# 1

# Preventing Disasters: the Grand Challenge for Earthquake Engineering Research

## THE EARTHQUAKE HAZARD

Earthquakes occur as a result of sudden displacements across a fault within the earth. The earthquake releases part of its stored strain energy as seismic waves. These waves propagate outward and along the earth's surface. It is the motion of the ground as these waves move past that is perceived as an earthquake. With most earthquakes, ground shaking is the direct and principal cause of damage to buildings and infrastructure. Considerable damage can be caused by fault rupture at the surface but this is generally limited to places near the fault. Sometimes indirect shaking effects such as tsunamis, landslides, fire caused by gas-line breaks, and flooding caused by water-line breaks also play a significant role.

**Sidebar 1.1**

**Economic Cost* of Selected Earthquakes**

Nisqually, Washington, 2001 (Magnitude 6.8, ~$2 billion in damage [University of Washington, 2001])
Taiwan, 1999, Magnitude 7.7, $20-$30 billion in damage [EERI, 1999b])
Izmit, Turkey, 1999 (Magnitude 7.6, >$5 billion in damage [EERI, 1999a])
Kobe, Japan, 1995 (Magnitude 6.9, $200 billion in damage [NIST, 1996] )
Northridge, California 1994 (Magnitude 6.7, $30 billion in damage [EQE, 1994])
Loma Prieta, California, 1989 (Magnitude 6.9, $5.9 billion in damage [EQE, 1989])

*in year of occurrence

Although fewer than 150 lives have been lost in the United States since 1975 as a result of earthquakes (Cutter, 2001), the potential for economic loss and social disruption is enormous (Mileti, 1999). Recent California earthquakes of even moderate magnitude, such as the Loma Prieta earthquake in 1989 and the Northridge earthquake in 1994 (as described in Sidebar 1.1), caused damage in the range of $10 billion to $30 billion dollars. While the seismic risk is highest in California, other regions as geographically dispersed as western Washington state, Alaska, Utah, South Carolina, the midcontinent, and areas around Boston, the St. Lawrence Seaway, and New York City all have significant potential for earthquake-related damage and economic loss. Studies conducted by the U.S. Geological Survey demonstrate that except for Texas, Florida, the Gulf Coast and the upper Midwest, most of the United States is at some risk from earthquakes (USGS, 2002).

Moreover, because of varying degrees of preparedness, a strong earthquake anywhere in the United States has the potential to be a disaster[1]. Average annual exposure to financial loss in the United States is estimated to be on the order of $4.4 billion (FEMA, 2001). The $4.4 billion estimate is extremely conservative and includes only capital losses—such as repairing or

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[1] An earthquake disaster is defined as a catastrophe that entails significant casualties, economic losses, and disruption of community services for an extended period of time.

replacing buildings, contents and inventory ($3.49 billion)—and income losses—business interruption, wage and rental income losses ($0.93 billion). It does not cover damage and losses to critical facilities, transportation and utility lifelines or indirect economic losses. A recent report of the Earthquake Engineering Research Institute calculates a total annualized loss exposure approaching $10 billion if losses due to infrastructure damage and indirect economic losses are included in this estimate, (EERI, 2003).

However, because the losses from a strong, damaging earthquake would be sudden and of great magnitude, the characterization of losses on an annualized basis, while useful for comparison, can be misleading (Sidebar 1.2). A single, large metropolitan earthquake could credibly result in $100 to $200 billion in direct and indirect losses (O'Rourke, 2003)—as much as seven times that experienced in the 1994 Northridge earthquake (Sidebar 1.1), the most costly domestic earthquake to date (Mileti, 1999). This potential economic loss is of the same order of magnitude as the $120 billion combined loss caused by the terrorist attacks of September 11, 2001, on the World Trade Center in New York City and on the Pentagon in Virginia (Wesbury, 2002). Thus, without better preparation, a large earthquake in a metropolitan center could devastate the nation, economically and socially.

**Sidebar 1.2**
**A Note on Annualized Risk**

Earthquake risk is often expressed on an annualized basis, that is, the cost of an event with an expected frequency of once in *x* years is discounted as an equal annual cost over that period. However, such first-order economics are somewhat misleading when applied to catastrophic earthquake losses. Although the expected annualized losses may be accurately calculated at say, $4 billion (a figure that appears quite manageable within a $10 trillion economy), in reality, the losses from a single catastrophic earthquake could approach thirty to fifty times that amount. Thus, the potential effects on the national economy of a loss of such magnitude which could, among other things, bankrupt the property insurance industry would seem inadequately represented by an annualized loss estimate.

## EARTHQUAKE ENGINEERING RESEARCH, THE NATIONAL SCIENCE FOUNDATION, AND NEES

Widespread concern following the Good Friday earthquake in Alaska in 1964, the Niigata earthquake in Japan in the same year, and the San Fernando earthquake in California in 1971 prompted the research that has since led to significant progress in understanding the nature of earthquakes and the application of this knowledge to the planning, design, and construction of earthquake-resistant structures. Over the past 30 years our understanding of the causative structure of earthquakes, the fundamentals of earthquake mechanisms, and earthquake-resistant design and construction practices has markedly improved. Decades of research and learning from all historical earthquakes have contributed to numerous successes in earthquake engineering a few of which are discussed later in this chapter. Appendix C lists significant discoveries that have helped to reduce earthquake losses.

### Earthquake Research Centers

Efforts in earthquake engineering research became increasingly more focused on risk reduction with the establishment of three national earthquake engineering centers by the NSF:

the Multidisciplinary Center for Earthquake Engineering Research (MCEER) at the State University of New York at Buffalo, which was founded in 1986 and renamed and re-funded in 1997; the Mid-America Earthquake (MAE) Center, founded in 1997 at the University of Illinois at Urbana-Champaign; and the Pacific Earthquake Engineering Research (PEER) Center, founded in 1997 at the University of California, Berkeley. Each center consists of a consortium of six to eight universities working collaboratively on topics such as performance-based earthquake engineering.

### Sidebar 1.3 The Value of Earthquake Engineering Research

The following vignettes provide a context for evaluating the ultimate benefits of earthquake engineering research. The first is a description of the effects of the magnitude 6.9 earthquake that struck Kobe, Japan and its surrounding area on January 17, 1995 (NIST, 1996). The second is a scenario that describes the vision of the Committee to Develop a Long-Term Research Agenda for the Network for Earthquake Engineering Simulation (NEES) for how increased earthquake resilience, made possible through research and application of the results, could significantly reduce the potential for catastrophic damage.

#### Kobe, Japan
#### January 1995

- The Hyogoken-Nanbu earthquake ruptured 35-50 km of the Nojima fault. All major highway, rail, and rapid transit routes were severely damaged, as was Kobe Port, the third largest in the world. All lifeline infrastructures were impacted with broken water and sewer lines, downed power and telephone lines, and leaking gas lines requiring weeks to repair. More than 150,000 buildings were destroyed, 6,000 people died, more than 30,000 were injured, and almost 300,000 left homeless.
- Strong ground shaking, liquefaction, and lateral spreading caused bridges, buildings, and port structures to collapse or become unusable and lifelines to fail, cutting off these services. The earthquake resulted in 148 fires that damaged more than 6900 buildings. Fire fighting efforts were largely ineffective because of damaged water mains and reduced pressure, blocked roads, and disrupted communications.
- Firefighters, police, health care services, and emergency management capabilities were made ineffective because of a lack of transportation, power, and operational facilities
- Economic and social activities were severely reduced for months or years as the damage was cleared, facilities rebuilt, and services restored. Many businesses closed forever.
- The national economy of Japan was burdened by losses estimated to reach $200 billion.

#### A Vision for the Future

- Advanced earth science, engineering, and emergency management simulations help assess the earthquake hazard in a given region, so that the general public and policy makers (public and private) can be notified of the earthquake risk in their region and informed of the planning, construction, and response measures available to reduce the risk and prevent a disaster.
- Public and private decisions are made to implement zoning, construction, response practices for disaster prevention, and increased post-earthquake response capabilities.
- Selected existing buildings and lifelines are upgraded in a cost-effective manner to minimize casualties, limit damage, and ensure functionality after an earthquake.

- Owners of single-family and multistory residential buildings are encouraged to retrofit their homes through the availability in the market of low-cost, proven strengthening techniques and municipal programs providing incentives to do so.
- New buildings and lifelines are constructed to limit damage and ensure needed functionality after an earthquake.
- Seismological instruments are widely deployed to alert emergency managers and operators of critical facilities to the occurrence of an earthquake. Computer simulations estimate the expected impact on facilities so that actions such as the orderly shutdown of commuter rail systems and power generation and control of traffic signals can be taken to reduce undesirable consequences. Timely evacuations are conducted for areas exposed to impending dam failure and tsunami inundation. Rapid simulations of expected damage are conducted so that emergency resources can be deployed where they are most needed.
- Real-time damage assessments are conducted so that search and rescue forces can be sent where they are most needed, health care is provided for the injured, fires are extinguished while they are still small, alternative routing is developed for utilities and for the conduct of commerce and manufacturing, and recovery activities are planned to hasten the return to normal economic and social activities.
- U.S. expertise in earthquake-resistant design and construction leads to reductions in domestic earthquake losses and a competitive advantage for U.S. firms in the global marketplace for earthquake disaster prevention products and services. Programs for the exchange of technology and researchers with less developed nations result in fewer casualties worldwide due to earthquakes and reduce post-disaster humanitarian aid expenditures by developed governments and nongovernmental organizations.

The magnitude of the Kobe earthquake is far from unique within the historic record and at the time of its occurrence, Kobe was as well prepared for a large earthquake as any major U.S. city or port, and better prepared than most. The committee realizes that its vision of preventing catastrophic losses associated with major earthquakes cannot be achieved overnight—it will require many decades of planning, research, and implementation. However, the committee believes that effective mitigating action, and all the benefits that would accrue from it, can be taken if only the necessary resources, imagination, and dedication are brought to the task.

## The Network for Earthquake Engineering Simulation (NEES)

Another way in which NSF has led in the development of a national program for basic earthquake engineering research is through the George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES). The goal of the NEES Program is to provide a networked, national resource of geographically-distributed, shared-use next-generation experimental research equipment installations, with teleobservation and teleoperation capabilities, which will shift the emphasis of earthquake engineering research from current reliance on physical testing to integrated experimentation, computation, theory, databases, and model-based simulation. NEES will be a collaboratory, i.e., an integrated experimental, computational, communications, and curated repository system, developed to support collaboration in earthquake engineering research and education. The advanced experimental capabilities provided through NEES will enable researchers to test and validate more complex and comprehensive analytical and computerized numerical models that will improve the seismic design and performance of our Nation’s civil and mechanical systems. Created to encourage revolutionary advances in earthquake engineering and science and building on the successful concept of engineering research centers, the NEES testing facilities, computational capabilities, and connecting grid are designed to integrate the diverse and multidisciplinary earthquake hazards community into a national program aimed directly at the critical threat posed by earthquakes.

NEES has funded 16 experimental facilities at universities around the country, all of which are scheduled to be operational by October 2004. A listing of NEES equipment grants and their host locations is shown in Table 1.1. In addition to the equipment grants, NSF has awarded one grant to develop the NEES Consortium and to create a 10-year (2004 to 2014) plan for

**TABLE 1.1 Summary of NEES Equipment Awards**

| Location | Equipment |
|---|---|
| University at Buffalo, State University of New York | Versatile High Performance Shake Tables Facility Towards Real-Time Hybrid Seismic Testing |
| University at Buffalo, State University of New York | Large-Scale High Performance Testing Facility Towards Real-time Hybrid Seismic Testing |
| University of Nevada Reno | Development of a Biaxial Multiple Shake Table Research Facility |
| Rensselaer Polytechnic Institute | Upgrading, Development, and Integration of Next Generation Earthquake Engineering Experimental Capability at Rensselaer's 100 g-ton Geotechnical Centrifuge |
| University of Minnesota, Twin Cities | System for Multiaxial Subassemblage Testing |
| University of California, Davis | NEES Geotechnical Centrifuge Facility |
| University of California, Berkeley | Reconfigurable Reaction Wall-Based Earthquake Simulator Facility |
| University of Colorado, Boulder | Fast Hybrid Test Platform for the Seismic Performance Evaluation of Structural Systems |
| University of Texas, Austin | Large-Scale Mobile Shakers and Associated Instrumentation for Dynamic Field Studies of Geotechnical and Structural Systems |
| University of California, Los Angeles | Field Testing and Monitoring of Structural Performance |
| Oregon State University | Upgrading Oregon State's Multidirectional Wave Basin for Remote Tsunami Research |
| Brigham Young University | Permanently Instrumented Field Sites for Study of Soil-Foundation-Structure Interaction |
| Cornell University | Large Displacement Soil-Structure Interaction Facility for Lifeline Systems |
| Lehigh University | Real-Time Multidirectional Testing Facility for Seismic Performance Simulation of Large-scale Structural Systems |
| University of California, San Diego | Large High Performance Outdoor Shake Table Facility |
| University of Illinois, Urbana-Champaign | Multiaxial Full-Scale Sub-structuring Testing and Simulation Facility |

SOURCE: National Science Foundation.

managing NEES and a second grant to design, develop, implement, test, and make operational the Internet-based, national-scale, high-performance network system for NEES. To augment these resources, high-performance computing and networking facilities, such as the TeraGrid and the Terascale Computing Systems described in Chapter 4, will be available to earthquake engineering researchers. When operational, NEES will consist of a system of specialized laboratories capable of conducting large-scale and/or complex experiments and supported by high-performance computing and simulation capabilities. These facilities will be accessible to qualified researchers from universities and government and private institutions, and the experimental data will be archived and available for use by academic, government, and private industry researchers throughout the world. Appendix A provides more detailed information about the NEES awards.

**Sidebar 1.4**

**The NEES Vision for Collaboration**

By bringing researchers, educators, and students together with members of the broad earthquake engineering and information technology communities, providing them with ready access to powerful experimental, computational, information management, and communication tools, and facilitating their interaction as if they were "just across the hall," the NEES collaboratory will be a powerful catalyst for transforming the face of earthquake engineering. The diversity of talents, backgrounds, experience, and disciplinary concerns to be represented within the NEES collaboratory will provide an unparalleled stimulus to intellectual inquiry and education. The collaboratory will transform the processes by which earthquake engineering research is initiated and performed, accelerate the generation and dissemination of basic knowledge, facilitate the development of effective educational programs, minimize the lag between knowledge development and its application, and hasten the attainment of universal goals for earthquake loss reduction.[2]

## THE GRAND CHALLENGE OF EARTHQUAKE ENGINEERING

Natural disasters involve the intersection of society, the built environment, and natural processes. As the committee worked through the many complex issues confronting the earthquake engineering community today, it was guided by the overarching vision that although earthquakes provide inevitable hazards to our growing urban populations, earthquake disasters are realistically preventable, and ultimately, may be eliminated entirely. The hazard is inevitable because we do not now know when an earthquake will strike any specific city nor how severe it will be, nor do we know when we might gain this predictive capability. However, *earthquake disasters* ultimately can be prevented[3] by implementing cost effective mitigation and response measures that will minimize the catastrophic losses normally associated with large earthquakes. By exploiting the knowledge and practices that can be produced by the Network for Earthquake Engineering Simulation (NEES) and other resources of the National Earthquake Hazards Reduction Program (NEHRP) the resilience of the built environment can be substantially improved, the public can be better informed of the risk and the options available to manage risk, and more enlightened public policy can be enacted and implemented. The grand challenge to NEES, the National Science Foundation, and the entire community of NEES stakeholders is to make the prevention of earthquake disasters a reality. Preventing earthquake disasters requires that the public and policy

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[2] S. Mahin, University of California, Berkeley, presentation to the committee on August 1, 2002.

[3] Throughout this report, the committee has reasoned that minimizing the catastrophic losses normally associated with major earthquakes can prevent an earthquake from becoming a disaster. By this reasoning, the committee believes that most earthquake disasters ultimately can be prevented, even if the earthquake itself cannot.

makers be convinced that is feasible, economical, and desirable to do so, and then making the needed investments in mitigation and response practices. The success of this endeavor will be determined, in part, by the quality of the partnerships formed to carry out and implement the results of NEES research. Fortunately, earthquake engineering, the branch of engineering devoted to mitigating earthquake hazards, has marked a trail of success for NEES to follow.

## EARTHQUAKE ENGINEERING SUCCESSES

Earthquake engineering research, and the application of the knowledge thus gained, has markedly improved the performance of constructed facilities. It is a testament to the effectiveness of modern building practices that the majority of direct economic losses in recent U.S. earthquakes (e.g. Loma Prieta in 1989, Northridge in 1994, Nisqually in 2001) were from damage to buildings and lifelines constructed before 1976 (when the Uniform Building Code was strengthened after the San Fernando Earthquake). However, there is still much to be done if the grand challenge of ultimately preventing earthquake disasters is to be realized. Continued progress in earthquake engineering (made possible by a robust research infrastructure) and implementation of the results through informed policy decisions, will be necessary to sustain continued progress.

The following three examples describe how government, academia, and the private sector collaborated to engage the research community in solving problems of engineering practice.

### Current Seismic Standards in the Nation's Building Codes

In 1972 the National Science Foundation and the National Institute of Standards and Technology (NIST) funded the Applied Technology Council (ATC) of the Structural Engineers Association of California to convene leading researchers and practitioners who would synthesize the available knowledge and develop seismic design and construction provisions suitable for adoption in national standards and building codes. Seismic design and construction provisions for buildings need to use consistent expressions for loadings and resistance for all types of buildings and all building materials to achieve consistent levels of safety. A comprehensive program involving all professional and materials interests was needed to achieve consensus for nationally applicable provisions for all types of buildings and building materials.

The ATC published tentative provisions in 1978. The Federal Emergency Management Agency (FEMA) then funded the Building Seismic Safety Council (BSSC) in the National Institute of Building Sciences (NIBS) to conduct trial designs that would test the efficacy and economy of the tentative provisions and to develop and update them. This process, which incorporates the latest advances from the National Earthquake Hazard Reduction Program (NEHRP) and other research, continues today. The U.S. Geological Survey supported and continues to support the effort by producing and maintaining earthquake hazard maps for use with the design provisions.

The Interagency Committee on Seismic Safety in Construction (ICSSC), together with all federal agencies concerned with seismic safety, drafted Executive Order 12699, *Seismic Safety of Federal and Federally Assisted or Regulated New Building Construction*, issued on January 5, 1990. This order requires federal agencies to apply the seismic provisions for federal buildings. The application of this requirement to federally assisted construction, such as new homes with Federal Housing Authority (FHA) or Department of Veterans Affairs (VA) mortgages, to be designed and constructed using standards considered appropriate by ICSSC achieved an even greater impact. This federal mandate was welcomed by the national standard and model building code organizations because it provided incentive for state and local governments to adopt and enforce seismic standards and codes to be eligible for federal assistance. By 1992, all model building codes incorporated seismic provisions, and NEHRP had achieved its goal of providing guidance for seismic resistance in all new U.S. building construction where these codes were in force. However, this was an effort that focused on life safety. The need for continued research that will lead to practices that also reduce property damage to acceptable levels is particularly borne out by observations made following the 1994 Northridge earthquake.[4]

## Government/Industry Cooperation to Develop an Innovative Structural System

The pre-cast concrete frame is an example of a successful government/industry cooperative project for earthquake-resistant construction. Precast concrete frame construction has not been used extensively in seismically active regions of the United States, despite its potential benefits in construction speed and quality control. This is because building code requirements were based on past experience with cast-in-place construction and regarded precast construction as an "undefined structural system," which had to be shown to be equivalent to cast-in-place systems and to provide sufficient lateral force resistance and energy absorption capacity.

Beginning in 1987, NIST, Charles Pankow Builders, and the University of Washington developed a post-tensioned, moment-resisting precast beam-column connection that would be energy-absorbing, economical, and easy to construct. The connection was a hybrid that used low-strength reinforcing steel and high-strength prestressing steel. Test results and design guidelines led to its provisional adoption as an American Concrete Institute standard and approval from the International Conference of Building Officials Evaluation Service for construction in seismic zones. Several structures using the hybrid connections have been built, including a $128-million, 39-story building in San Francisco that is the tallest concrete frame building ever to be built in a region of high seismicity.

## Resilience of Lifeline Infrastructure

Lifeline infrastructures are particularly vulnerable to earthquakes. As linear features their routings often cannot avoid faults, and much infrastructure built in earlier periods is still in service. However, past earthquakes provide valuable lessons for future designs which can be tested and refined through engineering research. Figure 1.1 is an aerial photo of the Trans-Alaska Pipeline System (TAPS) line near the Denali fault following the M7.9 Denali earthquake in 2002. This is where the line is supported by rails on which it can move freely in the event of fault offset. Alyeska Pipeline Service Company reported no breaks to the line and therefore no loss of oil despite a 2.5 m right-lateral offset of the nearby highway where it crosses the fault.

Experience from many California earthquakes has demonstrated that concrete bridge piers are subject to damage due to cyclic forces acting on unconfined concrete. As a result,

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[4] In the Northridge earthquake, seismic design provisions that focused on life safety were credited with the relatively low number of fatalities but were also held responsible for the thousands of damaged commercial structures that were subsequently labeled as “unsafe to occupy” or limited to a restricted use.

Caltrans began an aggressive program to identify retrofit methods for the large number of concrete bridges in the highway system and many have been improved. Figure 1.2 shows two concrete bridge piers following the 1994 Northridge earthquake. The Cadillac Avenue ramp had been retrofitted with steel jacketing in 1990 and is undamaged. On the other hand, the steel

Figure 1.1. An aerial photo of the Trans-Alaska Pipeline System (TAPS) line near the Denali fault, looking west. SOURCE: Alaska Division of Natural Resources.

Cadillac Ave. ramp at Interstate-10 (Santa Monica Freeway).

Highway 118/Bull Creek Bridge

Figure 1.2. Comparison of retrofitted and unimproved concrete bridge columns following the 1994 Northridge, California, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

reinforcement in the Bull Creek bridge column (built in 1976 and not upgraded) buckled due to lack of confinement of the concrete. This is an excellent example of the benefits of coupling earthquake engineering research and practice.

## Performance-Based Seismic Design

> "If NEES does not perform the work to develop the needed library of component response and performance data, Performance-based Earthquake Engineering will likely never be effectively implemented."[5]

Researchers and standards-writing organizations have begun exploring new approaches for evaluating and strengthening existing buildings and lifelines and for designing new buildings in order to control levels of damage at specific levels of ground shaking. Performance-based seismic design (PBSD) is one such approach. It differs from traditional prescriptive design methods because it focuses on *what to achieve* rather than *what to do*. Implementation of PBSD concepts will lead to structures that incorporate the life safety provisions of prescriptive codes while limiting earthquake damage to economically acceptable levels. As a result, in future earthquakes we should be able to anticipate not only fewer casualties, but also reduced economic and social losses. This will truly be a paradigm shift for building regulation in the United States but there is still not enough data on the performance of the various building components and systems to support the widespread application of PBSD. For example, PBSD methods require more detailed and extensive knowledge of how structures fail than do traditional prescriptive approaches. Since such knowledge is not available today and is difficult to attain, this should remain an area of active interest within the earthquake engineering community for many years to come. NEES research efforts can fill this critical knowledge gap by producing the data needed to implement performance-based design.

The remainder of this report identifies significant issues for earthquake engineering research, the unique capabilities of the NEES initiative to address them, the important role of information and communications technologies in NEES, a research plan incorporating short-, medium-, and long-term goals, and the committee's conclusions and specific recommendations.

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[5] Ronald Hamburger, ABS Consulting, presentation to the committee on April 26, 2002.

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