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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 were summarized in Table ES.1. However, these are not stand-alone 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 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.

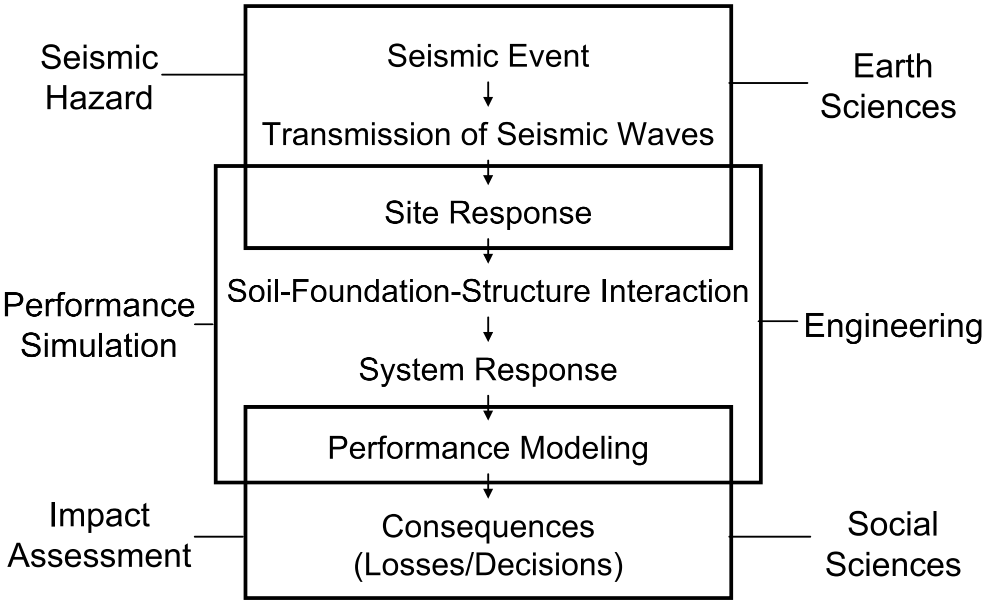

Figure 2.1 Nested linkages of activities and disciplines that NEES will bring to the resolution of earthquake engineering problems. SOURCE: G.Deierlein, Stanford University, presentation to the committee, April 25, 2002.

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.

EARTHQUAKE ENGINEERING ISSUES

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 large 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 strongly spatially 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 the 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 actual earthquakes can be recorded as it occurs and 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 residential 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 near shore 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 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 provides 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 nearshoreheads 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. (Currently for real-time warnings, NOAA 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. It is postulated that in the long term the need for real time tsunami data to forecast coastal effects may be eliminated as a result of research associated with the NEES program.)

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 run-up 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, warning and the evaluation of coastal effects, in the long run, can 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 which 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 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 regarding 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, Washington, have provided valuable field data on the performance of improved ground during strong ground shaking. The findings from these events shows 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 (e.g., 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 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 higher relative to 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.

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 these:

- *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 lifelines designed without consideration of earthquake effects. Some building types are particularly vulnerable in this regard, including unreinforced masonry buildings (URM), 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, Washington (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 developed 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 micro-electro-mechanical sensors (MEMS). Examples of smart actuator materials include shape memory alloys, piezoelectric ceramics, and magneto-rheological and electro-rheological 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 high 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 (ALA) 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 fire-fighting, 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 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 this damage came 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 (In light of the effects on wireless communications of the collapse of the World Trade Center on September 11, this issue may deserve additional attention.), which are identical to the concerns discussed for buildings elsewhere in this report.

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, fire-fighting, 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 fire-fighting 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 fire-fighting 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, material handling, and so on, and cover a broad range of products such as chemicals, fuels, electronics, mechanical equipment, 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 for 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; and
- 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 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.

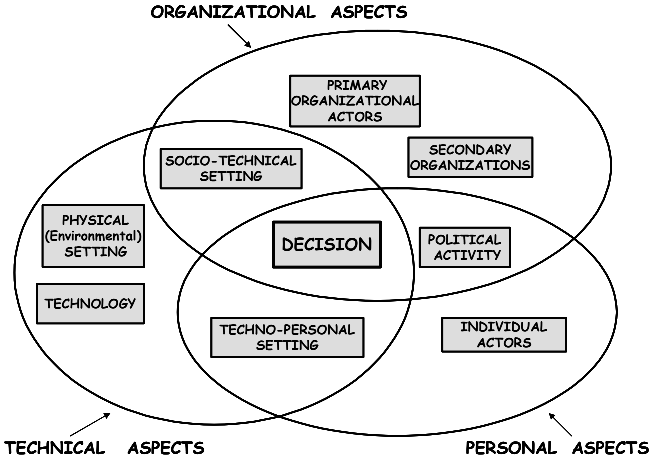

Figure 2.10. A socio-technical system view for decision-making. SOURCE: Linstone (1984).

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 the results of 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 their 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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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.

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.

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.

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.

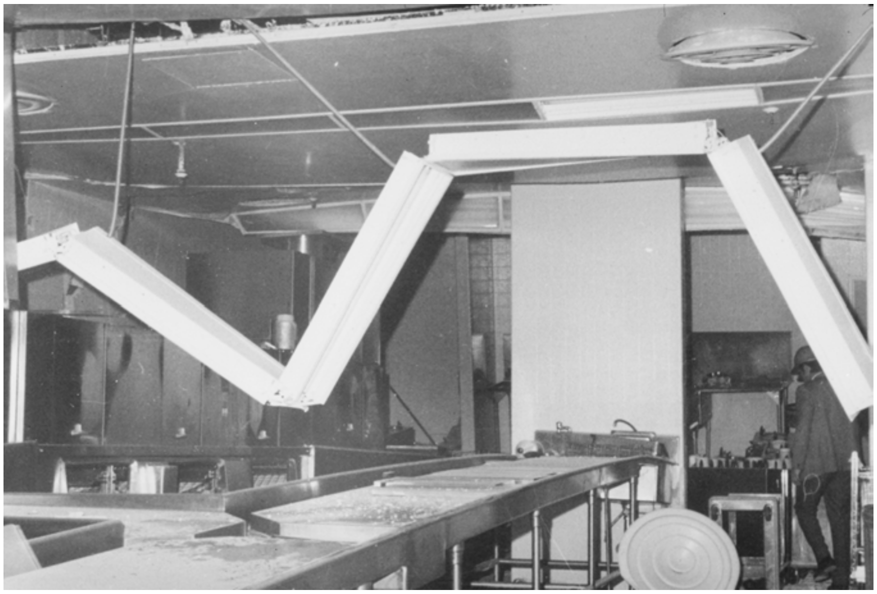

Figure 2.7 Nonstructural building damage at the Olive View Medical Center experienced in the 1971 San Fernando, California, earthquake. Reproduced courtesy of the National Information Service for Earthquake Engineering, University of California, Berkeley.

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 Division of Natural Resources.