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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 or "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.

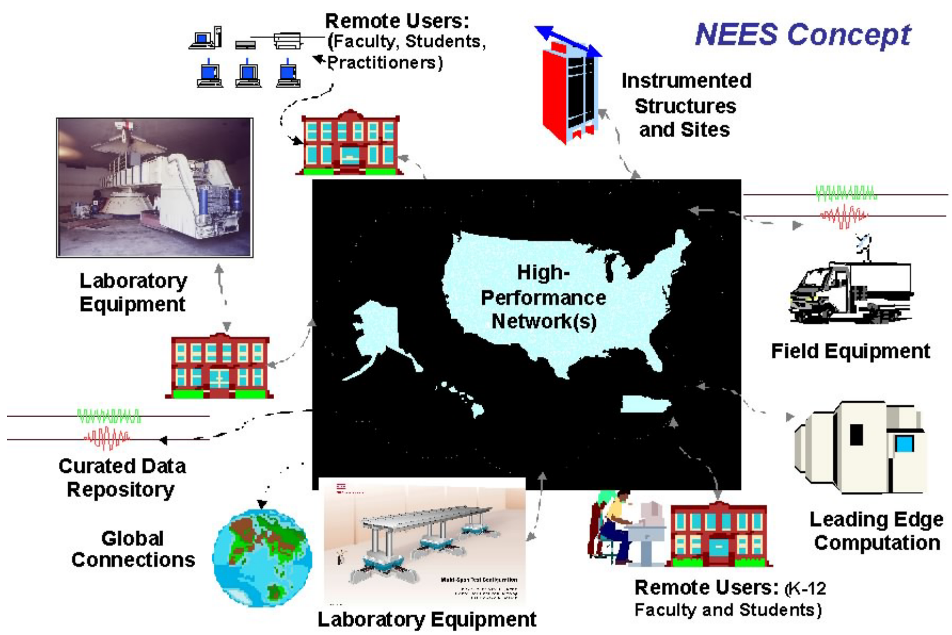

Figure 3.1 The NEES concept for remote collaboration in analysis, experimentation, simulation, and testing in earthquake engineering research. SOURCE: National Science Foundation.

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 enabling 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. 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., explosive) 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.

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.

Develop Economical Methods for Retrofit of Existing Structures

The economical retrofit of existing structures is perhaps the most important issue facing earthquake-prone communities today. For every new building or home constructed, there are literally thousands already existing—many built before 1976, when improved seismic provisions began to be required in building codes. Experimentation and validation testing conducted through NEES can help to make available new materials and techniques, ground motion modeling, soil strengthening, foundation enhancements, wall and beam strengthening, and in situ testing. The newly emerging technology of smart materials that can adapt to changing external factors also needs to be investigated for its potential application for retrofitting. A new generation of retrofit technologies that cost less than existing, less effective techniques but still preserve cultural and architectural resources and protect 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 regarding our understanding of the liquefaction phenomenon. On the other hand, many slopes did fail, in unexpected ways, indicating an equivalent weakness in our understanding of the slope deformation process. In addition, NEES should be used to move past the prediction of free field liquefaction to the next level, which would be the ability to predict deformations (both vertical and lateral) for structures, dams, and lifelines by considering the timing, sequence, and location of soil strength loss in the vicinity of the constructed feature.

Full Suite of Standards for Affordable Performance-Based Seismic Design

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

Convincing Loss Prediction Models to Guide Zoning and Land Use Decisions

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

Continuous Operation of Critical Infrastructure Following Earthquakes

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

Prediction and Mitigation Strategies for Coastal Areas Subject to Tsunamis

Since 1992, 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 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. 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. To do so systematically in an experimental and computational environment of known and consistent quality will be truly unique. 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

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. Interaction between the soil, the foundation, and the structure (SFSI) 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 the response if the structure were supported on a rigid base or even cause the structure to fail.

The complex nature of this coupling has made it difficult to determine the conditions under which 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 together these disciplines 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 together with each other and with the 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, the need for 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 shaking 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 that occur 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 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 (HBCUs) 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 caused by the presence of non-structural components 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 archived data from 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 introducting 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.

Forming Public Policy

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 forming 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 the 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, fire fighting, 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 shaking 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 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 fire-fighting 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 need to couple 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. 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.

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 more than $215 billion in losses 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, 1999, 2000, 2001).

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 population 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.

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 their 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. The student learns proper techniques for placing instruments by trial and error, which results in some localized sample disturbance. The student 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 the student spends manipulating, untangling, stepping on, plugging in, and unplugging the cables to over 80 instruments exceeds the amount of time the student 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. The student 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 the student has a question about instrumentation, an answer is quickly obtained from the NEES model builder's 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 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 investigator and research team are videoconferenced with the testing site for live discussion of the results and interactive decisionmaking 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 which allows project participants to see two-dimensional sections and three-dimensional views of the experimental setup, and 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 it 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. The student gets credit and recognition for their 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.

REFERENCES

National Oceanic and Atmospheric Administration (NOAA). 2003. Tsunami Event Database Search. Available at http://nndc2.ngdc.noaa.gov/nndc/servlet/gov.noaa.nndc.idb.ShowDatasetsServlet?bt_0=1992&st_0=2003&st_1=&bt_2=&st_2=&bt_1=&type_7=Like&query_7=&type_8=Exact&query_8=None+Selected&type_9=Exact&query_9=1&bt_3=&st_3=&bt_4=&st_4=&bt_5=&st_5=&type_10=Exact&query_10=None+Selected&bt_6=1&st_6=10000&query=&dataset=101327&search_look=7&display_look=7&source_id=101042&submit_all=Search+Database [July 20, 2003]

NRC (National Research Council). 2001. Grand Challenges in Environmental Science. Washington, D.C.: National Academy Press.

USAID (United States Agency for International Development). 2000. FY 1999 Annual Report of the U.S. Agency for International Development, Office of U.S. Foreign Disaster Assistance. Washington, D.C.: United States Agency for International Development. Available at http://www.usaid.gov/hum_response/ofda/publications/annual_reports/1999/1999annual-508.pdf [May 15, 2003].

USAID. 2001. FY 2000 Annual Report of the U.S. Agency for International Development, Office of U.S. Foreign Disaster Assistance. Washington, D.C.: United States Agency for International Development. Available at http://www.usaid.gov/hum_response/ofda/publications/annual_reports/2000/2000annual-508.pdf [May 15, 2003].

USAID. 2002. FY 2001 Annual Report of the U.S. Agency for International Development, Office of U.S. Foreign Disaster Assistance. Washington, D.C.: United States Agency for International Development. Available at http://www.usaid.gov/hum_response/ofda/publications/annual_reports/2001/2001annual-508.pdf [May 15, 2003].