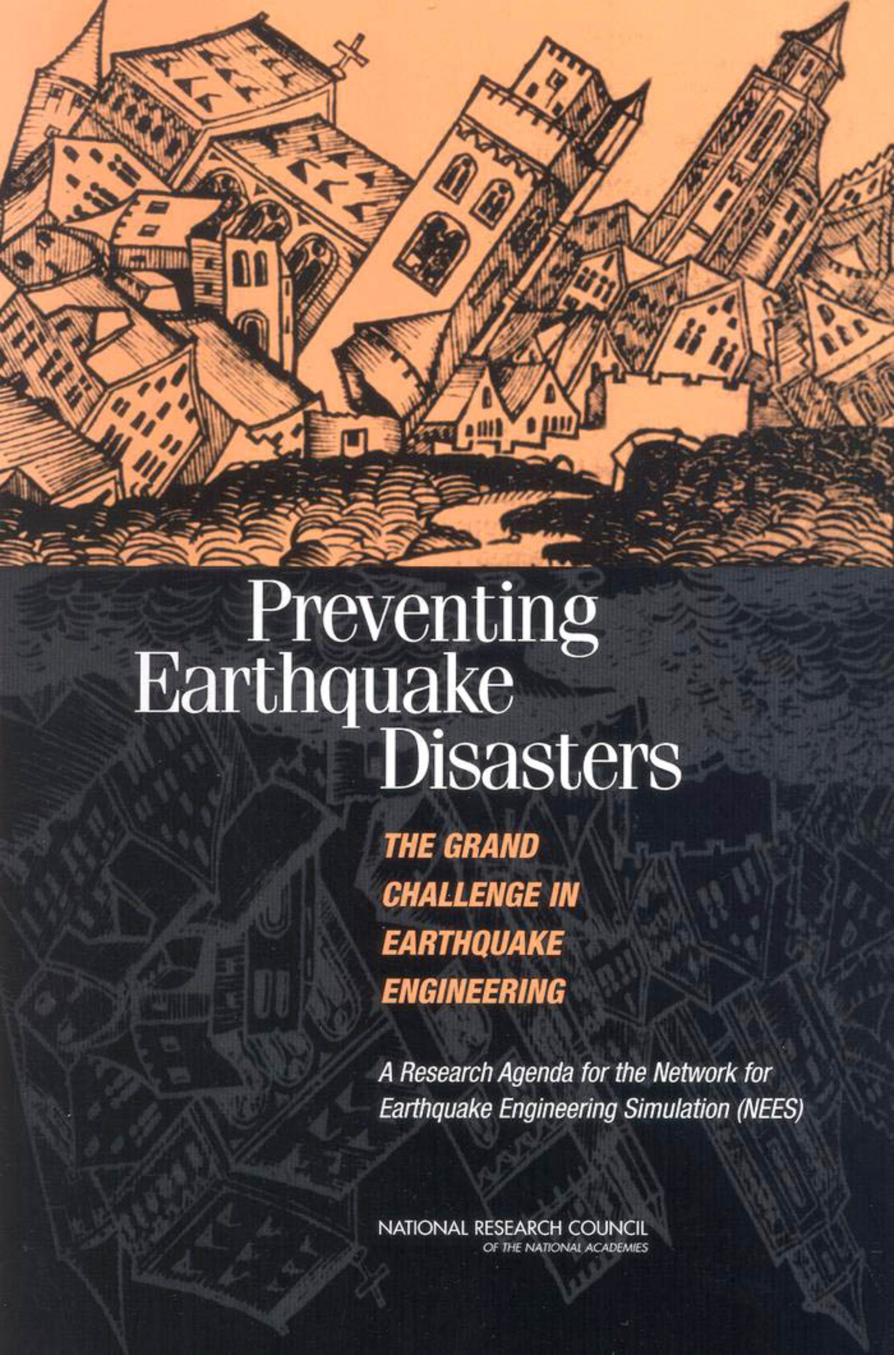

Preventing Earthquake Disasters

THE GRAND CHALLENGE IN EARTHQUAKE ENGINEERING

A Research Agenda for the Network for Earthquake Engineering Simulation (NEES)

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Committee to Develop a Long-Term Research
Agenda for the Network for Earthquake Engineering Simulation (NEES)

Board on Infrastructure and the Constructed Environment

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Preface

BACKGROUND

The George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES) is a collaboratory for integrated experimentation, computation, theory, databases, and model-based simulation in earthquake engineering research and education intended to improve the seismic design and performance of the U.S. civil and mechanical infrastructure. Administered by the National Science Foundation (NSF), NEES is mandated to be operational by September 30, 2004.

The NEES collaboratory will include 16 geographically distributed, shared-use, next-generation earthquake engineering experimental research equipment installations, with teleobservation and teleoperation capabilities networked through the Internet. (Appendix A in this report provides information about the equipment installations.) In addition to providing access for telepresence at the NEES equipment sites, the network will use cutting-edge tools to link high-performance computational and data-storage facilities, including a curated repository for experimental and analytical earthquake engineering data. The network will also provide distributed physical and numerical simulation capabilities and resources for the visualization of experimental and computational data. Through NEES, the earthquake engineering community will use advanced experimental capabilities to test and validate analytical and computerized numerical models that are more complex and comprehensive than ever. When the results of the NEES effort are adopted into building codes and incorporated into existing and new buildings and infrastructure, they will improve the seismic design and performance of our nation's civil and mechanical systems. The NEES equipment includes new and upgraded shake tables, centrifuges, an enlarged tsunami wave basin, large-scale laboratory experimentation systems, and field experimentation and monitoring installations.

NEES is envisioned as a new paradigm for earthquake engineering research. To take advantage of NEES's unique capabilities, NSF requested the assistance of the National Research Council (NRC) in developing a long-term research agenda. The purpose of the NRC effort was both to develop a process for identifying research needs and to consult stakeholders in framing the important questions to be addressed through NEES. The long-term research agenda will guide the next generation of earthquake engineering research and shape the conduct of a program of great national and international importance.

THE INVOLVEMENT OF THE NATIONAL RESEACH COUNCIL

In response to the request to review the NEES program and to offer recommendations for conducting a long-term research program, the NRC assembled an independent panel of experts, the Committee to Develop a Long-Term Research Agenda for the Network for Earthquake Engineering Simulation (NEES), under the auspices of the Board on Infrastructure and the Constructed Environment. The 14 members of the committee have expertise in seismology, earthquake engineering, theoretical structural dynamics, computer modeling and simulation, experimental methods for structures, soil dynamics, coastal engineering, behavior of lifeline infrastructure, group facilitation and consensus building, technology applications for distance learning and remote collaboration, research management, risk assessment, and loss estimation. Members are involved in the major U.S. organizations of the earthquake risk-reduction community (e.g., the Seismological Society of America, the Earthquake Engineering Research Institute, the American Society of Civil Engineers, and the Association of Engineering Geologists). They have had leading roles in the National Earthquake Hazards Reduction Program since its inception in 1978 and attend the major national and international conferences on earthquake risk reduction. (Biographical information about the committee members is provided in Appendix B.)

THE STATEMENT OF TASK

The committee was asked to perform the following tasks:

> 1. Articulate a dynamic, stakeholder-inclusive process for determining research needs that is capable of utilizing the multi-modal research capability embodied by NEES and assess how NEES might fundamentally change the paradigm for earthquake engineering research.
>
> 2. Identify the principal issues in earthquake engineering (e.g., structural [connections, soil/structure interaction, lifeline dynamics, tsunami effects, materials, reinforced concrete, steel, masonry, wood], appropriate investigative techniques), and possible synergies arising from an integrated research approach that incorporates analysis, computational modeling, simulation, and physical testing.
>
> 3. Assess and comment on the possible roles of information and communication technologies for collaborative on-site and remote research, the sharing of data (including the need for standardization in data reporting), metadata, and simulation codes, and identify additional research resources that are not currently available.
>
> 4. Produce a long-term (at least 10 years) research plan based on the short-, intermediate-, and long-term goals developed through the research needs process; identify general programs to achieve them, the estimated costs and benefits, and a business model for the involvement of industry, government (at all levels), and academia in the program.

Task 1 is addressed in Chapter 5 and by Recommendation 4. In addition, stakeholder involvement in the committee's process for determining research needs is described in Chapter 5 and Appendix E. Tasks 2 and 3 are addressed in Chapters 2 and 4, respectively. In response to Task 4, a research plan and business model are presented in Chapter 5.

ORGANIZATION OF THIS REPORT

Chapter 1 provides a brief overview of the threat posed by earthquakes, the contributions of earthquake engineering research to reducing that risk, a brief description of NEES, and the role anticipated for NEES in future research. Chapter 2 discusses research issues in the seven topical areas (seismology, tsunamis, geotechnical engineering, buildings, lifelines, risk assessment, and public policy) that the committee believes are key to achieving the prevention of earthquake disasters. Chapter 3 discusses the role of NEES in grand challenge research, outlines several grand challenge research ideas, and presents several examples of how NEES equipment sites could be configured to carry out collaborative research proposals. Chapter 4 discusses the potential impact and possible roles of new information and communications technologies with respect to earthquake engineering research and how these new and evolving technologies will affect NEES. Chapter 4 also considers the issues associated with teleobservation and teleparticipation in research, as well as sharing, archiving, and mining data. Chapter 5 presents the committee's research plan. Chapter 6 presents the committee's overall conclusions and specific recommendations on the role of NSF and NEES in preventing earthquake disasters.

ACKNOWLEDGMENTS

This report represents the efforts of many individuals and organizations. On behalf of the Committee to Develop a Long-Term Research Agenda for the Network for Earthquake Engineering Simulation (NEES), I would like to acknowledge and thank all the engineers and scientists who made presentations to us both in person and via teleconferencing as well as the organizations that supported them. These presentations were informative, understandable, and concise.

I want to express my appreciation to members of the committee for candidly expressing their opinions and views. Composed of engineers and scientists interested in earthquake engineering research generally and in the Network for Earthquake Engineering Simulation specifically, the committee truly represents a cross section of the earthquake engineering profession. The members made substantial contributions to this report and gave unselfishly of their time to ensure its timely completion.

Lastly, I want to thank Richard G. Little and other members of the National Research Council staff for their hard work and conscientious efforts on behalf of the committee.

William. F. Marcuson III, *Chair*
Committee to Develop a Long-Term Research Agenda
for the Network for Earthquake Engineering Simulation (NEES)

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Jill H. Andrews, California Institute of Technology,
Eddie Bernard, NOAA-Pacific Marine Environmental Laboratory,
Susan Cutter, University of South Carolina,
William J. Hall, University of Illinois at Urbana-Champaign,
James O. Jirsa, University of Texas at Austin,
Chris D. Poland, Degenkolb Engineers,
Robert V. Whitman, Massachusetts Institute of Technology, and
Mary Lou Zoback, U.S. Geological Survey.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Clarence

Allen, California Institute of Technology. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Figures, Tables, and Sidebars

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Acronyms

ANSS	Advanced National Seismic System
COSMOS	Consortium of Organizations for Strong-Motion Observation Systems
EERI	Earthquake Engineering Research Institute
FEMA	Federal Emergency Management Agency
GIS	geographic information system
IRIS	Incorporated Research Institutions for Seismology
IT	information technology
MAST	multiaxial subassemblage testing
MEMS	microelectromechanical system(s)
MRE	major research equipment
MUST-SIM	multiaxial full-scale substructures testing and simulation
NEES	Network for Earthquake Engineering Simulation
NEHRP	National Earthquake Hazards Reduction Program
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation

PBSD	performance-based seismic design
PEER	Pacific Earthquake Engineering Research Center
PITAC	President's Information Technology Advisory Committee
SCEC	Southern California Earthquake Center
SFSI	soil-foundation-structure interaction
SIG	single-investigator grantee
SUNY	State University of New York

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 phe-

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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.

nomena. 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 about 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 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 computa-

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[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).

tional models. Results from these simulations will have to be coupled with building inventories, data on 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 with developing 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 chal-

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[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.

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

Topical Area	Problem	Challenge
Seismology	In 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.

TABLE ES-1 *Continued*

Topical Area	Problem	Challenge
Lifelines	Lifelines are typically more vulnerable than conventional facilities to earthquake hazards, particularly geotechnical hazards, because there is less opportunity to avoid these hazards through prudent site selection or site improvement.	To develop the means to protect the vast inventory of lifeline facilities (complex transportation and utility infrastructure that 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.

lenge 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 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 to retrofitting. A new generation of retrofit technologies that cost less than existing, less effective techniques but 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. Yet 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 have 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, gaining this understanding 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 are another important component of loss modeling. These data need to be collected, either directly through NEES research efforts or from 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 loss of services that these systems provide that is 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 the physical behavior of components and systems in reaction 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. The National Science Foundation should also support NEES projects of more modest scope that will produce and report useful results within a 2- to 3-year time frame. 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 ultimately 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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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.

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, caused damage ranging up to $30 billion (Sidebar 1.1). 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).

Sidebar 1.1
Economic Cost (in year of occurrence) of Selected Earthquakes

Nisqually, Washington, 2001 (Magnitude 6.8, ~$2 billion in damage [University of Washington, 2001])
Taiwan, 1999 (Magnitude 7.7, $20 billion to $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])

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 replacing buildings, contents, and inventory ($3.49 billion)—and income losses, including business interruption and wage and rental income losses ($0.93 billion). It does not cover damage and losses to critical facilities and to 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 billion to $200 billion in direct and indirect losses (O'Rourke, 2003)—as much as seven times that experienced in the 1994 Northridge earthquake, 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.

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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.

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 30 to 50 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. Sidebar 1.3 outlines potential benefits of earthquake engineering research.

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 National Science Foundation (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.

The Network for Earthquake Engineering Simulation (NEES)

Another way in which the 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 (see Sidebar 1.4). 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 addressing 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 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

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 6,900 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 historical 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.

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.

SOURCES: Mahin, University of California, Berkeley, presentation to the committee on August 1, 2002.

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.

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 pose 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 or how severe it will be, nor do we know when we might gain this predictive capability. However, *earthquake disasters* ultimately can be prevented[2] by implementing cost-effective miti-

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[2] 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.

TABLE 1.1 Summary of NEES Equipment Awards

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

SOURCE: National Science Foundation.

gation 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 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 convincing the public and policy makers that it 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 have collaborated to engage the research community in solving problems of engineering practice.

Incorporation of 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 have 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 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 standards and model building code organizations because it provided an 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.[3]

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[3] 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 “unsafe to occupy” or limited to a restricted use.

Government/Industry Cooperation to Develop an Innovative Structural System

The precast concrete frame is an example of a successful government/industry cooperative project for earthquake-resistant construction. Despite its potential benefits in construction speed and quality control, precast concrete frame construction has not been used extensively in seismically active regions of the United States, because building code requirements based on past experience with cast-in-place construction 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.

Efforts to Improve the 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 magnitude 7.9 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, 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

FIGURE 1.1 An aerial photo of the Trans-Alaska Pipeline System (TAPS) line near the Denali fault, looking west. SOURCE: Alaska Department of Natural Resources. Photo by Rod Combellick, Division of Geological and Geophysical Surveys.

Cadillac Avenue ramp had been retrofitted with steel jacketing in 1990 and was not damaged, but the steel reinforcement in the Bull Creek Bridge column (built in 1976 and not upgraded) buckled due to lack of confinement of the concrete. Improved resilience 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.
>
> —Ronald Hamburger, ABS Consulting,
> presentation to the committee on April 26, 2002

Researchers and standards-writing organizations have begun exploring new approaches for evaluating and strengthening existing buildings

FIGURE 1.2 Comparison of retrofitted and unimproved concrete bridge columns following the 1994 Northridge, California, earthquake. *Left:* Cadillac Avenue ramp at Interstate 10 (Santa Monica Freeway). *Right:* Highway 118/Bull Creek Bridge. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

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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Issues in Earthquake Engineering Research

Earthquakes pose inevitable risks to everyone who lives in a seismically active region. Even though the hazard is well recognized, no one knows when an earthquake will strike or how severe it will be. Despite considerable effort over the years to develop the capability to predict earthquakes, it is unclear whether this ever will be achieved. In the face of this uncertainty, NEES offers an unprecedented opportunity to advance knowledge and practice that could ultimately lead to the prevention of earthquake disasters. By disseminating and implementing the cost-effective planning, design, construction, and response measures developed through NEES research, it will be possible to reduce injuries, loss of life, property damage, and the interruption of economic and social activity that have long been associated with strong earthquakes in densely developed regions. Earthquakes will continue to occur, but the disasters that they cause will be a thing of the past.

Technology is just one element of earthquake disaster prevention, however. Policy makers and the public they represent must be convinced that the threat is real and that preventing disaster is desirable, economical, and achievable. Action will be taken only when society is convinced that the investment in land planning and zoning, design and construction practices, and emergency response for disaster prevention provides measurable and greater benefits than those afforded by business as usual.

Much of the needed knowledge is already available, and more will be forthcoming if the recommendations for research contained in this report are implemented. More importantly, the unique capabilities of NEES-related research, simulation, and simulcast demonstration can be used to generate public support for seismic upgrades, open space zoning near faults and other hazardous areas, and the use of the best current knowledge for all aspects of disaster prevention. Such public awareness and support will hasten the further creation, communication, and application of new information.

This chapter discusses seven topical areas—seismology, tsunamis, geotechnical engineering, buildings, lifelines, risk assessment, and public policy—that the committee believes are key to preventing earthquake disasters. The principal problems and challenges presented by each topical area are summarized in Table ES.1. However, these are not standalone issues to be resolved on a narrow, discipline-oriented basis. The unique and exciting opportunity presented by NEES is the ability to formulate complex hypotheses regarding seismic excitation, system response, and social interaction at scales that range from individual structures and building components up to regional systems, and then to test these hypotheses using a coupled simulation employing field observations, physical experiments, theoretical analysis, and computer modeling.

Figure 2.1 illustrates this multilevel, interdisciplinary concept. The committee's presentation of the issues follows the logic embodied in Figure 2.1—namely, the fundamental earth science questions to be answered

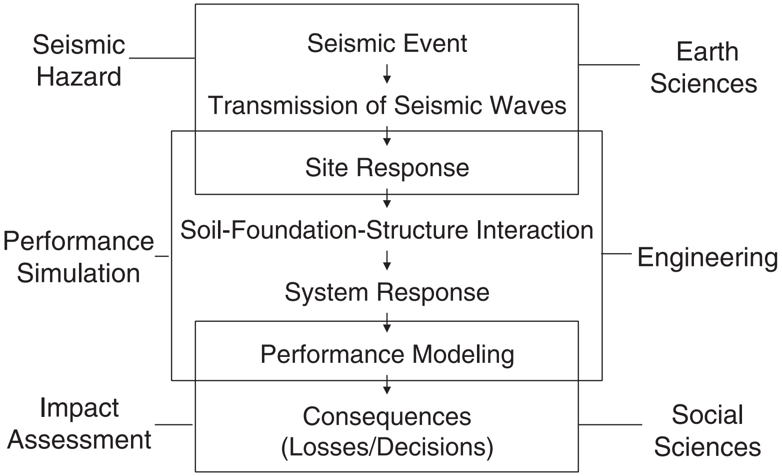

FIGURE 2.1 Nested linkages of activities and disciplines that NEES will bring to the resolution of earthquake engineering problems. SOURCE: G. Deierlein, Stanford University, presentation to the committee, April 25, 2002.

in seismology, the direct geologic effects of seismic excitation (tsunamis and ground failure), impacts on the constructed environment of buildings and lifelines, and, finally, risk assessment and public policy. NEES will play a critical role in addressing all these issues but will be more immediately involved in simulating earthquake hazards and their impact on the built environment. It is this knowledge that will inform risk assessments and loss estimates so that public policy options can be developed and evaluated.

The research plan presented in Chapter 5 anticipates a high degree of interaction among the NEES equipment sites in creating this knowledge base. This interaction will also include investigators from around the world and will cut across traditional discipline-based research. The connectivity provided by the NEES grid has the ability to make this oft-voiced rhetorical goal a reality.

SEISMOLOGY

Ground Motion

Knowledge of ground motion attributable to earthquakes is crucial for the design of new structures and the retrofit of existing ones, as well as for emergency planning and response. 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, the direct effects of ground shaking are the principal cause of damage (Holzer, 1994). Fault rupture can create considerable damage but it occurs only near the fault. 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 in some cases. Regional tilting and warping across folded strata may result in heavy lifeline damage across entire regions.

The factors that influence strong ground motion during earthquakes are traditionally divided into source, path, and site effects. A fundamental challenge for earthquake engineering is predicting the level and variability of strong ground motion from future earthquakes. Enhancing this predictive ability requires better understanding of the earthquake source, the effects of the propagation path on the seismic waves, and basin and near-surface site effects. Seismologists, geologists, and engineers base their understanding on knowledge of the dynamics of earthquake fault rupture, the three-dimensional elastic and energy-dissipation properties (anelastic structure) of the earth's crust, the modeled nonlinearities that occur in the shallowest parts of the earth's crust during strong earthquakes, and the complex interactions between structures and the seismic wavefield.

Earthquake Sources

Understanding the behavior of the earthquake source—the spatial and temporal behavior of slip on the fault or faults that rupture in an earthquake—is central to predicting strong ground motion. A large earthquake starts at the hypocenter and may rupture across several fault segments or even across multiple faults. Using strong ground motion recordings of large earthquakes, seismologists have determined that fault rupture typically propagates at a large fraction—usually about 80 percent—of the shear wave velocity of the ruptured material, although there is evidence that the rupture velocity can locally exceed the shear wave velocity (Bouchon et al., 2001). The slip velocity across the fault is much less well determined but is on the order of several meters per second in a large earthquake (Heaton, 1990). The combination of high rupture velocity and high slip velocity leads to strong directivity in the radiated wavefield—that is, seismic waves emanating from the fault get channeled more strongly in some directions than in others (Somerville et al., 1997).

In addition to these constraints, there is ample evidence that slip in earthquakes is a strongly spatial variable (Mai and Beroza, 2002; Somerville et al., 1999; Andrews, 1980). Because the excitation of ground motion by the earthquake source is dependent on the spatial variability of slip, efforts to predict strong ground motion from future earthquakes will probably involve source models that are described stochastically. Owing to the inability, at least for the foreseeable future, to predict the spatial variation of slip on faults, seismologists should opt for multiple realizations of stochastic slip models in describing future earthquake sources. A stochastic description of fault slip for scenario earthquakes should merge naturally with existing probabilistic descriptions of earthquake hazard. Collaboration with the geographic information science community could help to increase understanding of spatial variability in the modeling.

Earthquake Simulation

To date, most efforts to simulate the earthquake source have been kinematic, in that the rupture characteristics are constructed to be consistent with past earthquakes, with little regard for the physics of the rupture process (Aki and Richards, 1980). Improved simulation of near-fault ground motion will require considering dynamic effects on the earthquake source. Such physically based ground motion simulations could be significantly better than simulations based on kinematic models. Dynamic models differ significantly from kinematic models in their effects on strong ground motion in the near-fault regime because slip amplitude, rise time, the slip velocity, and the rupture velocity are correlated and spatially variable (Guatteri et al., 2003). This means that the directivity effect, for example, will depend not only on the position and the rupture velocity but also on the spatial and temporal evolution of the rupture.

Path Effects

Path effects—that is, the modification of the seismic wavefield as it propagates through the complex crust of the earth—have a strong, often dominant influence on strong ground motion. As a first approximation, the strongest variation of velocity with position in the earth is an increase in velocity with depth. In the earth's crust, however, this assumption is often incorrect, particularly in the tectonically active environments in which earthquakes occur, because active tectonics naturally leads to complex geologic structures. Large urban environments are often situated above these structures. To cite a specific example, the Los Angeles metropolitan area is built atop several large sedimentary basins. During earthquakes, seismic waves become trapped and amplified by such basins, resulting in strong ground motion of long duration and strong spatial variation in amplitude, which can substantially increase the seismic forces on structures and lifelines (see, for example, Borcherdt, 1970; Phillips and Aki, 1986; and Trifunac et al., 1994). Moreover, near the edges of such basins, complex interference effects can greatly amplify ground motion relative to what it would have been in the absence of edges and basin effects (Bard and Bouchon, 1985; Aki, 1988).

While the three-dimensional structure of the earth's crust is complex, it is fixed in time for the purposes of predicting strong ground motion. That is, when two different earthquakes occur in the same area, the waves propagate through and are modified by the same structure. Moreover, the mechanics of seismic wave propagation in three-dimensional elastic media is well understood. So, at face value, the problem would seem to be straightforward. The challenges, however, are substantial. The true three-dimensional structure of the earth's crust is incompletely known, and it is impractical to gather enough data to characterize it completely. Thus, the ability of seismologists to estimate with precision the effects of three-dimensional earth structure on the strong ground motion prescribed in a scenario earthquake currently is limited to frequencies below about 0.5 to 1 Hz and even then only in areas that have been well researched and characterized (Graves, 2002). A sustained effort will be required to map the three-dimensional structure of the earth's crust in seismic urban regions and to use this information to develop high-fidelity predictions of strong ground motion from scenario earthquakes. Currently, in the absence of such predictions, engineers use historical earthquake records of appropriate magnitude that are rich in the frequency range of interest (i.e., the resonant frequency of the structure under analysis) and apply attenuation relationships to determine peak acceleration values and scale the records to those peak values. This process, while not analytically rigorous, is appropriately conservative and allows engineering design to proceed.

A large part of the research in this area will take place outside the NEES research effort. While NEES will play a significant role, effective partnerships with seismological research centers and observational programs such as the Advanced National Seismic System (ANSS) will be essential (for example, ANSS will provide strong motion recordings of future earthquakes that will form the observational foundation for performance-based design.). To model wave propagation at frequencies in excess of 1 Hz, seismologists will likely have to turn to stochastic representations of the heterogeneities within the earth's crust or to a stochastic representation of the wavefield itself. Ultimately, improved prediction of ground motion based on the physics of the site and wavefield will be coupled with engineering design requirements. This will permit the current conservatism of the design process to be reduced and will result in improved performance at lower cost.

Wave Effects

Seismic waves are often referred to as elastic waves, but anelastic effects due to energy losses (e.g., interparticle friction), which give rise to the attenuation of seismic waves, cannot be neglected. The effect of attenuation on strong ground motion is profound, because the same soft materials near the earth's surface that lead to strong amplification of ground motion can also lead to rapid attenuation (Aki and Richards, 1980). The net effect on the level of ground motion is complex because of elastic and anelastic effects. To predict strong ground motion, seismologists and engineers will have to characterize and account for anelastic wave effects in the earth's crust. Again, research efforts in this area will probably require partnerships between NEES and seismological research centers so that time-series data on an actual earthquake can be recorded as it occurs and made available for NEES experimental and testing purposes.

Site Effects

Site effects are, in a sense, a specific example of path effects; they refer to the effects on ground motion when seismic waves interact with the complex geological environment in the shallowest 100 or so meters of the earth's crust. The low seismic velocities and impedances in shallow sediments can lead to extremely large and locally varying amplitudes during strong ground motion (Seed and Idriss, 1982; Rosenblueth and Meli, 1986). Moreover, in this domain, wave propagation during strong ground motion is often nonlinear, with large-scale damage to geologic materials themselves, which in turn can lead to (for example) strong, amplitude-dependent attenuation effects (Finn, 1988; Field et al., 1997). In saturated, cohesionless soils, the change in excess pore water pressure during earthquakes can approach or equal the effective vertical stress, causing liquefaction, which in turn can lead to large and sudden changes in the behavior of surficial soils (Seed and Idriss, 1982; Youd and Garris, 1995), including excessive deformation, which could threaten the integrity of structures built on these soils. Even in the absence of liquefaction, transient increases in pore pressure can lead to profound changes in strong ground motion. The NEES geotechnical facilities will be essential for studying the response of typical near-surface materials to strong ground motion inputs and developing soil-improvement techniques to mitigate this phenomenon.

Soil-Foundation-Structure Interaction

Earthquake ground motion varies considerably, both in amplitude and duration, from one location to another within a seismic region. This variation is due to the complexity of the source, the propagation path, and site effects. Improved understanding of such effects through observation and simulation can contribute greatly to the elucidation of important issues raised by recent earthquakes—for example, Why do similar buildings in a region have such different amounts of damage, even when they are sometimes located at nearby sites? How do directivity of the seismic waves, permanent displacements, and other near-fault phenomena affect different structures? How do the damaging features of blind faults differ from those of faults with surface rupture? How does the structural vibration affect the free-field ground motion? These issues would benefit from having seismic zones and microzones for an urban region that allow predicting regional impacts.

One manifestation of the interaction that takes place between a structure, its foundation, and the surrounding soil is the fact that a vibrating structure can generate its own seismic waves, which in turn affect the free-field ground motion. In fact, several well-known aspects of soil-structure interaction, including the two interactions described in what follows, are of primary importance to earthquake engineering and engineering seismology. First, the response to earthquake motion of a structure founded on a deformable soil can be significantly different from the response of the same structure on a rigid foundation (rock), mainly through an increase in natural periods, a change in the amount of system damping due to wave radiation and damping in the soil, and modification of the effective seismic excitation (see, for example, Jennings and Bielak, 1973; Veletsos and Meek, 1974). In certain cases, for large or elongated structures like dams, buildings with large dimensions, and bridges, it may be desirable to know the spatial distribution of the ground motion rather than the motion at a single location. However, the benefits of such geographically precise data must be weighed against the cost of obtaining them.

Second, the motion recorded at the base of a structure or in its vicinity can be different in important details from the motion that would have been recorded if there were no building. This effect can be significantly magnified if there are a number of structures in the same general vicinity, in which case the recorded motion can be affected by the presence of the structures—it might, for example, exhibit an elongated duration and increased or decreased amplitude due to diffracted surface waves generated by the structures (Borcherdt, 1970; Wirgin and Bard, 1996). The amplitude of this diffraction and of soil-structure-foundation interaction in general can be pronounced when stiff structures rest on soft soils. Forced-vibration tests of a nine-story structure in the Greater Los Angeles Basin showed that this diffracted wavefield could be significant up to large distances, even for stiff soils (Jennings, 1970). Despite this evidence and the practical importance for earthquake engineering, little work has been done to explain this effect or to quantify it predictably.

To model with greater reliability soil-foundation-structure interaction effects during strong earthquakes, integrated models that incorporate the structure, the surrounding soil, and more realistic, spatially distributed seismic excitation must be developed. This effort will require close collaboration between engineers and seismologists. The participation of NEES in this area will be particularly advantageous.

Ground Motion Prediction

The prediction of strong ground motion in future earthquakes is currently carried out primarily by applying attenuation laws, or parametric scaling relations (e.g., Abrahamson and Silva, 1997). These relations link parameters describing the seismic source, such as the magnitude, and the location of a site with respect to that source, to ground motion data sets characterized by a simple measure of ground motion severity, such as the spectral acceleration at a given period and damping. The current scarcity of strong motion data at short distances from the epicenters of large earthquakes means that there are not enough data to represent the near-field hazard from the most dangerous events. Computer simulation provides a way to fill this gap in the data. To fulfill the expectation of performance-based engineering, structural engineers will probably require full time histories of ground motion. This requirement suggests that a simple extrapolation of attenuation relations to larger-magnitude earthquakes will not suffice and that a combination of improved observations and large-scale simulation will be important for making progress in this area.

TSUNAMIS

Tsunami Generation

Tsunamis are generated by seismic fault displacements of the seafloor, landslides triggered by earthquakes, volcanic eruptions, or explosions. All of these generation mechanisms involve a displacement of the ocean boundary, either at the seafloor, at the shoreline, or at the water surface. Since at the present time seismic data alone cannot define the important wave generation characteristics of these various tsunami sources, real-time deep water tsunami data are essential to forecasting tsunami impacts and providing critical boundary conditions for numerical models of their coastal effects. The generation sites include oceans, harbors, lakes, reservoirs, and rivers. The run-up and inundation associated with tsunamis cause loss of life, destruction, and economic losses. ("Run-up" as used herein is defined as the maximum vertical excursion of the tsunami above mean sea level when the tsunami has propagated the farthest inland.)

Historical Impacts

Since 1992, 16 lethal tsunamis have occurred in the Pacific, resulting in more than 4,000 fatalities (NOAA, 2003). The tsunamis in all of these events struck land near their source, so little warning time was available. Of course, losses from offshore earthquakes occurring near the coast are not limited to the coast closest to the source. For example, the Chilean tsunami of 1960 caused loss of life and damage not only near the source in Chile but also thousands of kilometers away in Hawaii and Japan. Thus, ironically and unfortunately, scenic coastal areas that are preferred resi-

FIGURE 2.2 A view of damage in Aonae, a small town on Okushiri, an island in the Sea of Japan, from the 1993 Hokkaido tsunami and related fire. Photo courtesy of Commander Dennis J. Sigrist, acting director of the International Tsunami Information Center.

dential sites have been frequent and vulnerable targets for seismically generated sea waves from near and distant sources.

Between 1992 and 1994, the Nicaraguan tsunami, the Flores Island tsunami (Indonesia), and the Hokkaido tsunami (Japan) caused devastating property damage and many deaths. The measured run-up from several of these events was about 30 meters. In 1994 alone, four additional tsunamis occurred: at East Java (Indonesia), Shikotan Island (Russia/Japan), Mindoro (Philippines), and Skagway (Alaska). In the latter half of the 1990s, there were several more large tsunamis: the Peruvian tsunami in 1996, the Papua New Guinea tsunami in 1998, the Vanuatu and Turkey tsunamis in 1999, and the tsunami in Peru in 2001. Figure 2.2 shows the damage inflicted by the 1993 Hokkaido tsunami on Aonae, a small town on Okushiri, an island in the Sea of Japan.

Although the majority of the tsunamis during the 1990s were caused by seafloor displacements, at least three—the Skagway, the Turkey, and the Papua New Guinea tsunamis—are suspected (or known) to have been caused by land subsidence and/or landslides. The Papua New Guinea tsunami killed more than 2,000 people and completely destroyed three villages. Primarily because of these tsunamis, in recent years research on the modeling of landslide-generated sea waves has been intensified.

Similar landslide-generated waves can occur in bays, estuaries, rivers, lakes, and reservoirs. An example of an impulsively generated wave that occurred some distance inland from the sea is the one that resulted from a subaerial landslide—that is, a slide above the still water level—in the reservoir of the Vaiont Dam located in the Dolomite region of northern Italy in October 1963. The slide generated a wave that overtopped Vaiont Dam and killed 2,000 people downstream. The wave generation mechanism was a slope failure without an earthquake. Thus, the investigation of the tsunamis generated by subaerial and submarine earthquake-induced landslides has wide application for engineering design and hazard management planners.

Although most of the tsunamis during the 1990s described above occurred at locations along the Pacific Rim and did not affect our nation's coast, the United States is certainly not immune to distant or nearshore events. For example, the Alaska earthquake and tsunami of 1964 and the Chilean earthquake and tsunami in 1960 caused damage and loss of life along the Pacific west coast from Alaska to California as well as in Hawaii. Approximately 120 people lost their lives in the Alaska tsunami of 1964, and the estimated damage from that event along the West Coast and in Hawaii was about $600 million in current dollars.

Tsunamis in Waiting

It is well known that the Cascadia subduction zone off the Washington-Oregon-northern-California coast is a potential source of giant earthquakes and tsunamis. Indeed, past land subsidence and landward sand deposits postulated as being due to tsunamis provide geological evidence for Cascadia subduction zone events (e.g., Atwater, 1987). In addition, Satake et al. (1996) reported that several historic Japanese documents described coastal flooding on the east coast of Japan in 1700; they suggested that this flooding was caused by a tsunami generated by a Cascadia earthquake of magnitude 9. It is interesting that the size of this tsunami was consistent with a Native American legend of an earthquake and large wave striking and flooding the Washington coastal area (see, e.g., Heaton and Snavely, 1985). A major rupture at this subduction zone would create havoc in coastal cities along the West Coast of the United States.

McCarthy et al. (1993) suggested that landslides in the sediment stored at the heads of the numerous submarine canyons along the California coast in close proximity to the shoreline could generate tsunamis in the event of an earthquake. These nearshore canyons just seaward of relatively densely populated areas—for example, offshore of Port Hueneme, Redondo Beach, and La Jolla in southern California—accumulate sediment at their nearshore heads by normal wave activity along the coast. An earthquake occurring near these canyons could cause massive underwater landslides, generating tsunamis very near the coast with little warning time.

Numerical simulations have been employed worldwide for some years to evaluate the onshore effects of tsunamis generated nearshore and those generated far off. Recently, Borrero (2002) investigated the potential tsunami hazard to southern California using such a numerical simulation. Wave generation due to tectonic uplift or downthrow of the ocean bottom and submarine landslides near the coast was modeled. (In the downthrow simulation, damage was studied from a tsunami generated by an underwater avalanche resulting from the rupture of the Palos Verdes fault.) The results of this numerical model using a nearshore submarine landslide as a tsunami generation mechanism suggested that about 75,000 people would be in danger locally and that the operation of the ports of Los Angeles and Long Beach would be significantly affected by tsunami inundation. In addition, Borrero (2002) estimated that the economic loss suffered by the ports as a result of such an event (including the immediate damage, the associated repair and replacement costs, and the economic impact of the changes to the modes of transportation of goods) could be between $7 billion and $40 billion. Although this damage estimate certainly gives cause for concern, it should be realized that, in addition to the uncertainty associated with various economic estimates, the estimate is based on a single numerical tsunami propagation model—that is, one of a number of models that are currently available here and overseas (notably Japan).

Mitigation Measures

At a number of sites in Japan, seawalls have been constructed near the shoreline to minimize the inundation area created by tsunamis. Tsunami mitigation measures in Japan also take the form of land use management and a districtwide warning system. For example, a 10-meter-high tsunami seawall was built at Taro, Japan (a small fishing village in the Sanriku district northeast of Tokyo), shoreward of its fishing harbor, where residences and businesses seaward of this tsunami seawall are protected from storm waves by a much lower breakwater. With adequate warning of an approaching tsunami, the population seaward of the tsunami seawall is evacuated to the town. A different approach was taken to protect the city of Ofunato, also on the east coast of Japan's Honshu Island, which was flooded and significantly damaged by the Chilean tsunami in 1960. As a result of that event, a massive offshore breakwater was built at the entrance to Ofunato Bay. This tsunami breakwater functioned as designed and protected the city from damage due to a locally generated tsunami in 1968.

In the United States, the construction of coastal seawalls or massive offshore breakwaters for tsunami hazard mitigation is not a realistic approach, given the historic infrequency of serious tsunamis. Instead, the approach taken by the National Oceanic and Atmospheric Administration (NOAA), the agency responsible for the nation's tsunami warning system, is to estimate potential inundation zones along the coastline of the western states, Alaska, and Hawaii. (NOAA has launched a comprehensive effort to accomplish this.) Once inundation zones are defined, emergency preparedness authorities can determine evacuation routes and routes for search and rescue, while planners can develop priorities for measures such as the relocation of critical and high-occupancy facilities as well as for providing information to coastal residents. (For real-time warnings, NOAA currently uses real-time tsunami data from the deep ocean and from coastal sensors as well as real-time seismic data in concert with numerical models to forecast tsunami coastal impacts.)

An example of this approach to tsunami hazard mitigation is that taken for Hilo, Hawaii. Hilo sustained significant damage from tsunamis associated with the Aleutian Islands earthquake of 1946, the Chilean earthquake of 1960, and the Alaska event in 1964. The economically acceptable solution for protection against similar tsunamis was to create a buffer zone near the coast at Hilo that encompassed the area that had been inundated in 1960. Coupled with a tsunami warning system, this approach has proved effective up to now. However, simply using the inundation region from a past event as a basis for a mitigation program for future events is not prudent. Tsunami protection must be based on a careful application of an accurate numerical model that can predict runup and the extent of inland inundation at the site of interest on the basis of rational scenarios using realistic sources of tsunamis.

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 and warning and the evaluation of coastal effects, can, in the long run, significantly reduce the catastrophic consequences of these events.

Knowledge Gaps

In addition to defining the extent of the run-up and the zones of inland inundation for a given site, the expected number of casualties and property damage within the tsunami inundation zones for a given event must be estimated. The run-up tongue traveling onshore can be several meters thick, moving with velocities of several meters per second, which would cause considerable damage if such a wave struck coastal structures and ports. Hence, site-specific tsunami run-up patterns, that is, the variation of the run-up along the shoreline at a given location, must be predicted.

Tsunami-induced forces on coastal structures and scour effects of the waves at the location of interest also must be determined. Some of the damage on the island of Okushiri (Japan) caused by the 1993 Hokkaido tsunami can be attributed to a perhaps unexpected aspect of tsunami-induced forces—namely, the inundating wave toppled home fuel storage tanks mounted on supports above the ground, contributing to massive fires that caused significant damage in addition to that caused directly by wave inundation. Wave-induced forces can consist not only of the forces associated with the waves impacting structures but also of the impact forces of large debris, such as cars, trees, and poles that are transported by the waves. These become waterborne missiles that can impact and destroy structures in their path. Therefore, an important engineering problem is the determination of tsunami-induced forces to enable better design of coastal structures such as breakwaters, seawalls, docks, buildings, cranes, and so forth and to guide the decision-making process for land-use issues.

In addition to estimating the forces, it is important to understand the interaction of tsunamis with groups of structures to assist in planning. For instance, when a tsunami strikes a group of buildings, the spacing between buildings is critical. If they are too closely spaced, the interaction of structures with the attacking wave may produce a choking effect. In that case, the forces on any one structure might be much larger than that acting on the same structure if the structures were spaced further apart.

As a tsunami approaches the shore, coastal embayments and harbors could be resonantly excited by these nonlinear, transient, translatory long waves. The nonlinear aspects of the problem were investigated theoretically by Rogers and Mei (1977), Lepelletier and Raichlen (1987), and Zelt and Raichlen (1990). In the latter two investigations, experiments were conducted using a solitary wave (a single wave with its total volume above the still water level) as a model for a tsunami approaching simple harbor shapes in a direction orthogonal to the entrance. Additional research is necessary to investigate the resonant characteristics of single and coupled basins exposed to groups of transient, translatory, nonlinear long waves approaching the shoreline perpendicularly or obliquely. This research should also include the effect of waves trapped on the continental shelf. (Trapping of waves on the shelf and in harbors and bays as well as the reflection of wave energy from shorelines around the ocean's perimeter are the major reasons for the "ringing" of nearshore waters. This phenomenon may last for days after excitation by a tsunami that consisted of a series of waves lasting only tens of minutes.)

The challenge for tsunami hazard mitigation is to provide a real-time description of tsunamis at the coastline for warning, evacuation, engineering, and mitigation strategies. This can best be accomplished by means of a complete numerical simulation of tsunami generation, propagation, and coastal effects that is experimentally verified and, if necessary, combined with selected real-time tsunami data. The numerical simulation, on a regional scale, must be three-dimensional at the coast and must include the following essential features: the possibility of breaking waves as the tsunami approaches the shoreline, energy dissipation associated with boundary shear stresses and with wave breaking, run-up and run-down on the shore (including beaches and cliffs), wave–structure (and structure–wave) interactions, and sediment transport, (that is, local scour and deposition). Since the numerical model must also take into account the source region for both distant and nearshore tsunami generation, the source location, type, shape, and displacement-time history must be defined for such diverse events as tectonic seafloor motions, volcanic eruptions, explosions, and landslides (submarine, partially subaerial, and subaerial). In the case of nearshore underwater landslides, since the warning time to coastal communities may be short, the mitigation effort could include offshore instrumentation that would be triggered by the slide and coupled with the simulation to yield a realistic warning system for coastal evacuation.

GEOTECHNICAL ENGINEERING

Soil Failure and Earthquake Damage

Subsurface soil properties substantially affect the performance of constructed facilities and lifelines during earthquakes. Yet these materials are typically the most variable, least investigated, and least controlled of all materials in the built environment. As earthquakes have repeatedly borne out, more damage occurs in areas of weaker soil, and significant losses are often associated with earthquake-related problems such as liquefaction, soil amplification of ground motion, landslides and slope failures, fault displacement/offsets, and seismically induced instability of geotechnical structures (e.g., earthen dams, embankments, waste fills). It is instructive and encouraging to note that recent experience shows that proper engineering procedures, especially ground improvement, can mitigate earthquake-related damage and reduce losses. However, although great strides have been made in the past two decades to improve predictive capabilities and seismic engineering design practices, there remains an urgent need for improved modeling procedures and predictive tools, more powerful site-characterization techniques, and more quantitative guidelines for soil-improvement measures. The behavior of the soil is key to the design of structures. Facilities and lifelines in seismic environments—especially structures constructed of, founded on, or buried within loose, saturated sands, reclaimed land, and deep deposits of soft clays—are vulnerable to earthquake-induced damage. Soils of the types mentioned are common around marine and alluvial depositional environments, where many large cities are founded. Several urban centers in seismically active regions rely on reclaimed land areas to support industrial facilities, airports, and port and shipping facilities. For instance, in the United States, a significant percentage of the major port and shipping facilities on the West Coast are on reclaimed land, and all San Francisco Bay Area airports are on alluvial or reclaimed areas. A significant portion of Silicon Valley rests on a deep sedimentary basin. Under earthquake loading, the saturated, cohesionless soils commonly found in alluvial deposits or man-made land can lose strength, liquefy, and undergo large permanent deformations. Deep deposits of soft clays are especially prone to magnifying the amplitude and lowering the frequency content of an earthquake's ground motion, a condition that often results in greater damage to a structure, especially if the soil resonates with the structure.

Landslides

Landslides are a nationwide hazard, with direct and indirect costs estimated at between $1 billion to $2 billion a year (USGS, 2003). Landslides can be triggered by many factors, including earthquakes, large amounts of precipitation, and soil erosion. Factors like these contribute to massive slope failures, which in turn block roads or highways, interrupt or damage communication systems, destroy homes, divert or block waterways, and cause loss of life. A landslide triggered by the 1994 Northridge earthquake even led to an outbreak of coccidioidomycosis (Valley fever) that claimed three lives, or 4 percent of the total earthquake-related fatalities (Jibson et al., 1998).

The association between poor soil conditions or weak natural slopes and increased earthquake damage has been noted throughout history (e.g., in the San Francisco earthquake of 1906). However, it was not until the occurrence of a series of catastrophic and spectacular landslides during the Alaska earthquake of 1964 and extensive liquefaction in the Niigata, Japan, earthquake of 1964 that geotechnical engineers became actively engaged in understanding these phenomena (Idriss, 2002).

Liquefaction

Ground failure and permanent deformations due to liquefaction are pervasive forms of damage during earthquakes. The Niigata earthquake of 1964 provided the first well-documented modern example of the detrimental effects of liquefaction in an urban environment. Damage to buildings was widespread and pervasive, and it was shown that lifelines, especially bridges and buried utilities, were particularly vulnerable to such damage. Figure 2.3 shows the dramatic and catastrophic effects of liquefaction on large, well-constructed buildings. More recent events, such as the Loma Prieta earthquake of 1989 and the Kobe, Japan, earthquake of 1995 provide similar lessons. During the 1989 Loma Prieta event, large fires broke out in the Marina district of San Francisco as a result of liquefaction-induced ground movements that ruptured gas lines. Water lines

FIGURE 2.3 Foundation failures resulting from liquefaction, 1964 Niigata, Japan, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

FIGURE 2.4 Embankment failure due to liquefaction at the Lower Van Norman Dam, 1971 San Fernando, California, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

were also broken, leaving the city vulnerable to fire—almost a repeat of the scenario from the San Francisco earthquake of 1906, when much of the city burned. The direct damage from the Kobe earthquake of 1995 is estimated at $30 billion; more than half of this amount was the result of liquefaction-related damage. Earth structures such as dams and dikes or levees constructed of liquefiable materials are also vulnerable to this behavior. The near failure of the Lower San Fernando Dam (see Figure 2.4) during the San Fernando earthquake of 1971 offered an excellent case history of the seismic performance of embankment dams constructed on and of liquefiable materials. In fact, the most common problem leading to the instability of embankment dams in a seismic environment is the presence of liquefiable soils in the dams themselves or in the foundations on which they rest (Marcuson et al., 1996).

Soil Improvement Measures

Recent case histories have indicated that soil improvement can be effective in mitigating earthquake-related damage, especially liquefaction

(Mitchell and Martin, 2000; Hausler and Sitar, 2001). The Loma Prieta earthquake of 1989, the Kocaeli and Duzce earthquakes in Turkey in 1999, the Chi-Chi, Taiwan, earthquake of 1999, and the Nisqually earthquake of 2001 near Seattle have provided valuable field data on the performance of improved ground during strong ground shaking. The findings from these events show that less damage occurred at the improved sites than at nearby unimproved sites. The earthquakes in Turkey were particularly important because a wide range of well-documented improved sites were strongly shaken.

Although much progress has been made with respect to soil improvement, there is a critical need to learn how to prevent liquefaction and how to mitigate its effects in a practical and cost-effective manner. Current methods are largely qualitative, with few specific quantitative, performance-based guidelines. Also, ground modification under existing structures is often expensive, with the degree of improvement and cost being sensitive to the desired degree of expected performance. Further, verification of treatment in the ground is still an open issue—for example, What procedure should be used to determine the area of improvement and the postimprovement soil properties developed by the installation of stone columns in silty soils? More research is needed on new and advanced ground-improvement and foundation technologies and materials, including the full use of existing and new tools to measure the in situ properties of the improved ground and to then predict and verify the expected performance. As more data sets become available, the level of uncertainty in the effectiveness of mitigation will decline and cost effectiveness will increase.

In contrast to the increasing number of successful case histories for buildings, bridges, ports, or oil storage tank sites on improved ground, there have been few documented case histories for the earthquake performance of an embankment dam with an improved section or an improved foundation. One notable exception is the Lake Chaplain South Dam, improved with stone columns in the toe prior to the 2001 Nisqually, Washington, earthquake (Hausler and Koelling, 2003). Although no seismograph recordings are available at this site, peak ground acceleration was probably about 0.16 g and sufficient to damage a brick masonry inlet structure. No cracks, deformations, or evidence of piping were found in or around the dam after the earthquake. It is critical that engineers do no harm when making seismic improvements to an existing dam. It is counterproductive to improve the seismic performance of a structure and degrade the performance of the same structure during normal operating conditions.

Amplification of Ground Motion

Aside from their propensity to cause ground failure, poor soil conditions are often correlated with damage because of their tendency to amplify ground motions and/or promote resonance with overlying infrastructure. One of the earliest engineering studies of this phenomenon followed the Caracas, Venezuela, earthquake of 1967, in which the damage pattern to low-rise buildings and individual houses correlated well with local site conditions (Seed et al., 1970). A more spectacular example of soil-related motion amplification occurred during the Mexico City earthquake of 1985. The earthquake was centered more than 400 km from the city, and bedrock motions in Mexico City were almost negligible. However, since much of the city is founded on deep, soft soils (Lake Texcoco sediments), these soils amplified the motions and modified the frequency of ground shaking. Owing to the unique combination of the shaking frequency of the soil deposit and the prevalent height of the buildings in the area, the structures experienced strong resonance and were subjected to motions far above their design loads. Widespread damage and collapse of buildings occurred, killing more than 8,000 people and leaving 50,000 homeless. Although less dramatic, similar behavior led to the collapse of sections of the Cypress freeway in Oakland, California, during the Loma Prieta earthquake of 1989 (see Figure 2.5). The collapse of the freeway section accounted for 42 of the 63 deaths caused by this earthquake. Ground shaking in these areas, underlain by soft soils, was greater than the shaking in nearby surrounding areas founded on shallower, stiffer soils.

The significant increase in damage potential due to soft soils calls for a better understanding of how local soil conditions modify seismic shaking and how these conditions can be identified, designed for, and/or modified. This understanding will be especially important for the improvement of seismic engineering codes and the development of simplified procedures for achieving economical and safe designs. NEES efforts in this area will need to be supported by a substantial field data collection effort.

NEES represents an unprecedented opportunity to reduce earthquake damage attributed to soil conditions by addressing critical shortcomings in our engineering knowledge and advancing our ability to share and disseminate lessons learned. At the same time, NEES would provide mechanisms to achieve the types of research results that are needed for advancement of the growing trend of performance-based engineering analyses.

FIGURE 2.5 Collapse of the Cypress Avenue Freeway, 1989 Loma Prieta, California, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

BUILDINGS

The Loma Prieta earthquake in 1989 (EQE, 1989), the Northridge earthquake in 1994 (Mahin, 1998), and the Kobe earthquake in 1995 (Scawthorn et al., 1995) illustrate that despite advances in seismically resistant design in recent years, we must develop a better understanding of the behavior of building systems to ensure that new buildings are designed and old buildings are retrofitted to reduce their vulnerability to excessive damage and large economic losses during earthquakes. Priority issues in building-related earthquake engineering research include prediction of the seismic capacity and performance of existing and new buildings, evaluation of nonstructural systems, performance of soil-foundation-structure interaction systems, and determination of the performance of innovative materials and structures.

Prediction of the Seismic Capacity and Performance of Existing and New Buildings

Perhaps the greatest overall seismic risk in the United States is the severe earthquake damage (including collapse) to existing facilities and

FIGURE 2.6 Structural damage to masonry building resulting from the 1994 Northridge, California, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

lifelines designed without consideration of earthquake effects. Some building types are particularly vulnerable in this regard, including unreinforced masonry (URM) buildings, concrete-framed buildings, concrete wall "tilt-up" industrial buildings, precast concrete buildings, certain types of steel-framed buildings, and many pre-1975 structures, including wood-framed houses, apartments, and commercial buildings. Figure 2.6 shows structural damage to an unreinforced masonry building during the Northridge earthquake. Depending on their age, storage tanks, buried and aboveground pipelines, and bridges may also be excessively vulnerable. Therefore, it is imperative to develop tools to identify existing facilities and lifelines that are unacceptably vulnerable to damage and implement cost-effective upgrades for them. Historic buildings pose a special challenge for seismic retrofit because of the limitations placed on physical modification of the structure and the difficultly of testing structurally equivalent systems and components. Addressing earthquake vulnerability is generally less expensive and more straightforward for new construction than for existing buildings and lifelines. Implementing seismic design measures in new construction is generally far less complicated than retrofitting existing buildings and lifelines, and there are more opportunities to save money early in the process—that is, during the planning, siting, and design phases.

Evaluation of Nonstructural Systems

The majority of direct economic losses in buildings result from damage to nonstructural systems, as opposed to structural systems. Even in earthquakes with minimal structural damage, nonstructural damage can be substantial, as was the case in the Nisqually earthquake of 2001 near Seattle (Pierepiekarz, 2001). Figure 2.7 shows a common type of nonstructural damage experienced during earthquakes. Leaks and spills of hazardous materials from inadequately braced piping or fluid tanks can threaten the health and safety of emergency responders as well as individuals located in a wide area around a damaged building. The behavior of nonstructural components, such as architectural cladding, internal partitions, and utility distribution systems, and their interactions with buildings are complex phenomena. To understand adequately and to better model these interactions, full-scale models of buildings need to be devel-

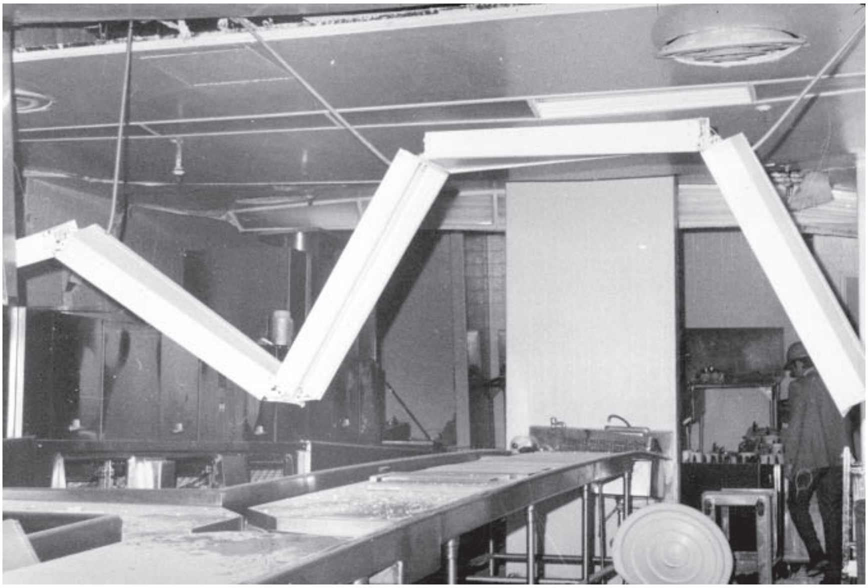

FIGURE 2.7 Nonstructural building damage at the Olive View Medical Center experienced in the 1971 San Fernando, California, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

oped and tested, with accurate representation of both structural and nonstructural components. The response of nonstructural elements in both as-built and retrofitted buildings can be measured and detailed cost-benefit analyses can be performed to assist local building owners and building officials in determining the course of action that makes the best economic sense and protects public safety.

Performance of Soil-Foundation-Structure Interaction Systems

Soil-foundation-structure interaction (SFSI) can have a significant effect on the seismic performance of building structures. Testing needs to be performed on representative structures and foundation systems to represent adequately the demand on both the building and the foundation. At present, data on the response of building-foundation systems are scarce, and research needs include developing advanced analytical methods for predicting SFSI effects, conducting large-scale shake-table and centrifuge testing of SFSI mechanisms, developing practical methods for estimating SFSI effects, and incorporating these effects in the design of foundations and superstructures.

Determination of the Performance of Innovative Materials and Structures

Innovative materials and structures will include clever new uses and configurations of conventional materials and novel developments of smart materials and structures. The use of smart materials and structures is an emerging concept in mechanical, aeronautical, and civil engineering. Smart (“autoadaptive” or “intelligent”) structures have the ability to respond to internal and/or external stimuli by varying their shape or mechanical properties. Smart materials can be used in sensors or actuators. Examples of smart sensing materials include optical fiber, shape memory alloys, and microelectromechanical systems (MEMS). Examples of smart actuator materials include shape memory alloys, piezoelectric ceramics, and magnetorheological and electrorheological fluids. The integration of sensing–actuating capability within conventional materials or structural systems will lead to smart structural systems. While research in smart materials has been performed for many years, few structures in the United States are using this technology. The challenge to acceptance of innovations is to systematically evaluate the performance of innovative materials and structural systems. Full-scale tests of buildings with a variety of innovative materials and systems would lead to verification of the behavior of these materials and systems and, ultimately, their practical application. Cost-benefit analyses are needed to illustrate fully the relative benefits of the various technologies. Applications of innovative materials, including smart materials, to structural systems will provide new, cost-effective retrofit, repair, and rehabilitation alternatives.

LIFELINES

The United States is served by a complex transportation and utility infrastructure that includes highways, railroads, ports, airports, electric power transmission and distribution, communications, gas and liquid-fuel pipelines and distribution systems, and water and sewage systems. The mitigation of earthquake hazards for lifeline facilities presents a number of major problems, owing primarily to the vast inventory of facilities and their spatial distribution.

Moderate to strong earthquakes have the potential to cause widespread damage throughout an area to a single lifeline system. For example, consider that the 1994 Northridge earthquake and the Kobe, Japan, earthquake of 1995 damaged numerous highway and rail bridges, and the Kocaeli, Turkey, earthquake of 1999 nearly obliterated the water distribution network. In addition, lifeline system operation could also be affected by damage to codependent lifelines (e.g., a water system could be affected by electric power outages).

Since the San Fernando earthquake of 1971, much has been done to improve the understanding of lifeline vulnerability to earthquake hazards, to improve the engineering and construction of new or replacement facilities, and to retrofit existing facilities where the consequences of earthquake-related failures have been great enough to merit such action. For example, in 1987, an action plan was developed to address seismic hazards to lifelines (FEMA, 1987). In 1998, FEMA and the American Society of Civil Engineers entered into a cooperative agreement to establish the American Lifelines Alliance to facilitate the "creation, adoption and implementation of design and retrofit guidelines and other national consensus documents that, when implemented by lifeline owners and operators, will systematically improve the performance of utility and transportation systems to acceptable levels in natural hazard events, including earthquakes." Many utilities in highly seismic areas have implemented programs to replace system components that have been judged vulnerable to earthquake hazards such as ground shaking or soil failure. Much is left to be done, however, especially in seismic areas of the United States outside California, and NEES can provide the technical knowledge to support these efforts.

Lifelines are typically more vulnerable to earthquake hazards than conventional facilities, because there is less opportunity to avoid these hazards through prudent site selection or site improvement. Lifelines must provide connectivity to vast regions and thus cannot always avoid crossing landslide hazard areas, liquefaction zones, or faults. In many cases, lifeline routes were established 50 to 100 years ago, without special attention to earthquake hazards. Lifeline systems contain a wide variety of components that may be susceptible to damage from earthquake ground shaking (e.g., equipment, storage tanks, and structural components) and must be designed to withstand seismic inertial forces much as buildings are designed. Adding to their importance, many lifeline systems play vital roles in disaster recovery. For example, water systems are needed for firefighting, communications are needed for the coordination and administration of emergency response, and highway systems are essential for moving supplies, equipment, and people. A brief discussion of each lifeline system and its associated earthquake issues and vulnerabilities follows.

Highways, Railroads, and Mass Transit Systems

Many elements of highway, railroad, and mass transit systems are potentially vulnerable to earthquake hazards; historically, the most vulnerable element in highway transportation systems has been bridges. Most of the damage in past earthquakes was related to bridge spans being dropped from their supports as a result of inadequate bearings or seat widths or because of the nonductile behavior of substructures (e.g., bridge columns). Figure 2.8 depicts the failure of a span of the Nishinomaya Bridge during the 1995 Kobe, Japan, earthquake. Other notable earthquake-related failures include landslides, which can block or carry away highway segments and rail lines, and liquefaction-induced ground movements, particularly lateral spreading at river and stream crossings, which can cause bridge supports to fail. Pavements may also be damaged from liquefaction, embankment failures, or fault displacement. Figure 2.9 shows a section of highway damaged by fault displacement during the 2001 Denali earthquake. Railroads have generally experienced damage similar to that for highways. Elevated track structures collapsed in the Kobe, Japan, earthquake of 1995 because of the failure of reinforced concrete bridge columns. Other elements of highway, railroad, and mass transit systems that require attention to seismic vulnerability include signal, lighting, and control systems and support facilities such as freight handling, subway and rail stations, and maintenance facilities.

In summary, the principal earthquake hazards for highways, railroads, and mass transit systems are ground shaking, seismic wave propagation, and ground failure. Research is needed on several aspects of the response of bridge spans to seismic motions—namely, relative displacement of girder ends as a result of differential ground motion, the use of

FIGURE 2.8 Failure of a span of the Nishinomiya Bridge during the 1995 Kobe, Japan, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

FIGURE 2.9 Lateral highway offset of 2.5 meters as a result of the 2002 Denali, Alaska, Earthquake. SOURCE: Alaska Department of Natural Resources. Photo by Patty Craw, Division of Geological and Geophysical Surveys.

isolation bearings to mitigate the effects of near-field motion, the performance of reinforced-concrete bridge piers, and the prediction and characterization of liquefaction-induced ground movement at abutments. For subway tunnels in soft ground, there may be need to develop innovative, cost-effective techniques to anchor tunnels against liquefaction-induced flotation in loose marine deposits. There is also a need to develop designs for ground transportation systems that can withstand permanent ground displacements along faults.

Ports and Air Transportation Systems

Ports and air transportation systems move people, commodities, and products by sea, inland waterways, and air. Port facilities are located throughout the United States in seismically active areas and are typically susceptible to structural damage resulting from foundation failure, such as liquefaction-induced ground settlement or lateral spread and tsunami run-up and impact. The Kobe, Japan, earthquake of 1995 damaged numerous waterfront facilities, mainly through liquefaction of loosely placed fill materials. Airports and air traffic control facilities are vulnerable to earthquakes in much the same way that various types of buildings and industrial facilities are. The principal research needs for ports and harbors relate to assessing liquefaction potential, predicting lateral spread and settlement, including the effects on earth retaining structures and foundations of berthing structures and docks, and tsunami mitigation methods.

Electric Power Transmission and Distribution Systems

Electric power systems consist of power generation stations, transmission and distribution substations, transmission and distribution lines, and communications and control systems. Control systems are unique in that they must be able to respond almost instantaneously to system changes in order to maintain operation (Schiff and Tang, 1995).

With respect to the extent and duration of power outages, the overall performance of power systems in past California earthquakes has been good. In the most heavily damaged areas, power was restored more slowly, but considering that it would be unsafe to restore power quickly to areas that might have gas leaks, the standard of service has been generally acceptable. There has been damage to high-voltage substations (220 kV and greater), most of it from the breakage of porcelain components such as insulators. The size, and hence the fragility, of porcelain insulators increases with voltage, so the level of damage generally increases with voltage as well.

The most important research needs for electric power transmission and distribution systems relate to the vulnerability of porcelain insulators and rigid bus bars. Research directed at developing components with improved seismic performance is ongoing.

Communications

Communications systems comprise two types of communication networks: the public switched network and wireless networks. Both types consist of switching, transmission, and signaling (Schiff and Tang, 1995). Damage to communications equipment in past earthquakes was generally light, but there have been instances of circuit card packs becoming disconnected, emergency power generators malfunctioning when commercial power was lost, and damage to battery racks, heating, ventilation, and air conditioning (HVAC) systems, and computer floors. Buildings that housed the communications were severely damaged, but typically the equipment inside performed well. Most of the disruptions to communications came from the high volume of calls following earthquakes, a problem that must be addressed by system control software.

The telecommunications industry has addressed earthquake hazards by developing vibration and anchorage standards for equipment. Other concerns relate to seismic design and the strengthening of buildings, which are identical to the concerns discussed for buildings elsewhere in this report. (In light of the effects on wireless communications of the collapse of the World Trade Center towers on September 11, 2001, this issue may deserve additional attention.)

Gas and Liquid-Fuel Systems

Gas and liquid-fuel lifelines are the infrastructure for the transportation and distribution of crude oil, natural gas, and refined products. Seismic damage to gas and liquid-fuel lines can cause environmental damage and interrupt energy supply to the local area as well as to distant delivery points. Gas and liquid-fuel systems consist of pipelines, pump stations, compressor stations, communications and control systems and support facilities, storage tanks, process equipment, and sometimes marine terminals. The principal earthquake hazards include ground failure due to liquefaction or landslides, settlement, ground-shaking effects on aboveground facilities and equipment, and the surface rupture of faults.

The principal research needs unique to gas and liquid-fuel systems relate to soil restraint and/or loading on buried pipelines; the determination of compressive, postbuckling strain limit states; and the study of strain localization associated with pipe wrinkling under high compressive loads. Only a limited number of test facilities worldwide have the capability to conduct such test programs, and most are located outside the United States.

Water and Sewage Systems

Water and sewage systems provide critical services to our society. Water is essential for public health and well-being, firefighting, business and industry, and agriculture. Sewage systems are needed to provide sanitary disposal and maintain public health. Water and sewage systems consist of pipelines, pump stations, compressor stations, storage tanks and reservoirs, control systems, and water purification systems. The principal earthquake hazards include ground failure due to liquefaction or landslides, settlement, ground-shaking effects on aboveground facilities and equipment, and surface rupture of faults.

Water and sewage systems have been damaged by earthquakes. Most of the damage was to transmission and distribution pipelines in areas that experienced ground deformation as a result of liquefaction or fault rupture. Pipelines fabricated of brittle materials such as asbestos, cement, or concrete have experienced more failures than welded, ductile steel pipelines. Water treatment facilities also experienced damage, but much less than the damage to pipelines. The potential for the release of chlorine gas can be a significant safety concern at water treatment plants.

Water systems are especially important when earthquakes occur, because large quantities of water may be needed for firefighting in damaged localities. For example, both the San Francisco earthquake of 1906 and the Loma Prieta earthquake of 1989 damaged the municipal water system, impairing firefighting efforts. The fire that devastated San Francisco in 1906 in the aftermath of the earthquake is well chronicled. Fortunately, there was no wind on the evening of the Loma Prieta earthquake in 1989, and fires were more easily contained (Schiff, 1998).

One of the more important knowledge gaps for water and sewage systems is the response of large-diameter, thin-wall pipe to seismic wave propagation. Methods for improved characterization of soil-pipe interaction are also needed along with validation by full-scale testing.

Industrial Systems

For the purpose of this discussion, industrial systems encompass various commercial processes such as refining, manufacturing, fabrication and assembly, and material handling and cover a broad range of products such as chemicals, fuels, electronics, mechanical equipment, and commodities—essentially everything that is produced or consumed in the United States. Industrial systems consist of process equipment, buildings, tanks, vessels, piping, switchgear, motor control centers, instrumentation and control systems, material-handling systems, emergency power systems, fabrication and assembly systems, material storage facilities—the list is nearly endless.

Industrial systems are a source of employment and/or of vital products for a region and are vital to its economic health. In addition, certain industrial facilities might transport, handle, or produce hazardous materials that could be released as a result of earthquake damage. As with buildings, the principal earthquake hazard affecting industrial systems is ground shaking. Proper attention to building design, equipment anchorage, and seismic qualification of essential systems usually allows them to withstand seismic shaking with minimal damage or interruption in operation. Performance-based design approaches require the selection of appropriate design parameters that will achieve the desired result. Liquefaction or landslides may also affect industrial facilities, but these hazards normally can be handled on a site-specific basis through prudent location or foundation improvement.

In general, the principal research needs for industrial systems mimic those for buildings, with the addition of performance-based design criteria for operating systems within industrial facilities, similar to such criteria for critical equipment within some of the other lifeline areas—electric power, communications, and gas and liquid-fuel lifelines.

RISK ASSESSMENT

The challenge in risk assessment is to provide decision makers with accurate and understandable information on risk exposure and risk mitigation alternatives and with the tools that will enable them to make prudent decisions based on that information. The major obstacle to developing convincing risk assessments is the lack of good data regarding performance of the natural and built environment—this information must come from tests and field observations, which can then be archived and available via the NEES grid. More specifically, it is necessary to do the following:

- Develop methods for risk assessment that are comprehensive, based on sound scientific and engineering principles, and usable by a variety of stakeholders.
- Develop the foundation and tools for rational decision making that leads to risk reduction.
- Formulate a framework for risk-mitigation and risk-reduction policies that can be implemented by the public and private sectors.
- Establish adequate incentives for incorporating risk-mitigation

measures that will lead to reduced earthquake risk and mechanisms for incorporating these incentives in practice.

Although damaging earthquakes are infrequent events, their consequences can be profound. Decision makers are often complacent with respect to the earthquake hazard because a damaging earthquake may not have occurred during their lifetimes or where they live. They may neglect earthquake risks in city planning, building design, and lifeline design and operation. However, a strong earthquake can kill thousands, destroy buildings and infrastructure, interrupt the nation's production of critical products and services for a long period, cause national economic collapse, and interfere with national security. It is only through the application of prudent and persistent risk-assessment and risk-mitigation actions that these problems can be addressed adequately.

Risk assessment requires knowledge of the following types of problems:

- The likelihood of earthquake events, their size and location, ground shaking and ground failures throughout their influence area, and the likelihood of their causing tsunamis or seiches.
- Physical damage, with its direct consequences in terms of death, injury, loss of operational functionality, and destruction of property.
- Social and economic consequences of the direct physical damage, including losses from damage to buildings, lifelines, and other critical structures; homelessness; unemployment; collateral losses resulting from damage to critical facilities, such as the spread of chemical and bacteriological agents from industrial plants; losses from business interruptions, large-scale business failures such as in the property loss insurance industry, and losses of markets to international trade competitors; and impairment of national security capabilities.

Improved loss estimation models that support cost-effective earthquake mitigation measures will be a critically important output of NEES. These models will need to couple with practical decision tools that can be used by policy makers, regulators, and building owners to select appropriate mitigation strategies. The social and policy sciences will have a major role to play in shaping this aspect of NEES activities.

PUBLIC POLICY

A major challenge for the earthquake community, and one of the most important measures of NEES success, will be to have earthquake hazard mitigation placed on public, municipal, and legislative agendas.

Although the findings from research discussed in this report will advance the state of practice over time, the revolutionary changes that NEES is seeking will be achieved only through the aggressive development and implementation of policy. The adoption of policy measures, supported by state-of-the-art technology, will significantly increase our nation's ability to prevent major disasters and thus reduce their devastating economic and social consequences.

There is a strong case to be made for a holistic technical-social-economic approach to implementing earthquake mitigation measures. Petak notes that mitigation technology has advanced considerably over the years but deployment has not kept pace, even in earthquake-prone California (Petak, 2003). He believes one of the principal reasons for the lag in deployment is that many view earthquake risk reduction as a technical problem with a technical solution. However, even once a technology has been proven, it requires institutions and people to implement workable solutions. Figure 2.10 illustrates how the elements of such a system work together for effective decision making.

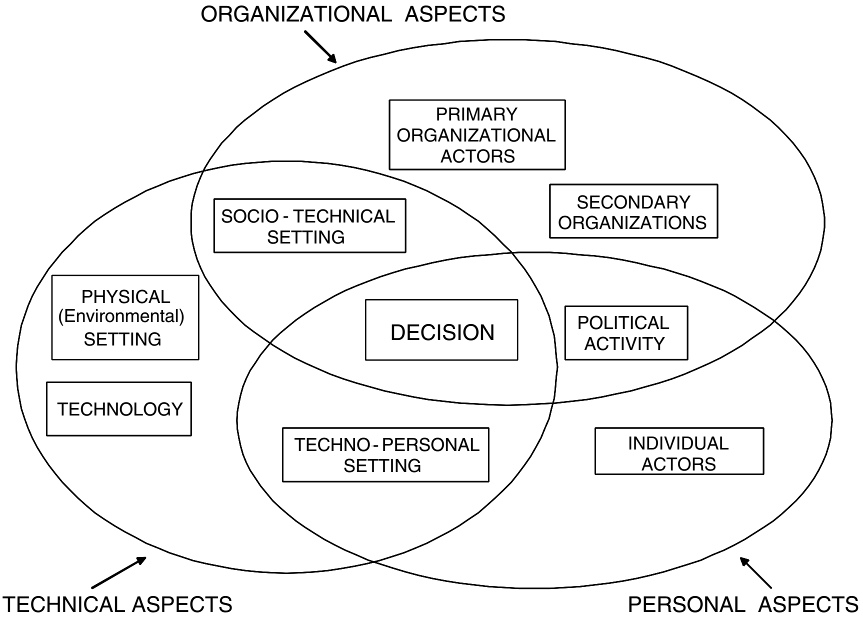

FIGURE 2.10 A sociotechnical system view for decision making. SOURCE: Linstone (1984).

One of the major difficulties in reducing the economic and social consequences of earthquakes is that policies for disaster mitigation and preparedness are generally inadequate to meet the challenge that disasters pose to a community. The many areas that must be addressed on the road to formulating and implementing disaster policy include the timeliness of the relevant policy; the education of decision makers; the education of stakeholders to obtain their support for introducing legislation; the identification of appropriate alternatives that are consistent with the risk exposure and the ability of a community to implement these policies; and the development of strategies for the implementing legislation. Issues of public policy that NEES activities can help advance are discussed below.

- *Getting on the agenda.* After any disaster, there is a clearing of the agenda of those directly involved, and it is in this "teachable moment" that long-term policy change is possible. The need is to be prepared to extend and take advantage of this teachable moment.
- *Understanding and addressing risks.* A community at risk needs to understand its risks in order to determine how to mitigate them and how to respond to emergency situations. The technical basis comes from integration of all the geologic, structural, and sociological data to plan for a realistic potential disaster. Knowledge from NEES and other NEHRP programs can define the earthquake hazard and simulate the vulnerability of community infrastructures. These simulations would provide a rational and understandable basis for public and private policy decisions on mitigation and preparedness.
- *Justifying the policies.* In formulating public policy, it is often necessary to undertake a cost-benefit analysis of the proposed policy or regulation. For a policy maker to advocate a potentially unpopular (or expensive) new hazard-mitigation policy requires a level of proof that is convincing to the policy maker and understandable to his or her constituency.
- *Defining alternatives.* Policy decisions on earthquake mitigation need to be informed by the best science and engineering available but ultimately will be shaped by community values. Better ways of integrating new technical knowledge with the decision-making process will require the collaboration of NEES researchers with the social and policy sciences. The decision tools thus developed would allow policy makers to differentiate among and evaluate alternatives.
- *Educating the public.* Most often, public policy is developed in response to public demand. The public is capable of making and influencing controversial (i.e., expensive) policy decisions, but only if people are sufficiently knowledgeable about the underlying issues and the alternative solutions and their implications.

- *Property rights.* In the United States, individual property rights are a fundamental constant in all zoning and land use decisions. It is difficult to deprive individuals (or companies) of their right to develop their property, even if it might be hazardous for them to do so. Overcoming this problem has been a challenge for planning agencies, the courts, and concerned citizens on both sides of the issue. However, if a community can be unified behind a decision to improve public safety through land use planning, the community can effect needed changes.

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3

NEES and Grand Challenge Research

THE VISION FOR NEES

This report is dedicated to the premise that the grand challenge of preventing earthquake disasters ultimately can be achieved. NEES seeks to contribute to this effort through a collaboration that will integrate theory, experimentation, simulation, computation, and data curation in earthquake engineering research. As previously described, NEES is envisioned as a geographically distributed collaboratory that will take full advantage of high-performance Internet connectivity to establish a virtual national facility, a "laboratory without walls," dedicated to earthquake hazard mitigation.

The NEES concept, illustrated in Figure 3.1, conveys a simple yet profound message—namely, that NEES will make possible the networked sharing of credible, standardized research and test data developed at myriad locations with researchers, teachers, analysts, and practitioners around the world. As such, NEES represents a new and ambitious approach for carrying out the research vital for vastly accelerated improvements in the seismic design and performance of the built environment, in the United States and around the world. However, there is also a deeper sense in which NEES will affect the course of earthquake engineering research.

The network capabilities required to make the NEES collaboratory a reality will create a community of networked investigators with both shared and complementary interests and expertise. Developing and en-

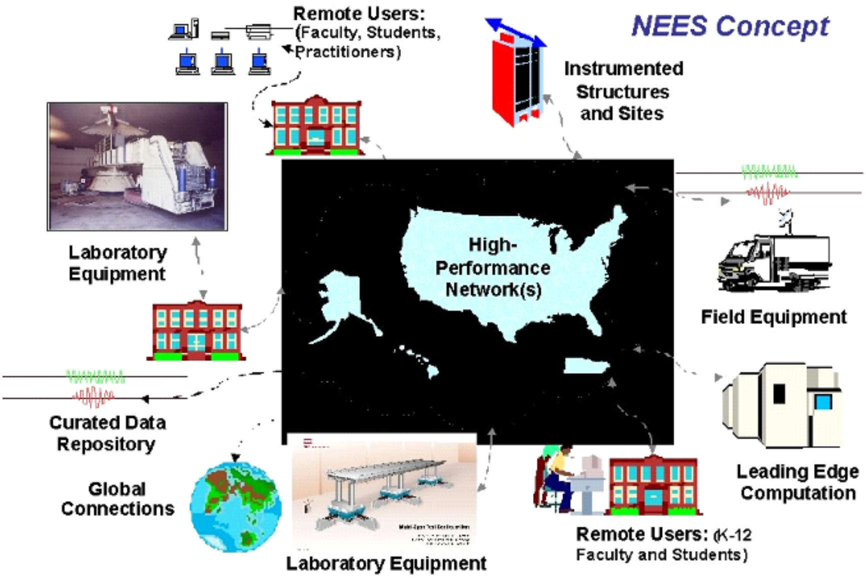

FIGURE 3.1 The NEES concept for remote collaboration in analysis, experimentation, simulation, and testing in earthquake engineering research. SOURCE: National Science Foundation.

abling this community will have profound benefits for research, education, and technology transfer. Students, faculty, research leaders, and practitioners from the entire earthquake engineering community will be able to interact with and learn from each other regardless of physical location. The NEES Web-based approach for conducting earthquake engineering research will dramatically decrease the costs of entry and infrastructural requirements of a potential investigator at any institution. Thus, NEES promises to democratize the research enterprise and greatly increase the talent pool from which research is initiated, conducted, analyzed, and transferred into practice.

Development and curation of data and metadata have the potential to accelerate progress in engineering research in much the same way that seismological data centers with open access—for example, the Incorporated Research Institutions for Seismology (IRIS) consortium—have revolutionized seismological research. The IRIS activity demonstrates that the value of experiments increases dramatically if the setup and results are carefully documented and the resulting data are shared and used by the larger scientific and engineering community.

The documentation and preservation of test results will be an important component of the NEES effort. Videos showing the physical effects of earthquakes (e.g., the progression of damage as an earthquake induces building collapse, the way that a beam/column connection fails if it is not properly detailed, and the occurrence of sand boiling and settlement during liquefaction) would be extremely effective at communicating these otherwise abstract hazards both to policy makers and to the general public. Visual documentation should help to convince these groups of the reality and severity of the earthquake threat and to promote the translation of research results into sustained public action.

Results from NEES experimentation and testing will also validate loss estimates from future earthquakes. When presented with credible loss estimates and the expectation that critical facilities or lifelines will be damaged or destroyed, regulatory bodies should be better able to make the difficult decisions necessary in order to reduce earthquake vulnerability. Current uncertainty surrounding loss estimates for such events encourages inaction. This underscores the importance of gathering meaningful damage and loss data when future earthquakes occur and archiving data from past earthquakes in a NEES-compatible format.

In addition, by serving as a model for parallel efforts in other earthquake-threatened countries, many of them in the developing world, NEES could have an international impact. Through participation in NEES activities, it may be possible for these nations to benefit from risk-reduction approaches developed through NEES (Sidebar 3.1). Aside from being a good global citizen, the United States would benefit from the increased stability accompanying reduced earthquake risk in the developing world. The international competitiveness of U.S. earthquake engineering and construction industries also would be enhanced.

Finally, the benefits of NEES activities could extend well beyond the specific goal of improving the performance of the built environment. Reducing the impact of future earthquakes will allow the nation to pursue other priorities without fear of interruption from a catastrophic earthquake. Strategies for designing, constructing, and retrofitting buildings and lifelines to be earthquake-resistant will also result in structures that are more resistant to other threats (e.g., explosives) as well.

By fostering collaborative research across disciplines and across the country, NEES will enable the exploration of new materials, new technologies, and new ideas for cost-effectively reducing the nation's earthquake vulnerability. The long-term goal of ultimately preventing earthquake disasters can become a reality through a concerted, unified effort by the entire earthquake engineering community working together with policy makers, government officials, and others.

Sidebar 3.1
International Benefits of NEES Research

In the last decade of the 20th century, earthquakes around the world killed almost 100,000 people. More than 14 million people were affected and losses totaling more than $215 billion have been estimated. In 1999 alone, two strong earthquakes in western Turkey caused the deaths of over 16,000 people and the destruction of more than 60,000 homes. Turkey sustained economic losses of about $40 billion (over one quarter of the country's GDP) as a result of these earthquakes. In 2001, a magnitude 7.7 earthquake centered near Bhuj in Gujarat, India, killed almost 17,000 people and destroyed 350,000 homes. Overall, almost 16 million people were affected. Estimated economic losses topped $4.5 billion, with production losses accumulating at a rate of $110 million per day (USAID, 2000, 2001, 2002).

In 1999, the U.S. Agency for International Development (USAID), through the Office of Foreign Disaster Assistance, provided over $21 million in direct earthquake disaster aid to Colombia, Turkey, and Taiwan following devastating earthquakes in those countries. In 2001, USAID provided over $30 million in earthquake disaster relief to El Salvador and India. The World Bank made a loan of $262 million to the government of Gujarat for emergency relief immediately following the earthquake and another $443 million for recovery 16 months later. The Asian Development bank has provided a $500 million loan.

The earthquakes in Turkey, Taiwan, and India prompted the National Science Foundation and other organizations to send research teams to the affected countries to learn lessons that may be useful for preventing similar urban earthquake disasters in the United States. The NSF-sponsored joint Turkey and Taiwan research project had an estimated budget of $1.5 million. Several other organizations, both public and private, provide funding for reconnaissance teams to visit earthquake-shattered regions. However, there are few formal mechanisms for transferring technology and lessons learned back to the affected country.

Low-quality building materials and methods, in combination with inadequate enforcement of building codes, contributed to the destruction of dwellings and loss of life in the earthquakes in Turkey and India. Unless appropriate and inexpensive retrofit technologies are made readily available, together with the knowledge to implement them and incentives for doing so, governments will be limited in their ability to reduce the vulnerability of their populations to future disasters. However, NEES has a unique opportunity to help reduce both the global death toll from earthquakes and the large outlays of funds by the United States and other countries and international organizations for postdisaster recovery in less-developed countries.

NEES could help to reduce the human and economic toll of earthquakes outside the United States by supporting research on innovative, low-cost methods for retrofitting foundations and structure types prevalent in developing countries and by encouraging the exchange of researchers and graduate students from the United States and the international community to participate in this work. Educational materials developed through NEES could also be used by the international academic community to develop and expand earthquake engineering curricula worldwide.

GRAND CHALLENGE RESEARCH

A research grand challenge has been defined as a major task that is compelling for both intellectual and practical reasons, that offers the potential for major breakthroughs on the basis of recent developments in science and engineering, and that is feasible given current capabilities and a serious infusion of resources (NRC, 2001). A grand challenge 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. On this basis, the committee presents six research ideas that it believes would be ideal for initial NEES efforts. These ideas would take advantage of the abilities of multiple NEES equipment sites to address the many interwoven technical issues in earthquake engineering and to offer ample opportunities for multidisciplinary collaboration and synergy, and they could provide enormous paybacks over time.

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 a real estate investment 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. Marine and alluvial soils of this type 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 that provide improved parametric input data for numerical models, 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 about 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 are another important component of loss modeling. These data need to be collected, either directly through NEES research efforts or by means of 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 as a result of 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, sixteen 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 for 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 and 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 NEES CONTRIBUTION TO GRAND CHALLENGE RESEARCH

Through the involvement of multiple investigators from many disciplines employing complementary equipment at several sites, in conjunction with advanced computational simulation methods, NEES offers an unparalleled opportunity to address the complex multidisciplinary problems in earthquake engineering just described. For example, the coupled simulation of strong ground motion, soil behavior, and structural response is now possible. The ability to work through the many permutations of earthquakes, soil types, and foundation designs for various building types will be invaluable for site assessment, performance-based seismic design, damage prediction, and loss estimation. The opportunity to do so systematically in an experimental and computational environment of known and consistent quality will be truly unique (Sidebar 3.2). Several examples of how NEES might be involved in grand challenge research are described below. These examples are intended to illustrate a collaborative research initiative, not to suggest specific collaborations.

SOME EXAMPLES OF POSSIBLE NEES INVOLVEMENT IN MEETING THE GRAND CHALLENGE

Characterizing Soil-Foundation-Structure Interaction

The Challenge

Strong ground motion induced by earthquakes causes complex and poorly understood interactions between the seismic waves, subsurface materials, building foundations, and the structures themselves. Interac-

Sidebar 3.2
NEES and the Graduate Researcher

The Life of a Graduate Student Doing Physical Model Testing Before NEES

The student spends days trying to use archaic equipment to produce sand samples of consistent density and starts to wonder if her dissertation, which was supposed to be on the deformation of piles in liquefying and layered soils, is really on the consistency of pluviated sand specimens.

The student manually tests each instrument, recording the outcome and calibration factors in a laboratory notebook. She learns proper techniques for placing instruments by trial and error, which results in some localized sample disturbance. She painstakingly measures the position of each instrument and records its location in a laboratory notebook. Because previous researchers failed to segregate malfunctioning instruments from functioning ones, the student embeds a broken instrument without knowing it. The amount of time she spends manipulating, untangling, stepping on, plugging in, and unplugging the cables to over 80 instruments exceeds the amount of time she spent conceiving the entire experimental setup.

During the test, the student forgets to reposition a video camera or change the gains on an instrument amplifier, which, in the case of geotechnical centrifuge testing, causes a delay of a few hours as the machine has to slowly spin down from 1 rotation per second and back up again, all while the principal investigator, who has driven or flown for many hours to watch the test, becomes increasingly frustrated with the delays.

To save time and money, several tests are performed on the same sample in sequence, without fully evaluating the results of each test, because several hours of postprocessing and quality control are required before the student can see all of the output time histories in engineering units. Sequential testing exacerbates the uncertainties in instrument positions, which are known only before and after the entire test series. After the test, the student questions the responses of some instruments, and only after cross-checking and rechecking the calibration factors, channels, amplifier gains, and typing errors made in inputting values from the laboratory notebook are the reasons found.

After the test, the student spends hours converting a low-resolution VHS videotape to digital format in order to show it in a small group presentation several months later. She spends hours and hours programming custom animations that will be viewed by a very small audience and can only be used with their data. Instead of spending the time extending the experimental findings to lessons that can be applied in practice, the student instead is overwhelmed by sorting, orienting, and labeling hundreds of still photographs. The research team sees the results of the tests only after several months, when a paper copy of the data report is transmitted.

After trudging up such a steep learning curve and reinventing so many wheels, the student graduates and accepts a job in industry. Although a journal paper is eventually coauthored with the principal investigator, the thesis, data report, laboratory notebook, and box of photographs end up sitting on a shelf gathering dust, unable to be evaluated, extended, or used by numerical modelers to calibrate their tools.

The Life of a Graduate Student Doing Physical Model Testing with NEES

After participating in the Best Practices in Instrumentation and Sample Preparation course provided by the NEES Consortium, the student arrives at the NEES facility equipped with requisite knowledge about proper calibration, testing, and placement of instruments. When she has a question about instrumentation, an answer is quickly obtained from the NEES model builders' chat room. The student breezes through the instrument functionality testing and easily adds these findings (e.g., the serial numbers of any malfunctioning instruments) and metadata (what calibrations were performed, date, time, student name) to the electronic instrument inventory kept at the site.

Consistent samples are easily obtained with new preparation equipment. Material-specific charts guide the student in choosing the appropriate equipment settings for the required material properties (the student, of course, learns to operate the equipment, verifies the settings, and gains an understanding of the factors that may cause variability in the sample).

Still photographs are taken with a programmable digital camera with voice recognition. The student can set a date, time, and experiment number stamp and speak the location or subject of the photograph. Using NEES-developed software, the student downloads the photos and all the metadata into a searchable, user-friendly NEES Consortium photo archive accessible on the Web through a secure server.

The use of smart, wireless instruments capable of knowing their position relative to a reference point in real time reduces the model preparation time and instrument position measurement uncertainty to a fraction of its pre-NEES value. Calibration factors used to convert the instrument data from voltage to engineering units are either already embedded in the data acquisition software or, in the case of smart instruments, transmitted by the chip in the instrument itself to the data acquisition system. The student simply has to flip the data acquisition switch for the smart instruments to transmit their identity, location, and calibration factor directly to the data acquisition software, to a metadata archive file, and to the animation and visualization software. The potential for archiving erroneous data is reduced.

During the test, cameras can be repositioned remotely and instrument amplification system gains can be changed remotely using teleoperation, with minimal interruption, delays, and sample disturbance.

High-speed digital video cameras transmit a live feed of the test to the Web, so that the principal investigator, the research team, and scientists and students from across the globe can watch the experiment in real time. Because some delays in physical model testing are inevitable, the Web site has an updatable ticker giving a countdown to the test. The digital video, with the necessary metadata (such as the experiment name, number, and series; principal investigator; site location; equipment; dynamic input; and so on) is automatically archived in the NEES Consortium video archive and made available through the Web to the project team.

Immediately following an experiment, time histories of input acceleration, excess pore water pressures in soils, bending stresses and strains in piles, and so on, are automatically displayed on a big screen in the control room and on the Web for the principal investigator and research team to view remotely. The principal

continues

Sidebar 3.2 Continued

investigator and research team are videoconferenced with the testing site for live discussion of the results and interactive decision making about the next experiment in the sequence.

After the test, the data acquisition software stores a backup of the raw data and the data converted to engineering units, with appropriate metadata and in a standard format developed by NEES, and automatically transmits the data to the NEES Consortium data archive. The data are automatically input into interactive Web-based software that allows project participants to see two-dimensional sections and three-dimensional views of the experimental setup and to simply click on an instrument position to, for example, cause an acceleration time history to pop up, filter it, integrate it to velocity or displacement, or generate a response spectrum (the student, of course, understands the procedures and shortcomings of the filtering and integration schemes applied). The data are also directly linked to model-based simulation programs, so that they can be immediately used by the numerical modelers on the research team to calibrate, test, and validate their models.

The student becomes a mentor and instructor at the next best practices seminar held by the NEES Consortium. She gets credit and recognition for the team's hard work by publishing the experimental results in the NEES E-Journal. The research team publishes several refereed journal papers and creates a roadmap for future tests on the same subject. The student graduates and obtains a faculty position and continues to conceive of and lead valuable and successful experiments. Having acquired a thorough understanding of the time, effort, skills, and expertise required to run NEES experiments, the new faculty member is able to assist future graduate students.

tion between the soil, the foundation, and the structure during the passage of seismic waves can cause partial weakening or failure of the soil surrounding the foundation; rocking, torsion, and translational motion of the foundation; and energy dissipation in the soil due to the shaking of the structure. Foundations may also filter the high-frequency excitation under a single building or a collection of buildings over an entire city block. Depending on the type of foundation (e.g., flat slab, footings, piles, caissons), structure, and incident seismic waves, these effects can either decrease or increase the earthquake response of the structure (relative to its response if it were supported on a rigid base) or can even cause the structure to fail.

The complex nature of this coupling has made it difficult to determine the conditions under which soil-foundation-structure interaction (SFSI) can be beneficial or detrimental to structural performance during a strong earthquake. Of course, SFSI is not restricted to building structures. Bridges and other lifelines, in particular those that are buried or whose lengths are as long as or longer than the wavelengths of the seismic waves, are especially susceptible. The study of SFSI encompasses seismology, geology, soil mechanics, foundation engineering, buildings, and lifeline design and analysis. One important measure of the success of NEES will be the extent to which NEES can bring these disciplines together to design relevant experiments and develop computer simulations that will help in understanding and solving earthquake problems involving not just individual components but entire engineering systems.

In the case of SFSI, seismologists, with the help of geologists, need to provide the input ground motion to the system, based either on an attenuation relationship that gives an estimate of the ground motion at a site (as measured by a single parameter) for a given earthquake or, more realistically, on modeling waveforms explicitly from first principles of physics, using earthquakes on potential causative faults. Geotechnical engineers need to evaluate the response of the site to the incoming seismic wave motion, including potential nonlinear behavior of the local soils, site amplification, and the effect of the resulting ground motion on the foundation. These effects, however, are influenced by the response of the structure, and vice versa. In addition, the presence of the structure affects not only the soil behavior but also the ground motion in the vicinity of the structure. Accordingly, there is need for an integrated approach in which the geotechnical engineer and the structural engineer (and/or the lifeline engineer in the case of lifelines) work with each other and with a seismologist or geologist to arrive at a design that will ensure the integrity of the complete soil-foundation-structure system.

To gain a better understanding of the physical processes that enter into this complex interaction, one cannot rely exclusively on either experimentation or simulation but must exploit both techniques. Certain aspects are best dealt with experimentally—for example, the analysis of soil behavior, structural components, and simple soil-foundation-structure (SFS) models under restricted forms of seismic excitation—while other aspects, such as determination of the input ground motion and analysis of the performance of a complex SFS system, are more amenable to model-based computational simulation. However, even when one resorts to numerical modeling, experimentation remains essential, because the constitutive behavior of the individual soil and structural components can only be determined experimentally.

Another important application of physical models and field tests is for the validation of mathematical models. Once validated, the models can often be applied to situations that are more general than those that experimentation alone will allow. Naturally, any extension of physically measured parameters beyond the range for which they were obtained must be done with caution.

The Role of NEES

With its new experimental facilities, its networking and integration system, and its access to advanced computational facilities, NEES will enable researchers to conduct experiments, simulations, and hybrid experiments and simulations, both in parallel and in tandem, and to share data generated during a single suite or multiple experiments and simulations conducted at different sites on common or related problems. Researchers will also be able to validate numerical models remotely using NEES data.

Two types of NEES facilities will be available for SFSI experimental studies: field sites and laboratory equipment. For field investigations, NEES will have two permanently instrumented field sites available, both for monitoring SFSI and ground motion, and a mobile field laboratory for forced-vibration testing at different amplitudes and at a wide range of frequencies. For laboratory research, several large, high-performance shake tables capable of reproducing near-source, strong ground motions for the seismic testing of large or full-scale structural or soil-foundation-structure systems have been funded. SFSI can also be studied using dynamic geotechnical centrifuges, which rotate at high speeds and thereby allow the stresses in the soil to be identical to those at the corresponding point in the full-scale prototype. This is an important requirement since the strength of granular soils depends on the confining pressure. The new centrifuges will be able to simulate soil layers up to 40 meters in thickness. The new centrifuge earthquake simulators (shakers) will be capable of inputting earthquake motion in two directions (two horizontal or one horizontal and one vertical). These new facilities will include robots to perform in-flight construction and inspection and will be capable of driving piles, performing soil improvement, and determining the properties of subsurface profiles through geophysical methods in flight. High-resolution digital cameras at all these facilities will provide critical documentation and visualization of failure mechanisms and the time, sequence, and location of deformations. They will also enable remote users to observe model testing in real time and to participate in the decision-making process while the experiment is taking place.

Hybrid Simulation Systems for Numerical, Laboratory, and Field Modeling

Arrays of physical tests interactively connected with computer models in a hybrid simulation concept would provide real-time stress-strain data to numerical, laboratory, and field models of real systems such as natural soil deposits, structures founded on soils, earthen structures, and lifeline structures embedded in soils. For example, an array of four to six cyclic simple shear devices run simultaneously and linked with a dynamic computer code could provide real-time values of soil spring stiffness for use in the laboratory simulation of soil-structure interaction. In real time, the response of the structure would be used to determine the loadings applied to the soil samples, and the soil response would be used to determine the response of the structure, and vice versa. These real-time interactions would be modeled using a computer code, thus allowing a true dynamic soil-structure interaction problem to be modeled with high-quality soil input data. This hybrid simulation concept offers many possibilities, such as the ability to test only the critical components of a system (i.e., key soil layers) to provide the best possible real-time parametric input data for numerical models being used to predict the behavior of the entire system (e.g., an embankment dam). Such an approach is obviously much more economical and efficient than testing the entire physical system.

There would be other advantages as well. By linking real-time soil data from laboratory tests in one facility to a computer code via the Internet, it would be possible to model a structure located in another facility interacting in real time with the soil. Or, the structure could be modeled virtually using the soil data as real-time input for parametric soil properties for certain elements in the model. Another potential hybrid simulation application would load undisturbed samples from critical soil layers in testing devices remotely linked with a dynamic computer model of the response of the soil profile. This real-time link between soil tests and computer codes would in itself represent a major leap forward in our simulation ability and lead to greatly improved numerical models and codes.

Networked, state-of-the-art experimentation and system integration facilities will enable NEES to expand greatly the capability to perform coupled experimental and simulation investigations of SFSI. For the first time it will be possible to fully elucidate the interaction effects on soil-foundation-structure systems during earthquakes and thus help to determine when these effects are beneficial and when they are deleterious to the performance of the structure and its foundation.

Predicting Building Response to Damaging Earthquakes

The Challenge

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). NEES can help to create a comprehensive body of research data and can develop convenient computer analysis tools that support the reliable and routine analysis of progressive earthquake damage in buildings and assess the influence of damage on the seismic response of buildings. This knowledge will help speed the development of cost-effective mitigation techniques for existing buildings and new construction.

Current methods for the dynamic analysis of structures that remain undamaged during an earthquake—that is, linear analysis methods—are well developed, tested, and incorporated into widely accepted engineering software packages. Engineers routinely use modified linear analysis theories and software for seismic design and seismic retrofit of buildings. However, dynamic analysis methods that include the effects of progressive damage during an earthquake—that is, nonlinear analysis methods—are less well developed and are still largely the province of researchers and a small group of practicing engineers. Seismic design codes and guidelines are rapidly shifting toward reliance on nonlinear analysis methods to obtain more accurate predictions of building response in damaging earthquakes and, consequently, more effective and economical seismic design and retrofit strategies. The development of building codes and guidelines is outpacing the development of structural engineering research and technology, because there is limited research and few practical tools available for engineers to use in implementing the advanced concepts contained in the newest codes and guidelines. This is an example of a challenge that could be addressed efficiently and in a timely manner through cooperative research within the NEES collaboratory and far less efficiently through research at individual research institutions.

The Role of NEES

Participating NEES equipment sites might include several from around the country. Participation in this collaborative, NEES-funded program from other NEES member institutions, including those that are not NEES equipment sites, would largely be based on the research interests and initiative of individual faculty members and might include researchers at government laboratories. Participants could include faculty members from institutions that have never before played a major role in earthquake engineering research—for example, small colleges lacking graduate programs that support engineering research or historically black colleges and universities lacking structural engineering research facilities. This effort could also support a parallel education and engineering career outreach program for K-12 curricula. The effort will require the collaboration of engineers from many disciplines, architects, building code specialists, simulation modelers, and software developers, among others. The curriculum elements will require the involvement of educational specialists.

Implementation of the Program

Several NEES equipment sites and other colleges and universities would jointly develop a research plan to support the task described above. The work products of each participant would be clearly defined, and these work products would be coordinated, leaving no significant knowledge gaps at the completion of the program. A partial list of coordinated research activities at NEES equipment sites follows:

- Three-dimensional testing of lightly reinforced concrete beam-column joints, normally reinforced concrete beam-column joints, and welded steel moment frame joints, supplemented with numerical simulations and software module development.
- Evaluation of nonlinear soil-structure-foundation interaction effects for typical building types supplemented with centrifuge experimental models and numerical simulations.
- Shake-table testing of scale model steel structures and concrete structures, including levels of ground shaking that intentionally introduce damage to structural elements, leading to nonlinear structural response. This would be supplemented by an investigation of new or existing computer models appropriate for global nonlinear structural analysis.
- Shake-table testing of model structures with and without nonstructural elements, such as exterior cladding, non-load-bearing interior partitions, and building contents. The purpose would be to investigate the nonlinear response effects of the presence of nonstructural components in order to model the influence of these components on the earthquake response of buildings and establish the relationships between building motions and nonstructural component performance.

Other research activities follow:

- Coordinate, assemble, and curate a database of tests on the nonlinear response of buildings and building components. Data would be assembled from the current coordinated research program as well as from archives of data obtained in previous research programs.
- Develop software models for specific types of nonlinear building elements and calibrate these models using available experimental data.

- Develop test programs by institutions that are not NEES equipment sites. These test programs could be carried out at a NEES equipment site and monitored remotely at the researcher's home institution.
- Study the influence of advances in structural analysis capabilities on the evolution of building codes and the development of public policy for the seismic safety of new and existing structures.
- Review and summarize foreign research on the subject of nonlinear seismic analysis of buildings and assemble a digital database of available foreign experimental data on the nonlinear earthquake response of building components and systems.
- Participate at the K-12 level, including developing grade-appropriate curricula aimed at both science education and introducing careers in earthquake-related fields of science and engineering. One element of this curriculum could be small, portable shake tables for classroom use by students to test ideas about what makes buildings resistant to earthquake damage. This could be supplemented with real-time teleobservation of actual shake-table tests at the NEES equipment sites, direct access to NEES researchers through e-mail, teleconferencing, and Webcasts, and teleoperation and observation of a model shake table maintained at one of the NEES sites.

All participants would contribute to a coordinated set of core software elements that would form (perhaps through additional commercial development) user-friendly software tools. The purpose of these software tools would be to support the reliable and routine analysis of progressive earthquake damage in buildings to assess the influence of damage on their seismic response.

Framing Public Policy Discussions

The Challenge

Despite continuing progress in identifying technical solutions to earthquake engineering issues, it is generally agreed by those in the earthquake community that real progress will require at least as much effort devoted to framing public policy as to implementing technical solutions. Informed public policy decisions will be required for implementation of earthquake risk-reduction practices based on knowledge that research by NEES and others can provide.

Action will be necessary in a number of areas:

- Development of credible loss prediction models that demonstrate the effectiveness and cost of alternative mitigation strategies and techniques.

- Adoption by owners and regulators of buildings and lifelines of risk assessment techniques and simulations that show clearly the economic and social consequences of earthquakes as functions of investments in mitigation, preparedness, and response capabilities.
- Acceptance by owners that earthquake-resistant structures are the economically preferable alternative.
- Acceptance by owners and regulatory authorities of advanced regulations and practices for earthquake-resistant design and construction of new facilities and for evaluation and strengthening or removal of unduly hazardous existing facilities.
- Incorporation, by educators, professional organizations, employers, and public authorities, of knowledge and practices for earthquake resistance into formal and continuing education programs and into qualifications required for design, construction, operation and maintenance, public safety, and emergency response staff.
- Adoption by lifelines and emergency management organizations of real-time information management and simulation techniques for levels of earthquake effects (including second-order effects such as fires and flooding), performance of buildings and lifelines, casualties, and status of emergency operations such as rescue, firefighting, health care, public safety, shelter, and identification of dangerous buildings and lifelines.
- Adoption by public authorities, owners, and investors of recovery simulation and planning techniques that lead to prompt restoration of economic and societal activities and to reduction of the risks of future earthquakes.

The Role of NEES

NEES equipment sites will allow generation of earthquake motions to determine the performance of structures and verify mathematical models for the simulation of structural performance. Data from the experimental studies and simulations of structural performance will be used by developers of standards, practices, and regulations to explore the effects of investments in structural resistance on life-cycle costs, including the social and economic costs of earthquake damage, and to specify the optimal performance levels for standards, practices, and regulations. Additional simulations, at scales ranging from individual buildings to whole cities, will then be used to show policy makers, building owners, and the general public the consequences of adopting or not adopting standards, practices, and regulations for seismic safety.

Designers of innovative building and lifeline systems, such as those employing smart materials, rightfully bear the burden of convincing owners and regulators that the innovative systems will be functional, economical, and safe. NEES equipment sites will be available to system designers, generally at the designers' expense, for their research. NEES large-scale shake-table and field testing capabilities will be especially valuable for full- or near-full-scale tests under realistic seismic loadings to demonstrate the efficacy of the innovative systems.

Simulation techniques and data produced through NEES will then be used to develop models of actual communities and cities, including their buildings, lifelines, human activities, and emergency management systems, to simulate the effects of a strong earthquake. These models will be used for emergency planning, with simulated earthquakes, to show public officials and private interests the damage that may occur and the resources needed for emergency response. When the real earthquake occurs, these same models will be used, with damage data from the earthquake, to focus emergency resources on the anticipated areas of damage. The models will include actual damage information as it becomes available and predict further effects such as spread of fires as a function of wind conditions, water supplies, and deployment of firefighting capabilities.

Simulations of the effects of earthquake damage on the social and economic functions of a city also can be used to guide recovery operations and investments. Decision aids to help officials decide which buildings and lifelines to repair, and in what order, will be based largely on functional, social, and economic modeling, which are not directly dependent on research at NEES equipment sites. However, simulations, including earthquake vulnerability modeling, that are based on NEES research results will be valuable for defining the levels of earthquake resistance to be required for rebuilding and repair.

NEES data and simulation capabilities will be accessible in real time to educators everywhere for development of curricula and conduct of courses for future seismologists, engineers, geologists, architects, planners, public officials, and emergency managers. These data and simulations also will be available online for continuing education and training of these professionals as new knowledge from NEES research and other sources is introduced into practice. NEES capabilities for the teleobservation of experiments, videos of completed experiments, and advanced graphics showing the key aspects of simulations will support the dissemination of key findings of NEES research and the acceptance and implementation of recommendations for practice based on NEES research.

THE PROMISE OF NEES

Substantive progress in preventing earthquake disasters will require research studies of unprecedented scope and scale. Major advances will be required in the simulation of seismic events, wave propagation, and the performance of buildings and infrastructure up to failure—all of which will rely on extensive physical testing and observation. Results from these simulations will have to be coupled with and drive performance-based system design, pre-event mitigation, post-event assessment and planning, and emergency response. Ultimately, knowledge-based systems will be required to develop decision-making environments for policy makers and planners.

Long-term partnerships among researchers, practicing engineers, computer and computational scientists, and social scientists will be key to success in these endeavors. Of even greater importance will be the education and training of the next generation of earthquake engineering talent (see Sidebar 3.2). The unique and exciting opportunity presented by NEES is the ability to address complex problems that cut across multiple disciplines and can involve multiple equipment sites and researchers and analysts from around the world—truly a new paradigm in earthquake engineering research.

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4
Revolutionizing Earthquake Engineering Research Through Information Technology

The committee was asked to assess and comment on the possible roles of information and communication technologies for collaborative on-site and remote research, the sharing of data (including the need for standardization in data reporting), metadata (data about data), and simulation codes, and to identify additional research resources that are not currently available. This chapter discusses these roles, along with opportunities, challenges, and issues, from two temporal perspectives. The first is the short term, which coincides with the initial equipment and system integration phase of NEES (i.e., plans and work that are already under way). The second is the longer-term view, looking 10 years out (2004-2014) and thinking about what needs to happen in the future. The long-term goal of NEES is to revolutionize earthquake engineering research, not just to improve it incrementally. Success here will mean making significant inroads in advancing basic and applied research in support of the overarching grand challenge: ultimately preventing earthquake disasters. 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.

Around the globe, governments and organizations are aggressively pursuing a vision of revolutionizing research and education in science and engineering by harnessing advanced emerging information technologies. Qualitative changes in the way that scientific research is conducted are well under way. Already, meetings, workshops, training, symposia, and reviews are routinely held electronically, using AccessGrid (ANL, 2002), a large-display collaboration environment that runs over the Internet and has participants around the world. The National Science Foundation's (NSF's) TeraGrid (NSF, 2002a) and its Middleware Initiative (NSF, 2002b), the Department of Energy's Scientific Discovery Through Advanced Computing (SciDAC) (DOE, 2002), the National Aeronautics and Space Administration's (NASA's) Information Power Grid (NASA, 2002), the United Kingdom's e-Science program (DTI, 2002), and the European Union's DataGrid project (EU, 2002) all represent significant long-term investments in building up the systems, core technologies, and domain applications that will serve as foundations for the collaboratories of the future and a new era of science and engineering.

These developments build on a decade of activity that saw the emergence of the World Wide Web, the development of the first electronic collaboratories (Olson et al., 2001; SPARC, 2002), and the appearance of grid computing (Foster et al., 1999). The grid embodies a pair of concepts: (1) the harnessing of distributed computing, data, and information resources in a seamless manner analogous to the electric power grid in support of the activities of (2) virtual organizations composed of geographically distributed people from multiple organizations and representing multiple disciplines. The name that the United Kingdom has chosen for its program, "e-Science," is particularly descriptive of what the committee believes NEES can accomplish with grid computing: revolutionary science and engineering enabled by distributed computing resources for distributed groups of people. The substantial efforts mentioned above are made in the belief that the grid can do for science and engineering what the Web has done for commerce, business, and information delivery to the general public. See Sidebar 4.1.

NEES is a member of a rapidly growing list of long-term, focused disciplinary projects that spans high-energy physics, biology, astronomy, climate, social sciences, engineering, and many others. The NEES initiative was founded on the fundamental vision of establishing a collaboratory that would realize a new paradigm for earthquake engineering research. The idea is to foster a paradigm shift in the field, moving toward integrated physical testing, model-based simulation, integration and fusion of distributed data, and collaborative participation and interaction among geographically distributed researchers.

The NEES collaboratory vision is consistent with the ideas expressed in the 1999 report of the President's Information Technology Advisory Committee (PITAC, 1999) and with the many activities around the world described above. The systems integration component of NEES, NEESgrid (NEESgrid, 2002; Kesselman et al., 2002; Prudhomme, 2002), parallels many of the ideas expressed in the recent NSF report *Revolutionizing Sci-*

Sidebar 4.1
Collaboratories, the Grid, Cyberinfrastructure, and the Future of Science and Engineering

The term "collaboratory"—a contraction of "collaboration" and "laboratory"—first came to light in 1989. The basic idea was (and still is) simple and compelling: to establish "laboratories without walls"—virtual electronic spaces where geographically distributed researchers can explore, learn, share knowledge, and partner and collaborate in order to solve hard science and engineering problems. This idea caught on nicely, and during the 1990s a number of collaboratory projects began in various agencies and problem domains. Perhaps one of the best known was the Upper Atmosphere Research Collaboratory (UARC) and its predecessor, the Space Physics and Aeronomy Research Collaboratory (SPARC). UARC is now a member of the Smithsonian Institution's permanent collection of information technology research.

Work continues on the development of collaboratories today, and there are now even collaboratories for studying collaboratories. To date, most of the collaboratories have been unique creations, each one carefully crafted for its given problem domain and scientific community. The earliest examples were even pre-Web. Obviously, such efforts were very challenging, not to mention expensive. It was pioneering work, and common sharable technologies and established methods generally did not exist.

The grand challenges in medicine, the environment, physics, and engineering demand the best and the brightest from all countries and continents—a perfect proving ground for the collaboratory idea. However, attacking many (probably most) of these difficult problem domains would require the use of a broad array of distributed computational resources: supercomputers, huge data archives, fast networks, sensors, and other complex instruments, including spaceborne observation platforms. How could all of these systems be used in concert? Enter the grid.

The 1998 book *The Grid: A Blueprint for a New Computing Infrastructure* focused on the concept of a new generation of computational capability, where geographically distributed resources were shared for virtual organizations. The concept of distributed computing was, of course, not at all new at that time and had its own long record of technological development and progress. What the new document offered was the broad concept of harnessing a collection of distributed computing resources for use by a virtual, distributed community. The choice of the term "grid" established a new metaphor: computing as a utility that one taps in much the same way as one taps into a wall receptacle for electricity and draws on the national power grid without knowing how or where the power was generated or

ence and Engineering Through Cyberinfrastructure (Atkins et al., 2003), and has established the following information technology (IT)-related goals for enabling the research, consulting, and educational communities:

- Perform teleobservation and teleoperation of experiments, what entity was responsible for it. In its most general form, a grid harnesses a collection of computing (data, storage, networking, instrumentation) resources that are geographically distributed and not necessarily under any form of centralized control.

Now, in 2003, we hear about all sorts of “grids”: access grids, data grids, computing grids, and a wide variety of grids for specific scientific and engineering endeavors. The avid reader will find articles about grid computing in the *Economist*, *Wired* magazine, and the *New York Times*. Businesses such as IBM and Sun Microsystems have made grid computing a prominent element of their long-term corporate strategies. So there is a lot of activity in this area and a number of different categories of grid technologies and environments. But the long-term vision sees a global interoperable fabric for computation and interaction that is ubiquitous and analogous to the Web. For this to happen, a global consensus must be reached on common protocols, interfaces, and services that can turn the vision into reality. Responding to this challenge, a new body called the Global Grid Forum (GGF) focuses on precisely these issues several times a year.

As mentioned above, grid computing is a metaphor for tapping the power grid, which is one important element of our societal infrastructure. Building our future collaboratories and knowledge environments is going to require an enormous amount of technological infrastructure, much more than we now have. Shared interoperating technology for federated data systems, digital libraries, visualization, collaboration, computation, security, and more will be needed. A new term has recently been coined to describe all of this: “cyberinfrastructure.” One of the central ideas and, indeed, the potential key benefit of cyberinfrastructure is enabling much more rapid and cost-effective development of next-generation systems, environment, and applications. The Atkins Report (Atkins et al., 2003) put it this way: “If *infrastructure* is required for an *industrial* economy, then we could say the *cyberinfrastructure* is required for a *knowledge* economy.”

Looking to the future, we can envision knowledge environments—new spaces where the collective experience and understanding of a global community can be synthesized, recorded, indexed, shared, and leveraged. If we can readily develop these for many problems and communities, there exists a unique opportunity to revolutionize the conduct of science, engineering, and education. Cyberinfrastructure, with grid computing as one component, will serve as a critical enabling technology foundation for framing the efficient and sustainable development of these new environments.

NEES sits somewhat uniquely at an intersection: As so aptly put by Kim Mish at a recent workshop, NEES is “where infrastructure meets cyberinfrastructure.”

- Maintain a repository of curated data using standardized language and format,
- Access computational resources and open-source analytical tools, and
- Access collaborative tools for experiment planning, execution, analysis, and publication.

Substantive progress in preventing earthquake disasters 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 have to be coupled 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. Progress on these long-term objectives will rely on major advances in information technology:

- Accuracy and computational performance of large-scale simulations,
- Hybrid physical and model-based simulation,
- Coupling between multiple analytical models,
- Analysis and visualization capabilities for both experimentation and simulation,
- Data sharing and interoperability,
- Effective collaboration across disciplines and subdisciplines, and
- Knowledge-based and geographic information systems (GIS).

Long-term partnerships among researchers, practicing engineers, computer and computational scientists, and social and policy scientists will be key to success in these endeavors. Of even greater importance will be the education and training of the next generation of earthquake engineering talent.

FOUNDATIONS FOR NEES

Crafting a collaboratory like NEES involves the integration of a variety of enabling technologies, including general Web capabilities, mobile software (e.g., Java), grid computing and, more recently, Web services (W3C, 2002). The Globus Toolkit (Globus Alliance, 2003) serves as one of the premiere examples of middleware for building grid environments. The architecture of NEESgrid (Kesselman et al., 2002; Prudhomme, 2002) incorporates all of these current and emerging technologies as well as a top layer of new, generalized collaboratory software (Knoop et al., 2001) that has emerged from the building, operating, and assessment of scientific collaboratory environments over the past several years.

Obviously, IT is evolving and changing at a furious rate. It is important to note here that system integration is perhaps not the best descriptor for the NEESgrid activities. It is, of course, that—but it is also an *initial* development effort that will need to grow in capability, leverage new information and communication technologies as they emerge (which is often), and expand dramatically in applications and user interfaces over the next decade. Building a collaboratory is not yet quite the same thing as building a machine or an instrument. As an example, in the 2003-2004 time frame, the four general technology areas mentioned above will be coalesced into a new generation of grid technology (Foster et al., 2002); provisions need to be in place to enable NEES to leverage such new developments and expand their functionality and usability. It is reasonable to expect the technology change and advancement ramp to be steep.

COLLABORATIVE ENVIRONMENTS AND DIRECTIONS

Information technology can enable collaboration in a variety of ways. E-mail, Web sites, and mailing lists provide asynchronous collaboration; these technologies are already widely and effectively used in this manner. Web-based collaboration environments expand on this level of capability and provide chat rooms, online data, and document sharing and have the potential to enable broad participation across the university, industrial, and education communities. Videoconferencing between individuals and groups is another important mode of collaboration. Dramatic reductions in the cost of entry have come about here, making these technologies available and practical for researchers and project participants with varying levels of infrastructure support. The past 2 years have also brought exciting and rapid advances in high-end, real-time, group-to-group collaboration, with the AccessGrid (Childers et al., 2000) serving as a prominent example. The AccessGrid environment leverages advances in network bandwidth and connectivity, commodity personal computer technology, inexpensive projection systems, and open-source software (PITAC, 2000). The AccessGrid has recently achieved remarkable penetration, especially in the academic community but also in the corporate and agency realms. There are now more than 100 sites around the world and perhaps double that number of actual systems (more than one system at each site). With its combination of capability, sense of presence, and growing availability, the AccessGrid is ushering in the beginnings of a revolution in how we meet, work together, and advance research goals.

NEESgrid is developing the collaboration environment by building Web-based portals that are based on collaboration frameworks developed at the University of Michigan, on electronic notebooks, and on grid middleware. For videoconferencing (i.e., real-time human collaboration), NEES has adopted commercial solutions for the first stage, emphasizing

FIGURE 4.1 An AccessGrid session on NEESgrid.

simplicity and cost-effectiveness. For the additional tasks of telepresence, data manipulation, and analysis and visualization, the adoption of a primarily Web-based approach democratizes access to NEES. Cost of entry and requirements for local support and infrastructure are minimal with this approach and are key to gaining use and buy-in from the larger community.

Advances in IT will bring many opportunities for improved capability to NEES. AccessGrid has excellent possibilities for use in the NEES context and is already used by the Consortium development group (see Figure 4.1). One challenge heard from the earthquake engineering research community was that of maintaining close communications and mentoring ties between students using the NEES facilities and their distant advisers. Live group collaboration environments such as the AccessGrid could be valuable in this regard. In addition, work is under way within the community to integrate additional collaboration capabilities, high-definition video, and analysis and visualization tools into the AccessGrid environment. All of these could one day be valuable to NEES, especially the high-definition video, which could be useful for teleobservation and telepresence activities.

Providing capabilities for teleoperation (i.e., remote control) of NEES resources has long been a stated goal of the effort, but it is a contentious issue. While collaboration capabilities in general appear to generate broad enthusiasm on the part of NEES sites and potential NEES users alike, it was the committee's observation that NEES sites were generally skeptical of the idea of remote control of the experimental equipment, citing deep concerns about security, varying levels of investigator proficiency, human safety, and the integrity of expensive equipment. The NEESgrid user requirements team delved into this matter in its survey (Finholt et al., 2002) of potential NEES users and found that a significant number of Ph.D.-level respondents asserted that teleoperation would be valuable to them. So the idea of enabling the remote operation of experimental equipment has some attraction, and from a technical standpoint, it is generally feasible.

Teleoperation in the NEES context is an idea worth exploring in a cautious and intelligent manner, bearing in mind security and safety considerations and that such a capability might be appropriate at some sites and for some purposes but not others. For example, there appear to be good reasons for enabling remote control for useful but safe operations, such as triggering measurements and orienting imaging devices (as opposed to large-mass or destructive operations). This type of remote control is sometimes referred to as telepresence. Teleoperation is already being explored as an educational tool (UCIST, 2002) and may also have interesting applications in training, which could be used to gain experience and familiarity with this mode of operation and the related security, safety, and technical issues.

MANAGING, CURATING, AND SHARING DATA

The sharing of data is an important underpinning for scientific collaboration. Success in this endeavor necessitates a number of capabilities: basic access to electronic data, common formats allowing data to be easily shared and reused, metadata standards that ultimately play a critical role in finding and using scientific data effectively, and Web-based data portals that provide sophisticated management and access functions for anyone with a commodity desktop system.

Many scientific communities have undertaken large-scale coordinated efforts aimed at developing broadly useful standards for data formats, software interfaces, and metadata conventions. In some cases, these activities have been going on for a decade or more. Metadata are essentially "data about data"—information about scientific data that is fundamental to discovering data, establishing their context, understanding their progeny, sharing them easily, using them correctly, and interoperating fluidly among diverse software systems. The Extensible Markup Language (XML) is emerging as a basic enabling technology and lingua franca that provides the glue for associating data and metadata, along with related information such as scientific papers, documentation, and the electronic services that provide access to data and metadata. Numerous examples of XML-based scientific markup languages have recently begun to emerge, spanning the gamut of science, engineering, and commerce. Bioinformatic Sequence Markup Language (BSML, 2002), Chemical Markup Language (Murray-Rust et al., 2002), and Astronomical Markup Language (Oasis, 2001) are just a few examples drawn from hundreds. Comparable efforts in the earthquake engineering community are only in their infancy. Model Testing Markup Language (Kutter et al., 2002) is an initial metadata effort for geotechnical physical model testing and the resulting data. COSMOS/PEER also has a project under way aimed at developing an environment for classifying, archiving, and disseminating geotechnical data over the Web (COSMOS/PEER, 2002).

The earthquake engineering community is just beginning to gain traction in the area of data standards and metadata, and effective strategies here are crucial to the data-sharing goals. With this operation in mind, NEES has established a task force devoted to factoring out common requirements for metadata across the NEES community. Through this task force it is developing metadata schemas, catalog services, and harvesting capabilities. This work is in its early stages but may serve as a catalyst for bringing the community together on important data issues. NEESgrid must track and leverage other efforts in metadata development and various efforts in developing databases and data services. For example, the concept of a National Spatial Data Infrastructure was first advanced by the Mapping Science Committee of the National Research Council in 1993. The Federal Geographic Data Committee, supported by the efforts of the NRC Mapping Science Committee, has been instrumental in fostering partnerships to encourage the documentation of data according to national standards to facilitate their sharing and to encourage the use of geospatial data in new applications (NRC, 1993, 1995, 2001).

Security and the protection of intellectual property are important concerns. In addressing them, NEES must have a data infrastructure that provides for flexible specification of access and management permissions. Over the course of its lifetime, a piece of NEES data would generally be assessed by populations ranging in size from individuals or small groups to large communities. Confidence and participation by investigators will hinge on the trustworthiness of these capabilities.

The NEES Consortium will be tasked with developing and maintaining a curated data repository. Curation will need to be undertaken on a level that goes beyond data integrity and persistence to data (and metadata) correctness. Careful consideration will need to be given to accomplishing this task, bearing in mind that discipline experts will probably need to be heavily involved. A voluntary program in this area may not be sufficient; instead, dedicated resources may be required to achieve success. Similarly, much work will be required to advance data and metadata methods and standards; discipline expertise will be critical to long-term success. Financial support and reward structure require careful consideration and, possibly, proactive steps. That said, early indications are that NEES researchers have begun to contribute advances in these areas in a commendable fashion.

Looking toward the future, it can be seen that researchers who are engaged in grand challenge work will need to draw on data that span large-scale numerical simulation (e.g., basin-scale earthquake models), NEES resources (e.g., structural performance of individual buildings and collections of buildings), GIS (e.g., infrastructure, lifelines, buildings), and other data sources required for assessing event damage and appropriate responses. NEES, as a resource, is only one component in all of this. The NEES Consortium faces a challenge and enjoys the opportunity to foster partnerships in which other technology efforts and NEESgrid efforts collaboratively define the evolution of NEES data strategies in support of frontier research problems.

In addition, emerging work in translational strategies among metadata standards will ultimately need to be explored, possibly building on emerging work in the development of domain ontologies—a necessary step for the fusion of multiple disparate data holdings for integrative experimentation, simulation, and impact studies (i.e., the grand challenges set out in this report). In this context, ontology is essentially a formal definition of the terms and relationships associated with a given domain. This concept forms the basis for a new area that has been receiving much attention as of late, the Semantic Web (Berners-Lee, 1998). Computer science researchers could carry out forward-looking work on the Semantic Web in the areas of information technology, digital libraries, and others. Examples of potentially synergistic efforts include the Alexandria Digital Earth Prototype Project (UCSB, 2002), the Digital Library for Earth System Education (DLESE, 2003), and the Geosciences Network (GEON, 2002).

From the foregoing discussion, it is clear that the NEES Consortium will develop massive quantities of data from both experimental and analytical research programs. Only if they are carefully managed and curated will these data be of use to the research community, policy makers, educators, and the general public. NEES will need to invest considerable effort in developing both the technology and the policies for storing, managing, and sharing these data. The key elements of a NEES data management and curation program are described below:

- *Raw project data.* Participants in a particular research project will need to share raw data as they are gathered from experiments. These data are not suitable for public distribution until they have been reviewed and processed into a form that is understandable by the research community at large. Thus, there must be a secure system for individual project researchers to share unprocessed data, work with the data, and convert them into a form that can be released for use by others.
- *Data for other NEES participants*. Researchers within the NEES consortium will want to access data from other NEES participants, particularly those working on projects with similar themes. A NEES data clearinghouse could create opportunities for such collaboration. The clearinghouse should be set up so as to encourage spontaneous collaboration among NEES researchers, allowing NEES data to be easily shared, compared, and combined.
- *Data for use by non-NEES researchers.* Once NEES data have been evaluated and reviewed, they should be published for use by researchers anywhere. A data repository would be created, and data placed in the repository would be provided in standard formats. Unless formats can be defined in advance for researchers, the effort to convert project data into this standard format will be considerable and not within the budget of individual research projects. Consideration should be given to designating funding specifically for the development of standard NEES data formats, conversion of research data into the NEES formats, and curation of the data sets stored in the data repository.
- *Data for standards writers, practitioners, and educators.* In addition to being included in the repository of detailed data described above, research results should also be summarized and stored in a format that highlights the significant technical findings of the research. These summary data will be the most useful format for standards writers, practitioners, and educators. Again, consideration should be given to funding the considerable effort required to create a data synopsis for each NEES research project.
- *Data for policy makers, the press, and the general public.* The technical data repositories and summaries described in the categories above are neither intended nor suitable for use by policy makers, the press, and the general public. To maximize the impact of NEES research results, the NEES Consortium should generate public policy briefs, press releases, and educational resources for the general public. Development of these resources would be administered by a committee of NEES researchers, consortium managers, and public relations specialists.

In summary, ease of access to quality data developed by NEES and ease of collaboration among researchers over NEESgrid are among the most important aspects of the collaboratory and will strongly influence the success of NEES in ultimately preventing earthquake disasters. Significant efforts must be made to ensure that NEES data are of good quality and are released in a timely fashion. Major advances have been made over the past 30 years in experimentation in earthquake engineering, but generally speaking the data generated have only been available for use by the investigators who conducted the research.

BEYOND EXPERIMENTATION: SIMULATION, DATA ANALYSIS, VISUALIZATION, AND KNOWLEDGE SYSTEMS

One of the primary goals of NEES is to foster a movement toward integrated computer simulation and physical testing. Initial NEES efforts encompass identifying simulation codes that are of interest to the community and providing repositories and integrated execution sites for them so that participants may use them readily. NEES activities currently under way in data analysis and visualization focus on delivering analysis, simple visualization tools, and capabilities for accessing video streams and imaging from within the collaborative Web-based portal environment. NEES should also seek inputs from other disciplines in these technical areas to assist in the development of more appropriate tools and techniques. Initial dialogue has begun with the OpenSEES (PEER, 2002) effort, a framework for constructing simulation models, as an initial candidate for the simulation repository. Ongoing work in the development of community models—such as the Southern California Earthquake Center's (SCEC's) Southern California Velocity Model (Magistrale et al., 2000) and ground motion simulation tools (Bao et al., 1998), and, more generally, its Community Modeling Environment—should be considered as well. SCEC has embarked on an ambitious program to develop physics-based models of earthquake processes and to integrate these models into a new scientific framework for earthquake hazard analysis and risk management. The Community Modeling Environment is under development at SCEC with an NSF Information Technology Research Grant in support of the seismic-analysis and risk-management efforts. It will function as a virtual collaboratory for the purposes of knowledge quantification and synthesis, hypothesis formulation and testing, data conciliation and assimilation, and prediction. Given that the purpose of this modeling environment is entirely consonant and complementary with that of NEES, significant potential exists for collaboration between the two activities. Early dialogue between the NEES and SCEC communities should be strongly encouraged.

Success in addressing the grand challenge of ultimately preventing earthquake disasters will be intertwined with related grand challenges in information technology. Large-scale integrative simulation activities will push the envelope of what is possible both scientifically and technically. With terascale computational platforms already available and petascale systems on the horizon in 10 years, it will be technically possible to perform integrations of tremendous resolution for tsunamis and regional seismic events. Uncertainties about the source of seismic events and soil material properties at the scale needed to model ground motion and system performance for frequencies of engineering interest make it necessary to introduce stochastic modeling. The requirements posed by analysis, visualization, and storage management will be formidable, perhaps even comparable to those posed by high-energy physics, cosmology, meteorology, and turbulence. Researchers will need new tools that scale to the complexity and size of the problem. These tools are in turn dependent on addressing the myriad data challenges. Management of the massive amount of information that will be generated by NEES experiments, field observations, and simulations was discussed in detail above. In addition, the visualization of this information will need to be a key component of the NEES effort. Visualization is essential to researchers, helping them to guide the design and execution of experiments and computer simulations. Moreover, with the huge amounts of data expected from NEES, the availability of tools for visualizing complex data sets will be crucial, allowing the researcher to interpret the results of experiments, observations, and simulations, which will in turn lead to the discovery of new results. Most important, sophisticated visualization tools will be essential for communicating the results and implications of the investigations to stakeholders, such as public officials and other policy makers, practicing engineers, students and teachers, and the public at large.

The current NEES integration effort is addressing the need for storing and displaying visualizations, but except for demonstration projects such as that shown in Figure 4.2, it is not addressing the need for visualization tools. Even though some generic tools are available commercially or are in the public domain, there has been little effort to date to develop a set of tools that will serve specifically the needs of NEES users in particular and the earthquake engineering community in general. For NEES to fully realize its promise, the development of suitable visualization tools needs to be explicitly encouraged and supported.

NEES has the potential to play a pivotal role in enabling frontier research activities. Through teleparticipation, the ready access to research results provided by NEESgrid, and the collaboratory nature of NEES in general, the social and policy sciences will be able to influence the course of research and application of the results. Earlier and better participation

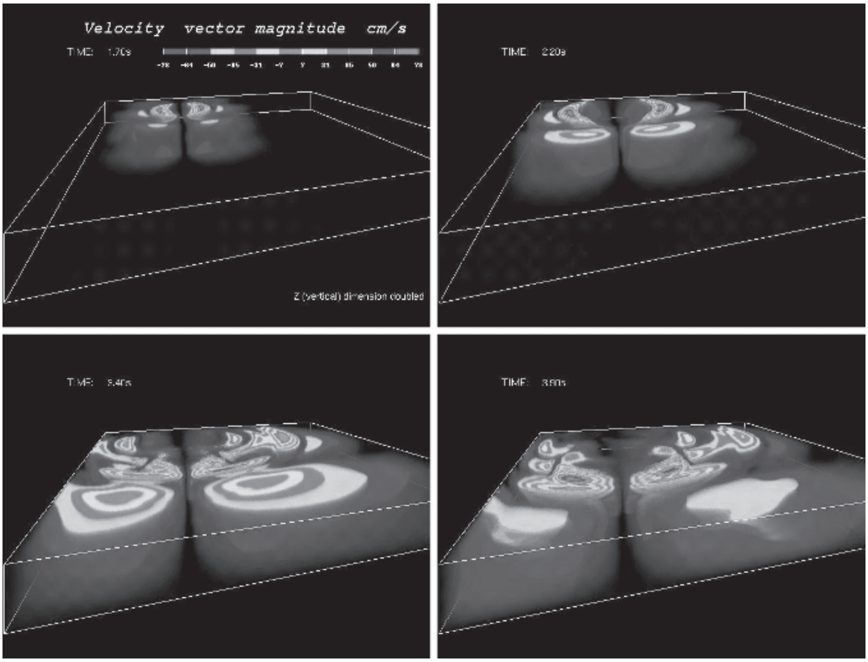

FIGURE 4.2 Visualization of the wave propagation in a layer over a half space due to an earthquake generated over an extended strike-slip fault. The distribution of the fault-parallel component of the horizontal velocity at different times following the onset of the excitation is shown. SOURCE: Simulation by Antonio Fernández and Jacobo Bielak, Carnegie Mellon University; visualization by Greg Foss, Pittsburgh Supercomputer Center.

of the social and policy sciences in engineering research will aid in the development of the new loss estimation models and decision-making systems (King et al., 1997) that will be needed for government and businesses to engage in effective pre-event mitigation and post-event emergency response and recovery. Ultimately, some of the problems posed will not fully submit to traditional analytical approaches, and a movement toward knowledge-based systems will be required if sustained progress is to be achieved. Such research endeavors would span the numerical simulation of seismic events and ground motion over large geographic regions; the simulation of tsunamis and the modeling of flood inundation; the physical and numerical simulation of infrastructure and building performance; event-impact prediction and assessment; collateral hazard analysis; damage evaluation; and emergency response. Rapidly evolving GIS capabilities will be invaluable for managing and analyzing the massive amounts of data that will be available from numerical simulations and other distributed databases. See, for example, Longley et al. (2001); Goodchild et al. (1999); and Greene (2002).

BUILDING COMMUNITY

NEES is a national facility targeted at fundamentally redefining traditional modes of earthquake engineering research. Building on the concept of a collaboratory, NEES has an explicit charter to enable and broadly serve researchers at universities across the United States as well as practitioners and researchers at private corporations and government facilities. NEES also has a responsibility to contribute to the education of students, the continuing education of faculty, and the elevation of public awareness of earthquake engineering and earthquake hazards in general. Also, although NEES is a national effort, earthquake research is a global concern. NEES should be expected to play a long-term role in advocacy, partnership, and joint research with other national and international projects. NEES should demonstrate leadership that will not only advance U.S. research interests but will also serve as an example for other nations and programs and as a catalyst for enhanced international cooperation in pursuing mutual research interests. Furthermore, NEES potentially has the opportunity to transfer new technology to developing countries. Over the past 3 years, the United States has spent in excess of $50 million on direct humanitarian aid and disaster relief (USAID, 2000, 2001, 2002). Proactive investments in technology transfer to developing countries could generate goodwill as they mitigate these expenses, and they also could lead to export revenues for U.S. companies.

Establishing a new paradigm for earthquake engineering is a sociotechnical problem. Choosing IT foundations that promote ready participation across all of the interested communities will be key to fostering the participation, buy-in, and feedback processes that are critical to long-term success. Technology and opportunity alone will not necessarily galvanize the community in new modes of work. Engaging in research in a highly collaborative mode is rather new to the earthquake engineering community. It will require sustained community building and the development of trust—trust among people and trust in the technology that manages precious data and protects intellectual investments. This should be considered a role of paramount importance for the NEES Consortium.

EDUCATION AND OUTREACH

Earthquakes, tsunamis, and natural disasters in general are enormously relevant and interesting to society at large and to students in the classroom in particular. IT has an important role to play in enabling educational and outreach programs that would leverage NEES investments and enhance awareness and visibility. Web-based environments for posing questions, running simple idealized simulations, and even engaging in simulated disaster response management will offer exciting possibilities for projects that leverage NEES offerings.

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5

Achieving the Grand Challenge: A Research Plan for NEES

BASIS FOR PLANNING

In formulating a research plan for NEES, the committee was guided by the vision that earthquake disasters ultimately can be prevented. However, this cannot be achieved immediately. Therefore the committee has chosen to focus on a series of progressive research needs to mitigate the effects of earthquakes. Cumulatively, and over the next two to three decades, the complete vision can become a reality. To provide strategic direction, objectives were established by the committee for coordinated and integrated progress in a number of interrelated areas. These include (but are not limited to) the following:

- Lower-cost but higher-resolution techniques for the identification of earthquake hazards,
- New construction materials and design techniques (e.g., performance-based seismic design) for earthquake-tolerant facilities,
- Lower-cost techniques and materials for retrofitting existing facilities that have unacceptably high seismic risk,
- Automated tools for the injury prediction and emergency response needs of an affected community following an earthquake,
- Validation of models for loss-estimation for insurance, land planning, and emergency response needs, and
- Demonstration tools to better communicate earthquake risk and

potential preventative actions to the general public, students, and government officials.

To accomplish this, the committee developed a research plan for the seven topical areas discussed in Chapter 2 of this report. The plan offers short-term (fewer than 5 years), medium-term (5 to 10 years), and long-term (10+ years) goals for addressing the challenges presented by seismology, tsunamis, geotechnical engineering, buildings, lifelines, risk assessment, and public policy. However, these are not stand-alone issues to be resolved on a narrow, discipline-oriented basis. NEES offers the earthquake engineering research community the opportunity to simulate complex problems of seismic excitation and system response and to couple the results with their social, economic, and political implications through multidisciplinary collaboration with the social and policy sciences. The knowledge gained from these interdisciplinary efforts can underpin an entirely new generation of analytical and predictive tools for improving building and lifeline performance, loss estimation, emergency preparedness and response, and risk assessment and management.

These new tools will support the two types of investments in earthquake hazard mitigation that are needed to prevent disasters. The first is the relatively modest but sustained investments that must be made for seismically resistant new buildings, lifelines, and communities. These investments are more often incurred for informing and educating decision makers than for the technology per se—in many cases actions to address seismicity cost little more to implement than actions taken without considering seismic vulnerability. The second category consists of the larger investments necessary to increase the resistance of existing buildings, lifelines, and communities. Often, because of cost, only the most critical vulnerabilities can be addressed, but when major retrofits are planned for other reasons, adequate seismic resistance often can be obtained for only modest additional cost.

THE RESEARCH PLAN FOR NEES

The committee did not interpret its charge to be the development of a research plan that could only be accomplished through NEES. The committee has identified what it believes to be the significant issues in earthquake engineering and the research that will be needed to address them over the next several years. Although the NEES equipment will undoubtedly facilitate heretofore impractical or impossible experiments and make possible new lines of research, the committee believes that it is the connectivity and multidisciplinary cooperation embodied in NEES that will most benefit earthquake engineering research. Research proposals to ad-

Objectives of NEES Research

- Lower-cost techniques and materials
- Higher-resolution analysis
- Increased validation of design
- Enhanced visualization and communication of effects

dress specific problems through NEES should demonstrate the connections between geoscience on one end and the potential benefits of loss reduction and disaster mitigation on the other. At the same time, potential investigators should be expected to take a multidisciplinary approach to the problem and to demonstrate how the results will be shared broadly throughout the earthquake engineering community. This will require the active collaboration of earth scientists, engineers, social and policy scientists, and education and communication specialists.

The committee's research plan anticipates that all research should have as an underlying objective the development of innovative new approaches that will lead to the construction and retrofit of safe, economical facilities, lifelines, and communities that perform acceptably during earthquakes. This research will be in critical areas such as foundation systems, structural and nonstructural building components and systems, and site treatment approaches. Research conducted through NEES should foster ancillary breakthrough technologies such as new imaging tools and site- and condition-assessment tools that can be used rapidly and economically to identify and evaluate site hazards or to reveal hidden flaws in structural components. Particularly needed is information that can be used as input for the emerging performance-based approach to the seismic design of constructed facilities and lifelines.

NEES will also play an important role in illustrating the effects of preventive measures such as zoning practices, building code modifications, and other loss mitigation strategies. For example, to avert a catastrophic tsunami loss in a coastal community, NEES research could provide local government with a series of practical options, such as

- Requiring structures to resist the wave impact,
- Constructing an offshore deflection structure,
- Modifying existing zoning and land use within the run-up area, and
- Undertaking a community education and awareness program.

Similarly, it is crucial to proactively increase capabilities for preparedness and emergency response, including more advanced simulation, instrumentation, and communication capabilities. Finally, education and the dissemination of policy information are key to creating public awareness and achieving policy objectives, and the dissemination component of the research should provide the necessary simulations, demonstrations, and curricular materials for this effort.

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 who will use the science and technology that 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 remainder of this chapter describes the committee's stakeholder involvement process, research needs within the seven topical areas, the expected benefits of research in these areas, and a business plan that integrates the needs, interests, and abilities of government, academia, and industry.

STAKEHOLDER INVOLVEMENT IN DEVELOPING THE RESEARCH PLAN

Since its inception, NEES has been envisioned as an inclusionary process that would address the needs and expectations of myriad stakeholders for earthquake engineering research. A specific objective of the committee was ". . . to articulate a dynamic, stakeholder-inclusive process for determining research needs for NEES and for changing the paradigm for earthquake engineering research."

This process began with the selection of the committee members who themselves represent, and further interact with, a broad range of stakeholders—graduate students, current and former professors and federal research managers, earth scientists, engineers, and an information specialist who represents practitioners and researchers. Committee members are deeply involved in the activities of the major organizations of the earthquake risk reduction community such as the Earthquake Engineering Research Institute, the Seismological Society of America, and the American Society of Civil Engineers. Many have had leading roles in the National Earthquake Hazards Reduction Program since its inception in 1978, and they personally participate in the major national and international conferences on earthquake risk reduction.

To gain further insight into the needs of the stakeholder community, the committee interacted with:

- Leaders of the National Science Foundation's (NSF's) Division of Civil and Mechanical Systems;
- The directors of the three NSF Earthquake Engineering Research Centers;
- Leaders of the NEES Consortium Development group, the System Integration group, and the NEES equipment sites;
- Leaders from industry and professional practice representative of the end users of NEES research results; and
- Researchers working on advanced sensing and information technologies, which will be exploited by NEES, and participating in collaborative efforts, which will exemplify NEES.

The committee meeting agendas included in Appendix D identify specific individuals with whom the committee interacted in its data-gathering sessions. In addition to this direct outreach, the committee initiated an electronic mailbox from September 1 through October 18, 2002, to solicit input from individuals with whom it could not interact directly. The mailbox format entailed posting the committee's statement of task to the National Academies' Web site and requesting comments. The results of the electronic forum are summarized in Appendix E.

GOALS FOR RESEARCH

Seismology

A fundamental challenge to earthquake engineering is predicting the level and variability of strong ground motion from future earthquakes. Improving this predictive ability requires a better understanding of the earthquake source, the effects of the propagation path on the seismic waves, and basin and near-surface site effects. Seismologists, geologists, and engineers base their understanding on a knowledge of the dynamics of earthquake fault rupture, the three-dimensional elastic and energy-dissipation properties (anelastic structure) of the earth's crust, modeled nonlinearities that occur in the shallowest parts of the earth's crust during strong earthquakes, and the complex interactions between structures and the seismic wavefield.

Challenge

Predicting the level and variability of strong ground motion from future earthquakes requires a combination of improved observations and large-scale simulation; simply extrapolating attenuation relations to larger magnitude earthquakes will not suffice.

Short-Term Goals

- Develop ground motion simulations from scenario earthquakes as input for engineering design.
- Integrate seismic ground motion excitation with the dynamic coupling of the soil in soil-foundation-structure interaction studies.
- Incorporate the effects of the spatial variation of ground motion into the design of large structures or lifelines.

Medium-Term Goals

- Map the three-dimensional velocity and attenuation structure of the earth's crust in major earthquake-threatened urban areas for ground motion modeling.
- Based on seismic observations, develop stochastic descriptions of the crustal heterogeneity in order to model ground motion at frequencies of greatest engineering interest.
- Develop measures of ground motion intensity that better predict the damage potential of strong ground motions.

Long-Term Goals

- Adopt simulation-based seismograms based on a properly validated fundamental understanding of the physics of earthquakes, wave propagation, and soil behavior, for performance-based design.
- Perform fully coupled soil-foundation-structure interaction analysis based on a fundamental understanding of the physics of soil nonlinearity.

Tsunamis

Tsunamis are generated by seismic fault displacements of the seafloor, landslides triggered by earthquakes, volcanic eruptions, or explosions. All of these generation mechanisms involve a displacement of the ocean boundary, either at the seafloor, at the shoreline, or at the water surface. Tsunamis can be generated in many locations, including oceans, harbors, lakes, reservoirs, and rivers. The run-up and inundation associated with tsunamis causes loss of life, destruction, and economic losses. Coastal areas, which are often preferred sites for residences, industry, and ports, are vulnerable to seismically generated sea waves from near and distant sources.

Challenge

A complete numerical simulation of tsunami generation, propagation, and coastal effects should be developed to provide a real-time description of tsunamis at the coastline for use with warning, evacuation, engineering, and mitigation strategies.

Short-Term Goals

- Investigate the run-up of both breaking and large, nonbreaking, nonlinear transient translatory long waves at the shoreline.
- Answer questions related to the resonant excitation of harbors and embayments by tsunamis.
- Determine how nearshore bathymetric features control the focusing and defocusing of breaking and near-breaking nonlinear waves.
- Study the propagation of waves generated by aerial, partially aerial, and submarine landslides in offshore, onshore, and alongshore directions and the associated run-up.
- Develop a better understanding of transient sediment transport in the direction of, and orthogonal to, the direction of wave propagation of transient translatory long waves.
- Quantify the impact forces on structures due to objects (e.g., cars, trees, and poles) transported by tsunami-like waves as well as the forces imposed by the wave and the run-up tongue on coastal structures.
- Determine the effect of tsunamis on individual buildings and groups of buildings.
- Work with the National Tsunami Hazard Mitigation Program, a three-agency/five-state partnership led by the National Oceanic and Atmospheric Administration (NOAA) to define research needs, so that the NEES program can best support NOAA's mission, bearing in mind that NOAA is responsible for the nation's tsunami warning system.

Medium-Term Goals

- Verify and validate the numerical models used for defining inundation limits for design and planning purposes in tsunami-prone areas—for example, the West Coast of the United States (including Alaska), Puerto Rico, and Hawaii.
- Work with the geotechnical community and centrifuge facilities to study the mechanics of aerial, partially aerial, and submarine landslides.

Long-Term Goals

- Develop comprehensive, interactive scenario simulations that integrate the physical aspects of the problem—tsunami generation, propagation, run-up, and structure interactions—with societal issues, such as the transmission of warnings to the public, evacuation, environmental impacts, rescue tactics, and short-term and long-term recovery strategies.

Geotechnical Engineering

Subsurface soils are one of the primary factors affecting the performance of constructed facilities and lifelines during earthquakes. Yet these soils are typically the most variable and least controlled and understood of all materials in the built environment. As historical earthquakes have repeatedly borne out, greater damage occurs in areas of weaker soil, and significant losses are often associated with soil amplification and soil-related failures such as liquefaction, landslides and slope failures, fault displacement/offsets, and seismically induced instability of geotechnical structures (e.g., earthen dams, embankments, waste fills). It is instructive and encouraging to note that recent experience shows that proper engineering procedures, especially ground improvement, can mitigate earthquake-related damage and reduce losses. Although great strides have been made in the past two decades to improve predictive capabilities and seismic engineering design practices, there remains an urgent need for improved modeling procedures and predictive tools, more powerful site-characterization techniques, and more quantitative guidelines for soil-improvement measures.

Challenge

Improved modeling procedures and predictive tools are needed along with more powerful site-characterization techniques and more quantitative guidelines for soil-improvement measures.

Short-Term Goals

- Improve understanding of soil-foundation-structure interaction due to seismic shaking.
- Develop a better understanding of how local soil conditions modify seismic shaking and how these conditions can be identified and designed or zoned for, especially in regions that contain deep, soft soil deposits that can amplify ground motions.
- Improve in situ testing of soil properties to achieve a three-dimen-

sional understanding of soil and site conditions and a quantification of parameters that directly relate to the engineering performance of soils.

- Develop detailed and curated databases on the performance and soil characteristics of sites subjected to strong earthquakes (i.e., liquefied and nonliquefied free-field areas, improved zones, and buildings, structures, and lifelines where soil failure or amplification contributed to damage).

Medium-Term Goals

- Develop new ground-improvement technologies, as well as more quantitative guidelines for existing ground-modification and foundation-retrofitting practices.
- Improve the ability to predict liquefaction-related deformations and responses of level and gently sloping ground and their effects on facilities and lifelines.
- Improve prediction of ground rupture patterns and structural interactions along faults.
- Improve geotechnical modeling procedures, both physical and numerical, and develop parameters that can be used for performance-based seismic engineering analyses.
- Validate methods for strengthening waste containment facilities, reinforcing slopes, and identifying potentially hazardous landslide areas.
- Expand and validate estimating tools for liquefaction triggering and permanent deformation so that they consider the influence of foundation and structural elements on the sequence, timing, and location of liquefaction and resulting deformations.

Long-Term Goals

- Predict earthquake-induced deformations and the response of natural slopes and earthen structures such as dams, dikes, levees, waste containment facilities, highways, and bridge approaches, with an emphasis on post-liquefaction-related deformations and failure phenomena.
- Produce three-dimensional, real-time simulations and visualization of soil, foundation, and structure deformations under conditions of liquefaction, soil amplification, or fault offset.
- Develop simplified procedures for use by practicing engineers based on a comprehensive understanding of the seismic behavior of the site-structure system.

Buildings

Damage to buildings in recent earthquakes illustrates that despite advances in the design and construction of seismically resistant buildings, a significant increase in the knowledge and understanding of building performance is needed to ensure people's safety and to limit economic losses during earthquakes. This will require an understanding of variations in building types nationally as well as variations in the adoption and enforcement of local building codes to address earthquake hazards. Performance assessments of the complete structural system rather than just individual components are of particular interest. Predicting the performance under extreme earthquake loads of existing buildings with little seismic resistance, of structures retrofitted to current standards, and of newly built structures continues to be a major challenge to structural engineers. This is particularly true when deformations are large and do not follow conventional linear deformation theory.

Challenge

There is a need to predict and improve the performance of existing buildings without seismic resistance, retrofitted buildings, and newly built structures when they are subjected to the extreme loads imposed by earthquakes.

Short-Term Goals

- Develop analytical models that can predict the seismic performance of existing buildings.
- Develop repair and retrofit technologies for existing high-risk structural systems such as unreinforced masonry buildings, concrete wall tilt-up industrial buildings, and many pre-1975 structures, including wood-framed houses, apartments, and commercial buildings.
- Develop retrofit strategies for historical buildings and structures that do not sacrifice historical integrity for seismic resistance.

Medium-Term Goals

- Validate the behavior of buildings having smart materials and structural systems. Perform analyses to fully illustrate the ability of smart technologies to achieve various performance objectives and evaluate their benefits and costs.
- Develop a curated data repository that contains information on

experimental models and test results for structural components, nonstructural components, and foundations.

Long-Term Goals

- Using a suite of integrated sensors, obtain diagnostic information on the condition of both structural and nonstructural components.
- Implement practical and economical smart structural systems.
- Make performance-based seismic design the standard of practice for the design of new buildings and the renovation of existing buildings. Buildings will be rated and designed for specific performance levels under various levels of earthquake input.

Lifelines

The mitigation of earthquake hazards for lifeline infrastructures presents a number of major problems, primarily because of the vast inventory of facilities and their broad spatial distribution. Lifelines are typically more vulnerable than conventional facilities to earthquake hazards, because there is less opportunity to avoid these hazards through prudent site selection or site improvement. Although much has been done since the San Fernando earthquake of 1971 to increase our understanding of lifeline vulnerability to earthquake hazards, to improve the engineering and construction of new or replacement facilities, and to retrofit existing facilities, much remains to be done, especially in seismic areas of the United States outside California.

Challenge

Technologies must be developed to protect the vast inventory of lifeline facilities (complex transportation and utility infrastructure, which 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.

Short-Term Goals

- Develop analytical models that can predict the seismic performance of existing lifeline systems.
- Improve the seismic resistance of porcelain insulators.
- Mitigate damage to rigid bus bars as a result of differential displacement of heavy equipment components.

Medium-Term Goals

- Develop performance-based design requirements that can guide the economical improvement of the nation's vast network of lifelines and facilities.
- Develop a fuller understanding of the impacts of complex infrastructure system failures on our social, economic, and political institutions.
- Improve our ability to predict liquefaction-related deformations and responses of level and gently sloping ground and their effects on facilities and lifelines.
- Improve the ability to predict and characterize liquefaction-induced ground movements at bridge abutments (river crossings).
- Improve methods for assessment of liquefaction and liquefaction-induced ground movements.
- Develop ground-improvement strategies for liquefiable marine deposits.
- Determine post-buckling compressive strain limits for pipe.
- Improve methods for analyzing strain localization in pipe resulting from upheaval buckling.

Long-Term Goals

- Improve characterization of soil-pipe interaction and validate with full-scale testing for various types of ground deformation.
- Predict earthquake-induced deformations and the response of natural slopes and earthen structures such as dams, dikes, levees, waste containment facilities, highways, and bridge approaches, with an emphasis on post-liquefaction-related deformations and failure phenomena.

Risk Assessment

The challenge in communicating risk is having the tools to adequately assess and convey hazard, exposure, vulnerability, and loss in a clear and quantitative manner to a nontechnical audience. Although damaging earthquakes are rare events in any particular community, they have the potential to change that community forever. Many people (citizens, business owners, government officials, elected representatives) are totally unaware of their potential exposure to a damaging earthquake or, if aware, of how devastating the consequences could be. Risk assessment and its widespread dissemination are a vital component of earthquake disaster prevention.

Challenge

Decision makers should be given information to reduce risk exposure and improved loss-estimation and risk-mitigation alternatives and tools that enable them to make better decisions to reduce risk than are currently possible.

Short-Term Goals

- Plan with FEMA's Natural Hazard Loss Estimation Methodology (HAZUS) and private-sector risk assessors for NEES contributions to improved risk-assessment technologies.
- Review loss models, including direct and indirect losses, to identify gaps and define research needs.
- Develop improved decision-support and risk-management models and tools for use in policy and financial decisions.

Medium-Term Goals

- Develop improved structural performance and vulnerability models and data for important building and lifeline types for use in risk assessments.
- Develop improved site hazard data and models for risk assessments.
- Develop improved models and data for building and infrastructure inventories.
- Develop simulation and visualization models and tools for consequence analysis and risk assessments for individual structures.
- Develop regional simulation and visualization models and tools for consequence analysis and risk assessment to study the interactions of buildings, lifelines, society, and economies.
- Develop improved cost models for existing and new seismically resistant buildings and lifelines.
- Develop advanced loss estimation models exploiting NEES capabilities.

Long-Term Goals

- Expand performance and vulnerability models and data to exploit advancing knowledge and innovative materials and systems.
- Incorporate advancing knowledge from site hazard models and data.

- Advance simulation and visualization techniques as user needs evolve and technical capabilities improve.
- Continually update cost- and loss-estimation models to incorporate new knowledge and experience.

Public Policy

Unless NEES research results are adopted into public law, local ordinance, or building, fire, and zoning codes, earthquake disaster reduction efforts are unlikely to progress fast enough to truly prevent disasters. One of the major measures of NEES's long-term success will be the retention of earthquake hazard mitigation as a public and governmental priority. The timely adoption of policy measures will be the path to the committee's vision of earthquake disaster prevention.

Challenge

The general public, local governments, and legislative bodies must raise their awareness and acceptance of earthquake hazard mitigation.

Short-Term Goals

- Increase the awareness of earthquakes and earthquake hazard mitigation across the spectrum of society: government officials, business leaders, private citizens, and students.
- Generate sufficient public support for the adoption and enforcement of current building codes in all communities that have more than a 1 percent per year risk of a damaging earthquake.
- Generate sufficient public support for structural retrofit programs for high-risk structures in all earthquake-prone communities.
- Persuade public opinion that seismically hazardous structures should be prominently labeled as such.

Medium-Term Goals

- Generate cost-effective techniques to retrofit existing structures to resist damage.
- Provide validated, quantitative loss-estimation methods that are not only specific to a local area but also generalizable to a regional scale.
- Require performance-based design for all structures occupied by more than 100 people.
- Generate sufficient political support to fund predisaster mitigation grants.

- Influence public opinion so that many communities begin to undertake coordinated, community-wide programs to reduce their earthquake vulnerability.
- Develop statistically reliable estimates of earthquake probability and scenario-based damage.

Long-Term Goals

- Provide information to support programs requiring retrofit or phasing out of all structures at risk of collapse in earthquakes above a predetermined magnitude.
- Reduce the risk of damage in structures constructed after 2010 to a small fraction of that for then-existing structures.
- Provide information to support programs requiring structural reinforcement or replacement of all public buildings that have excessive risks of earthquake damage.

EXPECTED BENEFITS OF THE NEES RESEARCH PLAN

Seismology

NEES research in engineering seismology will result in more accurate and reliable knowledge of earthquake ground motion in seismic regions. Knowledge of the anticipated ground motion is necessary in order to determine the inertial forces that a structure must withstand during an earthquake. Predicting the ground motion to which structures will be exposed during their lifetimes is a crucial first step in designing earthquake-resistant facilities and retrofitting existing structures.

Tsunamis

Tsunami simulation models developed through NEES research will serve as the real-time element of a nationwide tsunami warning system and will be helpful in the design of tsunami-resistant structures and facilities and the development of mitigation strategies. Some of the investigations, such as the scour and structural studies related to wave-induced impact forces, will ultimately be used to produce engineering design manuals for tsunami-resistant structures.

Geotechnical Engineering

There are many potential benefits from NEES research efforts in geotechnical engineering. A better understanding of slope and soil deformation and liquefaction under earthquake loadings will lead to improved methods for soil treatment to improve its performance. There are multiple benefits from this area alone—namely, better performance of foundations, buildings, and lifelines, which will result in reduced losses. At the same time, increased knowledge will permit the design of more economical foundations and earthen structures tailored to the specifics of geology and seismic risk. NEES will also support the development of advanced numerical models that should lead to more robust analyses and reduced testing costs.

Buildings

The results of the research produced by NEES will increase our understanding of the behavior of buildings and their structural and nonstructural systems and how to simulate their response to seismic loads on both structure and system levels. This understanding will include not only new construction but also the many at-risk structural types requiring retrofit. Historical structures pose particular challenges in this regard, because care must be taken so they do not lose their historical significance in the process of retrofitting them. NEES will provide the validation testing necessary for design engineers to incorporate new materials and smart systems into structures both new and old.

Lifelines

Because it has much in common with the preceding issues, NEES research into lifeline behavior will build on the work done in engineering seismology, geotechnical engineering, and buildings and structures. For example, high-reaction testing frames could be used in the bending test of pipe to calibrate finite element models; liquefaction studies would be applicable to lifelines as well as foundations; and shake-table studies could test many systems and components at full and reduced scales. This research would lead to mitigation strategies for the huge inventory of vulnerable capital assets throughout the country as well as standards for the development of performance-based design criteria. The ultimate outcome will be improved seismic performance at lower life-cycle cost.

Risk Assessment

Risk assessment provides the quantitative information needed to guide rational investments that will reduce the vulnerability of both new and existing facilities. Presentation of the results of risk assessments that are based on improved loss-estimation models in an appropriate decision-support framework can assist facility owners and government officials in evaluating risks and selecting alternatives that are consistent with their tolerance for risk exposure and available resources. NEES research will support the loss-estimation and risk-assessment activities that are critical to ensure the implementation of cost-effective mitigation strategies.

Public Policy

NEES research will provide key information and tools to facilitate policy decisions based on hazard and risk exposure for a specific region or the entire nation. Risk management strategies will need to consider the ability of a community to enact proposed legislation in the face of financial constraints and recognition of land use rights. Simulation models based on NEES research on analyzing losses from scenario earthquakes and policy options for mitigating them will help legislators assess the effectiveness and benefits of proposed policies. Success in this area will facilitate more rapid and widespread implementation of proactive seismic mitigation policy.

IMPLEMENTING THE RESEARCH PLAN

The NEES Business Model

The committee discussed at some length the potential for NEES to become self-sustaining as a research and testing enterprise in earthquake engineering. Initially, and for the foreseeable future, the committee foresees the majority of funding being provided by NSF and other NEHRP agencies. This position is based on historical funding patterns for earthquake engineering research in the United States. However, as the program matures, the NEES Consortium becomes firmly established as an operating entity, and a track record is established for producing results needed by the private sector, support from the private sector and other governmental agencies should be pursued. The committee believes that there are many potential relationships to involve individual NEES sites and other investigators in the research plan. They may help attract needed funding and provide for the effective involvement of the entire earthquake community of educators, graduate students, researchers, and practitioners, as well as for the effective transfer of research results to practice. These relationships include the following:

- The planned NEHRP research program,
- Cooperative research with federal and other public agencies,

- Cooperative research with industry and industry associations,
- Serving as a user facility for academic researchers,
- Serving as a user facility for industry researchers,
- Collaborative research with international research institutions that have similar and complementary experimental facilities, and
- Serving as an information source for researchers, practitioners, educators, government, industry, and the media.

The list of potential projects that can be undertaken by NEES to implement the research plan is extensive. NSF should make every effort possible to encourage the involvement of multiple equipment sites and many investigators in these research efforts. NSF should also take advantage of the research capabilities available through the existing earthquake engineering research centers as well as small teams or single investigators at universities and other laboratories by actively encouraging their participation. The unprecedented connectivity provided by NEES can bring these seemingly disparate elements to bear on major issues. NSF should strongly consider formulating future solicitations to encourage proposals that address these broad, multidisciplinary challenges.

- Single investigator grantees (SIGs) are the traditional heart of NSF's programs. Their unsolicited proposals are a source of unexpected good ideas for the advancement of knowledge and practice. NEES has to be open to SIGs to ensure its own health (by involving the best research and researchers) and to foster the public good by making the NEES resource available for the exploration of unplanned inspirations.
- Potential investigators, including SIGs, need continuing good access to information on NEES programs, capabilities, and accessibility. NEES facilities should be easy and economical to access in a timely manner. Investigators and students using a NEES facility should find good living and working conditions for both on-site and remote access. Both technical and human support will be needed. It is particularly important that participating investigators become an integral part of the intellectual community of NEES.
- To ensure that the research is driven by practical applications, cooperation and partnerships with federal agencies should be a critical component of NEES. This can have particular benefit when considering the potential transfer of earthquake disaster procedures to emergency situations involving national security.
- To increase cost-effectiveness and promote collaboration, there should be an effort to involve other large laboratories and laboratory equipment other than that at NEES equipment sites.
- NEES needs an intellectual environment celebrating and recogniz-

ing diverse contributions to work done in or with NEES. For instance, sharing best practices in instrumentation can greatly advance many investigators' work and reduce the slope of the learning curve for graduate students.

- Standard software applications will be required that can be used systemwide for data acquisition, processing, storage, display, and Web-based networking among participants and users of data. Ideally, these software applications should be developed using commercial off-the-shelf software platforms. Widely used software applications have the advantages of being upwardly compatible and supported by operating system managers, as well as offering new releases of their own applications. Custom applications developed by the NEES system integrator or individual laboratories will probably have high maintenance requirements. For the efficient use of funds, the goal should be to minimize software maintenance.
- Protection of intellectual property rights will be a challenge for NEES. Commercial sponsors will need to protect their intellectual property rights to profit from their investments in research. Clear guidance in this area is important to encourage effective marketing and exploitation of knowledge gained in NEES.

The development and funding of a NEES research program provides the opportunity to identify and address significant goals that will reduce the consequences of earthquakes for the nation's citizens.

A Stakeholder-Inclusive Process for Guiding NEES Research

It is essential that the talents of the earthquake community be used both for the continuing evolution of these program topics and for prioritizing them. However, the type of progress promised by NEES will not be achieved by relying on the serendipitous submittal of appropriate proposals. The committee believes that unlike the approach taken with traditional NSF research initiatives, strategic guidance must be provided from within NSF itself. It is for this reason that the committee believes that a strategic advisory group to engage the entire community of interest for earthquake engineering research should be established. The mission of this group would be to assess, on a periodic basis, the state of progress in resolving critical issues and to outline promising areas for NEES to pursue as research results become available. These periodic assessments would provide a framework for identifying and prioritizing new research directions and would also establish performance objectives for new lines of inquiry.

Some of the responsibilities and authority of the strategic advisory group might include the following:

- To recommend to NSF the short- and long-term goals of the program and relative funding levels,
- To recommend to NSF topical goals, prioritization of these goals, and allocation of funds to achieve them, and
- To assist in identifying opportunities for the implementation of NEES results.

Securing Society Against Catastrophic Earthquake Losses

The Earthquake Engineering Research Institute (EERI), with an NSF grant, recently released a 20-year research and technology transfer plan for earthquake engineering (EERI, 2003). The plan, *Securing Society Against Catastrophic Earthquake Losses*, identifies basic and applied research that can substantially reduce losses from earthquakes and also help protect the built environment from the devastating effects of disasters caused by wind, flood, fire, and terrorist bombings. The plan builds on the accomplishments of the past 25 years of research in earthquake engineering, while taking advantage of breakthrough opportunities that are presented by advances in computing, information processing, engineering, and understanding human behavior in earthquakes. The EERI plan is not presented simply as a research vision but rather as a vision for an entire society shocked into awareness of some of the catastrophic risks that it faces. The plan states that earthquakes are catastrophic risks that need to be addressed in a more concerted way than they have been to date and that doing so will have enormous benefits for society as a whole.

The recommended distribution of costs among the various activities of the EERI research and action plan for fiscal years 2004 through 2023 are summarized in Figure 5.1. Although the estimated annual cost of $325 million to carry out this research and action plan is significant, it amounts to less than one-thirtieth of the annualized U.S. earthquake risk of $10 billion estimated by EERI and 14 percent of the $4.4 billion annual loss calculated by FEMA. The total cost of $6.5 billion over the 20-year program life is less than one-fifteenth of the potential cost of a single catastrophic earthquake ($100 billion).

Funding for NEES

On the matter of an appropriate level of funding for NEES, the committee offers several observations. First and foremost, the committee notes that the various NEES equipment sites will provide the core of NEES

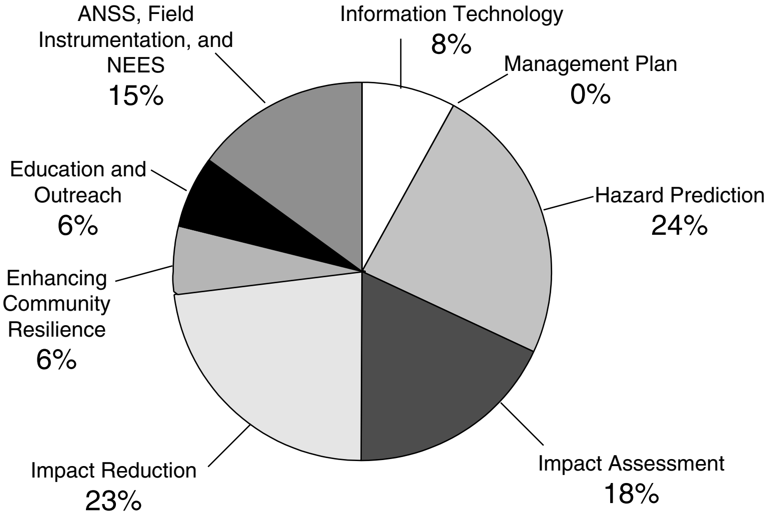

FIGURE 5.1 Distribution of costs in the EERI research and action plan budget for fiscal years 2004 to 2023. SOURCE: EERI (2003).

research activities. In addition to the testing equipment, this extensive research infrastructure will include many educators, researchers, graduate students, and technicians. Fully developing the capabilities of NEES will require that at each equipment site, the various players involved in a project function as a team and learn to work together to produce the best results possible. To do this will require that the equipment and the research team be continuously engaged in testing and experimentation—and have adequate resources to do so. It is the committee's carefully considered opinion that high-quality research cannot be produced consistently if the equipment is not fully utilized so that the research staff can learn its capabilities and limitations and maximize their skills. Second, NEESgrid is more than just a systems integration project. It encompasses the co-development of new collaboration technologies and data standards and is being constructed on information technologies that are new and evolving rapidly. Although there may be some expectation that the foundational information technologies are similar to the fixed investments of the NEES equipment sites, they are not the same. Once NEESgrid, the initial system integration project, is complete in 2004, a substantial foundation will be in place, but many problem-specific applications and capabilities will still need to be developed. Dedicated funding will be required to continue the development of the information technology components of NEES and to realize the research goals.

The committee is aware that there will never be enough money to fund everything that is important and that regardless of how much funding is provided, there will always be more needs than resources to address them. For this reason, an effort was made to develop a convergent solution. The committee identified the research needs and then, based on its collective experience, determined the basic amount necessary to operate and maintain a research program using the NEES infrastructure investment. The collective experience of the committee members suggests that the annual operating costs of large engineering research machines are on the order of 50 percent of the capital cost. In the case of NEES, this would be somewhat more than $40 million. The committee did not try to determine the level of investment in NEES research that was justified by the expected benefits; the long-term payoff is so great as to justify almost any investment level. The EERI research plan recommends funding in the amount of $325 million for fiscal years FY2004 through FY2008. This amount is for the entire earthquake program and includes earthquake prediction, engineering research, technology transfer, and education. Approximately $240 million, or an additional $48 million per year for the next 5 years, would be applicable to research that could be conducted through NEES, and the committee selected this as a baseline amount. This amount is of the same magnitude as the committee's empirical estimate. On this basis, the committee believes that NSF should be prepared to provide this general level of funding ($40 million to $50 million per year) as a minimum to support the NEES initiative. This amount is consistent with an earlier report on earthquake engineering research and testing capabilities in the United States (EERI, 1995). In light of this, the committee strongly recommends that NSF initiate whatever actions are necessary to ensure that this level of additional funding is available so that NEES can meet the grand challenge of ultimately preventing earthquake disasters. Should more funding be made available, the pace of research could be accelerated and the benefits of that research realized sooner.

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6

Recommendations for Meeting the Grand Challenge

The preceding sections of this report make a compelling argument that, while much has been accomplished, there is still much to be done to prevent earthquake disasters in the United States. Limiting or reversing the growth of seismic vulnerability in the United States will require a vigorous earthquake engineering research program over the next 10 years and beyond. Although earthquake engineering research has led to major advances over the past 30 years, much of this research is along fairly narrow, discipline-specific lines and is not well integrated from a broad systems perspective. Although the traditional research model has produced much work of value and undisputed improvement in the performance of the built environment, such fragmented research activities are not able to keep pace with the accelerating demands for new, more complex hazard mitigation solutions.

The committee believes that NEES, as the collaboratory network for earthquake engineering simulation, can make major contributions to developing comprehensive and fully integrated earthquake simulations that connect credible expectations for seismology and geophysics at one end with private and government actions to reduce risk at the other. Results from these simulations will have to be coupled with building inventories, information on 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. Knowing the magnitude and likelihood of expected losses would provide a benchmark for the value of mitigating actions, from better site selection, to improved structural designs, to land use regulation. Ultimately, knowledge-based systems will be developed to support decision making by policy makers and planners.

This is why the NEES collaboratory is so timely: By promoting collaboration and the sharing of resources, NEES can accelerate the pace of earthquake engineering research and the deployment of solutions to complex problems in earthquake hazard reduction. The NEESgrid will be a comprehensive system for archiving and sharing research data, real-time streaming video, experimental and simulation processes, teleparticipation in experimentation at distant locations, and other features yet to be conceived.

Although most NEES research will focus on expanding the science and technology knowledge base, public policy actions that translate research results into practice are essential for ultimately preventing earthquake disasters. These actions include land use planning and zoning, building code adoption, enacting requirements for identifying and correcting hazards in existing buildings and lifelines, and either directly funding or providing financial incentives for risk reduction. Informed decisions by property owners, businesses, and public utilities—such as whether to retrofit existing facilities, invest in new facilities, or sell vulnerable facilities and relocate to safer sites—also are essential for preventing earthquake disasters.

Similarly, it is crucial to increase capabilities for pre-earthquake preparedness and emergency response, including more advanced simulation, instrumentation, and communication capabilities. Finally, education and the dissemination of policy information are key to creating public awareness and achieving policy objectives, and the research community should provide the necessary simulations, demonstrations, and curricular materials for this effort.

All of these efforts will require multidisciplinary collaboration between, on the one hand, the scientists and engineers who will develop and test new theories on earthquakes, earthquake damage, and its mitigation and, on the other hand, the social and political scientists who will use the science and technology 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 remainder of this chapter presents the committee's recommendations. They are offered in the spirit of helping NSF 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.

> **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 this committee. Special emphasis should be placed on grand challenge research activities that include multiple equipment sites and investigators from many disciplines.**

Complex, multidisciplinary grand challenge research problems were identified and presented in Chapter 3 of this report. In Chapter 5, the committee articulates a research agenda with short-, medium-, and long-term goals that it believes should be pursued under the NEES initiative. The committee believes that NEES can address and resolve the problems that underlie progress in earthquake engineering by engaging several of the new equipment sites and investigators from many disciplines who may be located at those sites or elsewhere. Understanding can thus be advanced in quantum leaps rather than small, incremental steps. Several examples of collaborative partnerships are described in Chapter 3. Funding levels are discussed in Recommendation 3.

> **Recommendation 2. The National Science Foundation should also support NEES projects of more modest scope that will produce and report useful results within a 2- to 3-year time frame. 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.**

NEES is an ambitious program that has the potential to revolutionize the way that earthquake engineering research is conducted. Revolutions such as this do not happen overnight, however, and the adoption and acceptance of new technologies by a broad community are a matter having sociotechnical dimensions. NEES will have to demonstrate solid progress on tangible goals that are desirable and beneficial to researchers, practitioners, and educators alike, as well as to society in general. Compelling examples of what is possible are needed in order to accelerate interest, acceptance, and the critical community feedback processes that will inform the continued evolution of NEES.

> **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 infrastruc-**

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

First, the committee notes that the various NEES equipment sites will serve as the core of NEES research activities. In addition to the testing equipment, this extensive research infrastructure will include many educators, researchers, graduate students, and technicians. Fully developing the capabilities of NEES will require that at each equipment site, the various players function as a team and learn to work together to produce the best results possible. To do this will require that the equipment and the research team be continuously engaged in testing and experimentation—and that the team has adequate resources to do so. It is the committee's carefully considered opinion that high-quality research can be produced consistently only if the equipment is fully utilized, so that the research staff can learn its capabilities and limitations and maximize their skills. The committee believes that adequate funding must be available to operate and maintain the equipment sites in a high state of readiness.

Second, NEESgrid is more than just a systems integration project. It encompasses the co-development of new collaboration technologies and data standards and is being constructed on information technologies that are new and evolving rapidly. There may be some expectation that the foundational information technologies are fixed investments somewhat like the NEES equipment, but they are not the same. Once the initial system integration project (i.e., NEESgrid) is complete (in 2004), a substantial foundation will be in place, but many problem-specific applications and capabilities will still need to be developed. Dedicated funding will be required to continue developing the IT components of NEES and to realize the research goals.

The committee is aware that there will never be enough money to fund everything important and that regardless of how much funding is provided, there will always be more needs than resources to address them. For this reason, an effort was made to develop a convergent solution. The committee identified the research needs and then, based on its collective experience, determined the basic amount necessary to operate and maintain a research program using the NEES infrastructure investment. The collective experience of the committee members suggests that the annual operating costs of large engineering research machines are on the order of 50 percent of the capital cost. In the case of NEES, this would be somewhat more than $40 million. The committee did not try to determine the level of investment in NEES research that was justified by the expected benefits; the long-term payoff is so great as to justify almost any investment level. The EERI research plan recommends funding in the amount of $325 million for FY2004 through FY2008. This amount is for the entire earthquake program and includes earthquake prediction, engineering research, technology transfer, and education. Approximately $240 million, or an additional $48 million per year for the next 5 years, would be applicable to research that could be conducted through NEES, and the committee selected this as a baseline amount. This amount is of the same magnitude as the committee's empirical estimate. On this basis, the committee believes that NSF should be prepared to provide this general level of funding ($40 million to $50 million per year) as a minimum to support the NEES initiative. In light of this, the committee strongly recommends that NSF initiate whatever actions are necessary to ensure that this level of additional funding is available so that NEES can meet the grand challenge of ultimately preventing earthquake disasters. Should more funding be made available, the pace of research could be accelerated and the benefits of that research realized sooner.

> **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.**

To fulfill its potential and articulate and implement the vision of ultimately preventing earthquake disasters, NEES will require focused leadership. Research results must be tied to clearly understood objectives for earthquake loss reduction that transcend findings in a single discipline or group of disciplines. Achieving these objectives will require proactive management of the program that reflects problem-oriented, interdisciplinary research. The committee believes that unlike traditional NSF research initiatives, strategic guidance must be provided from within NSF itself. It is for this reason that the committee recommends the establishment of a strategic advisory group to engage the entire community of interest for earthquake engineering research. The mission of this group would be to assess, periodically, progress in resolving critical issues and to outline promising areas for NEES to pursue as research results become available. The periodic assessments would provide a framework for identifying and prioritizing research directions, and for allocating funding levels among program activities, and it would also establish performance objectives for new lines of inquiry. The advisory body could also work with NSF and the NEES Consortium to identify opportunities for the implementation of NEES results. It should include a broad range of disciplines, including the earth, social, and policy sciences, engineering, and computational modeling, and be geographically representative as well.

> **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.**

In addition to NSF, the NEES Consortium, and the agencies of the National Earthquake Hazards Reduction Program, federal, state, and local government agencies, government laboratories, and private industry all have some responsibility for addressing earthquake hazards. Effective outreach and coordination with these groups will maximize the effectiveness of NEES in creating earthquake-resistant communities.

> **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 ultimately preventing earthquake disasters in the United States.**

The NEES community must extend far beyond the designated NEES equipment sites and must foster the democratization of earthquake engineering research. NEES participants should include personnel at universities of all sizes, government laboratories, government agencies involved with the National Earthquake Hazards Reduction Program, private industry, and public policy makers. Ongoing financial support through NSF will be required to fund individual and multicollaborator research and to keep pace with the rapidly evolving landscape of information technology. Private industry should consider NEES as a resource for the development of solutions, and collaboration between NEES and private industry should be promoted to create a direct conduit between research and practice. The agencies of the National Earthquake Hazards Reduction Program, as well as other agencies at all levels of government, will benefit significantly from interactions with NEES. Government agencies should consider NEES as an adjunct in fulfilling their program needs and therefore should consider providing both logistical and financial support to NEES. As NEESgrid evolves, NSF and NEES will need to develop information management policies that recognize the intellectual property interests of individual participants while serving the needs of the larger research community by allowing it to access all NEES-generated research data. The data-related efforts of the NEES project are fundamental to its success and are being well received by researchers and practicing engineers alike. Progress in advancing data and metadata efforts for the earthquake engineering community is only in its infancy, but advances in this area are likely to have a high return on investment. These activities will have to be prioritized, funded, and continued into the future.

> **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.**

The ultimate success of NEES will be demonstrated by its ability to impact society and reduce earthquake risk. The results of NEES research must be transferred to individuals and institutions that can take advantage of them and implement the knowledge gained. Earthquakes, tsunamis, and natural disasters are enormously relevant and interesting to society in general and to students in the classroom. Web-based environments for posing questions, running simple, idealized model experiments or simulations or even engaging in simulated disaster response management offer exciting possibilities for leveraging NEES capabilities. NEES has a responsibility to contribute to the education of students, the continuing education of faculty, and the elevation of public awareness about earthquake engineering and earthquake hazard in society as a whole. To maximize the impact of NEES research results, the NEES Consortium should generate public policy briefs, press releases, and educational resources for the general public. For standards writers and practitioners, research results should be conveyed in a format that presents the relevant technical findings of the research and their impacts on practice. The NEES Consortium should facilitate open discussion between standards writers, practitioners, and researchers in order to clarify the implications of the research and identify gaps in understanding for future research endeavors.

> **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.**

The physical modeling, numerical simulation, and networking tools developed through NEES can be utilized to study and solve problems in an entire spectrum of geotechnical and structural engineering applications, such as the effect of construction and traffic vibrations on structures, the preservation and repair of historic structures, the impact forces of large debris such as cars and trees transported by floods, and the effect of intense heat and explosions on structural performance. Researchers interested in studying these and other appropriate issues should be invited to use NEES facilities when they are not fully occupied with earthquake engineering research. In addition, the Department of Homeland Security, government laboratories, and other federal agencies should be encouraged to treat the NEES collaboratory as a resource for enriching their own programs and should consider both logistical and financial support for NEES.

> **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.**

Although NEES is a national effort, earthquake research is a global concern, and NEES must play a long-term role in advocacy, partnerships, and joint research with other national and international projects. While knowledge transfer between developed nations has already accelerated the development of sophisticated earthquake-resistant design, NEES can do more with the dissemination of technology and knowledge transfer to developing nations. Proactive investments made with respect to the identification of problems in, and technology transfer to, developing countries will reduce future expenditures on earthquake-related disaster relief, limit the enormous detrimental effects of earthquake disasters on already struggling economies that are often felt worldwide, and satisfy a moral imperative to reduce the number of lives lost in future seismic events.

> **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.**

The strength of the NEES vision is in collaborative and integrative research that combines theory, experimentation, computational modeling, and physical testing for model validation. Integrating across disciplines will help to foster the problem-oriented research that is required to translate research results into effective risk-reduction practice. The need for multidisciplinary efforts suggests that multi-investigator and multi-institutional research will play an important role. At the same time, NSF needs to ensure that innovative, single-investigator research continues to thrive. There is a grave concern among many researchers in the earthquake engineering community that the NEES program will jeopardize the funding of researchers not directly affiliated with NEES equipment sites or with large, established engineering research organizations such as the national earthquake engineering centers. Similarly, there is concern among researchers not affiliated with NEES equipment sites or earthquake centers that the concentration of resources in those locations will place them at a competitive disadvantage for funding and attracting top-flight graduate students. NSF must ensure that researchers not directly affiliated with NEES equipment sites continue to receive strong support and that the NEES program is inclusive, drawing on a broad and diverse set of researchers. Efforts will have to be made to foster the formation of diverse teams in pursuit of solutions to the grand challenges in earthquake engineering. Funding initiatives that combine, for example, collaborative efforts among NEES awardees, the national earthquake engineering centers, university researchers not located at equipment sites, researchers at government laboratories, practicing engineers, social and policy scientists, and information technologists will be required in order to accomplish this. An important potential role for the NEES Consortium will be to promote the development of new, cross-disciplinary research proposals that span these cutting-edge areas, establishing partnerships between NEES experimental researchers and numerical modelers, practicing engineers, and academic researchers in computer and computational science and engineering, information technology, and knowledge systems.

Appendixes

A

The George E. Brown, Jr., Network for Earthquake Engineering Simulation

In 2001, the National Science Foundation (NSF) announced a major research equipment (MRE) award for the George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES). This MRE, the first to be funded under the NSF engineering directorate, is intended to "provide a national resource that will shift the emphasis of earthquake engineering research from its current reliance on physical testing to integrated experimentation, computation, theory, databases, and model-based simulation" (from the NSF Web site "About NEES").

The award is divided into three main components: (1) consortium development, (2) system integration, and (3) equipment, with the last mentioned including two phases of awards (see Table A.1). These three components will work together to form a national earthquake engineering research collaboratory through which researchers will share data and have access to equipment at remote sites. The three award areas total more than $80 million. The collaboratory is mandated to be operational by September 30, 2004, with an initial 10-year research plan.

CONSORTIUM DEVELOPMENT

The Consortium Development group is charged with developing and establishing the NEES Consortium and a 10-year (2004-2014) plan for managing NEES. The objectives of the Consortium Development group are threefold:

- To obtain community input and consensus on NEES structure and governance,
- To obtain community input and consensus needed for NEES system integration, and
- To coordinate outreach and training for the NEES equipment sites.

These objectives will be accomplished through activities such as national and regional workshops and interaction on the NEES Web site, http://www.nees.org. The group will prepare annual reports and a final summary report (September 30, 2004) to assess community reactions, visibility, and the performance of the executive council.

SYSTEM INTEGRATION

The System Integration group will design, develop, implement, test, and make operational the Internet-based, national-scale high-performance network system NEESgrid.

EQUIPMENT SITES

Sixteen projects at 15 different institutions throughout the United States were funded with NEES equipment awards for Phases I and II (see Table A.1). A brief description of each project follows.[1]

Phase I Awards

Versatile High-Performance Shake Tables Facility Towards Real-Time Hybrid Seismic Testing, State University of New York (SUNY) at Buffalo

Large-Scale High-Performance Testing Facility Towards Real-Time Hybrid Seismic Testing, SUNY Buffalo

These two projects will result in a versatile research facility, which will have two shake tables with 6 degrees of freedom. The tables will be able to contain specimens as long as 120 meters and weighing up to 100 metric tons. Large-scale, high-performance actuators will provide immediate capabilities for dynamic testing and pseudodynamic testing as well as the platform needed for the development of new testing methodolo-

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[1] Information on the 16 equipment sites is summarized from the NEES Web site at <http://www.nees.org>.

gies. In addition, the tables will be operated with equipment such as high-capacity, high-performance hydraulic supply and distribution systems and will be networked for tele-experimentation capabilities.

Development of a Biaxial Multiple Shake Table Research Facility, University of Nevada, Reno

This project will upgrade and expand the existing facilities at the University of Nevada, Reno. The two existing tables and a third new table will have the following specifications:

- 14-ft^2, 50-ton payload capability and 24-in. peak-to-peak stroke in the horizontal plane;
- Mounted on the strong floor of the hi-bay Structures Laboratory; and
- Relocatable so that a variety of table configurations may be assembled to meet present and future research needs.

In addition, it will be possible to operate the tables independently, in phase, or differentially. The facility will be telecapable, connected to the Internet-2 network for remote participation (allowing both teleobservation and teleoperation).

Upgrading, Development, and Integration of Next-Generation Earthquake Engineering Experimental Capability at Rensselaer's 100 Gton Geotechnical Centrifuge

The upgraded centrifuge will include the following:

- A two-dimensional (2-D) in-flight earthquake shaker (two prototype components) and associated 2-D laminar box container for more realistic 2-D modeling,
- A 4-degrees-of-freedom robot capable of performing in-flight operations,
- A networked data acquisition system with Internet teleobservation and teleoperation,
- Two high-speed cameras and image-processing software,
- New-generation sensors with better resolution of the measured model response, and
- Other equipment for increasing the capabilities of the centrifuge.

TABLE A.1 NEES Equipment Awards

Principal Investigator(s)	Goal(s)/Title	Award Amount ($)
Task/Consortium Development		
Robert Reitherman, Stephen Mahin, Robert Nigbor, Cherri Pancake, Sharon Wood	To develop the NEES Consortium and its 10-year (2004-2014) plan for managing NEES	1,999,907
Task/System Integration		
Thomas Prudhomme, Jean-Pierre Bardet, Ian Foster, Carl Kesselman	To design, develop, implement, test, and make operational the Internet-based, national-scale high-performance network system for NEES, called the NEESgrid	10,000,000
Task/Phase I Equipment		
Michel Bruneau, State University of New York at Buffalo	Versatile High Performance Shake Tables Facility Towards Real-Time Hybrid Seismic Testing	6,160,785
Michel Bruneau, State University of New York at Buffalo	Large-Scale High Performance Testing Facility Towards Real-Time Hybrid Seismic Testing	4,379,865
Ian Buckle, University of Nevada, Reno	Development of a Biaxial Multiple Shake Table Research Facility	4,398,450
Ricardo Dobry, Rensselaer Polytechnic Institute	Upgrading, Development, and Integration of Next Generation Earthquake Engineering Experimental Capability at Rensselaer's 100 G-ton Geotechnical Centrifuge	2,380,579
Catherine French, University of Minnesota, Twin Cities	System for Multiaxial Subassemblage Testing	6,472,049
Bruce Kutter, University of California, Davis	NEES Geotechnical Centrifuge Facility	4,614,294

TABLE A.1 Continued

Principal Investigator(s)	Goal(s)/Title	Award Amount ($)
Jack Moehle, University of California, Berkeley	Reconfigurable Reaction Wall-Based Earthquake Simulator Facility	4,268,323
P. Benson Shing, University of Colorado, Boulder	Fast Hybrid Test Platform for the Seismic Performance Evaluation of Structural Systems	1,983,553
Kenneth Stokoe, University of Texas, Austin	Large-Scale Mobile Shakers and Associated Instrumentation for Dynamic Field Studies of Geotechnical and Structural Systems	2,937,036
John Wallace, University of California, Los Angeles	Field Testing and Monitoring of Structural Performance	2,652,761
Solomon Yim, Oregon State University	Upgrading Oregon State's Multidirectional Wave Basin for Remote Tsunami Research	4,775,832
Task/Phase II Equipment		
T. Leslie Youd, Brigham Young University	Permanently Instrumented Field Sites for Study of Soil-Foundation-Structure Interaction	1,944,423
Harry Stewart, Cornell University	Large Displacement Soil-Structure Interaction Facility for Lifeline Systems	2,072,716
James Ricles, Lehigh University	Real-Time Multidirectional Testing Facility for Seismic Performance Simulation of Large-Scale Structural Systems	2,593,317
Frieder Seible, University of California, San Diego	Large High Performance Outdoor Shake Table Facility	5,890,000
Amr Elnashai, University of Illinois, Urbana-Champaign	Multiaxial Full-Scale Substructure Testing and Simulation Facility	2,958,011
TOTAL		72,481,901

SOURCE: National Science Foundation.

A System for Multiaxial Subassemblage Testing (MAST), University of Minnesota, Twin Cities

The MAST system will link large-scale testing of structures with three-dimensional nonlinear analyses of structural components and systems. The system will allow multiaxial cyclic and pseudodynamic tests of large-scale structural subassemblages. The equipment will include the following:

- High-performance actuators,
- Cross heads,
- A digital controller with 6 degrees of freedom,
- A hydraulic distribution system, and
- An L-shaped reaction wall system for lateral load resistance for the horizontal actuators.

With this system, a full 6 degrees-of-freedom loading condition can be imposed on test structures. In addition, the MAST system will have teleobservation and teleoperation capabilities.

A NEES Geotechnical Centrifuge Facility, University of California, Davis

This facility will be upgraded to include the following:

- Modification to enable operation up to 80 g;
- Upgrades to the existing horizontal shaker;
- One large hinged-plate container;
- One biaxial horizontal-vertical shaker;
- One 4-degrees-of-freedom robot, robot tools, and associated software, capable of installing and/or operating test devices;
- Networked data acquisition systems with teleoperation and teleobservation capability;
- Data visualization capabilities with a high-resolution projection system;
- Ten strands of 20 dual-axis digital MEMS accelerometers; and
- Topographic imaging and geophysical testing tools and methodologies.

Reconfigurable Reaction-Wall-Based Earthquake Simulator Facility, University of California, Berkeley

The facility will be designed to support the development of a new generation of hybrid testing methods and will leverage the capabilities of existing facilities at the university. The existing equipment includes a strong floor, a 4-million-pound Southwork-Emery Universal testing machine, and hydraulic oil pumps and piping. The new equipment includes the following:

- Advanced Hybrid Testing System (dynamic and static actuator assemblies, hydraulic distribution systems, high-performance accumulation system, digital control system with real-time hybrid control package and integrated data acquisition channels),
- Advanced 128-channel data acquisition system,
- Reconfigurable reaction wall with 13 3-ft reinforced concrete blocks and post-tensioning bars,
- Digital teleobservation equipment,
- Mobile robot avatar,
- Specimen instrumentation, and
- Local network equipment.

Fast Hybrid Test Platform for the Seismic Performance Evaluation of Structural Systems, University of Colorado, Boulder

The facility will incorporate high-speed actuators, a digital controller, a data acquisition system, computers, and simulation software for full-size and large-scale models of wall, columns, frames, and subassemblies under hybrid testing. Load rates will be between 10 and 100 percent of that experienced during an earthquake, which is higher than the capabilities currently available in pseudodynamic tests. The system will include the following:

- One new high-speed actuator;
- Upgrades to two existing actuators;
- High-performance digital servocontroller with three control channels and three-variable control capability;
- High-speed data acquisition;
- Three digital displacement transducers;
- Ten analog displacement transducers;
- Three accelerometers with frequency range up to 500 Hz;
- Three computers for numerical simulation, data processing, and data display/tele-observation;
- Expansion of existing data acquisition system; and
- Equipment for teleobservation and teleoperation.

Large-Scale Mobile Shakers and Associated Instrumentation for Dynamic Field Studies of Geotechnical and Structural Systems, University of Texas, Austin

For this project, field equipment will be developed, including the following:

- A large triaxial mobile shaker and associated transportation vehicle;
- Two stand-alone, three-dimensional cubical shakers on a support trailer;
- An instrumentation van with electrical generators;
- Field instrumentation; and
- Teleparticipation equipment.

This coordinated set of equipment will be used to generate large dynamic forces over a wide range of frequencies, while simultaneously measuring the appropriate response parameters with sensors. The equipment will be mobile and self-supporting and will be designed to test geotechnical systems (rock, soil, basins, earth dams, landfills) as well as foundations and structural systems.

Field Testing and Monitoring of Structural Performance, University of California, Los Angeles

This project will result in a mobile field laboratory for forced-vibration testing and earthquake-aftershock monitoring of full-scale structures. The equipment included in this field laboratory is as follows:

- Four forced-vibration sources:
    - —One omnidirectional eccentric mass vibrator with maximum force of 10 to 20 kips (1,000-lb loads) having continuous to intermittent operation and a frequency range of 0.1 to 4.2 Hz;
    - —Two unidirectional eccentric mass vibrators with maximum force of 100 kips and a frequency range of 0 to 25 Hz;
    - —One linear inertial shaker with maximum force of 5 kips and programmable arbitrary force (or acceleration) time history over a frequency range of 0 to 60 Hz;
- A wireless sensor and data acquisition system;
- A cone penetration truck with a seismic piezocone, 20-ton hydraulic push capacity, side augers, and in situ soil vibration sensors; and
- Networking equipment for real-time data acquisition, processing, and broadcasting.

Upgrading Oregon State University's Multidirectional Wave Basin for Remote Tsunami Research

This project will upgrade Oregon State University's multidirectional wave basin for tsunami research. After construction, the basin will be 48.8 m long, 26.5 m wide, and 2 m deep. A directional wave generator to be located at one end will be composed of 29 independent vertical bulkhead wave generator segments, each 0.91 m wide and 2 m high, moving as a piston capable of a 2.07-m maximum displacement with a maximum velocity of 1.87 m/s. The segments can be programmed to move together to produce long-crested, nonlinear, transient translatory long waves approaching the opposite end of the basin with the crest line perpendicular or oblique to the basin sidewalls.

The following data acquisition systems and instrumentation will be available for tsunami research:

Data Acquisition Systems

- A new data acquisition system is being assembled for the tsunami basin. At this time the system consists of a National Instruments PCI-6071E 64 channel data acquisition card, its host Dell computer, and 16 channels of Rockland Model 432 filters, which are used as anti-aliasing filters.
- A 16-channel IO Tech Wave Book 512 provides portable data acquisition for less data-intense experiments. Anti-aliasing filters are the Rockland 432 filters presently being used by the tsunami basin data acquisition system. This system uses simple IO Tech data acquisition software and is easy for students to configure and use.

Instrumentation

- *Wave gauges.* Sixteen channels of differentially driven resistive wave gauges will be available for use in the laboratory's basins. The signal conditioning units for these gauges allow for the length of the wave probes (and hence their range) to be scaled from 1 to 20 ft.
- *Current meters*. Three Sensordata Minilab SD-12 three-axis acoustic Doppler current meters are used to make velocity measurements in the three basins of the wave laboratory.
- *Strain gauge signal conditioners.* Twenty channels of Vishay 2100 system strain gauge signal conditioning are available. These provide signal conditioning for force transducers and pressure gauges at the Wave Research Laboratory.

- *Pressure transducers.* Ten Druck model PDCR 10 pressure gauges (5-psi range) are available.
- *Force transducers.* Force transducers are generally experiment-specific. Therefore, they are usually designed and fabricated on-site for a given experiment. The Wave Research Laboratory has a large number of previously constructed force gauges available.
- *String potentiometers.* The Wave Research Laboratory has a number of UniMeasure string potentiometers for the measurement of displacement. Eight units with a range of 75 in. are available. An additional 75-in. unit with a built-in velocity sensor is available. A unit with an 800-in. range and a velocity sensor is available. Signal conditioners exist for all units.

Phase II Awards

Permanently Instrumented Field Sites for Study of Soil-Foundation-Structure Interaction, Brigham Young University

The project will augment and upgrade the instrumentation of two field sites with state-of-the-art technology for the study of dynamic ground response, deformation, and the resulting structural response, from both active shaking experiments and local and regional earthquake excitation of the sites. The two sites are the Garner Valley Array and the Salton Sea Wildlife Refuge Liquefaction Array. Previously these two sites focused on the dynamic response of soils under seismic input by the monitoring of ground motion and pore water pressure response. Both sites, which are located adjacent to major southern California faults, have a previous history of recording ground motions from local and regional earthquakes and have been extremely well characterized. At Garner Valley, a structure will be built with sensors embedded in the soil, foundation, and building, and a shaker will be installed for active excitation experiments. At Salton Sea, there will be modernization and enhancement of existing equipment and the installation of a surface pad for mounting active shakers.

Large-Displacement Soil-Structure Interaction Facility for Lifeline Systems, Cornell University

This project, which is a partnership with Rensselaer Polytechnic Institute, will utilize advanced experimental facilities to simulate, at both centrifuge scale and full scale, capabilities for testing, evaluation, and analysis of soil-structure interaction in critical lifeline facilities. Full-scale testing will be supplemented with centrifuge experimental models, and analytical/numerical simulations will be used to expand the scope of the testing, as well as to investigate parameter sensitivity and to identify possible unforeseen effects prior to full-scale tests. Equipment at Cornell will consist of upgrades to the existing servo-hydraulic system for large geotechnical and structural testing of lifeline systems, including

- A hydraulic distribution system with one 190-L/min three-station hydraulic service manifold and three one-station manifolds, each with 115-V controls and a 1-L accumulator;
- Electronic control systems and controllers;
- Two large-stroke hydraulic structural actuators with load capacities of 295-kN tension to 500-kN compression with strokes of ±0.91 m;
- One large-stroke hydraulic structural actuator with load capacities of 445-kN tension to 650-kN compression with a stroke of ±0.64 m;
- One 227-L/min, 21-megapascal (MPa) hydraulic pump; and
- Friction grips for use in cyclic testing of advanced composites used in lifeline retrofit and design.

In addition, a modular reaction wall will be designed, constructed, and installed to accommodate the actuators used for large-scale physical models of the reinforced composite materials used in bridge structures.

Real-Time Multidirectional Testing Facility for Seismic Performance Simulation of Large-Scale Structural Systems, Lehigh University

For this project, Lehigh University will design, construct, install, commission, and operate a real-time multidirectional testing facility for seismic performance simulation of large-scale structural systems. The equipment will be installed at the Advanced Technology for Large Structural Systems Engineering Research Center and will make use of the existing strong floor (372 m^2 in surface area), the existing multidirectional reaction wall (15.2 m tall at one end and stepping down incrementally over a distance of 32 m from 12.2 m to 9.1 m to 6.1 m), an existing mechanical testing laboratory, existing hydraulic systems, and existing static actuators. The following equipment is provided under this award:

- Two 2,050-kN dynamic actuators ported for three 400-g/min servovalves, ±500-mm stroke;
- Three 1,500-kN dynamic actuators ported for three 400-g/min servovalves, ±500-mm stroke;
- Ten 400-g/min high-flow-rate servovalves;
- Hydraulic distribution lines and service manifolds;

- Surge tank and accumulators that will enable strong ground motion effects to be sustained for more than 30 seconds;
- Hydraulic system modifications;
- Digital eight-channel control system with real-time hybrid control packages;
- Digital video teleobservation system including a system of digital high-quality video cameras, network video cameras, a digital video server, a data server, a restricted access Web server, and a public access Web server;
- High-speed 256-channel data acquisition system; and
- Advanced sensors that include wireless MEMS-based accelerometers, piezoelectric transducers (strain and acceleration measurement), and fiber-optic strain gages.

The experimental facility will allow for multidirectional real-time seismic testing, combined with real-time analytical simulations, for investigation of the seismic behavior of large-scale structural components, structural subassemblages, and superassemblages (systems) through the combined use of the dynamic actuators, reaction wall, and strong floor. The experimental facility is also designed to support the development of new hybrid testing methods for multidirectional real-time testing of large-scale structures, including hybrid testing of multiple substructures, where the substructures involved are at different geographic locations connected by the NEES network.

Large High-Performance Outdoor Shake Table Facility, University of California, San Diego

This project establishes a NEES large, high-performance outdoor shake table, which will be 7.6 m wide by 12.2 m long and have a single (horizontal) degree-of-freedom system. The table will have the following capabilities:

- A peak horizontal velocity of 1.8 m/s,
- Maximum stroke of ±0.75 m,
- Maximum gravity (vertical) payload of 200 MN,
- Maximum overturning moment of 50 MN · m,
- Force capacity of actuators of 6.8 MN, and
- A frequency bandwidth from 0 to 20 Hz.

The major equipment for this facility will include servocontrolled, dynamically rated actuators with large servovalves; a large power supply; a vertical load/overturning moment bearing system; a digital three-variable, real-time controller; concrete foundation and reaction mass; and a weatherproofing system. The facility will be the only outdoor shake table in the United States and will enable large- to full-scale testing of structural systems and soil-foundation-structure interaction. These tests will be useful under conditions that cannot be readily extrapolated from testing at a smaller scale and for quasi-static or pseudodynamic test conditions, as well as for testing large-scale systems to observe their response under near-source ground motion.

Multiaxial Full-Scale Substructuring Testing and Simulation Facility, University of Illinois, Urbana-Champaign

This project, whose acronym is MUST-SIM, is planned to allow testing of full-scale structures or parts of structures, including foundations and soil mass, while simulating the remaining parts. The primary objective of the proposed effort will be to create a facility in which a full-scale subassembly can be subjected to complex loading and imposed deformation states at multiple connection points on the subassembly, including the connection between the structure and its foundation. The proposed Multiaxial Full-Scale Substructuring Testing-Simulation facility has the following components:

- Six-degrees-of-freedom load and position control at three connection points;
- System modularity to allow for easy expansion, and low-cost maintenance and operation;
- Multiple dense arrays of noncontact measurement devices;
- T-section strong wall creating two testing compartments, each providing support in three loading planes; and
- Advanced visualization and data-mining capabilities for integrated teleoperation and teleobservation.

The proposed MUST-SIM facility will develop modular, 6-degrees-of-freedom loading and boundary condition boxes, which will allow for precise application of complex load and boundary conditions. The boxes, which will be 3.5 m × 1.5 m × 1.5 m and will house six actuators each, will be able to impose motions on the test structures to be determined from the results of concurrently running numerical models of the test specimen and the surrounding structure-foundation-soil system employing pseudodynamic testing methods. Dense arrays of state-of-the-art, noncontact instrumentation will allow near-real-time model updating for the model-based simulation.

B

Biographies of Committee Members

William F. Marcuson III (NAE), *Chair***,** is president of W.F. Marcuson III and Associates, Inc., and director emeritus of the Geotechnical Laboratory of the U.S. Army Corps of Engineers' Waterways Experiment Station. He held the position of director of the laboratory from 1981 until his retirement in 1999 and was responsible for research, development, investigation, and analytical studies from both the theoretical and practical viewpoints in the fields of soil mechanics, engineering geology, rock mechanics, earthquake engineering, geophysics, military pavements, and Army mobility. His research activities focused on experimental and analytical studies of soil behavior related to geotechnical problems, seismic design and analysis of embankment dams, and seismically induced liquefaction of soils. He has authored more than 100 publications, including several state-of-the-art publications on in situ testing and sampling, soil dynamics, seismic design and analysis of embankment dams, and seismic rehabilitation of earth dams. Dr. Marcuson serves as a consultant on geotechnical problems and projects and is a licensed professional engineer in Mississippi and South Carolina and a chartered engineer in the United Kingdom. Dr. Marcuson holds a Ph.D. in civil engineering from North Carolina State University. He is an honorary member and fellow of the American Society of Civil Engineers (ASCE) and has served ASCE in a number of leadership positions. He has received numerous awards and honors, including the Walter L. Huber Research Prize (1981) and the Norman Medal (1997) from ASCE, the Federal Government Engineer of the Year (1995) from the National Society of Professional Engineers, and the Silver de Fleury Medal from the Army Engineer Association.

Gregory C. Beroza is an associate professor in the Department of Geophysics at Stanford University, where his research focuses on the physics of earthquake faulting as revealed by seismic waves and the implications for earthquake hazards and prediction. He holds a Ph.D. in geophysics from the Massachusetts Institute of Technology and received the National Science Foundation Presidential Young Investigator Award (1991 to 1996). He has served on the IRIS (Incorporated Research Institutions for Seismology) board of directors since 1990 and was secretary for the IRIS Global Seismic Network Standing Committee from 1990 to 1993. From 1996 to 1999, he was associate editor for the *Journal of Geophysical Research*. He has published more than 50 articles on geophysics and earthquakes.

Jacobo Bielak has been a professor in the Department of Civil and Environmental Engineering at Carnegie Mellon University since 1978. He holds a Ph.D. from the California Institute of Technology. His research interests include earthquake engineering, and structural and computational mechanics, such as large-scale computing, finite element, and boundary integral methods. In particular, he has focused on large-scale computing for modeling earthquake ground motion in large basins and has developed an original methodology for incorporating the effects of soil-structure interaction into the analysis and design of earthquake resistant structures. As principal investigator of the National Science Foundation's (NSF's) grand challenge project Earthquake Ground Motion Modeling in Large Basins, he led a team that developed a finite element methodology and tools for simulating elastic wave propagation in heterogeneous media on parallel computers. This tool has been used in several countries to perform earthquake hazard estimation studies. He is the principal investigator of a current NSF Knowledge and Distributed Intelligence (KDI) project, Large-Scale Inversion-Based Modeling of Complex Earthquake Ground Motion in Sedimentary Basins, whose objective is to develop the capability for generating realistic inversion-based models of complex basin geology and earthquake sources. The section on soil-structure interaction contained in the National Earthquake Hazard Reduction Program Recommended Provisions for the Development of Seismic Regulations for New Buildings, is based largely on his work. He is a corresponding member of the Mexican Academy of Sciences and a recipient of the Allen Newell Medal for Research Excellence.

Reginald DesRoches is an assistant professor in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. He holds a Ph.D. in structural engineering from the University of California at Berkeley. His primary research interests are seismic analysis and earthquake-resistant design of bridges, modeling and analysis of large structural systems, analytical modeling of seismic pounding in bridges and buildings, the application of smart materials for seismic retrofit of structures, and seismic isolation and passive damping applications. From 1989 to 1991 he worked as a structural designer for Mobil Offshore Engineering. He has served as session chairman and on the organizing committee for several conferences, such as the International Society for Optical Engineering conference in March 2001 and the Earthquake Engineering Research Institute 2000 conference. In 2001, Dr. DesRoches received the National Science Foundation's Career Award and the Presidential Early Career Award for Scientists and Engineers. He is also a recipient of the Outstanding Teaching Award from the School of Civil and Environmental Engineering.

Eldon M. Gath is president of Earth Consultants International. Mr. Gath has 20 years experience in the identification, investigation, and remediation of geologic hazards, involving land use planning, environmental assessments, and field exploration and analysis. He has particular experience with the evaluation of active faults for construction site planning, the development of seismic safety programs and policies, and the determination of remediation and design alternatives for geologically sound site development. He holds a B.S. in geology from University of Minnesota's Institute of Technology and has continued with postgraduate work at California State at Los Angeles, the University of California at Riverside, and the University of California at Irvine. He was president of the Association of Engineering Geologists in 1997.

Robert D. Hanson (NAE) is professor emeritus for the Department of Civil Engineering at the University of Michigan and a consultant for the Federal Emergency Management Agency (FEMA). He holds a Ph.D. in civil engineering from the California Institute of Technology and is a registered professional engineer in North Dakota (inactive) and Michigan (current). He began his teaching career at the University of Michigan in 1966 and served as chairman of the Department of Civil Engineering from 1976 to 1984. His research interests in earthquake engineering include evaluation of existing buildings for seismic vulnerabilities, design of seismic upgrades to minimize vulnerabilities, evaluation of earthquake-damaged buildings, design of repair and seismic upgrade schemes for earthquake-damaged buildings, use of supplemental damping systems to enhance seismic performance, development of new supplemental energy dissipation systems, and development of active control devices for vibration control of buildings using electrorheological materials. He has more than 100 publications and has received numerous awards, including being made an honorary member of the Earthquake Engineering Research Institute (2001) and a fellow of the American Society of Civil Engineers (1999). In 1996 he received the Meritorious Service Award from FEMA.

Elizabeth A. Hausler recently received her Ph.D. from the Department of Civil and Environmental Engineering at the University of California, Berkeley. Her dissertation research focused on the influence of ground improvement on settlement and liquefaction of soils supporting structures on shallow foundations. The research was highly experimental in nature, including six dynamic geotechnical centrifuge tests at the University of California, Davis, and the Public Works Research Institute (Japan), and a full-scale blast-induced liquefaction test using cement deep mixing to minimize settlement in Hokkaido, Japan. She holds an M.S. in geotechnical engineering from the University of California, Berkeley and an M.S. in environmental science, policy and law from the University of Colorado at Denver. She has five years' consulting experience in the fields of geotechnical engineering, environmental engineering, and environmental litigation support working for Dames and Moore in Denver and Salt Lake City, and Peterson Consulting Limited Partnership in Chicago. Dr. Hausler is currently a Fulbright scholar at the Indian Institute of Technology, Bombay. She is studying earthquake-resistant housing reconstruction and retrofitting programs in Gujarat, India.

Anne S. Kiremidjian is professor of civil and environmental engineering and director of the John A. Blume Earthquake Engineering Center at Stanford University. She holds a Ph.D. in structural engineering from Stanford University and has been on the faculty since 1978. Her research has focused on earthquake hazard and risk analysis modeling, earthquake damage and loss estimation, risk analysis of transportation systems, reliability analysis of industrial systems, and structural damage monitoring methods. Dr. Kiremidjian was the recipient of the School of Engineering Distinguished Advisor Award, Stanford University, June 1989; the National Science Foundation Faculty Award for Women, 1991-1995; the Society for Women Engineers Distinguished Educator Award, 1992; the American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering, Distinguished Service Award, 1995; the Applied Technology Council, Award for Excellence in Loss Estimations, July 1998. She has more than 150 publications, including journals, papers, technical reports, and conference proceeding papers.

James R. Martin II is an associate professor of civil and environmental engineering with the geotechnical division at Virginia Polytechnic Institute. He holds a Ph.D. in civil engineering from Virginia Polytechic Institute. Dr. Martin serves as codirector of the Earthquake Engineering Center for the Southeastern United States (ECSUS) and is a recently elected board member of the Centre for the Use of Research and Evidence in Education. His research focuses on geotechnical earthquake engineering, soil and site improvement, natural hazard assessment, numerical modeling, GIS applications, and engineering curriculum development. Recent projects include seismic hazard studies of the eastern and central United States, fundamental studies of the liquefaction behavior of silty and clayey soils, Geographic Information System seismic hazard mapping of South Carolina, and site response, liquefaction, and soil improvement studies associated with recent earthquakes in Turkey, Taiwan, and Nisqually in Washington State. His recent activities also include teaching at Federal Emergency Management Agency's Multi-Hazard Building Design Institute in Emmitsburg, Maryland. He has received eight teaching awards, including awards at the national, state, and university levels. He was the recipient of the American Society of Civil Engineers Norman Medal (1996), the State Council of Higher Education of Virginia Award for Excellence in Teaching and Research (1996), and the National Science Foundation Young Investigator Award (1993-1998). He is active in building code development, has frequently presented workshops on the application of building code provisions, and has coauthored seismic design standards for South Carolina. Finally, he is an active consultant and has worked on a variety of geotechnical and earthquake engineering projects for more than 40 private and public organizations. His typical projects involve probabilistic seismic hazard assessment and development of ground motions for the analysis of major dams and nuclear power plants, development of soil improvement schemes for the mitigation of seismic damages, and dynamic numerical modeling of soil-structure systems.

Don E. Middleton is head of the Visualization and Enabling Technologies Section in the Scientific Computing Division of the National Center for Atmospheric Research. He is responsible for leading a program that encompasses data access and analysis, advanced collaborative visual computing environments, enterprise Web engineering, and education and outreach activities. His professional interests center on analyzing and visualizing large, complex earth system data sets and communication using advanced visual technologies. He directed the development of the Virtual Earth System and Exploring the Earth System on the Second Web, a science and technology demonstration that blends virtual stereo three-dimensional technologies, virtual worlds, and three-dimensional animation representing scientific simulation and research. He is currently serving as co-principal investigator for the National Science Foundation-sponsored Visual Geophysical Education Environment and coordinating principal investigation on the Department of Energy-sponsored Earth System Grid Research Project. He holds an M.S. in electrical and computer engineering from Louisiana State University.

Douglas J. Nyman of D.J. Nyman and Associates is a consulting engineer with 30 years of experience. He received a Ph.D. in civil engineering (structural) from the University of Illinois and is a licensed professional engineer in Alaska and Texas. He is recognized as an expert in the mitigation of earthquake and geotechnical hazards for oil and gas pipeline systems. He has served as the principal seismic engineering consultant to the Trans-Alaska Pipeline System for nearly 20 years and previously was employed in a similar capacity by the pipeline company during the design and construction phases. He has authored numerous seismic criteria documents and design specifications for national and international pipeline projects. Dr. Nyman has served on U.S. government-sponsored panels and committees engaged in the development of seismic design standards for lifeline systems and was the principal investigator for a National Science Foundation project to develop guidelines for the seismic design of oil and gas pipelines. He is a Fellow of the American Society of Civil Engineers and has served in several leadership positions with the Technical Council on Lifeline Earthquake Engineering. He is also a member of the Earthquake Engineering Research Institute and the Seismological Society of America. In 2001 Dr. Nyman received the Distinguished Alumnus Award from the University of Illinois Department of Civil Engineering. He is the 2002 recipient of the Charles Martin Duke Lifeline Earthquake Engineering Award.

Fredric Raichlen (NAE) is professor emeritus of civil engineering and mechanical engineering at the California Institute of Technology. He received a B.E. from the Johns Hopkins University and an S.M. and Sc.D. from the Massachusetts Institute of Technology. His experience encompasses fundamental and applied research as well as teaching and consulting in coastal engineering. His research has focused on tsunamis: their generation, propagation, and coastal effects. Investigations relating to the latter have included problems of the run-up of nonbreaking and breaking tsunami-like waves, harbor resonance, ship mooring dynamics, and the structure of wave interactions. In addition to the tsunami research, he has investigated a range of problems dealing with breaking waves, such as the mechanics of the interaction of breaking waves with an armored sea bottom, the entrainment of air by plunging breaking waves and various characteristics of the bow waves of ships. He is the author of more than 70 publications in various areas of fluid mechanics and coastal engineering. Dr. Raichlen is a fellow of the American Society of Civil Engineers (ASCE), and the recipient of the ASCE 1994 John G. Moffatt-Frank Nichol Harbor and Coastal Engineering Award. He is a registered civil engineer in California and New Jersey and consults with various organizations on problems in hydraulics and coastal engineering.

Andrew Taylor is an associate with the structural engineering group of KPFF Consulting Engineers. He holds a Ph.D. in civil engineering from the University of Texas, Austin. He has 12 years of experience in structural engineering research and 5 years of experience in practice. His research experience includes experimental and theoretical investigation of reinforced concrete structures, seismic performance of nonstructural components, seismic damage modeling, and seismic isolation. His design experience includes a range of structural types, including six base-isolated buildings, a building with supplemental damping devices, and application of Federal Emergency Management Agency seismic design guidelines for both new and retrofit construction. Dr. Taylor has published papers on a broad range of earthquake engineering topics and conducted seminars and workshops on earthquake engineering. He received the American Concrete Institute 2001 Structural Research Award for Cumulative Seismic Damage of Circular Bridge Columns: Variable Amplitude Tests and the 1996 bronze medal from the National Institute of Standards and Technology for research in earthquake engineering.

Richard N. Wright (NAE) is retired as director of the Building and Fire Research Laboratory of the National Institute of Standards and Technology and as professor of civil engineering at the University of Illinois, Urbana-Champaign. He received bachelor's and master's degrees from Syracuse University and a Ph.D. from the University of Illinois, Urbana-Champaign, all in civil engineering. He has registered as a civil engineer in New York and structural engineer in Illinois. He has published more than 100 articles on building and fire research, computer-integrated construction, formulation, and expression of standards, performance of structures, structural design methods for earthquakes and other dynamic loads, flow and fracture in structural metals, and mechanics of thin-walled beam structures. He has been chairman of the Board on Infrastructure and the Constructed Environment of the National Academies; co-chairman of the Subcommittee on Construction and Building of the National Science and Technology Council; chairman of the Interagency Committee on Seismic Safety in Construction; U.S. chairman of the U.S.-Japan Panel on Wind and Seismic Effects; president of the International Council for Research and Innovation in Building and Construction; and president of the Liaison Committee of International Civil Engineering Organizations. He is an honorary member of the American Society of Civil Engineers, a fellow of the American Association for the Advancement of Science, and a member of the Earthquake Engineering Research Institute.

C

Time Line of Precipitating Events, Discoveries, and Improvements in Earthquake Engineering, 1811-2004

Year	Event	Highlights of Event/ Development in Earthquake Engineering
1811-1812	New Madrid earthquake (Missouri)	Three principal earthquakes occur over 3-month period. Extensive changes in ground configuration; chimneys destroyed in many parts of Midwest. Considered largest earthquake in modern history in continental United States. Effects felt as far east as Boston, Mass. Several people killed.
1886	Charleston earthquake (South Carolina)	Largest historical earthquake on East Coast of the United States occurs. More than 100 buildings are destroyed, 90 percent of buildings in Charleston damaged, nearly all chimneys down in the Charleston area; $5.5 million in damage; 60 people killed.
1890		First seismograph to record earthquake acceleration is developed.
1900		Fusakichi Omori develops the Omori scale of earthquake intensity: first scale relating ground motion (acceleration) to damage.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
1906	San Francisco earthquake (California)	More than 700 people killed; property losses reach $400 million, mainly due to fire.
1923	Great Kanto earthquake (Tokyo)	One of the most devastating earthquakes in Japan occurs. More than 142,000 people are killed; 694,000 homes are destroyed. Immediate changes in the building code follow, including limiting building height to 100 ft.
1925	Santa Barbara earthquake (California)	13 people are killed, 65 injured; approximately $15 million in damage. Leads to development of seismic appendix in 1927 Uniform Building Code.
1928	Failure of St. Francis Dam (California)	Dam failure under static conditions establishes need for geologic evaluation of dam foundations.
1932		M.A. Biot develops concept of response spectrum for earthquake acceleration.
1932		John R. Freeman publishes *Earthquake Damage and Earthquake Insurance*.
1933	Long Beach earthquake (California)	First recordings made of strong ground motion. Widespread damage is done to unreinforced masonry buildings—leads to widespread research in earthquake engineering. Earthquake leads to first substantive seismic design provisions: Riley Act—Buildings are to be designed for 2 percent of gravity. Field Act—Special seismic design requirements are set for schools.
1933	Tsunami (Japan)	Run-up of 30 m is observed at head of bay in Ryori Bay, Japan.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
1946	Aleutian Islands earthquake and tsunami	Damage and loss of life occur in Hilo, Hawaii, and other islands. Scotch cap lighthouse destroyed in Alaska; run-up of 30 m observed. Beginning of serious U.S. effort to understand various aspects of tsunamis. Disasters lead to initiation of Pacific Tsunami Warning Center and Alaska Tsunami Warning Center.
1948		First seismic probability map issued by Ulrich.
1948		First soil dynamics experiment is run at Harvard University.
1949		Earthquake Engineering Research Institute (EERI) is formed.
1952	Arvin-Tehachapi earthquake (California)	First damaging post-World War II earthquake in United States occurs. Significant damage to lifelines is sustained.
1952		The concept of earthquake design spectrum is introduced by George W. Housner.
1955		Experimental investigation of waves produced by submarine landslides is carried out.
1956		1st World Conference in Earthquake Engineering is held in Berkeley, California.
1958		First earthquake engineering research grants are funded by NSF.
1958	Lituya Bay earthquake and tsunami (Alaska)	Following 8.0-magnitude earthquake in Lituya Bay, a large aerial rockslide causes run-up of 520 m on opposite slope. This is the largest run-up ever recorded.
1959		Recommended lateral force requirements are published, highlighting the importance of the structure period.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
1960	Chilean earthquake	Possibly the largest earthquake in modern history occurs with a moment magnitude of approximately 9.2. This earthquake is critical in advancing the fields of plate tectonics and seismology. The earthquake generates a Pacific-wide tsunami. Approximately 2,000 people are killed by the earthquake and tsunami. Disasters initiated significant research on tsunamis, including numerical modeling of Japanese bays and harbors.
1964	Good Friday earthquake (Alaska)	Soil liquefaction and landslides lead to first zoning and land use regulations related to seismic hazards. Damage to short reinforced concrete columns leads to exploration of ductile detailing for concrete structural elements. Failure of precast concrete wall panels leads to research on cladding connection details. Damage to liquid storage tanks stimulates research on seismic performance of tanks. More than 120 people are killed by tsunami (106 in Alaska, 4 in Oregon, 12 in California). Nearly 2-m run-up in Crescent City, California. Extensive damage highlights the importance of including tsunami effects in seismic hazard assessments. Earth science and engineering communities are mobilized to investigate the earthquake.
1964	Niigata earthquake (Japan)	Dramatic liquefaction-induced building failures occur.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
		First documentation is made of liquefaction effects on lifeline structures. First demonstration of successful implementation of ground improvement occurs.
1967		U.S. West Coast and Alaska tsunami warning system is established.
1967	Caracas earthquake (Venezuela)	Damage to reinforced concrete frames leads to understanding of the importance of continuity of reinforcement in frames.
1968		The first large U.S. shake table is constructed at the University of Illinois, Urbana-Champaign.
1969		Gonzalo Castro articulates principles of soil liquefaction.
1969		National Academy of Sciences prepares report on state of knowledge and research needs for earthquake engineering.
1970		The first comprehensive earthquake loss scenario is developed by S.T. Algermissen and K.V. Steinbrugge.
1971	San Fernando earthquake (California)	Earthquake leads to passage of Alquist-Priolo Earthquake Fault Zonation Act in California, which requires geologic investigations to restrict housing construction across active faults. Damage to bridge structures leads to new bridge design code and to ductile detailing in bridges. Damage to reinforced concrete hospitals results in new requirements for ductile seismic detailing of reinforced concrete hospitals. Following the collapse of upstream portion of San Fernando Dam in this earthquake, major programs for seismically resistant design of earth dams are implemented.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
		First ground acceleration in excess of 1 gravity recorded.
1971		H.B. Seed and I.M. Idriss develop simplified procedure for assessing liquefaction potential.
1972		Applied Technology Council initiates ATC 003 effort, which is the first comprehensive seismic design document based on modern dynamic analysis principles.
1973		First conference held on microzonation for liquefaction hazard identification.
1975		U.S. Army Corps of Engineers initiates national dam inspection program.
1976	Tangshan earthquake (China)	More than 500,000 people are killed by dam failure and collapse of unreinforced masonry construction.
1976		Geotechnical site factors are incorporated into Uniform Building Code.
1976		First national seismic hazard maps with explicit and consistent probabilities of exceedance are developed by S.T. Algermissen and D.M. Perkins.
1977		In response to San Fernando earthquake of 1971, Congress passes the Earthquake Hazards Reduction Act (Public Law 95-124) to "reduce the risks to life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program." To accomplish this, the act establishes NEHRP.
1980		Geotechnical centrifuges are first used for earthquake experiments.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
1983	Tsunami (Japan)	Tsunami generated in Japan Sea results in large loss of life and damage to harbors and ships on west coast of Japan and South Korea. Numerical simulations of tsunami propagation and run-up are studied extensively in Japan.
1985		First base-isolated building is constructed in the United States, the Foothill Communities Law and Justice Center in Rancho Cucamonga, California.
1985	Mexico City earthquake (Mexico)	Strong local ground motions due to a distant earthquake source result in more than 8,000 people killed and over 50,000 left homeless. Research initiated on local soil amplification effects, particularly basin effects. Nonductile, reinforced concrete structures exhibit poor performance. Mixed performance of cross-braced steel structures leads to new research.
1989	Loma Prieta earthquake (California)	Good performance of reinforced masonry buildings is confirmed. Poor performance of open first stories (storefronts, garages) leads to upgrade recommendations for this condition. Poor performance of older steel bridges leads to major upgrades and replacements. Collapse of nonductile reinforced concrete bridges confirms poor seismic performance of this structure type. Upgraded nonductile concrete bridges perform with marginal success. Poor performance of some wharf structures results in recommendations for wharf upgrades.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
		Studies of performance of structures on various soil types leads to refinement of soil factors in building codes.
		Gas and water pipelines rupture in liquefiable soils.
		Landslides cover 15,000 square kilometers.
		Successful performance of improved ground is confirmed.
		Seismic Hazards Mapping Act passes in California, requiring geologic and geotechnical investigations to mitigate seismically induced liquefaction and landslide hazards.
1992	Tsunami (Nicaragua)	First formally organized international field survey (United States, Japan, Nicaragua) takes place.
1992	Flores Island tsunami (Indonesia)	Loss of life and damage occur in Indonesia. Damage pattern at Babi Island is investigated experimentally, theoretically, and numerically.
1993	Okushiri Island tsunami (Japan)	Loss of life, complete destruction of town are caused by tsunami and fire. Leads to awareness of destructive potential of overland flow for triggering co-tsunami fires.
1994	Northridge earthquake (California)	Costliest natural disaster in U.S. history ($30 billion).
		Collapse of wood-frame buildings with open parking garages at ground level results in code changes and renewed research on wood-frame buildings.
		Brittle fracture of connections in welded steel moment frames leads to extensive research programs on evaluation and upgrade of existing steel moment frames and design of new steel moment frames.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
		Good performance of recently upgraded unreinforced masonry buildings is confirmed.
		Poor performance of tilt-up concrete panel buildings results in upgrade recommendations and new code provisions for this structure type.
1995	Kobe earthquake (Japan)	Earthquake is costliest natural disaster in world history ($100 billion).
		First comprehensive set of strong, near-field ground motion records from a single event creates new opportunities for research into near-fault effects.
		Fractures and collapses of steel frames lead to reexamination of steel design codes and practices in Japan and confirm importance of ongoing welded steel moment frame research in United States.
		Widespread failures of bridges lead to reexamination of bridge design codes and practices in Japan and shed new light on bridge design provisions and practices in the United States.
		Extensive damage caused by soil liquefaction and lateral spread places new emphasis on research into prediction of liquefaction potential and techniques for mitigating liquefaction hazards.
		Japanese government invests significantly in new and existing experimental facilities for earthquake engineering research. Several collaborative programs between United States and Japan are established.
1995	Manzanillo tsunami (Mexico)	Large earthquake off Pacific coast of Mexico results in tsunami in city of Manzanillo. Large currents cause damage to port. Photographs of depression waves bring about studies of leading waves of nearshore tsunamis.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
1998		FEMA issues first set of comprehensive guidelines for seismic design that incorporate principles of performance-based seismic design (PBSD): NEHRP Guidelines for Seismic Rehabilitation of Buildings (FEMA 273).
1998	Tsunami (Papua New Guinea)	One of the most devastating tsunamis in the past century occurs; run-ups are as high as 15 m, and more than 3,000 people are killed or missing. The tsunami accelerates research in the area of underwater landslide generation.
1999	Izmit earthquake (Turkey)	More than 16,000 people are killed by the collapse of improperly constructed buildings. Bearing capacity-type failures occur in soils not considered liquefiable by existing criteria, leading to criteria revision. Successful performance of improved ground at industrial facilities is confirmed.
1999	Chi-Chi earthquake (Taiwan)	Near-fault effects and large fault displacements are observed. Successful use of ground improvement at port facilities is confirmed.
2000		Earthquake risk reduction in developing countries is a central theme of 12th World Conference in Earthquake Engineering; a consensus declaration is made that developed countries are not doing enough to help reduce the risk.
2001	Bhuj earthquake (India)	Deaths of at least 13,800 people from collapse of modern, multistory reinforced concrete and poorly reinforced masonry structures highlight need to ensure compliance with building codes.

Year	Event	Highlights of Event/ Development in Earthquake Engineering
		Satellite imagery reveals huge subsided areas inundated with surface water from liquefaction.
		Deep basin effects contribute to structural collapses.
2001	Nisqually earthquake (Washington)	Liquefaction-related damage harms port structures under weak shaking.
		Areas improved with ground treatment technologies perform successfully.
2002	Denali earthquake (Alaska)	Despite large (>6 m) horizontal ground displacements, Trans-Alaska Pipeline suffers minimal damage and no product loss.
2004		NEES equipment sites are slated to be operational.

D

Agendas for the Committee's Public Meetings

MEETING I
MARCH 25–26, 2002

National Academy of Sciences
Washington, D.C.

Monday, March 25

1:00-1:15 p.m.	*William Marcuson, Committee Chair* Welcome and Introductions
1:15-2:15	*Priscilla Nelson, Director, Division of Civil and Mechanical Systems, National Science Foundation*
2:15-2:45	*Bruce Kutter, University of California at Davis* NEES Awardees—Equipment Sites (via videoconference) A NEES Geotechnical Centrifuge Facility
2:45-3:15	Discussion

3:45-4:30	*Robert Reitherman, Executive Director, Consortium of Universities for Research in Earthquake Engineering (CUREE)* NEES Awardees—Consortium Development
4:30-5:00	*Theva Thevanayagam, University of New York at Buffalo* NEES Awardees—Equipment Sites (via videoconference) Versatile High Performance Shake Tables Facility Towards Real-Time Hybrid Seismic Testing
5:00-5:15	Discussion

Tuesday, March 26,
Open Session (8:00 a.m.-1:00 p.m.)

8:30-9:15 a.m.	*Thomas Prudhomme, University of Illinois at Urbana–Champaign* NEES Awardees—System Integration
9:15-9:45	*Arturo Schultz, University of Minnesota* NEES Awardees—Equipment Sites (via videoconference) A System for Multi-axial Subassemblage Testing (MAST)
10:15-10:45	*Kenneth Stokoe, University of Texas, Austin* NEES Awardees—Equipment Sites Large-Scale Mobile Shakers and Associated Instrumentation for Dynamic Field Studies of Geotechnical and Structural Systems
10:45-11:15	*Solomon Yim, Oregon State University* NEES Awardees—Equipment Sites Upgrading Oregon State's Multidirectional Wave Basin for Remote Tsunami Research
11:15-12:15 p.m.	*Paul Somerville, URS Corporation* Draft EERI Research Priorities Report (via videoconference)

MEETING II
APRIL 25–26, 2002

National Academy of Sciences
Irvine, California

Thursday, April 25
Open Session (8:00 a.m.-5:15 p.m.) Briefings and Committee Discussions about the Study

8:30-8:45 a.m.	*William Marcuson, Committee Chair* Welcome and Introductions
8:45-9:30	*Greg Deierlein, Stanford University* Pacific Earthquake Engineering Center and NEES
9:30-10:15	*Dan Abrams, University of Illinois, Urbana-Champaign* Mid-America Earthquake Center and NEES
10:45-11:30	*Michel Bruneau, State University of New York at Buffalo* Multidisciplinary Center for Earthquake Engineering Research and NEES
11:30-12:00 p.m.	Discussion
1:00-2:00	*Chuck Farrar, Los Alamos National Laboratory* Assessing Structural Damage
2:00-2:30	Discussion
3:00-4:00	*Charles Thiel, Telesis Engineers* NEES: Toward a Positive Future?
4:00-5:00	*Frieder Seible, University of California, San Diego* Structural Experimentalist View of the Potential for NEES
5:00-5:15	Discussion

Friday, April 26
Open Session (8:00 a.m.-11:00 a.m.)

8:30-9:30 a.m.	*Ahmed Elgamal, University of California at San Diego* Geotechnical Modeling

9:30-10:30	*Ron Hamburger, ABS Group* Perspective of the Earthquake Engineering Design Community on Research Needs for Code Development (via teleconference)
10:30-11:00	Discussion

MEETING III
AUGUST 1, 2002

National Academy of Sciences
Washington, D.C.

Thursday, August 1

8:30-8:45 a.m.	*William Marcuson, Committee Chair* Welcome and Introductions
8:45-9:30	*Bill Spencer, University of Illinois at Urbana-Champaign* Construction of Smart Buildings
9:30-10:15	*Joy Pauschke, National Science Foundation* Update on NEES Progress
10:45-11:30	*Stephen Mahin, University of California, Berkeley* NEES Vision and Collaboration
11:30-12:15 p.m.	*Jeremy Isenberg, President and CEO, Weidlinger Associates, Inc.* Practitioner Viewpoint of the Potential of NEES (via teleconference)
1:15-2:00	*Ahmed Elgamal, University of California, San Diego* Geotechnical Modeling of Large Datasets
2:00-2:45	*David Frost, Georgia Institute of Technology* GIS and Information Technology (via videoconference)
2:45-3:30	*Tom Finholt, University of Michigan* Collaborative Research

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The Stakeholder Forum

In addition to the direct outreach to the stakeholder community described in Chapter 5, the committee initiated an electronic mailbox from September 1 through October 18, 2002, to solicit input from individuals with whom it could not interact directly. The mailbox format entailed the posting of the committee's statement of task to a National Academies' Web site and requesting comments. Notification of the solicitation was sent via e-mail to numerous interest groups and list servers, a total of 470. A link was also provided from the Web site http://www.nees.org. The posted form was visited 330 times. The 31 comments received ranged from the general—for example, "NEES should consider collaborating with practicing design engineers to develop simple, reliable, economical systems for retrofitting the built environment"—to extremely specific—"The structural engineering profession has pressing need to fully understand the global system behavior of steel braced frames in response to earthquake forces." Although 91 percent of all visitors came from the United States, there were international visitors from 15 different countries, with multiple visits from Canada, Switzerland, Turkey, Japan, and Taiwan. Approximately 52 percent of the visitors came from educational institutions, 38 percent from the commercial and network domains, and 7 percent from government. (The remaining 3 percent were from miscellaneous domains.)

Although only 31 comments were received in response to the solicitation notice, the response rate of approximately 10 percent is in keeping with, and in fact slightly higher than, that for a recent study on the utilization of Web-based tools to obtain customer notice (Doubleclick, 2002). All comments provided to the electronic mailbox were carefully considered by the committee and helped it to formulate the recommendations presented in this report.

This report considers NEES as a new paradigm for earthquake risk reduction. Its aim is to foster a research environment that will bring formidable capabilities of NEES in physical and computational simulation to bear on developing cost-effective risk-mitigation measures for the prevention of catastrophic losses due to earthquakes. This will require the integration of earth science, engineering, planning, the social and policy sciences, emergency management, and public and business administration. The existence of effective loss estimation and loss prevention techniques that can be readily visualized will help make clear the significance of earthquake risks to all decision makers, including homeowners, business owners, utilities managers, emergency managers, and public officials and, most important, will enable them to develop and implement their own strategies for preventing earthquake disasters. However, the voices of all these communities must be heard and responded to if NEES is to be successful. The committee believes that it has developed a process for NEES to maintain dynamic currency with the research needs of its multiple stakeholders. This process incorporates direct outreach and remote, Web-based interaction. As an ongoing process it can serve to ensure that NEES maintains productive contact with its stakeholders as the research program matures and evolves.

REFERENCE

Doubleclick. 2002. Email Trend Findings Include Rise in Bounces: Q2 Email Trend Report, September. New York, N.Y.: DoubleClick, Inc. Available online at <http://www3.doubleclick.com/market/2002/10/dc/feature1.htm> [August 1, 2003].