Executive Summary

Although fewer than 150 lives have been lost to earthquakes in the United States since 1975, the cost of damage from just a few moderate events during that time exceeds $30 billion (Cutter, 2001). Today, we are aware that even larger events are likely, and a single catastrophic earthquake could exceed those totals for casualties and economic loss by an order of magnitude. Despite popular perceptions that earthquakes are an issue only for the western states, much of the United States is at risk, and major cities in the Midwest and on the East Coast are particularly vulnerable owing to a lack of awareness and preparedness. If this nation is to avoid the consequences—in human, economic, social, and political terms—of an earthquake disaster,[1] it must act to ensure that communities are well-planned to avoid hazards, that buildings and lifelines are robust and resilient in their construction, and that the inevitable emergency response will be timely and targeted.

Fortunately, over the past 40 years considerable progress has been made in understanding the nature of earthquakes and how they cause damage, and in improving the performance of the built environment. Unfortunately, much remains unknown or unproven. Progress has been achieved primarily by observation following earthquakes of what failed and what did not and then developing responses to the observed phenomena. Damaging earthquakes are relatively infrequent, however, and progress from lessons learned in this manner is unacceptably slow. To counter the slow pace of advance, earthquake engineering research, which embodies theoretical analysis, experimentation, and physical testing, emerged to speed the development and deployment of practices to mitigate the effects of damaging earthquakes. However, we again find ourselves in a position where the threat posed by major earthquakes has outpaced our ability to mitigate the consequences to acceptable levels. The process of identifying and deploying cost-effective technologies and informing political bodies and the general public of the benefit of comprehensive strategies to mitigate earthquake losses needs to be accelerated.

The National Science Foundation, long a major supporter of earthquake engineering research, has awarded over $80 million in grants to establish the Network for Earthquake Engineering Simulation (NEES) to foster improvement in the seismic design and performance of the nation's civil and mechanical infrastructure. NEES was conceived as a networked collaboratory[2] that extends research beyond physical testing and emphasizes integrated experimentation, computation, theory, database development, and model-based simulation in earthquake engineering research. The research equipment sites funded through NEES will permit the controlled simulation of complex problems in seismology, seismic excitation, and structure response that formerly had to await an actual earthquake that occurred under random, uncontrolled conditions. Through the NEESgrid, the curated data from these efforts will be widely available to researchers and practitioners throughout the United States and around the world regardless of whether they participated in a particular

[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.

[2] A collaboratory is envisioned as a future "…'center without walls' in which the nation's researchers can perform their research without regard to geographical location—interacting with colleagues, accessing instrumentation, sharing data and computational resources, [and] accessing information in digital libraries" (Wulf, 1989).

experiment. A fundamental objective of NEES, and the purpose of NEESgrid, is to change the paradigm so that earthquake engineering research within the NEES Consortium becomes a collaborative effort rather than a collection of loosely coordinated research projects by individuals.

Substantive progress in minimizing the catastrophic impacts of major earthquakes will require multidisciplinary research studies of unprecedented scope and scale. In particular, major advances will be required in the computational simulation of seismic events, wave propagation, and the performance of buildings and infrastructure—all of which will rely on extensive physical testing or observation for validation of the computational models. Results from these simulations will need to couple with building inventories, historical earthquake damage, and alternative build-out scenarios and will drive performance-based system designs, pre-event mitigation planning, emergency response, and post-event assessment and recovery. Ultimately, knowledge-based systems will be developed to support decision-making by policy makers and planners.

This report is the result of an 18-month effort by the NRC's Committee to Develop a Long-Term Research Agenda for the Network for Earthquake Engineering Simulation. The committee was charged to develop a long-term earthquake engineering research agenda that utilized the unique capabilities of NEES, both in physical and computational simulation and information technology.

The committee's overarching vision as it formulated the research agenda was that earthquake disasters, as the committee defined them, can ultimately be prevented.[3] This is the committee's grand challenge to the broad community of NEES stakeholders, to make the prevention of earthquake disasters a reality. To do so will require creativity in formulating research problems that tax the capabilities of NEES and skill in building the partnerships to carry out the research.

GRAND CHALLENGE RESEARCH

Research grand challenges have been defined as major tasks that are compelling for both intellectual and practical reasons, that offer the potential for major breakthroughs on the basis of recent developments in science and engineering, and that are feasible given current capabilities and a serious infusion of resources (NRC, 2001). Grand challenge tasks in earthquake engineering research should have a high probability of technical and practical payoff, large scope, relevance to important issues in earthquake engineering, feasibility, timeliness, and a requirement for multidisciplinary collaboration.

As a first task, the committee identified research challenges and issues in seven topical areas (i.e., seismology, tsunamis, geotechnical engineering, buildings, lifelines, risk assessment, and public policy). These issues are summarized in Table ES-1. From these many issues, the committee distilled six research problems that it believes are ideal grand challenge tasks for initial NEES efforts. These tasks would take advantage of the ability of multiple NEES equipment sites to address the many interwoven technical issues, offer ample

[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.

opportunities for interdisciplinary collaboration and synergy, and provide enormous paybacks over time.

Develop Economical Methods for Retrofit of Existing Structures

The economical retrofit of existing structures is perhaps the most important issue facing earthquake-prone communities today. For every new building or home constructed, there are literally thousands already existing—many built before 1976, when improved seismic provisions began to be required in building codes. Experimentation and validation testing conducted through NEES can help to make available new materials and techniques, ground motion modeling, soil strengthening, foundation enhancements, wall and beam strengthening, and in situ testing. The newly emerging technology of smart materials that can adapt to changing external factors also needs to be investigated for its potential application for retrofitting. A new generation of retrofit technologies that cost less than existing, less effective techniques but still preserve cultural and architectural resources and protect real estate investments from total loss, is long overdue.

Cost-Effective Solutions to Mitigate Seismically Induced Ground Failures Within Our Communities

Historical earthquakes have repeatedly borne out that damage is greater in poorer soil areas, and significant property losses (and sometimes human casualties) are often associated with soil-related failures. Buildings and lifelines located in earthquake-prone regions, especially structures constructed of, founded upon, or buried within loose saturated sands, reclaimed or otherwise created lands, and deep deposits of soft clays, are vulnerable to a variety of earthquake-induced ground damage such as liquefaction, landslides, settlement, and distributed fault rupture. Deep deposits of soft clays and liquefiable soils are common in many large U.S. cities. It is encouraging that recent experience shows that engineering techniques for ground improvement can mitigate earthquake-related damage and reduce losses. Although great strides have been made in the last two decades to improve our predictive capabilities and seismic engineering design practices, there remains an urgent need for more robust modeling procedures and predictive tools, more powerful site characterization techniques, and more quantitative guidelines for soil improvement measures. Researchers need to validate the current liquefaction susceptibility mapping techniques so that they truly delineate the zones that liquefy during an earthquake. During the Loma Prieta and Northridge earthquakes, both in California, very little of the areas mapped as high liquefaction hazard zones actually did liquefy, which raises serious questions regarding our understanding of the liquefaction phenomenon. On the other hand, many slopes did fail, in unexpected ways, indicating an equivalent weakness in our understanding of the slope deformation process. In addition, NEES should be used to move past the prediction of free field liquefaction to the next level, which would be the ability to predict deformations (both vertical and lateral) for structures, dams, and lifelines by considering the timing, sequence, and location of soil strength loss in the vicinity of the constructed feature.

Full Suite of Standards for Affordable Performance-Based Seismic Design

A performance-based building code does not prescribe specific construction requirements (e.g., specific structural details or fire resistance ratings). Rather, it provides a framework of performance goals and permits the use of a variety of methods, systems, devices, and materials to achieve those goals—i.e., it spells out *what to achieve* rather than *what to do*. Performance-based seismic design (PBSD) is an approach to limit damage to specified levels under specific levels of ground shaking. With the growing emphasis on performance-based seismic design, there is a need to develop a comprehensive understanding of the earthquake response of a building when damage occurs in the structural system over the course of the earthquake (cracking, yielding, crushing, fracture, and so forth). Because PBSD methods require more detailed and extensive knowledge of how structures fail than do traditional prescriptive approaches, this will require a comprehensive body of research data, convenient computer analysis tools that support the reliable and routine analysis of progressive earthquake damage in buildings, and assessment of how damage affects the seismic response of buildings. NEES can increase the availability of data on the performance of the various building components and systems to allow the widespread application of PBSD.

Convincing Loss Prediction Models to Guide Zoning and Land Use Decisions

The magnitude of an earthquake-induced loss is heavily dependent on the size of the event and the quality and strength of the structures and facilities it impacts. Because there is little that can yet be done to control naturally occurring events, most earthquake mitigation measures have been directed at the built environment. There is a sociopolitical aspect of mitigation, however, that must also be considered. Land use planning and zoning are the principal tools available to communities to control their physical development. Although communities have the authority to restrict development of hazard-prone areas, it is often difficult to implement the necessary policies and ordinances to do so. Local zoning boards and governing bodies are under intense pressures to allow the development of questionable lands for economic and other reasons. Without credible methods to illustrate the potential losses that would be incurred if development in these areas experienced a damaging earthquake (and therefore the public benefit of limiting development), it is difficult for these bodies to restrict development to uses compatible with the hazard. As a consequence, development continues in the potential path of intense ground shaking, ground failures, and seismic sea waves, and existing development in these areas remains at risk. For positive change to occur, decision makers will need strongly supported and clearly communicated facts on which to base their decisions on new development and, possibly, on modifying existing zoning in high risk areas for a more compatible use. Loss prediction models, validated through test and experiment and augmented by simulation videos, could be the needed instrument of change. However a lack of data on existing housing stock and the nonresidential building inventory, including construction type and replacement value, is an impediment to the development of improved loss prediction models. At the same time, damage and loss data from historical earthquakes is another important component of loss modeling. These data need to be collected, either directly through NEES research efforts or a supporting activity.

Continuous Operation of Critical Infrastructure Following Earthquakes

Lifeline infrastructures are vital systems that support a nation's economy and quality of life. Modern economies rely on the ability to move goods, people, and information safely and reliably. Adding to their importance is that many of the lifeline systems serve vital roles in disaster recovery. Consequently, it is of the utmost importance to government, business, and the public at large that the flow of services provided by a nation's infrastructure continues unimpeded in the face of a broad range of natural and technological hazards. The linkage between systems and services is critical to any discussion of infrastructure. Although it is the performance of the hardware (i.e., the highways, pipes, and transmission lines) that is of immediate concern following an earthquake, it is actually the services that these systems provide that are the real loss to the public. Therefore, a high priority in protecting these systems from hazards is ensuring the continuity (or at least the rapid restoration) of service. Hazard mitigation for lifeline infrastructures such as water, electricity, and communications has generally focused on first-order effects—designing the systems so they do not fail under the loads imparted by earthquakes, and NEES can make an important contribution to the testing of physical behavior of components and systems to ground shaking, ground failure, etc. However, as these systems become increasingly complex and interdependent, hazard mitigation must also be concerned with the secondary and tertiary failure effects of these systems on one another. Perhaps even more significant are the impacts of complex infrastructure system failures on our social, economic, and political institutions.

Prediction and Mitigation Strategies for Coastal Areas Subject to Tsunamis

Since 1992, 16 lethal tsunamis have occurred in the Pacific Ocean, resulting in more than 4,000 fatalities (NOAA, 2003). In all of these events the tsunamis struck land near their source, so little warning time was available. Tsunamis are truly a panoceanic problem, because losses due to offshore earthquakes occurring near a coast are not limited to the coastal areas closest to the source. Reducing the losses from tsunamis will require a better understanding of the factors leading to their generation, improved models of inundation and physical impact from which loss predictions can be generated, and, ultimately, mitigation strategies. It is important to link prediction with mitigation, because coastal areas are preferred sites for residences, industry, and ports. Better predictive tools will enable the development of better loss estimation models, which will guide land use and construction techniques in tsunami-prone areas. The vulnerability to tsunamis is particularly acute in developing countries as well as in small coastal communities in developed countries where people live in close proximity to the sea and have few resources either to relocate to less vulnerable areas or to implement protective measures. It will be challenging to realize the committee's vision of preventing earthquake disasters in such areas where people have little choice but to live with these tsunami risks. The committee believes that NEES, by offering a real promise of improved tsunami detection, warning, and evaluation of coastal effects, in the long run can significantly reduce the catastrophic consequences of these events. Working without these tools is a major challenge for regulators and providing them will be a grand challenge task for NEES.

THE PROMISE OF NEES

The committee believes that NEES truly is synergistic and can become much more than the sum of its parts. The fundamental premise of the committee's research agenda is that even though research needs are presented in terms of topical areas, these are not stand-alone issues to be resolved on a narrow, discipline-oriented basis. The committee believes that the promise of NEES is that the collaboratory approach can address and resolve the complex, multidisciplinary problems that underlie progress in earthquake engineering by engaging several of the new equipment sites and investigators from multiple disciplines located both at the NEES equipment sites and elsewhere. Understanding can thus be advanced in quantum leaps rather than small, incremental steps. All of these efforts will require multidisciplinary collaboration between the scientists and engineers who will develop and test new theories on earthquakes, earthquake damage, and its mitigation, and the social and political scientists and educational specialists who will use the science and technology that will come from NEES to develop better risk assessment tools, loss estimation models, and communication and teaching strategies to help enact and implement more enlightened policies on earthquake loss mitigation. The committee has developed a series of recommendations that are offered in the spirit of helping the National Science Foundation and the NEES Consortium realize the full potential of this ambitious and worthwhile initiative, and to make NEES truly a new paradigm for earthquake engineering research.

RECOMMENDATIONS

Recommendation 1. The National Science Foundation should encourage, and fund at appropriate levels, research projects that address the high-priority issues in earthquake engineering and science identified by the committee. Special emphasis should be placed on grand challenge research activities that include multiple equipment sites and investigators from many disciplines.

Recommendation 2. NSF should also support NEES projects of more modest scope that will produce and report useful results within a 2 to 3 year timeframe. These projects could serve as models for additional studies and demonstrate positive outcomes that would encourage other investigators to become involved in NEES collaborative research.

Recommendation 3. The National Science Foundation should ensure that funding is provided for appropriate maintenance, support, and utilization of the NEES investment. At the same time, funding to support and maintain the research

infrastructure not located at NEES equipment sites should be continued at an appropriate level.

Recommendation 4. The National Science Foundation, as the lead agency in the NEES partnership, should assume leadership and put in place a management structure to articulate objectives, identify and prioritize research needs, and assure a stable flow of support to achieve the objectives established for NEES. This should include the establishment of an advisory body to provide strategic guidance to NEES program activities.

Recommendation 5. The National Science Foundation and other stakeholder agencies should develop a partnership with a shared vision for earthquake loss reduction and for undertaking research and development to achieve that vision.

Recommendation 6. The partnership of public and private organizations that will support NEES efforts should build a national consensus to ensure that the research and development needed to achieve earthquake loss reduction is fully appreciated at all levels of government and is provided with adequate resources to realize the vision of preventing earthquake disasters in the United States.

Recommendation 7. In addition to the potential of NEES to foster collaboration in research, its capabilities as a tool for education and outreach should be exploited to the greatest extent possible.

Recommendation 8. Although NEES is directly targeted at earthquake engineering research, its capabilities for simulation, physical testing, and experimentation can and should be applied to a wide range of civil engineering applications.

Recommendation 9. The capabilities of NEES should be viewed as a global asset whose value can be utilized for increasing the U.S. contribution to international earthquake loss reduction.

Recommendation 10. Although the potential value of research conducted under the aegis of NEES is enormous, it is important that individual researchers and other groups not directly affiliated with NEES equipment sites be supported.

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TABLE ES-1 Summary of Topical Problems and Challenges for Earthquake Engineering Research

Topical Area	Problem	Challenge
Seismology	For most earthquakes, ground shaking is the principal source of losses.	To predict the level and variability of strong ground motion from future earthquakes, a simple extrapolation of attenuation relations to larger-magnitude earthquakes will not suffice; a combination of improved observations and large-scale simulation will play a key role in progress in this area.
Tsunamis	Coastal areas that are preferred residential, industrial, and port sites have been frequent and vulnerable targets of seismically generated sea waves from near and distant sources.	To develop a complete numerical simulation of tsunami generation, propagation, and coastal effects to provide a real-time description of tsunamis at the coastline for warning, evacuation, and engineering purposes.
Geotechnical Engineering	Facilities and lifelines in seismic environments, especially structures constructed of, founded on, or buried within loose saturated sands, reclaimed lands, and deep deposits of soft clays, are vulnerable to earthquake-induced ground damage.	To attain more robust modeling procedures and predictive tools, more powerful site-characterization techniques, and more quantitative guidelines for soil-improvement measures.
Buildings	Despite advances in seismically resistant design in recent years, there is a need to develop greater understanding of the behavior of building systems in order to ensure that new buildings are designed and old buildings are retrofitted to reduce significantly their vulnerability to large economic losses during earthquakes.	To predict the performance of existing, retrofitted, and newly built structures when they are subjected to extreme loads such as earthquakes.
Lifelines	Lifelines are typically more vulnerable than conventional facilities to earthquake hazards, particularly geotechnical hazards,	To develop the means to protect the vast inventory of lifeline facilities (complex transportation and utility infrastructure that

	because there is less opportunity to avoid these hazards through prudent site selection or site improvement.	includes highways, railroads, ports, airports, electric power transmission and distribution, communications, gas and liquid-fuel pipelines and distribution systems, and water and sewage systems), despite their wide spatial distribution and interdependencies.
Risk Assessment	Earthquakes are infrequent hazards, but their consequences can be profound.	To provide decision makers with information on risk exposure and risk-mitigation alternatives and the tools that enable them to make prudent decisions.
Public Policy	The “teachable moment” following an earthquake is too short to educate the public and policy makers and create broad demand for improved seismic performance.	To extend the teachable moment and place earthquake hazard mitigation on the public, municipal, and legislative agendas.