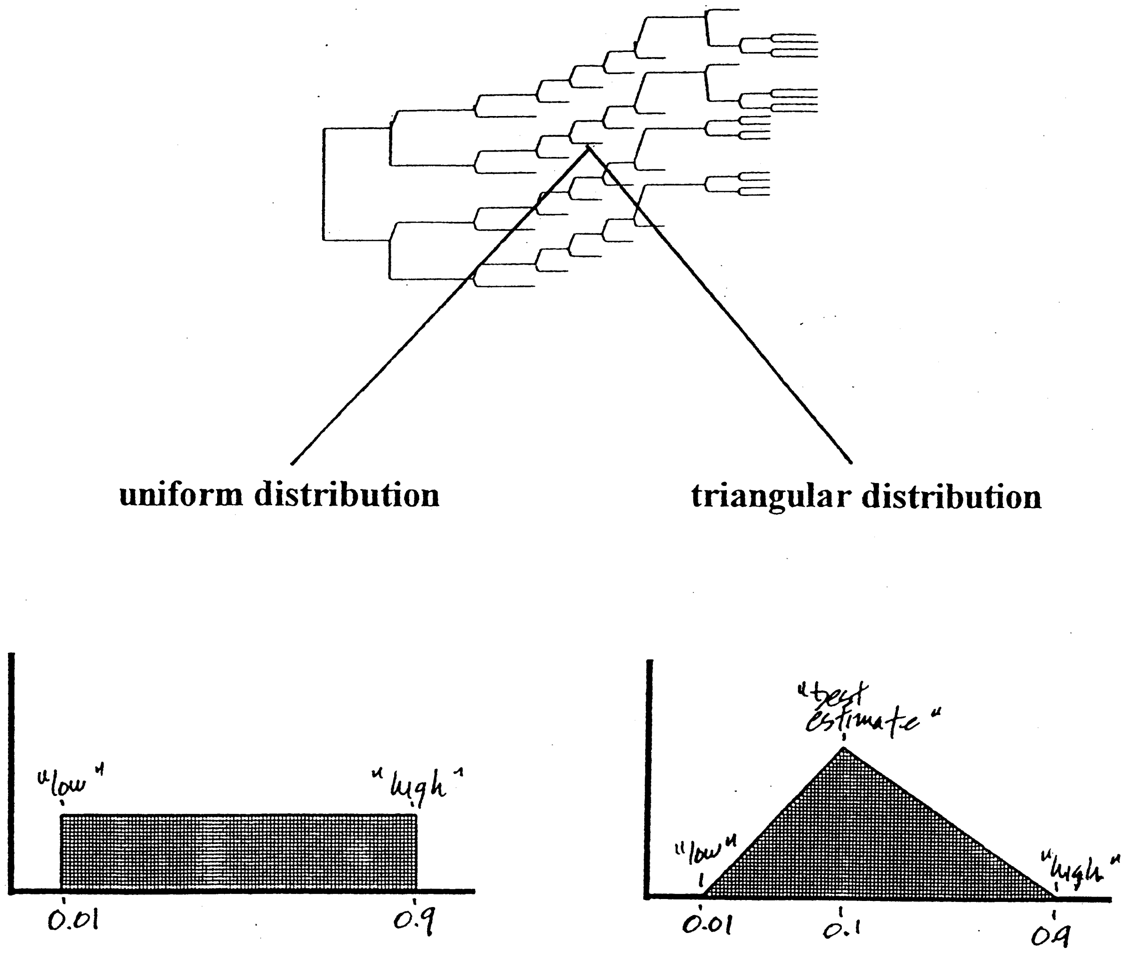
    (i.e., different inductive reasoning strategies)

    (i.e., differences in personal judgment)

Why was this uncertainty addressed for Navajo Dam?

- long history of seepage
- exceptionally comprehensive information to work with
- different interpretations of seepage cause, severity, and implications
- consensus sought, while still recognizing, capturing, and expressing individual interpretations of conditions
- "pilot study" for techniques

Probability distributions for component events



coherence for annual initiator probabilities:

- check using annual Bernoulli trials and binomial theorem
- prompts for statistical reasoning strategies (representativeness bias)
- invokes underlying base-rate frequency information from past performance

if p_i in any given year is 0.1,
then in 30 years, $p_{30} = [1 - (1-0.1)^{30} = \mathit{0.96}$ ......etc.

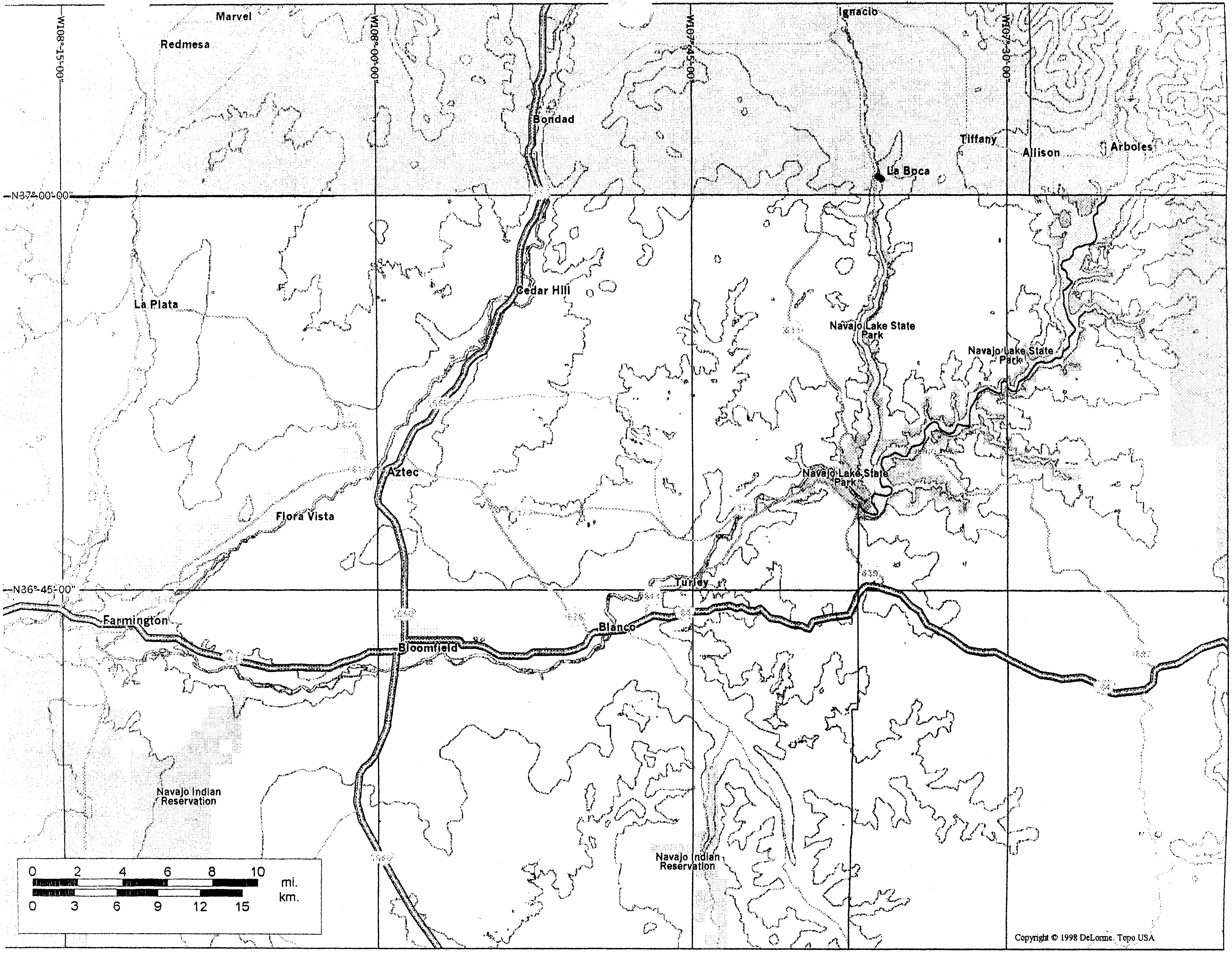
Probability distributions for loss of life

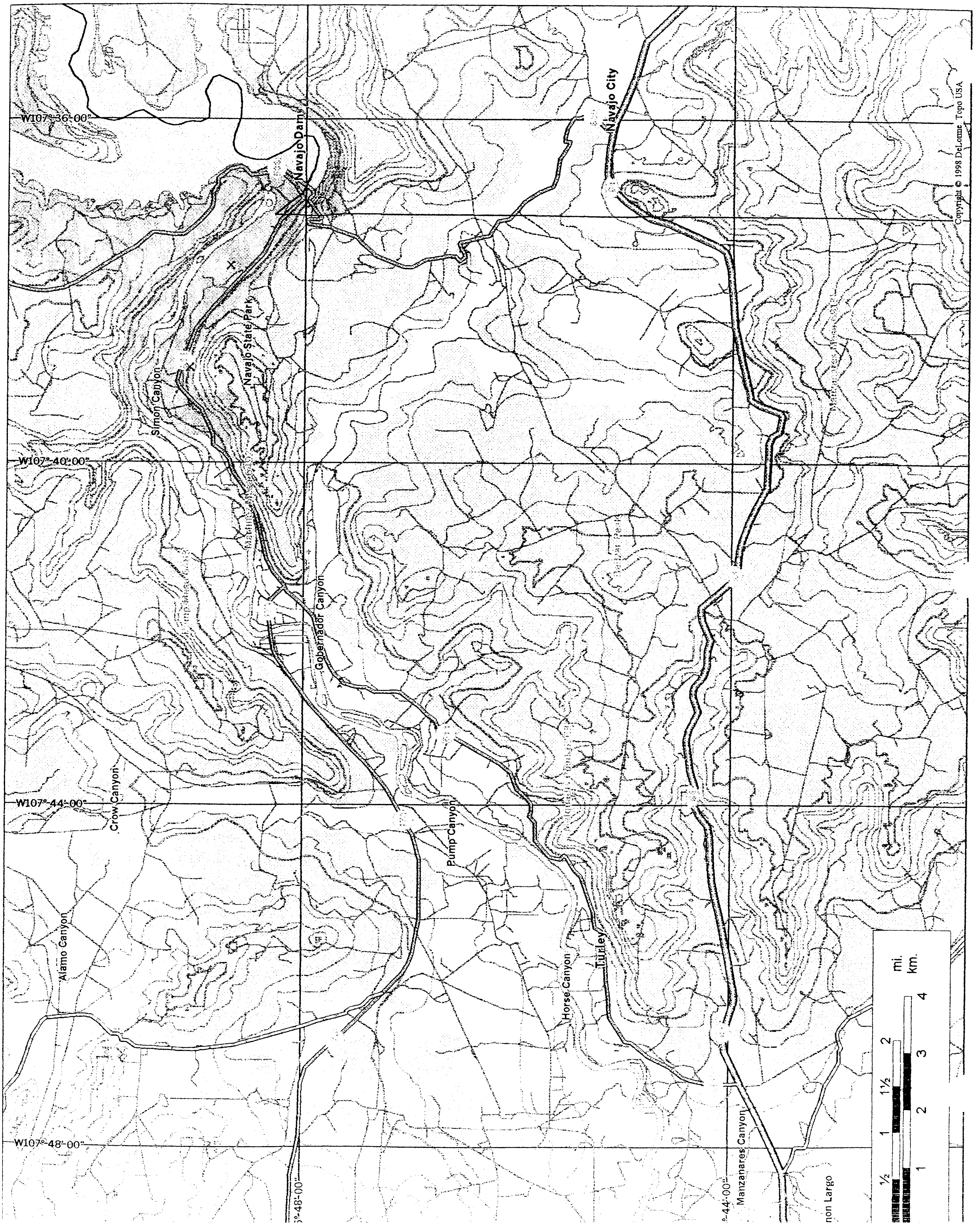
DeKay and McClelland (logistic regression)

LOL = f(PAR, warning time, Force)

Factors considered explicitly:

- PAR partitioned into downstream regions
- rate at which failure process would progress to breach
- day/night influences
- effectiveness and operability of warning system detection devices/protocols
- EAP training and communications networks
- "oblivious individuals"


W108°-15'-00"
W108°-00'-00"
W107°-45'-00"
W107°-30'-00"
N37°-00'-00"
N36°-45'-00"
Marvel
Redmesa
Ignacio
Bondad
Tiffany
Allison
Arboles
La Boca
Cedar Hill
La Plata
Navajo Lake State Park
Navajo Lake State Park
Navajo Lake State Park
Aztec
Flora Vista
Turley
Farmington
Blanco
Bloomfield
Navajo Indian Reservation
Navajo Indian Reservation
0 2 4 6 8 10 mi.
0 3 6 9 12 15 km.


W107°36'00"
W107°40'00"
W107°44'00"
W107°48'00"
6°48'00"
°44'00"
Navajo Dam
Navajo City
Navajo State Park
Simon Canyon
Gobernador Canyon
Crow Canyon
Pump Canyon
Alamo Canyon
Horse Canyon
Turley
Manzanares Canyon
non Largo
mi.
km.
½
1
1½
2
1
2
3
4

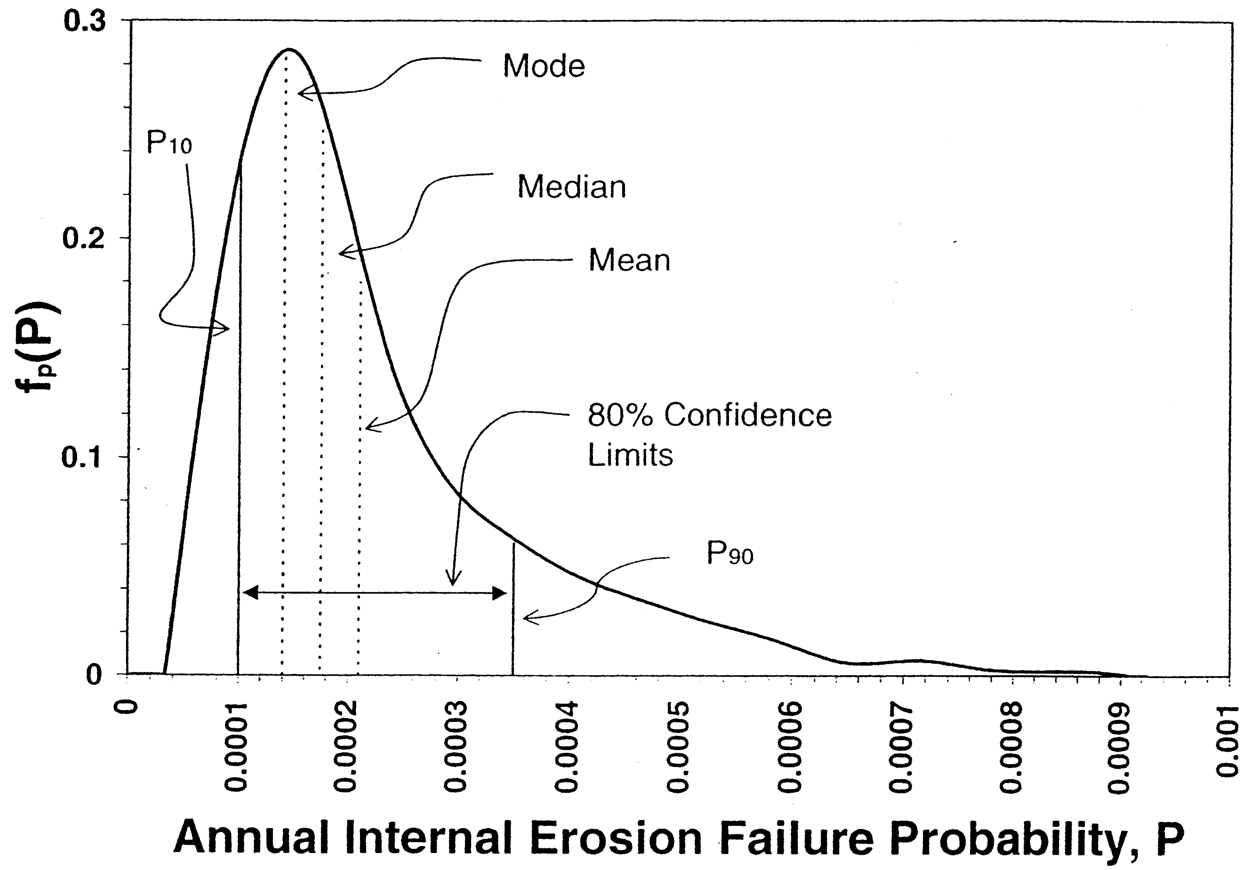
Combining probability distributions

- joint PDF's for p_f and lives lost cannot be determined algebraically in closed form

- approximate solution techniques:
  - "point estimate" method (PEM)
  - "first-order second-moment" (FOSM)
  - Monte Carlo simulation

- Monte Carlo techniques ("random walk" through event tree)
  - random number generator
  - realizations in proportion to probability distributions assigned
  - joint PDF derived from relative frequency of realizations

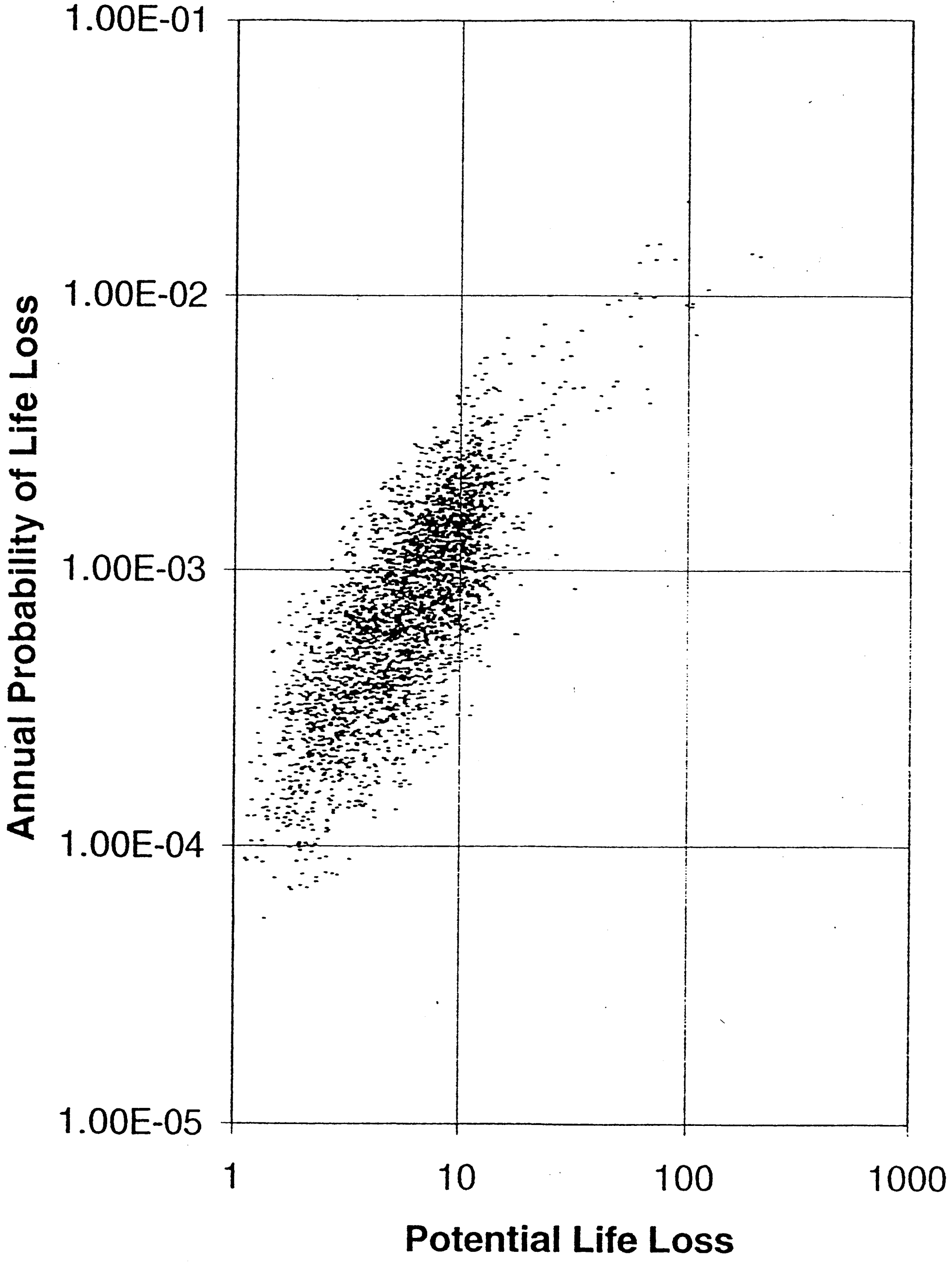
Results



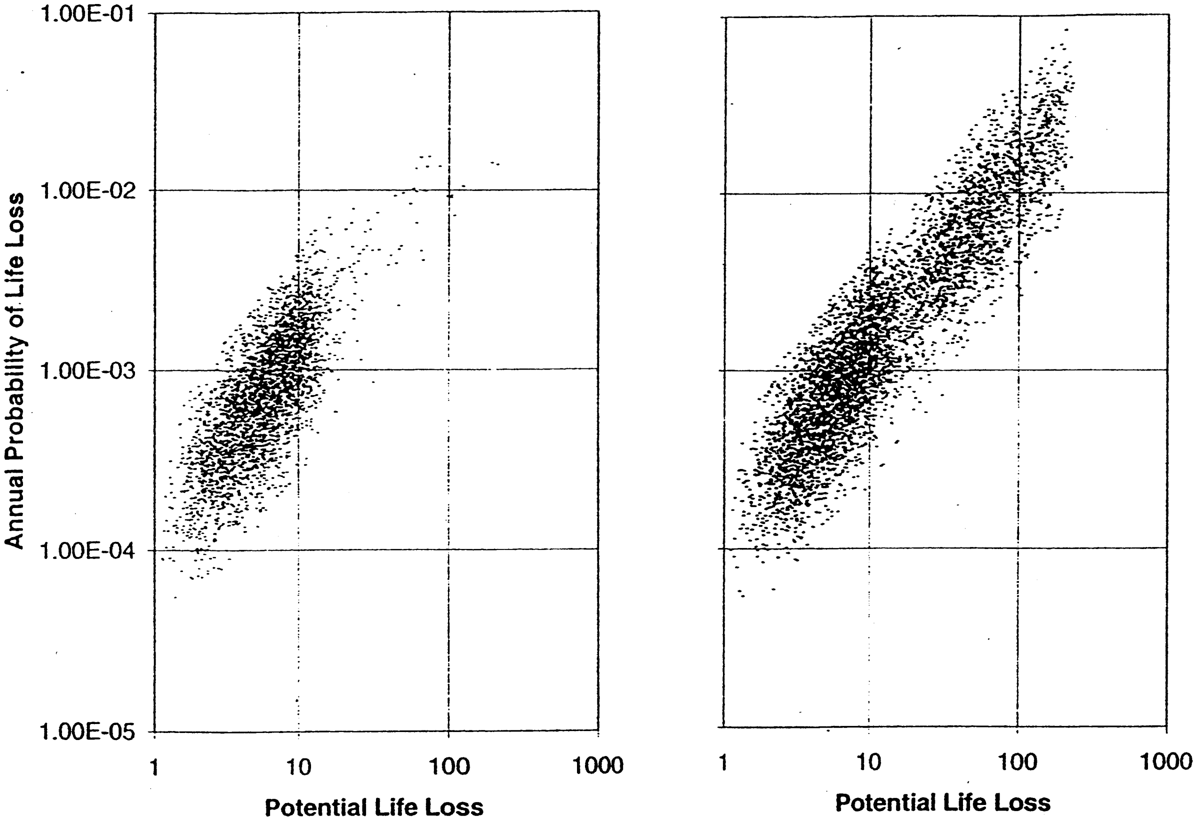
note that p_f is lognormally distributed:

- **implied by central limit theorem**
- **asymmetric, with longer "tail" at higher probabilities, depending on architecture of event tree**

Results (cont.) - Reclamation "Tier 1" format



Influence of current warning system

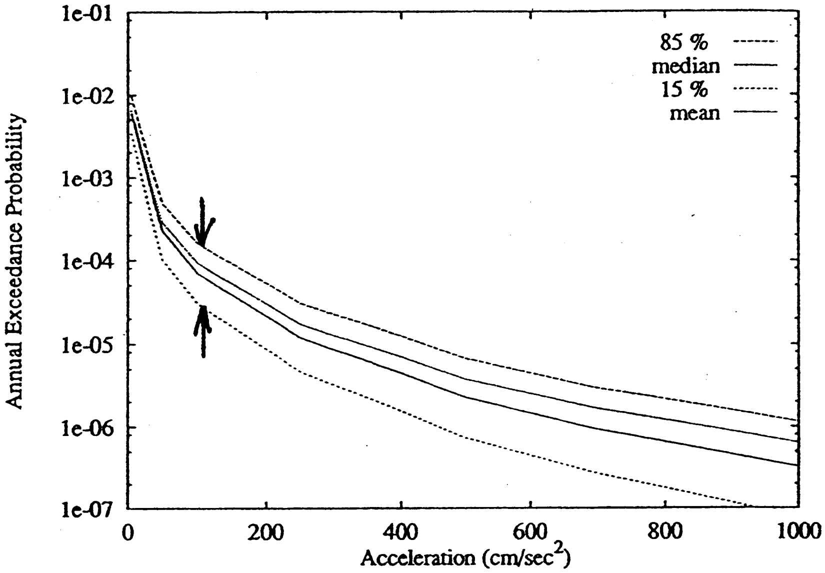


current warning system and EPP measures

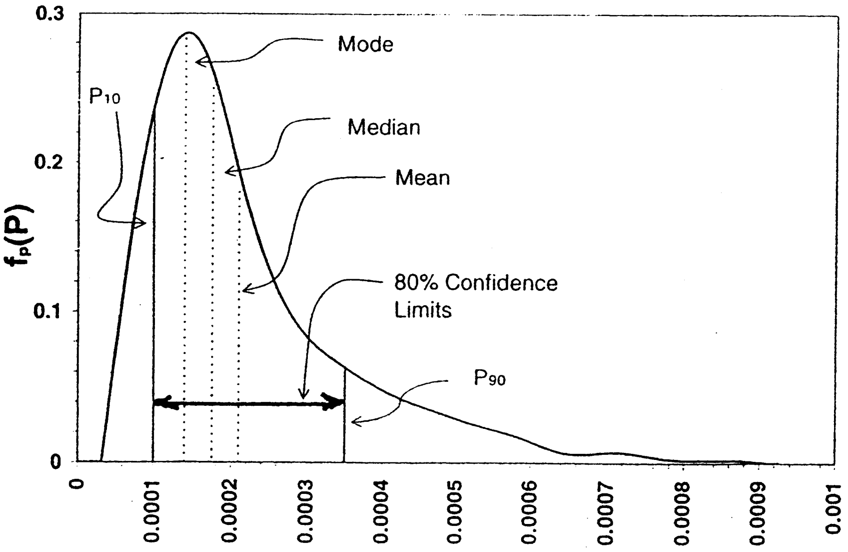
no warning system/EPP in place

Comparison of relative uncertainties

annual PGA exceedance probabilities for Washington DC



annual internal erosion failure probability for Navajo Dam

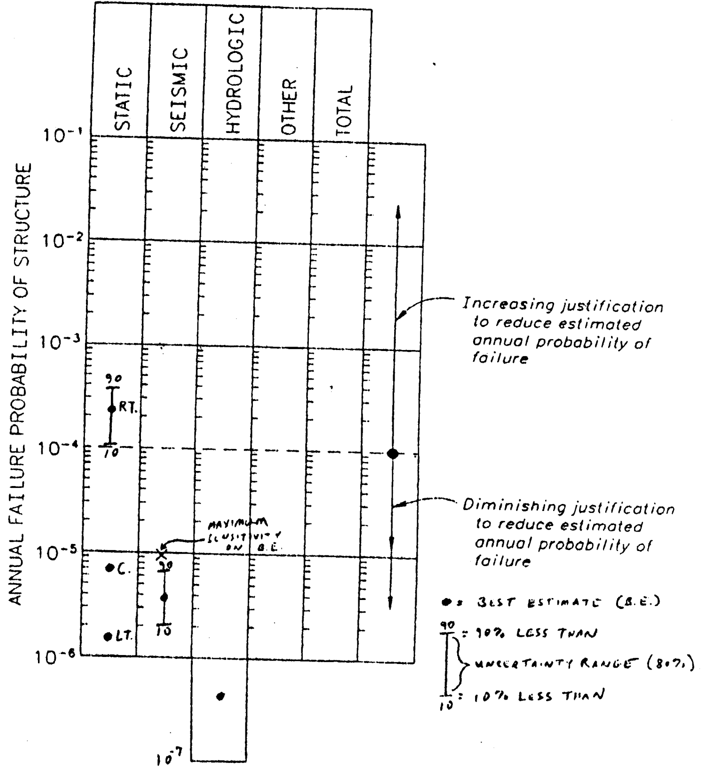


<u>Conclude:</u>

It is possible to estimate internal erosion failure probabilities with a level of confidence generally comparable to that for seismic initiator probabilities when reasonably good subsurface and monitoring data exist

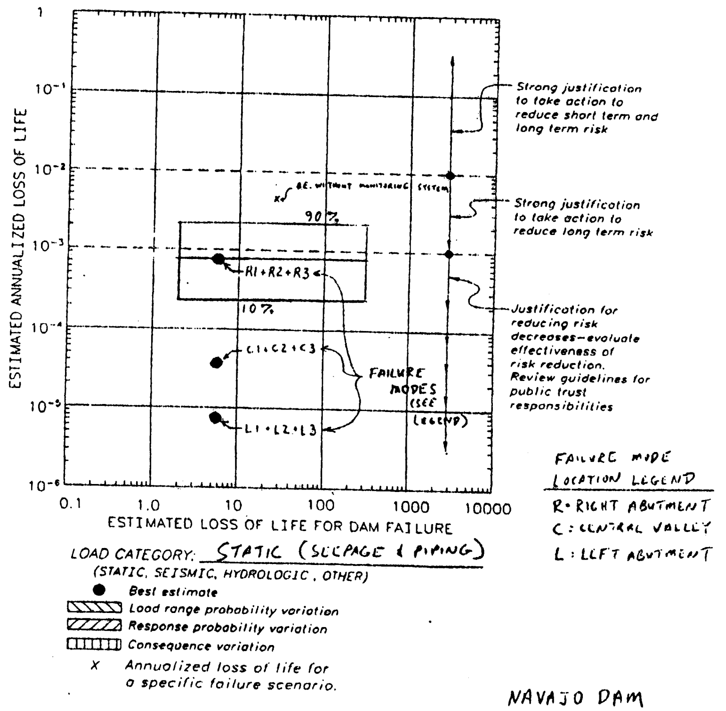
QUANTITATIVE RESULTS

TIER 2 GUIDELINES
(FAILURE EVENT PROBABILITY)



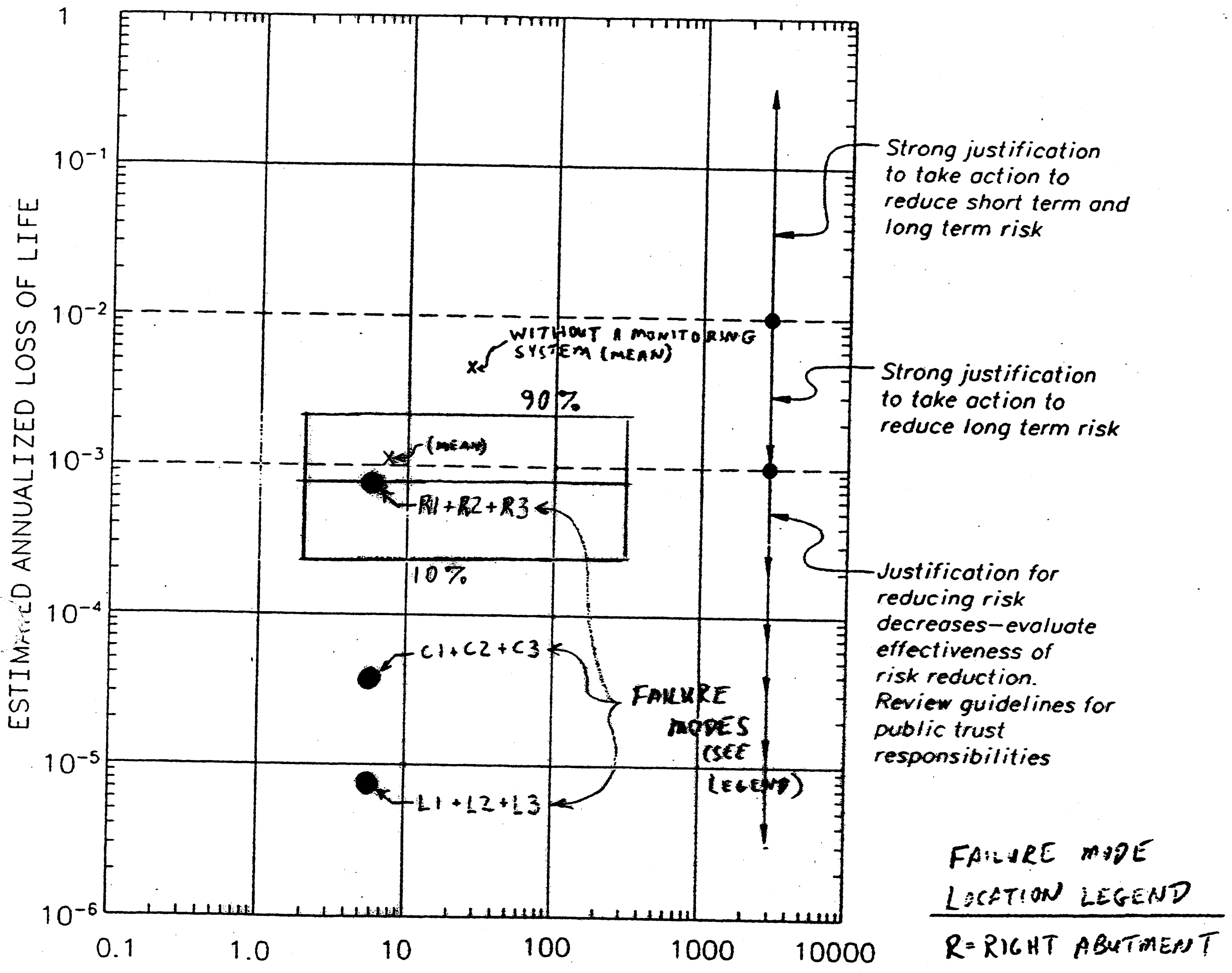
NAVAJO DAM

TIER 1 GUIDELINES
(LOSS OF LIFE)



NAVAJO DAM

TIER 1 GUIDELINES
(LOSS OF LIFE)



LOAD CATEGORY: STATIC (SEEPAGE & PIPING)

(STATIC, SEISMIC, HYDROLOGIC, OTHER)

● Best estimate

▧ Load range probability variation

▨ Response probability variation

▥ Consequence variation

X Annualized loss of life for a specific failure scenario.

NAVAJO DAM
FIGURE B-2

Potential "Life Loss / Probability of Life Loss" Pairs
Static - (datpipe7)

TIER I - STATIC (SEEPAGE & PIPING)

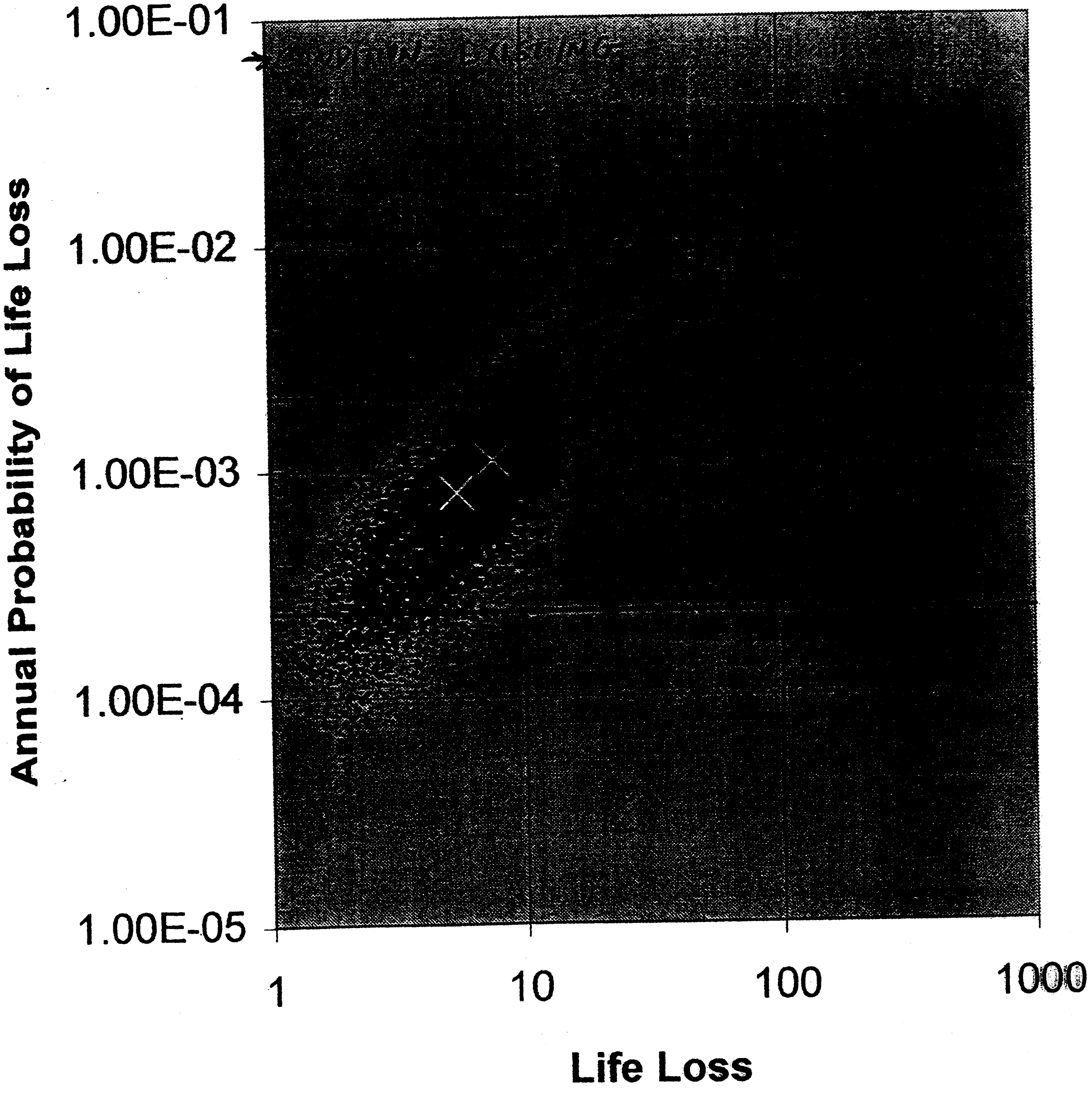
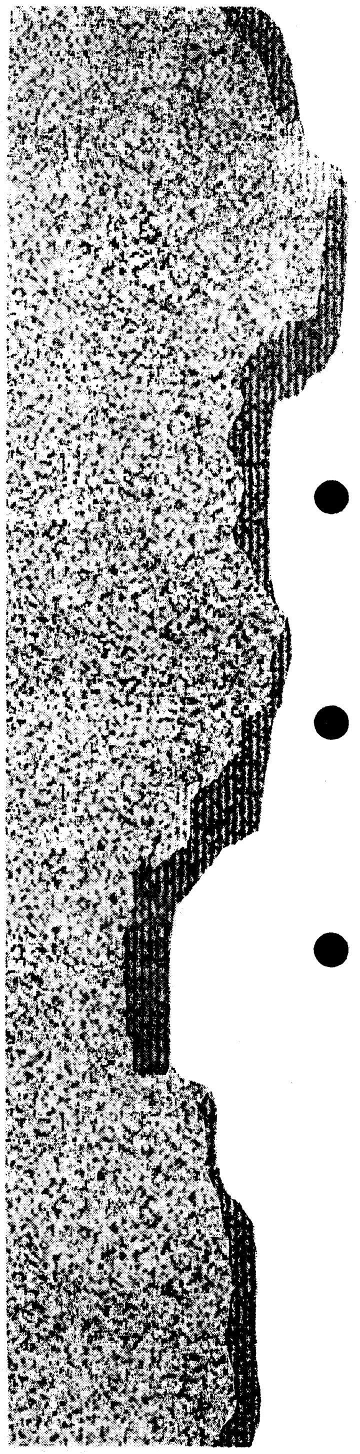
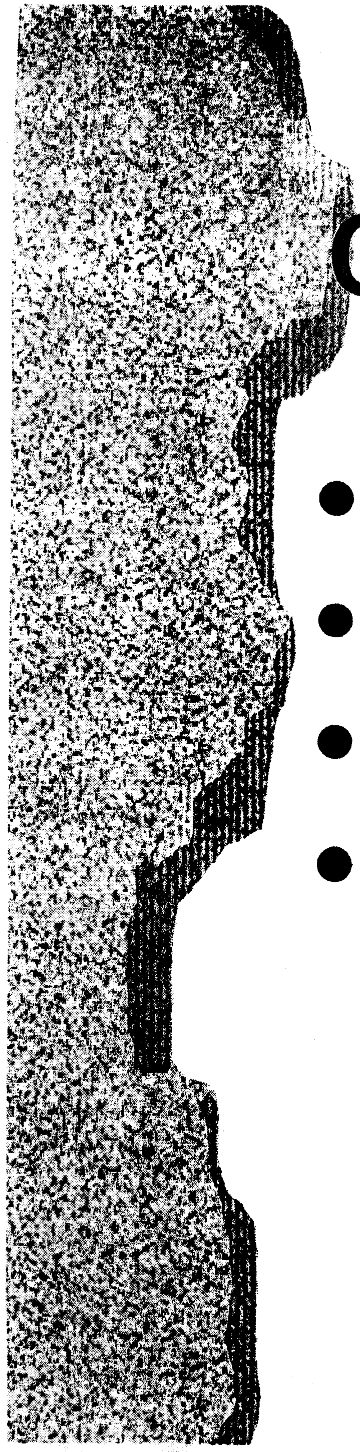


FIGURE B-4



Navajo Dam Findings

- Original failure mode represents mean risk lower than guidelines
- Other piping failure modes judged more likely
- Current monitoring has significant impact on keeping risks low



Comments on Risk Analysis

- Judgements becoming ‘transparent’
- Failure modes becoming ‘relative’
- Uncertainty is ‘significant’
- FM’s are thought through better and are more explainable

COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGTIÈME CONGRÈS
DES GRANDS BARRAGES
Beijing, 2000

DAM SAFETY RISK ANALYSIS FOR NAVAJO DAM (*)

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UNITED STATES OF AMERICA

1. INTRODUCTION

Navajo Dam is located on the San Juan River near Farmington, New Mexico in the southwestern United States. Constructed in 1963 by the U.S. Bureau of Reclamation for irrigation, recreation, and flood control purposes, it has a reservoir capacity of 2.1×10^9 m^3. Seepage through the abutments and related potential for internal erosion have been a concern since shortly after first filling, and in 1998 Reclamation carried out a comprehensive risk assessment to better evaluate these and other dam safety matters. Recognizing the uncertainties associated with formulating likelihood judgments for the complex geologic and internal erosion conditions encountered, special measures were adopted to formally incorporate the potential variability of probability estimates and to quantify confidence limits on the risk analysis results obtained. These results demonstrated the importance of instrumentation, warning systems, and emergency preparedness measures currently in place.

2. FEATURES AND CONDITIONS

Navajo Dam is a zoned earthfill structure with a height of 122.6 m. Figure 1 shows a plan view of the embankment and appurtenant structures that include an uncontrolled, concrete-lined ogee spillway and 5.7 m diameter main outlet works. The spillway has a maximum capacity of 968 m^3/s, and combined discharge from the main and auxiliary outlets can produce reservoir drawdown on the order of 0.6 m per day.

---

*Analyse Des Risques De Sécurité Du Barrage Navajo

The embankment is situated across a sharp and deeply-incised meander bend of the San Juan River, where a narrow rock promontory on the inside of the bend comprises the right abutment. The abutments and the foundation are composed of cliff-forming sandstones with interbedded shales and siltstones of the Tertiary San Jose formation. These sandstones are horizontally-bedded, with grain size varying from fine to coarse and conglomeratic. Their cementation is also variable, and some of the weakly-cemented and coarser materials are moderately to highly permeable. In addition, soluble gypsum occurs both as an intergranular cementing agent and occasionally as joint infilling.

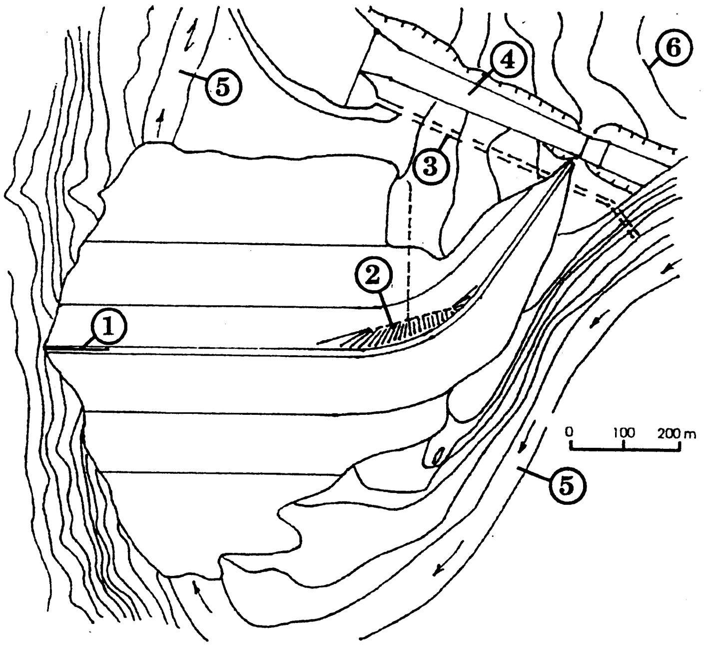


Fig. 1

Plan View of Navajo Dam and Remedial Seepage Measures
Plan du barrage Navajo et mesures correctives contre les infiltrations

(1)	Left abutment concrete Diaphragm cutoff wall	(1)	Mur parafouille à diaphragme en béton de la butée gauche
(2)	Right abutment drainage Tunnel and drain holes	(2)	Tunnel et orifices de drainage de la butée droite
(3)	Main outlet	(3)	Conduite principale de drainage
(4)	Spillway	(4)	Déversoir
(5)	Original river channel	(5)	Lit de rivière original
(6)	Contour (15m interval)	(6)	Profil (à intervalles de 15 m)

Stress relief behind steep cliff faces on the abutments produced joint openings as much as several centimeters wide. Although the more severely affected materials were removed by presplit blasting during construction, some high-angle open joints remained. No blanket grouting or other surface treatment was performed beneath the embankment core, and the single-row grout curtain is unlikely to have completely intercepted all of the high-angle fractures or penetrated the infilling materials they may have contained.

These conditions result in a seepage regime dominated horizontally by essentially impervious but discontinuous shale layers in higher portions of the abutments, along with locally higher primary (intergranular) permeability associated with bedding-controlled layers of higher sandstone porosity. The horizontal flowpaths are vertically interconnected by high-angle stress relief and regional jointing, but these linkages are complex and irregular. Additionally, some of the highly pervious and weakly-cemented materials in the right abutment sandstone have been interpreted as ancient channel infill deposits, although their extent or continuity is not well defined. Together these seepage conditions and the presence of possible pathways for particle migration pose a potential for internal erosion of embankment fill into open joints, and for internal erosion within joint infilling materials or in weakly-cemented portions of the abutment rocks themselves.

3. SEEPAGE HISTORY, CORRECTIVE MEASURES, AND CURRENT STATUS

Seepage appeared on both abutments almost immediately after reservoir filling began in 1963, discharging as seeps and wet areas on rock surfaces and along the downstream embankment contact, and it continued to increase to almost 110 l/s during the following years as the reservoir was allowed to fill to progressively higher levels. Although particle transport was not directly observed, concerns related to the potential for internal erosion eventually led to construction of seepage-control features in 1988. As shown on Figure 1, different measures were adopted on the left and right abutments.

On the left abutment, a concrete diaphragm cutoff wall was constructed using slurry trench methods extending through the embankment crest and into the left abutment to a maximum depth of 122 m, a record at the time. The sandstone was penetrated using a "Hydrofraise" device with counter-rotating cutter heads [1, 2]. The completed cutoff resulted in major reduction in surface seepage discharge, as well as elimination of any direct particle migration pathways along or immediately beneath the abutment/fill contact [3].

The same techniques were not well adapted to the greater length of the right abutment, and instead the solution devised here was a drainage tunnel with radiating drainage holes (Figure 1). As shown on Figure 2, the tunnel itself was successfully driven beneath a continuous, low-permeability shale layer, but drilling of the drain holes upward through this layer was not without incident. Four of the 42 drain holes had to be grouted shut after tapping a highly pressurized zone with inflows up to 45 l/s, and approximately 40 m^3 of cohesionless sand flowed into the tunnel from one of these.

The effect of the right abutment drainage system was to divert about 45 l/s of the total 75 l/s seepage flow that formerly discharged at the surface, and to reduce the total area of surface seepage by 20 to 30 percent. At the same time, however, the experiences during drain hole drilling served to confirm the presence of pervious conditions, high gradients, and mobile particles conducive to internal erosion.

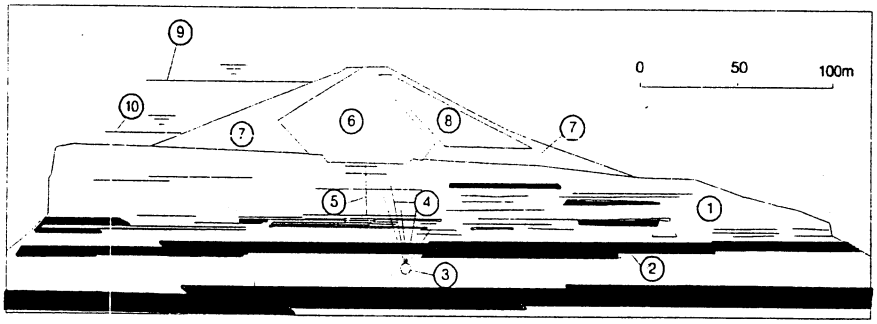


Figure 2
Section Through Right Abutment
Coupe de la butée droite

(1)	Sandstone	(1)	Grès
(2)	Shale and siltstone	(2)	Schiste argileux et siltstone
(3)	Drainage tunnel	(3)	Tunnel de drainage
(4)	Drain holes	(4)	Orifices de drainage
(5)	Grout curtain	(5)	Écran d'étanchéité
(6)	Sandy clay	(6)	Argile sableuse
(7)	Sand and gravel	(7)	Sable et gravier
(8)	Random fill	(8)	Matériau de remblayage
(9)	Maximum operating level	(9)	Niveau d'exploitation maximum
(10)	Minimum operating level	(10)	Niveau d'exploitation minimum

Principally due to the continuing internal erosion uncertainties at the right abutment, Navajo Dam is currently heavily instrumented, with 164 observation wells and piezometers of various types, 16 surface seepage weirs, and provisions for flow monitoring from 25 of the tunnel drains. Continuous surveillance is maintained at the damsite, and visual inspections are conducted daily to monitor and evaluate seepage discharge conditions. Data from all instruments at the dam are currently relayed to Reclamation's Technical Service Center in Denver via satellite and computer modem where they are available for instant review and retrieval on a computerized instrumentation database. Certain key instruments are linked to an automated telephone dialing system for immediately alerting emergency management personnel at the damsite and downstream communities at pre-set instrument response levels. These systems have been tested in "dry run" rehearsals of evacuation plans in cooperation with local authorities to verify their operability and to provide valuable training exercises.

These measures have been accompanied by continuing dam safety evaluations and investigations. In 1996 a variety of potential failure modes were identified for Navajo Dam, many related to internal erosion of the right abutment, in conjunction with Reclamation's Performance Parameter program for better relating monitoring data to response actions [4]. These failure modes provided a focal point for Reclamation's most recent Comprehensive Facility Review for Navajo Dam, which recommended that they be further developed in a comprehensive risk assessment [5]. Concurrent with these efforts were detailed geologic studies to compile and interpret information from observed conditions, instrumentation data, and the more than 100 post-construction exploration drillholes. These studies provided an uncommonly comprehensive information base for performing the risk assessment.

4. RISK ANALYSIS PROCEDURES

The risk analysis for Navajo Dam was performed according to Reclamation procedures described by Cyganiewicz and Smart [6], but went beyond the usual level of detail due to complexity and spatial variability in the dam configuration and geology. To provide a comprehensive framework for risk estimation and comparison, potential failure modes under hydrologic, seismic, and static loading conditions were addressed.

Hydrologic failure modes, including overtopping and structural response of the spillway and stilling basin, were evaluated under several levels of reservoir inflows. These were quickly determined to be comparatively small contributors to overall risk and were not developed in great detail. Seismic failure modes, especially related to liquefaction potential of alluvial materials beneath the central portion of the embankment, were also evaluated but are not described here. Comprehensive documentation of these and other aspects of the risk analysis is provided elsewhere [7].

Greatest effort and attention were devoted to static (internal erosion) failure modes in synthesizing all of the information on dam performance and geologic conditions gathered over time. This required evaluating separately the different conditions at the left abutment, central, and right abutment portions of the dam and the various remedial measures they incorporate. Of these three regions, only the right abutment, which was ultimately found to be the principal risk contributor, is described here.

The risk analysis team assembled to evaluate internal erosion issues included persons with specialized knowledge of geologic conditions; previous embankment modifications; instrumentation response; and operational procedures and emergency preparedness measures in place at the damsite. The interactions among these specialists and risk analysis facilitators was an essential aspect of the risk analysis process central to specifying the various ways by which internal erosion mechanisms might progress to failure, their rate of development, and the downstream effects that could result.

The first product of these efforts was the construction of event trees that defined the component events in several failure sequences and the associated warning time scenarios. Although four separate internal erosion failure modes were developed for the right abutment, it was later determined that only two constituted the dominant contributors to internal erosion risk at this location. These involved internal erosion of embankment fill into abutment rock discontinuities, and internal erosion within the rockmass itself leading to abutment collapse.

The event tree structure for these two primary failure modes is portrayed on Figure 3. For each one, it incorporates component events representing reservoir level, initiation and progression of internal erosion development, and various intervention measures including reservoir drawdown and others that could be undertaken to retard or arrest the failure process. Also explicitly incorporated are component events related to the rate of breach development and detection, and the resulting influence on warning time.

The next stage in the process required assigning probabilities to each component event in the tree to reflect their assessed likelihood of occurrence. These are largely based on a degree-of-belief probability approach rather than statistically-derived frequencies not applicable to the nature of most events considered. However, it was apparent from the start that several factors would make it difficult for any single probability value to fully characterize the range of reasonable probability estimates that could be assigned to a given event. These factors included the complexity of the geologic conditions in the right abutment, different possible geologic interpretations of these conditions, and various conceptual models of how internal erosion might develop. Equally important were uncertainties related to the rate at which the process might progress and resulting effects on warning time.

As a result, probability distributions were elicited for each component event in order to better describe potential ranges of probability variation. These were of two forms: a uniform distribution for probabilities judged equally likely to lie between specified upper and lower bounds, and a triangular distribution where a central tendency ("most likely" value) was expressed. The bounding values reflected group consensus in some cases and individual preferences in others, but in all cases the assigned distributions were validated by group concurrence. Although this required some additional effort compared to single-value probability estimation, propagating these distributions through the analysis allowed quantified confidence limits on risk estimates to be derived as an integral part of the risk analysis results. For Navajo Dam, this added an important dimension to the risk information provided to dam safety decisionmakers.

Probability distributions were also assigned to dam failure consequences. Given various possible warning times, loss of life was estimated with the aid of procedures described by DeKay and McClelland [8] adjusted for site-specific factors. This allowed distributions elicited for warning time to be converted to those for loss of life. For the conditions at Navajo Dam, the fitted probability distribution on loss of life was truncated at a minimum of 2 and a maximum of 300 fatalities for internal erosion failure modes involving less than 3 hours of warning.

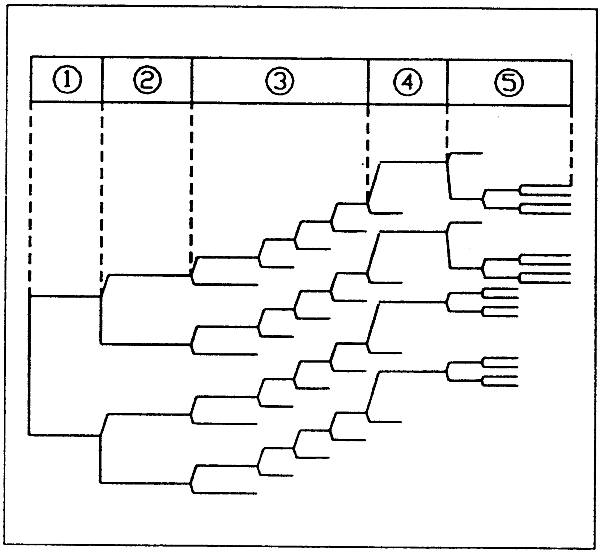


Figure 3
Event Tree For Right Abutment Internal Erosion
Arbre d'événements pour l'érosion souterraine de la butée droite

(1) Failure mode	(1) Mode de défaillance
(2) Reservoir level	(2) Niveau du réservoir
(3) Internal erosion development	(3) Survenue d'érosion souterraine
(4) Reservoir drawdown	(4) Vidange du réservoir
(5) Failure development and warning time	(5) Survenue d'une défaillance et délai d'alerte

5. DERIVATION OF RESULTS

The probability distributions assigned to individual component events were aggregated using Monte Carlo simulation as a solution technique to derive the joint distribution for failure probability. In any given iteration of the simulation process, a discrete value from each individual distribution is sampled, and the addition and multiplication operations prescribed by the event tree are performed to yield the value of failure probability calculated from that particular set of sampled values. Repeated over many thousands of such simulation trials, the frequency of the calculated values will correspond to the joint probability distribution on the results.

Figure 4 shows the joint distribution on internal erosion failure probability for Navajo Dam obtained in this way. This probability density function (PDF), derived from the uniform and triangular distributions assigned to component event probabilities, is asymmetric and lognormal in form. It represents the aggregated group judgment on internal erosion failure probability, and it allows the group's quantified confidence in the probability estimate to be expressed as a measure of its intended reliability. For example, Figure 4 shows values for p_{10} and p_{90}, which represent internal erosion failure probabilities having 90% and 10% likelihood of exceedance, respectively. Since there is an 80% likelihood that internal erosion failure probability lies between them, this makes it possible to state that the group is 80% confident that internal erosion failure probability is between 1.0 x 10^{-4}/yr and 3.5 x 10^{-4}/yr. Confidence limits can be determined from the PDF at any desired level of certainty, with greater confidence associated with wider probability bounds and vice versa.

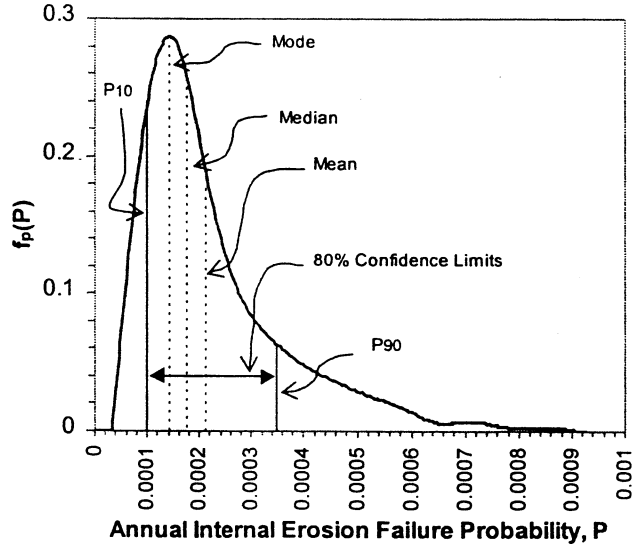


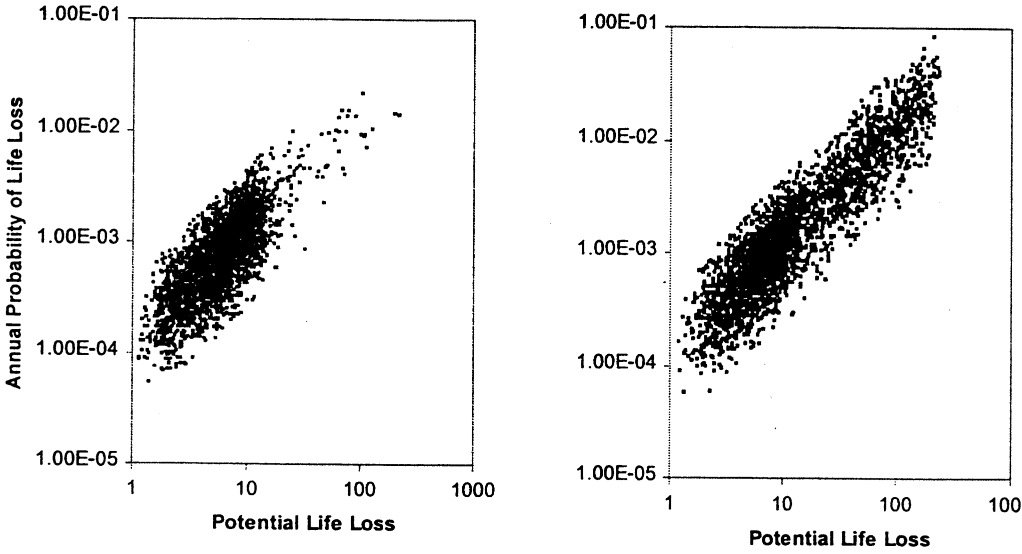
Fig. 4
Probability Density Function for Internal Erosion Failure
Densité de probabilité pour la défaillance par érosion souterraine

The central tendency of the PDF allows for specification of a point-value "best estimate" value to represent it, and its skewness results in several ways to do so. As depicted on Figure 4, the mean probability would represent the weighted preference of the group, the median would be the probability exceeded by half the group, and the mode or peak would be the single value most likely to be specified. Regardless of which of these measures might be adopted, it is clear from Figure 4 that none of them alone would provide the richness of information on probability variability that the distribution itself conveys.

Other parameters besides confidence limits can be used to characterize this variability, including standard deviation for the "width" of the distribution or the coefficient of variation for normalized width. The degree of variation will be controlled by factors that affect probability estimation such as the amount of information available; the complexity of the conditions encountered; the understanding of physical processes involved; and diversity of interpretations within the group. All of these factors will differ from one dam to another, but any of the available measures for characterizing variability can provide a convenient means for comparing the reliability in probability estimates they produce.

The probability distributions estimated for loss of life for Navajo Dam also make it possible to evaluate the variability in estimated risk. Risk is defined with respect to loss of life as annual failure probability multiplied by lives lost, or equivalently the annual probability of life loss denoted here as R. Customary Reclamation practice is to portray risk along with the absolute value of loss of life (N) as a two-dimensional plot in the manner shown on Figure 5. Using Monte Carlo solution techniques previously described, potential variation in both R and N together can be represented as a scattergram of simulation trials like that provided on Figure 5(a) for internal erosion failure modes. The "cloud" of simulation trials reflects the potential variability in position of (R,N) pairs on the plot, and the relative confidence in any such position is directly proportional to the density of simulation points at that location. This portrayal of risk variability has intuitive visual appeal, and quantitative confidence limits can also be described by contours of point density in the same format.

Figure 5(a) represents internal erosion risk under the existing conditions for Navajo Dam that include the warning and emergency preparedness measures described earlier. The scattergram shows that the possibility of more than about 20 fatalities is relatively small, with scattergram points lying beyond this number attributable mainly to the possibility that the onset of failure might not be immediately recognized, that failure might progress too rapidly for much warning to be issued, or that the warning system and evacuation measures might not perform as planned. For comparison, Figure 5(b) shows the results of sensitivity studies to determine corresponding internal erosion risk and life loss for Navajo Dam if no warning system were in place. In this case, warning and evacuation would depend on failure precursors being fortuitously observed, reported, and acted upon. The difference between the scattergrams of Figure 5(a) and 5(b) is immediately apparent, and this difference illustrates the benefits being realized from the warning and emergency provisions currently in place. It also amply demonstrates the importance of continuing to maintain and refine these systems and the high level of vigilance their effectiveness requires.



(a) Current Warning System and EPP Measures (b) No Warning System
(a) Système d'alerte en place et mesures (b) Pas de système d'alerte

Figure 5
Internal Erosion Risk Scattergrams
Diagrammes de dispersion des risques d'érosion souterraine

6. CONCLUSIONS

The potential for internal erosion into and within rock foundations is among the most difficult dam safety issues to evaluate, whether risk-based procedures are adopted or not. The risk analysis performed for Navajo Dam provides some useful insights in this regard.

First, it demonstrates that risk analysis techniques can be used to develop sensible estimates for internal erosion failure probability using procedures such as those described here. These rely fundamentally on sound engineering judgment and group interaction among interdisciplinary specialists to evaluate the likelihood of various components of the internal erosion failure process. For complex geologic mechanisms and conditions, these assessments can be aided by formally incorporating the variability and uncertainty arising from different possible interpretations of geologic information, using probability distributions to supplement point-value best estimates and propagating these distributions through the analysis by Monte Carlo or other solution techniques.

The Navajo Dam risk analysis was performed with the benefit of geologic and related information whose comprehensiveness and diversity are not often duplicated elsewhere. Extensive seepage, piezometric, and surveillance monitoring carried out over many years was supplemented by extensive drilling data as well as the opportunity to directly observe foundation response to the remedial measures constructed. Notwithstanding the nature and extent of this information, the resulting internal erosion failure probability estimates still retained a significant degree of potential variability. This variability can be characterized and quantified but not eliminated, and the distribution on probability estimates will not be reduced to a unique and singular probability value for problems of this class no matter how much information might be obtained.

It is interesting to relate this variability to that for probability estimates of other types and in other settings. Internal erosion failure probability estimates for Navajo Dam were shown to be subject to potential variation of roughly one-half order of magnitude at the 80% confidence level. By comparison, seismic hazard studies performed in the eastern United States and affected by a number of significant uncertainties have resulted in estimated variability in ground motion exceedance probability of about one-half to one order of magnitude at similar confidence levels [9]. Viewed in this context, it appears possible with good information to achieve a degree of reliability for internal erosion probability generally commensurate with that for probabilities in related areas of the risk analysis process. However, internal erosion probabilities must often be estimated with information far less comprehensive and complete, and their reliability in other cases might be benchmarked to that for Navajo Dam according to the conditions described here.

Other observations pertain to communication of risk analysis information from those performing the analysis to dam safety decisionmakers and others who use it. When only point-value "best-estimate" failure probability or risk values are generated without any formal statement of their potential variability, a frequently voiced concern is that they may be interpreted with an unintended and unwarranted degree of precision. Quantified confidence limits on these estimates can go far toward alleviating these concerns, and they provide a necessary supplement for informed understanding of risk analysis results. The Navajo Dam case also shows that the uncertainties associated with loss of life prediction can equal or exceed in importance those related to failure probability. Visually portraying or otherwise quantifying variability in risk estimates can help assure this is adequately conveyed by the results generated.

And finally, the value of warning systems and related emergency preparedness measures is widely acknowledged as a risk mitigation strategy, but quantitative determination of these benefits is not often found in the risk analysis literature. Navajo Dam provides such an example, and it demonstrates the measurable contribution to risk reduction these strategies can provide.

7. REFERENCES

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CASE STUDY - AUSTRALIA

INITIAL PHASE OF RISK ASSESSMENT

FOR

HUME DAM

Len McDonald

- retired, formerly Assistant Principal Engineer, Dams and Civil, NSW Department of Public Works and Services
- Chairman, New South Wales Dams Safety Committee
- Convenor, Working Group on Risk Assessment of Australian National Committee on Large Dams (ANCOLD)
- Member, ICOLD Committee on Dam Safety and a primary author for the Committee's bulletin in preparation "Risk Assessment as an Aid to Dam Safety Management"

INTRODUCTION

NEED FOR DAM SAFETY EVALUATION

- Continuing downstream movement (some 450mm since monitoring began years previously) at dog-leg, Bank No. 1
- Prescription of dam under Dams Safety Act 1978
- Dams Safety Committee concern following inspection 1993
- Owner agreed to a comprehensive investigation

TECHNICAL GUIDANCE

- Owner appoints a Technical Review Committee (TRC) of independent, highly experienced dams engineers to advise on needed investigations and remedial actions
- Geotechnical specialist appointed to assist the TRC

GEOTECHNICAL INVESTIGATION

- Major investigation program, 1994
- Drilling and testing at all banks
- Subsequent investigations as new problems identified

TRADITIONAL ANALYSES

- Safety reviews of concrete dam and all banks undertaken, 1994 to 1996

RISK ASSESSMENT

- Initial phase of risk assessment commissioned 1996 (the subject of this presentation)
- Subsequent phases commissioned 1997

REMEDIAL ACTION

- Remedial works commenced in 1996 and have continued to the present time
- Expenditure to date is some AUD 50 million (about USD 33 million)

DESCRIPTION OF HUME DAM

MILESTONES

- Constructed late 1920's with unregulated spillway
- Storage level raised by some 7m in late 1950's, with the installation of 29 vertical lift spillway gates, raising of embankments and construction of new Bank No. 3
- Concrete dam post-tensioned early 1960's
- Monitorable, restressable post-tensioning cables installed in concrete dam mid-1980's
- Major safety upgrades undertaken, 1996 to present

CONCRETE GRAVITY DAM

- 45 m high and 336m long
- 9 spillway blocks, 6 non-overflow blocks
- 29 vertical lift gates, 7.5m high by 6.1m wide
- Stabilised by monitorable, restressable cables

BANK NO. 1

- up to 40m high and 1,184m long
- central concrete core wall slotted into bedrock
- upstream and downstream shells founded on recent or Tertiary alluvium (according to location) or on residual soil (at the higher foundation levels)
- embankment fill strongly dispersive
- embankment fill poorly compacted
- concrete parapet wall 1.37m high

BANK NO. 2

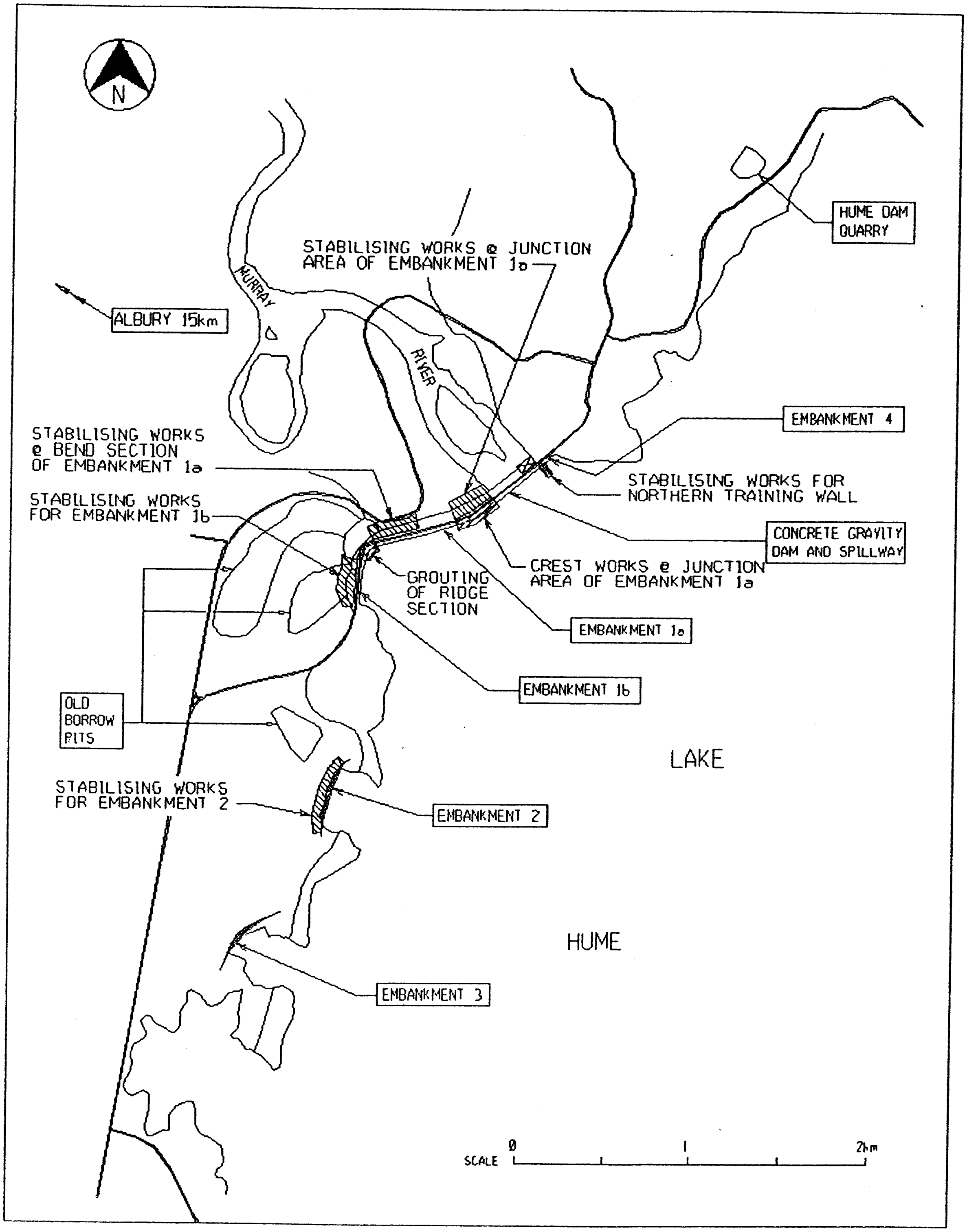
- up to 18.3m high and 488m long
- homogeneous section of strongly dispersive soil
- founded on Tertiary alluvium

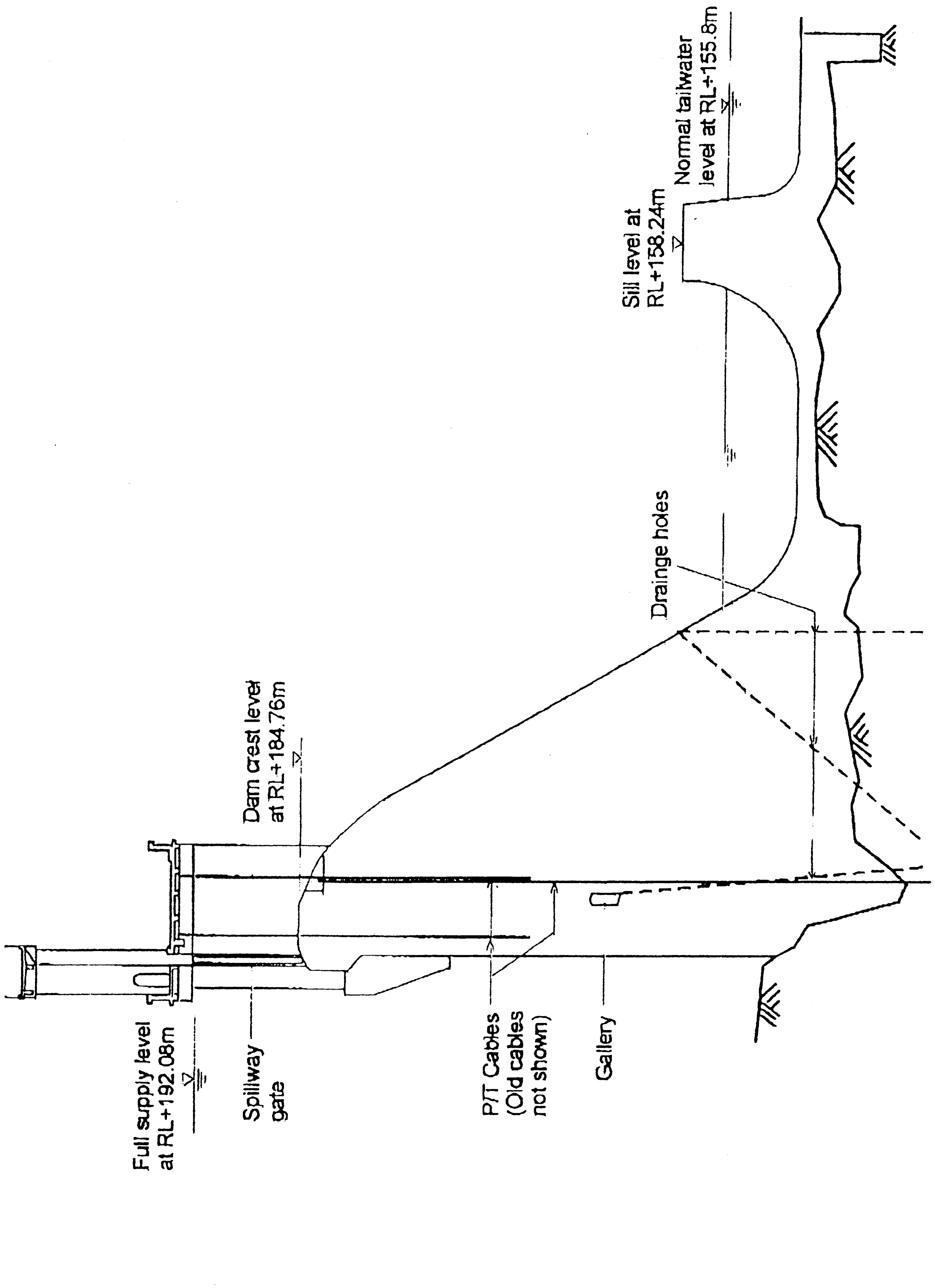
BANK NO. 3

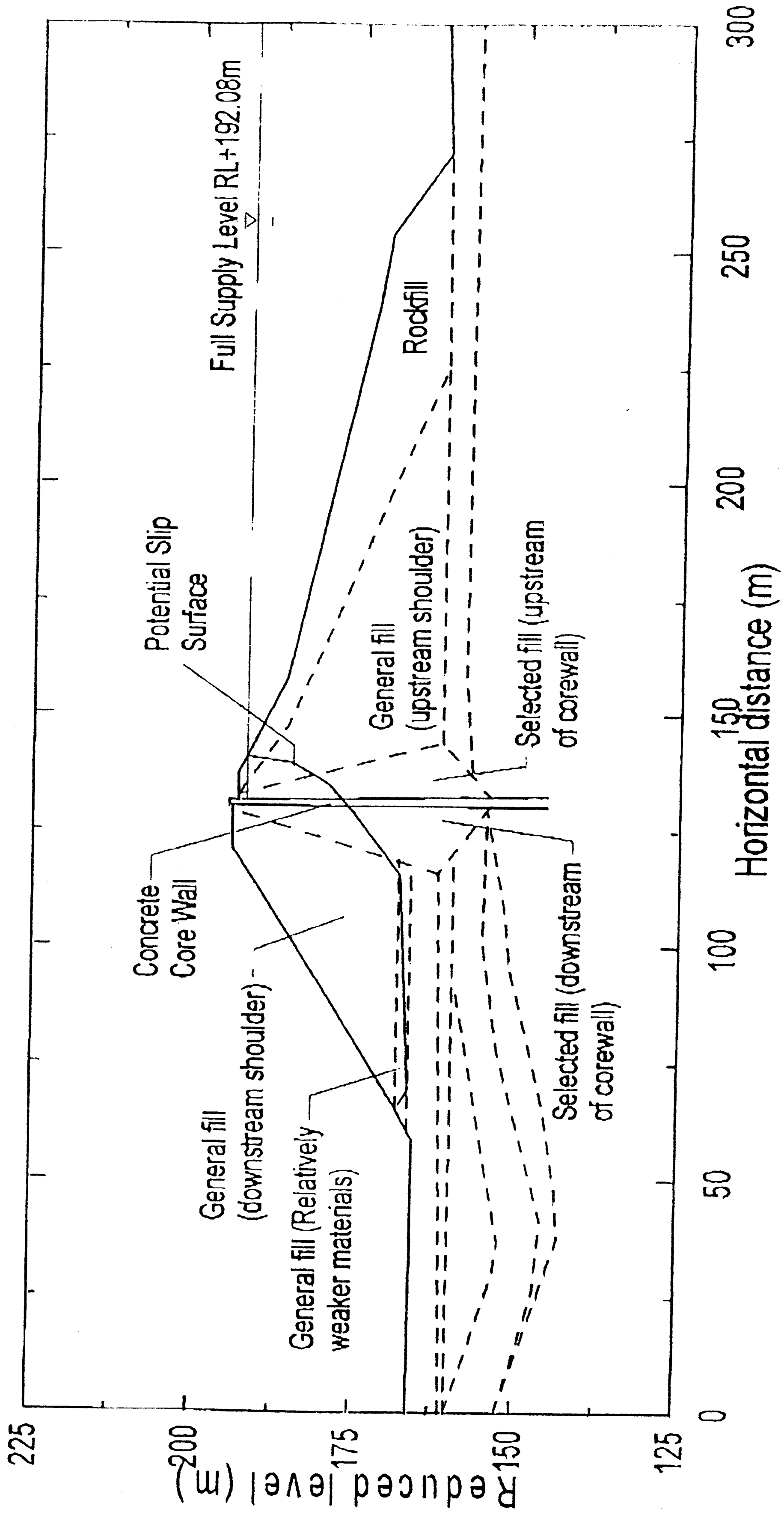
- up to 7.4m high and 447m long
- zoned section of mildly dispersive fill
- founded on Tertiary alluvium

BANK NO. 4

- up to 18m high and 100m long
- central concrete core wall slotted into bedrock
- non-dispersive fill
- founded on residual soil


N
MURRAY
RIVER
ALBURY 15km
HUME DAM QUARRY
STABILISING WORKS @ JUNCTION AREA OF EMBANKMENT 1a
STABILISING WORKS @ BEND SECTION OF EMBANKMENT 1a
STABILISING WORKS FOR EMBANKMENT 1b
EMBANKMENT 4
STABILISING WORKS FOR NORTHERN TRAINING WALL
CONCRETE GRAVITY DAM AND SPILLWAY
GROUTING OF RIDGE SECTION
CREST WORKS @ JUNCTION AREA OF EMBANKMENT 1a
EMBANKMENT 1a
EMBANKMENT 1b
OLD BORROW PITS
LAKE
STABILISING WORKS FOR EMBANKMENT 2
EMBANKMENT 2
HUME
EMBANKMENT 3
SCALE
0
1
2km


Full supply level at RL+192.08m
Spillway gate
P/T Cables (Old cables not shown)
Gallery
Dam crest level at RL+184.76m
Drainge holes
Sill level at RL+158.24m
Normal tailwater level at RL+155.8m



Full Supply Level RL+192.08m
Rockfill
Potential Slip Surface
General fill (upstream shoulder)
Selected fill (upstream of corewall)
Concrete Core Wall
General fill (downstream shoulder)
General fill (Relatively weaker materials)
Selected fill (downstream of corewall)
Reduced level (m)
225
200
175
150
125
Horizontal distance (m)
0
50
100
150
200
250
300

PURPOSES OF INITIAL PHASE OF RISK ASSESSMENT

- to provide for more informed decision making
- to discover any potential failure modes that had not previously been recognised
- to provide an enhanced basis for setting priorities for investigations and remedial action
- to improve understanding of the dam's safety status

Note that the later phases of the risk assessment, undertaken by others, enabled the satisfaction of additional purposes.

RISK ANALYSIS TEAM

RISK ANALYSTS

- Team Leader - engineer with wide experience of dams and knowledge of probabilistic analysis
- Analyst - engineer experienced in computer simulation and modelling, macros, spreadsheets

SPECIALISTS

- Hydrologist
- Hydraulics specialist
- Slope stability specialist

QUALITY ASSURANCE ENGINEER

- Dams engineer with wide experience and the ability to critically review the study outputs

REVIEW PANEL

Composition variable according to session, but typically included:

- relevant manager from the client organisation
- independent dams engineer of wide experience
- independent geotechnical specialist
- engineer responsible for operation of the dam
- engineer responsible for surveillance and monitoring of the dam

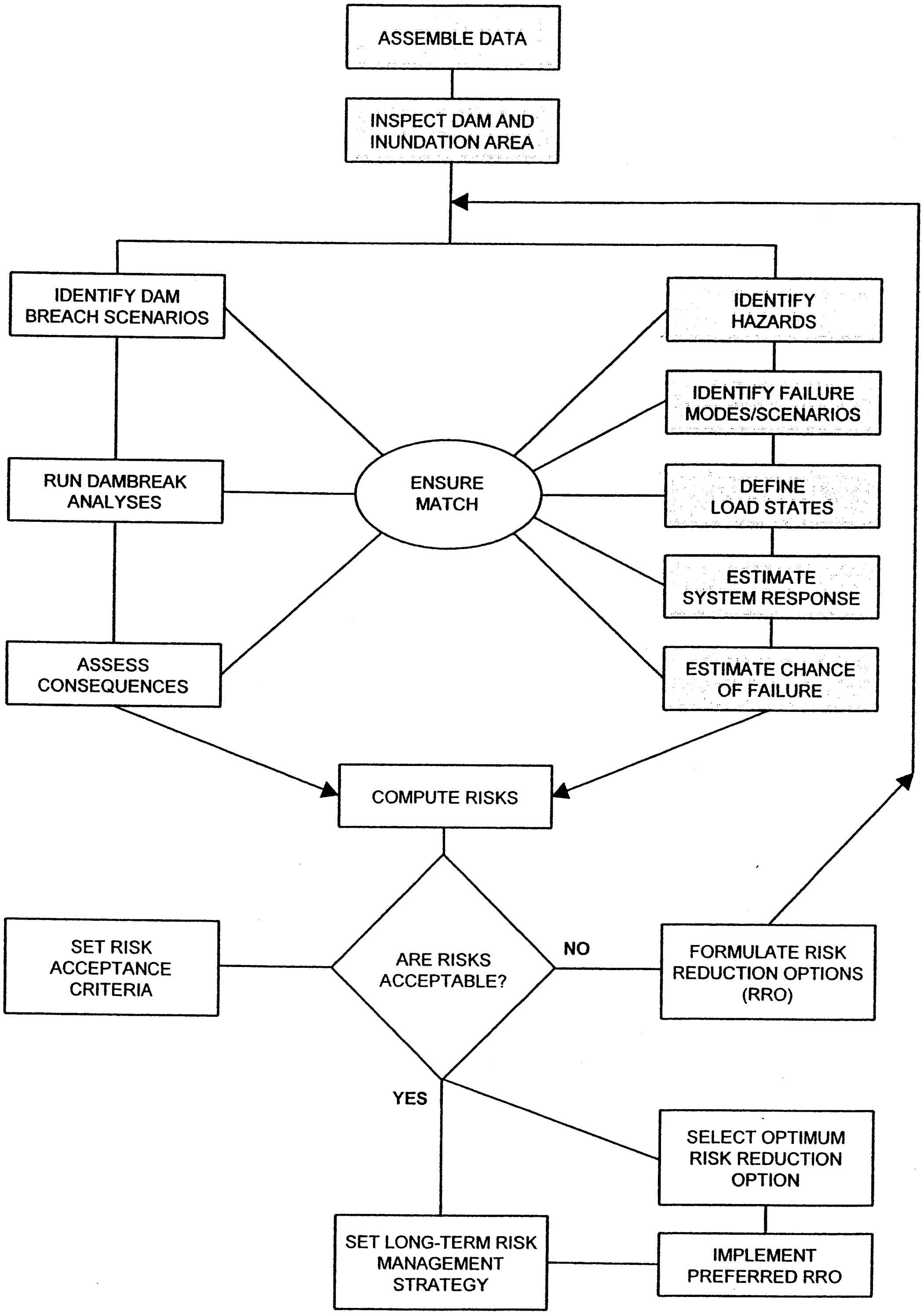
INTERNATIONAL REVIEW CONSULTANTS

- Engineer with experience of risk assessment for dams
- Engineer specialising in geotechnical engineering

RISK ANALYSIS PROCESS AND SCOPE

- DATA COLLECTION
- DEFINITION OF LOAD STATES
- FAILURE MODES ANALYSIS
- PANEL REVIEW OF FAILURE MODES ANALYSIS
- FAILURE PATHWAYS ANALYSIS
- PANEL REVIEW OF PATHWAYS ANALYSIS
- DEVELOPMENT OF SYSTEM RESPONSE FOR MAJOR ASPECTS
    - static slope stability
    - overtopping erosion
    - post-liquefaction instability
    - piping
    - concrete dam instability training wall instability
    - failure of spillway gates to operate as intended
- DEVELOPMENT OF RULES TO ACCOUNT FOR LENGTH AND NUMBER EFFECTS
- WRITING OF PROTOCOLS AND RATIONALE
- PANEL REVIEW OF PROTOCOLS
- CONSTRUCTION OF INTEGRATED MODEL
- ENTERING OF VALUES INTO THE MODEL
- PANEL REVIEW OF VALUES
- AMENDMENT OF VALUES AND GENERATION OF OUTPUTS
- WRITING OF THE STUDY REPORTS

The following chart clarifies the scope of the study, shaded boxes being the tasks that were undertaken.


ASSEMBLE DATA
INSPECT DAM AND INUNDATION AREA
IDENTIFY DAM BREACH SCENARIOS
RUN DAMBREAK ANALYSES
ASSESS CONSEQUENCES
ENSURE MATCH
IDENTIFY HAZARDS
IDENTIFY FAILURE MODES/SCENARIOS
DEFINE LOAD STATES
ESTIMATE SYSTEM RESPONSE
ESTIMATE CHANCE OF FAILURE
COMPUTE RISKS
SET RISK ACCEPTANCE CRITERIA
ARE RISKS ACCEPTABLE?
NO
FORMULATE RISK REDUCTION OPTIONS (RRO)
YES
SELECT OPTIMUM RISK REDUCTION OPTION
SET LONG-TERM RISK MANAGEMENT STRATEGY
IMPLEMENT PREFERRED RRO

DATA COLLECTION

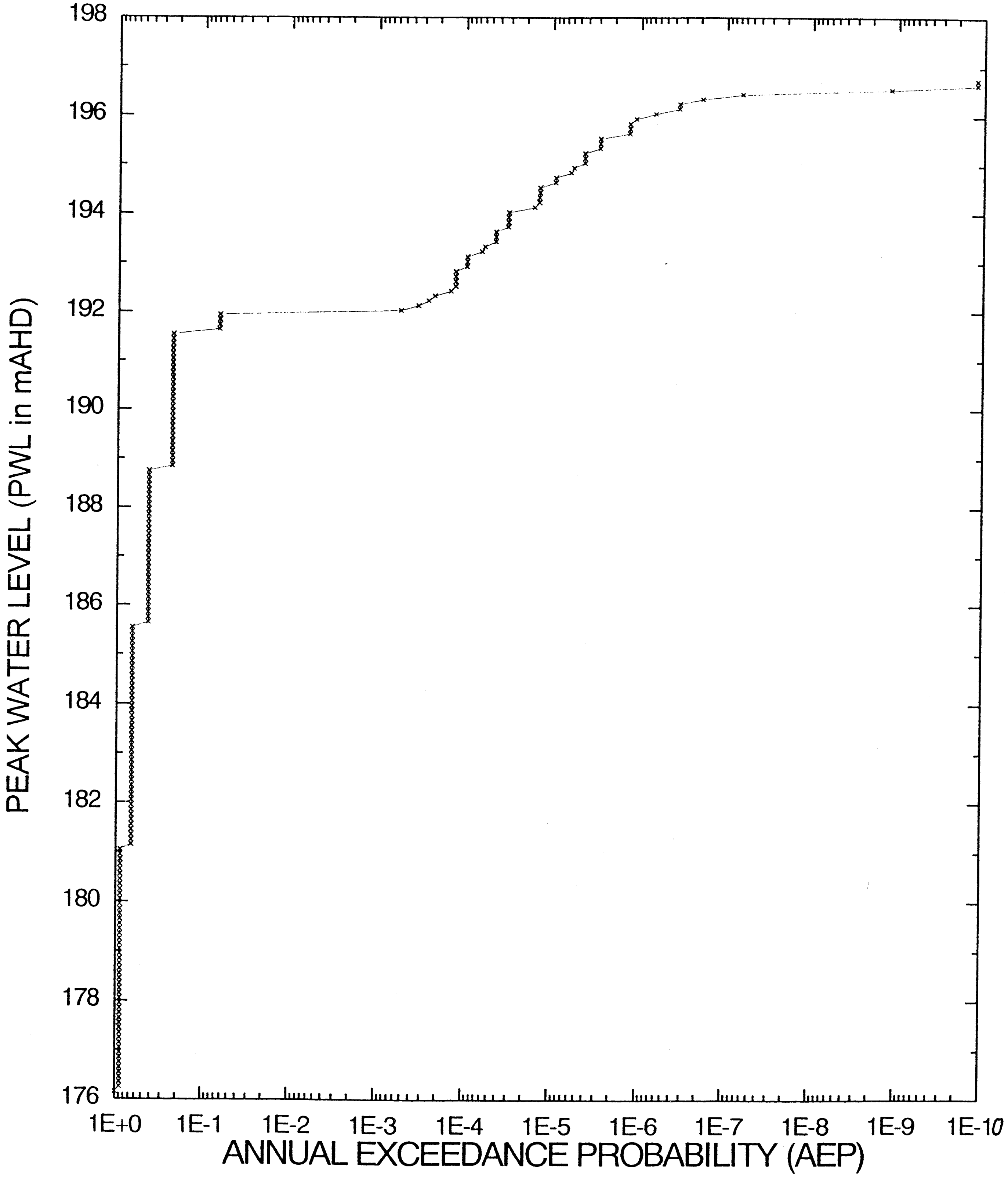
- TEDIOUS, BUT CRITICALLY IMPORTANT
- STUDY REPORT LISTED KEY DATA SOURCES
- SOME KEY DATA NOT AVAILABLE, SUCH AS CREST PROFILE OF THE BANKS AND ACCURATE SURVEY OF LOW GROUND AROUND BANK NO. 3
- IT WAS NECESSARY TO RECORD THE DAM CONFIGURATION FOR STUDY PURPOSES, BECAUSE OF CONFLICTING DIMENSIONS IN THE RECORDS
- NOTE THE IMPORTANCE OF DEFINING THE POINT IN TIME TO WHICH THE STUDY RELATES. THIS WAS PARTICULUARLY SO FOR HUME DAM BECAUSE:
    - DAM CONFIGURATION WAS CHANGING WITH TIME DUE TO REMEDIAL WORKS
    - PROBABILITY OF FAILURE, FOR SOME FAILURE MODES, WAS PROGRESSIVELY INCREASING FOR A GIVEN CONFIGURATION
- IT IS IMPORTANT TO MAKE A SUFFICIENT RESOURCE ALLOWANCE FOR DATA COLLECTION. THE RISK ANALYSTS NEED TO GO THROUGH ALL REPORTS TO IDENTIFY RELEVANT MATERIAL, AND NEED TO RESOLVE CONFLICTS IN THE INFORMATION AVAILABLE.

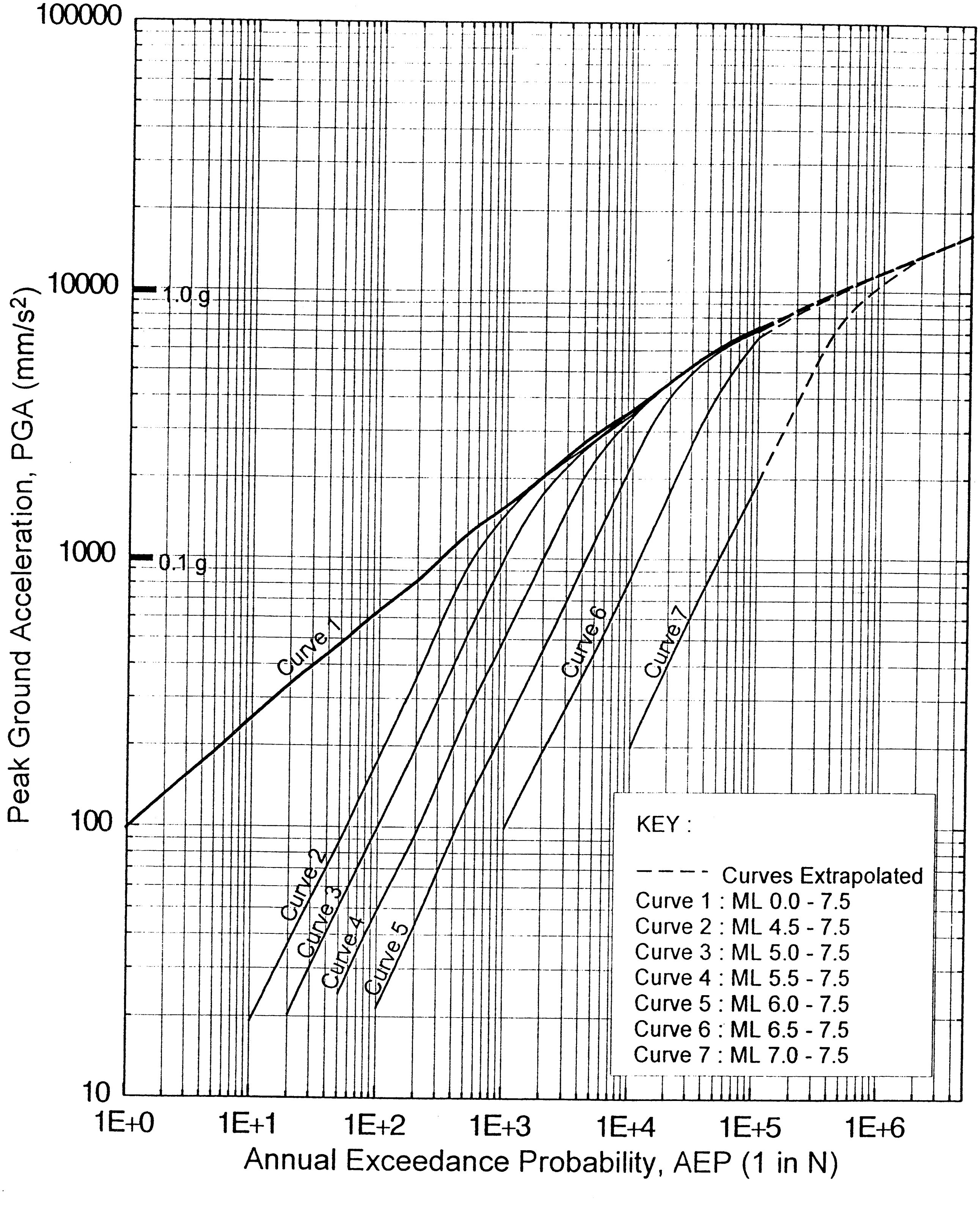
DEFINITION OF LOAD STATES

- IT MAY BE BETTER TO DO THIS AFTER FAILURE MODES ANALYSIS; BUT IN THE HUME CASE IT WAS DONE FIRST
- VALUE IN HAVING A SEPARATE "IDENTIFICATION OF HAZARDS" PHASE, BUT AT HUME THIS WAS DONE UNDER LOAD DEFINITION
- NUMBER OF PARTITIONS AND LOCATION OF PARTITION POINTS IS IMPORTANT. NEED TO STRIKE A BALANCE BETWEEN INCREASING COSTS AND AVOIDING LOSS OF ACCURACY. PARTITION WIDTH CAN BE VARIABLE TO CAPTURE SAFETY THRESHOLDS
- OUTFLOW FLOOD DISCHARGE VERSUS AEP (ANNUAL EXCEEDANCE PROBABILITY) FOUND FROM OUR USE OF FLOOD ROUTING MODEL DEVELOPED BY OTHERS. MODEL TOOK ACCOUNT OF GATE OPERATING RULES. SOME 500 FLOOD ROUTINGS UNDERTAKEN
- 21,384 FLOOD LOAD SCENARIOS, MADE UP OF
  - 10 NATURAL FLOOD PEAK INFLOW DISCHARGE STATES
  - 1 UPSTREAM DAM FAILURE FLOOD STATE (DARTMOUTH DAM, 180m HIGH)
  - 6 PRIOR STORAGE STATES
  - 4 GATE OPERATING STATES (29, 28, 24 OR ZERO GATES)
  - 6 WIND VELOCITY STATES (INCLUDING "CALM")
  - 16 FETCH/DIRECTION STATES (UP TO 4 PER BANK)

  PEAK WATER LEVELS (PWL) RANKED TO PRODUCE PWL VERSUS AEP CURVE. THIS CURVE PARTITIONED INTO 7 PWL STATES
- 48 BASIC EARTHQUAKE LOAD STATES, MADE UP OF A MATRIX OF 8 PEAK GROUND ACCELERATION (PGA) STATES BY 6 PRIOR STORAGE STATES. ADDITIONALLY, ONE OF THREE DIFFERENT EVENT MAGNITUDE RANGES APPLIED, ACCORDING TO THE FAILURE MODE UNDER CONSIDERATION
- "PROBABILITY" OF A PRIOR STORAGE STATE WAS THE ESTIMATED PERCENTAGE OF TIME THAT STORAGE LEVEL IS WITHIN THE PARTITION. COMMON BASES FOR ESTIMATES ARE:
  - HISTORIC RECORDS OF STORAGE LEVEL
  - STORAGE LEVELS SIMULATED FROM THE HISTORIC RECORD ON THE BASIS OF PRESENT DEMAND PATTERNS
  - STORAGE LEVELS SIMULATED FROM THE HISTORIC RECORD ON THE BASIS OF PROJECTED FUTURE DEMAND LEVELS

  FOR HUME, OTHERS HAD UNDERTAKEN A SIMULATION BASED ON FUTURE DEMAND PATTERNS


198
196
194
192
190
188
186
184
182
180
178
176
PEAK WATER LEVEL (PWL in mAHD)
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
ANNUAL EXCEEDANCE PROBABILITY (AEP)


100000
10000
1000
100
10
1.0 g
0.1 g
Peak Ground Acceleration, PGA (mm/s²)
1E+0
1E+1
1E+2
1E+3
1E+4
1E+5
1E+6
Annual Exceedance Probability, AEP (1 in N)
Curve 1
Curve 2
Curve 3
Curve 4
Curve 5
Curve 6
Curve 7
KEY :
– – – – Curves Extrapolated
Curve 1 : ML 0.0 - 7.5
Curve 2 : ML 4.5 - 7.5
Curve 3 : ML 5.0 - 7.5
Curve 4 : ML 5.5 - 7.5
Curve 5 : ML 6.0 - 7.5
Curve 6 : ML 6.5 - 7.5
Curve 7 : ML 7.0 - 7.5

FAILURE MODES ANALYSIS

- SYSTEMATIC, COMPREHENSIVE SEARCH FOR ALL CONCEIVABLE FAILURE MODES BY CONSIDERING ALL ELEMENTS OF EACH BANK AND HOW THEY COULD FAIL TO FUNCTION AS INTENDED
- WHERE IT COULD BE SAID WITH ASSURANCE THAT CHANCE OF FAILURE IS NEGLIGBLY LOW, MODE WAS EXCLUDED FROM ANALYSIS BUT REASONS WERE DOCUMENTED. ALL OTHER MODES INCLUDED FOR LATER RISK ANALYSIS
- MODES CLASSIFIED BY HAZARD SITUATION AS:
  - NORMAL OPERATING CONDITIONS
  - FLOOD
  - EARTHQUAKE
- IT WAS JUDGED THAT RISKS FROM OTHER HAZARDS, SUCH AS SABOTAGE, ACT OF WAR, VOLCANIC ACTIVITY, WERE NEGLIGIBLY LOW
- FOUR CLASSES OF FAILURE:
  - TYPE 1 - WHOLE STORAGE LOST, CATASTROPHIC FLOODING
  - TYPE 2 - PARTIAL STORAGE LOSS, SERIOUS FLOODING
  - TYPE 3 - PARTIAL STORAGE LOSS, MODERATE FLOODING
  - TYPE 4 - SERIOUS DAMAGE, NO STORAGE LOST
- TOTAL OF 80 FAILURE MODES INCLUDED FOR RISK ANALYSIS
- BY HAZARD SITUATION:
  - NORMAL OPERATING CONDITIONS - 20 MODES
  - FLOOD - 33 MODES
  - EARTHQUAKE - 27 MODES
- BY BANK:
  - CONCRETE DAM - 10 MODES
  - BANK NO.1 - 23 MODES
  - BANK NO. 2 - 8 MODES
  - BANK NO.3 - 12 MODES
  - BANK NO. 4 - 27 MODES
- ASPECTS RELIANT ON JUDGMENT - THE EXCLUSION OF MODES FROM LATER ANALYSIS. HOWEVER SOME EXCLUSIONS WERE BASED ON COMPLIANCE WITH TRADITIONAL ANALYSIS CRITERIA. ALSO EXCLUSION OF HAZARDS, SUCH AS SABOTAGE, WAS BASED ON JUDGMENT.

NO. 2 BANK FAILURE INITIATORS

A. HYDROLOGIC EVENTS (RESERVOIR WATER LEVELS EXCEEDING 192.076m AHD)

A1. Initiators Included

HYDROLOGIC EVENT FAILURE INITIATOR	EXPLANATION FOR INCLUSION	FAILURE TYPE
Piping in Foundation	The dam lies on alluvium, some of which is cohesionless. Artesian pressures have been measured at the toe. Foundation piping, boils and blowout could occur especially under high reservoir head.	1
Piping in Embankment	The embankment does not have fully intercepting filters. The fill material is dispersive. The risk of embankment fill piping into foundation alluvium also needs consideration. The security against embankment piping is less than now required for high hazard dams.	1
Overtopping	Overtopping could cause erosion at the dam toe or crest which could develop into a breach. The soil dispersivity increases this risk.	1

A2. Initiators Excluded

HYDROLOGIC EVENT FAILURE INITIATOR	REASON FOR EXCLUSION
Steady Seepage Downstream Stability	Analyses show acceptable factors of safety at full supply level. Higher storage levels would make little difference. The risk of dam failure is negligible.

NO. 2 BANK FAILURE INITIATORS

B. EARTHQUAKE EVENTS

B1. Initiators Included

EARTHQUAKE EVENT FAILURE INITIATOR	EXPLANATION FOR INCLUSION	FAILURE TYPE
Piping in Foundation	There is cohesionless alluvium in the foundation. Artesian pressures have been measured at the toe. Earthquake shaking could lead to increased pore pressure which triggers boils, piping and blowout.	1

PANEL REVIEWS

- REVIEWS WERE HELD AT KEY STAGES OF THE RISK ANALYSIS. THE AIM WAS TO REACH AGREEMENT ON WORK TO THAT TIME WHICH WOULD AFFECT THE SUBSEQUENT ANALYSES.

- TO FACILITATE REVIEW BY PANEL MEMBERS, THE STUDY REPORT WAS WRITTEN AS WORK WAS DONE. THE REPORT OF WORK TO DATE WAS PROVIDED TO EACH PANEL MEMBER BEFORE THE MEETING.

- THE INTERNATIONAL REVIEW CONSULTANTS PARTICIPATED IN MOST PANEL REVIEWS

- AT THE REVIEW MEETING THE PANEL WENT THROUGH THE REPORT, WITH MEMBERS QUESTIONING THE ANALYSTS AS TO THE REASONS FOR PARTICULAR CONCLUSIONS. IF PANEL MEMBERS HAD A DIFFERENT VIEW, THEY WERE REQUIRED TO GIVE THEIR REASONS. THE MEETING EITHER DECIDED, WITH THE AGREEMENT OF THE ANALYSTS, TO MAKE A CHANGE OR REQUIRED FURTHER WORK OF THE ANALYSTS.

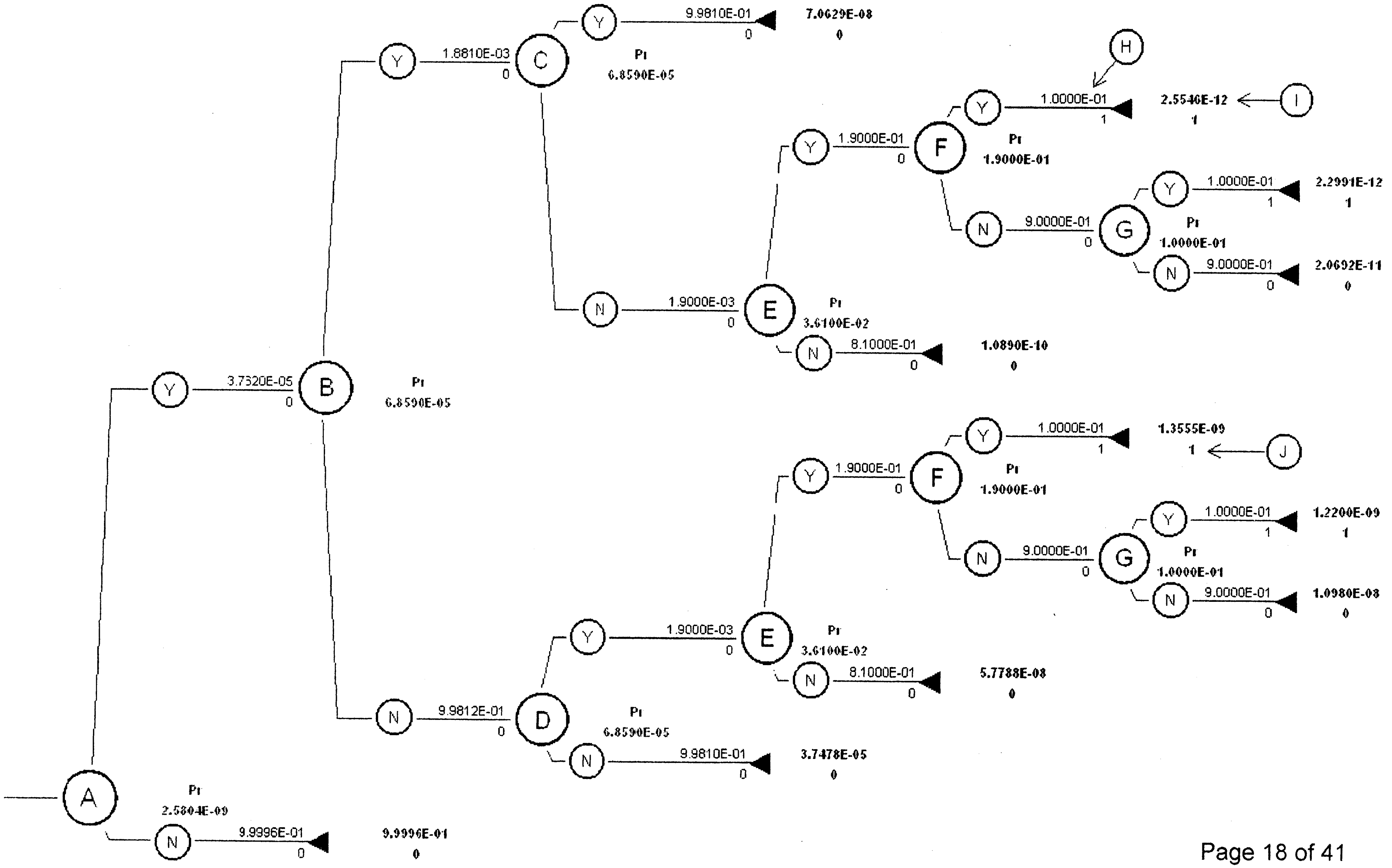
- THE REQUIREMENTS OF THE PANEL, EITHER FOR CHANGES OR FOR FURTHER WORK, WERE RECORDED IN A REPORT. IN SUBSEQUENT WORK THE ANALYSTS WERE REQUIRED TO RESPOND TO ALL POINTS OF THE REPORT - THEY WERE NOT AT LIBERTY TO IGNORE ANY POINTS

- PANEL REVIEWS WERE HELD FOLLOWING COMPLETION OF:
  - FAILURE MODE ANALYSIS
  - FAILURE PATHWAYS ANALYSIS
  - PROTOCOLS FOR PROBABILITY ASSIGNMENT

  MEETINGS WERE NOT ALWAYS HELD AT THE IDEAL TIME BECAUSE OF THE NEED TO TAKE ADVANTAGE OF THE INTERNATIONAL REVIEW CONSULTANTS' VISITS TO AUSTRALIA

FAILURE PATHWAYS ANALYSIS

- DIS-AGGREGATION OF THE FAILURE PROCESS AS AN AID TO PROBABILITY ASSIGNMENT
- EVENT TREES USED FOR ALL FAILURE MODES.
- HOWEVER FAULT TREES USED TO ANALYSE PROBABILITY THAT SPILLWAY GATES WOULD NOT OPERATE AS INTENDED
- IN RETROSPECT FAULT TREES SHOULD HAVE BEEN USED TO ANALYSE FAILURES OF THE SPILLWAY ROAD AND HOIST BRIDGES. THIS IS BECAUSE THERE ARE PARALLEL FAILURE PATHWAYS, WHERE FAILURE OF EITHER OR BOTH OF "PEIR FAILURE" OR "DECK FAILURE" CAN RESULT IN BRIDGE FAILURE
- BRANCHES FOR THE CHANCE OF A SUCCESSFUL INTERVENTION WERE INCLUDED WHERE THAT WAS A REALISTIC POSSIBILITY
- BRANCHES WERE INCLUDED TO EXAMINE THE CHANCE THAT A DAM, ALREADY DAMAGED BY A LOADING, WOULD FAIL DUE TO A SUBSEQUENT EVENT DURING THE PERIOD REQUIRED FOR REPAIRS. FOR EXAMPLE, A BANK MAY SLIDE DUE TO LIQUEFACTION OF FOUNDATION ALLUVIUM DURING AN EARTHQUAKE, BUT THERE IS NO PROMPT FAILURE BECAUSE THE RESERVOIR LEVEL IS BELOW THE BASE OF THE BANK. BUT THE DAM IS THEN AT RISK FROM AN OVERTOPPING FAILURE IF A FLOOD OCCURS BEFORE REPAIRS ARE MADE


A
Y
3.7320E-05
0
B
Pr
6.8590E-05
Y
1.8810E-03
0
C
Y
9.9810E-01
0
7.0629E-08
0
Pr
6.8590E-05
H
Y
1.0000E-01
1
2.5546E-12
1
I
Y
1.9000E-01
0
F
Pr
1.9000E-01
Y
1.0000E-01
1
2.2991E-12
1
N
9.0000E-01
0
G
Pr
1.0000E-01
N
9.0000E-01
0
2.0692E-11
0
N
1.9000E-03
0
E
Pr
3.6100E-02
N
8.1000E-01
0
1.0890E-10
0
Y
1.0000E-01
1
1.3555E-09
1
J
Y
1.9000E-01
0
F
Pr
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Y
1.0000E-01
1
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1
N
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Pr
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D
Pr
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0
3.7478E-05
0
Pr
2.5804E-09
N
9.9996E-01
0
9.9996E-01
0

STATIC SLOPE STABILITY

• DATUM TO AID UNDERSTANDING

The first step was to undertake a First Order Second Moment (FOSM) reliability analysis, that would give probability of a major slide as a function of computed Factor of Safety, F. Aim is to define the Probability Density Function (PDF) of F. If the PDF of F is taken as Normal, all that is needed are mean value of F and its standard deviation. Principles are that, if mean values of input parameters are used in a stability analysis program, the resulting value of F will be the mean, and that the variance in F is the sum of the input parameter variances weighted by the square of the parameter sensitivity (the change in F, given unit change in the parameter). But for slope stability, account must be taken of the spatial variability of fill strength to allow for the self-cancelling effect. This is done by estimating the Autocorrelation Distance (AD), a measure of how erratic strength variations are. The procedure was similar to that outlined by Christian et al (1994).

• USE OF FOSM RELIABILITY ANALYSIS

FOSM reliability analysis gives the chance that the true value of F will be less than 1.0 (the definition of the sliding threshold if mean parameter values are used), given the computed value of F. It follows that FOSM is applicable to prospective situations, where the situation has not yet been put to the test, such as the case where an embankment is yet to be constructed or a structure is yet to experience an unprecedented load. If, as is normal in traditional stability analyses, conservative shifts are made in input parameter values such as fill strength, adjustments are needed.

• INSIGHTS FROM FOSM RELIABILITY ANALYSIS

If computed F is greater than 1.0, an increase in standard deviation gives an increase in probability of sliding, but if computed F is less than 1.0, increased standard deviation means a lower chance of sliding. If computed F, based on mean parameter values, is 1.0, the chance of sliding is 0.5 regardless of the standard deviation in F (this result is without allowance for model error). It follows that, given standard deviation is uncertain, uncertainty in chance of sliding is least when that chance is high and is greatest when chance of sliding is low. Acceptably low chance of sliding in the prospective case is only achieved by making conservative shifts in parameter values.

• EXISTING DAMS

If an existing bank has not suffered a slide, it follows that the true value of F (from mean values of parameters) is greater than 1.0. If conditions remained constant, the probability of a slide would be zero. But banks do suffer delayed slides (defined as occurring more than five years after construction) under Normal Operating Conditions. Possible reasons are:

- true value of F was only marginally above 1.0, and some minor perturbation, such as a change in seepage conditions, is enough to take true F below 1.0
- there is some occurrence, such as a transverse crack, which radically changes seepage or other conditions and causes a dramatic reduction in true F.

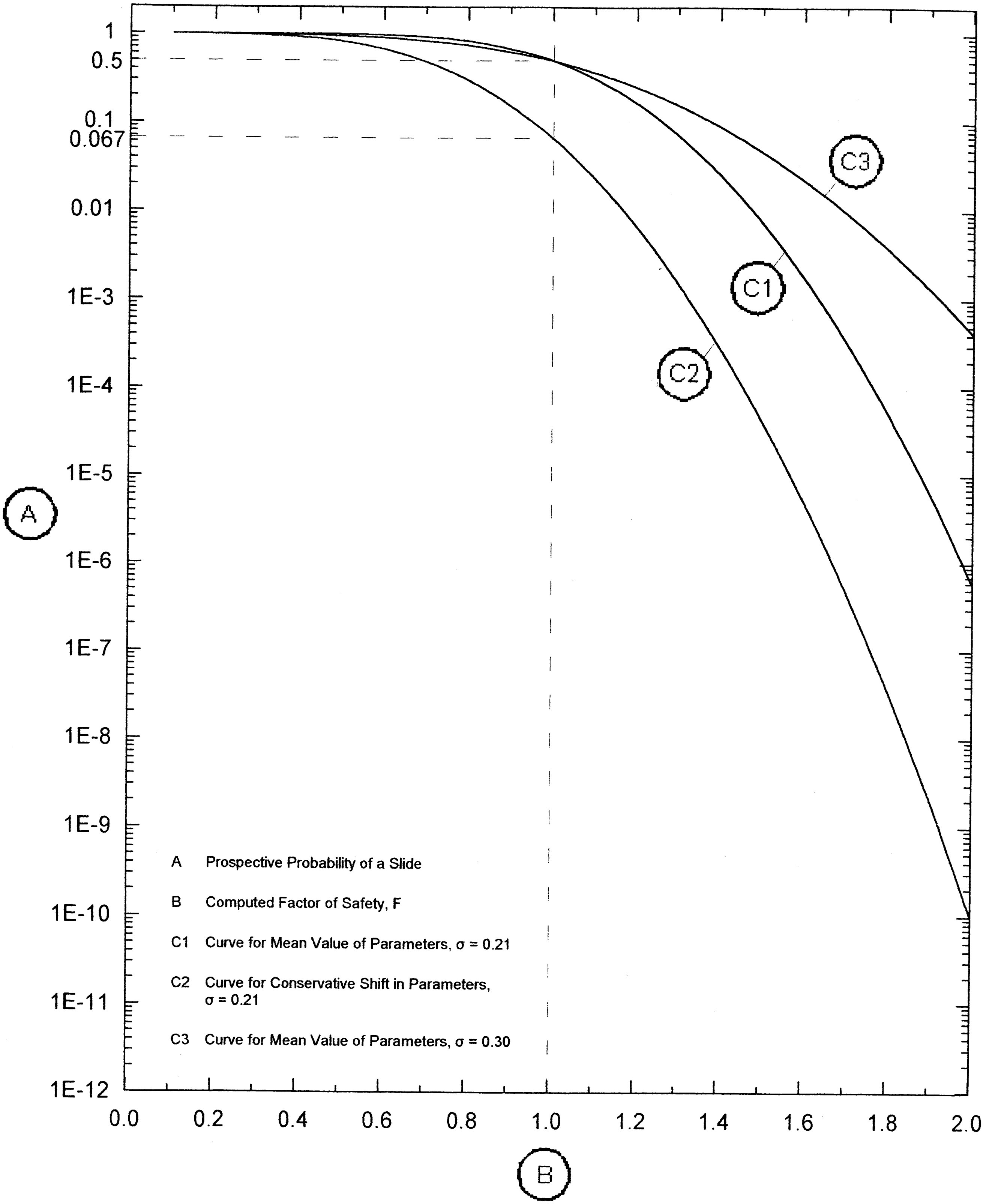
First situation poses extreme difficulty for risk analysis, there being no recognised methodology for analysis. In the second case, if the precipitating cause has not yet occurred, the case is prospective and FOSM can give an estimate of the conditional probability of sliding given the precipitating cause, provided the drop in true F can be estimated. The probability of the precipitating cause occurring is a separate problem. A typical precipitating cause at Hume Dam was the possibility of the Bank No. 1 core wall rupturing due to strong earthquake shaking. If that happened, the downstream fill would wet up, there would be significant pore pressures in the downstream zone and the true value of F would reduce dramatically. Indeed that scenario had already unfolded at the junction of Bank No. 1 with the concrete dam, where the integrity of the core wall seal had been breached.

• ASPECTS RELIANT ON JUDGMENT

At Hume, there were good data (continuous cone penetrometer logs) at the northern end of Bank No. 1 and this is where FOSM analysis was made. Fill had been affected by seepage, with loss of strength on wetting. Stability was governed by a weak horizontal layer at base of slide surface. The estimated AD was for the vertical direction, whereas critical need was AD for the horizontal direction normal to dam axis. That had to be judged. Standard deviation was taken to apply to all Hume Banks, another judgment. Methodology to estimate chance of a slide for the banks under Normal Operating Conditions, where there was no cause for a radical drop in F, was based largely on judgment.

• RESEARCH NEEDS

Matters for research. Methodology to estimate chance of sliding for existing banks under Normal Operating Conditions when there is no occurrence to cause a marked change in stability. It is interesting to note that traditional analysis treats the prospective and existing dam cases in the same way, by requiring a specified minimum F value, but risk analysis recognises the two cases as being quite different. Standard deviation was taken as constant over full range of computed F - may not be so - needs research. Lack of knowledge as to stability analysis model error is a problem at present.


1
0.5
0.1
0.067
0.01
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
A
B
C1
C2
C3
A Prospective Probability of a Slide
B Computed Factor of Safety, F
C1 Curve for Mean Value of Parameters, σ = 0.21
C2 Curve for Conservative Shift in Parameters, σ = 0.21
C3 Curve for Mean Value of Parameters, σ = 0.30

OVERTOPPING EROSION

• APPROACH

A review of the literature yielded no methodology for estimating the conditional probability of breaching of embankment dams, given overtopping. It was necessary to develop a system response curve on the basis of engineering judgment.

• DATA TO AID JUDGMENT

Data on cases of breaching and survival of overtopped embankments were obtained from published sources, such as Powledge et al (1989). These data were plotted on a graph of peak overtopping depth versus peak overtopping duration. No clear boundary between breaching and survival cases was evident. However the sample data did give some feel for the chance of breaching of a bank with a hydrograph time base in the same order as Hume Dam, and it was judged that for a bank of "average" erosion resistance there would be a conditional probability of breaching of 0.6 for an overtopping depth of 300mm.

• HUME DAM SYSTEM RESPONSE CURVE

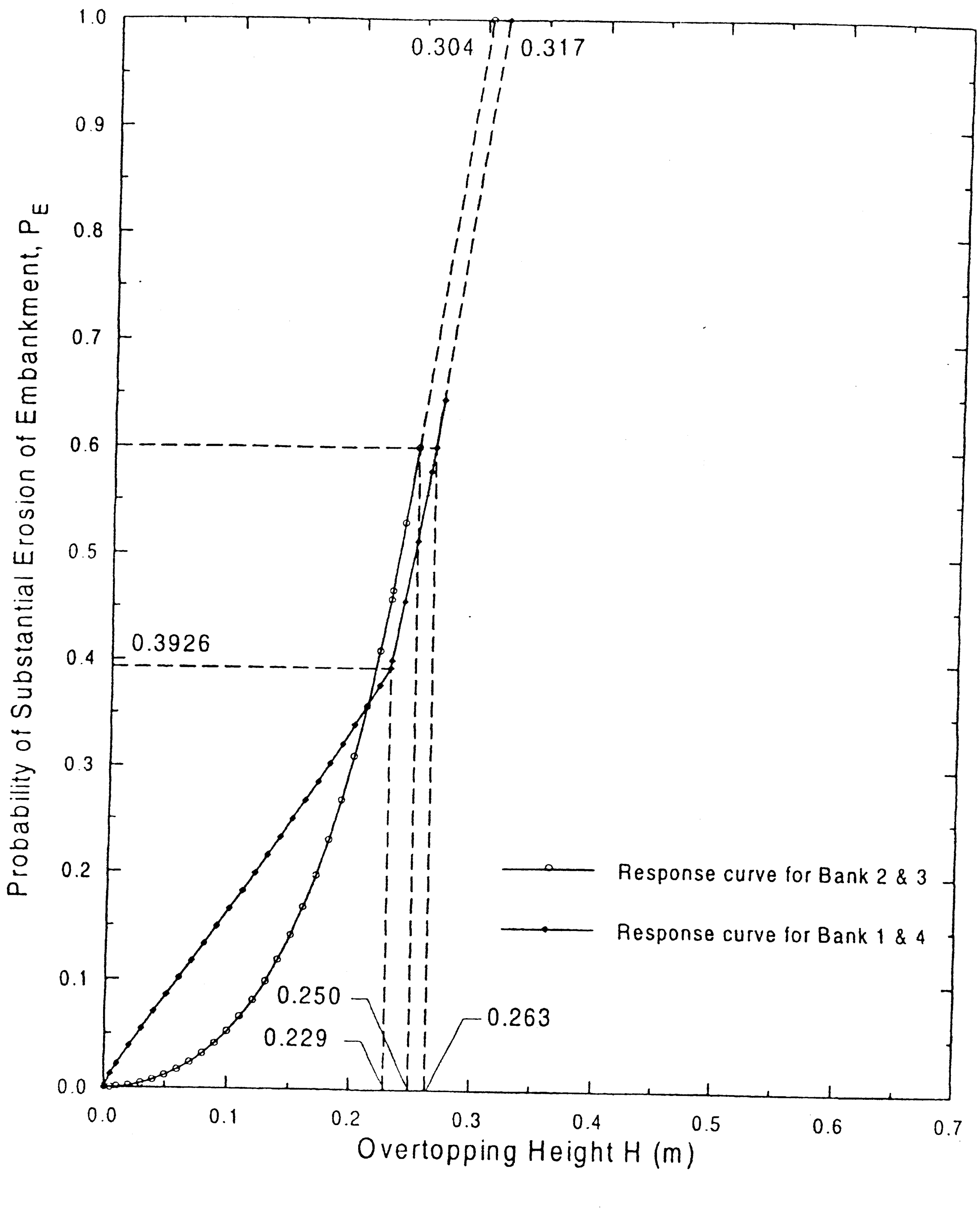
It was judged that the Hume Dam banks were more vulnerable than the average because of:

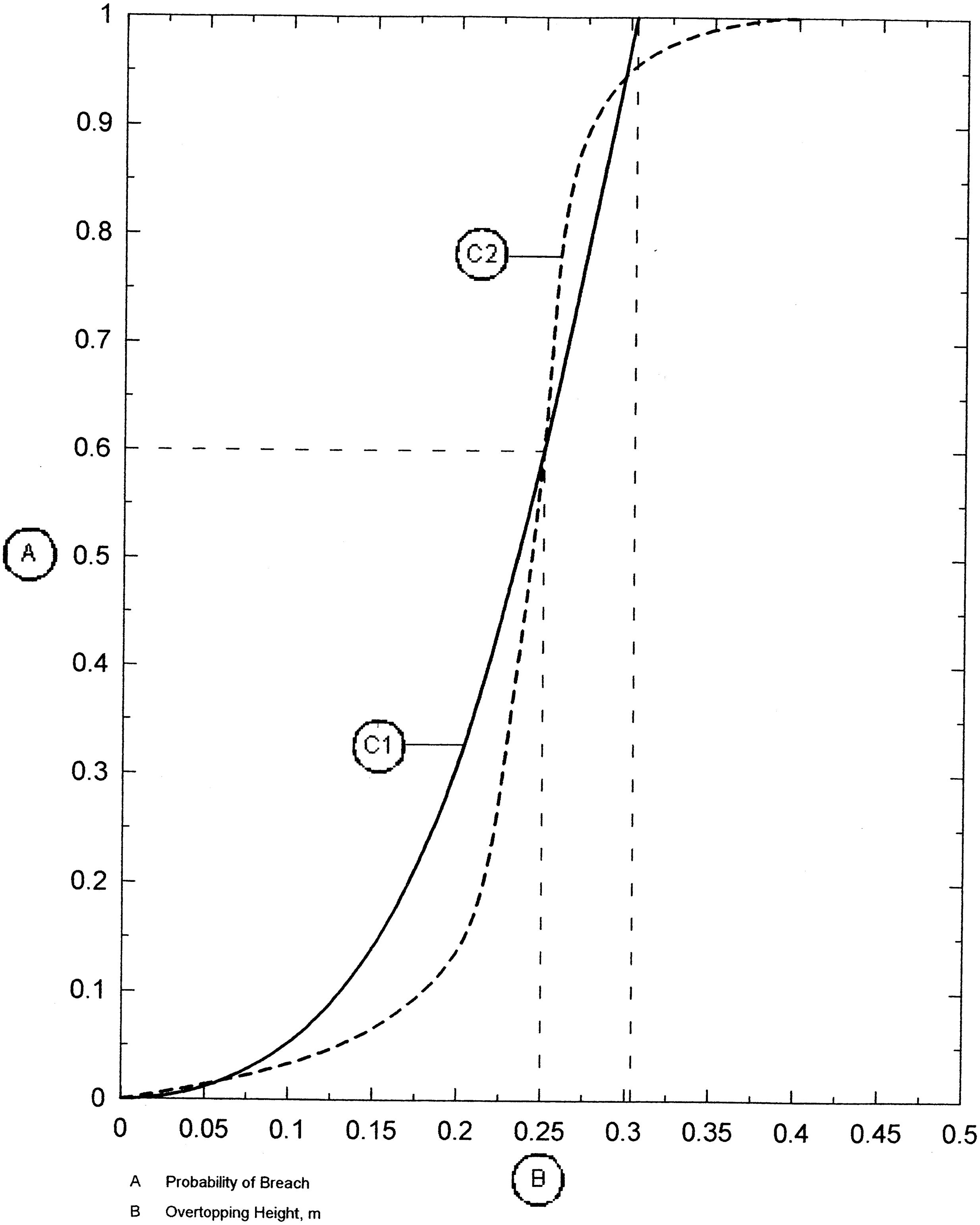
- strongly dispersive embankment fill
- low clay content of embankment fill
- poor grass cover
- possible low spots

After considerable debate in Review Panel sessions, the curve shown for Banks Nos. 2 and 3 on the following slide was agreed as reasonable. This curve was modified for Banks Nos. 1 and 4, to take account of the erosive effect of water flowing over the parapet walls, thus increasing the probability of breaching at low overtopping depths.

• SHAPE OF SYSTEM RESPONSE CURVE

The analysts originally produced a curve that flattened at the top end and became asymptotic to the conditional probability equals 1.0 line. Review Panel members questioned this, on the basis that overtopping depth and duration increase together thus progressively intensifying the tendency to initiation of a breach. On this view it was argued that the system response curve should progressively steepen until it intersects the conditional probability equals 1.0 line at a large angle. That view was accepted at the time. The author now believes that the system response curve should be seen as the cumulative distribution function derived from the probability density function for the depth at which breaching initiates. On this view the original flattening of the curve at the top end was more correct. The main point of this issue is that the debate has continued over a long period, and there are very experienced dams engineers in support of both views, thus illustrating how poorly dam failure processes are understood in probabilistic terms.


Probability of Substantial Erosion of Embankment, P_E
Overtopping Height H (m)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.304
0.317
0.3926
0.250
0.229
0.263
Response curve for Bank 2 & 3
Response curve for Bank 1 & 4



A	Probability of Breach
B	Overtopping Height, m
C1	Curve that Progressively Steepens
C2	Curve that Flattens at Top End.

POST-LIQUEFACTION INSTABILITY

• APPROACH

The approach for assignment of probability was:

- procedure of Liao et al (1988) for probability of liquefaction
- prospective case static stability response curve from FOSM reliability analysis for probability of a major slide, given liquefaction.

• PROBABILITY OF LIQUEFACTION

Two interlinked spread sheets were created as follows:

- one for input of test data from exploratory drilling of the foundation alluvium
- one for estimating probability of liquefaction by solution of the Liao et al equations.

Each test result (SPT value with associated particle size grading and pore water pressure) was a row on the data input spreadsheet. Each data row was then run through the probability of liquefaction spreadsheet to obtain a result for each test location according to the peak ground acceleration state and the earthquake event magnitude state. The probability of liquefaction was taken to be zero if event magnitude was less than M5.0, since it was reasoned there would be too few stress reversals to cause liquefaction.

The highest probability of liquefaction from each borehole was taken as the probability of liquefaction for that location. At a number of exploration cross sections there were three boreholes downstream of the dam axis. It had been assessed that localised liquefaction, in the vicinity of only one borehole, would not cause a major slide. The question arose as to the probability of liquefaction at all three boreholes, given the widely varying probabilities of liquefaction at each of the boreholes. From the theory of uni-modal bounds it was decided that the lowest of the three probabilities was the upper bound probability for liquefaction at all three locations.

• PROBABILITY OF A MAJOR SLIDE, GIVEN LIQUEFACTION

An FOSM analysis provided a curve of conditional probability of a major slide, given liquefaction, as a function of the computed post-liquefaction F value. The residual undrained strength of the liquefied zone was based on the work of Stark and Mesri (1992) and was expressed as an equivalent friction angle in the range of 4 to 9 degrees. The liquefiable alluvium at Hume Dam was capped by a layer of low permeability material, so that there was no possibility of significant pore pressure relief by drainage during shaking.

• ASPECTS RELIANT ON JUDGMENT

The probability of a breach of the dam, given a major slide and reservoir water level, was determined by judgment. No studies were made of the final configuration of the slide mass.

• MATTERS FOR RESEARCH

Development of procedures for estimating probability of liquefaction, that are specific to dams, would be valuable and would need to take account of the possibilities for drainage during earthquake shaking.

PIPING

• APPROACH

Piping can be triggered by earthquake or flood loading, but can also occur, years after construction, under Normal Operating Conditions. It is a difficult problem, because it is not amenable to analysis and because the probability is governed by the most vulnerable pathway, rather than average properties, so that the needed data cannot be discovered by usual geotechnical investigations.

Faced with these difficulties, the analysts decided to take the historic failure rate of delayed piping, and modify this by multipliers that reflected the judged effect of factors known to influence the chance of piping. Account was also taken of the chance of a successful intervention in the event a piping incident occurred. There had been a piping incident at the junction of Bank No. 1 and the concrete dam (the Southern Junction) some years ago and this was successfully arrested by intervention.

• HISTORIC FAILURE RATE

Taking information from various published sources, the analysts estimated average failure rates of:

- 3.6E-05 per embankment dam per annum
- 1.5E-04 per erodible foundation (without positive cutoff) per annum.

A number of unverifiable judgments were required to arrive at these figures.

• INFLUENCING FACTORS

Factors allowed for, in the case of embankment piping, were:

- soil dispersivity
- fill density
- zoning
- potential for low fill stress
- prior incidents of seepage or piping
- potential for fill to pipe into foundation alluvium
- fill grading and clay content.

The multipliers were based on judgment as to the properties of a notional dam that was seen as representative of the historic database of dams. Multipliers were then assigned to each of the Hume banks according to its properties. Some multipliers were greater than 1.0, thereby increasing chance of failure, whilst others that were less than 1.0 reduced the chance. By applying all of the multipliers for a bank to the historic failure rate, a "probability" of piping failure was obtained for each bank,

- at full supply level (FSL)
- without any intervention
- under Normal Operating Conditions (NOC).

A similar approach was taken for foundation piping.

• EFFECT OF RESERVOIR WATER LEVEL

The effect of water level was taken into account by applying a multiplier of 1.0 for FSL and of zero for water level at the base of the embankment in question. A curve based on judgment provided multipliers for intermediate prior storage levels.

• INTERVENTION

The chance of a successful intervention was based on judgment, following a systematic consideration of such factors as:

- access to the location
- workloads on site staff
- effects of shock and stress on site staff
- access to materials, such as filter media
- quality of monitoring and surveillance procedures
- drawdown capacity of the reservoir
- time required for decisions
- breach development time according to location of piping, storage level.

For example, in the case of earthquake loading there were 48 values for chance of a successful intervention, being one for each cell of the matrix of 8 earthquake loading states by 6 prior storage states.

• FLOOD LOADING

Increment of risk based on judgment and took account of

- vulnerability of bank in question (determined for NOC)
- short duration of elevated water levels (thus insufficient time to develop new flownet)
- possibility of drying cracks close to dam crest
- “first filling” nature of water coming against upper part of bank for the first time.

• EARTHQUAKE LOADING

All recorded embankment dam failures due to earthquake, appear to have involved liquefaction. Matahina (New Zealand) and Austrian (California) Dams demonstrated the potential for failure due to piping triggered by earthquake. For Hume Dam, a judgment was made that the conditional chance of piping of the most vulnerable bank, given the highest earthquake loading state (0.915g) would be 0.01 for storage at FSL. The probability for other banks was scaled according to their base vulnerability (determined for NOC). Curves were produced for each bank showing a slow increase from zero chance up to yield acceleration for the bank, and then a rapid increase in chance of piping for higher loadings.

A similar approach was taken for foundation piping.

LENGTH AND NUMBER EFFECTS

- LENGTH OR NUMBER OF DAM ELEMENTS CAN AFFECT THE CHANCE OF FAILURE - EQUIVALENT TO MORE THROWS OF DICE

- VERY LITTLE TREATMENT OF THIS ASPECT IN THE LITERATURE

- FOR HUME DAM, THE UPPER BOUND CHANCE OF FAILURE FOR SEPARATE ELEMENTS (SUCH AS BLOCKS OF THE GRAVITY DAM) WAS TAKEN AS THAT OF THE UNION OF THE EVENTS, THE FAILURE OF THE INDIVIDUAL ELEMENTS

- A SIMILAR APPROACH WAS TAKEN TO ACCOUNT FOR LENGTH OF EMBANKMENTS BY DEFINING A "BASIC SEGMENT LENGTH" TO WHICH THE BASIC ESTIMATE FOR CHANCE OF FAILURE RELATED. BANKS WERE DIVIDED INTO ZONES FOR WHICH ANALYSIS RESULTS WERE REPRESENTATIVE. THE PROBABILITY OF FAILURE FOR EACH ZONE WAS

  $$P[Z] = 1 - (1 - P[S])^n$$

  where P[Z] = probability of failure for zone
  P[S] = probability of failure for basic segment length
  n = ratio of zone length to basic segment length

  THE OVERALL CHANCE OF FAILURE WAS THEN TAKEN AS THAT FOR THE UNION OF THE EVENTS, THE FAILURE OF EACH ZONE

- THE DIFFICULTY WAS TO DECIDE WHAT THE BASIC SEGMENT LENGTH SHOULD BE. FOR PROBABILITIES BASED ON THE HISTORIC DATABASE OF FAILURES, SUCH AS THAT FOR PIPING, THIS WAS TAKEN TO BE 500m WHICH IS ABOUT AN AVERAGE LENGTH FOR EMBANKMENT DAMS. FOR SLOPE STABILITY IT WAS TAKEN AS 100m WHICH IS ABOUT THE LENGTH FOR HUME DAM AT WHICH END EFFECTS BECOME NEGLIGBLE AND THE 2D VALUE OF F APPLIES

- IN MOST SITUATIONS, LENGTH AND NUMBER EFFECTS HAVE LITTLE PRACTICAL SIGNIFICANCE. BUT IT IS IMPORTANT TO HAVE A PROPER UNDERSTANDING OF THE EFFECT. RESEARCH INTO THIS ASPECT WOULD BE OF VALUE.

PROTOCOLS AND RATIONALE

• THE NEED

Risk analysis generates a vast mass of numbers. In reviewing earlier risk analyses by others, the Hume analysts had become confused, and found it difficult to ensure logical consistency throughout the study, because of the mass of numbers presented.

For the Hume study, which was much larger than the earlier studies just referred to, a number of needs were apparent:

- to coherently deal with a mass of numbers on an unprecedented scale
- to ensure logical consistency throughout a very wide ranging study, with the several elements of the dam and the very large number of failure modes
- to provide a vehicle for manageable review by the Review Panel and the International Consultants
- to permanently record, in a concise way, the reasons in support of a huge number of probability values.

The solution devised to meet these needs was the Protocols and Rationale.

• FORMAT

Protocols were dot point instructions for assignment of probabilities. There was a protocol for every event tree (that is, for every failure mode). Within each protocol there was a dot point for every branch of the event tree. And within each dot point there was an instruction for every load state.

• BASIS FOR PROBABILITIES

Some of the key probabilities came from system response curves or tables, developed for such aspects as post-liquefaction instability, as previously described. Others were based on judgment made in the light of traditional analyses. For example, for Bank No.1 there was the question of the chance of a dam breach, given a major slide. The moment and shear capacity of the core wall was analysed and the imposed moment and shear loads were plotted as a function of the depth to which fill had been removed on the downstream side of the wall. Judgments were then made in light of that information. Still other probabilities were based largely on judgment, but always in light of a systematic consideration of relevant factors. An example is the chance of a successful intervention to arrest piping triggered by a major earthquake, where consideration was given to such aspects as drawdown capacity of the reservoir, workloads on staff, state of shock for staff and access to the dam.

• RATIONALE

The rationale followed the protocol, with a dot point that corresponded with each of the dot points of the protocol, where the justification for that point of the protocol was set out.

INTEGRATED RISK MODEL

• INITIAL SITUATION

Following the early review sessions, the analysts had to change various probability values. This was a tedious task. For reasons of logical consistency, a change to a value in one event tree, would typically require changes in several other event trees. The International Consultants suggested that a model of the whole risk analysis process should be constructed.

• CONSTRUCTION OF MODEL

The model was essentially a series of interlinked spreadsheets. Considerable effort went into its construction, but this turned out to be a very worthwhile investment.

• POST MODEL SITUATION

Changes made following the later review sessions involved very little effort. The change was made in the relevant spreadsheet, and was automatically propagated through to the study outputs. The probability assignment protocols considerably aided the use of the risk model, especially as regards logical consistency across failure modes and the various dam elements.

• COMMON CAUSE FAILURES

Because some failure modes are not mutually exclusive, it was necessary to build into the model the facility to report upper and lower bound probabilities. The lower bound probability of failure was the maximum of the individual mode probabilities, and the upper bound probability of failure was the probability for the union of the events, the individual mode failures. For all cases where failure modes were not mutually exclusive, the model automatically propagated the probability bounds through to the study outputs.

• SENSITIVITY TESTING

The sensitivity of the study results to some key uncertainties was tested and reported. An interlinked risk model can facilitate sensitivity testing.

STUDY REPORTS

• DETAILED REPORT

The aim of the detailed report was to provide a permanent record of the study inputs, methodology and outputs. Consequently it is a large report, with 483 pages of text and many more pages in 11 appendices.

• SUMMARY REPORT

A common complaint about risk analysis reports is that dam owners and their managers find the great mass of numbers that are reported to be confusing and incomprehensible. This problem was recognised in the case of the Hume Dam study and a separate Summary Report was produced. This report, with 52 pages of text and one appendix, is directed to the needs of the decision makers. There was only a brief outline of methodology, with emphasis on the degree of acceptance for each methodology. Study results were presented in summary form.

FURTHER WORK

The risk analysis which is the subject of this presentation was termed that for the "Pre-existing condition" in later studies. It looked at the dam in its unmodified condition, except for a stabilising berm at the "dog-leg" section of Bank No.1.This was the configuration that existed at August 1996.

The risk assessment has now been taken further by RAC Engineers and Economists. This further work has included:

- estimation of failure probabilities for the dam, as upgraded to September 1997 (the "Existing Dam")
- estimation of failure probabilities for the dam as it would be on completion of upgrades that were firmly committed ("Phase 2 risk reduction measures")
- estimation of failure probabilities for the dam as it would be if additional upgrades, not yet decided on, were undertaken (work beyond Phase 2)
- integration of the upstream Dartmouth Dam into the study
- estimation of failure consequences, including loss of life
- estimation of risks (probability/consequence pairs)
- comparison of risks with tolerable risk criteria
- estimation of costs of risk reduction measures
- generation of measures of cost effectiveness for risk reduction measures

REFLECTIONS

SOME REFLECTIONS OF THE AUTHOR IN LIGHT OF EXPERIENCE WITH THE HUME AND OTHER RISK STUDIES:

- METHODOLOGIES FOR ESTIMATION OF THE PROBABILITY OF DAM FAILURE ARE POORLY DEVELOPED OR NON-EXISTENT
- THE CURRENT STATE OF METHODOLOGY DOES NOT, IN GENERAL, SUPPORT A CONCLUSIVE "SIGN OFF" ON THE SAFETY STATUS OF A DAM
- HEAVY RELIANCE ON ENGINEERING JUDGMENT IS NECESSARY AT THE PRESENT STAGE OF DEVELOPMENT OF RISK ANALYSIS METHODOLOGIES. IT IS DESIRABLE THAT A SHIFT TO MORE ANALYSIS AND LESS JUDGMENT IS ACHIEVED, BUT JUDGMENT WILL REMAIN AN IMPORTANT AND NECESSARY ELEMENT.
- SERIOUS RISK ANALYSIS CURRENTLY ENTAILS A HIGH LEVEL OF EFFORT, SOME OF WHICH IS DIRECTED TO THE DISCOVERY OR DEVELOPMENT OF METHODOLOGIES
- DESPITE THE PROBLEMS, RISK ANALYSIS AND ASSESSMENT IS CURRENTLY OF VALUE TO DAM SAFETY PROGRAMS AS AN ENHANCEMENT TO THE TRADITIONAL METHODS OF DAM SAFETY EVALUATION
- RISK ANALYSIS PROVIDES A "COMMON CURRENCY" FOR COMPARISON OF RISKS ACROSS DAMS, ACROSS LOADING CONDITIONS AND ACROSS FAILURE MODES
- RISK ANALYSIS CONSIDERABLY IMPROVES UNDERSTANDING OF THE SAFETY STATUS OF A DAM; THAT IS, CONSIDERABLE VALUE LIES IN THE PROCESS ITSELF RATHER THAN IN THE NUMERICAL OUTPUTS
- THERE IS A TENDENCY FOR THE OUTPUT NUMBERS TO BE GIVEN MORE CREDENCE THAN THEY DESERVE. RISK COMMUNICATION IS A GREAT CHALLENGE - HOW TO CONVEY THE LIMITATIONS ON THE NUMBERS WHILST PRESERVING THE CREDIBILITY OF THE PROCESS.

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APPLICATION OF RISK CONCEPTS IN A STANDARDS-BASED FRAMEWORK FOR DAM SAFETY IN THE STATE OF WASHINGTON

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INTRODUCTION

This paper summarizes the use of probability and risk concepts in the state of Washington's dam safety program. The approach can be characterized as employing risk concepts and procedures in a standards-based framework. Under this approach, probability methods, risk concepts, and elements of risk assessment are combined with decision making in setting performance standards that provide acceptable levels of protection.

This approach was selected based on a number of considerations. A primary consideration was the need to provide consistent levels of protection across the state. There was also a need to provide methods of analysis that were manageable with limited resources. The state is responsible for over 800 dams, and has limited staffing and resources to apply toward detailed risk assessment. Likewise, most of the regulated community has smaller dams with limited project budgets. Finally, we needed an approach that could be used for the design of new projects as well as for analysis of existing dams. Performing quantitative risk assessments for every project would not be feasible given these considerations. However, employing risk concepts and procedures in a standards-based framework allowed us to address these issues, while realizing the benefits of using a risk-based approach in a relatively simple and inexpensive manner.

GOVERNING DESIGN PHILOSOPHY

The philosophy of the Washington dam safety program utilizes several design principles that provide a framework for evaluating and establishing what design/performance levels are appropriate for the various elements of a dam project. The primary principles related to risk are *Critical Elements, Balanced Protection* and *Consequence Dependent Design Levels.*

Critical Elements – Critical project elements are those elements of a project whose failure could result in dam failure and an uncontrolled release of the reservoir. These elements include principal and emergency spillways (inflow floods); impounding barriers (static and seismic loading); outlet conduits (outlet integrity and seepage control); and impounding barriers and foundations (seepage control).

Balanced Protection - A dam is comprised of numerous critical elements, and like the old chain adage, "is only as strong as the weakest link". The *Balanced Protection* concept incorporates a systems approach in the philosophy of design/analysis for a project. Using this concept, a common Annual Exceedance Probability (AEP) is used to set the set for the design or evaluation of each critical project element. This provides reasonably consistent levels of protection across all elements of a dam project.

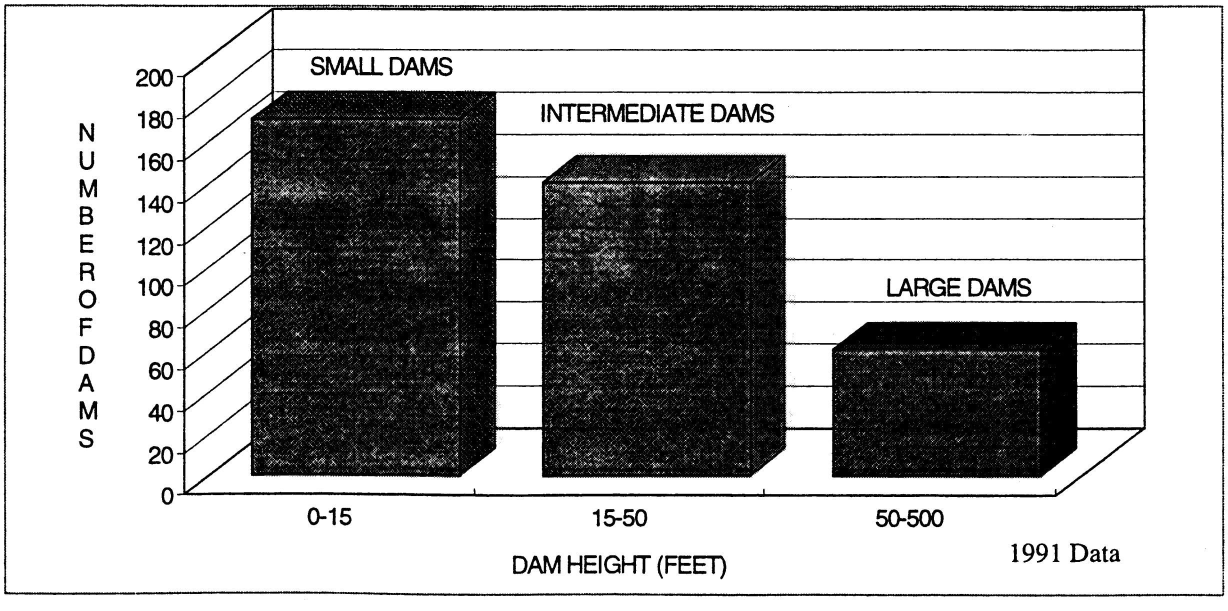
Consequence Dependent Design Levels – Standard practice in the civil engineering community is that the degree of conservatism in design should correspond with the consequences of failure of a given element. If failure of the element poses no public safety concern, the design level is usually based on economic considerations. However, if failure of a given element could pose a threat of loss of life, design levels are typically much more conservative. That conservatism increases with an increase in the potential magnitude of loss of life and property at risk. This concept is called *Consequence Dependent Design Levels.*

CHOICE OF PROBABALISTIC APPROACH OVER DETERMINISTIC APPROACH

In the past, the standard design events used in the dam safety community for high hazard projects have been the Probable Maximum Precipitation (PMP) and the Maximum Credible Earthquake (MCE). The engineering community commonly assumed the PMP and MCE provided a consistent level of protection with the implication of "zero risk" design level. In reality, these are estimates of the theoretical maxima that commonly approach, rather than meet, the theoretical upper limits. Furthermore, in the Pacific Northwest, the annual exceedance probabilities (AEP) of these events can vary widely across the region. For instance, the PMP has an AEP that varies from about 10^{-5} on the coast, to 10^{-6} in the Puget Sound region to 10^{-9} in some areas of Eastern Washington[1]. Thus, the use of these values does not provide zero risk and does not provide consistent levels of protection across geographic areas.

The situation was further complicated when we looked at smaller dams where only a few lives would be at risk. This situation represents the majority of dams regulated by Washington and other states (Figure 1). Regulatory organizations have recognized that PMP and MCE are too stringent for the design/analysis of these smaller projects, and typically, some percentage of the theoretical maximum is used for a loading condition. For example, 50% PMP is frequently used by many regulatory agencies as the lower bound where only a few lives are at risk. However, when ratios of the PMP (or MCE) are taken, wildly differing levels of protection may result. Based on a regional analysis of some 10,000 station-years of precipitation data covering the Pacific Northwest, 50% of the PMP is about a 100-year event in the marine climate on the Pacific Coast, while being closer to a 10,000-year event in parts of the arid eastern half of the state.

Figure 1 – Dams Sited Above Populated Areas In Washington State



Recognizing that the PMP/MCE (much less % PMP/MCE) approach is not zero risk and provides unbalanced protection across the state, we decided to employ a probabilistic approach for setting the performance levels for the design and evaluation of dams in Washington. In keeping with the balanced protection philosophy, the probabilistic approach would apply not only to hydrology, but also to seismic, seepage, structural and conduit design issues. The format for selecting probabilistic design/performance levels is termed the Design Step Format and was originally developed in 1990. It is described in the following section.

DESIGN STEP FORMAT

The philosophies of Balanced Protection and Consequence Dependent Design are implemented through the Design Step Format. This format utilizes eight steps, where the design events become increasingly more stringent as the consequences of failure become more severe. Design Step 1 has an annual exceedance probability of 1 in 500, and would apply where the consequences of dam failure are minimal and there would be no chance for loss of life. Design Step 8 applies to large dams where a dam failure would be catastrophic, with hundreds of lives at risk. In this situation, extreme design loads are used to provide the extremely high levels of reliability needed to properly protect the public. Thus, the AEP of Step 8 is set at 1 in 1,000,000, or the theoretical maximum events (PMP, MCE), whichever is greater. The design Step 8 AEP of 10^{-6} is based on existing design standards (EPRI[2]) and a review of recommendations for engineered structures with extreme consequences of failure, such as nuclear power plants.

The design step format was completed by providing uniform performance increments between the design steps such that the AEP's decrease tenfold for every two design steps. Thus, this format strives to provide a reliability of design with a tenfold increase in protection for every 2 step increase. Figure 2 shows the 8-step format employed by the Washington dam safety program.

Figure 2. Design Step Format

Design Step	Exceedance Probability	Consequence Rating Points
1	1 in 500	< 275
2	1 in 1000	275 - 325
3	1 in 3000 (actually 3160)	326 - 375
4	1 in 10,000	376 - 425
5	1 in 30,000	426 - 475
6	1 in 100,000	476 - 525
7	1 in 300,000	526 - 575
8	1 in 1,000,000 (or theoretical maximum)	> 575

BENCHMARKS FOR SELECTING DESIGN STEPS

The next step in developing the design step format was the selection of benchmarks for setting design levels that would be consistent with levels of safety provided by other engineering disciplines and governmental regulation. Because the actual levels of protection in engineering applications are obscured by standards and codes (sometimes intentionally), the actual design levels and probabilities of failure had to be back calculated. This back calculation had been done for the establishment of performance goals in the design and evaluation of Department of Energy facilities[10]. Additional guidance was obtained by examining the levels of risk to which the public is exposed in ordinary life. Several of these risks are shown in Figure 3. This information was combined to set the benchmarks shown in Figure 4.

Figure 3 – Listing of Risks and Performance Levels

ACTIVITY/ITEM	TYPICAL NUMBER OF PERSONS AT RISK	RISK LEVEL	PERFORMANCE LEVEL
NATIONAL FLOOD INSURANCE PROGRAM • Risk from Natural Flooding	Varies Widely		1/100 AEP 100 Year Flood
FATAL DISEASE[3] • All Causes	1	1/120 AC	
ASCE STRUCTURAL CODE[4] • Performance of Individual Structural Members for Ordinary Buildings Subject to Natural Hazards due to Wind and Earthquake Loads	Typically 1-20		1/1000 AEP
EXISTING OFFSHORE DRILLING PLATFORMS[5] • Performance Subject to Wind, Wave and Earthquake Loads	Varies 0 - 25		1/1000 AEP
ACCIDENTAL DEATH[6] • All Causes	Few 1-3	1/2000 AC	
ACCIDENTAL DEATH[4] • Motor Vehicles	1-6	1/3000 AC	
ACCIDENTAL DEATH[4] • Non-Motor Vehicles	Few 1-3	1/6000 AC	
UNIFORM BUILDING CODE[7] • Performance of Essential Buildings such as Hospitals and Emergency Response Facilities to Maintain Building Functionality and Protect Occupants for Buildings Subjected to Wind and Earthquake Loads	Typically 50-200		1/5,000 AEP
BRITISH SPILLWAY DESIGN[8]	Small Community More than 30		1/10,000 AEP 10,000 Year Flood
DEPT. OF ENERGY BUILDINGS[9] • Performance of Building to Contain Radioactive or Toxic Materials and Protect Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads	Varies - Often Large Numbers of People at Risk		1/10,000 AEP
DEPT. OF ENERGY BUILDINGS[7] • Very High Confidence of Containment of Radioactive and Toxic Materials and Protection to Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads	Varies - Often Large Numbers of People at Risk Both Onsite and Offsite		1/100,000 AEP
NUCLEAR POWERPLANTS[10] • Damage to Core of Nuclear Powerplant from Earthquakes	Varies Potentially Very Large Numbers of People		1/100,000 AEP
AIR TRANSPORTATION[4] • Fatalities - All Aircraft	Varies 1-300	1/150,000 AC**	
AIR TRANSPORTATION[4] • Fatalities - Commercial Airlines	Varies 50-350	1/700,000 AC**	
NUCLEAR POWERPLANTS[8] • Performance Goal for Radioactive Releases Greater than 25 REM	Varies Potentially Very Large Numbers of People at Risk		1/1,000,000 AEP

Note: AC - Annual Chance of Occurrence AEP - Annual Exceedance Probability ** - Based on an "Average Traveler"

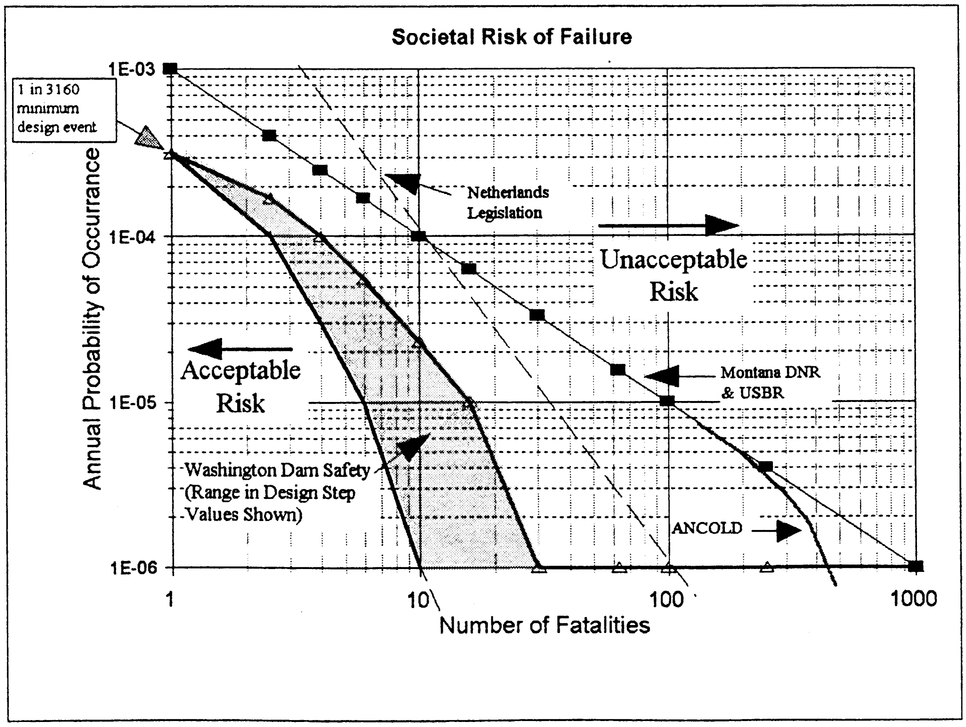
Figure 4 – Benchmarks for Calibrating Point rating Algorithm For Use in Decision Framework

BENCHMARK	CHARACTERISTICS OF IDEALIZED PROJECTS	MINIMUM DESIGN STEP	DESIGN/PERFORMANCE GOAL AEP
1	1 or More Lives at Risk	3	3×10^{-4}
2	Large Dam, over 50 feet High No Downstream Hazard	3	3×10^{-4}
3	Intermediate Dam No Commercial Development 10 Residences at Risk	4	10^{-4}
4	Large Dam Limited Commercial Development 34 Residences at Risk	6	10^{-5}
5	Large Dam Significant Commercial Development 100 Residences at Risk	8	10^{-6}

Note: AEP - Annual Exceedance Probability

A review of both these tables shows a basic trend. In those activities where few lives are at risk, nominal values of protection are accepted by the public. Conversely, as the number of persons at risk and the consequences of a failure increase, the level of protection expected by society and the engineering profession increases significantly. This viewpoint is termed “risk-averse” with regard to loss of life. This is illustrated in Figure 6, which shows DSO criteria compared to other risk criteria such as Montana and the USBR[11], which are risk neutral (i.e., a constant value of risk of 1 in 1000 loss of life/year).

Figure 5 – Comparison of Societal Risk Criteria



ADDITIVE POINT RATING SCHEME

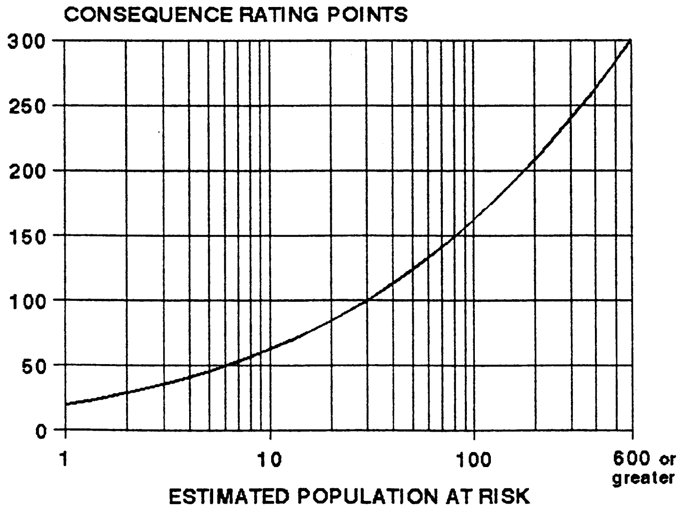
An additive weighting scheme was developed to determine numerical ratings of the consequences of dam failure. This scheme reflects the relative importance and range of severity of the impacts posed by each consequence. Cumulative rating points with values between 200 and 800 points were used to define the working range for the eight-step format. Factors were selected within the 3 general categories shown in Figure 6, which described the nature of the consequences of dam failure.

Figure 6 – Numerical Rating Format for Assessing Consequences of Dam Failure

CONSEQUENCE CATEGORIES	CONSEQUENCE RATING POINTS	INDICATOR PARAMETER	CONSIDERATIONS
CAPITAL VALUE OF PROJECT	0 - 150	DAM HEIGHT	Capital Value of Dam
	0 - 75	PROJECT BENEFITS	Revenue Generation or Value of Reservoir Contents
POTENTIAL FOR LOSS OF LIFE	0 - 75	CATASTROPHIC INDEX	Ratio of Dam Breach Peak Discharge to 100 Year Flood
	0 - 300	POPULATION AT RISK	Population at Risk Potential for Future Development
	0 - 100	ADEQUACY OF WARNING	Likely Adequacy of Warning in Event of Dam Failure
POTENTIAL FOR PROPERTY DAMAGE	0 - 250	ITEMS DAMAGED OR SERVICES DISRUPTED	Residential and Commercial Property Roads, Bridges, Transportation Facilities Lifeline Facilities Community Services Environmental Degradation from Reservoir Contents (Tailings, Wastes.)

Utility curves or consequence rating tables were developed for each of the indicator parameters in Figure 6 to implement the additive weighting scheme. An example of the utility curve for Population At Risk is shown in Figure 7. A worksheet was then developed for compiling the rating points and selecting an appropriate design step. The point rating scheme was calibrated using a wide cross-section of project types and downstream settings to yield results (design steps) consistent with the 5 benchmarks shown in Figure 4.

Figure 7 – Consequence Rating Points for Population at Risk



IMPLEMENTATION OF THE RISK-BASED STANDARDS

The final step in implementing our standards-based approach was the determination or selection of magnitude-frequency relationships associated with extreme events such as floods and earthquakes. This is an area where much work is still needed around the United States. Washington State has the necessary hydrologic data to logically and consistently employ it in our risk based design/performance practice. However, our efforts to implement probabilistic criteria for determining the seismic adequacy of existing dams in the western half of Washington is mired in a number of technical difficulties.

Hydrologic Analysis

In Washington State, we benefited from Dr. Schaefer's detailed studies of extreme storms in the Northwest[12,13], and his development of probabilistic based procedures[14] for generating site-specific precipitation magnitude-frequency relationships. In follow up studies, major storms were researched to determine the values of key parameters that combined with the precipitation to generate the reservoir inflow flood. For new dams, a relatively conservative approach is utilized in the design of critical project elements. Conservative values are typically used for the key hydrologic parameters in the rainfall-runoff model, commensurate with common engineering practice for the design of new dams. The conservatism employed in determining the design flood produce a much higher performance level than the triggering event probability would suggest. This increase in design protection produced by conservatism in analysis is termed the "Knockdown Factor". For new projects, a higher knockdown factor produced by the standards provides greater reliability, and the incremental cost of achieving this reliability is relatively inexpensive compared to the overall cost of the project.

The procedure used for evaluating hydrologic adequacy at existing dams more closely resembles true risk assessment than the standards-based approach used on design of new dams. In this case, however, the goal is to determine if the probability of flood overtopping of the dam is commensurate with the performance level specified by the design step. We still use the design step approach to selecting the design precipitation magnitude. However, we generally employ less conservatism in the key hydrologic parameters in the rainfall-runoff model than those used for design of a new dam. This approach is consistent with our goal of evaluating the performance of the existing structure. Typically, values closer to the mean are used in the model for snowpack, antecedent moisture, and storm distribution. This approach has been verified in recent flood studies[15,16] by Dr. Schaefer, which have utilized stochastic, events-based rainfall runoff models to compute magnitude frequency estimates for flood peak discharge and runoff volume. Monte Carlo sampling procedures were used to allow the climatic and hydrologic input parameters to vary in accordance with that observed in nature. These studies have shown that employing undue conservatism in key hydrologic parameters for a precipitation event of a given AEP, results in a large flood peak and volume that have a much lower exceedance probability than that of the storm.

Seismic Analysis

Typically, seismic design of new construction across the state complies with our probabilistic performance goals. Embankment zoning, modern construction practice, minimum freeboard levels and suitable foundation treatment all combine to yield dams that are inherently resistant to seismically induced, uncontrolled release of the reservoirs. Obviously, settlement, surficial slides and some cracking are anticipated under extreme earthquakes, but this would not result in an uncontrolled release of the reservoir.

Unfortunately, our desire to extend our risk-based performance to existing dams regarding seismic loading has been thwarted in the western half of the state by a combination of events. Step 1, our minimum performance level for low-hazard dams sets the annual probability of an uncontrolled release of the reservoir at 0.002 or 1 chance in 500. Over the last fifteen years, our understanding of the seismicity of the Pacific Northwest has undergone a major transformation. It is now accepted that great subduction earthquakes as large as Moment Magnitude (M_w) 9 can occur along the coast. The stratigraphic record of the last 6000 years includes 13 seismic events, which represents a mean frequency of some 450 years. The impact of this could be to as much as double the level of seismic accelerations predicted for the 500-year event in the densely populated Puget Sound region. A blind application of our performance criteria would require that all dams under our purview in the western half of the state survive this event. We neither have the resources or the capability to enforce such a standard on all existing dams in Western Washington, especially those with low downstream hazard classifications.

The Dam Safety Office expends considerable effort in analyzing existing dams where a failure could conceivably result in loss of life. The peak bedrock accelerations used are the mean predicted values from attenuation relationships. To date, we have not made our determinations of adequacy based on the peak acceleration value at the mean plus-one standard deviation level. We understand that it would be preferable to incorporate variance in our assessments. But, we believe that the present variance is unduly large in the estimation of the embankment resistance to seismic loading, i.e., "capacity" (possibly on the unconservative side), and in earthquake motions through the foundation/embankment section, i.e. "demand" (on the conservative side). This opinion reflects our assessment of the state of practice in the various disciplines that collaborate to predict the seismic safety of dams.

In the seismological arena, we are encouraged by work underway on the catalogues of recorded accelerations to identify such phenomena as "fling", basin edge effects and amplification in relatively low velocity surficial rock, and to more rigorously cull errors such as inaccurate source-to-recorder distances. We anticipate that this effort will reduce the variance about the mean of attenuation relationships. Fling and other effects would then be included where site conditions warrant.

On the capacity side, there is considerable uncertainty as to the post-liquefied strength of soils. Research is now actively underway to gain a consensus on appropriate and practical models of the dynamic response of soils. At present, one can often justify a post-liquefaction soil strength that can yield either success or failure, in accordance with the analyzer's prejudice. This paper is not the venue for detailing the various conservatism and the high degree of uncertainty associated with assessing seismic loads and the dynamic response of embankments. Suffice it to say that recent practice in the involved disciplines is placing the analyses on a more rigorous footing.

The Dam Safety Office is also upgrading its analysis techniques by moving from equivalent-linear finite elements models to a non-linear, effective stress, finite difference analysis. The goal is to better model site response and to predict embankment displacements. We wish to be in a position to take full advantage of better quality data as it is generated by the seismological and geotechnical communities. In a manner of speaking we are treading water awaiting the issuance of more realistic input and capacity models from the multiple disciplines necessary to assess the seismic stability of existing dams. As that data is generated we will revisit our past judgments of the adequacy or inadequacy of projects in the light of the public safety concern they may pose. Presumably, some projects will be found with unacceptably low levels of safety and this office will address that population with the priority placed on first fixing those dams posing the greatest public safety concern.

Other Critical Elements

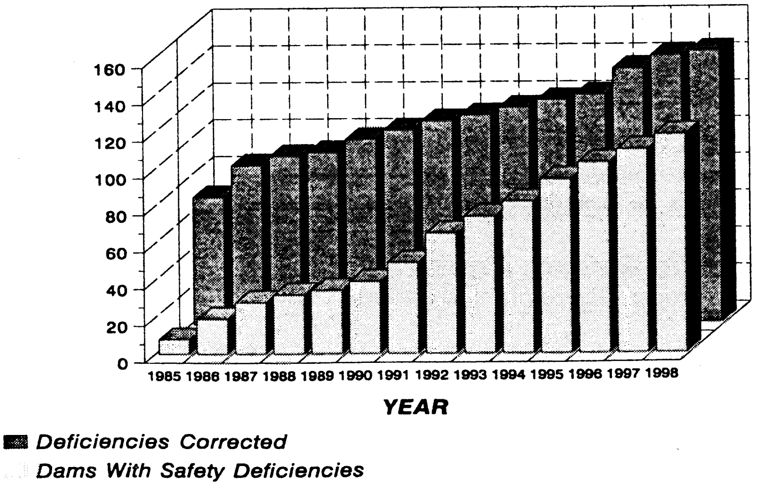
For critical elements at new dam projects where a design loading is not readily applicable (e.g. conduits, seepage), a qualitative approach is used, where redundancy and survivability concepts are employed to achieve adequate reliability against failure. For these critical elements on existing dams, a qualitative approach is used, rather than a quantitative assessment. However, the goal in making the qualitative assessment is the same as for floods and earthquakes: to achieve a probability of failure commensurate with the design step. This is achieved through review of the design and identification of deficiencies for the critical element, coupled with a qualitative assessment of the likelihood of failure based on past experience and engineering judgement. However, we are considering the utilization of some of the more formal risk assessment procedures for these elements currently employed by the Bureau of Reclamation.

CONCLUSIONS

Since its implementation in 1990, the use of the risk-based standards approach has been quite successful in Washington State. It has provided a consistent level of protection against failure between projects located across the state, despite significant differences in seismicity and rainfall. For new dams, we have been able to apply risk concepts in a standards-based approach that is fairly straightforward and easy to use.

For the evaluation of existing dams, we have been able to utilize a combination of probabilistic methods, risk concepts and risk-based standards to determine if the dam has an adequate level of protection against failure. If dams do not meet state standards, we are able to estimate the relative level of risk they currently pose, and prioritize our compliance efforts on those projects with the greatest risk. It has also allowed us to inform dam owners not only that their dams are "unsafe", but also educate them as to what level of risk their unsafe project poses to the downstream public. This approach has resulted in great progress in repairing the backlog of dams with identified safety deficiencies in the State of Washington. For example, of the 46 dams inspected under the National Dam Inspection Program still listed as unsafe in 1990, 40 had been repaired by 1999. In addition, 78 of the 101 additional dams identified by the state dam safety program since 1985 have been repaired. Figure 8 shows the cumulative summary of corrective action since 1981.

Figure 8 – Cumulative Number Of Dams Repaired in Washington Since 1981



Despite our success in using the risk-based approach, there remain several areas of difficulty. The most significant problem lies in the area of seismic risk assessment, which was discussed earlier. Other areas where the level of risk is difficult to assess include steady-state seepage, static stability, and conduits where probability of the design loading is 1.0. It is anticipated that advances in technology will continue to be made that will improve the ability to quantify the protection afforded by these critical project elements. At that time, our procedures will need to be modified to incorporate a more comprehensive approach. Until then, Washington Dam Safety will continue to use a combination of quantitative and qualitative approaches to make a reasonable assessment of the reliability of a dam project.

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ALAMO DAM DEMONSTRATION RISK ASSESSMENT

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Abstract

A demonstration risk assessment was conducted on the 283-foot high rolled-earthfill Alamo Dam as part of a U.S. Army Corps of Engineers (USACE) Research and Development program. The existing dam and 19 structural risk reduction alternatives were evaluated for flood, earthquake and normal operating conditions. The paper summarizes the risk assessment process, results, findings and recommendations. It also provides an evaluation of the risk assessment process and recommendations for better positioning the USACE to use risk assessment for dam safety evaluation and decision support.

Introduction

As part of a USACE initiative to explore the use of risk-based procedures to support dam safety decisions, a demonstration risk assessment (DRA) was conducted on Alamo Dam. The overall purpose was "To provide USACE staff with exposure to applying risk assessment (RA) techniques to dam safety decision making." In addition, experience gained from the project will provide a basis for formulating USACE policy on the use of RA in its Dam Safety Assurance Program (DSAP) and for identifying research and development needs.

Alamo Dam is a 283-foot high rolled-earthfill dam that was completed by the USACE in 1968 to provide flood control, water conservation and recreation. Although the dam is in good structural condition, recent estimates of the standard project flood (SPF) and the probable maximum flood (PMF) have increased above design values. As a result, overtopping of the dam would be expected to occur for events approaching the magnitude of these floods. The RA considered earthquake and static (normal operating conditions) loading cases in addition to flood loading.

The DRA involved an engineering team and a consequences assessment team from the USACE Los Angeles (LA) District. Facilitation and coordination was provided by RAC Engineers & Economists. Through their participation in the project, the LA District desired to strengthen their dam safety program and decision making in the public interest, to make progress in addressing Alamo Dam DSAP efforts, and to evaluate the risk-enhanced approach for addressing hydrologic deficiencies.

The remainder of this paper is divided in six sections, as follows: a brief description of the Alamo Dam; the general dam safety RA process; the Alamo Dam RA; a summary of results; a summary of overall findings and recommendations for the Alamo Dam; and an evaluation and recommendations relating to the RA process.

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Alamo Dam

Alamo Dam is located on the Bill Williams River, 39 miles upstream from its confluence with the Colorado River in Lake Havasu. The 4,770 square mile drainage area for Alamo Dam is in west central Arizona, and is generally mountainous. Discharges from the U.S. Bureau of Reclamation's (USBR) Parker Dam, which forms Lake Havasu, flow through the Parker Strip, Blythe, Yuma and Mexicali, Mexico.

The top of Alamo Dam is at elevation 1265 feet and the spillway crest is at elevation 1235 feet. Reservoir storage at the spillway crest is about one million acre-feet and at the top of the dam it is about 1.3 million acre-feet. Existing spillway capacity is 41,500 cfs. The USACE Threshold Flood is about 33% of the PMF. The PMF inflow event has a peak flow rate of 820,000 cfs and a volume of 1.39 million acre-feet. It is estimated that the existing dam will overtop by 20 feet during the PMF, with a peak outflow of 362,000 cfs, assuming that embankment failure did not occur. Dam breach floods are estimated to have a peak flow rate of about 3 million cfs.

Risk Assessment Process

Demonstration Risk Assessment

The concept of a demonstration risk assessment was developed by RAC for the state dam safety regulator in Victoria, Australia, as a key part of a statewide program for introducing RA into dam safety management (Watson 1998). A DRA can provide an effective way for a dam owner or regulator to gain practical experience with RA and to evaluate its benefits within the context of their organizational mission.

The Alamo Dam DRA began with a meeting of the RA Team to review available information, to make a site visit, and to identify potential failure modes, an event tree risk model, possible risk reduction measures and additional information and analyses needed to perform the RA. At the second team meeting the failure modes were reviewed and revised based on the additional information and analyses completed after first team meeting. In addition, system response probabilities for the existing dam and risk reduction measures were estimated and factors affecting warning times were assessed for use in the risk model.

After the second team meeting flood and earthquake loading relationships were developed, dam break inundation flood routings were performed, and cost estimates were made for risk reduction measures. Life loss, economic damages and environmental consequences were assessed for various breach-inundation cases. The risk analysis model was run for the existing dam, various sensitivity cases, and the risk reduction alternatives. Results were evaluated against various reference criteria and preliminary findings and recommendations were formulated. These were presented to the USACE RA Team and LA District and USACE Headquarters management and finalized in a project report. An evaluation of the DRA process was conducted and recommendations for strengthening it were developed. Throughout the DRA, observers from various USACE offices attended team meetings to become familiar with RA and to offer advice for strengthening the process.

Steps in Dam Safety Risk Assessment

The overall RA process comprises the following major steps: 1) risk identification, 2) risk estimation, 3) risk evaluation, and 4) risk reduction (Bowles et al. 1998a). The first two steps combine to form risk analysis. Risk identification is the process of recognizing the plausible failure modes for each type of initiating event. Typically, failure modes are represented using an event tree risk analysis model. Risk estimation consists of determining loading and system response probabilities, and the consequences of various failure and no-failure scenarios, so that incremental consequences can be estimated. Probability and consequence estimates are then input to the various branches of the event tree. Risk reduction alternatives are developed and analyzed by changing various model inputs to represent improved performance.

Estimated risks for an existing dam and for each risk reduction alternative, are evaluated against risk-based criteria and other considerations such as ALARP (as low as reasonably practicable) and de minimis risk (Bowles et al 1998b). It is emphasized that a RA process does prescribe dam safety decisions. For the Alamo Dam, these decisions should be made by the USACE. Through using the risk-enhanced approach, which supplements traditional engineering approaches with insights obtained from RA, the USACE should be in a better position to make informed decisions and to prioritize dam safety work.

RAs should be staged, with more detail being justified by the value expected to be added for decision making. The Alamo Dam DRA was conducted at a “moderate” level of detail. It was based both on existing information (e.g. engineering reports, analyses, and monitoring records) and additional supporting analyses conducted by the LA District.

Alamo Dam Risk Assessment Inputs

Failure Modes

Overtopping, toe erosion, and wave action were identified as the flood failure modes and foundation and embankment liquefaction as earthquake failure modes. Earthquake failure modes comprised a sequence of events beginning with liquefaction, followed stability failure, and leading to a breach. Embankment piping and slope stability were considered for internal (static or normal operating condition) failure modes. Foundation failure was not included because of the excellent foundation conditions. Piping along the outlet works, which is located in bedrock in the left abutment, was not considered to be a credible failure mode.

Loading Probabilities

Relationships were needed to define the likelihood of flood, earthquake and static loading conditions over a full range of these loads. Flood loading was characterized using a peak reservoir elevation annual exceedance probability (AEP) relationship for the existing dam (Figure 1) and each flood risk reduction alternative using the following procedure. A volume frequency analysis was performed for the 1929-1998 period of recorded inflows to establish 1- to 30-day volume-frequency curves out to an AEP of 1 in 100. These relationships were extrapolated to the PMF, SPF+PMF with 23 days spacing, and SPF+PMF with 5 days spacing, with assigned AEPs of 1 in 10^6, 1 in 10^7, 1 in 10^9, respectively. Balanced hydrographs of reservoir inflow were constructed for a range of events up to the PMF, based on the volume frequency relationships and using the HEC-1 model. These hydrographs and the SPF+PMF events were routed through the reservoir using the HEC-5 model with the Bill Williams River Corridor Technical Committee (BWRCTC) dam operation plan modified to reflect the Colorado River reservoir system operations for flood control. The appropriate spillway rating relationships for the no-failure dam and abutment overtopping. Upper and lower bounds were estimated based on typical uncertainty in key parameters in precipitation-runoff modeling and assigned notional uncertainties on the AEP of the PMF and SPF+PMF events.

Earthquake loading was characterized using a peak ground acceleration versus return period relationship (Figure 2) based on seismic risk studies reported by Bausch and Brumbaugh (1997) out to a best estimate of 0.12g, which has an AEP of about 1 in 2,200. This relationship was extended to smaller AEP events using regional information and upper and lower bound curves were estimated.

Static loading was represented using a reservoir stage duration relationship that was obtained from an HEC-5 simulation of 1929-1998 daily inflow record using the modified BWRCTC dam operation plan.

System Response Probabilities

System response probability relationships were estimated for each branch on the event tree model based on laboratory testing, engineering analysis, experimental evidence, engineering judgement and historical performance of comparable dams. In some cases these estimates were calculated directly, and for other cases they were estimated based on deterministic analysis and judgement. Depending on the purpose for which a RA is performed, different levels of effort are justified for system response probability estimation, with more detailed approaches aimed at narrowing the uncertainty and increasing the confidence in estimates. Figures 3 and 4 are examples of overtopping and foundation liquefaction system response probability relationships, respectively, for the existing dam.

The probability of failure for internal failure modes was based on the historical failure record for dams taken from McCann et al. (1985), Hatem (1985) and Foster et al. (1998). For piping and slope stability, these probabilities were estimated for different reservoir elevation intervals. The probability of failure by piping was estimated using Foster et al. (1998).

Breach-inundation Runs

Inundation areas and various flood routing characteristics, such as travel time, are needed to estimate life loss, economic and environmental consequences. A total of 13 breach-inundation runs were made covering flood no failure and flood and sunny day failures.

Dam breach analysis for RA requires realistic estimates of breach parameters. These parameters were estimated through a process that combined information from empirical relationships, historical experience, and professional judgement. All empirical methods predicted that the size of the breach would be larger than the size of Alamo Dam and this was used a basis for the breach-inundation runs.

Consequences

The Bill Williams and Colorado rivers from Alamo Dam into Mexico and back to the Salton Sea were divided into eight major consequence centers. Economic damages were assessed for the following cases based on information from the 13 breach-inundation runs:

- Flood no failure cases - as a function of peak (no failure) discharge rate.
- Flood failure cases – as a function of reservoir breach stage at the time of failure.
- Earthquake and static failures cases – as a function of reservoir stage at the time of failure.

Examples of these three relationships are shown in Figures 5, 6 and 7 for Center 4. For each loading condition economic damages were interpolated in the risk model.

An inventory of the number and square footage of single family residential, multi-family residential, mobile homes, commercial, industrial, and public structures was completed based

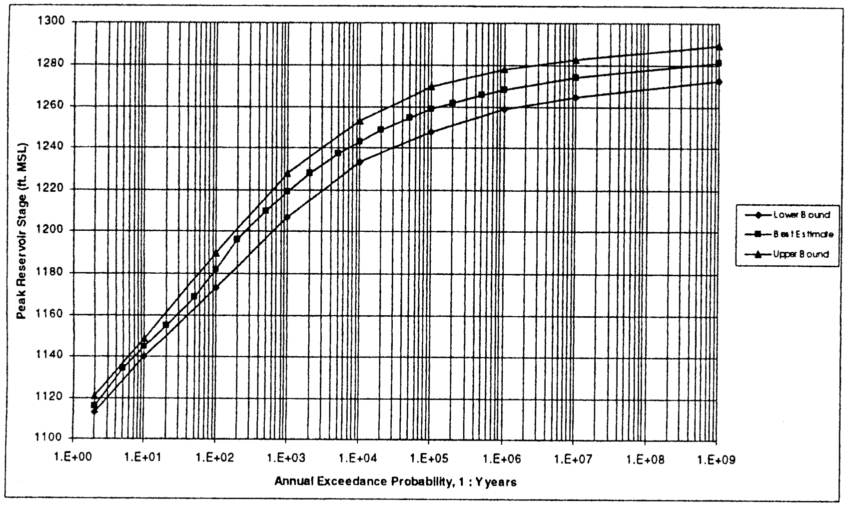

Figure 1. Existing dam flood loading – AEP relationship

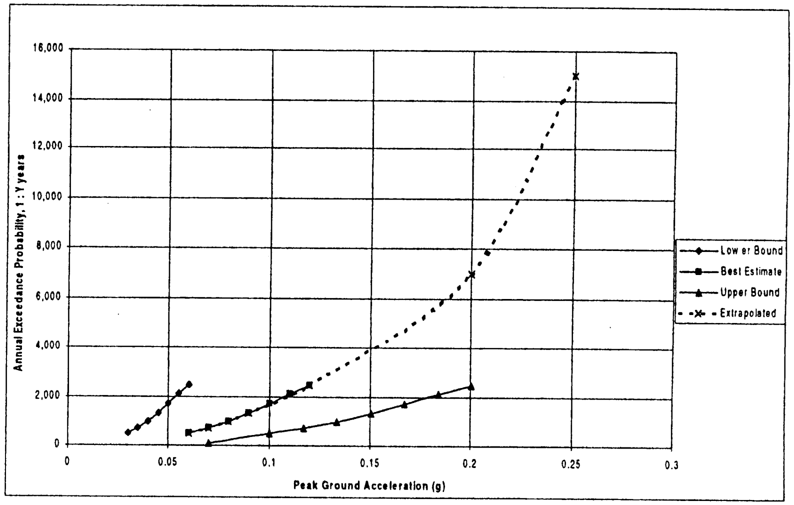

Figure 2. Earthquake loading –AEP relationship

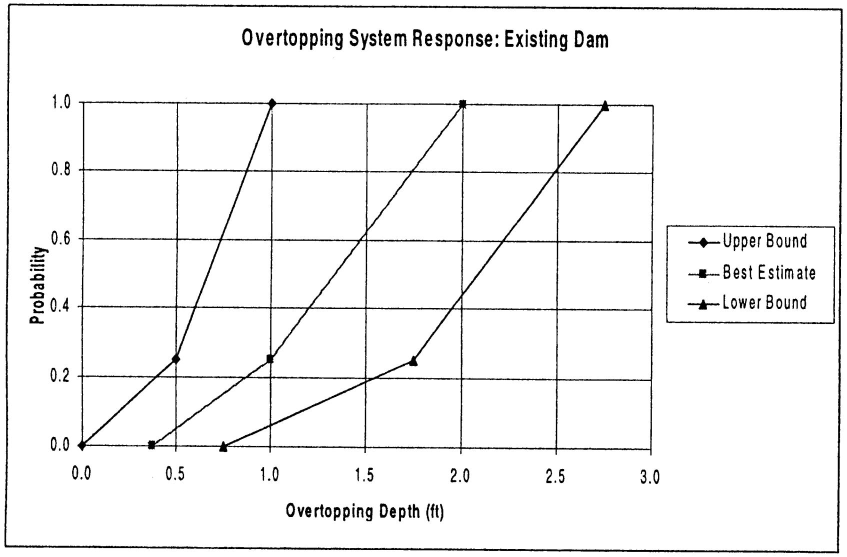

Figure 3. Existing dam overtopping system response

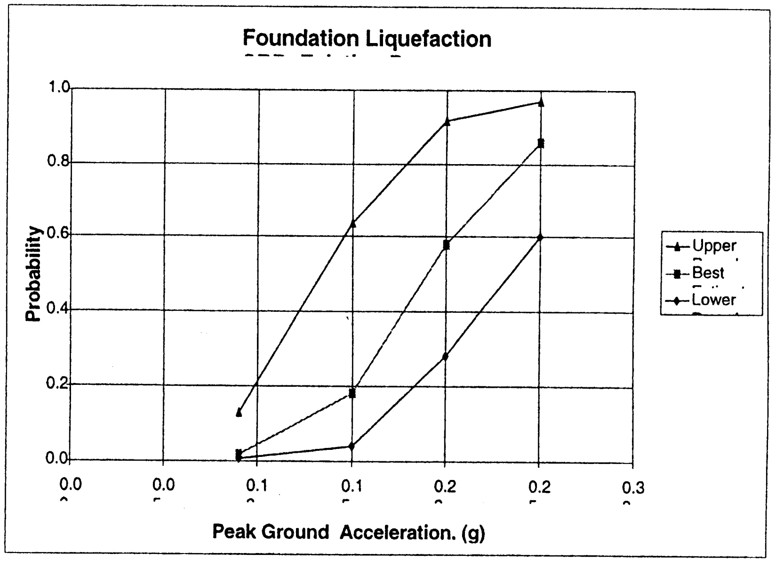

Figure 4. Existing dam foundation liquefaction system response

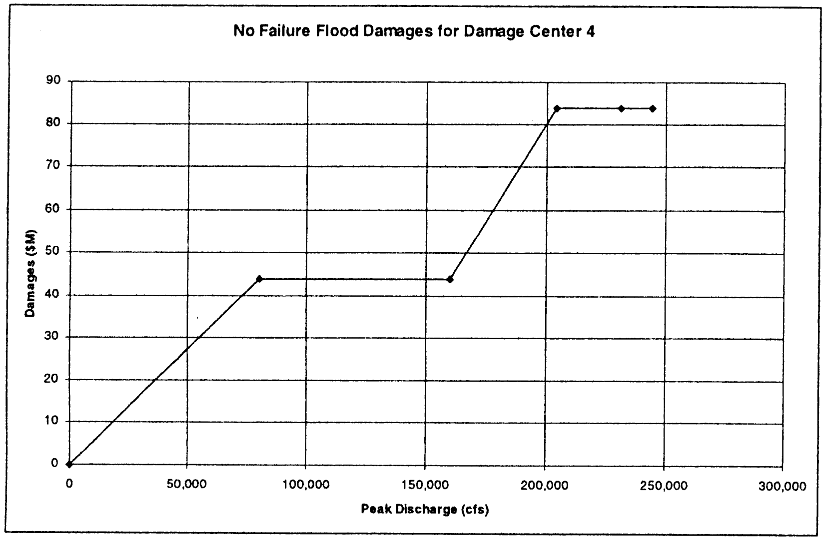

Figure 5. Example of no failure flood economic damages

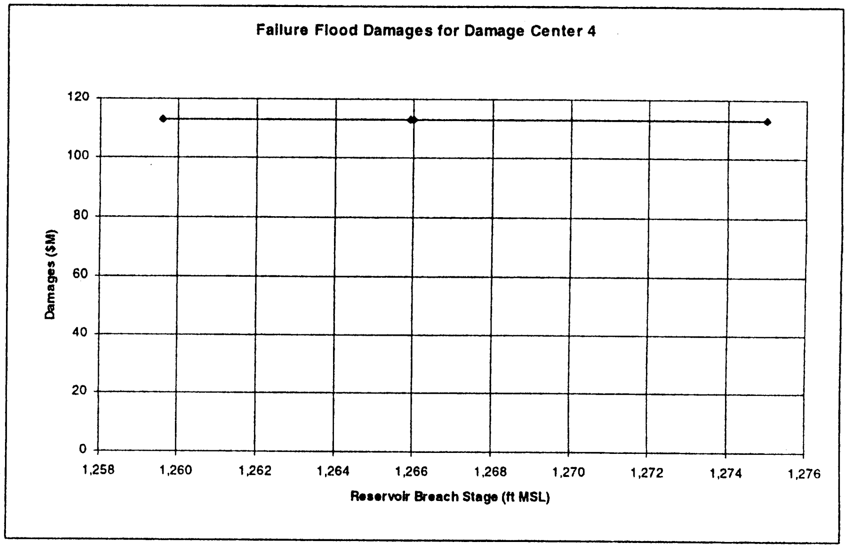

Figure 6. Example of flood failure economic damages

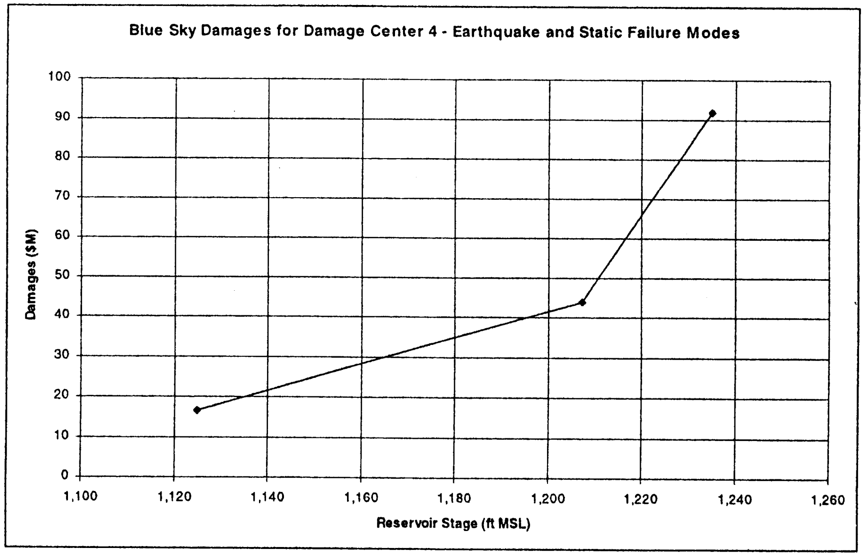

Figure 7. Example of earthquake and static failure economic damages

Table 1. Summary of risk evaluation criteria.

Risk Evaluation Type			Rating Code	Explanation
Life Safety-Societal Risk	ANCOLD (1998) Interim Amended Societal Risk Criteria *(for all failure modes combined)*	Limit	N	Does not meet limit criterion - F-N plots above limit criterion
			Y	Meets limit criterion - F-N plots below limit criterion
		Objective	N	Does not meet objective criterion - F-N plots above objective criterion
			Y-ALARP?	Meets objective criterion, but ALARP must be evaluated - F-N plots below objective criterion
	USBR (1997) Interim Tier 1 Public Protection Guidelines *(for flood, earthquake and static failure modes separately)*		N-StrongL&S	Strong justification for long- and short-term risk reduction measures - Expected incremental loss of life exceeds 0.01 lives/year
			N-StrongL	Strong justification for long-term risk reduction measures - Expected incremental loss of life between 0.01 and 0.001 lives/year
			Y-ALARP?	Diminished justification for long-term risk reduction measures (i.e. ALARP must be evaluated) – Expected incremental loss of life less than 0.001 lives/year
	USBR (1997) Interim Tier 2 Public Protection Guidelines *(for total of failure modes)*		N	Increasing justification to reduce probability of failure - Probability of failure exceeds 1 x 10^{-4} /year
			Y-ALARP?	Decreasing justification to reduce probability of failure (i.e. ALARP must be evaluated) - Probability of failure less than 1 x 10^{-4} /year
	BC Hydro (1993) Interim Societal Risk Criteria *(for total of failure modes)*		N	Does not meet criterion - Expected incremental loss of life exceeds 0.001 lives/year
			Y-ALARP?	Meets criterion, but ALARP must be evaluated - Expected incremental loss of life less than 0.001 lives/year
Life Safety–Individual Risk	ANCOLD (1994) Average over PAR *(for total of all failure modes)*	Limit	N	Does not meet limit criterion – Incremental probability exceeds 1 x 10^{-5}
			Y	Meets limit criterion - Incremental probability less than 1 x 10^{-5}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1 x 10^{-6}
			Y-ALARP?	Meets objective criterion - Incremental probability less than 1 x 10^{-6}, but ALARP must be evaluated
	ANCOLD (1994) Person at most risk *(for total of failure modes)*	Limit	N	Does not meet limit criterion - Incremental probability exceeds 1 x 10^{-4}
			Y	Meets limit criterion - Incremental probability less than 1 x 10^{-4}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1 x 10^{-5}
			Y-ALARP?	Meets objective criterion - Incremental probability less than 1 x 10^{-5}, but ALARP must be evaluated
	BC Hydro (1993) Interim Person at most risk *(for total of failure modes)*		N	Does not meet criterion - Incremental probability exceeds 1 x 10^{-4}
			Y-ALARP?	Meets criterion - Incremental probability less than 1 x 10^{-4}, but ALARP must be evaluated
Economic/ Financial	NSW Total Asset Management Risk Example Guidelines *(for flood, earthquake and static failure modes separately)*		N-Major	Major risk - Imperative that risk reduction be implemented
			N-Medium	Medium risk - Risk reduction required in a reasonable time
			Y-ALARP?	Low risk - Risk reduction to be ALARP

on previous reports, telephone conversations with city officials, and assessor's data retrieved through TRW. These structures were valued in 1998 dollars by the depreciated replacement value method using the Marshall and Swift Real Estate Valuation Service. Structure and content values were then applied to the national FEMA depth-damage relationship to obtain estimates of the damages for each breach-inundation case.

The population at risk (PAR) was estimated for each consequence center using the number of structures (adjusted for unoccupied structures) within flood boundaries and multiplying by the household densities for the major communities using Census data. These estimates were then adjusted for employment patterns, weekend activities, and school children allocations to arrive at PAR projections for two seasons (floods - November to March and non-flood - April to October) and four daily exposures (week day, week night, weekend day, and weekend night).

Life loss was estimated using the DeKay and McClelland (1993) method, which relates life loss to PAR, warning time and the intensity of flooding. Warning time was estimated as travel time plus an adjustment, which was provided by the engineering team. The adjustment accounted for the estimated time needed for detection, decision to notify, and notification for each failure mode (breach) type. As with all approaches to estimating life loss, there are significant limitations to the DeKay and McClelland approach. However, based on a consideration of these limitations in the context of the Alamo DRA and an evaluation based on case histories, it was concluded that it is very unlikely that any incremental life loss would result for the flood failures. The nearest population is located almost 40 miles away around Lake Havasu with best estimate warning times ranging from 12 to 21 hours (travel time + 6 hours). Warning times are much greater below Parker Dam on the Colorado River and are several days near the Mexican border. During the flood season, the most exposed individual is located near Lake Havasu with best estimate warning time ranging from 12 to 19.7 hours.

For earthquake and internal failure cases the most exposed individuals are a work crew that is located near Lincoln Ranch for a period during the non-flood season. There is no known mechanism for warning this crew and travel time is close to an hour.

A qualitative inventory of existing environmental conditions and resources was developed to provide an initial assessment of the environmental impacts of projected flooding due to dam failure. Ideally, an analysis of the incremental impacts of dam failure flooding relative to no-failure conditions should be made. The assessment was made with incomplete data since the Bill Williams River corridor has not been systematically surveyed for cultural and environmental resources. There are 13 different species that would be adversely affected by flooding projected at the blue sky failure conditions, with 7 of these species being significantly affected. Cottonwood, Goodding willow and salt cedar are the common flora within the Bill Williams corridor. High mortality of seedlings of cottonwood and willow is likely to result at the projected depths and velocities of flooding, but seed dispersal would be enhanced by high water flows in the area. The cottonwoods are the least tolerant of inundation.

There are considerable cultural resource sites in the Bill Williams and Colorado River corridors. These are mainly associated with the three native American populations that abut the rivers. Many of these sites are already inundated by existing reservoirs.

Risk Criteria

Quantitative criteria can serve a useful role in the risk evaluation process. When they are used, the effects of uncertainties in the risk analysis process should be considered. However, dam safety decisions should be made by those responsible for ensuring dam safety after all the relevant factors have been assessed and weighed; they should not be the automatic result of applying a criterion to the outcomes of a risk analysis. Thus, the use of RA enhances the decision-making process, but does not replace reference to traditional engineering criteria and other relevant factors.

Table 1 is a summary of life safety (societal and individual) and economic/financial risk criteria (or guidelines) from the USBR, BC Hydro and the Australian Committee on Large Dams (ANCOLD). These criteria were used on a reference or benchmarking basis in the DRA since the USACE does not have risk criteria for dam safety. However, it is important to remember that the degree of risk accepted, and the risk criteria established, by one organization may not be appropriate for adoption by another organization.

All criteria listed in Table 1, except the ANCOLD individual criteria, are interim. The ANCOLD criteria are being widely used on a reference basis in Australia with limited examples of dam safety decisions being made that incorporate these criteria as at least a part of their justification. The USBR guidelines are being routinely used as a significant consideration in decision making on both the priority and level of risk reduction. BC Hydro's criteria were not formally adopted by management, or approved by their regulator, although it is understood that they were used to support several significant dam safety decisions (Salmon 1999).

Risk Model Runs

Risk model runs were made for the existing Alamo Dam and various risk reduction alternatives. Sensitivity runs were made for the following: flood loading, flood system response probabilities (SRPs), earthquake loading, earthquake SRP's, and static failure mode probabilities. No sensitivity runs were made for warning times since life loss was estimated to be extremely unlikely for all reasonable warning times using the Dekay-McClelland method.

Risk model runs were made for 19 combinations of risk reduction measures listed in Table 2 with their estimated costs and codes that are used to refer to them in this paper.

Summary of Results

Existing Dam

1) Life loss is extremely unlikely based on the long warning times that are expected.
2) The existing dam appears to meet all life safety risk criteria based on best estimates and all sensitivity cases.
3) The best estimate of total probability of failure for the existing dam is about 5×10^{-6} (1 in 500,000) per year, which is a low probability of failure. Earthquake failure modes are estimated to comprise approximately a third of the best estimates for flood and static failure modes (Figure 8). The upper bound sensitivity estimate for flood loading is about 2×10^{-5} (1 in 50,000) per year, for earthquake loading is about 1.1×10^{-5} (1 in 90,000) per year, for earthquake system response is about 3×10^{-5} (1 in 30,000) per year, and for static failure probabilities is about 1.5×10^{-5} (1 in 70,000) per year.
4) Incremental (dam failure) damages are estimated to range between about $350M and $1B for the failure modes considered for the existing dam. They are of a similar order of magnitude for all loading types. Considering their associated probabilities, they would be categorized as "low risk" using the NSW TAM economic consequence example criteria, with risk reduction recommended according to the ALARP principle.

5) "Without project" flood damages are estimated at about $200,000/year for the existing dam and to vary from about $80,000/year to almost $320,000/year for lower and upper bound flood loading cases.

Table 2. Risk Reduction Alternatives

Group	Code	Description	Cost ($M)
Existing Dam	E	Do Nothing	-
Partial Flood Fixes	FR10	Downstream toe protection	1.59
	FR15	Wave protection at crest	1.47
	FR14	Raise embankment 5 ft., includes FR15	2.61
	FR16	Combine FR10 and 14	3.80
	FR12	Raise embankment 9 ft., includes FR10 & FR15	9.03
Complete Flood Fixes (Each includes FR10 and FR15)	FR1	Raise embankment 17.3 ft	13.92
	FR8a	Hardening downstream embankment face (concrete)	31.22
	FR8b	Hardening downstream embankment face (RCC)	18.64
	FR2a	Widen spillway to 220 ft, raise embankment 13.5 ft	21.35
	FR3a	Lower spillway 10 ft, raise embankment 15.4 ft	14.07
	FR3b	Lower spillway 20 ft, raise embankment 13.6 ft	13.88
	FR3c	Lower spillway 30 ft, raise embankment 11.9 ft	13.96
	FR6	Fuse gates, raise embankment 15.5 ft, lower spillway 10 ft	18.32
	FR9	Widen spillway to 220 ft, lower 10 ft, raise embankment 10.5 ft	21.38
Earthquake and Internal Fixes	ER1	Upstream & downstream berm	47.86
	ER2	Downstream berm	14.81
	ER3	Soil mixing of foundation material/chemical grouting	40.09
Combined Flood, Earthquake and Internal	FER1	ER1 and FR9	48.52
	FER2	ER2 and FR3c	25.12

Risk Reduction Alternatives

1) The largest benefit:cost ratio (B:C) is estimated to be 0.004 for FR14 (raise embankment 5 ft. and wave protection). Therefore no fixes have a B:C justification (Figure 9).
2) The least total economic cost complete flood alternative is the existing dam (Figure 10).
3) The existing dam appears to meet all life safety risk and economic/financial criteria, and thus there is no justification for fixes based on changes in these criteria.
4) The ALARP condition for life loss appears to be met by the existing dam since life loss was estimated to be extremely unlikely.
5) Smaller cost fixes may have a possible de minimis risk justification for implementation, even though they are not cost effective based on ALARP considerations.
6) Toe protection (FR10) and wave protection (FR15) are estimated to have an imperceptible effect on probability of failure (Figure 11), incremental risk costs (or rehabilitation benefit), and incremental probability of individual life loss for the person at greatest risk (Figure 12). There is no justification for these fixes based on B:C or CPLS. However, since the costs for each of these fixes are estimated to be about $1.5M, there may well be a de minimis risk justification for them. This justification is further strengthened because both measures are considered normal dam engineering practice.

7) Similar to FR10 and FR15, FR14 (raise embankment 5 ft. and wave protection) and possibly FR16 (same as FR14 plus toe protection) may have a de minimis risk justification, since their estimated costs are \$2.6M and \$3.8M, respectively.
8) Reductions in annualized flood control benefits are largest (approximately \$250,000/year) for the 30 ft. spillway lowering, representing roughly a doubling of the no failure flood control damages for the existing dam from about \$200,000/year to \$450,000/year (Figure 13). Spillway widening also reduces flood control benefits, but not as significantly as lowering. All other fixes (i.e. raising, hardening downstream embankment face, toe protection and wave action protection) reduce flood control benefits to a lesser degree than changes in spillway geometry. These other fixes affect flood control benefits because they extend the range of AEPs over which no failure damages exist for the fix – this actually represents a shift in probability from dam failure to no failure. However, the relative magnitude of incremental (failure minus no failure) damages and no failure damages determines whether rehabilitation benefits are more or less than the reduction in flood control benefits, and hence, whether net benefits are positive or negative, respectively.
9) Combining the FR9 flood fix and the ER1 earthquake and internal fix into FER1, the total probability of failure is estimated to be reduced by two orders of magnitude from 5×10^{-6} (1 in 500,000) per year to 5×10^{-8} (1 in 50,000,000) per year. Similarly, total incremental probability of individual life loss for the person at greatest risk is estimated to be reduced by two orders of magnitude from 2.1×10^{-9} (1 in 500,000,000) per year to 2.4×10^{-11} (1 in 40,000,000,000) per year.

Overall Findings and Recommendations for Alamo Dam

Overall findings

An evaluation of the risk analysis results against various risk-based criteria, indicates that a basis does not appear to exist for proceeding with any but the lower cost fixes. These fixes are toe protection, wave protection, and raising the embankment 5 ft. (i.e. FR 10, FR 14, FR 15 and FR 16). However, even though RA does not appear to provide an economic or life safety justification for proceeding with the more costly fixes, the USACE may choose to do so for other reasons, such as environmental protection or policy requirements to pass the SPF + PMF. It is likely that there are many other USACE projects that would return a much greater risk reduction than investing in these measures at the Alamo Dam. Such projects could be identified through a portfolio risk assessment (Bowles et al 1998b).

Since Alamo Dam is a well-engineered modern dam, which is located away from any significant populations, it does not appear to pose any significant risk of loss of life. Hence, the Alamo Dam DRA does not provide a typical example of the how risk based life safety criteria can be used to evaluate and justify risk reduction measures.

Recommendations

1) Before any long term risk-decisions are made on fixes for the Alamo dam, other than perhaps the less costly toe erosion and wave protection measures, various inputs to this DRA should be reviewed and strengthened to the extent that they will affect RA results. The RA should be rerun with the improved inputs. The following inputs are listed in order of their expected cost effectiveness, that is, the expected improvements in the quality,

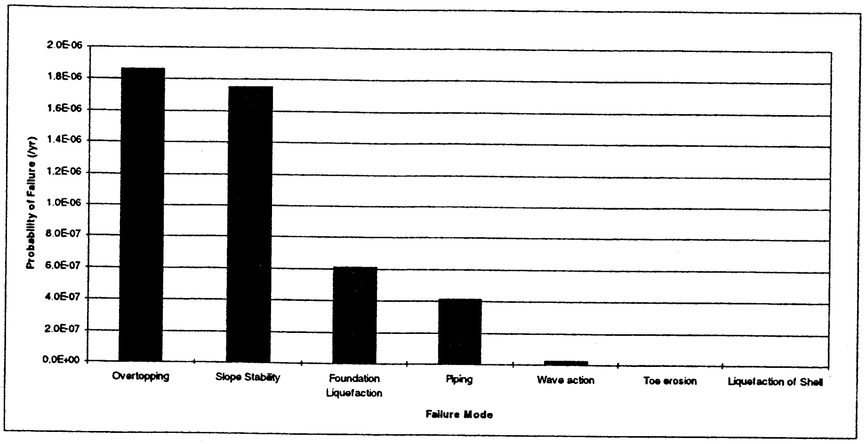

Figure 8. Contributions to total probability of failure

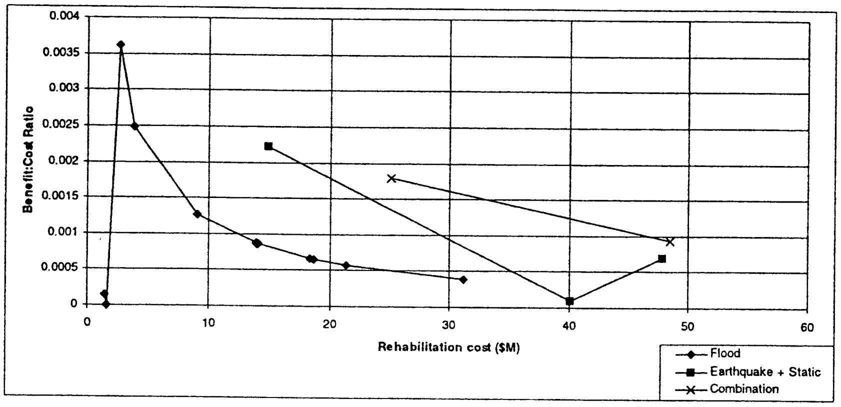

Figure 9. Benefit:cost ratio vs. rehabilitation cost

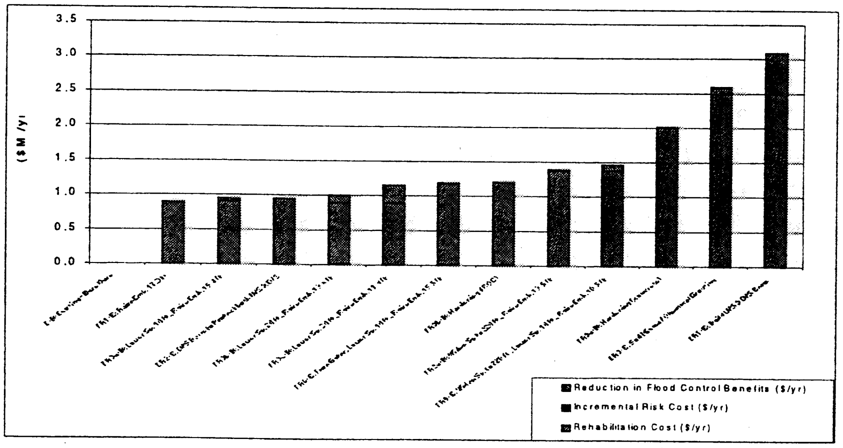

Figure 10. Total economic costs including reduction in flood control benefits

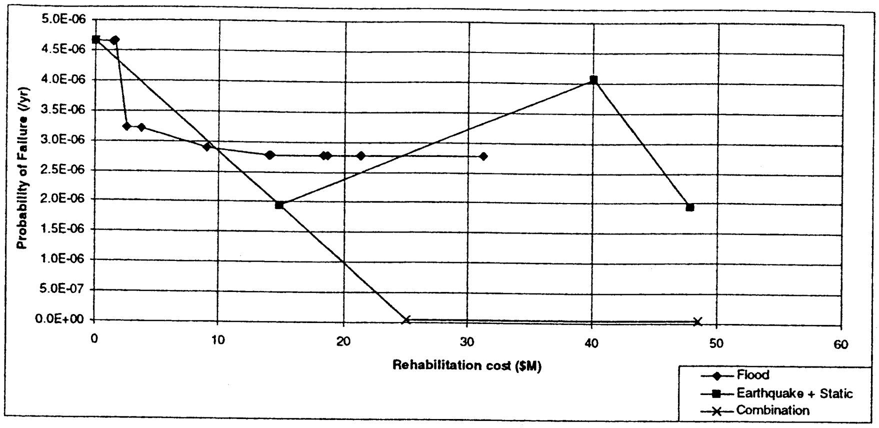

Figure 11. Probability of failure vs. rehabilitation cost

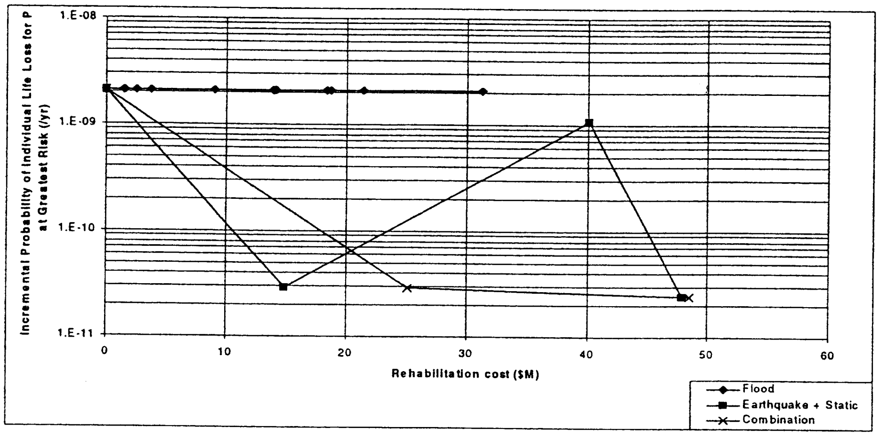

Figure 12. Incremental probability of individual life loss for person at greatest risk vs. rehabilitation cost

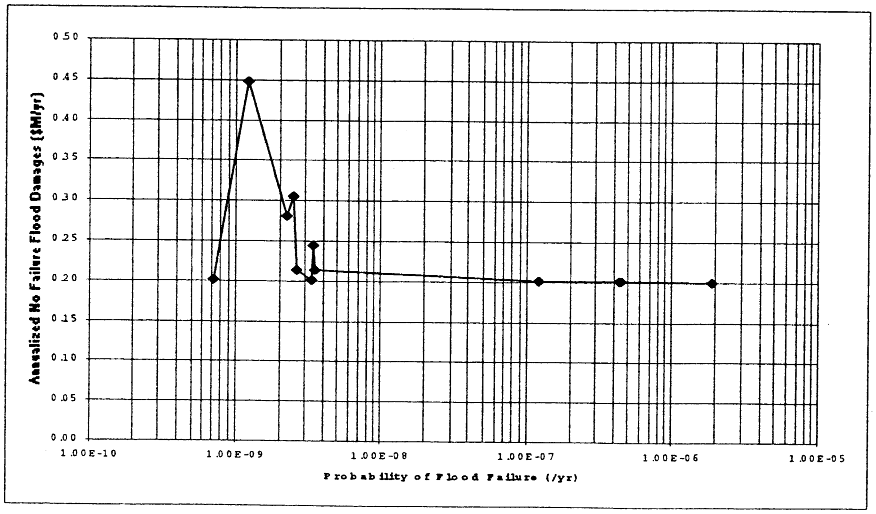

Figure 13. Annualized no failure flood damages vs. probability of flood failure

defensibility and confidence in the RA outcomes relative to the expected costs of obtaining them:

1) Static slope stability failure probabilities.
2) Potential for failure of Parker Dam.
3) Life loss estimates.
4) Potential for liquefaction through a better definition of foundation conditions.
5) Flood SRPs.
6) A site-specific earthquake loading relationship.
7) Flood loading relationship.

Risk Assessment Process: Evaluation and Recommendations

Evaluation

The DRA showed that with experienced facilitation USACE District technical staff can conduct a dam safety RA and that a reasonably detailed RA can be accomplished for about the same budget as most USACE major rehabilitation studies. Some savings in effort could have been achieved if it were not for the demonstration nature of this project. Through portfolio risk assessment, resources available to perform RAs can be allocated to those dams which are most likely to yield returns. Some supporting analyses could have been improved with additional time and funding, but in the spirit of a staged approach to RA, these are addressed in recommendations for a more detailed update to the DRA.

. LA District team members stated that the RA approach appeared to be a natural and holistic approach that should lead to better dam safety evaluation and design. They also stated that the RA results from the RA seemed to make sense. Improved insights into the dam safety issues of Alamo Dam were obtained through the RA process and it is unlikely that these insights would have been developed through the traditional approach.

Recommendations

Procedures should be developed so that the USACE can carry out RAs with achieve quality and consistency across the agency. Some requirements of the USACE DSAP and the Major Rehabilitation Program will need to be revised so that the results of RA can be incorporated into them. Other USACE R&D needs that were identified included the following:

- Characterization of the AEPs for a wide range of floods and earthquakes.
- Procedures for estimation of SRPs, including analytical approaches, subjective estimation protocols, and case histories.
- Procedure for characterizing flood travel times for failure and no failure flood waves.
- Improved procedures for obtaining life loss estimates.
- A practical uncertainty analysis approach.
- Development of guidance for risk-enhanced evaluation of dams.

Acknowledgements

The authors would like to thank the USACE for permission to publish this paper. They also acknowledge the valuable contributions made to the Alamo Dam DRA by staff of the USACE's LA District and the Hydrologic Engineering Center, and by Dr. Sanjay S. Chauhan, Utah State University.

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A·S·D·S·O

Proceedings from the 6th ASDSO Annual Conference

October 1-5, 1989
Albuquerque Marriott
Albuquerque, New Mexico

Published by the
Association of State Dam Safety Officials

Introduction

> *The body of knowledge that emerges from the collective experience of a specialized group of individuals forms the structure of a profession...*
>
> E.M. Myers
>
> American Society of Association Executives

Information exchange is one of the primary purposes for ASDSO's existance. Our national annual conference has been highly successful in helping to accomplish this goal by bringing dam safety experts together on a formal and informal basis to discuss innovations, federal and state policy, and experiences in dam safety.

This publication compiles the formal presentations made at the ASDSO 6th Annual Conference held on October 1-5, 1989 in Albuquerque, New Mexico. These speakers were chosen by the ASDSO Board of Directors from approximately 150 that submitted proposals for presentation.; the decision regarding which to cut was a diffuclt one, in most cases, but a very positive sign for the direction and caliber of this conference.

The majority of chosen speakers have submitted full papers for this publication – for those who were unable to do so, an abstract has been included. Biographies for each presenter are listed at the end of the Proceedings – addresses and phone numbers are listed where possible.

ASDSO thanks the New Mexico State Engineer's Office for hosting this event and for the assistance of Don Lopez, Chief of the New Mexico Design and Construction Section and his staff before and during the conference.

DAM SAFETY EVALUATION FOR A SERIES OF UTAH POWER AND LIGHT HYDROPOWER DAMS, INCLUDING RISK ASSESSMENT: The Owner Perspective

Richard B. Waite, P.E.
Utah Power & Light/PacifiCorp

ABSTRACT

Utah Power and Light Company (UP&L) owns a series of six dams on the Bear River in Utah and Idaho. These dams are regulated by the Federal Energy Regulatory Commission (FERC). Not all the dams currently meet the FERC's standards for flood and earthquake loading. Their internal conditions, however, have been found to meet all important FERC criteria. A dam safety evaluation study was performed to explore the suitability of site specific standards for the UP&L dams and to propose and evaluate alternative remedial actions. The investigation was performed to provide UP&L management with information for use as a basis for their proposals to the FERC for remedial actions at their Bear River dams.

Why We Decided on a Risk Assessment

Of our fifteen licensed or exempted dams, we had, in early 1987, four older dams located on one river and three others on separate rivers were questioned for safety reasons by the Federal Energy Regulatory Commission (FERC). All seven had been evaluated under the National Dam Safety Inspection Program as possible sources of significant downstream impact. These dams had also been reviewed by independent consultants, as required periodically by FERC regulations, and found to be deficient under present probable maximum flood (PMF) standards or recently revised maximum credible earthquake stability conditions. These dams had all been considered safe and sound and without significant problems in the past, and our company has always had an active policy of giving very high priority to safety problems of any kind.

We found the problem hard to comprehend or believe. We estimated that all the remedial upgrades involved would cost at least $20 million and possibly as much as $25 million for dams having a total generating capacity of about 128 megawatts. Thus we projected a remedial cost in the range of $155 to $195 per installed kilowatt, a shocking financial impact. This would increase our average cost of generation for these units by three to four mills per kilowatt-hour, no joke in our competitive, over-abundant market. One of the dams, for instance, completed in 1927, had passed a 12,700 cfs flood of record in 1986 without difficulty; yet the projected probable maximum flood for the dam was 195,000 cfs. In another case, a 1910 dam was in the high hazard classification because of two potentially impacted homes and our inability to obtain PMF flood plain zoning development relief from the local county. In every case the PMF values seemed inordinately excessive, and at the time, FERC did not offer any encouragement when we considered challenging the National Weather Service precipitation model used as a basis for deriving the PMF. Was this safety problem real, or was it of bureaucratic manufacture?

What should we do? We were ready to fight! After we calmed down a bit we took a closer look at our options at each site. At the site with the two houses we noted some other potential problems that had yet to become FERC issues, and we decided that prudent management required us to solve these problems before they became serious. We could combine the corrective work with a planned unit upgrade at the site and keep costs under reasonable control. Another case involved a FERC Exemption for an electrically isolated generating unit installed in a thermal generating station's cooling water storage reservoir. Again the PMF value was extreme, but the dam could marginally contain the flood without overtopping. We decided to vacate the FERC Exemption and perform the minor modifications needed when required by the state involved. In this latter activity FERC was very encouraging and helpful. These decisions still left us with five problems, one involving four facilities on the Bear River in Idaho and Utah and the other involving our Viva Naughton Dam on the Hams Fork River in Wyoming.

After our initial review, we still did not know the extent of the real problems at the these five dams. What was the actual possibility of instability and flood-caused failures at each site? Given the possibility of such failures, what was their probable hazard to the public, their property and to our employees and property? These questions involved issues of existing dam conditions, probability of various failure inducing forces occurring and at what intensities, the risks of failure associated with various levels of the forces, the exposure of people and property should failure occur, and the probable level of damage associated with the exposure. We also thought it only fair that credit be given in our evaluation to the flood control and economic benefits resulting from the existence of these dams. In every case, the dams provided river regulation that had not existed in prior times, and this provided very significant irrigation and flood damage benefits to local communities as well as giving us a saleable product.

Considering the range of questions involved, we believed that only a wide ranging technical review and risk assessment could effectively and fairly provide the safety exposure, economic impact, and benefit assessment required to responsibly select a remedial program. The alternative seemed to be to accept the extreme FERC safety criteria without consideration of the level of benefit and the incremental cost impact that would result. This latter "deterministic" approach, called for in FERC's regulations at the time, seemed neither beneficial to the public nor ourselves. We elected the expensive, wide-ranging evaluation program, and its resulting remedial program, in preference to the apparently very expensive, arbitrary, but less controversial deterministic solution.

FERC staff was very uncomfortable with our decision, and they have our sympathy in this regard. We think they visualized the result could be a whitewash of genuine safety problems, inadvertently or intentionally superficial, politically controversial, and not result in a truly balanced evaluation or solution. They seemed particularly concerned that the technical and economic review would have insufficient depth to provide an effective information base and that insufficient information was generally available to make reliable risk judgments. They said such a "risk assessment" would miss too many factors and details, currently handled as intangible factor-of-safety components, and result in a risky model. Even if we did a proper job on the evaluation, we think that FERC was concerned about a possible precedent that would allow later, less well founded work by others to jeopardize industry safety standards. The decision to go ahead with the risk assessment was executed with mixed feelings within our own organization, too.

How We Decided to Carry Out the Risk Assessment

Given the concerns, we had no choice; the assessment had to be as thorough and complete as we could reasonably make it. We did not have the in-house resources or competence to get the job done; we needed outside professional help from individuals with a proven track record with this activity, and we needed high caliber engineering, economics, and risk evaluation professionals on the job. Since very little in-depth risk evaluation work had been done with specific dams in the past, we also needed an effective model for the study. These needs were complicated by the limited time we had to complete such an extensive study, further emphasizing the need for a highly effective, well coordinated, professional job. It was now early 1988, and FERC wanted see the results that fall.

Picking a model for the study was easy; the only complete, tried, practical model (USBR ACER Technical Memorandum No. 7) we could find had been developed by Larry Van Thun and his staff at the US Bureau of Reclamation. Near clones have been developed by the US Corps of Engineers and by the Federal Emergency Management Agency for the same purpose but were unavailable to us. The US Bureau of Reclamation approach was well thought out and organized, seemed complete, had been put together by people with practical experience in answer to needs very similar to ours. Also, its procedures had been used for several dam safety evaluations by them and in at least two other cases that we were aware of by consulting engineers. Its methodology was recommended for existing dams by the American Society of Civil Engineers. ACER-TM-7 didn't answer all our needs or questions, but it provided a sound methodology and organization for our risk assessment.

Picking a study team was more difficult. The law required us to competitively bid the work if possible, and very limited sources existed with the combination of skills and direct dam application experience needed. We also need a team having local professional background, if possible. There was no avoiding the site specific nature of dam risk assessments, and we did not have the time for a team to get thoroughly acquainted with five dams' local settings as well as their individual designs and construction. We needed a cross-disciplinary team capable of effectively performing incremental flood routing studies, precipitation probability evaluations, seismic evaluations, local economic and property appraisals, dam design and construction stability estimates, risk exposure and impact probability analyses, population and crop surveys, public infrastructure reviews, and so on. We also needed a team that had an existing, thorough database of dam failure information that could be correlated with the specifics of each of our dams and their settings. The team participating in this panel's presentation, along with a consulting economist, UP&L and outside hydrologists, several of our operating people, and both company and consultant property managers constituted the core of our study team.

A Brief Description of the Dams Involved

The dams in the study consist of the Viva Naughton Dam in southwestern Wyoming; the Soda, Grace, and Oneida Dams in Southeastern Idaho, and the Cutler Dam in North Central Utah. The Viva Naughton dam is located on the upper reaches of a Green River tributary (Colorado River drainage), the Hams Fork River. It is about 15 miles northwest of Kemmerer in a gentle, sparsely populated rangeland valley. The Soda, Grace, Oneida, and Cutler Dams are located (in the order given) on the Bear River between Bear Lake and the Great Salt Lake. Bear River is one of the first controlled rivers in the United States. UP&L regulates its flow by diverting water to and from Bear Lake which is located between Idaho and Utah and very near Wyoming.

Viva Naughton is a 90 foot high embankment dam with a 3,500 foot long crest. It was constructed in the early 1960's and raised in 1967. The elevation of the reservoir's normal high water level is 7,240 feet msl; the top of its core is at elevation 7,245 feet, and its crest is 3 feet above the top of the core. At normal high water, the reservoir stores 42,400 acre feet of water, which is largely dedicated to UP&L's Naughton power plant cooling tower consumption. In practice and on an informal basis, a major portion of the stored water is used for local municipal consumption and irrigation. The dam has a draw gated spillway capable of releasing 7,860 cfs at normal pool level and an emergency spillway blocked with a rip-rapped plug. The maximum runoff release on record is 2,500 cfs (1984), and the National Weather Service model PMF peak inflow is predicted to be 45,850 cfs. The local municipal water system has a small condemned dam and reservoir immediately downstream of Viva Naughton; this year, the dam is being repaired after years of disuse. Downstream, the river passes through the small adjacent communities of Frontier, Kemmerer, and Diamondville; otherwise, the river passes through open country. A PMF event would overtop and presumably fail this downstream dam.

Soda Dam, also known as Soda Point Dam, was built in 1924, is 488 feet wide, raises 103 feet above the stream bed, and consists of a 210 feet wide gravity section with a 5,725 foot crest elevation on the right end, a 109 foot wide center powerhouse section, a three-bay 114 foot wide concrete spillway section with a crest elevation of 5,707.5 feet, and a 55 foot wide earth embankment "plug' on the left end which has a crest at elevation 5,730 feet. Galleries exist in each of the concrete sections and extend into the embankment portion. The reservoir, with a 5,720 foot maximum normal pool elevation, can store 14,875 acre-feet of water of which 11,800 is usable by the power plant. In 1911, the dam location's record of 4,740 cfs occurred, and the dam's National Weather Service model projected that the PMF inflow is 74,600 cfs. The spillway consists of three 30 foot wide by 12.5 foot tainter gate sections capable of passing a projected total of 63,000 cfs. The top of the embankment is essentially the same elevation as its rock abutment; a similar situation exists between the gravity section and its right abutment. The dam is located on the left side of a wide agricultural valley at a point where the river makes a left turn from west to south at the western end of a high, steep rock hill. It is located approximately 5 miles downstream and west of Soda Springs and about 6 miles upstream and north of Grace Dam and the town of Grace. A PMF event would overtop this dam and breach the embankment plug. The gravity sections fail to meet present FERC earthquake stability criteria.

Grace Dam, located on the northern outskirts of Grace, Idaho, was built in 1951 to replace a 1910 structure. It is a rock filled, timber crib structure and is 180 feet wide by 52 feet high with a crest elevation of 5,556.4 feet. It is an integral part of a new 250 foot extension of the old dam's 127 feet wide embankment, located on the crib section's right, which has a crest elevation of 5,559.0 feet. The dam serves as a diversion structure to supply water to the Grace and Cove hydroelectric plants, located several miles to the southwest. The associated flowline intakes are located in the old embankment section. The dam has a discharge capacity of 14,315 cfs and a projected PMF inflow similar to that of Soda. The spillway is a three bay flashboard scheme, sectionalized by 6 foot thick timber crib piers; it has a crest elevation of 5,547.3 feet. Both the dam and the town are located in a very wide, flat valley. A PMF event would overtop and fail this dam.

Oneida Dam, built in 1915, is located in a deep, narrow valley 13.5 miles northeast of Preston, Idaho and roughly 30 miles south of Soda Point. Except for the dam and power plant, the valley is undeveloped grazing and forest land. The dam consists of two portions which are separated by a knoll. The concrete gravity section, the right end of the multi-structure, is 110 feet high, 455 feet wide, and contains a 5-section tainter gated, controlled spillway which is 79 feet wide (crest, 4,870.65 feet) on its left end and an uncontrolled 176 foot wide spillway (crest, 4,880.9 feet) on its right end. Its center, non-overflow portion (crest elevation, 4,884.9 feet) contains two low level outlets, the inlets of which are blocked by reservoir sediment (sediment has reached elevation 4,823 feet). The spillways have a combined capacity of 16,000 cfs with the pool level at the gravity section crest and 40,800 cfs at the embankment section crest. The projected PMF inflow is 74,700 cfs; the outflow record of 5,480 cfs occurred in 1922. The concrete dam does not satisfy present FERC stability criteria and was post tension anchored in the past to satisfy prior stability criteria.

Oneida's embankment section is about 1,100 feet wide and has a maximum height of 40 feet. The freeboard at a normal high water elevation of 4,882.9 feet is 9 feet, placing the crest at elevation 4,891.9 feet. The powerhouse is located about 2,000 feet from the two penstock intakes which are located in the embankment section about one third of the way from the left abutment. The embankment would be overtopped by a PMF event.

Cutler Dam, built in 1927, is located in a gorge about 13 miles northwest of Logan, Utah in the mountains separating Cache and Great Salt Lake Valleys northeast of the lake. It is a concrete gravity arch 545 feet wide and 112 feet high with an irrigation canal intake structure in each abutment and a center four-section tainter gated spillway section. The dam is 70 feet thick at its base and 7 feet thick at the top. The tainter gates are each 14 feet high and 30 feet wide; they can pass 34,000 cfs with the pool at the dam crest. The postulated PMF inflow is 195,000 cfs and the outflow of record was 12,700 cfs in 1986. The condition of the concrete in the piers restraining the tainter gate trunnion blocks was questioned at the time of the study and has since been determined to be poor. It is doubtful that the dam would fail because of either a PMF or an MCE event, but the dam would be overtopped by a PMF and the irrigation canals built into the hillsides below the dam would probably be seriously damaged.

DAM SAFETY EVALUATION FOR A SERIES OF UTAH POWER AND LIGHT HYDROPOWER DAMS, INCLUDING RISK ASSESSMENT: Work Plan, Project Description, Remedial Action

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ABSTRACT

The study comprised an incremental consequence assessment and a risk assessment. The concepts and procedures for each are summarized. Each dam was evaluated considering its potential for complete or partial failure due to floods, earthquakes, internal causes, or upstream dam failure. The evaluation considered various human safety, economic and environmental factors. In this paper, the location, type and condition of each dam, various human safety factors, and economic and environmental factors are briefly presented. Also, potential failure modes and alternative remedial actions are discussed.

INTRODUCTION

A dam safety evaluation of Utah Power and Light Company (UP&L) facilities on the Bear River was performed to evaluate the appropriateness of applying FERC maximum standards of Probable Maximum Flood (PMF) and Maximum Credible Earthquake (MCE) in assessing the safety of the dams. Previous FERC Part 12D studies of the facilities, performed by Harza Engineering Company, have judged the facilities to meet FERC criteria regarding protection against internally-induced failure modes, but the studies also identified the inability of the dams to meet the FERC's PMF flood loading and MCE earthquake loading standards.

The dam safety evaluation was performed through an incremental consequence assessment and a risk assessment. Incremental consequence assessment, which is recognized by FERC Subpart 12D regulations [18 CFR Ch. 1 (4-1-86 edition) § 12.35 (b)(2)], provides estimates of increases in economic damages or life loss for postulated scenarios of dam failure compared with cases which consider no dams on the Bear River (i.e. natural flows). While incremental consequences deal with potential damages due to the dam being part of the river system, they do not include consideration of the chance of these failure scenarios actually occurring; therefore, it's a "what if" type of assessment. To add the perspective of the chance of occurrence, risk assessment was performed for the UP&L Bear River dams. The risk assessment approach is specifically mentioned in FERC

Engineering Guidelines, Section 2.3, and it is currently used for this purpose by the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, the Federal Emergency Management Agency, and some state dam safety offices for evaluating the safety of existing dams. Also, its use has been recommended for evaluation of existing dams in reports by the American Society of Civil Engineers (1988) and the National Research Council (1983, 1985). The Risk assessment was conducted in accordance with the method described by Bowles, Anderson, and Glover (1987) and by the U.S. Bureau of Reclamation in the "Guidelines for Decision Analysis, ACER Technical Memorandum No.7".

In the incremental consequence assessment, the flood water levels that would occur for a range of postulated cases of dam failure were projected and compared to the case that would have occurred if no dam existed. Flood, earthquake, and internal failure modes were considered, and the analysis was performed over a full range of loading conditions. In developing the hydrologic and earthquake loading events, the 1983 Bear River Basin Study and several inspection and safety reports by Harza Engineering Company were used so that the basis for the study was consistent with the basis for the Harza FERC Subpart 12D studies. Any increases in economic damages or life loss, exceeding the no dam case, were attributed to existence of the dam. These increases were projected for floods caused by general storms and by local thunderstorms, with flows ranging up to the PMF for each storm type. Earthquake-caused dam failure was also considered. However, incremental consequence assessment cannot be applied to consideration of internally-caused dam failure.

A quantitative risk assessment of an existing dam aids in identifying which factors (e.g. initiating events, failure modes, and exposure factors) or ranges of factors, contribute most to the total risk associated with dam failure. By considering the interaction of initiating events, failure modes, system responses, and resulting consequences, risk assessment provides a framework for evaluation of safety criteria appropriate to a specific dam. This approach can lead to identification of an option (remedial action alternative) that is most promising or cost effective for achieving risk reduction.

The scope of this study was such that two risk assessments were performed. A preliminary risk assessment--based upon preliminary estimates of loads, loading probabilities, system responses, extent of inundation, and consequences--was performed to identify the relative importance, sensitivities, and uncertainties associated with each dam and each initiating event. The preliminary risk assessment identified the ranges of loads appropriate for evaluating remedial action alternatives and focused the efforts of the final risk assessment to give greater emphasis to work tasks that are more significant, more sensitive, or more uncertain.

Risk assessment adds the perspective of the chance that each of the failure modes, postulated in the incremental consequence assessment, actually could occur. Thus, estimates of the chance of dam failure and associated damages or life loss were obtained. Also, the potential economic benefits of upgrading the existing UP&L Bear River dams to safely pass the PMF (or to withstand the MCE) or of installing a dam break/flood warning system were estimated. Findings from the risk assessment were used by the dam owner (UP&L) and the regulator (FERC) in the ultimate selection of site specific standards for these dams, from which appropriate remedial actions were identified.

PROJECT DESCRIPTION

The UP&L Bear River facilities included in this study are:

Facility	State
Soda Point Hydro Facility	Idaho
Grace Hydro Facility	Idaho
Oneida Hydro Facility	Idaho
Cutler Hydro Facility	Utah

Site specific conditions of the dam-foundation-spillway system of each facility were examined. Pertinent data on existing conditions were obtained through site visits, review of historical design and construction data, and subsequent field and laboratory investigations. The site conditions that were studied included surface and subsurface conditions at each dam site, hydrologic data for the entire Bear River Basin, and earthquake data for the Intermountain Seismic Belt.

After gathering and interpreting the necessary data, a broad range of dam response scenarios that could be caused by the range of loading conditions identified as likely to be imposed on the dam and its appurtenances was postulated. Mechanisms which traditionally have led to dam failures, such as foundation and embankment instabilities due to oversteepended slopes, inadequate filter and drainage protection, overtopping, erosion, piping, excessive pore pressures, spillway failures, excessive uplift, undermining, adverse operating characteristics, material deterioration and inadequate energy dissipation, were considered. Generally accepted structural analyses of the concrete dams were also performed. Each postulated dam response was evaluated for the probability of that response occurring. System response relationships were developed for each dam as described in the following paper.

Consequence assessments that considered human safety, economic, and environmental factors for each of the postulated system responses were performed. The human safety assessment was performed to characterize the conditions which threaten life in the floodplain and to help in make decisions about modifying the risk of possible human life loss. This assessment involved: (1) identifying the population at risk, (2) evaluating warning time and factors which affect responses to a warning, (3) developing the exposure probability of the population at risk, and (4) estimating the possible resultant loss of life. The purpose of the economic damage assessment was to evaluate whether protection of a dam above its existing level was economically justified. The economic damages were categorized as related to failure of a dam and non-failure related so as to define appropriate benefits hereby balancing benefits and costs related to modifying a risk condition through an investment. The environmental damage assessment was performed to define the impacts associated with the existing facilities under the various possible system response scenarios.

To reduce the probability of dam failure or to reduce the downstream damages and possible loss of life due to dam failure, several structural and non-structural corrective alternatives were evaluated for each dam. Typical structural alternatives included no action (do nothing), decommission the dam, anchor or armor the dam to allow overtopping without breach, and increase the capacity of the spillway. Typical non-structural alternatives included no action, install a flood warning system, and zoning of downstream damage centers. Prior to evaluation, the remedial action alternatives were subjected to a comparative screening process, whereby the alternatives that had the potential for reducing consequences at the lowest cost were identified. These alternatives were carried through the risk assessment for further evaluation. Conceptual design and construction cost estimates were developed for each of the identified alternatives.

Soda Point Dam

Soda Point Dam is a concrete structure, 103-feet high, with a 14,000 kW generating station, and a spillway capacity of 63,000 cubic feet per second. The left end of the structure is a 55-foot long earth embankment that is five feet higher than the crest of the concrete dam. The March 1983 probable maximum flood study for Soda Reservoir gave a peak inflow of 72,100 cubic feet per second. The dam was built in the mid-1920's.

There are potential hydrologic failure modes for both the concrete dam and the earth embankment. Over-stress of the concrete dam was considered as the possible system response associated with the earthquake event at Soda Point Dam. Failure of the concrete dam was postulated to result in total failure of the dam, and failure of the earth embankment was postulated to result in partial failure of the dam.

Several structural and non-structural alternative remedial actions were considered for the Soda Point Dam site. They were : (1) no action, (2) decommission the dam, (3) anchor the concrete portion of the dam to allow overtopping and raise the embankment dam on the left abutment to prevent overtopping, and (4) construct a dike at the town of Grace, Idaho to reduce flood inundation. Conceptual designs and construction cost estimates were prepared for each of these alternatives.

Grace Dam

The 52-foot high Grace Dam is a timber crib structure, which serves a 33,000 kW powerplant through a 5.5 mile penstock. It has a spillway capacity of about 14,000 cubic feet per second. The March 1983 probable maximum flood study for Grace Reservoir gave a peak inflow of 63,700 cubic feet per second. Grace Dam was built in 1910 and modified in 1951. The only potential failure mode postulated for Grace Dam was overtopping of the embankment caused by hydrologic loading. Earthquake related failure was not considered as a possible failure initiating event due to its very remote probability of occurrence.

Three alternative remedial actions were considered for Grace Dam. These included: (1) no action, (2) decommission the dam, and (3) protect the earth embankment portion of the dam to allow overtopping. Conceptual designs and construction cost estimates were prepared for each of these alternatives.

Oneida Dam

The Oneida Dam built shortly after 1910, is a concrete gravity structure, 110-feet high, that has discharged an all-time high flow of 5,480 cubic feet per second. An earth embankment dam (separated from the main dam by a ridge) closes off a low saddle to the left of the main dam. The total spillway capacity is about 12,000 cubic feet per second. The March 1983 probable maximum flood study for the Oneida Reservoir gave a peak inflow of 74,700 cubic feet per second. The hydropower generating station has a capacity of 29,000 kW. There are potential hydrologic failure modes for both the concrete dam and the earth embankment. Overstress failure of the concrete dam and slope instability of the embankment were considered as possible system responses associated with the earthquake events. Failure of the concrete dam was postulated to result in total failure of the dam, and failure of the earth embankment was postulated to range from partial failure to total failure of the dam.

Several structural and non-structural alternative remedial actions were considered for the Oneida dam site. They were: (1) no action, (2) decommission the dam, (3) anchor the main concrete dam to allow overtopping and raise the embankment dam to prevent overtopping, (4) install a flood warning system, and (5) restrict recreation on the reservoir and below the dam. Conceptual designs and construction cost estimates were prepared for the first four of these alternatives. The fifth alternative was eliminated from consideration due to its conflict with FERC objectives of multiple use of water resources.

Cutler Dam

The 112-foot high Cutler Dam is a concrete gravity arch structure that was built in the late 1920's. The hydropower generating station has a capacity of 30,000 kW. Spillway capacity is 22,000 cubic feet per second. The March 1983 probable maximum flood study for the Cutler Reservoir gave a peak inflow of approximately 195,500 cubic feet per second. Cutler has historically spilled a peak flow of 12,600 cubic feet per second without causing significant flooding or damages in the downstream river valley.

There are potential hydrologic and earthquake failure modes for Cutler Dam. The hydrologic loading condition was postulated to cause failure of the lateral canals at each abutment due to overtopping. Failure of the concrete dam in the form of failure of the tainter gates that occupy the main spillway section was postulated as a possible earthquake event system response. Both of these failure modes were judged to result in only partial failure of the dam.

Several structural and non-structural alternative remedial actions were considered for Cutler Dam. They were: (1) do nothing, (2) decommission the dam, (3) modify the canal intakes at both abutments to prevent overtopping, (4) raise the dam to accommodate the PMF event, (5) strengthen the spillway tainter gates to withstand the MCE event, (6) relocate houses downstream of the dam, and (7) install a flood warning system. Conceptual designs and construction cost estimates were prepared for each of these alternatives.

DAM SAFETY EVALUATION FOR A SERIES OF UTAH POWER AND LIGHT HYDROPOWER DAMS, INCLUDING RISK ASSESSMENT: Seismic and Hydrologic Considerations, System Responses and Potential for Serial Failure

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ABSTRACT

The seismic and hydrologic settings of the Bear River Basin will be described with particular reference to the potential for extreme floods and earthquakes at each dam-site. The representation of system responses over a range of imposed loadings up through the probable maximum flood or maximum credible earthquake will be presented for typical cases. The results of flood routings for natural flow, no failure, and failure scenarios will be presented in terms of incremental flooding. Also, the evaluation of and conclusions relating to the potential for serial dam failure will be discussed.

INTRODUCTION

A good risk assessment model must consider the potential for dam failure from all reasonably probable loading events. The most important events for a single dam can be categorized as hydrologic, seismic, and static. A variety of other rare events such as sabotage and meteorite impact could also be considered but generally are not. When there are dams in series on a river, it is necessary to consider the loading caused by the failure of an upstream dam. It is also necessary to consider failure from a full range of loading conditions, not just the extreme events. It is possible, even probable, that the greatest risk in terms of both economic damages and loss of life could be due to a loading condition that is much less than the "maximum" event because the lower event has a much higher probability of occurring. The risk model must explicitly consider all reasonably probable failure modes resulting from the various initiating events. Consideration must be given to joint occurrence of the failure modes in making the risk assessment. To facilitate cost - effective risk reduction/safety improvements the model must identify which factors contribute most to the total risk of failure.

The risk assessment model that was used in this study considers the probability of an initiating event and the following conditional probabilities of the system response, the outcome and the exposure, and then it evaluates the consequences of the outcome in terms of economic damages and loss of life (Bowles, et al. 1987). The consequences of failure can then be evaluated to determine if the risk acceptance criteria have been met. If these criteria have not been met then various risk aversion steps can be considered to reduce the consequences of failure.

This paper will focus on the response to seismic and hydrologic loading events for Utah Power and Lights (UP&Ls) four dams in series (Soda Point, Grace, Oneida and Cutler dams) on the Bear River in Utah and Idaho. Other aspects of the risk assessment procedure for the Bear River project are discussed in the four comparison papers included in this technical session.

HYDROLOGIC LOADING

Hydrologic loading on a dam is due to the hydrostatic and dynamics forces acting on the reservoir/spillway/dam system during routing of the flood represented by the inflow hydrograph associated with the hydrologic event being considered.

The risk assessment study for the Bear River Dams was based on the concept of assessing partial risks for several load levels over the entire range of postulated loading conditions. The partial risks, attributable to each loading, were summed to determine the total risk. Probabilistic hydrologic hazard analysis was performed to identify the estimated frequency of floods associated with flood loading conditions, ranging up to the probable maximum flood (PMF), for use in dam response and downstream damage assessments.

In the probabilistic hydrologic hazard analysis, flood events were divided into general storm-caused flood events and thunder-storm-caused events because for the Bear River watershed, these events are considered to be statistically independent since they result from distinctly different types of meteorological and hydrological conditions. Floods caused by general storms in the Bear basin usually occur in late spring and early summer with storms over a large portion of the watershed combined with snowmelt. Floods caused by thunderstorms occur in summer months with intense isolated storms over a relatively small area immediately upstream from the reservoir--there is no snowmelt runoff.

Flood frequency curves for both general storm and thunderstorm floods were established. Probable Maximum Flood (PMF) hydrographs for the general storm and the thunderstorm were taken from earlier hydrologic and PMF studies performed by others. Flood frequency curves were established for both general storm and thunderstorm floods, using available flood records at selected USGS stations on the river, up to the 100 year return period. Risk-based analyses conducted in this study require the establishment of discharge-probability relationships for the entire range of flood events, from no flow over the spillway up through the PMF. Due to the lack of definite knowledge about the probability of PMF occurrence, the methodology suggested by the NRC and presented in USBR ACER Technical Memo No. 7 (1986) was followed to assign a probability of occurrence for flood events with a return period beyond one in one hundred years. The NRC method requires the construction of frequency curves in two phases. The first portion of the curve, up to a 100-year flood event, was derived as a straight-line extension of the confidence limit curves on lognormal probability paper. Further, straight-line extensions were made from the 5 and 95-percent confidence limit curves at the 100-year event to the PMF level at arbitrarily assigned exceedance probabilities of 10^{-6} and 10^{-4} per year. The theoretical (median) frequency curve lies between the 95-percent confidence limit curves and is assigned an exceedance probability of 10^{-5} per year for the PMF.

Ten different hydrologic loading ranges were used to cover a wide range of flood peaks from no flow over the spillway up to the PMF (194,500 cfs for the general storm at Cutler Dam). The system response of each dam and the resulting consequences were established for each loading range. Flood frequency curves were used to determine the event probability for each flood loading range of each dam. The annual probability of occurrence of each selected flood event (which was representative of a flood range) was read from these frequency curves and entered into the risk model. Inflow hydrographs associated with each selected flood event were developed for breach analyses and flood routing computations. The inflow hydrographs for floods other than the PMF were obtained by prorating them to either the general storm or thunderstorm PMF hydrograph.

EARTHQUAKE LOADING

Earthquake loadings on dams and their appurtenances result from earthquake-induced ground accelerations in the foundation materials at the site. Both the ground acceleration produced by the earthquake and the duration of the strong ground shaking influence the response of a dam to earthquake loading. The acceleration of the earthquake motion is a function of the magnitude of the earthquake and the distance from the causative fault to the site. Duration of strong ground shaking is a function of the magnitude of the earthquake. Therefore, both magnitude and the distance from each site to possible causative faults must be considered in establishing the earthquake loading conditions.

Unlike the deterministic analysis of dams, the risk assessment procedure requires analysis of dams under a full range of loading conditions. Therefore, the event probability for earthquake loading must be described as an annual frequency of exceedance versus peak acceleration from earthquakes in a given magnitude occurrence.

The study area is bisected by the Intermountain Seismic Belt. The occurrence of earthquakes in the study area is common and has been documented since 1950. The Seismic Zone Map of the United States, contained in the Uniform Building Code, classifies the study area as Zone 3. Algermissen, et al. (1982) developed probabilistic estimates of maximum acceleration in rock in the contiguous United States. The maps represent contours of maximum acceleration with a 10 percent probability of being exceeded in 10-year, 50-year and 250-year exposure periods. The dams of concern on the Bear River are near the contour representing a 10% probability of exceeding an acceleration of 0.2 g in 50 years.

The seismic hazard in the region is strongly related to the presence of the 370-km long Wasatch Fault zone which extends from Gunnison, Utah on the south to Malad City, Idaho on the north. The Wasatch Fault zone is an active westward-dipping, normal fault. Geologic evidence indicates that it is active; it has had many large magnitude earthquakes during the last 10,000 years. Recent geologic studies of the Wasatch Fault suggest that the fault is segmented with at least ten identifiable segments, Machete et al. (1986). In general, each segment is capable of earthquakes with maximum magnitudes ranging from 6-1/2 to 7-1/2. Other specific faults were also considered. It is likely that there are many faults in the region that are capable of generating small to moderate earthquakes that would not rupture the ground surface. Generally, earthquakes that do not rupture the ground surface have magnitudes less than about 6 to 6-1/2. A background seismicity was used to represent these faults; it was assumed that the spatial distribution of these small to moderate earthquakes, would be uniform. The historic record was used to establish the annual frequency of exceeding given levels of acceleration.

Up to ten different earthquake loading ranges were established for each dam site from 0g up to the acceleration corresponding to the maximum credible earthquake. The maximum acceleration ranged from 0.45g at Soda Point, Grace, and Oneida dams to 0.66g at Cutler dam.

SYSTEM RESPONSE ANALYSIS

To estimate the probability of failure for a given dam, it is necessary to predict the response of the dam under a full range of loading conditions for each failure mode identified in the risk model. To accomplish this, it is necessary to examine the configurations, characteristics, and site-specific conditions of the dam-foundation-spillway system and to perform static and dynamic analyses of the dam. Probability of failure for each of the Bear River dams was evaluated for hydrologic, and earthquake initiating events.

As each response was settled on, the team estimated the probability of that response occurring. Probabilistic analysis methods are not well established for evaluating the response of dams to hydrologic, static, or earthquake loads; therefore, to establish the response probability curves, it was necessary to use professional judgement, deterministic analysis, and a knowledge of the past performance of dams under similar loading conditions. The general procedure for evaluating the probability of failure by a given failure mode under a range of loading conditions consists of: (1) establishing a threshold loading condition below which the probability of failure is considered to be zero, (2) establishing an upper bound loading condition above which the probability of failure is estimated to be one, (3) estimating the probability of failure for the maximum credible loading at the site, and (4) using the bounds set in 1, 2, and 3 to develop a system response curve for each possible system response.

Since a given loading condition may be capable of inducing failure by more than one system response, probability response curves were developed to account for the joint occurrence of system responses that could lead to failure. Probability response curves were developed for each loading event using the procedure by Anderson and Bowles (1987).

The hydrologic system response curve for Oneida Dam is shown on Figure 1. Note that there are two possible system response (failure modes): (1) overtopping the concrete dam, and (2) overtopping the embankment dam. Figure 1 illustrates that once the embankment dam is overtopped, embankment dam failure would quickly become the dominant failure mode even though the concrete dam would be overtopped well before the embankment dam. Similar hydrologic system response curves were developed for each dam on the Bear River. Earthquake system response curves were also developed for each dam. These curves related probabilities of failure to maximum acceleration.

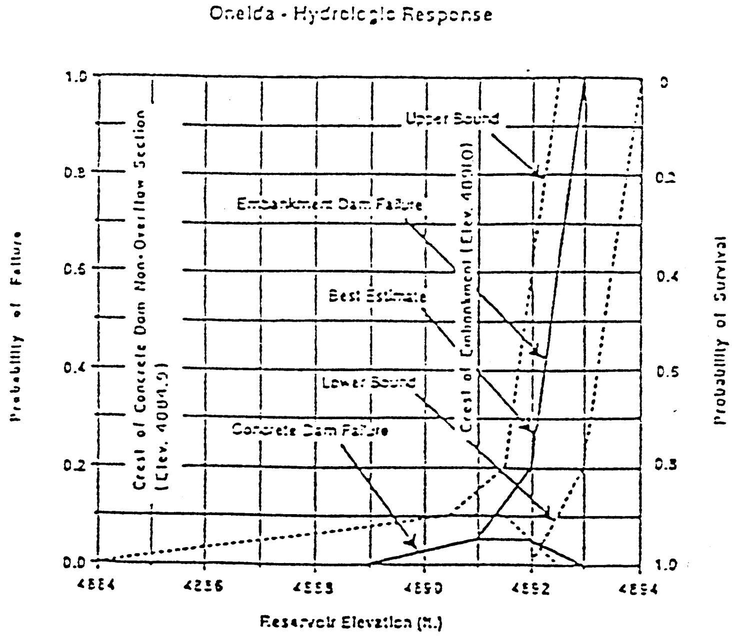

Figure 1

POTENTIAL FOR SERIAL FAILURE

Flood Routing Studies

Flood events considered in the study cover the entire range of floods, up through the PMF, and included the threshold floods. Three types of initiating events at each dam were considered in the dam failure scenario. These events were: hydrologic, earthquake and internal failure.

For Individual Dam

For each flood event, the inflow hydrograph was routed through each reservoir and the downstream river reaches to the next reservoir located downstream on the Bear River, under the with and without dam failure assumptions and with the dam under existing structural condition (no rehabilitation or structural improvement). For non-flood events, only sunny day dam failure routings were performed. All flood routing computations were performed using the National Weather Service DASMBRK model.

The same flood routing computations were necessary for every proposed rehabilitation alternative considered for each dam. This information was essential for the damage assessment associated with each loading event and each proposed improvement.

Flood routings for the natural flow (assuming no dam in place) scenario were also performed. This is the base condition in the establishment of incremental flooding in the river reaches.

For Serial Dam Failure

When dams are located in series, an upstream dam can be both a threat and a means of protection to a downstream dam. Typically, at lower flows associated with a regional or local runoff event, an upstream dam will safely pass floods with some attenuation that will thereby reduce the magnitude of the flood imposed on downstream dams. However, at higher flows, the possibility of failure of the upstream dam may exist, and that would usually lead to outflows that are higher than either natural or no-failure flows under the same runoff conditions. Thus, inflows to downstream dams will be increased and the likelihood of their failure may also increase.

The four dams involved in the study on the Bear River are located in series. The event tree incorporating serial failure for initiating events at Soda Point Dam (the most upstream dam) is shown on figure 2. A similar event tree was developed for Oneida Dam. Serial failure initiating at Grace Dam was not considered because the impacts of all its failure modes are small and are completely contained in the Oneida Reservoir. Cutler Dam is the most downstream dam on the Bear River system and therefore would not initiate a serial failure.

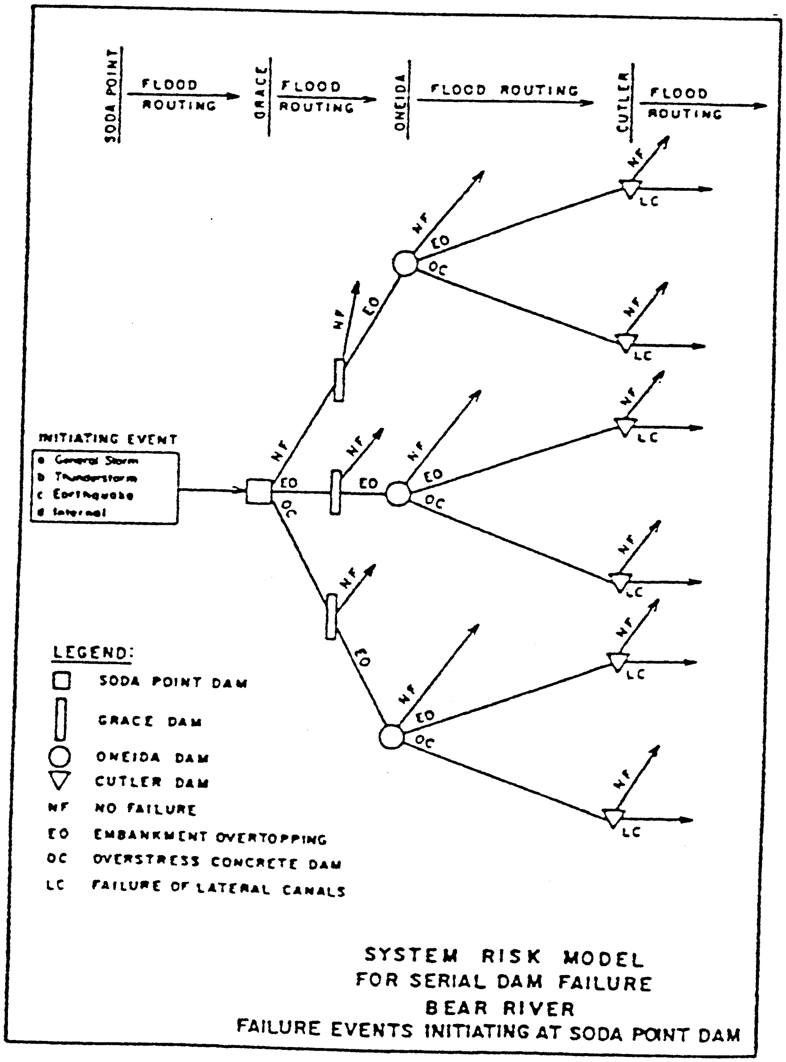

Figure 2

The Hydrologic and non-flood loading events which were identified for individual dams were repeated in the serial dam failure analyses. The increase in reservoir water surface elevation of a dam due to the incoming flood from the failure of the upstream dam constitutes an additional loading condition for that dam. System response curves for different loadings were developed for each dam. The system response of the dam subjected to an upstream failure loading was evaluated by first routing the breach flow from the upstream dam failure into the reservoir under consideration. The system response then depended on the increase in the elevation of the reservoir. Downstream consequences were then evaluated depending on the system response.

Results of Serial Dam Failure

System routing analyses for the serial dam failure scenarios reveal the following results:

a. General storm PMF at Soda Point Dam may cause Oneida Dam to fail and overtopping of Cutler Dam, even if the Soda Dam does not fail.

b. Thunderstorm PMF at Soda Point Dam would cause failure of Oneida Dam only if failure of Soda Point Dam in caused by overstress of the concrete dam. However, failure of Oneida Dam under this condition may not cause overtopping of Cutler Dam.

c. Sunny day failure (seismic or internal initiating event) at Soda Point Dam would not cause failure of Oneida or Cutler Dams.

d. General storm PMF initiating at Oneida reservoir would cause failure of the Oneida Dam and consequent overtopping of Cutler Dam.

e. Thunderstorm PMF initiating at Oneida reservoir would cause failure of the dam but may not cause overtopping of Cutler Dam.

f. Sunny day failure of Oneida Dam would not cause overtopping of Cutler Dam.

DAM SAFETY EVALUATION FOR A SERIES OF UTAH POWER AND LIGHT HYDROPOWER DAMS, INCLUDING RISK ASSESSMENT: Results

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ABSTRACT

Safety evaluation results will be presented in three categories: based upon the applicable FERC guidelines, the incremental consequence assessment, and the risk assessment. Incremental consequence assessment results for floods and earthquakes show the potential for increased life loss, economic damages, or environmental damages as the result of dam failure scenarios. The risk assessment adds the perspective of the likelihood of each failure scenario occurring. Risk assessment results will be presented for floods, earthquakes, and internal failure modes as risk of incremental life-loss, cost of improving human safety, probability of breach or partial failure, benefit-cost ratio for remedial action alternatives, and total annual cost (risk cost, plus remedial action cost) for each alternative.

INTRODUCTION

Findings for the Bear River study are reported in (ECI and RAC, 1988). In the next section of this paper risk acceptance criteria are discussed to provide a context for the interpretation of results from both an incremental consequence assessment and a risk assessment. Results for the Soda Point dam are summarized to illustrate the types of information provided by both the incremental consequence assessment and the risk assessment. These findings were used by dam owner (UP&L) and were also provided to the regulator (FERC) for use in the selection of remedial actions for the Bear River dams.

RISK ACCEPTANCE CRITERIA

For hydrologic loading, various criteria have been proposed to define a site specific, base safety condition. If an incremental consequence assessment (which is recognized in the FERC guidelines), is performed, the following criteria are commonly used as yardsticks against which downstream consequences are measured and evaluated:

- No significant incremental threat to life as a result of dam failure. "Incremental threat-to-life" is defined as the difference between threat-to-life for failure and natural flow cases for inflow rates from the failure threshold up through the PMF; and "significant" can be defined as one or more lives expected to be lost as the result of a hydrologically-induced dam failure.

- Insignificant incremental economic damages. "Incremental damages" are defined as the difference between damages for failure and natural flow cases at each inflow rate from the failure threshold up through the PMF and insignificant can be defined by the ability of the dam owner to compensate for damages and the split of damages between the dam owner and others.

These criteria can be applied for hydrologic and earthquake loading, but not for the internal static failure modes. Incremental consequence assessments cannot be meaningfully applied to internally initiated events since a failure threshold cannot be defined.

Although incremental consequence assessment does solve the issue of properly differentiating between naturally and artificially induced damages, it provides no information on the chances that such events will happen. To add this perspective, a risk assessment was performed for the UP&L Bear River dams. Additional criteria are needed for defining a hydrologic base safety condition using risk assessment. The following criteria may be used:

- Acceptably small risk (probability) of incremental-life-loss to dam failure. Where "acceptability" can be defined either by comparison with other dams, or the failure of other types of civil works.

- Acceptably large cost-to-save-a-life for proposed remedial action. Where "acceptability" can be defined by comparison with investments made in protecting public safety in other areas such as environmental regulations.

- Acceptably small probability of dam failure. Where "acceptability" can be defined either by comparison with historical dam failure rates, or historical failure rates of other types of civil works.

- Acceptable benefit-cost ratio or rate of return on investment in proposed remedial action. "Acceptability" is evaluated in terms of standards established by the dam owner for investments; benefits are defined as the reduction in risk costs estimated to be achievable by implementation of the remedial action alternative; and costs are those associated with providing, maintaining, and operating the alternative.

- Remedial alternatives with their capacity selected using the minimum total cost criterion. Total cost is defined as the sum of total annual risk costs and annualized costs associated with providing, maintaining, and operating the alternative. Also, one of the remedial alternatives considered is the existing dam without modification.

Some of these criteria address economic risk acceptance considerations. Each criterion may lead to the definition of a different base safety condition. Therefore, in this study, each dam was evaluated according to all appropriate criteria so that alternative base safety conditions could be compared. A dam owner does not have to use any single risk acceptance criteria and may introduce additional factors in his decision making process.

SUMMARY OF FINDINGS - SODA POINT DAM

FERC Guidelines

Soda Point Dam is a concrete gravity structure, 103 feet high with a small embankment section at the left abutment. The dam does not meet the FERC PMF standard or the FERC maximum credible earthquake standard, but it does meet FERC criteria for the internal condition of the dam. The dam is the most upstream of the UP&L dams on the Bear River.

Incremental Consequence Assessment

Incremental Hazard to Human Life

Failure of the existing Soda Dam is not expected to result in additional life-loss above that projected due to the effects of a natural flood without the dam in place. Therefore, upgrading of the dam to safely pass the PMF (by installing anchors in the concrete dam and raising the embankment on the left side) is not projected to reduce hazard of life-loss.

For an earthquake-caused failure of Soda Point Dam, life loss is predicted to be about five lives at the UP&L hydropower facilities at Soda Point and Grace. Upgrading the dam to withstand the maximum credible earthquake could be achieved by adding anchors to the concrete dam which would reduce predicted life loss to zero.

Incremental Economic Damages

Increases in economic damages due to dam failure vary with the flow rate at which dam failure is postulated. The maximum increases projected for the existing Soda Point Dam for a general storm flood is estimated to be $9 million, but only $2.2 million of these losses would be to non-UP&L parties. For thunderstorm floods, the maximum increase is projected to be about the same as for a general storm flood. In both cases, damages at Grace Hydro Facility and in Grace City are included. These levels of damages, while not small, (according to UP&L representatives) are within insurance coverages that UP&L carries.

Failure damages for earthquake failure of Soda Point Dam are projected to be up to $8.8 million with non-UP&L losses being only $0.5 million.

Risk Assessment

Risk of Incremental Life Loss

No chance of incremental or increased life loss is projected due to flood-caused failure of Soda Point Dam when compared with the case of no dam.

It is predicted that if an earthquake or internal failure were to occur, about five lives may be lost. The chance of an earthquake failure occurring is estimated to be 1 in 43,500 per year and 1 in 18,500 for an internal failure. These are much less likely than 1 in 5,000 per year, the historical probability of life-loss from dam failures in the United States due to all causes (i.e. flood, earthquake and internal failures). The existing Soda Point Dam has, however, been found to satisfy FERC criteria with respect to its internal condition.

Cost-to-Save-a-Life

The cost of increasing human safety can be expressed on a "per statistical life saved" basis (i.e. cost-to-save-a-life). This is the cost of providing safety and not in any sense a value for human life. Since no life loss could be attributed to the Soda Point Dam under flood loading, it follows that upgrading of the dam would not be predicted to save any lives. Therefore, the cost-to-save-a-life for remedial upgrading of the flood performance of the dam is infinitely large.

The cost-to-save-a-life for installing anchors in the concrete section of the Soda Point Dam, so that it could withstand the maximum credible earthquake, is calculated to be approximately $1.9 billion per life saved.

A dam break/flood warning system was considered for reducing the hazard to human life in the event of an earthquake or internal failure of Soda Point Dam. It was calculated that the cost-to-save-a-life for this system would be approximately $240 million per life saved. However, this system would not be expected to reduce life loss at the Soda Point Hydro Facility itself. If the Soda Point Dam were decommissioned, the cost-to-save-a-life was calculated to be approximately $3 billion per life saved.

These costs can be compared with costs-to-save-a-life calculated for regulated areas such as nuclear power plant design ($4 - $10 million), environmental protection ($4 million) and occupational health and safety ($4.5 million and $300 million for OSHA Benzene regulations).

Probability of Dam Failure

The chance of a breach failure of Soda Point Dam from floods, earthquakes, and internal causes, is estimated to be 1 in 11,000 per year. This is approximately equal to the historical probability of dam failure in the United States due to all causes.

Benefit-Cost Ratio

Economic benefits are predicted to be less than one percent of the estimated costs for installing anchors in the concrete dam and raising the embankment on the left side of Soda Point Dam. No structural alternatives were considered for internal failure modes since the Soda Point Dam has been found to meet FERC standards for these cases.

Total Annual Cost

The sums of the predicted annualized damages (risk costs) and estimated annualized costs are: $238,000 for installing anchors in the concrete dam and raising the embankment on the left side; $3,300 for the do-nothing alternative i.e. maintain the existing dam; and $362,000 for abandoning the facility. Thus, the existing dam alternative was found to have the lowest total annual cost of these three alternatives.

Environmental Impacts

A reconnaissance-level, environmental evaluation of dam failure impacts was performed. For flood-caused failure scenarios, the additional area of environmental impact was predicted to be small when compared to the natural flooding case. The probability of dam breach impacts occurring was found to be approximately 1 in 11,000 per year.

CONCLUSIONS

The results summarized in this paper illustrate the types of information which can be provided by incremental consequence and risk assessment studies. This information has proven very useful to dam owner and operations and others who are responsible for making dam safety decisions. Other uses of information obtainable from these approaches include the assessment of liability exposure for dam owners and operators, the choice of interim measures for improving safety at dams which are awaiting permanent fixes, the efficient allocation of effort for dam safety studies, the sequencing of remedial actions at a group of dams which cannot be budgeted or scheduled to be performed simultaneously, and the provision of a basis for insurance coverage of dams.

The Bear River study showed that estimated dam failure probabilities were low. Predicted incremental damages were low, and in most cases damages would affect the owner to a far greater extent than other parties. The probability of life-loss was estimated to be low, and the cost-to-save-a-life was calculated to be high for all structural and nonstructural alternatives. No economic justification for alternative fixes could be shown. However, safety and social factors should also be considered in the decision-making process. Evaluation of potential serial failure modes did not show large increases in failure probabilities from this type of initiating event. In the case of Grace Dam, a decrease in failure probability can be attributed to the protection provided by the upstream Oneida Dam.

As with other studies with which the authors have been associated, the use of incremental consequence assessment and risk assessment were shown to be valuable tools for providing inputs to the decision-making process. The approach to risk assessment used in the Bear River study did not involve placing a value on human life, nor did it involve using a specific decision criterion, such as minimum total annual cost. The selection of remedial actions was made by the dam owner and regulator using study results and other considerations.

DAM SAFETY EVALUATION FOR A SERIES OF UTAH POWER AND LIGHT HYDROPOWER DAMS, INCLUDING RISK ASSESSMENT: Owner Perspectives on the Role of the Evaluation in the Selection of Remedial Measures

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ABSTRACT

In this paper the dam owner will describe the role of dam safety evaluation results in selection of remedial measures which were proposed to, and accepted by, the FERC. For the dam owners, this paper will address the value of insights gained from this type of detailed dam safety evaluation study. The importance of understanding the hydrologic, seismic, structural, safety, economic, social-environmental, and risk aspects of a dam safety decision will be illustrated through the discussion of the UP&L decision-making process.

Was the Study Worth It?

Including the internal utility costs the risk assessment study for the five dams cost close to $500,000. What did we get for our money besides FERC's discomfort? First and foremost, we developed an in-depth understanding of these dams' potential for failure, and we internally justified the necessary remedial activities. Without this thorough review, we would probably have had bad feelings about any of the work for a considerable time to come, and we may have otherwise sought very costly legal remedies. Second, the study developed alternatives that would probably have been missed or bypassed without this penetrating scrutiny. Based on our initial estimates and contingency plans, we feel the study came very close to saving us $10 million in current remedial costs, about 40% to 50% of the money we had anticipated spending. Third, we fell that FERC was better able to appreciate, benefit of avoiding some of the work we would have otherwise done, and we were better able to appreciate some of their concerns. For instance, during the study it became rapidly evident that the failure of the plug section at Soda and failure of the dam at Grace would be beneficial during a PMF event. Forth, some of the work, such as the incremental flood studies would have been needed in any case, and they were a material portion of the study cost, perhaps 20% of the total.

Procedurally, did the study go as anticipated? No, not entirely. Personally, if we had it to do again, I would insist on physical evaluation of the facilities condition being given greater emphasis. In the interest of both time and cost, information generated in prior FERC Subpart 12D independent inspections was relied upon heavily to evaluate the dams' physical condition. Subsequent developments, such as the condition of the Cutler tainter gate piers, have emphasized the need to obtain more physical evidence during a risk assessment. If you don't examine existing conditions closely, you will probably learn your lesson later.

The other lesson we have since learned is to be sure that flood routing studies are based on as good a model of the real channel geometry as possible. In several cases, we now believe, projected PMF flood routing consequences could have been shown to be less significant if flow obstructions had been modeled more effectively. For instance, it recently has been determined that sudden failure of the tainter gates at Cutler would produce a peak flow well within the same magnitude as we could expect from projected gate capacity and roughly equal to our outflow of record. Don't short change development of the details in a risk assessment.

We had a good team that was determined to do a proper job of a complex, difficult study. On the whole, it was very well worth the effort.

A REGULATOR'S PERSPECTIVE AND EXPERIENCE WITH RISK ASSESSMENT FOR DAMS

Len McDonald

- Chairman, New South Wales Dams Safety Committee

THE LEGISLATION

- *Dams Safety Act, 1978* and *Mining Act, 1992.*
- Dams Safety Act established the Dams Safety Committee (DSC).
- Sets out functions of DSC, some key ones being:
  - to maintain surveillance of prescribed dams
  - to examine designs for construction or modification of prescribed dams
  - to formulate measures to ensure the safety of dams.
- Confers power to collect information on any dam.
- In respect of prescribed dams, confers power to:
  - require owners to do anything set out in a notice by DSC to ensure the safety of a dam (Section 18)
  - hold inquiries into the safety of a dam
  - advise the Minister on the declaration of a state of emergency
  - where a state of emergency is declared, the Committee may take charge of a dam, release the storage, or undertake works (including demolition of the dam) and recover the costs from the owner
  - for DSC to enter into contracts
  - for DSC to enter into agreements with public authorities
  - for DSC to enter into agreements for investigations, studies or research
  - exercise of powers is subject to approval of the minister.
- Under the Mining Act, the Committee is the regulator of underground or open cut mining near or under presribed dams or their stored waters.

THE REGULATOR

- DSC is the regulator of the safety of presribed dams.
- DSC has 8 members, as follows:
    - 5 drawn from public agencies that own or design dams
    - 2 nominated by the Institution of Engineers, Australia
    - 1 nominated by the Minister administering the Mining Act.
- There is a small permanent staff seconded from public agencies.
- There is a permanent office.
- DSC meets about eight times each year. Two meetings are held in regional centres, in conjunction with inspection tours of dams.
- DSC has a web site http://www.damsafety.nsw.gov.au

THE DAMS

- The safety of dams prescribed under the Act is regulated.
- DSC regularly advises on additions to or removals from the list of prescribed dams.
- Any dam may be prescribed, but DSC policy is to prescribe:
  - All dams of height greater than 15m
  - Any dam, regardless of size, the failure of which would pose a significant threat to life, property, community welfare or the environment.
- Currently there are some 260 prescribed dams in New South Wales.

THE PROCESS

- Dams are classified according to potential failure consequences - determines monitoring and surveillance requirements and needed safety levels. Three consequence classes at present, but will shortly be changed to five in line with ANCOLD guidelines that are about to be published.

- Surveillance reports are required every five years. Condition and performance of dam to be assessed on basis of inspection and review of available records. Any questions over safety or emergency planning are to be brought to notice.

- Where safety is in question, a safety review is required - an analysis of safety in light of present day practice and knowledge.

- Where a safety deficiency is confirmed, owner is required to advise intended actions to bring the dam to acceptable safety levels, and a program for same. DSC monitors compliance. Interim measures to protect the public, such as flood warning and evacuation, are required pending implementation of permanent measures

- Owners are required to have:
    - ♦ Operations and Maintenance manuals (which include monitoring and surveillance requirements)
    - ♦ Dam Safety Emergency Plans (which include dambreak analyses and inundation maps)

- Where dams are identified as deficient, state emergency service has specific dambreak flood evacuation plans. Otherwise situation is covered by their regular flood plans

REQUIRED SAFETY LEVELS

- Policy is to determine requirements on a case by case basis.
- But Committee's "normal requirements" are published in technical information sheets as a guide to owners and consultants - see DSC Web Site. Examples are DSC11 - *Acceptable Flood Capacity for Dams* and DSC16 - *Requirements for Earthquake Assessment of Dams.*
- Generally normal requirements are based on ANCOLD (Australian National Committee on Large Dams) guidelines, usually with qualifications or additional requirements. ANCOLD guidelines reflect current international practice.
- Whilst the ANCOLD documents offer "guidelines", their endorsement by DSC gives them the force of law in New South Wales, unless DSC determines otherwise in a particular case.

POLICY POSITION ON RISK ASSESSMENT

- DSC has not formally endorsed the 1994 ANCOLD guidelines on risk assessment or the 1998 position paper on revised life safety criteria. This situation reflects the need for a regulator to be cautious in adopting the detailed aspects of new approaches and criteria. DSC supports the principles of risk assessment.

- DSC has resolved to consider proposals based on risk assessment on a case by case basis.

- For the few proposals based on risk assessment that have been put forward to date, DSC has advised it will require a formal process of public consultation with a project impact document publicly exhibited. Among other things, the document is to disclose the risks and by whom they are borne. It is important that the public are made aware of the differences between a risk-based approach and an alternative traditional deterministic approach (for example, respective probabilities of failure, consequences of failure, implementation costs). Any person may make submissions, which must be considered by the owner.

- DSC seeks to have owners allocate resources in such a way as will achieve the maximum rate of risk reduction. The objective is to give first priority to those dams that have the highest ratio of risk to dollar of remedial cost. In practice, because of insufficient information at the time priorities are assigned, it is often a case of dealing with the highest risk dams first, with some judgmental account taken of the likely cost of risk reduction.

ATTITUDE TO RISK ASSESSMENT

Some key points are:

- DSC sees significant value in risk assessment as an aid to systematic and effective dam safety management.

- At the present time DSC is not prepared to make risk assessment the general basis for a conclusive "sign off" of the safety status of a dam, or as the determinant of required safety levels, on two main counts:
  - the lack of well developed methodologies for producing probabilities of dam failure
  - the lack of well established life safety criteria

    and one lesser count
  - the need for better models for estimating probable loss of life.

- Some concerns at present are the uncertainty of estimated risks and the legal defensibility of a new approach.

- Traditional methodologies and criteria are an intuitive form of risk assessment. The new risk assessment approach is an attempt to examine risks more explicitly and rigorously, as an aid to the traditional approach.

- Expensive upgrades of existing dams demand consideration of the widest practicable range of issues. Risk assessment is a tool for more informed decision making.

- Risk assessment, through comprehensive failure modes analysis, can bring to light deficiencies that were previously unrecognised, thereby allowing for early remedial action.

- DSC continues to use traditional approaches and criteria, enhanced by risk assessment.

- DSC sees that portfolio risk assessment is useful in allocating resources so as to achieve the maximum rate of risk reduction.

- DSC is actively supporting the further development of risk assessment methodologies and criteria.

- DSC sees that the traditional approach to safety evaluation produces dams with an acceptably low risk to life. It does not give a zero risk to life - a widespread perception, even among engineers. Risk assessment is simply trying to quantify such low risks as exist.

- DSC sees that the traditional approach to dam safety has gaps which risk assessment can help to fill - for example, there appears to be no internationally recognised practice on required security against piping failure for old embankment dams

ACTIVITIES

Some key activities are:

- Commissioning of research by CSIRO (Commonwealth Scientific and Industrial Research Organisation) into community perception of acceptable risk - completed 1992.
- Funding support for two research programs into probability of dam failure (piping and stability) and probability of slope failure, by the University of New South Wales - *see Foster et al, "Risk Assessment - Estimating the Probability of Failure of Embankment Dams from Piping", ANCOLD Bulletin No. 112, August 1999. Further projects continue.*
- Barrister's opinion obtained on the legal implications of risk based decision making - *September 1989.*
- Two Risk Management Forums held with regulators from other industries (Land Planning and Nuclear Safety) - *February 1999 and November 1999.*
- Members and staff involvement with international meetings (for example, Trondheim 1997) and contacts with overseas workers.
- Members and staff involvement with preparation of ANCOLD and ICOLD documents on risk assessment.
- All prescribed dams rated for risk as a guide to priority for action, and to assist state emergency service with priorities for flood planning. Rating is a qualitative points allocation system that takes account of:
    - flood capacity
    - earthquake withstand capacity
    - vulnerability to piping
    - static stability status
    - conduit design (that is, whether there is an unencased metal pressure conduit in an embankment dam)
    - documentation status (operations and maintenance manual, dam safety emergency plan)
    - consequences in event of dam failure.

SAFETY UPGRADE HISTORY

- 35 Dams Upgraded since DSC commenced operation.
- Range from small projects to A$150 million (US$96 million).
- Reasons
  - 29 cases flood capacity (11 concrete, 18 embankment)
  - 3 for earthquake withstand capacity (all embankment)
  - 10 for stability or piping safety (5 concrete, 5 embankment).
- 19 other dams are currently listed as having significant safety risks.
- Other dams have minor deficiencies.
- And there are dams where safety questions are still under investigation.
- All upgrades for flood deficiency have been to PMF capacity where failure would be expected to cause loss of life. A capacity less than 0.5 PMF was the basis for high priority remedial action.
- A sub-PMF upgrade has been accepted for one small dam (5m high) on basis that incremental risk to life has become acceptable at that spillway capacity (base safety condition).
- Another small dam (11m high) has been accepted with a sub-PMF capacity on the basis that a flood warning system, which has been proved effective over several flood events, means that loss of life would not be expected in the event the dam fails.
- There has been only one explicitly risk based decision to accept a dam, with its present sub-PMF spillway capacity, on the basis that risks to life are acceptably low. Dam is 29m high and stores 4800ML. The population at risk is 4 persons. A permanent flood warning system is in place and is regularly exercised.
- Two cases that may involve a risk-based decision, but which are yet to be determined, are outlined in the following sections.

FIRST CASE

- Earth and rockfill dam, 31m high, 13,000ML reservoir volume.
- Catchment area 120km^{2}.
- Main water supply source for provincial University City of some 20,000 people.
- Spillway capacity a little over 0.5PMF.
- Dam upgrade to PMF capacity would cost some a$15 million
- There are 7 dwellings, about 20 people, at risk. First dwelling over 30km downstream of dam. Population at risk is now within the area of the local government authority, which owns the dam.
- Owner investigating a risk based solution on basis that a permanent warning and evacuation plan will ensure acceptably low risks to the population at risk.
- DSC has said it is prepared to consider a risk based solution, provided:
  - there is a formal public consultation program
  - there is general community acceptance
  - there is a plan to ensure the long term effectiveness of warning and evacuation.
- State Emergency Service (SES) has written to the owner noting that the proposal involves a transfer of risk from the owner to SES and the population at risk - these concerns are not yet resolved.
- It is difficult to predict the outcome at this stage.

SECOND CASE

- Earthfill dam, 21m high, 5400ML reservoir capacity.
- Catchment area 100km^{2}.
- Sole source of water for a small rural town of 2,000 people. Town has been in decline due to closure of major rail junction.
- Spillway capacity is less than 0.25PMF.
- Upgrade to PMF capacity would likely cost A$15million.
- Dam is located in hilly country but valley suddenly becomes a wide flat plain some 5km downstream.
- Two dwellings at risk in hill country and some twenty on the plain - perhaps 80 people all told.
- Townspeople incapable of funding an upgrade.
- Solution not yet identified, but may involve a mix of:
  - non-structural measures (purchase of the dwellings in the hill country close to the dam)
  - base safety condition (some increase in spillway capacity so as to flood the homes on the plain prior to dambreak), thereby ensuring there is an acceptably low incremental risk to life for those living on the plain
  - reducing risks to life by a permanent warning and evacuation plan.
- A solution based on risk assessment demonstrating acceptably low risks to life may well be proposed.
- DSC would be sympathetic, subject to community acceptance and a long term plan to maintain the effectiveness of warning and evacuation. Accountabilities and responsibilities in the event of a failure would need to be clearly identified.

LIFE SAFETY CRITERIA

- In principle, DSC sees that it is reasonable to set life safety criteria, since inherently hazardous facilities inevitably impose a small risk on the community.

- DSC is legally protected in making policy decisions provided it takes account of relevant factors in a responsible and reasonable way.

- Before adopting or setting life safety criteria, DSC is concerned to exercise due diligence by establishing what is done in other industries and elsewhere in the world, and by the dams engineering profession worldwide. Hence the risk management forums it has organised, and the efforts to interact with overseas practitioners.

- These efforts have revealed differences in approach and in the way that individual and societal risks are calculated, factors which complicate comparison of life safety criteria.

- There is a question over the ANCOLD 1994 tolerable individual risk to the person or group most at risk (10^{-4} chance per annum). This question arises from the values in use in the land planning field (10^{-5} chance per annum by UK Health and Safety Executive) and their more conservative method of computing risk (exposure all of the time and no allowance for evacuation).

- At this time, DSC is comfortable with the ANCOLD view that F-N curves are a practical means of considering societal risk, whilst recognising that the issue is controversial. The latest criteria, proposed by ANCOLD but still under consideration, are on the following page.

- In line with the latest ANCOLD thinking, DSC sees that life safety criteria should be a guide rather than a hard prescriptive “pass or no pass” boundary, with emphasis on the limit of tolerability and use of the ALARP (As Low As Reasonably Practicable) principle to decide what is safe enough.

- DSC shares the ANCOLD view that expected value has limited usefulness as a measure of risk for dams, especially life safety risks, primarily because of the very rare but catastrophic nature of dam failure. Also expected value hides information.

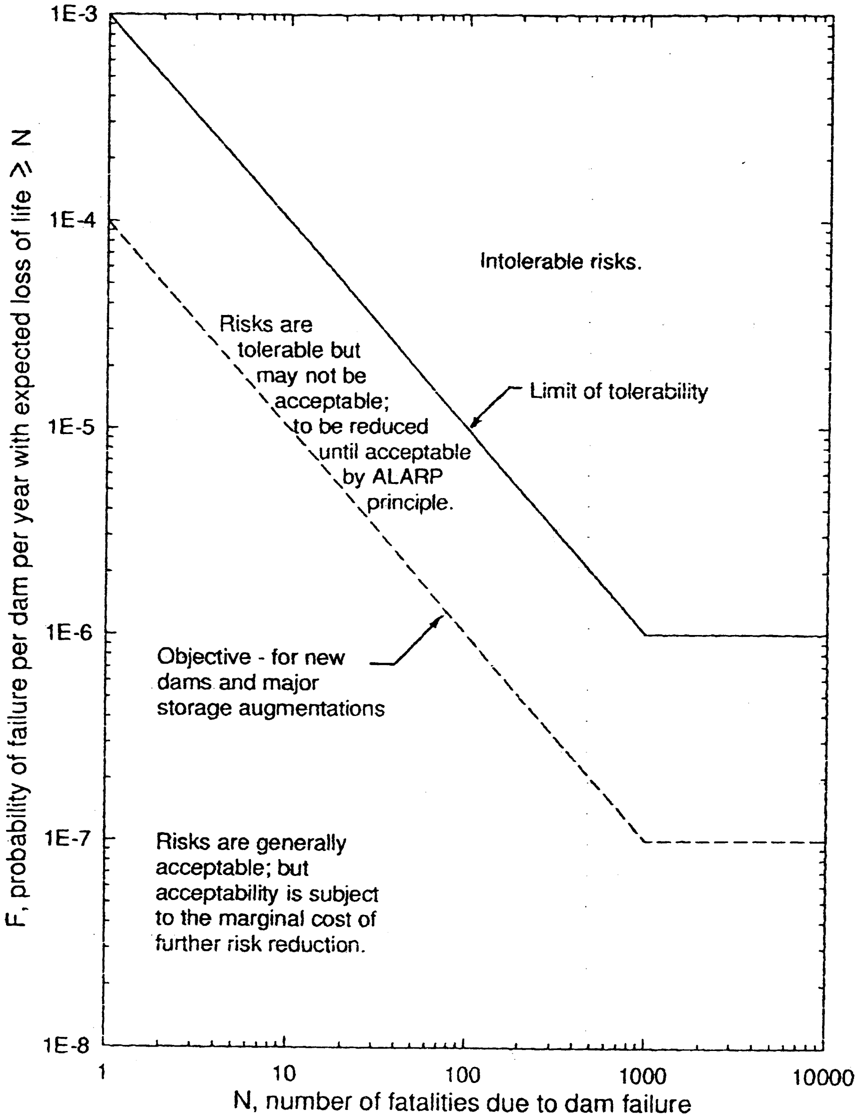
- The f,N pairs (probability of failure and expected life loss for each failure scenario) are basic outputs of risk assessment and should always be presented.

- In answer to those who say that the setting of life safety criteria is not a matter for engineers, but for the body politic and the wider community, DSC would say that, by that logic, the setting of spillway capacity and earthquake design standards is also a matter for the body politic, since these indirectly set life safety criteria.

- In principle, it would be desirable for the body politic and the wider community to endorse life safety criteria, but it is doubtful there is a means of getting an informed debate. A publicly exhibited issues paper has been suggested. Government endorsement of life safety criteria would be the ideal, but ultimately it may be that DSC, as regulator, will need to set criteria.

- DSC is aware that the dams industry in some countries does not support risk to life criteria.

PROPOSED REVISED SOCIETAL RISK CRITERIA



Important note: **Where fatalities are expected in the event of dam failure, consultation with the affected public is required as part of the final decision process.**

CONSTRUCTION FLOOD PROVISION

AN INSIGHT AND A QUESTION

- The ANCOLD guidelines on design floods for dams, 1986, suggest that for a one year period of exposure, an acceptable flood provision during construction is the Annual Exceedance Probability (AEP) 1 in 100 event where there are serious failure consequences such as loss of life.
- The rationale is that this provision gives the same risk of dam failure during construction as would apply for a dam in service that is safe up to the AEP 1 in 10,000 event over a life of 100 years. A similar approach is taken in the United Kingdom
- How does risk assessment see the issue?
- If an embankment dam is overtopped during construction when the bank is just below spillway level, the resultant flood will have much the same severity as the failure of the dam in service
- If there are people living in the valley not far downstream from the dam, the conditional probability of fatality, given dam failure, could be around 0.5
- A probability of dam failure of 1 in 100 per annum, multiplied by a conditional probability of fatality of 0.5, gives an imposed individual risk of 5.0E-03 (1 in 200) per annum.
- This is a far higher increment of individual risk than allowed by any life safety criteria, and is several times the background risk for young adults
- The question is: "is it permissible to impose on citizens, for a short period of one year, a risk that is several times their background risk?"
- Risk assessment can enable regulators to see issues from another angle.

SITUATION ELSEWHERE IN AUSTRALIA

- **QUEENSLAND**

There is legislation with powers to control and ensure the safety of all dams in the state. The regulator is a unit within the Department of Natural Resources. Risk assessment is being used to examine the safety status of a number of dams. The regulator is seeking to develop specific risk management policies.

- **VICTORIA**

There are several areas of legislation covering safety of publicly owned and large private dams. However, as the vast majority of medium and large dams are owned by Water Authorities, the water industry regulator, which is a unit within the Department of Natural Resources and Environment, has a key role. A useful distinction has been made between "business" and "community" risks. A Business Risk Assessment of Water Authority dams, completed in 1998/99 was a condition for government funding assistance to overcome safety deficiencies in dams allocated to newly established corporate water authorities, in order to cost effectively maximise risk reduction in implementing dam safety improvements. A review of the regulatory framework and development of appropriate regulations for all potentially hazardous dams is currently under consideration.

- **TASMANIA**

There is no legislation and no regulator, although an earlier proposal for dam safety legislation, that includes establishment of a regulator, may come under consideration again in the near future. There is a Dam Safety Committee that was established by government direction, but its role is restricted to gathering information on dams. Risk assessments are being undertaken for some dams.

- **SOUTH AUSTRALIA**

There is no legislation and no regulator. The major owner (a corporatised former government agency) uses risk assessment to provide for more informed decisions and as a basis for priorities.

- **WESTERN AUSTRALIA**

Legislation was passed in 1978, but has never been proclaimed. There is currently no regulation. The major owner (a corporatised former government agency) uses risk evaluations as a basis for priorities and to ensure that major risks are identified and evaluated.

CONCLUSION

- Whilst DSC has strong powers, its policy is to work co-operatively with owners, usually through personal contact, to achieve and maintain acceptable dam safety. Use of its powers is rare.

- Almost all owners recognise it is in their interests to achieve and maintain proper dam safety management, once they become aware of their liabilities. DSC sees risk assessment as a useful tool to paint a full picture of liabilities.

- Portfolio risk assessments undertaken by major dam owners have assisted DSC in its policy of achieving the maximum rate of risk reduction.

- In the view of DSC, risk assessment methodologies and criteria are not yet sufficiently developed to provide a general basis for a conclusive assessment of dam safety status, or for determining required safety levels.

- DSC is interested in, and supports, the further development of risk assessment methodologies and criteria.

- Whilst recognising the shortcomings of present risk assessment methodologies and criteria, DSC asks what better tools are available as a basis for assigning priorities. Risk assessment provides a basis for comparison of risks across owners, across dams, across elements of a dam and across failure modes.

AREAS FOR IMPROVEMENT, BASED ON EXPERIENCE WITH RISK ASSESSMENT FOR DAMS IN VICTORIA, AUSTRALIA

David Watson, Department of Natural Resources and Environment, Victoria

Risk assessment is continuing to evolve with a number of key issues subject to vigorous debate and extensive research, in particular:

- Lack of confidence in subjective numerical probabilities (likelihood), inability to determine certain probabilities (eg. Probable Maximum Flood) and not providing adequate analytical rigour to satisfy legal scrutiny;
- The contrary view that probability figures are an effective common unit for risk assessment (just like dollars are for financial considerations), provided adequate uncertainty considerations are included in the assessment;
- Ability to predict consequences. In particular, incremental potential life loss compared with population at risk because of human behaviour and other prevailing circumstances at the time of an incident and significant concern over existing techniques such as DeKay-McClelland;
- Concepts of acceptable risk levels (such as limit and objective lines on F-N charts) and various approaches in terms of individual and societal risk and expected value and community expectations;
- The quantification of environmental and social impacts;
- The variations in results between deterministic and risk-based, acceptable safety levels have resulted in many dam owners adopting deterministic guidelines because they are often seen as more legally defendable. This occurs even if the guidelines produce significant variations in risk for different events or risk levels are assessed as higher than designated limit criteria;
- Risk levels can vary significantly depending on the methodology used and the level of subjectivity;
- Risk assessments need to be performed only if deterministic methods identify deficiencies versus the view that risk assessment is to effectively identify potential risks and thus deficiencies;
- The approach based on staged refinement (lowest level to give adequate confidence) incorporating appropriate uncertainty analysis and recognising cost-effective assessment;
- The applicability of F-N and f-N charts and other forms of risk presentations such as cost-to-save-a-life;
- The value of insurance in achieving and maintaining appropriate levels of dam safety;
- The level, type and success of public consultation and associated public education on risk issues;

- Recognising that the current deterministic approach has, in reality, an empirical risk basis, notwithstanding that it is often hidden, sometimes inconsistent and does not necessarily address all risks effectively. Nevertheless, the deterministic approach has the benefit, unlike current risk management concepts, of many years of refinement and acceptance;

- Risk-based decisions may be disguised as those based on deterministic methods;

- Recognising that risk management initiatives are not synonymous with cost savings but have the potential, if tackled correctly, to achieve a cost-effective outcome; and

- Further research is needed before consistent, transparent and defendable risk-based decision-making can be achieved with a high level of confidence.

Although risk management concepts are becoming established and their value is increasingly accepted, areas still remain where uncertainties are significant. The Department has recognised some of these areas and is actively involved, through funding of research programs and by direct involvement in ANCOLD guideline development. The larger projects where funding has been provided include the Annual Exceedance Probability of Probable Maximum Precipitation, piping failure of embankments and life loss estimation due to dam failures.

The Department recently commissioned a pilot study to assist in identifying all referable and larger dams through a satellite imaging and digital mapping technique. If shown to be successful, the project will be extended to identify the hazard rating on all referable and large dams. The objective is the creation of a comprehensive database consisting of basic details and consequence information that can be readily updated. While this information will be used for dam safety regulatory purposes, its value for resource management would also be significant.

CONCLUSIONS

Water authority business risk assessments of their portfolios of dams have provided:

- Confidence that the next five-year program of improvements should address the highest priority improvements cost effectively,

- Significant enhancement of the State's dams data base and a state-wide risk reduction profile which can be used as a performance indicator,

- Heightened awareness of directors' liability and management's risk management obligations and responsibilities, including incident response and recovery.

Risk management is seen as critical to continually improving understanding and achieving an acceptable level of dam safety. More specifically:

- Risk assessment for dams is a valuable tool for better managing dams. This tool provides processes for:

  (a) Identification and addressing risks;
  (b) Prioritising risk;
  (c) Maximising reduction in liability cost effectively;
  (d) Demonstrating due diligence/duty of care;
  (e) Interim risk reduction measures;

(f) Emergency management;
(g) Validation; and
(h) Disclosure and reporting.

- Risk assessment enhances but does not replace traditional engineering guideline/deterministic safety analysis. The traditional deterministic approach is required to provide the basis for determining

(a) The performance capability of a dam against the likelihood of failure and areas of works;
(b) Operation, maintenance and other management and emergency potential deficiencies; and
(c) Technical improvements required.

- Risk assessment provides a structured methodology to ascertain the relative risk position against reference criteria such as ANCOLD guidelines:

(a) For an individual dam;
(b) Across a portfolio of dams;
(c) Across the dam owners' businesses;
(d) Incorporate the concept of ALARP;
(e) Low-cost risk reduction; and
(f) Prioritising improvements.

Key issues involve:

(a) Current probability assessments which are not providing sufficient analytical rigour;
(b) Estimates of potential life loss;
(c) Determining acceptable levels of risk versus traditional deterministic methods; and
(d) Public consultation approaches.

It is recognised that risk assessment is an evolving process. Much investigation, research and development, peer review, debate and consultation needs to continue to achieve a wider level of confidence in the value of risk assessment for dam safety decision-making. It is comforting to note that these actions are continuing to take place in different parts of the world, with Australia being one of the leading players.

While it is likely that a regulatory framework may not be able to be solely established on risk performance at this time in view of the areas of debate yet to be resolved, any future dam safety regulation developed or reviewed should:

- Promote risk management, not hinder it, and
- Be the platform on which regulation is based.

Risk management guidelines for dams should be developed and reviewed to reflect positive benefits, current issues and regulatory and legal implications. Such guidelines should recognise the disparate audiences that need to understand them from dam owners through to technocrats.

MEMORANDUM

LAND & WATER
CONSERVATION

To: Norm Himsley
Executive Engineer
Dams Safety Committee

From: Dermot Armstrong, Manager, Litigation, for Director, Legal Services
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Phone: (02) 9895 7339, Fax: (02) 9891-2887

REC'D
14 AUG 1998
DAMS SAFETY COMMITTEE

Date: 10 August, 1998

Subject: Advice - Liability - Risk Assessment

10.104.005

Issue:

Precis of the advice of peter McClellan QC concerning the risks to the DSC of assessing dams on a risk assessment basis.

Commentary:

Attached is a copy of the advice received from Mr McClellan QC.

For your assistance, I provide the following precis and commentary:

Mr McClellan QC was requested to advise -

1. is the DSC able to take the proposed new approach to dam safety assessment?
2. what risks does the DSC take by embarking on the new approach?
3. what precautions might be taken in order to minimise risks?
4. what risk is there to the DSC if it attempts to rely upon the standards based approach or the risk based approach in its' discretion according to the case in hand?

In order to answer these questions he provided the following analysis of the relevant law.

S.14 of the Dams Safety Act is the foundation for the DSC setting standards of dam safety.

It is obvious that the DSC cannot require a standard of safety which ensures that there is no danger arising from the existence of a dam since that would be too restrictive

Whether the DSC owes a duty of care to any person is not certain.

Subject: Advice - Liability - Risk Assessment

The law in relation to the duty of care of public authorities has been the subject of several significant cases.

Although not yet settled, it seems that in order to establish a liability in negligence the law may look for

- reasonable foreseeability on the part of a wrongdoer that particular conduct would be likely to cause harm to the person who suffered injury or loss
- a "relationship" between the wrongdoer and the person who suffers injury or loss
- it must be "fair, just and reasonable" to impose a duty upon the wrongdoer towards the person who suffered loss or injury.

When analysing the issue of duty of care (whether using the last mentioned framework of questions or not) the Courts take the view that they are not competent to review decisions by public authorities concerning use of resources (policy determinations).

Ultimately, whether a duty of care exists would turn on issues of policy - the decision to take a risk assessment approach is a policy decision. Provided the decision to take this approach is rational and made taking into account relevant matters Courts will not find the approach objectionable. However, the putting into effect of a decision must be without negligence.

A risk assessment approach is accepted in other hazardous industries and so must be acceptable in the context of dam safety but fundamental to its' adoption and application is identification of the level of safety parameters. Reference to standards used in other hazardous industries may be a useful guide for the DSC.

It is not necessary for community views concerning risk assessment to be obtained but the DSC may avoid complaint subsequently if views are obtained.

<u>Summary</u>

- The DSC is able to adopt a risk assessment approach to determining dam safety standards
- The DSC must approach such a policy with care and should be as fully informed as to acceptable standards in the dam safety industry and other industries as is reasonably possible.
- Implementation of the policy must be done with great care.

Dermot Armstrong

RECEIVED
14 AUG 1998
DAMS SAFETY COMMITTEE

IN THE MATTER OF

ADVICE CONCERNING THE DAMS SAFETY COMMITTEE AND RISK ASSESSMENT OF DAM SAFETY

MEMORANDUM OF ADVICE

5 August 1998

Mr Paul Percival,
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IN THE MATTER OF

ADVICE CONCERNING THE DAMS SAFETY COMMITTEE AND RISK ASSESSMENT OF DAM SAFETY

MEMORANDUM OF ADVICE

My instructing solicitor acts for the Director of Legal Services, Department of Land and Water Conservation, and seeks advice in a matter concerning the New South Wales Dams Safety Committee.

The Dams Safety Committee ("DSC") is a statutory corporation created by s.7 of the *Dams Safety Act* 1978 ("the Act"). The functions of the DSC are set out in s.14 of the Act. A fundamental function is to oversight the safety of dams in New South Wales. The DSC carries out its functions by assessing the safety of dam structures and if deemed necessary, prescribing the dam, which has the consequence that various powers can be exercised in relation to the facility.

The traditional method of assessing dam safety is a "deterministic, standards based", approach. Generally, this approach involves specifying certain fixed categories of hazard rating (related to consequences of a dam failure) in relation to structures and requiring certain standards of safety to apply to a structure which comes within each category. If the consequences of dam failure are not serious (that is, no loss of life and low economic and environmental impacts are expected) the DSC will accept an appreciable risk of failure. The standards based approach, in so far as it relates the acceptable chance of failure to the consequences, is a relatively simple and fundamental intuitive form of risk decision-making.

The DSC has been considering whether to alter its approach to dam safety and apply an overtly "risk assessment" approach. I understand that although this form of approach is used in relation to other potentially hazardous facilities, it has not so far been adopted by other dam safety authorities. This has raised concern for the DSC as to whether or not its Committee may be subject to any risk if it adopts this different approach.

The fundamental concern is that if this approach is adopted the DSC would be accepting criteria which, in extreme situations, would contemplate a loss of life ranging from a few to hundreds. Several countries, including Canada, the USA, Netherlands and Norway, are developing risk based methodology and criteria for dams but the DSC would be the first regulatory authority to accept safety decisions based on acceptable risk to life criteria. In these circumstances, I am asked to advise in relation to the following questions:

1. *Is the DSC able to take the proposed new approach to dam safety assessment?*
2. *What risks does the DSC take by embarking on the new approach?*
3. *What precautions might be taken in order to minimise risks?*
4. *What risk is there to the DSC if it attempts to rely upon the standards based approach or the risk based approach in its discretion according to the case in hand?*

Section 14(d) of the Act provides that a function of the DSC is "to formulate measures to ensure the safety of dams". This provision provides the foundation for the DSC setting standards for dam safety. I am instructed, although reflection would make it obvious, that in identifying any standard it is not possible for the DSC to absolutely ensure that there is no danger arising from the existence of a dam. To take that approach would involve imposing a standard of safety which was so unrestrictive that the benefit from the dam would be largely lost.

The DSC is a government agency and supervises structures which are, I assume, fundamentally owned by government in its various forms. Undoubtedly it owes obligations to those who own the dams or who may be at risk in the event of a failure. However, whether those obligations give rise to a duty of care is not certain.

The law in relation to the liability of public authorities has been discussed in many cases in recent years. It has been held that a body such as a council or other government agency may owe a duty of care when exercising its statutory powers or duties (see *Sutherland Shire Council v Heyman* (1985) 157 CLR 524). However, the basis upon which the duty may be owed was not determined in any uniform manner in that case. Although the subject of much critical comment (see *Pyrenees Shire Council v Day* (1998) 72 ALJR 152), proximity has survived as the concept which must exist before there is a duty of care. Foreseeability of loss alone is insufficient; proximity depends upon the relationship between the particular authority and the individual or corporation seeking to sustain liability. Although embraced by Mason J in *Sutherland Shire Council v Hayman* and McHugh J in *Parramatta City Council v Lutz* (1988) 12 NSWLR 293, general reliance has been rejected by the High Court by a majority in *Pyrenees*. The question as framed by Giles J in *Central Coast Leagues Club v Gosford City Council & Ors* (June 1998, Giles CJ, ComDiv - unreported) is *"Was there the known reliance and assumption of responsibility normally of significance in establishing proximity?"*

It is not apparent that in any particular circumstance a prospective plaintiff would be able to establish reliance in the event of the failure of a dam. I suspect that in most cases any person injured by the collapse of the dam wall would have no knowledge and would not have had made any decision dependent upon knowledge of the role of the DSC in assessing the structural adequacy of the dam or any knowledge of the design standard which it accepted as adequate. Accordingly, such a person would not be able to establish proximity and in the absence of general reliance (which for my own part was an attractive doctrine) liability would depend upon the court's view of the relationship between the particular dam, the DSC's role and the individual. Largely it would become a policy decision for the court.

Although it is not settled, I believe it is at least possible that the High Court may unify around the approach expressed by the House of Lords in *Caparo Industries Plc v Dickman* [1990] 2 AC 605 which was embraced by Kirby J in *Pyrenees* (p.201). Kirby J expressed it in these terms:

> *"To decide whether a legal duty of care exists the decision maker must ask three questions:*
>
> *1. Was it reasonably foreseeable to the alleged wrongdoer the particular conduct or an omission on its part would be likely to cause harm to the person who has suffered damage or a person in the same position?*
>
> *2. Does there exist between the alleged wrongdoer and such person a relationship characterised by the law as one of 'proximity' or 'neighbourhood'?*
>
> *3. If so, is it fair, just and reasonable that the law should impose a duty of a given scope upon the alleged wrongdoer for the benefit of such a person?"*

Kirby J proceeds to analyse these concepts in the context of the facts of that case. In the course of the discussion he expressed the view that a court is not necessarily competent to review the decisions of public authorities as to the use of their resources.

> *"Typically a court does not have the financial, economic, social or political factors or constraints, before it that are available to the officers of the public authority in the deployment of its resources. Courts have drawn a distinction between 'policy.' decisions which they will leave to the public authority itself and 'operational' decisions which they will have competence to evaluate. Although the distinction is far from perfect, it has some validity."*

He accepted the injunction of Lord Hoffmann in *Stovin v Wise* [1996] AC 923 at 958 that courts should be wary of undue intervention in decisions having significant implications for the budgets of public authorities because:

> *"This would distort the priorities of local authorities, which would be bound to try to play safe by increasing their spending on road improvements rather than risk enormous liabilities for personal injury accidents. They will spend less on education or social services. I think that it is important, before extending the duty of care owed by public*

> *authorities, to consider the cost to the community of the defensive measures which they are likely to take in order to avoid liability."*

It is apparent, in my opinion, that whether or not a duty of care could arise in the present circumstances would ultimately turn upon considerations of policy matters. As the approach which is proposed is a reflection of an endeavour to identify a cost effective method of providing for satisfactory water storage, I do not believe, provided the decision is based upon a rational analysis of relevant matters and is directed towards maximising the efficient use of resources, a court would be likely to impose liability in the event of failure. Of course the decision itself and the calculations on which it is based must be free of negligent error.

In determining its requirements for dam safety, I am instructed that the DSC relies on the expertise of its own members, which includes government and non-government engineers experienced in dam engineering. There are Australia-wide guidelines and approaches to the problem identified through the National Conference body, the Australian National Committee on Large Dams ("ANCOLD"). ANCOLD is not a corporate body, but I understand it is intended to become an incorporated association registered in New South Wales by December 1998. ANCOLD publishes papers which reflect the views and recommendations of this "peak" national forum. The DSC is also in contact with inter-state government agencies which deal with dam safety, but I understand no other State has established an oversighting agency with the broad role of the New South Wales DSC. The DSC also examines international practice through an international forum of engineers concerned with dam safety, the International Commission on Large Dams ("ICOLD"). ICOLD operates in a similar way to ANCOLD in publishing papers recommending practices and procedures. The DSC also has regular contact with foreign government bodies concerned with dam safety, particularly the US Corps of Engineers, US Bureau of Reclamation, New Zealand, Canadian and Scandinavian dam safety agencies.

I understand that ICOLD and ANCOLD have been examining the assessment of dam safety on a risk management basis for some years. Some of the members of the DSC have been significantly involved in these tasks. Although the DSC always takes notice of any publication by ANCOLD, it has maintained an independent mind in relation to the guidelines which it adopts.

In the present case the DSC has considered papers published by ANCOLD on the risk assessment approach to dam safety. It is now seeking to ensure that the extent to which it adopts a risk assessment approach is acceptable within the dam engineering community as well as the community at large. I have examined the paper prepared by the DSC entitled "Risk Assessment in Dam Safety Evaluation". It is not necessary for me to discuss it in detail in this advice. However, it is plain that the approach contemplated is one which reflects an approach used by many industries engaged in the task of endeavouring to provide satisfactory levels of safety, having regard to the inherent risks involved in their activity. This is true of all industries using hazardous chemicals, power generating facilities, and a great many other essential processes which nevertheless involve risk to property and life. There can be no question but that the approach is an acceptable method of assessment. However, fundamental to its adoption and application in particular cases would be the level of safety which would be required of any particular facility. Identification of these parameters is fundamental.

In this respect, I note that there does not appear to be any world standard to which reference could be made. I assume that the application of this method of analysis to other industries has given rise to criteria which are accepted as appropriate having regard to the risk to life and property. It may be that reference to these standards would provide a useful guide for dam safety.

The paper raises a number of questions. I shall not set them all out in this advice. However, it follows from my remarks that in my opinion the risk based decision-making criteria contemplated by the DSC should be approached by having particular regard to what occurs in other industries. I do not believe that legal or community views are essential to the adoption of appropriate criteria, nor do I believe that if the community is not consulted, criteria which are adopted after careful consideration would be set aside by any court. However, it may be, because the question is of such significance, in any particular case the matter should be the subject of public discussion. This will inevitably occur if a public authority is contemplating the construction of a new dam, for Part 5 of the *Environmental Planning and Assessment Act* would require the publication of an Environmental Impact Statement which would raise these issues for public discussion. The situation is not the same when the standard to be applied to an existing facility is being considered. However, it may be that it would be prudent, in the interests of the DSC, if a document was published which invited public comment. Indeed, it may be that the best approach before new criteria are adopted would be for a formal publication of an issues paper, with wide advertising and invitation for public submission, to be incorporated into the decision-making process. If this was done it could not subsequently be argued that the decision was not made after appropriate consultation and having regard to all relevant policy matters.

Accordingly, having regard to the discussion of the difficult questions of liability of public authorities in recent cases, I am of the view that provided the DSC adopts an approach to the safety of dams which reflects contemporary thinking in relation to public safety issues, it could not be liable in negligence in the event of a dam failure. However, the task of adopting a new standard requires appropriate care to be exercised by the DSC and adoption of criteria which are rational and defensible having regarding to contemporary standards in other industries. In my opinion it would be appropriate to approach the adoption of new standards through the release of documentation calling for public discussion, and decisions thereafter being made which have regard to all of the relevant community interests.

With respect to the specific questions, I answer as follows:

1. Yes.

2. The DSC does not take any particular risks. However, it is important that it undertakes the task of identifying new standard with appropriate care. If the standards which it

adopted were not rational or defensible, it may be that a court would say they fall outside acceptable policy criteria and liability could arise.

3. The DSC should be careful to undertake the adoption of new standards by having regard to current contemporary thinking throughout the world on the safety of dams. An attempt should be made to identify the approach taken in other industries and make the approach to dam safety compatible with the method of analysing risks and the adoption of appropriate risk levels in other industries which necessarily create hazard for life and property.

4. I do not believe, if the steps I have indicated are taken, the DSC is subject to any risk. I do not believe that, provided it is rational, a standard which, for good public policy reasons necessarily contemplates that in extreme circumstances there may be danger to life, would attract any common law or criminal liability. However, the task must be undertaken with great care and having regard to all relevant interests.

PETER McCLELLAN QC

Chambers
5 August 1998

ANCOLD GUIDELINES ON RISK ASSESSMENT

POSITION PAPER ON REVISED CRITERIA

FOR

ACCEPTABLE RISK TO LIFE

by

ANCOLD Working Group on Risk Assessment

August 1998

Please forward your endorsement, concerns or
comments re this paper to Len McDonald, Convenor,

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By February 1999 preferably, or at any other time
during 1999

ANCOLD GUIDELINES ON RISK ASSESSMENT

POSITION PAPER ON REVISED CRITERIA

FOR

ACCEPTABLE RISK TO LIFE

by

ANCOLD Working Group on Risk Assessment

INTRODUCTION

In 1994 ANCOLD (Australian National Committee on Large Dams) published Guidelines on Risk Assessment for the first time. That document sought to identify the fundamental concepts that underpin risk assessment and to provide a philosophic foundation that would enable practitioners to start applying risk assessment principles in the evaluation of dam safety. In the 1994 Guidelines, ANCOLD took the controversial step of setting quantitative criteria for acceptable risk to life after considering actual and proposed criteria in land use planning and in the chemical and nuclear industries. By the early 1990's, there was almost universal acceptance that the earlier trend to value human life in dollar terms (see for example. ASCE, 1973) was not appropriate to contemporary societal values. In other industries, the concept of placing limits on the probability of life loss was emerging as the preferred way of dealing with risks to human populations. Nevertheless very few, jurisdictions had actually established quantitative criteria for acceptable risk to life. ANCOLD took the view that it was better to provide clear guidance by way of quantitative criteria, albeit conservative criteria initially, than to make vague statements about the importance of limiting risks to life. The need to stand ready to review those criteria as knowledge and experience were gained, was recognised at the time.

The 1994 Guidelines have been very successful in promoting widespread integration of risk assessment into the process of dam safety evaluation in Australia. Understandably, as the Guidelines were put into practice, a need soon emerged for clarifications. Also as better understanding was achieved through experience in applying the Guidelines, improvements were suggested. As a means of dealing with such issues in this rapidly developing field, ANCOLD appointed a working group charged with preparing a Commentary on the 1994 Guidelines. The group has been active since late 1995 and now has ten members. Developments, both in Australia and in other countries, have been so rapid that it is now apparent that updated Guidelines, rather than a Commentary, are needed to keep ANCOLD members abreast of current practice. The ANCOLD Executive has approved of the production of new Guidelines and drafting of the document is well in hand.

In the interim, the working group has substantially finalised its position on criteria for acceptable risk to life. The primary purpose of this statement is to apprise practitioners of the updated criteria so that they can be taken into consideration in dam safety reviews, pending publication of the new Guidelines. A secondary purpose is to provide an opportunity for debate on the criteria and to identify any aspects requiring clarification, prior to publication of the updated Guidelines. Risk to life criteria are a critically important facet of risk-based decision making. It remains the case that ANCOLD is the only national body to have set quantitative criteria for acceptable risk to life in the evaluation of dam safety. For these reasons it is desirable that the criteria are publicised as widely as possible and that controversial aspects are vigorously debated. Also, for the same reasons, it is critically important that the criteria are applied cautiously and that decision makers consider them together with traditional deterministic assessments and in light of consultation with the affected public.

MAIN FEATURES OF THE 1994 CRITERIA

Sub-section 2.7 of the 1994 Guidelines provides the rationale for the risk to life criteria proposed in that document and Guideline G.12 gives the criteria.

Individual Risk

Individual Risk is the increment of risk imposed on particular persons by the existence of a dam. People live with a background risk of death throughout their lives. Figure 2.4 of the 1994 Guidelines is reproduced from the work of Chicken (1975). It shows that the average background risk of death in Britain, at that time, started at about 2E-02 per annum at birth and declined rapidly to a minimum value of 5E-04 per annum at ages eight through fifteen (later referred to as the "young person" risk). Thereafter the risk increased steadily with age, reaching 1E-01per annum at age eighty for example. Individual Risk criteria aim to limit the increment of risk imposed by a facility such as a dam to a small fraction of the average background risk level for young people in the age bracket eight to fifteen.

The Individual Risk criteria were expressed as a **Limit** of tolerability (higher risks are unacceptable in all circumstances) and an **Objective** that owners of dams should aim to meet (lower risks are negligible and are generally acceptable). Between these bounds the acceptability of risk was to be judged according to the **ALARP** (As Low As Reasonably Practicable) principle.

The ALARP principle basically states that risks should be regarded as tolerable only if risk reduction is impracticable or if the cost is grossly disproportionate to the improvement gained. Consideration of ALARP is meant to be a stern test and is well described by HSE (1992). In the 1994 Guidelines, the criteria required that new dams, and modifications of existing dams, meet the Objective risk levels. Thus, for existing dams, the ALARP question was: "Is it impracticable or disproportionately costly to reduce the risks of this dam to the Objective level, given that the present risk level is lower than the Limit value?" If the answer was "yes", the existing situation would be acceptable. If the answer was "no", the risk was to be reduced to the Objective level. If the existing risk was higher than the Limit value, the risk was to be reduced to the Objective value and ALARP did not enter into consideration.

Individual Risk is **the total increment of risk imposed on individuals** by a dam. Thus the risks contributed by all failure modes and scenarios need to be combined to obtain the overall risk. The chance of death per annum contributed by each flood and earthquake failure mode, is the product of:

- the annual probability of the flood or earthquake event
- the conditional probability of dam failure, given the event
- the conditional probability of the individual's death, given dam failure

The annual chance of death contributed by failures under normal operating conditions, is the product of:

- the annual probability of a dangerous condition, such as piping or a bank slide, occurring
- the conditional probability of dam failure, given the piping or the slide or other dangerous condition
- the conditional probability of the individual's death, given dam failure

A difficulty arises with the estimation of Individual Risk where only one aspect of dam safety, such as spillway adequacy, is under examination. The updated guidelines will provide some suggestions for dealing with such situations in a practical way.

The 1994 Guidelines proposed that Individual Risk would be computed as the **average Individual Risk over the population at risk**, or as the **Individual Risk for the person most at risk.**

The average conditional probability of death, given dam failure, is the expected loss of life (LOL) divided by the population at risk (PAR). A difficulty with the average risk concept is that LOL/PAR declines as the study reach is extended downstream. The fact that average Individual Risk is a function of the extent of the study reach was recognised in the 1994 Guidelines. In an effort to ensure consistency of approach, the "Dambreak Affected Zone" was defined in the 1994 document, in an attempt to have practitioners select the study reach in a uniform way (at least for purposes of computing average Individual Risk).

The Individual Risk for the person most at risk is the value that really matters. In 1994 no consistent way of identifying that person, and then of estimating the conditional probability of death, was recognised and so no real guidance was given. It would be fair to say that the focus was on average Individual Risk in the 1994 Guidelines.

Against this background, the Individual Risk criteria of the 1994 Guidelines were effectively:

- Limit value of average Individual Risk: 1E-05 per annum (2% of young person background risk)
- Limit value of Individual Risk for person most at risk: 1E-04 (20% of young person background risk)
- Objective value of average Individual Risk: 1E-06 per annum (0.2% of young person background risk)
- Objective value of Individual Risk for person most at risk: 1E-05 (2% of young person background risk).

Societal Risk

Societal Risk criteria aim to take account of society's aversion to disasters that involve multiple fatalities. The general principle is that the greater the expected loss of life in the event of dam failure, the lower the acceptable chance of dam failure should be. The present approach to Societal Risk criteria seems to have originated with Farmer (1967) who proposed criteria for the siting of nuclear power plants in Britain. A constant expected value of loss of life (that is the product of the probability of dam failure and the loss of life given failure) as the number of lives lost (N) increases, would require that if the number of lives lost doubled, the acceptable probability of failure would halve. Such an approach is termed "risk neutral" (Rowe, 1981). Those who would make choices that require a reduction in expected value of life loss as the number of lives lost increases, are termed "risk averse" by Rowe. A majority of people seem to be risk averse, based on Rowe's research.

Two features of Societal Risk criteria are:

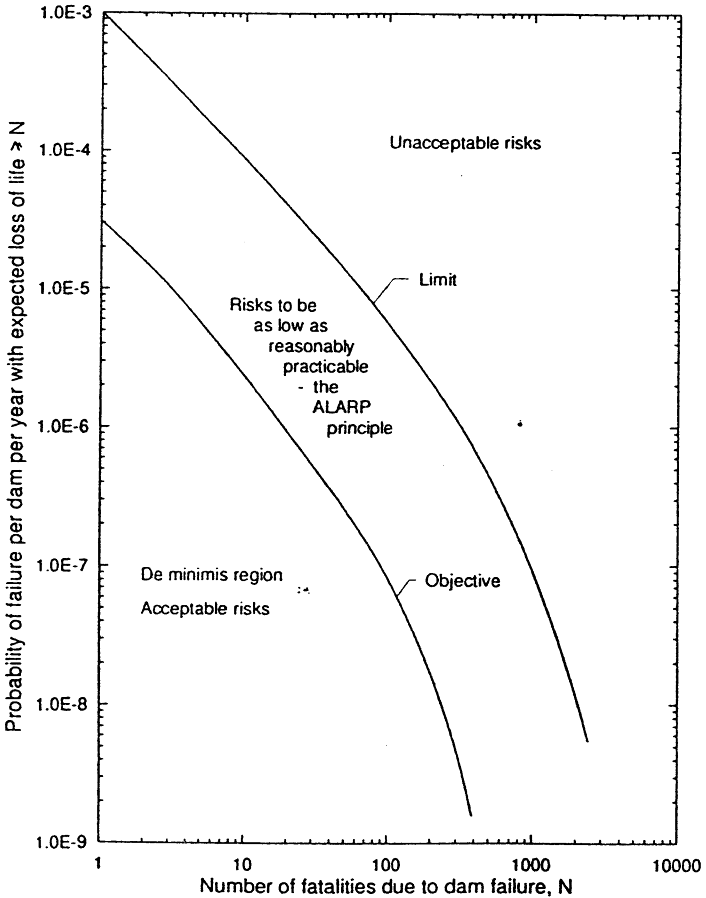
- they are concerned only with the **number of lives lost, and not with the identities** of the persons involved. Thus itinerant campers count equally with permanent residents (contrary to the situation with Individual Risk)
- they are **event based**. Thus each individual dam failure scenario (for example, piping due to earthquake, storage 85% full, night time, summer holiday season) is considered separately in judging whether a dam complies (unlike Individual Risk where the focus is on the total risk posed by the dam).

In the 1994 Guidelines, **the Societal Risk criteria were expressed as F/N curves**, where N is the number of lives lost and F is the probability of failure that results in loss of N or more lives. Thus F is a cumulative distribution function. In the text of the 1994 document, the symbol f was used in the text for the cumulative function, but by convention F is more appropriate. The F/N curves were plotted with both axes to the same log scale, so that a line with a slope of minus 1 represents a constant expected value of life loss. A decrease in expected value as N increases can be achieved by steepening a straight line to a larger constant negative slope or by having a curved line that shows a progressive increase in slope. Farmer (1967) argued for a slope steeper than minus 1, although he was plotting magnitude of radiation release rather than loss of life. In the Netherlands, the approach of a steeper straight line has been adopted in two jurisdictions (see Figures 52 and

53 of CUR, 1990). In both those cases there is a proportionality between the acceptable probability of failure and the square of the number of deaths.

In the 1994 Guidelines, the second approach, of having a progressive increase in slope, was adopted. There are reasons for thinking that the second approach more nearly reflects community values (Higson, 1990). Governments or corporations spend heavily to prevent recurrence of accidents involving many fatalities (Granville rail disaster, Kempsey bus smash). As a result, curves of national accident statistics tend to show a progressive increase in slope as N increases (see Figure 1 of DOP, 1992). The 1994 Guidelines interim criteria for Societal Risk were based on those proposed by Higson (1990) for the nuclear industry. So far as is known, Higson's curves have not been adopted in any other jurisdiction. In 1994, these curves (see Figure 1) seemed defensible, though probably conservative, for dams because they started, at the left hand axis, at probability levels consistent with existing ANCOLD deterministic guidelines (ANCOLD, 1986) and they showed an accelerating reduction in expected value of life loss as N increased.

The concepts of Limit, Objective and ALARP apply with Societal Risk as they do with Individual Risk.



(Refer ANCOLD Figure 2.7 : Interim ANCOLD Societal Risk Criteria)

Figure 1 Interim Societal Risk Criteria of the 1994 Guidelines

It was acknowledged in the 1994 Guidelines that the whole issue of Societal Risk criteria is difficult and controversial. For example, HSE (1989) and DOP (1992) had both considered the issue and had decided not to set quantitative criteria.

Compliance

The final feature of the 1994 Guidelines was that **all criteria were to be satisfied.** Thus a dam would only be regarded as satisfactory if it met the average Individual Risk criterion, the criterion for Individual Risk to the person most at risk, the Societal Risk criterion and the ALARP test, as applicable.

THE REVISED CRITERIA

Overview

With experience in applying the 1994 Guidelines, and with developments internationally, there is now a better understanding of risk to life criteria. Inevitably the current view is more practical and less theoretical than the understanding of 1994. Whether the present view is more or less acceptable to the community at large, is impossible to say. A main reason for publicising the new criteria is to gauge their acceptance, at least within the technical and scientific communities.

The main changes to the criteria are:

- a different approach to the application of the ALARP test
- new Societal Risk criteria curves

The New ALARP Test

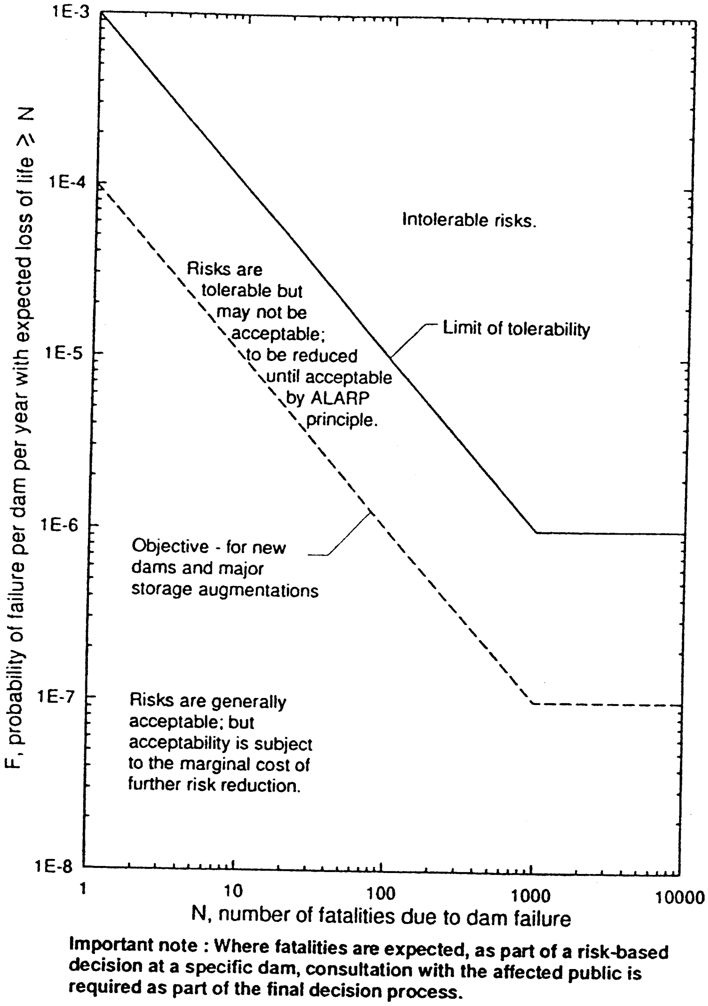
The **change in the application of the ALARP test** has to do with the acceptable risk level for upgraded dams. The changes are:

- for an existing dam with risk levels higher than the Limit, compliance would require that the risk be reduced to a value lower than the Limit, the acceptable value being determined by application of the ALARP principle (in the 1994 Guidelines the risk was to be reduced to the Objective value)
- for an existing dam with risk levels lower than the Limit, but above the Objective, the ALARP test determines whether further risk reduction is economically and practically feasible. If so, the acceptable risk will be determined by consideration of the ALARP principle (in the 1994 Guidelines the question of whether risk reduction is required by the ALARP test was posed in the context of any risk reduction being such as would reduce risks to the Objective value)
- for an existing dam with risk level lower than the Objective value, the risk is prima facie acceptable. There may be a legal duty to further reduce risk if the difficulty and cost of doing so is slight or negligible
- for new dams and major augmentations of storage capacity, it would normally be expected that risks would be lower than the Objective value having regard to long term safety considering the potential for further development downstream. Major augmentations are those where the marginal cost of risk reduction is similar to that for a new dam.

The new approach is in accordance with the ALARP principles as set out by HSE (1992) and others. In the 1994 Guidelines, a deliberate modification of the HSE view of ALARP was made because of a belief that upgraded existing dams should have the same safety levels as new dams. This view has attracted criticism on the grounds that the marginal costs of risk reduction are generally appreciably higher for existing dams than for new dams. The Working Group has, after consideration, decided that ANCOLD should fall into line with the view as outlined by HSE (1992).

The New Societal Risk Criteria

The new **Societal Risk criteria curves** are given at Figure 2.



Important note : Where fatalities are expected, as part of a risk-based decision at a specific dam, consultation with the affected public is required as part of the final decision process.

Figure 2 Revised Societal Risk Criteria Curves

The basic change to these curves is the truncations at 1E-06 for the Limit and 1E-07 for the Objective, the use of a slope of minus 1 (that is, a constant expected value of life loss) until the truncation levels are reached and a narrowing of the band between Limit and Objective. The truncations reflect a view that it is not possible, at a practicable cost, to provide lower probabilities of failure given the uncertainties of material properties and geotechnical conditions; or at least, it is not possible, given the state of the art, to reliably assess probabilities of failure to such very low values. Once truncations at these levels are accepted, there is little point in providing a steepening of the curves above the truncation levels, because such a steepening would make only a small difference at those higher levels.

Some points in support of the proposition that risks lower than the truncation levels cannot reasonably be delivered, are:

- the average historic chance of dam failure is about 1E-04 per dam per annum (Whitman 1984 and Von Thun, 1985). The Limit truncation is thus 1% , and the Objective is 0.1%, of the average historic risk. It seems hardly credible that even lower risks could be reliably provided with existing dam design and construction technology. Certainly the costs of bringing all existing dams into conformity with lower risk levels would likely be unrealistically high.

- the Limit truncation is a little below, and the Objective truncation is significantly below, the risk levels corresponding to the traditional dam design standards for some types of dams. For example, the Probable Maximum Flood standard, in the case of earth dams, represents a probability of failure of something a little less (after allowing for the conditional probability of breaching at low overtopping depths) than 1E-05 to 1E-07 per annum if there is no freeboard above peak flood level (Laurenson and Kuczera, 1998).

Other Aspects of Revised Criteria

There will be a shift in focus from average Individual Risk to the Individual Risk for the person (or more typically, the group) most at risk. There is a view that average Individual Risk should be abandoned as an acceptable risk criterion, but the Working Group is yet to come to a final position on this question.

ESTIMATION AND PRESENTATION OF RISKS TO LIFE

There is now an improved understanding of how risks to life should be estimated and presented. The detailed treatment of this topic will be provided in the revised guidelines document. At this stage the aim is to give a broad indication of the new approaches. The main areas of change in assessing and presenting risks to life are:

- an improved understanding of the concept of dam failure scenario
- new procedures for estimating loss of life
- better understanding of the difficulties in estimating loss of life
- a better understanding of how Individual Risk is to be computed
- a clearer understanding of how Individual Risk to the person most at risk is to be assessed
- clarification of the rules for combining probabilities when obtaining the overall Individual Risk
- clarification of the place of expected value of life loss (product of failure probability, f, and loss of life. N) in assisting appreciation of risks to life
- an improved understanding of the quirks of F/N curves, and of how to interpret these curves.
- clarification of the role of cost-to-save-a-life in assessing risks to life
- a much improved understanding of how to present Societal Risks

Detailed guidance on estimation and presentation of risks will be fully set out in the updated guidelines now in preparation. Only a brief mention of the main points follows:

- failure scenario refers to a suite of states that defines the circumstances of each failure considered in a risk assessment. Typical states making up a scenario are loading (flood or earthquake magnitude), prior storage, failure mode (the relevant event tree), breach location (for example, main or saddle dam), concurrent downstream and tributary streamflow, time of day, season of the year. In theory, a detailed risk assessment may generate some hundreds of scenarios. Again in theory, each scenario yields two values, that for "f" (probability of failure per annum) and that for "N" (predicted loss of life). The fact that a study has only a relative few "f,N" pairs as output would generally be due to aggregation of scenarios in order to limit the cost of the study.
- the DeKay and McClelland (1993) procedure for estimation of loss of life should be regarded as better than the US Bureau of Reclamation (1989) procedure set out in Appendix D of the 1994 Guidelines, notwithstanding that the former raises many difficulties. The procedure of Assaf et al (1997) may be an improvement on the DeKay and McClelland (D-M) approach, but there is no real experience of its application in Australia as yet (August 1998). Clearly Assaf et al regard their procedure as an improvement on the D-M and earlier methods.
- Dr Mike DeKay (1997) has computed confidence limits for the regression equations of the DeKay and McClelland procedure. These are shown in Table 1 and are very wide. This is not surprising on

reflection, because there are only 26 data cases; and situations, that in reality are very complex, are represented by only three parameters (Population at Risk - PAR, Warning Time - WT and Force). A proper understanding of the D-M approach requires a careful study of the data cases on which the procedure is based, as reported by the US Bureau of Reclamation (1989). Warning Time requires great care in estimation, since it depends on many uncertain factors, such as the availability of formal Dam Safety Emergency Plans and Warning/Evacuation Plans through interaction of the owner, the emergency authority and the community, the reliability of warning hardware, response of emergency services personnel and status of public communications systems, typically under emergency conditions (severe flood or earthquake). Users of the D-M procedure need to be aware that the High Force and Low Force curves cross over at a Warning Time of about 1.7 hours. Also, for low Warning Time and low Population at Risk, the approximate formula given by D-M is seriously in error and the accurate formulae should be used for such cases. There is a need for an experienced person to make a sanity check of the predicted loss of life result, to ensure that it is realistic in terms of the circumstances of a specific case. There is a view that the D-M result should be taken as a base estimate and then adjusted upwards or downwards according to the particular circumstances of the case at hand, taking account of factors as set out in Section 3-1 of US Bureau of Reclamation (1989). The merits of such an approach will be discussed in the new guidelines. In the new guidelines there will be advice on interpretation of results where predicted loss of life is less than one. There will also be guidance on how to deal with variations in PAR over time of day and season of the year.

Table 1

Confidence Limits for the DeKay and McClelland Data Cases

Dam Failure/Flash Flood Events		Population at risk (PAR)	Hours warning (WT)		Flooding forcefulness index (See note 1)	Actual loss of life (LOL)	Predicted loss of life (LOL)		
			Estimated	Used for predicting LOL			Mean	95% confidence interval	
								Lower limit	Upper limit
1	Allegheny County, PA, 1986	2200	-	0	0	9	6	0	100
2	Austin, TX, 1981	1180	-	1	1	13	9	1	137
3	Baldwin Hills, CA, 1963	16500	-	1.5	1	5	9	0	200
4	Bearwallow, NC, 1976	8	0	0	1	4	5	0	8
5	Big Thompson, CO, 1976	2500	<1.0	0.5	1	144	59	4	662
6	Black Hills, SD, 1972	17000	<1.0	0.5	1	245	174	10	2538
7	Buffalo Creek, WV, 1972	5000	<1.0	0.5	1	125	87	6	1074
8	Bushy Hill Pond, CT, 1982	400	2-3	2.5	0	0	0	0	6
9	Centralia, WA, 1991	150	-	0	0	0	1	0	20
10	Denver, CO, 1965	10000	2.33-4.0	3.17	0	1	1	0	24
11	Kansas City, MO, 1977	2380	<1.0	0.5	1	20	57	4	640
12	Kelley Barnes, GA, 1977	250	<0.5	0.25	1	39	31	2	170
13	Laurel Run, PA, 1977	150	0	0	1	40	40	3	128
14	Lawn Lake, CO, 1982	5000	0.0-1.0	0.5	0	3	6	0	104
15	Lee Lake, MA, 1968	80	0	0	1	2	26	2	71
16	Little Deer Creek, UT, 1963	50	0	0	0	1	1	0	10
17	Malpasset, France, 1959	6000	0	0	1	421	406	23	3436
18	Mohegan Park, CT, 1963	1000	0	0	0	6	4	0	61
19	Northern NJ, 1984	25000	>2.0	3	0	2	2	0	45
20	Shadyside, OH, 1990	884	-	0	1	24	127	9	646
21	Stava, Italy, 1985	300	-	0	1	270	64	5	243
22	Swift and Two Medicine Dams, MT, 1964	250	<1.5	0.75	1	28	8	0	86
23	Teton, ID, 1976 (Dam through Wilford)	2000	<1.5	0.75	1	7	25	2	326
24	Teton, ID, 1976 (Rexburg to American Falls)	23000	>1.5	2.25	0	4	4	0	67
25	Texas Hill Country, 1978	2070	<1.5	0.75	1	25	25	2	333
26	Vega De Tera, Spain, 1959	500	0	0	1	150	89	7	387

NOTE :

1. Flooding forcefulness index = zero represents "Low Force" (ie. flood waters are likely to be relatively shallow and slow).
Flooding forcefulness index = 1 represents "High Force" (ie. flood waters are likely to be deep and swift).

- contributions to Individual Risk should be computed for every failure scenario as one or other of the products given in the fourth paragraph under "MAIN FEATURES OF THE 1994 CRITERIA" above. The total Individual Risk is then easily computed.
- it is now apparent from experience with risk assessment, that it will usually not be possible to identify a single individual who is most at risk, but it will be possible to identify a group who are clearly most at risk. Typically there will be a dwelling, or several dwellings or even a small community where all

persons have the same minimum or zero Warning Time. Or there may be a nursing home where all residents have a high level of vulnerability. The suggested approach for estimating the risk to the person most at risk, is to identify the group most at risk and to then apply the D-M procedure as though that group was the only Population at Risk. The ratio of estimated Loss of Life to Population at Risk for that group then provides the conditional probability of death to be used in computing the Individual Risk for the person most at risk. In other words, the average risk over the most vulnerable group is taken to be the risk to the person most at risk. Of course, where there is special vulnerability combined with low Warning Time (for example, a nursing home with zero warning time) there may be a case to take conditional probability, given dam failure, as 1.0.

- where there are several failure modes that are not mutually exclusive, the overall conditional probability of failure lies somewhere between the bounds of:

  - the maximum conditional probability as lower bound
  - the probability of the union of events, the several failure modes, as upper bound

  If any of the conditional probabilities are high (say greater than 0.01), the sum of the conditional probabilities is not sufficiently accurate as the union of events, and the correct formula must be used. The union of events is to be computed on the conditional probabilities of failure (that is, before multiplying by the probability of the loading event). These factors need consideration in obtaining the overall Individual Risk. It is often not correct to simply sum the contributions to Individual Risk of each failure scenario. Example calculations will be given in the new guidelines.
- expected value of life loss, "f. N", is a useful measure, especially for identifying the relative contributions of the various failure scenarios to the overall risk to life. However, ANCOLD does not favour the use of the overall expected loss of life as the single measure of Societal Risk. The reason is that the total expected value of life loss hides the various life loss scenarios that can occur. The total expected value is a single number and there are an indefinite number of combinations of life loss scenarios that can produce that figure. In other words, the single number of total expected value of life loss tells a decision maker nothing of the range of life loss that could occur. In contrast, an "F/N" plot does give information about the many life loss scenarios that can occur. It is for this reason that ANCOLD prefers F/N plots as the main measure of Societal Risk, notwithstanding their acknowledged problems. It should be noted that the overall expected life loss cannot be overlaid onto F/N graphs and there is no means of comparative plotting of the two measures (expected value and F/N plots). Some incorrect overlays have been published in the literature.
- It is the case that F/N curves are difficult to interpret for those who are not experienced in their use. Also the results can depend on the formulation of the risk problem in a given situation (Evans and Verlander, 1997), which means that F/N plots are not a totally satisfactory measure of risk. Finally, where several failure scenarios have the same "N" value, the F/N plot varies according to the order in which the scenarios are listed when computing the cumulative distribution function "F". Notwithstanding these problems, ANCOLD is satisfied that F/N plots are the most valuable and practical measure of Societal Risk that is presently available. The last of the problems mentioned can be overcome by combining the probabilities of all failure scenarios with the same "N" value, before computing "F". Societal Risk is to be taken as not meeting the criteria if any part of the F/N plot passes above the criterion line. If only a small portion passes above the line then only one or a few failure scenarios require risk reduction in order to meet the criterion.
- the concept of cost-to-save-a-life is useful in evaluating remedial measures. It is the annualised cost of risk reduction measures divided by the reduction in expected life loss per annum that is achieved by those measures. This measure should be seen as a means of rating cost effectiveness of remedial action. It is not to be seen as placing a monetary value on human life. Thus where there are several options that reduce risk to a required level, that with the lowest cost-to-save-a-life would be preferred on grounds of cost effectiveness in reducing risk to life. This measure can also be used as a quantitative aid in applying the ALARP principle. Cost-to-save-a-life values typically cover a very wide range and are often very high. Figures published by the US Office of Management and Budget (1992 - Table C-2) show that US$30 to 50 million per life saved are moderate values.

- it is apparent that a range of measures should be reported to decision makers to give a comprehensive picture of risk to life. Tabular and graphical presentations of all relevant values in a clear, concise format is valuable. The updated guidelines will make suggestions on reporting format. Values should be reported by each failure scenario and then correctly combined to give the overall summary values. Each of the failure scenarios is a possible outcome and reporting by scenarios paints a picture of the range of possible outcomes for a decision maker. Equally, the decision maker needs the overall values because it is too difficult to mentally combine all of the scenario values (there may be some tens or even hundreds in a large study) into an overall rating of the risk level.

DECISION PROCESS

Community Consultation

There is no precedent, that ANCOLD is aware of, for truncated Societal Risk curves, as in Figure 2. This fact reinforces the importance of community consultation, as provided for in Guideline G4 and under "Legal Matters" of Section 6 of the 1994 Guidelines on Risk Assessment. The affected public need to be apprised of the risks and given an opportunity to be heard. A document that is placed on public exhibition, such as an Environmental Impact Statement, is a suitable medium for communicating risks and for inviting submissions. The responses to such an invitation need to be taken into account in decision making.

The Decision Process

Neither calculated risks nor acceptable risk criteria are precise. They should be viewed as a guide to decision making along with the outcomes of the traditional deterministic assessment procedures. Decisions on dam safety are difficult and involve a range of complex considerations. A decision maker requires a broad understanding of the problem with insights from both risk assessment and the traditional forms of assessment.

Apart from risks to life, a decision maker needs to consider business risks, environmental risks and a range of social and political considerations. In particular cases, these may be a greater influence on the final decision than risks to life.

CONCLUSION

ANCOLD recommends that the criteria and points set out in this statement be cautiously applied in risk assessment practice, pending publication of the updated Guidelines on Risk Assessment. In cases where a final risk management decision, for a specific dam, involves expected loss of life should the dam fail, consultation with the affected public is required as part of the decision process.

The risk assessment methodologies and outcomes are to be considered in conjunction with the traditional deterministic approach and criteria.

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Washington

COMMENTARY ON
ALGORITHM FOR PRIORITIZATION RANKING OF DAMS WITH SAFETY DEFICIENCIES

January 1990

Although simple in concept and application, the scoring and ranking algorithm has been found to be quite adequate for producing an initial ranking of projects. This ranking is used as a starting point where other project specific considerations and intangibles can be considered by management. These discussions then lead to management decisions for allocating staff for compliance and enforcement actions on those dams that pose the greatest risks to public safety.

Some of the underlying logic in the development of the algorithm include:

1) For dams with similar deficiencies, those dams with the greater consequences should be given higher priority

2) For dams with similar consequences, those dams with the more serious deficiencies should be given higher priority

3) For dams with similar deficiencies and similar consequences, those dams with a poorer chance of warning to the public should be given higher priority

4) For dams with only minor deficiencies, those dams should be ranked lower than dams with significant deficiencies, regardless of the consequences

5) The risk associated with three minor deficiencies is ranked just below that of one moderate deficiency

6) The risk associated with two moderate deficiencies is ranked just below that of one major deficiency

7) All things being equal, the older dams should be given higher priority

WASHINGTON STATE DAM SAFETY PROGRAM
ALGORITHM FOR PRIORITIZATION RANKING OF DAMS WITH SAFETY DEFICIENCIES
January 1990

IF ONE OR MORE SAFETY DEFICIENCIES RATED MODERATE, MAJOR OR EMERGENCY

PRIORITY POINTS = [HAZARD CLASS] + [WARNING] + [SUM (SERIOUSNESS OF DEFICIENCIES)] + [AGE/2]

IF ALL SAFETY DEFICIENCIES ARE RATED MINOR

PRIORITY POINTS = 0.5* ([HAZARD CLASS] + [WARNING] + [SUM (SERIOUSNESS OF DEFICIENCIES)] + [AGE/2])

RATING POINTS FOR CONSEQUENCES - HAZARD CLASS

High Hazard
Hazard Classification - 1A ---> 500 points - 100+ homes at risk
Hazard Classification - 1B ---> 400 points - 11-99 homes
Hazard Classification - 1C ---> 300 points - 3-10 homes
Significant Hazard
Hazard Classification - 2 ---> 200 points - 1 or 2 homes
Low Hazard
Hazard Classification - 3 ---> 100 points

RATING POINTS FOR ADEQUACY OF WARNING

Inadequate Warning ---> 100 points
Marginal Warning ---> 50 points
Adequate Warning ---> 0 points

RATING POINTS FOR SERIOUSNESS OF EACH DEFICIENCY

Primary Focus on Safety Deficiencies that could lead to an Incident or Dam Failure (Uncontrolled Release of Reservoir)

Emergency Condition ---> 250 points
Major Deficiency ---> 145 points
Moderate Deficiency ---> 65 points
Uncertain Seriousness ---> 65 points
Minor Deficiency ---> 20 points

WASHINGTON STATE DAM SAFETY SECTION
PROCEDURES FOR PRIORITIZED RANKING OF DAMS WITH SAFETY DEFICIENCIES

January 1990

CONDITION	HYDROLOGIC ADEQUACY	EMBANKMENT STABILITY	SEEPAGE EARTHEN EMBANKMENTS FOUNDATIONS, ABUTMENTS	OUTLET CONDUIT	OPERATION & MAINTENANCE	EMERGENCY ACTION PLAN
SATISFACTORY	Can Accommodate IDF	Meets Criteria for Static and Seismic Stability	Minimal Seepage Consistent with Past Behavior or Seepage Deemed not a Cause for Concern	Conduit Rating of 8 or Better	Well Maintained Dam Adequate O&M Manual	Up to Date EAP
MINOR DEFICIENCIES	Can Only Accommodate Flood 1 Step below Design Step	Meets Criteria for Static Stability Marginal Seismic Stability under Design Earthquake	Minor Seepage Quantity No Evidence of Internal Erosion	Conduit Rating of 6-8	Poorly Maintained Dam Inadequate O&M Manual	Inadequate or Non-Existent EAP
MODERATE DEFICIENCIES	Can Only Accommodate Flood 2 Steps below Design Step	Marginal Static Stability $1.3 < FS < 1.5$ Inadequate Seismic Stability or Liquefaction Concerns under Design Earthquake	Moderate Seepage Quantity or Anomalous Increase in Quantity Minor Concern of Internal Erosion	Conduit Rating of 4-6		
MAJOR DEFICIENCIES	Cannot Accommodate 500 Year Flood or Can Only Accommodate Flood 3 Steps Below Design Step	Inadequate Static Stability $1.0 < FS < 1.3$ Inadequate Seismic Stability or Liquefaction Concerns under Moderate Earthquake	Relatively Large Seepage Quantity Multiple Points of Seepage and/or Moderate Concern of Internal Erosion	Conduit Rating of 2-4		
EMERGENCY	Cannot Accommodate 25 Year Flood	Significant Slope Failures that Intercept the Dam Crest and Involve a Major Portion of the Embankment	Large Seepage Quantity or Rapidly Changing Seepage Quantity Multiple Points of Seepage and On-going or Intermittent Internal Erosion	Conduit Rating of 0-2		

Note: Conduit Rating includes assessment of conduit condition, integrity of joints, leakage, existence of conduit encasement, internal erosion along conduit, etc..

PORTLAND OREGON'S EXPERIENCE WITH RISK ASSESSMENT

ASDSO/FEMA Specialty Workshop
On Risk Assessment for Dams

Logan, Utah
March 7-9, 2000

James L. Doane PE
Principal Engineer
Bureau of Water Works
Portland, Oregon
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First phase of Risk Assessment Program

Risks of not being able to supply water to customers

THE SETTING

- Supply water to 850,000 people
- 27,000 hectare (103 square mile) Bull Run watershed
- Unitary operational goal-maximizing water supply
- No filtration - susceptible to heavy rainfall
- Three large pipelines from watershed to town
- Geological instability

Backup Wellfield

- Turbidity in the Bull Run water > 5 NTU
- Other interruption (landslides)
- Well use will increase
  - Wetter than normal climate cycle
  - Releases for salmon preservation
  - Growing population

Bull Run Watershed

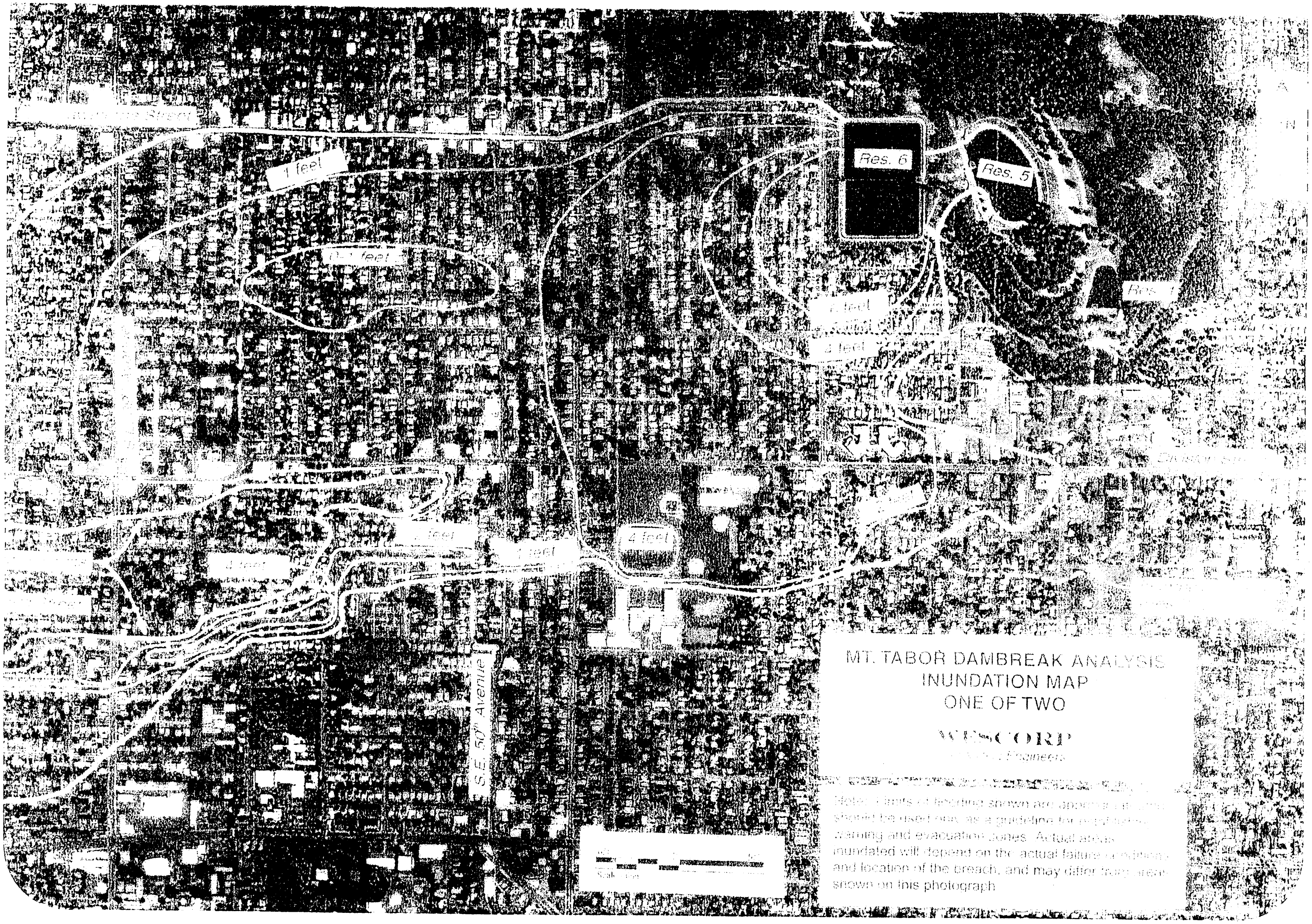
- Dam #1
    - Concrete gravity arch dam completed in 1929
    - 59 meters (194 feet) high, crest length of 330 meters (1082 feet)
    - Reservoir impounds 76 $\times 10^6$ M^3 (60,000 acre-ft)
    - 1981 powerhouse - one 24 MW Francis turbine

- Dam #2
  - 4 km downstream of Dam #1
  - Rockfill dam completed in 1962
  - 44 meters (145 feet) high, crest length of 365 meters (1200 ft)
  - Reservoir impounds 38 $x10^6 M^3$ (30,000 acre-ft)
  - 1981 powerhouse - one 12 MW Kaplan turbine

- Water treatment operator at Dam #2 24-hours per day
- Meet current standards for PMF and MCE loadings
- Emergency Action Plans tested annually

Portland

- Five open storage reservoirs
- 45,000 M^3 (36 acre-ft) to 280,000 M^3 (230 acre-ft)
- Located immediately adjacent to and above heavily populated residential and commercial neighborhoods



MT. TABOR DAMBREAK ANALYSIS
INUNDATION MAP
ONE OF TWO

WESCORP

Engineers

Note: Limits of flooding shown are approximate and should be used only as a guideline for establishing warning and evacuation zones. Actual areas inundated will depend on the actual failure conditions and location of the breach, and may differ from areas shown on this photograph

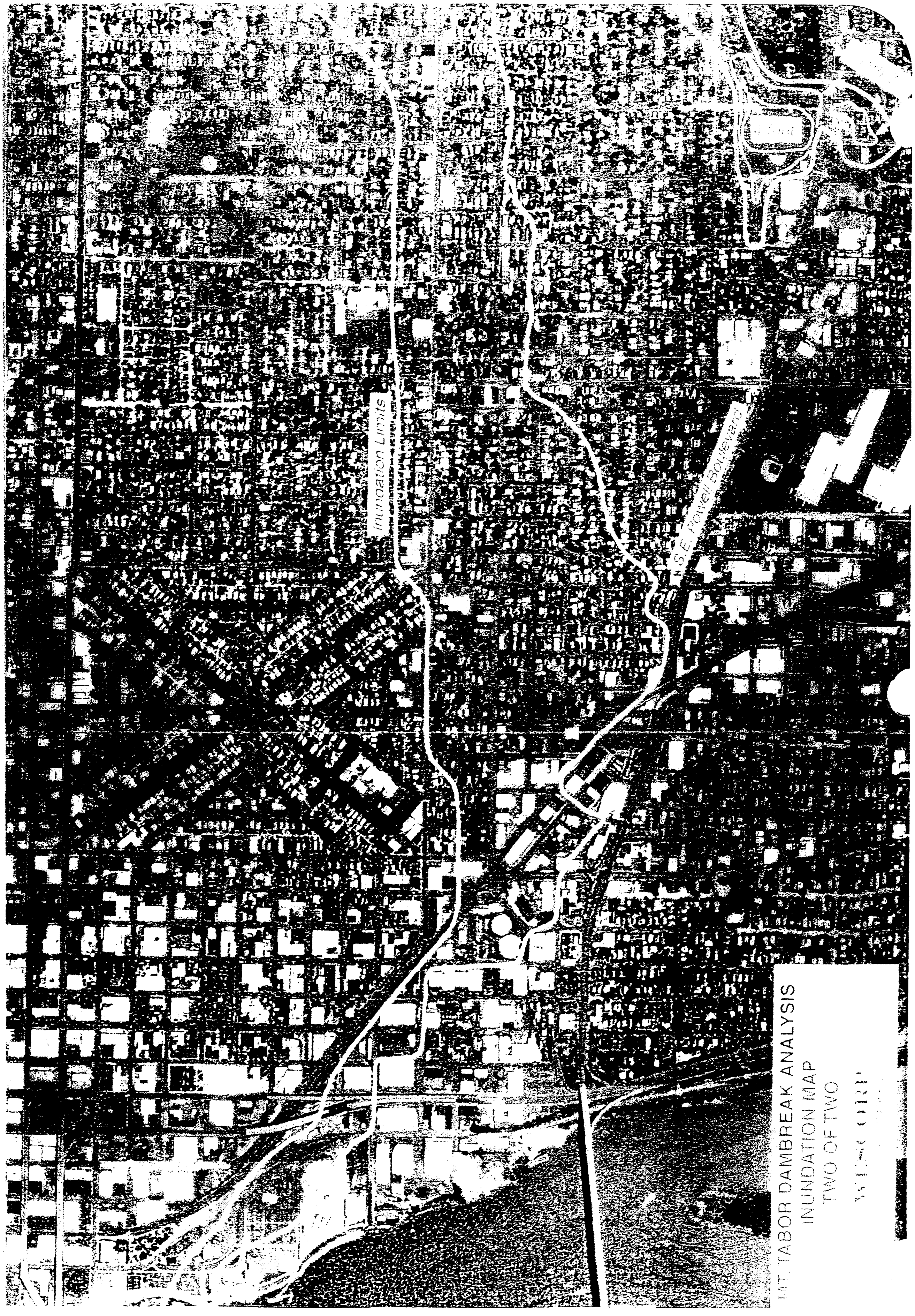
Mt. Tabor Park

- Three dams on extinct volcano
  - Reservoir #1
    - 45,000 M^3 (36 acre-ft)
    - Same elevation as Reservoir #5
    - 1894, soil fill, concrete liner
    - Overlooks college campus and neighborhood

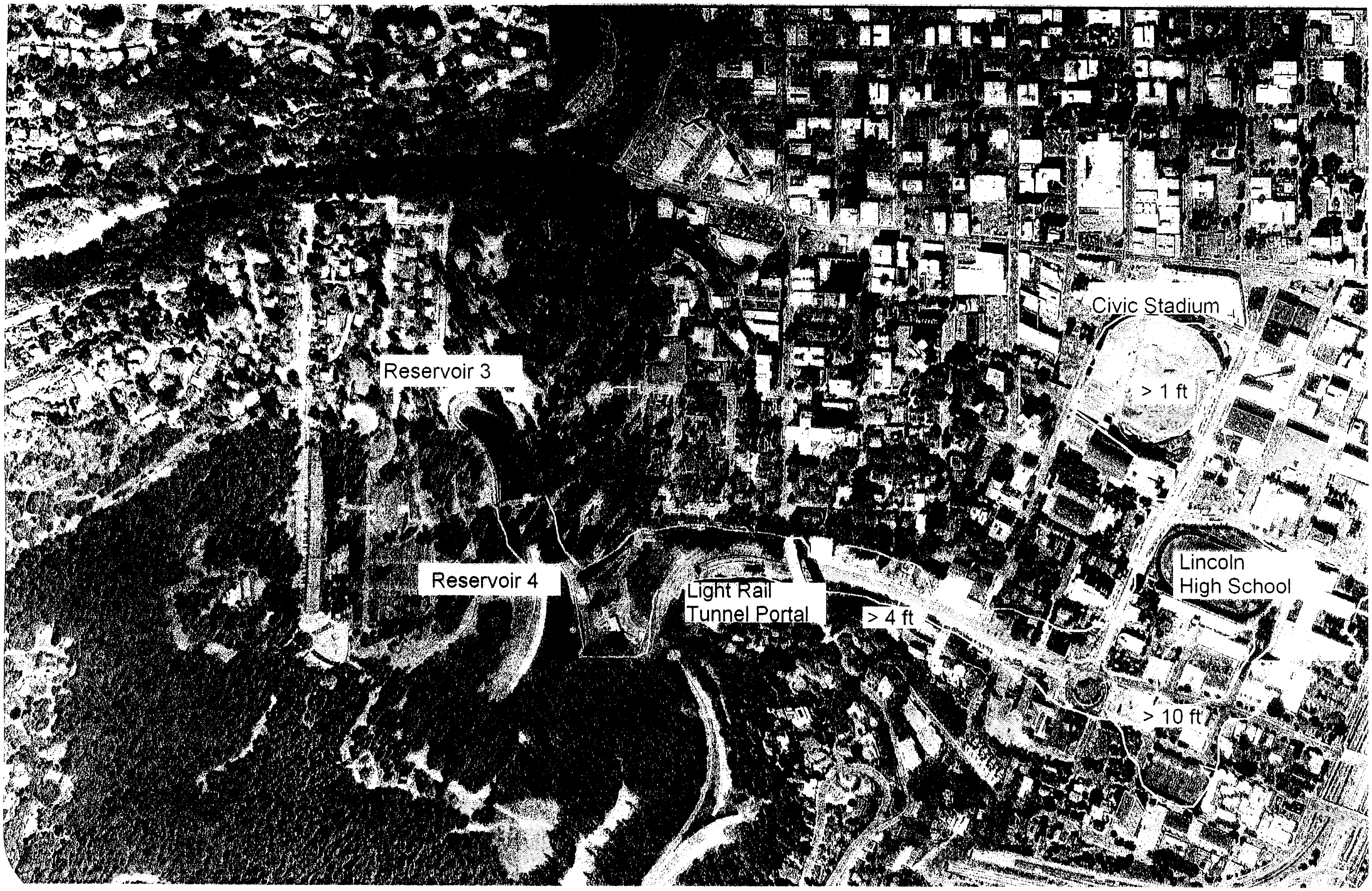
- Reservoir #5
  - $185{,}000\ M^3$ (150 acre-ft)
  - 1911, buttress dam, concrete liner
  - Above Reservoir #6
  - 21 meters (70 feet) higher
  - 100 meters (325 feet) in length

- Reservoir #6
  - 280,000 M^3 (230 acre-ft)
  - Located in residential neighborhood.
  - 1911, soil fill, concrete liner
  - 9 meters (30 feet) deep
  - 30 meters (100 feet) away and 12 meters (40 feet) higher than the nearest homes

- Hydroelectric facilities
  - 21 meters (70 feet) fall between Reservoirs 5 and 6
  - Emergency Action Plan tested annually
  - PMF is not an issue
  - MCE will cause damage but not uncontrolled releases



MT. TABOR DAMBREAK ANALYSIS
INUNDATION MAP
TWO OF TWO
[illegible]


Civic Stadium
> 1 ft
Reservoir 3
Lincoln
High School
Reservoir 4
Light Rail
Tunnel Portal
> 4 ft
> 10 ft

Washington Park

- Two dams
  - 60,000 M^3 (49 acre-ft)
  - 1894, concrete gravity structures
  - Reservoirs located on a deep flow slide
  - Moving slowly toward downtown Portland since their construction
  - Reservoir #3, 15 meter (49 ft) high, above Res #4
  - Reservoir #4, 12 meter (40 ft) high

- **Washington Park Reservoirs**
  - Just above the east portal of a commuter light rail tunnel
  - ½ kilometer from high school
  - ¾ kilometer from major below grade open air sports complex
  - Inundation map completed, EAP underway
  - PMF is not an issue
  - MCE analysis not completed - site adjacent to West Hills Fault

Other Bureau Facilities

- 32 pump stations (11 kw to 9.6 Mw)---(15 hp to 13,000 hp)
- 70 tanks
- 3000 km (1864 miles) of pipe
- Backup well system

Need for a Risk Assessment Study

- Only miscellaneous studies of sites or individual hazards
- November 1995 landslide severs 2 of the 3 pipelines
- February 1996 flood

Contingent Valuation Study

- Determine:
  - Community expectations about supply issues
  - Attempt to develop a monetary value for expectations
  - Measure of the willingness to pay to avoid something
  - Large sample used (600 people)
- Result---willing to pay 90% more to avoid a small event (10% reduction in summer supply once every 30 years)

System Vulnerability Study

- Identify risk of system damage and failure
- Probabilistic based risk assessment
- 38 natural and human caused hazards (excluding drought)
- Mitigation plan
  - Quantification of the most significant risks
  - Identification of the mitigation measures for those risks
  - Included improving emergency response

Natural Hazards
Floods – Columbia, Willamette, Sandy, Columbia River Dike Failure
Snow Melt/Rain on Snow – Bull Run/Local (PMF) (also see Turbidity)
Land/Rock Slides/Debris Flow
Tree Fall (Structure Impact, Slope Destabilization) (also see Electrical, Wire Communications)
Winter Snow/Ice Storms (Structural) (also see Electrical, Wire Communications)
Prolonged Freezing
Earthquake (Ground Motion, Liquefaction) (also see Landslide)
Seiche
Volcanic Activity (Sandy River Debris Flow) (also see Turbidity, Electrical)
Fire in Watershed (also see Turbidity)
Forest Park Fires (West Hills)
Urban Firestorms
Turbidity
Microbial Contamination

Human / Technological Hazards
Staff Unavailable (Public Health Catastrophe, Labor Dispute, Staffing)
Intentional Act
Bureau Building Piping Flood
Bureau Building/Facility Fire/Explosion
Chemical Release
Computer Disruption
Groundwater Contamination (existing, unknown and new)
Bull Run Dams Failure
Mechanical Failure
Third-Party Damage
Redundancy
Operational Error

Transportation Hazards
Airplane Crash
Airplane Fuel Dump
Truck/Car Structural Impact
Marine (River Crossing) (also see Groundwater Contamination)
Light Rail

Lifeline Service Loss Hazards
Electrical
Wire Communications
Wireless Communications (Cellular, 800 MHz, Satellite, 900 MHz, SCADA)
Sewer
Natural Gas/Propane
Liquid Fuel
Treatment Chemical Supply and Delivery

Values and expectations of our customers

- Fifty interviews
- Expectations for performance for various hazards and time periods
- Customers' expectations of system performance emerged
  - No system-wide interruption for hazards that can be expected in 100 years
  - Will tolerate short-term system-wide interruptions for time >100 years as long as water is available for emergency services

- Compared expectations to probability of an outage for various risks
- Included expected duration of the outage
- Mitigation measures identified where expectations not met
- Mitigation measures used in conjunction with other needs to set Bureau priorities

Evaluations

- Minimum flow to meet customers’ expectations
- Type and cost of improvements to give expected reliability
- Evaluations carried out for critical non-Bureau operations
    - Dikes on the Columbia River
    - Electrical power system
    - Wire and wireless communications systems
    - Chemical suppliers

Mitigation Alternatives - High Hazards

Component	Hazard	Recurrence (years)	Outage (days)	Annualized outage	Benefit/ Cost	Mitigation Project
Watershed	Turbidity	5/100	7/365	2.13	10.2	Increase reliability of groundwater
Watershed	Turbidity	5/100	7/365	2.13	10.2	Construct a water treatment plant
Bowman's Bridge	Quake, Flood	100	180	1.80	340.6	Strengthen bridge, foundation, pipe
Conduit 2/4 Bridge	Quake, Flood, Volcanic	100	180	1.80	21.3	Construct a Sandy River undercrossing for conduits 2/4
Trestles 2/4	Flood, Quake, Failure	100	30	0.30	57.7	Upgrade joints, foundations, pipe

Mitigation Alternatives - High Hazards

System	Intentional Act	100	90	0.59	18.5	Deterrence, antiterrorism
Willamette River Crossings	Quake, Failure	50	180	0.72	3.5	New crossing, & Westside Header
WCSL	Quake, Flood, Scour	100	180	0.54	6.5	Mitigate or parallel WCSL
Conduits / Headworks	Landslide, Quake	10	7	0.45	14.4	Landslide monitoring and mitigation

Mitigation Alternatives - Medium High Hazards

Component	Hazard	Recurrence	Outage	Annualized outage	Benefit/ Cost	Mitigation Project
GWPS	Quake	500	180	0.30	10.4	Make GWPS resistant to quakes
Conduit 3 Bridge	Quake, Flood, Volcanic	100	180	1.17	13.9	Construct new undercrossing
Conduits	Response to failure	10	30	1.05	12.5	Phase I Intertie
Larson's Bridge	Quake, Flood	100	180	1.17	221.8	Strengthen bridge, replace old pipe

Mitigation Alternatives - Medium High Hazards

Dam 1 & 2	Mechanical Failure	100	30	0.30	4.7	Maintain sluice gates, guard valves, needle valves
Conduit 3 Trestles	Flood, Quake	100	30	0.20	37.9	Upgrade joints, foundations, pipe
Washington Park Reservoirs	Quake, Failure, Intentional	100	30	0.06	0.4	Replace facilites

Mitigation Alternatives - Medium Hazards

Component	Hazard	Recurrence	Outage	Annualized outage	Benefit/ Cost	Mitigation Project
System	O & M	50	30	0.39	13.4	Develop and maintain GIS
Conduits 3 & 5	Flood	500	90	0.12	13.4	Encase conduits 3 & 5, or deepen plunge pool
Marquam 1, Vernon 1, 2	Quake	100	180	0.09	4.0	Evaluate performance

Mitigation Alternatives - Medium Hazards

Conduits	Conduit condition	50	7	0.09	3.0	Conduct internal inspection
Powell Butte	Quake	500	90	0.12	3.8	Upgrade reservoir
Mt. Tabor	Quake	100	30	0.09	1.1	Replace Site Piping, cover reservoirs

Association of State Dam Safety Officials/
Federal Emergency Management Agency

Draft
Bibliography: Risk Assessment for Dams

March 2000

Prepared by

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Utah State University

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FORWARD

This bibliography was prepared for the ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams. The workshop was hosted and organized through the Institute for Dam Safety Risk Assessment at Utah State University, March 7-9, 2000. The categories into which references are divided follows the general structure of the Workshop.

References contained in the bibliography were obtained by conducting key word searches in the following indexes:

Applied Sci&Tech Abstracts

Current Contents

Dissertations

Ei Compendix

Library of Congress Online Catalog

NTIS

Public Science

Water Resources Abstracts

Web Spirs

Northernlight.com

Snap.com

Dialog.com

ASCE.org

In addition, Workshop participants were invited to provide references to their own work and the work of others. Sarah Mayfield at the ASDSO provided a listing of all related references from the ASDSO index and provided helpful suggestions for preparing this bibliography. The ASDSO intends to make this bibliography accessible through its Web Site (www.damsafety.org), which will have a search engine capability.

Drs. Sanjay S. Chauhan and David S. Bowles were assisted in the preparation of this bibliography by Rosemary Tolman Weiland, Library Assistant, and Ivonne Harris, Publications Supervisor, Utah Water Research Laboratory.

WORKSHOP PARTICIPANTS ARE INVITED TO PROVIDE US WITH CONTRIBUTIONS THAT CAN BE INCLUDED IN THE FINAL VERSION OF THIS BIBLIOGRAPHY. WE PLAN TO INCORPORATE THESE CONTRIBUTIONS AND OTHER REFERENCES, WHICH EXIST IN OUR PERSONAL LIBRARIES, BEFORE FINALIZING THE BIBLIOGRAPHY. PLEASE SEND ALL CONTRIBUTIONS TO THE FOLLOWING BY MARCH 31, 2000:

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1.0 QUALITATIVE RISK ASSESSMENT

1.1 Approaches

Comparison of failure modes from risk assessment and historical data for Bureau of Reclamation dams. (YEAR?). J. Tatalovich. Dam safety research report.

(?)Safety of dams - a new approach for the decision making process. (1994). S. C. Kuperman, G. Re and A. P. Canholi. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 11-14, 1994, p. 545-553.

(Index terms: hazard classification international programs, risk assessment). A new approach has been devised to classify dams according to their safety level. It provides owners and inspectors with a numerical tool that can help them in making decisions on difficult subjects such as the frequency of inspections, comparison of the performance of different dams, money investments to maintain a certain safety level, among others. The methodology consists of estimating numerical values for parameters called "Hazardous Potential" (HP) and "Actual Performance" (AP) for each dam, With the application of coefficients and a simple equation they generate the so called "Behavior Index" (Bl). These parameters and indexes can be easily used in the decision process and can reflect changes in the conditions of the dam such as those due to preventive or corrective maintenance work or to any important deterioration.

1.2 Case Histories

An experience of failure mode, effect, and criticality analysis on UK hydropower, C. Beak, J. Findlay, and D. Aikman. (1997). Hydropower, E. Broach, et al. (eds.), Balkema.

2.0 QUANTITATIVE RISK ASSESSMENT

2.1 Approach

(?)Taking a closer look. (1999). International Water Power and Dam Construction, Wilmington Bus., Publ., p. 30-34.

A comparison of methods for integrated risk assessment of dams. (1987). D. S. Bowles. In: L. Duckstein and E. Plate (Eds.). Engineering Reliability and Risk in Water Resources, M. Nijhoft, Dordrecht, The Netherlands.

A framework for applying and conducting risk-based analysis for dams. (1998). M. W. McCann and G. Castro. USCOLD Annual Meeting, U.S. Committee on Large Dams. (Index terms: risk assessment).

A framework for risk analysis of earth dams. (1980). J. C. Howell, L. R. Anderson, D. S. Bowles, and R. V. Canfield. Report submitted to Water and Power Resources Service (U.S. Bureau of Reclamation), Engineering and Research Center, Denver, Colorado. December, 87 p.

A hybrid deterministic- risk-based approach to hydrologic dam safety analysis. (1998). E. E. Eiker, D. M. Goldman and D. W. Davis. Dam Safety '98, Association of State Dam Safety Officials, Oct. 11-14, 1998, Las Vegas, NV, p. 23-34.

> *Dam owners and Federal and state regulatory agencies, have a unique responsibility to the public to assure the highest level of safety for individuals living downstream of dams. The catastrophic nature of a dam failure, in terms of potential loss of life and property damage, the long lasting social consequences that can result from a dam failure and the fact that most people living in harms way did not knowingly choose to accept this risk, dictate nothing less. In establishing hydrologic dam safety criteria, the horrible lessons learned from previous dam failures, even though infrequent, must not be forgotten. Similarly, the current hydrologic dam safety design criteria, based on accommodating extreme floods, should not be cast aside without a great deal of thought. During the last fifteen years, there has been a concerted effort to develop risk-based analysis (RBA) procedures for application in hydrologic dam safety evaluation studies. Several theoretical procedures to carry out RBA studies have been formulated. Application of these approaches, however, has been limited because of our inability to define critical components, such as the probability of extreme precipitation and floods, and in setting meaningful decision criteria to fully consider loss of life and social consequences. In view of these limitations, we must ask ourselves whether RBA, as now formulated, is a tool that is ready for widespread application in hydrologic dam safety studies. RBA has been successfully applied in related areas, such as in the formulation of flood damage reduction projects. However, in these cases hydrologic probabilities were not*

required for extreme events and hazard potential for a design exceedance could be addressed by a separate residual risk analysis. This paper presents a framework for a new approach to be used in the identification and evaluation of hydrologic deficiencies of dams and a process for prioritization of identified hydrologic deficiencies requiring mitigation. The procedure may also be used to establish the size and scope of a required modification for a specific project. The paper presents a brief history of deterministic approaches used to develop safety design floods, beginning with the use of Precipitation (PMP) and Probable Maximum Flood (PMF). Also included is a short discussion of incremental hazard evaluation, prioritization and scoping of remedial work at existing dams. A review of RBA approaches currently being developed and their inherent strengths and weaknesses is presented. These discussions form the bases for the formulation of the recommended framework. This framework is essentially a hybrid approach that attempts to capture the strengths of both the deterministic design flood approach and the risk-based methods. The suggested framework builds on the principles embodied in the concepts of PMP and PMF, while explicitly and analytically incorporating considerations of risk and uncertainty into the analysis, thus providing significantly more information to decision makers, whether dam owners or regulators.

Analytical risk assessment for dams. (1982). F. Gruetter and N. J. Schnitter. 14th Congress, International Commission on Large Dams, Q.52, R.039 pp. http://www.icold-cigb.org. (Index terms: overtopping, risk assessment).

An analytical method for estimating, evaluating and managing risks involved in dams is described and demonstrated by a practical example for the case of overtopping. The method is basically a cause-consequence analysis. It enables to highlight events and conditions, which contribute most to dam accidents, to assess quantitatively consequences of possible incidents, and to estimate net premiums which would be justified for insuring dams against the hazards considered.

Application of probability risk analysis to the safety of dams. (1984). J. Franzini, B. M. McCann, and C. Shah. Eighth World Conference on Earthquake Engineering, July 21-28, San Francisco, California.

Application of probability to spillway design flood estimation, floods and their computation. (1969). G. N. Alexander. International Association of Scientific Hydrology, Publication No. 84 (UNESCO-WMO), p. 536-543. (Index terms: computer programs design flood risk assessment spillway capacity).

A Systems Approach to Risk Analysis for an Earth Dam. (1978). D.S. Bowles, L.R. Anderson, and R.V. Canfield. In E.A. McBean, et al. (Ed.). Proceedings, 'International Symposium on Risk and Reliability in Water Resources.' Volume II. University of Waterloo, Waterloo, Ontario, Canada June 26-28.

From time to time the failure of a dam will focus public attention on the subject of dam safety. Regardless of the care taken in the siting, design, and construction of a dam, some residual level of risk of a catastrophic failure of the structure will remain. The event that causes the failure may be of natural origin (e.g., flood, earthquake), it may be related to the structure itself (e.g., uneven settlement, embankment slips), or it may be related to human error (e.g., incorrect operation, acts of war). The techniques of risk-based design have not been developed for, and applied to earth dam projects. These techniques involve the identification and estimation of risks, and the taking of risk reduction or risk acceptance actions using a decision analysis framework. The paper presents an event-outcome-exposure-consequence path approach to risk analysis for earth dams. The proposed approach will make use of additional data as it becomes available during the life of an earth dam project and will handle ' total risk ' rather than risk associated with only a single failure mechanism.

Broad-based approach to dam safety risk assessment, ASDSO annual conference. (1999). J.L. Von Thun. Association of State Dam Safety Officials, Oct 14-15, p. 653-663. (Index terms: risk assessment).

Includes introduction to risk assessment, broad-based use of risk assessment, variation in risk assessment use as a function of dam inventory size, guidance on the most effective ways to implement the use of risk assessment, implementation of a failure mode and effects analysis, decision point on the nature of the second phase in risk assessment, implementation of a quantitative risk analysis, completing the risk assessment process when a quantitative risk analysis has been completed, and diagram of relationship between risk analysis, risk assessment, risk management in dam safety decision making, and Attachment: Potential Failure Mode - Example Description.

Bureau of Reclamation use of risk analysis. (1987). N.F. Parrett. Application of Frequency and Risk in Water Resources. Proceedings of the International Symposium on Flood Frequency and May 1986, Louisiana State University, Baton Rouge, LA. D. Reidel Publishing Company, Boston, MA, p. 411-428.

The Bureau of Reclamation's philosophy and methodology in using risk-based analysis to select appropriate actions in its safety of dams program is presented. Actual failures of modern major dams result most often from causes other than floods, usually piping, and usually resulting from a condition not detected by the designers before the failure. The Bureau's programs for design of dams and assessing existing dams strive for balance in assessing the several loading events that may threaten a dam. Due to additional stream flow data in most basins and revised procedures for developing the probable maximum flood (PMF), virtually all dams require a new PMF to be prepared. The application of risk analysis has been in the areas of hazard assessment, impacts of alternative actions and comparisons of hazard, and other identified factors for a risk management decision. Two hypothetical case studies are used to illustrate the Bureau's *application of its philosophy: one case indicates a small incremental difference in population at risk and estimated loss of life for inflow flood levels above 60% of the maximum discharge and significant incremental property damages for all flood levels with a failure of dam potential and the second case illustrates a situation in which the incremental estimated loss of life is significant for all flood levels up to the PMF. (See also W90-02507) (Stoehr-PTT).*

Classes of risks for dams. (1996). R. Lafitte. International Journal on Hydropower & Dams, v. 3, n. 6, Aqua-Media International Ltd., p. 59-66.

Classification of risk. (1973). E. Gruner. 11th Congress, International Commission on Large Dams, Madrid, Q.39, R.024 pp. http://www.icold-cigb.org.

Attempt for classifying the risks arising from dams and reservoirs. Records of accidents and failures are computed according to site conditions, hydraulic features, type of structure, quality of work, operation and maintenance, the influence of environment and consequences of similar works. The mission entrusted to the Committee on Risk to Third Parties from Large Dams of the International Commission on Large Dams, would benefit of a better knowledge of the occurred damages.

Consequence-based dam safety: A balanced risk approach. (1995). D.N.D. Hartford, N.M. Nielsen, and P.C. Gaffran. Waterpower - Proceedings of the International Conference on Hydropower 3, Jul 25-28. Sponsored by ASCE, p. 2177-2186.

Consideration with regard to the choice of recurrence interval for a design flood. (1988). J. J. Cassidy, C. D.B., S. L. Hui and J. E. Welton. 16th Congress, International Commission on Large Dams, Q.63, R.036 pp. http://www.icold-cigb.org. (Index terms: case studies, design flood, financial aspects, rehabilitation, risk assessment, spillways).

This paper discusses quantitative requirements for risk assessment in the choice of a recurrence interval for a design flood. Two examples are discussed where dams in Northern California were studied to determine the degree of modification the two dams and spillways should receive in order to pass a satisfactory design flood. The hypothetical optimum capacity for a spillway similar to the existing spillway was determined based on a purely economic risk analysis.

Dam failures: Insights to nuclear power risks, low-probability/high-consequence risk analysis. (1984). W.L. Baldewics. p. 81-90. (Index terms: failures/incidents, risk assessment).

Dam safety and risk assessment procedures for hydrologic adequacy reviews. (1988). N.B. Wellington. Transactions of the Institution of Engineers, Australia: Civil Engineering, v CE30, n 5, Dec., p. 318-327.

Dam Safety Risk Analysis - New Directions. (1997). S. Vick. Int. Water Power and Dam Construction, May.

Dam safety risk analysis methodology [Version 3.3]. (1999). United States Bureau of Reclamation. Technical Service Center. United States. Bureau of Reclamation., Sept 1999, Denver, CO, 74 pp. http://www.usbr.gov/main/index.html.

Document on risk analysis addresses how to identify loading conditions, potential failure modes and consequences, and how to estimate the probabilities for each event. Questions such as "Does the identified risk justify further action?" and "What should be done to reduce risk?" belong to risk assessment, which is beyond the scope of this document. While the primary topic is risk analysis, this document starts by providing a brief introduction to risk assessment and risk management concepts. This helps the reader understand where risk analysis fits into the entire dam safety process, what the legislative mandate for risk analysis is, and some of the appropriate uses of risk analysis. The remainder of the document discusses how to prepare for and how to conduct a risk analysis, and how to report the findings from a risk analysis.

Design level risk assessment for dams. (1987). D. S. Bowles, L. R. Anderson, and T. F. Glover. Invited Keynote Paper in "Dynamics of Structures." Proceedings in the Session on Seismic Considerations in Risk Analysis of Dams, Structures Division Specialty Conference, American Society of Civil Engineers, Orlando, Florida. August, p. 210-225.

Development of hydrologic risk-based methodology for evaluation of dam safety in Missouri. (1988). R.L. Peyton, J.L. Hubbard, and B.J. Swenty. Mining-Engineering, v. 40, Jan. p. 38-42.

Engineering application of dam safety risk analysis. (2000). S. Vick. 20th Int. Congress on Large Dams, ICOLD, Beijing (in press).

Evaluation and presentation of dam failure and flood risks. (1997). K.D. Thompson, J.R. Stedinger, and D.C. Heath. Journal of Water Resources Planning and Management, vol. 123, no. 4, p. 216-227.

Safety studies for existing dams have found that some do not satisfy current estimates of the probable maximum flood (PMF). An event or influence diagram can describe the random factors that contribute to major inflow floods and that determine reservoir operation and possible downstream damages during a flood event. This allows calculation of the probability of dam failure and the distributions of damages and loss of life using combinations of various analytical and Monte Carlo methods. This paper discusses the efficiency of different evaluation methods: event trees, simple Monte Carlo sampling, Latin hypercube sampling, importance sampling, and an analytical/stratified Monte Carlo (A/SMC) method. The analysis suggests that the A/SMC method and importance *sampling have great potential for the efficient estimation of dam failure risks. Numerical examples employ the distributions of damages and loss of life to show the character of trade-offs presented by many dam safety decisions and illustrate problems with the partitioned multi-objective risk method (PMRM). The use of partial expected damage and loss of life functions is recommended to show the importance of low-probability/high-consequence events.*

Evaluation procedures for hydrologic safety of dams. (1988). Task Committee on Spillway Design Flood Selection, Committee on Surface Water Hydrology, Hydraulics Division, American Society of Civil Engineers, New York, NY. 95 p.

Procedures are proposed for selecting the safety design flood for both new and existing dams. The procedures are based on a quantitative risk assessment in which the likelihood and consequences of failure under present and anticipated future conditions are evaluated. Three categories of dams are proposed depending upon failure consequences and effort required to select a design flood. A reconnaissance-level appraisal of failure consequences is adequate to select the design flood for categories 1 and 3 where damages are either very large (category 1), or low and confined to the dam owner (category 3). Category 2 requires a detailed analysis to determine the safety design flood. Selecting a safety design flood for a category 2 dam incorporates consideration of the probability of failure, the consequences of failure (both those which can be measured in monetary terms and those which cannot), and the project cost. The economic analysis of failure consequences which can be quantified in monetary terms requires the dam owner to include the cost of indemnifying possible victims of dam failure against financial loss. The social and environmental consequences which cannot be reduced to monetary terms are displayed for specific inclusion in the safety design decision based on the cost to avoid these non-monetary consequences. Because the relative weighting of non-monetary consequences and their comparison to dollar savings is a matter of judgment which will vary among decision makers for each site examined, no criteria are provided for making the final safety design decision. The report discusses a number of important related issues including legal liability for dam failure and the determination of indemnification.

Guidelines for consequence-based dam safety evaluations and improvements. (1993). BC Hydro. (Index terms: risk assessment).

Guidelines on risk assessment. (1998). Australian National Committee on Large Dams. (Index terms: international programs, risk assessment).

Improving the state of the art in risk analysis. (1999). J. L. Foster. Hydro Review, HCI Publications, Inc., Oct. 12-14 pp. http://www.hydroreview.com. Risk assessment will be used to help prioritize investment decisions for USACE dams.

Initiative for risk-based flood design. (1987). Dawdy, D.R. and Lettenmaier, D.P. Journal of Hydraulic Engineering JHEND8, Vol. 113, No. 8, p 1041-1054. (Index, terms: design flood, risk assessment).

A recent report of the Interagency Advisory Committee on Water Data found that there is no current procedure for assigning an exceedance probability to the probable maximum flood (PMF)...in a reliable, consistent or credible manner. 'This conclusion was used as justification for continuation of the current, quasi-deterministic, PMF-based spillway design methods used by all federal agencies. This is despite criticism by both researchers and practitioners that PMF-based methods tend to lead to a false sense of security and to misallocation of resources for dam safety improvements. As an alternative to perpetuation of the status quo, four general areas in which research should be promoted for improved estimation of extreme floods are outlined, well as research aimed at development of a method for incorporation of risk information into a spillway design. If the federal action agencies were to promote research in the areas suggested, the current stagnation that has set in would be broken, and the self-fulfilling prophecy that there are no alternatives to current practice could no longer be justified.

Measuring and managing the safety of dams: the role of risk. (1996). G. M. Salmon and D. N. D. Hartford. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 8-11, 1996, p. 191-202. (Index terms: risk assessment).

Many people don't want to know the amount of risk associated with hazardous facilities because, to the vast majority, risk is the antithesis of safety. This paper demonstrates that this view of risk is inappropriate and that the comfort gained by avoiding risk issues represents a false sense of security. Unfortunately risk and uncertainty are inevitable in all practical matters - this is as true for dams as it is for other hazardous facilities and all other aspects of life. With dams, we know that there is some risk but we usually don't know how much. Without considering risk explicitly, adoption of the incremental hazard classification method had the effect of making risks due to dams more uniform. High hazard dams were designed for larger floods and earthquakes than were low hazard dams. Risk as used herein is the product of failure probability and failure consequences summed over the entire range of potential failure modes. The (low) level of risk associated with dams is a true measure of their safety. If the risk associated with all dams could be easily measured, it would be a straight ward matter to identify those that should be upgraded and which upgrades would be most effective in increasing the level of safety (i.e. decreasing risk). A major problem in evaluating risk is that traditional methods of analysis are based on avoiding any condition that could result in failure, with little or no consideration of the nature or likelihood of that condition. Consequently, our understanding of failure processes is very poor. For the widespread successful application of risk assessment, new methods of analysis developed from a "failure driven" perspective are needed to permit prediction of the conditions under which failure will occur. Once risk can be accurately *assessed, it provides a meaningful measure of the safety of existing dams, and a basis for the comprehensive management of their safety in the face of uncertainty.*

New directions. (1997). Steven Vick. International Water Power and Dam Construction, v 49, n 5, May. Wilmington Bus Publ. p. 40-42.

Overtopping risk evaluation for an existing dam. (1982). Shui Tuang Cheng. University of Illinois at Urbana, Champaign, DAI, vol. 43-09B, p. 29-76.

A probability-based methodology to evaluate quantitatively and systematically the overtopping risk of dams is formulated. This study considers mainly the overtopping induced by occurrences of flood and wind. Risk models for overtopping consist of fault tree analysis and random process modelling of the flood, wind, and other geophysical forces. A load combination model is established to account for the combined effects resulting from concurrence of flood and wind. A complete procedure for evaluating the risk of overtopping induced by flood and wind including a detailed uncertainty analysis of relevant parameters is presented. The methodology can be generalized to consider other conditions affecting dam safety. Four risk computation techniques are studied and compared; namely, direct integration method, Monte Carlo simulation method, mean-value first-order second-moment method, and advanced first-order second-moment method. The advanced first-order second-moment method, which linearizes the Taylor series expansion of the performance function at the failure point, and utilizes the first and second moments of the component variables, is shown to be the preferred one at present for risk evaluation of dams. A medium sized earth dam located in northern Illinois is used as an example to demonstrate how to evaluate the risk of overtopping over a given period of time interval using the proposed risk model and procedure. Overtopping risk evaluated using the normal pool level of the reservoir together with an inflow flood generated by a 24-hour rainfall, which is the current practice of the U.S. dam safety inspection program, is found to be conservative.

Overtopping risk for an existing dam, civil engineering studies, hydraulic engineering research series. (1982). S. T. Cheng, B. C. Yen, W. H. Tang and National Science Foundation (U.S.). no. 37., Dept. of Civil Engineering University of Illinois at Urbana-Champaign, Urbana, IL., xvi, 195 pp.

Performance evaluation safety assessment and risk analysis for dams. (1997). K. Hoeg. Norges Geotekniske Institutt/Norwegian Geotechnical Institute, n 201, Norwegian Geotechnical Inst., 8pp, 0078-1193.

Performance evaluation, safety assessment and risk analysis for dams. (1996). K. Hoeg. International Journal on Hydropower & Dams, v 3, n 6, Aqua-Media International Ltd., p. 51-58.

Preliminary safety and risk assessment for existing hydraulics structures—an expert system approach. (1987). Bruno Marie Franck. University of Minnesota, DAI, vol. 49-03B, p. 0849.

This thesis describes the engineering knowledge and reasoning processes required to execute the preliminary risk assessment process for existing concrete gravity dams. The research describes the concepts of stability of a concrete dam. An expert system has been developed to contain that knowledge and is validated so that it can be used as an effective engineering decision making tool to assist in the field inspection of a dam. The expert system identifies failure modes, remedial measures, and requests additional information if required. The deterministic evaluation process is concerned mostly with the structural stability of the dam, but takes into account the hydraulic and geotechnical factors that have a direct bearing on the stability evaluation. The emphasis of the research is on the identification and computer modeling of the knowledge rather than the development of a new expert system shell. The present expert system was developed with the shell Personal Consultant Plus. The original aspects of this research are: (1) The research identified the nature and the components of stability in such a way that an expert system could "learn" how to evaluate the stability of any concrete gravity dam in any given loading condition; (2) the expert system does not use a pre-determined fault tree for the risk assessment, because it creates the branch of the fault tree as required by the particular consultation; (3) the expert system combines the reasoning processes to conduct a qualitative evaluation of a dam and to analyze the results of a traditional quantitative engineering evaluation; (4) the methodology takes advantage of both the expert system technology and the qualitative physics and common sense reasoning approaches of artificial intelligence. The refinement and validation of the knowledge base are done by analyzing three different dams under varied loading conditions, and comparing the expert system's results with those of independent engineering evaluations.

Preliminary safety evaluation of existing dams. (1983). M. W. J. McCann, J. B. Franzini, E. Kavazanjian and H. C. Shah. Stanford University, Dept of Civil Engineering. (Index terms: public safety, risk assessment).

Private sector risk analysis applied to dam safety. (1989). Catalino B. Cecilio. Journal of Management in Engineering, v 5, n 4, October, p. 379-384.

Probabilistic hydrologic risk assessment: input for the decision maker. (1991). M. W. J. McCann, N. Markevich and C. Cecilio. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 29 - Oct 2, 1991, p. 254-259. (Index terms: design flood, financial aspects, public safety, rehabilitation, risk assessment, standards).

In recent years dam owners have faced the prospect of major, expensive modifications to existing dams due to the results of the reevaluation of the design *basis flood, Experience indicates that a reassessment of the flood design basis, using data and methods of analysis not available at the time the dam was built, produces a design flood that is greater than the current capacity of the project. Coupled with this ratcheting upward of the design basis is the fact that dam owners must balance the potentially expensive costs to modify an existing project with other competing demands on limited financial resources. This problem applies universally to public and private, large and small dam owners alike. As a result, difficult questions are asked as to the benefits (e.g., improved safety) that are derived from an increase in the design basis and at what expense. In a number of cases dam owners have performed a probabilistic hydrologic risk assessment (PHRA) in an effort to gain some insight to the trade-offs in terms of safety, cost and incremental-risk reduction. For the most part the experience in performing PHRAs is limited (compared to PRA experience in other engineering fields). As a result, the risk assessments that have been performed often fail to provide the owner or regulator with the kind of information/insight that can facilitate the decision-making process. This paper discusses some of the questions that should be asked by a manager/regulator (decision maker), the products that should be provided and the format of the results, prior to starting a PHRA. The answers to these types of questions gives some assurance that valuable input to the issue at hand will be provided. The paper also lists some opportunities for developing acceptable risk standards for dams.*

Probabilistic risk analysis of large dams: its value and limits. (1993). R. Lafitte. International Water Power and Dam Construction IWPCDM, vol. 45, no. 3, p. 13-16.

The application of probabilistic risk, as opposed to deterministic risk, to mechanical structures such as dams began 20 years ago. Risk can be expressed mathematically by multiplying the probability of occurrence of an undesirable event by the probable extent of the damage caused by that event. The establishment of fault trees (relating to causes) and subsequent quantitative analysis are invaluable for determining the possible failure mechanisms of complex systems containing numerous components and for calculating their probability. Categories of dam failure include static failure, seismic failure, and hydrologic failure caused by high water levels. Dam failure results from flaws in design, quality of construction, operations, and the environment. The use of event trees (relating to consequences) provides a method of monetarily assessing potential damages. The path of the flood wave can be calculated from the failure mode of a dam, and measurements on potentially flooded areas can be used to estimate the human, economic, and environmental losses. It is not acceptable to put monetary value on loss of human life, but it is possible to use the concept of risk acceptance. In the design or rehabilitation of a dam, it is imperative that risk analysis for failure be included. Risk analysis is a powerful tool which is indispensable in the design of complex mechanical systems, but it is not yet effective when applied to dams. (Rohrbach-PTT).

Progress report on implementing quantitative risk assessment in Reclamation. (1996). J. L. Von Thun. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 8-11, p. 203-204. (Index terms: federal programs, risk assessment).

Risk assessment has been an integral part of policy and practice in Reclamation's comprehensive dam safety program since the inception of that program in the late 1970's. Risk evaluation is conducted as a matter of principle to meet the objective of achieving the most reduction in risk to the public with available funds. In practice, risk management approaches have been used in Reclamation for: · prioritizing dams for initial investigation and subsequent analysis; · prioritizing finding for modifications; · selecting remediation alternatives; · evaluating the economic justification for modification due to property damages and loss in benefits from darn failure. However, prior to 1995, Reclamation criteria for formulating dam safety modification plans was that ~ determination of significant incremental risk of life loss would require mitigation (structural or non-structural). The risk or likelihood of incurring that loss was not quantified and projects with very high risk and very great consequences in terms of life loss were not formally distinguished from those with lower risk and less severe consequence. Beginning in 1995,Reclamation initiated a process to incorporate quantitative risk assessment as an integral part of all significant dam safety modification decisions. The emphasis here is on the word "quantitative." Quantitative risk assessment for dam safety requires a numerical estimate or "quantification" of the risk and consequences of dam failure and an established criteria or acceptable standard against which the risk and consequences are compared. The author believes that the primary benefit of quantitative risk assessment is the learning derived by the risk evaluation team from the process of quantifying risks and consequences. This benefit is generally recognized by all participants at the conclusion of the study. However, there are three fundamental questions which continue to be raised among participants in implementing fill scale quantitative risk assessment. They are: 1. Can the likelihood of dam failure due to remote events or other causative conditions be reasonably estimated? 2. Can an acceptable risk criteria for potential loss of life be established that will be generally recognized and accepted as legitimate demarcation between structures that are satisfactory and ones that present unacceptable risks to the public? 3. Can a decision process be established and used that will consider the risk assessment results as one input among several inputs in reaching a course of action if all factors have not been formally incorporated into the risk assessment? Believing that the response to each of these questions is yes, but needing the answer to be developed by Reclamation staff for acceptance and use by the agency, an internal team was established to formulate Reclamation's quantitative approach. A consultant (Utah State University) was also added to provide technical assistance. The team, while operating as a whole, had four sub-teams. These four sub-teams, not surprisingly, addressed the fundamental questions identified earlier. 1. Methodology - How should the quantitative estimates of risk and consequences be made? 2. Implementation - Who should participate and on

what type of studies? What training skills are required? 3. Criteria - What criteria should be used? 4. Presentation - How should the results be formulated and presented to facilitate decision making? The team convened in late 1995. Several pilot studies were performed within Reclamation to not only serve the needs of the various projects for which they were used, but also to gain some current, practical experience to help the formulation team members in establishing the direction for future studies. The status of the developments of each sub-team will be presented at the 1996 ASDSO Annual Conference. It maybe noted that the products to be delivered by these sub-teams are not just for the record. The processes, procedures, plans and criteria are being or will be integrated directly into the ongoing darn safety work and darn safety decisions. The goal is to improve the quality of the decisions being made relative to the most cost effective way of reducing risk to the public with the finds that are available. Risk assessment can provide an effective tool for assistance with that goal for any part of a project or study at any phase of the study. Recognizing this, Reclamation's Dam Safety Office is seeking the development of a risk assessment process that can be consistently applied as an integral (and non-controversial) part of all dam safety work.

Quantitative risk assessment using the capacity-demand analysis. (1999). M. Morgenroth, C. R. Donnelly, G. D. Westermann, J. Wang and T. Lam. 2nd Annual Conference, Canadian Dam Association, Oct 3-7, 1999, Sudbury, Ontario, pp. http://www.cda.ca/.

Re-evaluating spillway adequacy of existing dams. (1973). American Society of Civil Engineers. Journal of the Hydraulics Division, American Society of Civil Engineers, Feb., pp. http://asce.org.

Risk analysis and management of dam safety. (1998). Lester B. Lave and Tunde Balvanyos. Carnegie Mellon Univ. Risk Analysis, v 18, n 4, Aug. p. 455-462

Risk analysis for dam safety evaluation - hydrologic risk. (YEAR). J. Stedinger, D.C. Heath, and K. Thompson.

Risk analysis for dam safety, Part I. (1995). G. M. Salmon and D. N. D. Hartford. International Water Power and Dam Construction, 1995a, pp. (Index terms: public safety, risk assessment).

Risk analysis for dam safety, Part II. (1995). G. M. Salmon and D. N. D. Hartford. International Water Power and Dam Construction, April 1995b, 47, 4 Reed Business Publishing Ltd., p. 38-39. (Index terms: public safety, risk assessment).

Risk analysis for dam safety. (1995). G.M. Salmon and D.N.D. Hartford. International Water Power and Dam Construction, Reed Business Publishing Ltd. p. 42-47.

Risk analysis in British Columbia. (1994). N.M. Nielsen, S.G. Vick, and D.N.D. Hartford. International Water Power and Dam Construction, vol 46, n 8, Mar, 6p.

Risk analysis in dam safety practice. Uncertainty in the Geologic Environment: From theory to practice. (1996). S. Vick and R. Stewart. In: C. Shackelford, P. Nelson, and M. Roth (Eds.), Geotech. Spec. Pub. No. 58, ASCE.

Risk analysis in dam safety practice. (1996). Steven G. Vick and R.A. Stewart. Geotechnical Special Publication 58/1, Jul 31-Aug 3. Sponsored by ASTM, ASCE, p. 586-603.

Risk assessment for dams - the thaw, ASDSO annual conference. (1997). M.W.J. McCann. Association of State Dam Safety Officials, Sept 7-10, 1997, p. 709-721. (Index terms: risk assessment).

In the last couple of years there has been a discernible change in climate with respect to the use of risk-based analysis for dams. The once frigid stance of many is facing the equivalent of global warming in the form of accountability, defensibility and balanced decision-making. The interest in the use of risk assessment in dam engineering and dam safety is hardly new. For at least a generation, civil engineers have formally contemplated using risk-based analysis for dams as part of spillway design evaluations (ASCE, 1973). For at least forty years, civil engineers have looked at issues of uncertainty in relation to engineering design, structural safety and decision making. With this back drop, it seems we may be entering a period in which risk-based analysis takes a formal place in dam safety practice. This paper takes a look at some of the reasons for these changes and at issues associated with risk management as applied to dam safety.

Risk assessment for tailings dams. (1999). H. McLeod. 2nd Annual Conference, Canadian Dam Association, Oct 3-7, pp. http://www.cda.ca/. (Index terms: risk assessment, tailings dams).

Risk-based dam safety evaluations - conference report: Part two. (1998). International Journal on Hydropower & Dams, v 5, n 2, Aqua-Media Int. Ltd., p. 73-82.

Risk-based dam safety evaluations. (1998). International Journal on Hydropower & Dams, v 5, n 1, Aqua-Media Int. Ltd., p. 89-97.

Risk-based decision analysis for dam safety. (1982). E. H. Vanmarcke and H. Bohnenblust. Massachusetts Institute of Technology, Department of Civil Engineering. (Index terms: public safety, risk assessment).

Risk-based decision making in water resources. (1989). American Society of Civil Engineers. Engineering Foundation Conference on Risk-Based Decision-Making

in Water Resources, American Society of Civil Engineers, Oct 15-20, 1989, Santa Barbara, California, pp. http://asce.org.

Papers address the application of risk analysis to a wealth of water resources problems. Current risk-assessment issues confronting water resources planners are evaluated along with areas of uncertainty. Requirements and procedures currently promoted by engineers in federal and state water resources agencies are identified.

Task committee on dam risk management. (1998). D.N.D. Hartford. Journal of Hydraulic Engineering, vol. 124, no. 7, p. 662-663.

The possibility of using risk-analysis techniques in dam-safety management was first identified over 25 years ago. Shortly thereafter, several agencies began to consider using these techniques. The 1979 Federal Guidelines for Dam Safety (Ad-Hoc Interagency Committee of Dam Safety 1979), for example, prominently featured risk-analysis techniques. Until recently, however, risk analysis has found little favor with many owners, regulators, and dam engineers. To further complicate matters, proponents of risk-based methods in dam safety decision-making have not agreed on a common approach for advancing the status of these techniques in dam safety practice. The success in reducing the failure rate of dams to a very small number through traditional practices does not preclude recognition of the value of accepting risk-based methods as legitimate dam-safety practices. Engineers have not yet developed dam-safety management techniques that are demonstrably efficient and effective. Yet, they have a responsibility for public safety and, at the same time, for ensuring that the limited available resources are not wasted. Achieving this balance can be difficult, and demonstrating that it has been achieved is an even more arduous task. Furthermore, even though resources are usually limited, there is no established process for prioritizing dam safety improvements. Herein lie some of the most significant challenges faced by civil engineers who are charged with the efficient and effective management of the safety of dams. These issues can be addressed, to varying degrees, through the use of formal risk-management techniques. Unfortunately, and despite some notable exceptions, the civil engineering profession has generally not embraced risk-based processes for dam safety decision-making. Many object to the application of formal risk-based techniques to dam safety, and the controversies surrounding this has resulted in many years of bitter debate within the engineering profession and elsewhere. This debate is ongoing, without an end in sight.

Understanding and managing the risks of aging dams: Principles and case studies. (1999). D.S. Bowles, L.R. Anderson, T.F. Glover, and S.S. Chauhan. 1999 USCOLD Annual Meeting, Atlanta, Georgia, May.

Workshop on risk assessment. (1999). L. Von Thun, D. Bowles and M. McCann. [in conjunction with ASDSO Annual Conference], Association of State Dam Safety Officials, Oct 14-15, 1999, 325 (est.). (Index terms: reference, risk assessment).

2.1.1 Probability Estimation

Considerations for estimating structural response probabilities in dam safety risk analysis. (1999). S.C. Vick. United States. Bureau of Reclamation. Technical Service Center, Sept 1, 1999, Denver, CO, 22 pp. http://www.usbr.gov/main/index.html.

This report treats various methods and procedural techniques for estimating structural response probabilities in the context of current Reclamation practice. Many of these methods have already been adopted, but their technical underpinnings may not be universally appreciated or commonly understood by the technical specialists who apply them and the dam safety decision-makers who use them. One purpose of this work is to enhance this understanding. Inasmuch as engineering judgment is a prerequisite for any dam safety assessment, its quantification as subjective, degree-of-belief probability receives special emphasis. This aspect of probability is seldom treated in its engineering literature, residing instead in such diverse fields as cognitive and experimental psychology, business management, decision theory, and artificial intelligence. Corresponding emphasis is placed on these cognitive, behavioral and judgmental aspects as they pertain to dam safety risk analysis, with key references to work in these fields.

The status of estimation of the probability of failure of dams for use in quantitative risk assessment. (2000). R. Fell, D.S. Bowles, L.R. Anderson and G. Bell. Proceedings of the 20th International Commission on Large Dams (ICOLD) Congress, Beijing, China. September.

2.1.1.1 Floods

A framework for characterization of extreme floods for dam safety risk assessment. (1999). D.S. Bowles and R.E. Swain (Eds.). A Report prepared for the Dam Safety Office, U.S. Bureau of Reclamation, Denver, Colorado.

A framework for characterization of extreme floods for dam safety risk assessments. (1998). R. E. Swain, D. Ostenaa and D. S. Bowles. Dam Safety '98, Association of State Dam Safety Officials, Oct. 11-14, 1998, Las Vegas, NV, p. 659-672.

Risk-based decisions require different types of information than standards-based or deterministic decisions. Reclamation's past practice used the probable maximum flood as the standard for decisions on flood risk. In this type of deterministic analysis, the objective is simply to not exceed structural capacity, irrespective of the probability of such an event. However, when decisions are to *be based on an assessment of risk posed by the response of engineering structures to natural events, a better understanding of the underlying processes is required. Risk-based decisions require sound, physically based estimates of a full spectrum of hydrologic events, as well as characterization of the uncertainty associated with these estimates. The Bureau of Reclamation convened a workshop at Utah State University to develop a practical, robust, consistent, and credible framework for estimating extreme floods for use in dam safety risk assessments. A group of about 20 professionals from North America, Australia, and the United Kingdom reviewed Reclamation practice, and evaluated various advances in hydrometeorology for potential use in the framework. Multiple approaches were used to characterize hydrologic flood risks over the range of exceedance probabilities and durations of interest. Traditional sources of information used in flood frequency analysis and flood hydrograph development include gaged streamflow records, indirect discharge measurements, and precipitation records. Generally these data sources have records that are less than 100 years in length. The framework for developing hydrologic inputs to risk assessments uses the length of record to determine the extrapolation limits used in the flood frequency analysis. Since risk assessments require estimation of floods with return periods in the 10,000- to 100,000-year range and beyond, emphasis is put on developing flood frequency relationships with regional hydrometeorological data and paleoflood information. The uncertainties associated with descriptions of flood flow exceedance probabilities are likely to be substantial and an important attribute for the characterization of hydrologic inputs. In general, the scientific limit to which the flood frequency relationship can be extended based upon available data will fall short of the probable maximum flood for a site. Probable maximum flood estimates provide a useful reference to past practice and can be compared with hydrologic inputs for risk assessment. However, there is limited scientific basis for assigning an annual exceedance probability to the probable maximum flood. If estimates of annual exceedance probabilities beyond scientific limits are required, then prescriptive approaches should be adopted following an evaluation of alternative approaches. No single approach is capable of providing the needed characterization of hydrologic inputs over the full range of exceedance probabilities required for risk assessment. Therefore, results from a number of approaches need to be combined to yield a composite flood risk description; this means several methods and sources of data are needed. The application of several independent methods applicable to the same range of annual exceedance probabilities will increase the credibility and resulting confidence in the results.*

A Monte Carlo approach to determine the variability of PMF estimates. (1996). B. Barker, M. G. Schaefer, J. Mumford and R. Swain. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 8-11, p. 107-122. (Index terms: case studies, flood analysis, hydrology, PMP/PMF, risk assessment).

This study was conducted to examine the range and distribution of floods that could result from the occurrence of the Probable Maximum Precipitation (PMP). This effort is part of a larger joint investigation by the Bureau of Reclamation and Washington State to develop procedures for estimating the magnitude-frequency characteristics of extreme floods. The methodologies developed in these studies are to be used in flood analyses for assessing spillway adequacy and quantifying safety at Bureau of Reclamation projects. Current practice for computation of an Inflow Design Flood (IDF) typically utilizes a hydrologic model with conservative, single valued input parameters. This approach often results in a design flood where the flood event is more rare than the causative precipitation event. The magnitude of the increase in conservatism between the precipitation event and flood event caused by this practice is generally unknown. In the analysis presented in this paper, the hydrologic model input parameters were treated as variables. Monte Carlo procedures were used to allow the model input parameters to vary in accordance with that observed in nature while preserving the natural dependency that exists between some climatic and hydrologic parameters. Specifically, five-hundred flood simulations were performed using PMP and parameters sampled from the respective climatic and hydrologic probability distributions. The resultant floods were then examined to reveal the range and distribution of floods generated by various combinations of the input parameters. This procedure allows for the determination of the conservatism of the PMF by comparison with the distribution of floods which can be generated by PMP.

A non-inundation approach to paleoflood hydrology for the event-based assessment of extreme flood hazards. (1994). D. Levish, D. Ostenaa and D. O'Connell. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 11-14, p. 69-82. (Index terms: flood analysis, hydrology, risk assessment).

Most streams are flanked by a stair-step series of abandoned flood plains. These abandoned flood plains are terrace surfaces. Terrace surfaces record the time interval since the last major flood inundation, and may range in age from several hundred to tens of thousands of years. These surfaces are underlain by stream-transported flood plain sediment, and thereby are quite sensitive to inundation. During extreme flood events, streams are often profoundly modified and many reaches exhibit clear evidence of erosion and deposition. If ages can be derived for flood-modified terrace surfaces, the terrace surfaces become conservative datums that limit the magnitude and the frequency of large floods. Likewise, the absence of features indicative of inundation provides positive evidence of the non-occurrence of floods exceeding a specific stage over a measurable time period. Following the framework introduced by Stedinger and Cohn (1986), this type of flood record spanning hundreds to thousands of years can be input into flood frequency calculations. This long-term flood record accurately portrays the ability of a specific basin or region to produce extreme floods and significantly *narrows the confidence intervals around predicted flood magnitudes at long return periods.*

Design storm construction. (1992). M. Schaefer. Washington Department of Ecology. Water Resources Program, July. (Index terms: design, risk assessment standards, state programs).

Development of hydrology for spillway evaluation within California's dam safety program. (1989). E. R. Calzascial and F. J. Sage. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 1-5, 1989, p. 63-68. (Index terms: flood analysis, hydrology, risk assessment, state programs).

The topography and climate of California are extremely diverse, ranging from low elevations at the coast to the high altitudes of the Sierras, from less than 3 inches of annual rainfall in the southeast desert basins to over 120 inches on the extreme north coast. Drainage basins for dams vary in size from portions of an acre to thousands of square miles. Stream gages are sparse in most areas and are essentially nonexistent in the undeveloped areas. Accurate estimation of rare flood flows from recorded data is especially difficult due to the lack of basic site-specific flow data from which the flood producing potential of a drainage basin can be predicted. However, estimates of rare floods must be developed for all dam sites to be used in evaluation of spillway capacities. To this end, precipitation records are employed in lieu of actual flow data. A method was developed by California's Division of Safety of Dams (DSOD) to estimate flood hydrographs for ungaged or poorly gaged watersheds for use in spillway evaluation.

Event-based assessment of extreme flood hazards for dam safety. (1996). D. A. Ostenaa and D. R. Levish. ASDSO Western Regional Conference, Association of State Dam Safety Officials, April 14-16, 1996, p. 41-54. (Index terms: flood analysis PMP/PMF, risk assessment).

In the western U.S. terrace surfaces, abandoned flood plains, that range in age from hundreds to tens of thousands of years flank most streams. The soils and stratigraphy underlying these surfaces record the time interval since the last major flood inundation. Preserved, non-inundated surfaces known age for conservative limits for the paleostage of past large floods. These paleostage limits can be input into a step-backwater model to estimate the maximum discharge that would not significantly inundate, and therefore significantly modify, a particular geomorphic surface. The maximum discharge, together with the age of the surface, forms a conservative limiting bound on peak discharge over a long time period. These bounds are not actual floods, but instead they are limits on flood magnitude over a measured time interval. In this way, these bounds represent stages and discharges that have not been exceeded since the geomorphic surface stabilized. For dam safety, the critical issue is not the accurate estimation of a complete record of floods well within the operating

range of the structure, but rather the frequency of floods that could challenge the operational capacity of the structure. The key issues are the precision of the frequency estimate of such large floods, and the probability that the operational capacity of the dam will not be exceeded. Floods near the magnitude of the paleohydrologic bounds are direct indicators of the likelihood of large floods that might compromise dam safety. The results of paleoflood studies in California, Oregon, and Utah demonstrate that discharge with calculated annual probabilities of 1 in 10,000 are in the range of five to 20 percent of hypothetical Probable Maximum Flood (PMF).

Expected annual flood damage computation. (1977). United States. Army Corps of Engineers. United States. Army Corps of Engineers. http://www.usace.army.mil/.

Flood and drought risk models for tailings management areas. (1999). H. Belore, J. Balins and R. Payne. 2nd Annual Conference, Canadian Dam Association, Oct 3-7, 1999. http://www.cda.ca/. (Index terms: models, risk assessment, tailings dams).

Fragility analysis for concrete gravity dam safety under flood. (1999). L. A. de Bejar. Dam Safety 1999, Association of State Dam Safety Officials, Oct. 10-13, St. Louis, MO.

An engineering methodology is developed to assess the safety of concrete gravity dams under flood loading. The extreme flood hazard is estimated in probabilistic terms. Critical random parameters to model the two-dimensional nonlinear behavior of the dam-rock system are identified. A rational approach to include the proper limit states, damage, and the associated consequences of damage intensity up to failure is developed. The conditional probability of damage for a given limit state, given that a certain magnitude of the flood hazard has occurred, is estimated using fragility analysis and statistical sampling techniques. Both economic and life risks are evaluated separately and compared with values commonly accepted by society. Considering the Bluestone Lake Dam as an example illustrates the practical applications of the technique.

Hydrologic parameter effects on small-dam risk analysis in Missouri. (1990). R. Lee Peyton, and Arthur R. Kalmes. Journal of Irrigation and Drainage Engineering, v 116, n 4, p. 465-478.

Notional probabilities of estimated PMP events. (1994). Helen J. Pearce. National Conference Publication - Institution of Engineers, Australia, 3 94/15 Nov 21-25, p. 55-61.

Paleohydrology: Event-based information for validating dam safety decision models of hydrologic risk. (1997). D. A. Ostenaa, D. R. Levish and D. R. H. O'Connell. ASDSO Western Regional Conference, Association of State Dam Safety

Officials, May 5-7, p. 43-52. (Index terms: design flood, flood analysis, risk assessment).

Dam safety conditions on structural or operational modifications to mitigate for hydrologic risk issues require accurate information on hydrologic hazards. Traditional standards for hydrologic safety such as PMF (Probable Maximum Flood) are not real floods, but rather are deterministic, upper limit models that should be verified by actual data. Precipitation and streamflow records that extend only a few tens of years do not provide sufficient information to validate models or to test alternatives. Floods that are critical for dam safety are most often those with return periods of thousands of years or more. The appropriate type of data for testing models of extreme floods critical to dam safety decisions is paleohydrologic data that represents thousands of years of flood history on a particular river or region. The most direct method to accurately estimate the magnitude and frequency of extreme floods is to study the record of past floods, primarily in the Holocene (last 10,000 years) through paleoflood hydrology. Detailed reconstruction of a record of past floods is not always possible or economically feasible. However, for mist streams in the western U.S. if it is possible to set bounds on the magnitude and frequency of floods through analysis of the geomorphology and soil stratigraphy of terrace surfaces along streams. The relatively high gradient of streams in the west facilitates this analysis because even shallow inundation results in high stream power and shear stress that change this morphology of an inundated surface and leave a stratigraphic and geomorphic record. A paleohydrologic bound is a geoomorphically and underlying stratigraphy, geomorphic surfaces adjacent to streams form limits on the paleostage of large floods over thousands of years. These paleostage limits can be then input into a hydraulic model to calculate the maximum discharge that would not significantly inundate, and therefore not significantly modify, a particular geomorphic surface. This maximum discharge, together with the age of the surface, is a conservative limiting bound on flood discharge through time that forms input for flood-frequency analysis. These bounds are not actual floods, but instead they are limits on flood magnitude over a measured time interval. Therefore, these bounds represent stages and discharges that have not been exceeded since the geomorphic surface stabilized. Paleohydrologic data provides a direct record of the integrated response of a river basin to changing conditions of climate and vegetation over time scales of thousands of years. By allowing hydrologic risk assessments to proceed directly from data on peak discharge and frequency, dependence on unverified models and assumptions is greatly reduced. The use of paleohydrologic bounds spanning thousands of years in flood frequency analysis permits more robust estimates of floods with return periods of thousands to tens of thousands of years than is possible with only short, historic annual peak discharge or rainfall records.

Re-evaluation of design floods and dam safety. (1982). V.K. Hagen. 14th Congress, International Commission on Large Dams, Q.52, R.029 pp. http://www.icold-cigb.org. (Index terms: design flood, risk assessment).

Current trends in risk analysis are generally directed toward estimating the theoretical probability of dam failures. Difficulty of assigning probabilities is addressed.

Regional interdisciplinary paleoflood study to assess the risk of extreme floods for Elkhead Reservoir, Northwestern Colorado. (1997). R. D. Jarrett. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 7-10, p. 705-706. (Index terms: flood forecasting, PMP/PMF, risk assessment).

Worldwide, floods are one of the most destructive events related to meteorological processes. In the United States, an average of 95 people are killed and about $2.4 billion in damages occur annually from floods. Therefore, accurately estimating the risk of extreme flooding is important. Estimating the magnitude of extreme floods in many river basins is difficult because of relatively short streamflow-gauging-station records. For many streams, gaged records do not contain large-magnitude, low frequency floods. Estimates of large floods are needed to provide accurate flood-frequency relations for the design of structures such as dams and highway infrastructure located in floodplains and for flood-plain management. For about the past 50 years, the design criteria for construction of structures such as dams have included an estimate of the probable maximum flood (PMF). The PMF is an estimate of the maximum flood potential for a given drainage basin and is derived from an analysis of the probable maximum precipitation (PMP). In the past decade, there has been a growing interest by dam-safety officials to incorporate a risk-based analysis for design-flood hydrology.

Risk from natural hazards: Contrasting risk from hydrologic and seismic hazards. (1997). D. A. Ostenaa and J. P. Ake. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 7-10, 1997, 707. (Index terms: risk assessment, seismic behavior/analysis).

Traditional dam safety evaluations of hydrologic and seismic loadings have utilized concepts for maximum loading conditions such as the Probable Maximum Flood (PMF) and Maximum Credible Earthquake (MCE). In concept, both the PMF and MCE were hypothetical maximums based on upper bounding values of observed data. In the context of standards-based safety analyses, without considering risk, this approach was thought to provide reasonable and comparable levels of safety from both flood and earthquake loadings. However, recent work suggests the currently applied practices of flood and earthquake hazard assessment has lead to a discrepancy in imposed risk. Estimates of flood hazard are typically derived by model result extrapolation from temporally limited streamflow and rainfall records within a standardized set of procedures.

Through time, as new rainfall and flood records have accrued, estimates of the PMF have steadily grown. While estimates of earthquake loading functions have increased as well, so has the scope and complexity of associated technical studies. In particular, earthquake hazard studies in the western United States usually include a large component of site specific, geologic investigations to define fault sources, recurrence information and site response characteristics. These investigations often strictly limit the earthquake sources and loading that are considered 'credible' for a site. Paleohydrologic and other data now indicate that the annual probability of the PMF at most sites in the western United States is likely 10-'0 or less, whereas fault studies show that annual probabilities for MCE'S and associated ground motions are as large as 10-3 at some sites in California and are most commonly 10-4 to 10-5. Fault and ground motion parameterization has typically focussed on preferred or median estimates. Conversely, flood estimates have typically focussed on limit values for many or all model parameters. This philosophical divergence explains in part the contrasting annual probabilities mentioned above. In contrast to earthquake-related dam failure scenarios, most flood-related dam failure scenarios have some warning time, a factor shown to be very important in reducing fatalities. Likewise, the probability of failure due to the occurrence of these loadings is only rarely unity. In this light, the additional conservatism in loading can result in severe inconsistencies in imposed risk due to floods and earthquakes, where risk is the product of loading, system response, and failure consequences.

The value of paleohydrologic information in dam safety decision-making. (1999). D. R. H. O'Connell, D. A. Ostenaa and D. R. Levish. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 10-13, 1999, p. 707-718. (Index terms: design flood, flood analysis, risk assessment).

As the dam safety community moves away from deterministic analyses, there is a need for robust methods for probabilistic estimation of extreme floods. For most dam safety decisions, the critical need is for estimating the magnitude of floods with annual probabilities in the range of 1 in 1000 to 1 in 10,000. In engineering flood hazards, past practice has generally focused on flood plain management issues where the range of interest is typically 1 in 100, or on deterministic upper limit floods with no associated probability. The latter case has been the emphasis of past deterministic dam safety analyses, but is difficult to employ in probabilistic analysis. Paleohydrologic data from the western United States demonstrates that the long geologic record of floods does not generally match the extrapolations often made with conventional statistical tools based on short historical records. Detailed studies on more than 20 river systems throughout the 11 western states indicates that paleohydrologic bounds can be readily developed using the geologic record from at least the past 1000 to more than 10,000 years. This actual record of floods is substantially different than extrapolations from historical records alone. Extrapolations from short gage records both overestimate and underestimate the magnitude of low probability floods. The *paleohydrologic record also provides a basis for assessing the validity and probability of extreme floods derived from deterministic concepts such as PMP and PMF. Concerns have been raised in regard to the applicability of paleohydrologic information in light of past and future climate change. For dam safety decisions, the key issue is selection of data or records that provide robust predictive value for extreme floods. Proxy climate records for the past 10,000 years demonstrate that strong decadal-to century-scale fluctuations are persistent and that present climate is not outside the range of fluctuations that has characterized the past 10,000 years. These data indicate the need for extreme caution in using predictions of extreme floods based on short records alone. In contrast, the paleohydrologic record contains 10's to 100's of these fluctuations and thus captures multiple opportunities for extreme conditions. Models of extreme hydrologic behavior are only the first step. These models must be validated with actual data, and then reformulated to satisfy that data. Without constraints from actual data, the predictive capabilities of model results are unknown. By virtue of being the only available long-term record of extreme flood history, paleohydrologic data are the only basis for validating models of extreme floods behavior. Thus, these data are essential if a goal is to quantify extreme flood probabilities for use in Dam Safety risk assessment.*

TVA practice in flood frequency and risk analysis. (1987). D. W. Newton. Application of Frequency and Risk in Water Resources: Proceedings of the International Symposium on Flood Frequency, Louisiana State University, Baton Rouge, U.S.A. D. Reidel Publishing Company, Boston, MA. 1987. p 429-4384.

In carrying out its responsibilities TVA has constructed dams and fossil and nuclear power plants, operates and maintains its dams including their safety evaluation, and maintains a program of floodplain management activities with communities, industries , and individuals. The flood frequency and risk analysis procedures used by TVA in these activities are described. Discussed are (1) TVA 's conclusions about the most accurate methods to compute flood frequency at ungaged locations including use of limited site historic flood data obtained through TVA 's flood documenting activities; (2) the procedures and data used by TVA to estimate the probable maximum flood (PMF) to ensure that estimates are realistic and compatible with meteorological experience; (3) approaches TVA has used to define flood frequencies of extreme events up to and including the PMF; and (4) risk analysis as applied by TVA in community planning and dam safety evaluations. Recommendations as to additional procedures needed to enhance the engineer 's capability for improved flood frequency and risk analysis include: (1) a nationally consistent standard for determining the PMF; (2) an ' agreed-to ' procedure to evaluate flood probabilities up to and including the PMF; (3) procedures for incorporating into the design decision the economic, social, and environmental impacts of dam failure; and (4) improved procedures for estimating flood frequencies at ungaged locations.

Use of atmospheric models and a distributed watershed model for estimating the probability of extreme floods. (1998). J. D. Cattanach and W. Luo. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 11-14, 1998, p. 673-684. (Index terms: flood forecasting, models, hydrology, PMP/PMF, risk assessment).

Studies are currently underway to estimate the magnitude-frequency characteristics for extreme floods on the Upper Columbia watershed. The approach includes the use of atmospheric models, the findings from a precipitation regional analysis, the distributed precipitation-runoff flood model WATFLOOD, and Monte Carlo sampling methods to examine floods resulting from various combinations of hydro-meteorological conditions. A simplified atmospheric boundary layer model has been used to simulate daily precipitation and temperature on a 4-km grid spacing over the Upper Columbia basin for the 96 year period from 1899-1994. This data in combination with streamflow records have been used to calibrate the WATFLOOD model for use in estimation of floods produced by extreme precipitation. A new generation of high-resolution non-hydrostatic atmospheric model MC2-PMS is used to generate extreme storms. The MC2-PMS model was developed by the Numerical Prediction Research Division (RPN) of Environment Canada and is designed for three-dimensional perturbation of initial storm conditions as the generated storm picks up moisture in moving over the Pacific Ocean. The model will generate severe storms up to the range of PMP consistent with statistics of storm components observed over the past 100 years. The MC2-PMS provides the temporal and spatial distribution of the precipitation as well as temperature for each generated storm on the 4 km grid spacing. The exceedance probability of the extreme storm is determined based on the findings of precipitation regional analyses. The watershed runoff model WATFLOOD is then used to simulate the hydrologic response of the watershed. WATFLOOD is used in a continuous simulation mode prior to the arrival of the storm generated by the MC2-PMS model. Antecedent conditions are determined by Monte Carlo sampling methods based on watershed conditions observed in the 96-year simulation period. The resultant floods are then used to develop the magnitude-frequency relationships for flood peak discharge, runoff volume and maximum reservoir level.

Use of extreme storm data in assessing the hydraulic adequacy of spillways in Washington State. (1994). M. G. Schaefer. 1994 Western Regional Conference Proceedings, Association of State Dam Safety Officials, May 3-4, 1999, p. 3-20. (Index terms: flood analysis/spillway capacity, hydrology, PMP/PMF, risk assessment spillways, state programs).

Probabilistic methods and risk based criteria have been adopted for use in evaluating the hydraulic adequacy and safety of spillways in Washington State. There are four principal components to the evaluation procedure: regional analyses of precipitation annual maxima for estimating the magnitude-frequency characteristics of extreme storms; probabilistic procedures for assembling *synthetic hyetographs that have the characteristics of historical extreme storms; rainfall-runoff modeling criteria to provide guidance in parameter selection to reflect the flood experience in Washington; and risk based evaluation criteria to aid in decision making. Elements of the studies to develop each of the four components are summarized and the findings are discussed briefly.*

2.1.1.2 Earthquakes

Calculation of the seismic risk of an earth dam susceptible to liquefaction. (1998). M. K. Lee, K. Y. Lum, and D. N. D. Hartford. Geotechnical Earthquake Engineering and Soil Dynamics III, American Society of Civil Engineers, August 3-6, p. 1451-1460. http://asce.org. (Index terms: embankment dams, risk assessment, seismic behavior/analysis).

Engineering guide to seismic risk to dams. (1992). J.L. Hinks and J.A. Charles. International Water Power and Dam Construction, v 44, n 3, Mar, p. 46-47.

Engineering guide to seismic risk to dams in the United Kingdom, and its international relevance. (1994). E.M. Gosschalk, R.T. Severn, J.A. Charles, and J.L. Hinks. Soil Dynamics and Earthquake Engineering, v. 13, n. 3, Elsevier Applied Science Publ Ltd., p. 163-179.

Geological and seismological evaluation of earthquake hazards at Ririe Dam, Idaho. (1991). E. L. Krinitzsky, J. B. Dunbar. United States. Army. Corps of Engineers. Walla Walla District and U.S. Army Engineer Waterways Experiment Station, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 75, [66] pp.

Risk from natural hazards: Contrasting risk from hydrologic and seismic hazards. (1997). D. A. Ostenaa and J. P. Ake. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 7-10, 1997, 707 (abstract only) pp. (Index terms: risk assessment, seismic behavior/analysis).

Traditional dam safety evaluations of hydrologic and seismic loadings have utilized concepts for maximum loading conditions such as the Probable Maximum Flood (PMF) and Maximum Credible Earthquake (MCE). In concept, both the PMF and MCE were hypothetical maximums based on upper bounding values of observed data. In the context of standards-based safety analyses, without considering risk, this approach was thought to provide reasonable and comparable levels of safety from both flood and earthquake loadings. However, recent work suggests the currently applied practices of flood and earthquake hazard assessment has lead to a discrepancy in imposed risk. Estimates of flood hazard are typically derived by model result extrapolation from temporally limited streamflow and rainfall records within a standardized set of procedures. Through time, as new rainfall and flood records have accrued, estimates of the

PMF have steadily grown. While estimates of earthquake loading functions have increased as well, so has the scope and complexity of associated technical studies. In particular, earthquake hazard studies in the western United States usually include a large component of site specific, geologic investigations to define fault sources, recurrence information and site response characteristics. These investigations often strictly limit the earthquake sources and loading that are considered 'credible' for a site. Paleohydrologic and other data now indicate that the annual probability of the PMF at most sites in the western United States is likely 10-'0 or less, whereas fault studies show that annual probabilities for MCE'S and associated ground motions are as large as 10-3 at some sites in California and are most commonly 10-4 to 10-5. Fault and ground motion parameterization has typically focussed on preferred or median estimates. Conversely, flood estimates have typically focussed on limit values for many or all model parameters. This philosophical divergence explains in part the contrasting annual probabilities mentioned above. In contrast to earthquake-related dam failure scenarios, most flood-related dam failure scenarios have some warning time, a factor shown to be very important in reducing fatalities. Likewise, the probability of failure due to the occurrence of these loadings is only rarely unity. In this light, the additional conservatism in loading can result in severe inconsistencies in imposed risk due to floods and earthquakes, where risk is the product of loading, system response, and failure consequences.

Rufiji Basin Development Authority (RUBADA) and Norges teknisk-naturvitenskapelige forskningsråd (1978). F. Ringdal, H. Bungum, Aktieselskabet Hafslund, , Stiegler's Gorge, Tanzania, hydroelectric power project : seismic risk analysis, phase I, NORSAR technical report; no. 1/78, Aktieselskabet Hafslund, Oslo, 100 pp.

Seismic Rehabilitation of Existing and Abandoned Tailings Dams. (1991). T. G. Harper, H. N. McLeod and B. O. Watts. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 29 - Oct 2, 246 (abstract only) pp. (Index terms: design, models, rehabilitation, risk assessment, seismic behavior/analysis, standards, tailings dams).

Seismic design criteria for tailings dams has become more stringent as a better understanding of seismicity, soil behaviour, and failure impact evolves. Tailings dams are often constructed with hydraulic fill techniques, which mainly include cycloned and spigotted sand from the tailings stream. The placement techniques, and hence the density, vary considerably and have a direct influence on their susceptibility to liquefaction under seismic loading. A large number of existing and abandoned tailings dams are now recognized to have a potential "risk of failure" as new seismic criteria is applied. Conventional deterministic approaches are often not appropriate for assessing the degree of risk and/or benefit due to dam safety upgrading. This paper describes techniques for assessing the probability of failure with a seismic liquefaction model. The model takes into account the seismicity (earthquake epicentres, magnitude and *acceleration), the predominant period of the impoundment and the response of the tailings. The model has been used successfully on an assessment of a major tailings structure and provides a quantitative method for comparing and assessing various risk reduction options for tailing dam rehabilitation.*

Seismic response component in the risk assessment of dams. (1987). L. R. Anderson and D. S. Bowles. Invited paper in "Dynamics of Structures" Proceedings in the Session on Seismic Considerations in Risk Analysis of Dams, Structures Division Specialty Conference, American Society of Civil Engineers, Orlando, Florida. August, p. 241-260.

Seismic safety of embankment dams: Developments in research and practice 1988-1998. (1998). W.D. Finn and Liam. Geotechnical Special Publication, v 2, Aug 3-6, ASCE, p. 812-853.

2.1.1.3 Normal operating conditions

Risk assessment - estimating the probability of failure of embankment dams by piping. (1998). M. R. Foster, R. Fell and M. Spannagle. ANCOLD/NZSOLD Conference on Dams, Australian National Committee on Large Dams, 11 pp. (Index terms: embankment dams, piping, risk assessment).

2.1.2 Consequence Assessment

Dams and flood risks. (1996). Francois Lemperiere. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15, p. 51-55.

GIS for dam and valley safety management. (1997). Miguel Gamboa and Maria A. Santos. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov. 13-15, p. 173-178.

2.1.2.1 Dam break and inundation modeling

Detection and assessment of dambreak-scenarios. (1997). K. Kast and A. Bieberstein, A. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15, 1996, p. 133-142.

Flood routing techniques for incremental damage assessment. (1994). E. F. Jayyousi, D. S. Bowles, and R. W. Jeppson. Proceedings of the Association of State Dam Safety Officials Western Regional Conference, Park City, Utah. May.

Land use management and dam break flood risk: The Arade River case study. (1997). Vitor Farrajota Campos. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15, p. 127-129.

2.1.2.2 Life loss

A procedure for estimating loss of life due to dam failure. (1997). W. J. Graham. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 7-10, 1997, p. 629-640. (Index terms: public safety, risk assessment, warning systems).

An integral part of any risk assessment is the determination of the loss of life that would result from failure of a dam. Procedures for estimating loss of life have appeared in Reclamation' s "Guidelines to Decision Analysis, " published in 1986 and in "Policy and Procedures for Dam Safety Modification Decision-making", published in 1989. The procedures presented in this document incorporate information from these earlier references. A step by step process for estimating loss of life resulting from dam failure is presented.

An automated assessment method for the potential loss related to a dam failure, dam safety from theory to practice. (1994). C. Marche, E. McNeil and R. Boyer. [1994 CDSA/CANCOLD Conference], Oct 1994, p. 341-354. http://www.cda.ca/. (Index terms: computer programs, risk assessment).

Assessing the threat to life from dam failure. (1988). C. A. Brown and G. W.J. Water Resource Bulletin, Dec 1988, p. 1303-1309. (Index terms: failures/incidents, public safety, risk assessment).

Estimating loss-of-life due to dam failures: pitfalls, fallacies and recommendations. (1999). M. W. J. McCann and M. J. Robertson. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 10-13, p. 639-652. (Index terms: public safety, risk assessment, warning systems).

There are a number of applications in which it is useful, if not necessary, to assess the potential for loss-of-life in the event of dam failure. Applications include classification of a dam's hazard class, probabilistic risk assessments, and emergency planning. In certain applications, such as probabilistic risk analyses for dams, it is necessary to estimate the actual number who may lose their life. It is intuitive that the problem of estimating the what fraction of the population-at-risk is inherently random due to such factors as time of day, dissemination of warnings to those downstream (with/without the benefit of emergency action plan). Such assessments are further complicated by the limited data that is available to construct models for making such predictions. As part of recent study, the authors were required to estimate the potential for loss-of-life in the *event of a dam failure and to assess the uncertainties in such estimates. Based on this case study, a measure of the natural variability and the uncertainty in model predictions were quantified. The results were surprising in a number of respects. In this paper we present results for a number of case studies, lessons and insights from these applications. In this paper we identify and demonstrate the difficulties and biases associated with empirical models that have been developed to estimate the loss-of-life in the event of dam failure. One model in-particular developed by DeKay & McClelland (D&M) (1993), which is an extension of earlier work by the U.S. Bureau of Reclamation, is an empirical approach to estimate the fraction of population-at-risk that would lose their life in the event of a dam failure. On close examination of this model and the data on which it is based, a measure of the randomness in the potential for loss of life, and more importantly the uncertainty in the model predictions is developed.*

Life-loss estimation: What can we learn from case histories? (1999). D.M. McClelland and D.S. Bowles. Proceedings of the 1999 Australian Committee on Large Dams (ANCOLD) Annual Meeting, Jindabyne, New South Wales, Australia. November.

Predicting loss of life in cases of dam failure and flash flood. (1993). M. L. DeKay and G. H. McClelland. Risk Analysis, p. 193-205. (Index terms: public safety, risk assessment).

Setting decision thresholds for dam failure warnings: a practical theory-based approach. (1991). M. L. DeKay and G. H. McClelland. University of Colorado Center for Research on Judgment and Policy, December 31, 1991. (Index terms: risk assessment, warning systems).

The reality of life safety consequence classification. (1999). I. R. Kerr, H. Assaf and D. N. D. Hartford. 2nd Annual Conference, Canadian Dam Association, Oct 3-7, 1999. http://www.cda.ca/. (Index terms: hazard classification, public safety, risk assessment).

Using threat to life studies to guide dam safety decisions. (1993). Wayne J. Graham. Proceedings - National Conference on Hydraulic Engineering, pt 1, Jul 25-30. Sponsored by: ASCE Publ., p. 678-683.

2.1.2.3 Economic and financial

Assessing cost of dam failure. (1993). B. Ellingwood, R. B. Corotis, J. Boland, and N. P. Jones. Journal of Water Resources Planning and Management (ASCE) JWRMD5, Vol. 119, No. 1, p. 64-82.

Dams of significant size fail in the United States at an average rate of more than one per year. During the period from 1965 to 1985, there were seven dam and *levee failures in the United States that were serious enough to be classified as disasters by the federal government. Policy studies and decisions regarding dam safety involve many considerations, and different state and federal agencies have different perspectives on dam-safety assessment. These perspectives may include post-disaster assistance, risk-benefit analysis, and regulatory issues. An initial phase of an investigation to develop a methodology for estimating the total costs of a dam failure included the fundamental issues of accounting stance, damage to fixed assets, loss of income, intangible losses, and loss of life and limb. A literature review of historical floods and dam failures was used as the starting point for developing a framework for evaluating dam failure costs. Cost-related information was portrayed by type and collection priority in a data collection matrix to guide an on-site investigation. This matrix was tested by evaluating five major dam failures that occurred in the United States during the past 20 years, and significant limitations in the current data were identified. The methodology might be used to assist in conducting a probabilistic safety assessment of a dam, or to develop more rational public policies aimed at risk mitigation, once validated by trial data collections. (Author's abstract).*

Economic aspects of the Bureau of Reclamation Safety of Dams program. (1993). R. Walker. Proceedings - National Conference on Hydraulic Engineering, pt 1, Jul 25-30. Sponsored by ASCE, p. 684-688.

2.1.2.4 Other consequences

Dam safety: Risks and measures. (1993). R. Boivin. Bureau de soutien de l'examen public du projet Grande-Baleine and Comité d'évaluation. Background paper / Great Whale Public Review Support Office ; no. 6, the Office, Montréal, iv, 49 pp. http://www.biblinat.gouv.qc.ca:6611/cgi-bin/bestnstatus?rec=452761825&sc=2.

Social sciences involvement in dams and safety management of downstream valleys: A first approach to Arade and Funcho's dam break flood risk perception. (1997). Sousa e Silva Delta. In: A.A. Balekam (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15, p. 111-121.

2.1.3 Risk Criteria/Guidelines

(?)Guiding principles. (1995). Angela Macdonald-Smith. International Water Power and Dam Construction. Reed Business Publishing Ltd., p. 16-17.

Comparison of hazard criteria with acceptable risk criteria. (1995). D. S. Bowles, L. R. Anderson, and T. F. Glover. Proceedings of the annual meeting of the

Association of State Dam Safety Officials, Atlanta, Georgia. September 17-20, 1995, p. 293-302.

(Index terms: design flood, flood analysis, hazard classification, risk assessment). Hazard classification criteria are commonly used as a basis for determining the design flood requirements for dams. Threat-to-life and economic damages are used to assign a low, significant, or high hazard rating with the high rating commonly leading to the requirement for passing the probable maximum flood. Many states, government agencies, and professional bodies have developed their own version of hazard classification criteria which contain different definitions of low, significant or high ratings, and sometimes more than three ratings are used. When these different definitions are carefully examined they can be shown to lead to potential inconsistencies in design flood requirements. Examples of these inconsistencies are described in this paper through a comparison of several different hazard criteria, which are in current use, against internationally-used acceptable risk criteria for life safety. In some cases, hazard classification appears to lead to dam safety requirements that may exceed those at nuclear power plants, or for the siting of hazardous industrial facilities. The comparison will include a summary of the results of preliminary risk assessments of twenty dams.

Estimation of the normative dam safety on the base of risk criteria. (1997). D.V. Stefanishin. Gidrotekhnicheskoe Stroitel'stvo, n 2, Feb. Izdatel'stvo Meditsina, p. 44-47.

Guidelines for achieving public protection in dam safety decision making. (1997). U.S. Bureau of Reclamation. 19 pp. (Index terms: federal programs, public safety, risk assessment).

Selection of tolerable risk criteria for dam safety decision making. (1994). N. M. Nielsen, D. N. D. Hartford and T. F. MacDonald. Canadian Dam Safety Conference. (Index terms: risk assessment).

The role of government in assessing the acceptability of risk and the efficacy of safety. (1980). D.S. Bowles. Panel discussion, Proceedings of the Engineering Foundation Conference on Risk/Benefit Analysis in Water Resources Planning and Management, Pacific Grove, California. September, 7 p.

2.1.4 Decision Making/Policy Issues

(?)Designing safety into dams. (1990). P.A.A. Back. International Water Power and Dam Construction, v 42, n 2, Feb., p. 11-12.

(?)Repair and upgrading of dams. (1996). Anon. International Journal on Hydropower & Dams 3 5 1996 Aqua-Media International Ltd. p. 74-85.

A role for risk assessment in dam safety management. (1997). D.S. Bowles, L.R. Anderson and T.F. Glover. In: Broch, Lysne, Flatabo, and Helland-Hansen (Eds.). Balkema, Rotterdam, Proceedings of the 3rd International Conference HYDROPOWER '97, Trondheim, Norway. June.

Achieving public protection with dam safety risk assessment practices. (1997). Charles Hennig, Karl Dise, Bruce Muller. Risk-Based Decision Making in Water Resources. Proceedings of the Conference, Oct 12-17. Sponsored by ASCE, p. 19-32.

Consequence-based dam safety: A balanced risk approach. (1995). D.N.D. Hartford, N.M. Nielsen, and P.C. Gaffran. Waterpower - Proceedings of the International Conference on Hydropower, 3 Jul. 25-28. Sponsored by ASCE, p. 2177-2186.

Cost effective improvements in fill dam safety. (1995). F. Lemperiere. International Journal on Hydropower & Dams 2, 1 Jan. Aqua-Media International Ltd. P. 50-53.

Credibility and defensibility of dam safety risk analyses. (1997). D. N. D. Hartford and G. M. Salmon. Hydrovision '97, June 1997, pp. (Index terms: public safety, risk assessment).

Dam failure versus flood risk perception. (1997). M.L. Lima. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15, 1996, p. 103-110.

Dam safety - an overview of a risky business, conference on frontiers in hydraulic engineering. (1983). W. S. Bivins. American Society of Civil Engineers, Aug 1983, p. 445-450. http://asce.org. (Index terms: public safety. Reference, risk assessment).

Dam safety and risk-based decision analysis, frontiers in hydraulic engineering. (1983). C. T. Yang and T. A. Luebke. American Society of Civil Engineers, Aug 1983, p. 475-579. http://asce.org. (Index terms: risk assessment).

Dam safety policy for spillway design floods. (1996). James R. Dubler, and Neil S. Grigg. Journal of Professional Issues in Engineering Education and Practice, 122, 4, Oct., ASCE, p. 163-169.

Dam safety process. (1993). Chris J. Veesaert. Proceedings - National Conference on Hydraulic Engineering, pt 1, Jul 25-30. Sponsored by ASCE Publ., p. 556-561.

Dammed if you do and dammed if you don't. (1981). R. S. Decker, S. H. Nickel and M. McMeekin. ASCE Meeting, Oct. 27, 1981, pp. http://asce.org. (Index terms: risk assessment).

Database for dam safety management. (1997). Joao Palha Fernandes and Manuel Jorge Andrade. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15, p. 179-185.

Gambling with public safety? (1998). Des Hartford. International Water Power and Dam Construction, v. 50, n. 11, November. Wilmington Bus Publ, 3p.

Impact of risk-based analysis on hydrologic design practices. (1990). T. Giorgis Goitom and Anand Prakash. Water Resources Infrastructure: Needs, Economics, and Financing, Apr 18-20. Sponsored by: ASCE, Water Resources Planning and Management Div, New York, NY, USA; American Water Resources Assoc, USA; American Water Works Assoc, New York, NY, USA; ASCE, Texas Section, Fort Worth, TX, USA; Int Water Resources Assoc; et al Publ by ASCE, p. 70-75.

Implementation of risk analysis principles into the Bureau of Reclamation's dam safety program actions. (1998). D. G. Achterberg, C. Hennig and C. Redlinger. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 11-14, 1998, p. 49-62. (Index terms: age factors, federal programs, risk assessment).

Reclamation is the owner of 382 high and significant hazard dams in the 17 western states. Over 50 percent of the inventory is more than 50 years old. As structures age, continued safe performance becomes a greater concern. Reclamation places great reliance on recurring and ongoing dam safety activities to detect, intervene, and effectively respond to dam safety incidents. While Reclamation has previously used risk assessment approaches for the evaluation of potential economic losses, the agency is now implementing regular use of risk assessment to evaluate and prioritize issues involving the personal safety of the public. Risk assessment provides a systematic approach to the prediction of the likelihood of how the structure will perform not just an assessment of how they were designed to perform. Risk assessment approaches to assess dam safety is not a new idea The Federal Guidelines for Dam Safety in 1978 encouraged the development of risk-based approaches. However, the implementation of risk assessment in Reclamation has had its challenges, as would any change in a large organization. Risk assessment procedures continue to evolve as Reclamation continues to develop an increased understanding of risk assessment as a tool in decision making in a variety of programmatic areas. The implementation of risk assessment approaches has identified many areas where additional information or research is needed to improve our understanding of probable loads, likelihood of response, and the identification of potential consequences. Reclamation has been pursuing many of these issues to improve our risk management through workshops and research with noted industry experts and practitioners. Risk assessment has already provided benefits to Reclamation in the justification of risk reduction actions performed for the Office of Management and Budget and to the public.

Incremental-Hazard Evaluation (IHE): An Alternative to Evaluate Inadequate Spillways. (1998). B. Auld. ASDSO Southeast Regional Conference, Association of State Dam Safety Officials, June 7-10, p. 25-33.

Legal liability for dam failures, Association of State Dam Safety Officials. (1992). D. Binder. 55 pp. (Index terms: construction, design, emergency preparedness, failures/incidents, financial aspects, inspection, legal aspects, maintenance, ownership, risk assessment, standards).

Managing the risks of dam project development, safety and operation. (1998). United States Committee on Large Dams. Committee on Dam Safety. Eighteenth annual USCOLD lecture series, Buffalo, New York, August 10-14, U.S. Committee on Large Dams, Denver, CO, viii, 589 pp.

Multiobjective risk-partitioning: an application to dam safety risk analysis. (1988). Y.Y. Haimes, R. Petrakian, P.O. Karlsson, and J. Mitsiopoulos. Available from the National Technical Information Service, Springfield, VA, 136 p.

An application of the partitioned multiobjective risk method (PMRM) to a real dam safety case is documented. During the course of the analysis, useful relationships were derived that greatly facilitate the applications of the PMRM not only to dam safety problems, but also to a variety of other risk-related problems. Three main objectives for the study were identified: (1) evaluate the applicability of the PMRM to a realistic dam safety problem; (2) examine the sensitivity of the results generated by the PMRM to variations in the value of the return period of the probable maximum flood (PMF); and (3) determine the sensitivity of the PMRM to changes in the probability distribution used to describe extreme flood flows. Results obtained for the first of these objectives showed that the PMRM was indeed superior to the use of the unconditional expected value. To address objective (2) and (3), the PMRM calculations were performed for the dam modification problems in question assuming four different distributions and four different values of the return period. The results showed that the absolute magnitude of the conditional expected risk of low-probability/high-consequences events is sensitive to the value of the return period of PMF. (Lantz-PTT).

New dam safety legislation and the use of risk analysis. (1998). K. Hoeeg. International Journal on Hydropower and Dams, vol. 5, no. 5, p. 85-89.

The current approach to dam safety legislation and the concept of risk analysis as a tool for decision making in safety management are discussed by ICOLD's President. The article is based on his keynote address at the European Symposium on Dam Safety, which took place in Barcelona, Spain, earlier this year.

Optimization of available resources for dam safety. (1997). Rui Martins and Teresa Viseu. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov 13-15 1996, p. 57-61.

Potential downstream risk assessment in Spanish dam safety legislation. (1996). Jesus Peñas. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys, Nov. 13-15, p. 79-87.

Risk analysis and management of dam safety. (1998). Lester B. Lave and Tunde Balvanyos. Risk Analysis, v 18, n 4, Aug., Plenum Publ Corp. p. 455-462.

Risk analysis as an aid to engineering judgement in dam safety evaluations. (1994). N. M. Nielsen and D. N. D. Hartford. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 11-14, 1994, p. 171-183. (Index terms: risk assessment).

B.C. Hydro, the Provincial Electric Utility of British Columbia, Canada, is developing risk analysis techniques to supplement its existing dam safety program. This paper presents an overview of B.C. Hydro's initiatives in applying risk based analysis to dam safety issues with particular emphasis on the methods used to determine the components of total risk associated with a dam, and the management of these risks. The risk assessment techniques that are described in this paper differ from the conventional aspects of B.C. Hydro's dam safety program in that they involve a weighted emphasis on the relative importance of each potential failure mode, whether or not it is possible to calculate a factor of safety by means of analysis techniques. While every effort is made to use standard analysis methods, the process as described is "failure driven" in as much as it considers the conditions and potential failure modes that are unique to each dam. These concepts also provide a means of addressing the issue of "extreme event escalation" whereby, a dam, formerly determined to be safe, instantly becomes "unsafe" not as a result of any change in the condition or reliability of the dam, but rather due to an increase in the estimated maximum design flood or earthquake event. Details of the specific procedures being developed by B.C. Hydro to evaluate both the probability of failure of a dam and the associated consequences of failure are presented in terms of a summary overview of a worked example. The risk management techniques that are described include details of how dam safety criteria can be expressed in terms of risk and how the estimated risk can be used to improve any safety deficiencies that may be identified in the analysis.

Risk assessment in dam safety decision making (1990). D. S. Bowles. In Y. Y. Haimes and E. Z. Stakhiv (Eds.). Invited paper in Risk-Based Decision Making in Water Resources. Proceedings of an Engineering Foundation Conference, American Society of Civil Engineers. p. 254-283.

Risk assessment of extreme events: application. (1989). P.O. Karlsson and Y.Y. Haimes. Journal of Water Resources Planning and Management (ASCE), vol. 115, no. 3, p. 299-320.

The safety of many existing dams could be improved by modifying them structurally in accordance with recent advances in statistical hydrology and improved availability of meteorological and hydrological data. Any increase in safety that might be gained by structural changes must be balanced against their costs. The risk analysis methodology known as the partitioned multiobjective risk method (PMRM) is explored in this paper through a dam-safety problem. The PMRM is well suited to the task of solving the probabilistic optimization problem posed by such risk-versus-cost considerations. With the PMRM, a number of conditional expected-damage functions are generated. Of these, one that represents events of a more extreme and catastrophic character is of particular interest here. The close relationship that exists between the expectation of damage and the statistics of extremes is shown to simplify the implementation of the PMRM, and the relationship also permits the derivation of closed-form equations that determine (for any partitioning of the probability axis) the expected damage, given that a flood with a return period that equals or exceeds a specific number of years occurs. Finally, an analysis is made as to how the choice of the distribution function representing the annual flood peaks might affect the conditional expectations. (Author 's abstract).

Risk assessment: A tool for dam rehabilitation decisions. (1993). D. S. Bowles. Geotechnical Special Publication, n 35, Apr 25-28. Sponsored by ASCE, p. 116-130.

Risk assessments support dam safety decisions. (1997). J. L. Von Thun and J. D. Smart. USCOLD Newsletter, U.S. Committee on Large Dams, Nov 1997. (Index terms: federal programs, public safety, risk assessment).

Risk of extreme events in a multiobjective framework. (1992). Y.Y. Haimes, J.H. Lambert, and D. Li. Water Resources Bulletin WARBAQ, vol. 28, no. 1, p 201-209.

Risk management inherently leads to a multiobjective analysis, in which trade-offs among costs, benefits, and risks must be addressed in a multiobjective framework, given the noncommensurate units/dimensions of each objective function. Recognition of the wide gap between what the expected value of a random variable implies and what water resources planners and managers intend to use it for has led to the development of the partitioned multiobjective risk method (PMRM). The PMRM builds upon various advantages of methodologies (Bayes' Rule, expected-value criterion, Laplace criterion, minimax criterion, Hurwicz's rule, or uncertainty sensitivity index method) for decision-making under risk and uncertainty, e.g., differentiating among ranges of damage severity in a spirit similar to those of the minimax and expected-disutility criteria.

Application of the PMRM to dam safety has shown that the method conveys additional information about risk when used together with the expected value of damage. Understanding of the potential extreme consequences of a remedial action or dam design is enhanced by the risk measure of extreme events. Adoption of the PMRM for the ranking of components facilitates the differentiation of the risks of moderate-severity and extreme-severity events such as hazardous waste sites in a multi-attribute ranking approach. (Brunone-PTT) 35 015207007 55 24 Jun 92.

Risk versus standard based approaches to dam safety: The consequences for community involvement in decision making and safety management in the Australian context. (1997). Geoffrey J. Syme. CSIRO Australian Research Cent for Water in Soc. In: A.A. Balkema (Ed.). Proceedings of the International NATO Workshop on Dams and Safety Management at Downstream Valleys Nov. 13-15, p. 91-101.

Risk-based dam safety evaluations - -conference report: Part two. International Journal on Hydropower & Dams, v. 5, n. 2, p. 73-82.

Risk-based decision making for dam safety. (1997). Jerry L. Foster. Risk-Based Decision Making in Water Resources, Proceedings of the Conference, Oct 12-17. Sponsored by ASCE, p. 10-18.

Safety perspectives. (1997). Des Hartford. International Water Power and Dam Construction, v. 49, no. 2, February, Wilmington Bus. Publ. P. 29-30.

Some remarks on practice of flood frequency and risk analysis by the federal energy regulatory commission. (1987). C.L. Cooper. Application of Frequency and Risk in Water Resources: Proceedings of the International Symposium on Flood Frequency, Louisiana State University, Baton Rouge, U.S.A. D. Reidel Publishing Company, Boston, MA. 1987. p 485-489.

The Federal Energy Regulatory Commission (FERC) has been in dam safety regulation since 1920. As of October 1, 1985, there were about 2,050 dams under its jurisdiction. Almost all of its spillway inflow design floods creep higher and higher with passing years. Mathematical probability methods provide no guidance to the shape and magnitude of the hydrographs of rare floods, which would be substantially above the measured data. Risk analysis should include the probability of engineering, administrative, or other human error. Therefore, the FERC requires that the adequacy of both new and existing dams be evaluated by considering the hazard potential, which would result from failure of the project works during flood flows. If structural failure would present a hazard to human life or cause significant property damage, the dam must withstand the loading or overtopping which may occur from a flood up to the probable maximum (risk analysis that involves loss of life is not permitted). In most cases, the dam owner is permitted to use risk analysis, if the failure will not cause loss of life or significant property damage.

?System stewardship for dams and reservoirs: Risk & resource management toward the 21st century. (1998). Canadian Dam Association. Canadian Dam Association Conference [1st], Canadian Dam Association, Sept. 27-Oct. 1, 1998, Halifax, Nova Scotia, vi, 336 pp. http://www.cda.ca/.

The practice of dam safety risk assessment and management: its roots, its branches, and its fruit. (1998). D. S. Bowles, L. R. Anderson and T. F. Glover. Proceedings of the 1998 USCOLD Annual Lecture, Buffalo, New York. August.

Understanding and managing the risks of aging dams: principles and case studies. (1999). D.S. Bowles, L.R. Anderson, T.F. Glover, and S.S. Chauhan. 1999 USCOLD Annual Meeting, Atlanta, Georgia. May.

2.2 Case Histories

A case study of risk analysis in dam design. (1988). S. Vick. Proceedings Third Annual Symposium, Vancouver Geotechnical Society.

Aging spillway rehabilitation construction, value engineering, and risk analyses. (1999). R. Rudolph, C. Feild, E. Faulkner and C. McKnight. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 10-13, p. 577-589. (Index terms: case studies, financial aspects, gates, rehabilitation, risk assessment, spillways).

The Jim Falls Main Spillway Rehabilitation Project, located in Wisconsin, replaces a flashboard section and steel gates constructed in the 1920's with new fixed crest gravity and gated spillway sections. The overall project includes primary (gates and overflow sections) and secondary (fuse plug) spillway capacities. This work done over a five-year period was done without dewatering the reservoir and yet protecting a major fishery. The site constraints, design considerations, construction methods, changed conditions, and solutions are discussed. Value engineering was applied to the spillway renovation project as the project was ongoing. It was applied from the conceptual design through the construction phases of the renovation project and resulted in significant cost and time savings while addressing public safety and environmental impact concerns. The final number of gate bays to be reconstructed and associated length of the remaining fixed crest spillway to be constructed in fifth year was determined by evaluating the following: § The actual costs of gate bay reconstruction during years 2-3 compared to costs of a fixed crest spillway during year 1; § Potential impacts on public safety and property; § The primary and total spillway capacity required by FERC (PMF) and State of Wisconsin; § Historic, recurrence frequency, and PMF flows with and without dam failures; § Risk analyses; and § Ecosystem impacts. The final year selected option, approved by FERC, reduced the primary spillway capacity and realized substantial cost savings. In addition to *the cost savings, value-engineering and risk analysis addressed changes in design criteria, agency guidelines, and construction goals.*

Alamo dam demonstration risk assessment. (1999). D. S. Bowles, L. R. Anderson, J. B. Evelyn, T. F. Glover and D. M. Van Dorpe. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 10-13, p. 621-635. (Index terms: case studies, risk assessment).

Alamo Dam is a 283 foot high rolled-earthfill dam which was constructed by the US Army Corps of Engineers in the 1960's to provide flood control, water conservation and recreation. Although the dam is in good structural condition, recent estimates of the standard project flood and the probable maximum flood have increased above design values. As a result, overtopping of the dam would be expected to occur in the event of the updated design flood or events approaching the magnitude of this flood. As part of an initiative to explore the use of risk-based procedures to support dam safety decisions, a demonstration risk assessment was conducted on Alamo Dam. The risk assessment considered earthquake and static (normal operating conditions) loading cases in addition to flood loading. Potential failure modes were identified and organized into an event tree risk analysis model. Economic, life safety and environmental consequences associated with normal flood operation and various failure scenarios were estimated. More than a dozen risk reduction alternatives were formulated and explored using the risk analysis model, which was adapted to represent changes in reservoir routing, stage-discharge, breach characteristics, and engineering performance for each alternative. Risk assessment results were presented for the existing dam and for each risk reduction alternative. It appears that the existing dam meets all interim risk-based criteria or guidelines that have been developed by the US Bureau of Reclamation, B.C. Hydro, and the Australian National Committee on Large Dams (ANCOLD). However, a possible case can be made for proceeding with some lower cost measures, such as additional toe and wave protection, and a relatively small raise of the embankment. Even though risk assessment does not appear to provide an economic or life safety justification for proceeding with the more costly fixes, the Corps may choose to do so for other reasons, such as environmental protection or existing dam safety policy requirements. However, it is likely that there are many other Corps projects that would return a much greater risk reduction for the same investment of funds at the Alamo Dam. The demonstration risk assessment involved an engineering team and a consequences team from the Corps Los Angeles District. Facilitation and coordination was provided by RAC Engineers & Economists. Observers from several Corps offices attended all team meetings. In addition to presenting risk assessment results and findings, the paper summarizes the demonstration risk assessment process, including supporting hydrologic and hydraulic, seismic, stability, breach and inundation, economic, life safety, environmental and other analyses. An assessment of the demonstration risk assessment process is provided together with recommendations for research and development activities to better *position the Corps to use risk assessment in the future for dam safety evaluation and decision support.*

Calculation of the seismic risk of an earth dam susceptible to liquefaction. (1998). M.K. Lee, K.Y. Lum, and D.N.D. Hartford. Geotechnical Special Publication, v. 2, Aug 3-6, ASCE, p. 1451-1460.

Case study: Steele Creek dam safety analysis. (1991). B. Auld and B. A. Tschantz. Bristol, Tennessee, Waterpower '91: A New View of Hydro Resources, p. 1248-1254. http://asce.org. (Index terms: case studies, flood analysis, hydrology, public safety, risk assessment, spillway capacity).

Hydrologic analysis of the Steele and Beaver Creek watersheds was performed separately for HMR-52 derived fractional Probable Maximum Storms and inflow flood hydrographs were derived for each storm level. Dam failure was assumed when overtopping occurred. A stage-discharge rating curve was developed for Beaver Creek from the combined Beaver Creek and Steele Creek Dam discharges. From this stage-damage data for the home and trailer areas, a cost analysis study was utilized for developing several options to determine the optimal structural or non-structural alternative to deal with an under-sized spillway.

Case study: Lesson and probabilistic determination on eroded earth spillway rehabilitation. (1997). S. Samuel Lin, Joseph S. Haugh, and L. Lynn Clements. Proceedings, Congress of the International Association of Hydraulic Research, IAHR, v A, Aug 10-15. Sponsored by ASCE, p. 464-469.

Dam safety evaluation for a series at Utah Power and Light hydropower dams, including risk assessment: The owner perspective. (1989). R. B. Waite. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 1-5, 1989, p. 167-171. (Index terms: financial aspects, hydropower ownership, rehabilitation, risk assessment standards).

Utah Power and Light Company (UP&L) owns a series of six dams on the Bear River in Utah and Idaho. These dams are regulated by the Federal Energy Regulatory Commission (FERC). Not all the dams currently meet the FERC'S standards for flood and earthquake loading. Their internal conditions, however, have been found to meet all important FERC criteria. A dam safety evaluation study was performed to explore the suitability of site specific standards for the UP&L dams and to propose and evaluate alternative remedial actions. The investigation was performed to provide UP&L management with information for use as a basis for their proposals to the FERC for remedial actions at their Bear River dams.

Dam safety evaluation for a series at Utah Power and Light hydropower dams, including risk assessment: Owner perspectives on the role of the evaluation in the selection of remedial measures. (1989). R.B. Waite. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 1-5, p. 189-190. (Index terms: hydropower ownership, risk assessment).

In this paper the dam owner will describe the role of dam safety evaluation results in selection of remedial measures which were proposed to, and accepted by, the FERC. For the dam owners, this paper will address the value of insights gained from this type of detailed dam safety evaluation study. The importance of understanding the hydrologic, seismic, structural, safety, economic, social-environmental, and risk aspects of a dam safety decision will be illustrated through the discussion of the UP&L decision-making process.

Dam safety evaluation for a series of Utah Power and Light hydropower dams, including risk assessment: Work Plan, Project Description, Remedial Action. (1989). G. S. Tarbox, J. E. Priest, and C. A. Thompson. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct 1-5, 1989, P. 172-176.

The study comprised an incremental consequence assessment and a risk assessment. The concepts and procedures for each are summarized. Each dam was evaluated considering its potential for complete or partial failure due to floods, earthquakes, internal causes, or upstream dam failure. The evaluation considered various human safety, economic and environmental factors. In this paper, the location, type and condition of each dam, various human safety factors, and economic and environmental factors are briefly presented. Also, potential failure modes and alternative remedial actions are discussed.

Dam safety evaluation for a series of Utah Power and Light hydropower dams, including risk assessment: seismic and hydrologic considerations, system responses and potential for serial failure. (1989). Y. Au-Yeung and L. R. Anderson. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct. 1-5, p. 177-183. (Index terms: financial aspects, flood analysis, hydropower, risk assessment, seismic behavior/analysis).

The seismic and hydrologic settings of the Bear River Basin will be described with particular reference to the potential for extreme floods and earthquakes at each dam-site. The representation of system responses over a range of imposed loadings up through the probable maximum flood or maximum credible earthquake will be presented for typical cases. The results of flood routings for natural flow, no failure, and failure scenarios will be presented in terms of incremental flooding. Also, the evaluation of and conclusions relating to the potential for serial dam failure will be discussed.

Dam safety evaluation for a series of Utah Power and Light hydropower dams, including risk assessment: Results. (1989). D. S. Bowles and T. F. Glover. ASDSO Annual Conference, Association of State Dam Safety Officials, Oct 1-5, p. 184-188. (Index terms: case studies, financial aspects, hydropower, risk assessment).

Safety evaluation results will be presented in three categories: based upon the applicable FERC guidelines, the incremental consequence assessment, and the risk assessment. Incremental consequence assessment results for floods and earthquakes show the potential for increased life loss, economic damages, or environmental damages as the result of dam failure scenarios. The risk assessment adds the perspective of the likelihood of each failure scenario occurring. Risk assessment results will be presented for floods, earthquakes, and internal failure modes as risk of incremental life-loss, cost of improving human safety, probability of breach or partial failure, benefit-cost ratio for remedial action alternatives, and total annual cost (risk cost, plus remedial action cost) for each alternative.

Dam safety risk analysis for Navajo Dam. (2000). K. Dise and S. Vick. 20th Int. Congress on Large Dams, ICOLD, Beijing (in press).

Decision analysis: Lake Almanor and Butt Valley dams. (1997). Patrick J. Regan, Norman A Abrahamson, and Faiz Makdisi. Proceedings of the International Conference on Hydropower – Waterpower, v 2, Aug 5-8. Sponsored by ASCE, p. 1468-1477.

Determining spillway design capacities considering downstream risk. (1990). D. Toy and D. R. Lawrence. ASDSO Annual Conference, Association of State Dam Safety Officials, October 14-18, p. 247-255. (Index terms: flood analysis, public safety, risk assessment, spillway capacity).

The State of Arizona has had a program for Safety of Dams since 1929. In 1971, the State Legislature placed the Safety of Dams function within the Arizona Department of Water Resources (ADWR). ADWR has the authority to perform all eight recommended and statutory functions of an adequate state program. Currently, the ADWR has regulatory responsibility for 199 dams. Seventy–one of these dams are classified as high hazard dams. Seventeen of the high hazard dams do not currently meet ADWR guidelines for spillway adequacy. ADWR current spillway sizing criteria is dependent on the height of the dam, the reservoir capacity, and an estimate of the downstream hazard potential. Although allowed by ADWR guidelines, additional site specific information is generally not considered when" sizing a spillway. In Arizona, spillway construction costs are typically a substantial portion of a dam's construction costs. Since it is impossible to design a dam to completely eliminate the probability of failure, the most realistic design criteria is to maximize benefits while minimizing risks within the funding constraints. A more simple question is, "How much safety can we afford?" or "How much risk can we accept?" Risk analysis has been suggested as an alternative method to incorporate additional site-specific information to size a spillway. Detailed information such as the hydrology, economics, social, environmental, and downstream channel hydraulics must be considered in each decision-making process. By using risk analysis, it is hoped that an acceptable risk can be balanced with costs. This paper is a case study on spillway sizing and *using risk analysis to determine spillway size. Lyman Dam, a dam currently being considered for spillway and other modifications will be used as an example. Lyman Dam, located in North East Arizona, has a storage capacity of 31,600 acre–feet and classified by ADWR as an "unsafe" high hazard dam. Insights gained from this type of detailed dam safety evaluation study will be discussed.*

Evaluating dam safety retrofits with uncertain benefits: The case of Mohawk Dam (Walhonding River, Ohio). (1990). D. Resendiz Carrillo, and L.B. Lave. Water Resources Research WRERAQ vol. 26, no. 5, p 1093-1098.

Mohawk Dam, built on the Walhonding River, Ohio in 1938, was designated a high-hazard dam, unable to survive a probable maximum flood, after a study 10 years ago. The dam height was raised, and the spillway was widened at a cost of $8 million. The smallest return period for the probable maximum flood of 10,800 cu m/s was 2 million years. During the 65-year record, the highest flow was about 2000 cu m/s, and the second highest flow was about 1500 cu m/s. Applying a previously proposed framework to select the social cost minimizing capacity of a dam, it was shown that Mohawk Dam had sufficient capacity that any retrofit had a social cost larger than expected benefits ($50 per year). Sensitivity analyses were performed adjusting the peak flow distribution, the costs of modification and downstream flood damage, as well as the possibility of loss of life. For any reasonable value of these variables, the structure was deemed safe with respect to extreme floods so that no retrofit was necessary. Using risk-based methods to evaluate the reservoir safety (National Research Council committee recommendations) confirmed these conclusions.

Evaluation of dam safety at a series of hydropower dams including risk assessment. (1990). D.S. Bowles, L.R. Anderson, T.F. Glover, G.S. Tarbox, R.B. Waite, and Y. Au-Yeung. Proceedings of the Conference of the British Dam Society, Sep 12-15, p. 119.

Examples of risk assessment in dam safety decision making, Waterpower '91: A new view of hydro resources. (1991). D. S. Bowles, L. R. Anderson, T. F. Glover and G. S. Tarbox. American Society of Civil Engineers, July 24-26, p. 1265-1277. http://asce.org. (Index terms: risk assessment).

Three examples of risk-based dam safety evaluation performed for dam users or operators are summarized. These studies were conducted by major U.S. engineering firms and involved experienced dam engineering professionals. For each example the background which led up to the commissioning of the study is presented, study results are summarized, and the study outcome is described, including an assessment of the value of the information obtained from the risk-based approach.

Hydrologic parameter effects on small-dam risk analysis in Missouri. (1990). A.R. Kalmes and R.L. Peyton. Journal of Irrigation and Drainage Engineering (ASCE) JIDEDH, vol. 116, no. 4, p. 465-478.

The U.S. Army Corps of Engineers found that Missouri had the largest number of ' unsafe-emergency ' dams in the nation. Since then, the state ' s dam safety council has established a permit program. The sensitivity of risk cost to hydrologic parameters was evaluated to determine the feasibility of risk analysis as an alternative approach to existing requirements for rehabilitation of small dams in Missouri. The sensitivity to probable maximum precipitation (PMP) exceedance probability is greatly reduced by interpolating rainfall exceedance probabilities between the PMP and the rainfall depth that initiates failure, instead of the PMP and the 100-year return period depth. This approach also reduces by a small amount the sensitivity of risk cost to the assumed probability distribution function. Variations in the time distribution of rainfall and the antecedent moisture condition (AMC) have a large influence on risk cost. Probabilistic combinations of the three AMC classes result in risk costs within 13% of the risk cost using AMC II, the 'average' condition. Of the three dam-breach parameters evaluated, risk cost is most sensitive to breach-development time and least sensitive to breach side slopes.

Incremental risk assessment techniques for choosing inflow design at Dulce Lake Dam and Lower Mundo Lake Dam. (1997). C.W. Cox. ASDSO Western Regional Conference, Association of State Dam Safety Officials, May 5-7, 1997, p. 173-182. (Index terms: design flood, public safety, risk assessment).

Two small earthfill dams were analyzed for safety deficiencies including the adequacy of the spillways. An Incremental Risk Assessment method was used to define the Inflow Design Flood at both dams. The analysis modified the standard USBR method to give consideration to variable levels of risk based on the intensity of flooding. The level of flood lethality was used to divide the Population At Risk into two groups based on the level of risk. This allowed predicted Baseline Loss of Life to be modified to account for flood lethality. The Inflow Design Flood at Lower Mundo Lake Dam was determined to be 100% of the probable Maximum Flood. The Inflow Design Flood at Dulce Lake Dam was determined to be 40% of the Probable Maximum Flood.

Risk analyses of three Norwegian rockfill dams. (1997). P. Johansen, S. Vick, and C. Rikartsen. Proceedings of the Third Int. Conference Hydropower '97, Trondheim, Norway.

Risk analysis applications for dam safety. (1991). David A. Moser. Proceedings of International Conference on Hydropower, Jul 24-26. Sponsored by US Bureau of Reclamation; Western Area Power Administration; Bonneville Power Administration; US Dept. of Energy; Federal Energy Regulatory Commission; et al, Published by ASCE, p. 1255-1264.

Risk analysis as a tool to determine spillway design capacities. (1990). D. Toy and D. Lawrence. Hydraulics/Hydrology of Arid Lands (H2AL). American Society of Civil Engineers, New York. 1990. p 171-176.

The safety of 197 non-federal dams in Arizona is regulated by the Arizona Department of Water Resources (ADWR), and 16 of 71 high hazard dams in jurisdiction do not currently meet the ADWR guidelines for spillway adequacy. Lyman Dam, an earth and rockfill structure located on the Little Colorado River approximately 11 miles south and upstream of St. Johns, Arizona, does not. Most recently, ADWR completed a risk assessment of the potential for overtopping failure under several repair options. The risk analysis methodology included the identification of both economic and non-dollar-denominated consequences of dam failure for different rehabilitation options, described as: minor repairs to the outlet works and repairs to stabilize the dam embankment; upgrades to safely pass 0.25 PMF (probable maximum flow) with a new spillway and conservation storage; upgrades to safely pass 0.50 PMF with a new spillway and conservation storage; upgrades to safely pass 0.75 PMF with a new spillway and conservation storage; and upgrades to safely pass full PMF with a new spillway and conservation storage. ADWR staff estimated flood damages downstream of Lyman Dam corresponding to flood elevations near the US Highway 666 Bridge at St. Johns ranging from $2.34 million to $6.02 million. Damage assessment for the five options includes the routing of successively larger storm runoff hydrographs through the respective spillways up to one resulting in wave overtopping and potential breach. The results indicated that if minimizing the dollar-denominated consequences is the only consideration, then the minimal option is preferable. (See also W92-04441) (Brunone-PTT).

Risk analysis for dam design in Karst. (1989). S.G. Vick and L.G. Bromwell. Journal of Geotechnical Engineering (ASCE) JGENDZ, vol 115, no 6, p. 819-835.

Probabilistic risk analysis is a useful technique in assessment of dam safety issues, and also has important applications in the early phases of dam design when design options are being compared and exploration strategies planned. At this stage, few data are usually available and judgment-based decisions are most important. An application of probabilistic risk analysis to design of a dike in Karst terrain is described. Assessments based on geologic information, observations, and subsurface investigations are expressed using a simple probability model. Options considered to reduce the likelihood or consequences of sinkhole-induced failure include a secondary containment structure, a warning system, and additional exploration. These options are evaluated using an expected monetary value criterion. It is shown that simple probabilistic formulations consistent with preliminary levels of information reduced major sinkhole uncertainties into more readily evaluated components. These techniques identified the most cost-effective design strategy for reducing the risk of sinkhole-induced dike failure and provide an effective vehicle for communicating *geotechnical judgments, risk, and alternatives to the project owner. (Author 's abstract).*

Risk analysis for seismic design of tailings dams. (1985). S. Vick, G. Atkinson, and C. Wilmot. Journal of Geotechnical Engineering, ASCE, vol 111, n 7, July.

Risk analysis in British Columbia. (1994). N.M. Nielsen, S.G. Vick, D.N.D. Hartford. International Water Power and Dam Construction, v. 46, no. 8, March, 6 p.

Risk assessment of Nambe Falls dam. (1996). J. Lawrence Von Thun. Geotechnical Special Publication 58/1, Jul 31-Aug 3, Sponsored by ASTM, p. 604-635.

Risk assessment of rockfall hazard at Horse Mesa Dam: A case history, uncertainty in the geologic environment: From theory to practice. (1996). P. M. Kandaris and K. M. Euge. (Uncertainty '96), American Society of Civil Engineers, July 31-August 3, p. 1402-1416. http://asce.org. (Index terms: case studies, risk assessment).

Risk evaluation of a natural flood control reservoir. (1973). D. Rosbjerg. Risikoanalyse af vidåsystemet Series paper; 2, Institute of Hydrodynamics and Hydraulic Engineering Technical University of Denmark, Lyngby, 106 pp.

Risk management at Wahleach Dam. (1997). Gary Salmon, Dave Cattanach, and Desmond Hartford. American Society of Civil Engineers, v. 67, p. 39-41.

In a risk-of-its-kind application, engineers at British Columbia Hydro, Burnaby, British Columbia, used risk analysis to make event-driven design decisions in the evaluation of dam safety improvements at Canada's Wahleach Dam in British Columbia. British Columbia Hydro's innovative efforts incorporated the newly initiated dam safety guidelines of the Canadian Dam Safety Association and formulated a process that calls for a balanced level of risk among all of its dams. The risk-based method was used to determine what level of design and safety modifications was justified at Wahleach Dam. Details of the project are provided.

Safety and risk analysis for two large rockfill dams in Romania. (1982). R. Priscu, S. Ionescu and D. Stematiu. 14th Congress, International Commission on Large Dams, Q,52, R.017 pp. http://www.icold-cigb.org. (Index terms: design, risk assessment, rockfill dams, stability analysis).

The failure mechanism in cases of rockfill dams sealed with upstream membrane or central clay core and the external loadings and strength paramenters are presented. Failure probabilities are determined by numerical estimation of the convolution integrals. Cost minimization is considered in regard to the choice of the optimum design alternative on a probabilistic basis.

Safety assessment of an existing concrete gravity dam. (1989). Romeo B. Baylosis, and Richard M. Bennett, Proceedings of ICOSSAR '89, the 5th International Conference on Structural Safety and Reliability, Part I, Aug 7-11, Publ. by ASCE, p .279-286.

Seismic risk analysis for earth dams. (1991). M.K. Yegian, E.A. Marciano, and V.G. Ghahraman. Journal of Geotechnical Engineering, v. 117, n. 1, Jan, p. 18-34.

Seismic risk assessment of hydraulic works in Italy. (1997). A. Castoldi. International Journal on Hydropower & Dams, v 4, n 2, Aqua-Media Int Ltd., p. 74, 76-77.

Seismic risk assessments of small earth dams. (1991). Carl J. Costantino, and Y.T. Gu. Proceedings of the 3rd US Conference on Lifeline Earthquake Engineering, Aug 22-23. Sponsored by ASCE, Technical Council on Lifeline Earthquake Engineering Publ. by ASCE, p. 704-713.

Seismic risk study of the Cerrillos and Portugues dam sites, Ponce, Puerto Rico. (1980). Weston Geophysical Corporation. Wgc, 1 v. (Index terms: case studies, reservoirs, risk assessment, seismic behavior/analysis, stability analysis).

Sinkhole development and repairs at Willow Creek Dam, Montana. (1997). T. Hepler, R. Oaks and R. Torres. ASDSO Annual Conference, Association of State Dam Safety Officials, Sept 7-10, p. 5-15. (Index terms: case studies, financial aspects, foundations, gates, outlet works, rehabilitation, risk assessment, sinkholes).

The development of an 18-foot-diameter sinkhole at Willow Creek Dam was completely unexpected for a small (6-foot-diameter) outlet tunnel excavation with up to 40 feet of bedrock cover and over 30 feet of overlying embankment. Contributing factors were the open fractures and large void in the bedrock, and the erodible nature of the embankment materials. Foundation excavation and treatment, reconstruction of the dam embankment, installation of a larger air vent, and partial lining of the tunnel with CIPP were performed using emergency dam safety funds to mitigate a potential failure, with minimal project impacts. The proposed addition of a new trashrack structure and rehabilitation of the gate operating system will improve the reliability of the outlet works for future operations. The total construction cost for the dam safety repairs will be less than $1 million, which is below the limit authorized by Congress. An assessment of all potential failure modes and associated risks to the downstream public was made, which may result in the future construction of a downstream stability berm and filtered buttress to address both dynamic stability and internal erosion deficiencies. With these modifications, Willow Creek Dam will continue to serve the historic Sun River Project of western Montana well into the future.

Skiatook spillway erodibility investigation and dam safety assurance evaluation report. (1997). E. D. Erwin, M. W. Soufhern and F. L. Oler. ASDSO Annual

Conference, Association of State Dam Safety Officials, Sept 7-10, p. 671-682. (Index terms: erosion, financial aspects, public safety, risk assessment, spillways).

In the past, unlined limited service spillways were constructed without much consideration of headcutting erosion beyond engineering judgement. A lot of these spillways across the United States and the world were constructed assuming that damage would occur during the spillway design event. However, there were no analytical tools to estimate the extent of damage to expect. The spillway at Skiatook Dam, located in northeastern Oklahoma, has yet to experience a pool-related flow. However, significant erosion and headcutting due to normal rainfall runoff has been experienced at the spillway, raising concerns about the ability of the spillway to resist erosion during periods of flow through the channel. This inspired the request to reevaluate the spillway to determine if it could safely pass the design flood event without an uncontrolled release of the reservoir. This paper describes the existing condition of the spillway at Skiatook Dam, the process used to analyze the uncontrolled spillway during the spillway design flood and lesser events, the results obtained from this analysis, and the proposed remedial treatment.

Spillway design criteria of the "Quebrada De Ullum" reservoir: San Juan River. (1973). A. D. Pronsato, F. C. Castellanos and M. Lhez. 11th Congress, International Commission on Large Dams, Madrid, Q.41, R.48 pp. http://www.icold-cigb.org.

The "Quebrada de Ullum" project required accurate geological, geotechnical and hydrological studies: the site is located in a seismic area, the rock characteristics are unfavourable, the design flood was 4,000 m3/s. The solution of a side spillway was adopted, with a maximum discharge capacity of 2,500 m3/s; the flow conditions were carefully studied. The downstream risks being significant, a high degree of security in operation was sought.

Spillway dimensioning revision modifications in Planddescunm and San Esteban Dams. (1988). J. C. Baltar and J. L. B. Seoane. 16th Congress, International Commission on Large Dams, Q.63, R.077 pp. http://www.icold-cigb.org. (Index terms: design flood, development, outlet works, rehabilitation, risk assessment).

Periodical checking of outlet works in existing dams, verifying the flood design on the basis of additional information gathered during operation, and considering potential change in the surrounding area is recommended. After general considerations on the problems in this field at 34 large dams operated by IBERDUERO, S.A. the improvements carried out at two of them are described.

Stabilization of Pueblo Dam using RCC, ASDSO Annual Conference. (1999). J. Trojanowski. Association of State Dam Safety Officials, Oct. 10-13, p. 457-467. (Index terms: case studies, cracking, risk assessment, roller-compacted concrete).

Construction of Pueblo Dam, which is the Bureau of Reclamation's first and only massive head buttress dam, was completed in 1975. A 1996 comprehensive risk analysis of Pueblo Dam revealed the potential for failure of the 150-foot high, 550-foot wide spillway portion of the dam. During the original construction, the downstream spillway plunge pool excavation exposed shale seams and sandstone bedding planes in the foundation. At the time these surfaces were not believed to be continuous. Recent studies show that the combination of sandstone bedding planes and weak shale seams connected by high angle joints can produce continuous sliding failure surfaces. With the city of Pueblo, Colorado just six miles downstream from the dam, there are approximately 14,000 lives at risk from a potential dam failure. In 1997 Reclamation began designing a dam modification to reduce this hazard. A variety of modification alternatives that would provide active or passive resistance to sliding or a combination of the two were evaluated. Active solutions included increasing the normal load on the sliding surfaces by filling the spaces between the buttresses and adding weight at the downstream toe, installing rock bolts, and installing post-tensioned tendons. Passive solutions included various alternatives to buttress the dam by placing concrete in the downstream plunge pool. Although a completely active resistance solution was preferred, the presence of both deep and shallow failure planes in the foundation, and space limitations between the dam and plunge pool meant that no single active resistance solution could be economically employed. An alternative was selected that includes downstream buttressing, adding weight, and rock bolts. The downstream buttressing was accomplished by filling the plunge pool with roller compacted concrete (RCC) and placing a RCC toe block downstream from the spillway apron. RCC was added at the toe of the dam for weight. Rock bolts were installed through the toe block. This solution will provide increased safety factors during all loadings conditions. The initial configuration of the RCC mass negatively impact the hydraulic performance of the spillway plunge pool. A hydraulic model study was used to adjust the configuration of the RCC in the modified plunge pool until the configuration was acceptable from both a hydraulic and structural standpoint. Because the space in the plunge pool was limited, the resulting RCC configuration required that details of the RCC and the contact areas between the existing concrete and RCC be carefully designed and constructed to maximize the dam stability. Some of the concepts developed for this modification may have the potential for a variety of future applications throughout the industry. One of the unique aspects of the RCC design was the way in which crack inducers were used for the contraction joints. Based on temperature studies for the RCC mass, it was concluded that cracks would develop in the RCC once the mass cooled. After full reservoir load is applied, these open cracks would close. The movement required to close the cracks would limit the effectiveness of load transfer from the foundation to the downstream rock. Placing crack inducers at carefully controlled locations will ensure that the cracks can be drilled and grouted after cooling and shrinkage of the RCC occurs. The grouting of the contraction joints will improve load transfer through the RCC mass while requiring minimal deformation of the dam foundation.

Stiegler's Gorge, Tanzania, hydroelectric power project: Seismic risk analysis, phase I. (1978). F. Ringdal and H. Bungum. Stiegler's Gorge Power Project report ; no. 24., Aktieselskabet Hafslund, Rufiji Basin Development Authority (RUBADA), teknisk-naturvitenskapelige forskningsråd,, Feb 1, 100 pp. (Index terms: habitat conservation/restoration, international programs, risk assessment, seismic behavior/analysis).

Understanding and managing the risks of aging dams: Principles and case studies. (1999). D.S. Bowles, L.R. Anderson, T.F. Glover, and S.S. Chauhan. 1999 USCOLD Annual Meeting, Atlanta, Georgia, May.

Use of risk assessment to identify potential hazards associated with a large waste impoundment. (1999). C. S. Bodimeade and D. G. Judge. 2nd Annual Conference, Canadian Dam Association, Oct 3-7, pp. http://www.cda.ca/. (Index terms: risk assessment, tailings dams).

3.0 PORTFOLIO RISK ASSESSMENT, PRIORITISATION AND RISK PROFILING

3.1 Approaches

A hybrid deterministic- risk-based approach to hydrologic dam safety analysis. (1998). E. E. Eiker, D. M. Goldman and D. W. Davis. Dam Safety '98, Association of State Dam Safety Officials, Oct. 11-14, 1998, Las Vegas, NV, p. 23-34.

Dam owners and Federal and state regulatory agencies, have a unique responsibility to the public to assure the highest level of safety for individuals living downstream of dams. The catastrophic nature of a dam failure, in terms of potential loss of life and property damage, the long lasting social consequences that can result from a dam failure and the fact that most people living in harms way did not knowingly choose to accept this risk, dictate nothing less. In establishing hydrologic dam safety criteria, the horrible lessons learned from previous dam failures, even though infrequent, must not be forgotten. Similarly, the current hydrologic dam safety design criteria, based on accommodating extreme floods, should not be cast aside without a great deal of thought. During the last fifteen years, there has been a concerted effort to develop risk-based analysis (RBA) procedures for application in hydrologic dam safety evaluation studies. Several theoretical procedures to carry out RBA studies have been formulated. Application of these approaches, however, has been limited because of our inability to define critical components, such as the probability of extreme precipitation and floods, and in setting meaningful decision criteria to fully consider loss of life and social consequences. In view of these limitations, we must ask ourselves whether RBA, as now formulated, is a tool that is ready for widespread application in hydrologic dam safety studies. RBA has been successfully applied in related areas, such as in the formulation of flood damage reduction projects. However, in these cases hydrologic probabilities were not required for extreme events and hazard potential for a design exceedance could be addressed by a separate residual risk analysis. This paper presents a framework for a new approach to be used in the identification and evaluation of hydrologic deficiencies of dams and a process for prioritization of identified hydrologic deficiencies requiring mitigation. The procedure may also be used to establish the size and scope of a required modification for a specific project. The paper presents a brief history of deterministic approaches used to develop safety design floods, beginning with the use of Precipitation (PMP) and Probable Maximum Flood (PMF). Also included is a short discussion of incremental hazard evaluation, prioritization and scoping of remedial work at existing dams. A review of RBA approaches currently being developed and their inherent strengths and weaknesses is presented. These discussions form the bases for the formulation of the recommended framework. This framework is essentially a hybrid approach that attempts to capture the strengths of both the deterministic design flood approach and the risk-based methods. The suggested framework *builds on the principles embodied in the concepts of PMP and PMF, while explicitly and analytically incorporating considerations of risk and uncertainty into the analysis, thus providing significantly more information to decision makers, whether dam owners or regulators.*

Business risk assessment of dams - An Australian (Victorian) experience. (1998). D. J. Watson. USCOLD Annual Lecture Series. (Index terms: financial aspects, risk assessment).

Portfolio Risk Assessment: A Basis for Prioritizing and Coordinating Dam Safety Activities. (1998). D. S. Bowles, L. R. Anderson and T. F. Glover. Dam Safety '98, Association of State Dam Safety Officials, Oct. 11-14, 1998, Las Vegas, NV, 351-368 pp.

A Portfolio Risk Assessment (PRA) of a group of existing dams is based primarily on available information, without performing extensive additional analyses or investigations. A PRA provides a baseline assessment of a group of existing dams and an initial prioritization of future dam safety investigations and remedial works. The basis for this prioritization is maximizing the rate of risk reduction, but other factors that are important to the regulatory program or to the owner's business can be included. As a baseline assessment, the PRA should become a "living document" that is updated using additional information as it becomes available, thus providing a firm basis for decisions on remedial works and coordination of all aspects of dam safety risk management, including the following: monitoring and surveillance, operations and maintenance; staff training and awareness of potential failure modes; and emergency warning systems. This paper summarizes the PRA process and the role that it can play in a dam safety regulatory program or the dam safety program of a private or governmental dam owner. Results are displayed for individual dams and the entire portfolio. The safety of each dam is compared with both engineering standards and dam safety tolerable risk criteria. Various options are provided for ranking risk reduction measures across the portfolio and for displaying portfolio risk reduction against time or expenditure. The information provided has proven to be valuable for regulators and dam owners in developing their dam safety management programs and for capital budgeting, due diligence considerations and evaluation of loss financing and insurance programs. Examples of PRA outputs will be based on several PRAs completed by the authors and will include a discussion of the use to which these outputs are being put by regulators and owners. Comparisons will be made with traditional approaches to prioritizing dam safety programs.

Portfolio risk assessment: a tool for dam safety risk management. (1998). D. S. Bowles, L. R. Anderson, T. F. Glover and S. S. Chauhan. USCOLD Annual Lecture Series, U.S. Committee on Large Dams. (Index terms: risk assessment).

3.2 Case Histories

Portfolio risk assessment: a basis for prioritizing and coordinating dam safety activities. (1998). D. S. Bowles, L. R. Anderson and T. F. Glover. Dam Safety '98, Association of State Dam Safety Officials, Oct. 11-14, 1998, Las Vegas, NV, p. 351-368.

A Portfolio Risk Assessment (PRA) of a group of existing dams is based primarily on available information, without performing extensive additional analyses or investigations. A PRA provides a baseline assessment of a group of existing dams and an initial prioritization of future dam safety investigations and remedial works. The basis for this prioritization is maximizing the rate of risk reduction, but other factors that are important to the regulatory program or to the owner's business can be included. As a baseline assessment, the PRA should become a "living document" that is updated using additional information as it becomes available, thus providing a firm basis for decisions on remedial works and coordination of all aspects of dam safety risk management, including the following: monitoring and surveillance, operations and maintenance; staff training and awareness of potential failure modes; and emergency warning systems. This paper summarizes the PRA proc