REDUCTION OF EARTHQUAKE RISK IN THE UNITED STATES: BRIDGING THE GAP BETWEEN RESEARCH AND PRACTICE

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ABSTRACT

Continuing efforts, under the auspices of the National Earthquake Hazards Reduction Program (NEHRP), are underway in earthquake prone areas of California, Alaska, Puget Sound-Portland region, Intermountain seismic belt, New Madrid seismic zone, Southeastern and Northeastern United States, Puerto Rico-Virgin Islands region, and Hawaii to improve earthquake hazard and risk assessments, transfer technology, and reduce the risk. Scientists, architects, engineers, urban planners, emergency managers, and health care specialists are working at the margins of their disciplines to bridge the gap between research and practice by changing policies and practices for earthquake risk management.

INTRODUCTION

Earthquakes, although they occur less frequently than floods, landslides, wildfires, and severe storms, cause average annual losses of 1.5 billion in the United States. Most of the world's earthquakes occur along the Circum-Pacific or "Ring of Fire."

An assessment of the earthquake threat for a nation, a geographic region, a community, or the location of an essential building or critical lifeline or facility requires research to answer three simple, but highly complicated technical questions. They are: "where?," "how big?," or "how severe?," and "when?."

The answers to the questions: "where?," "how big?," or "how severe?," and "when?" quantify the geologic and geophysical parameters of the hazard environment. They specify: 1) the location(s) of the most likely future earthquake(s), 2) when or how often earthquakes of various magnitudes will occur at these locations, and 3) how severe the physical effects such as ground shaking, liquefaction, surface fault rupture, etc., induced by future earthquakes will be and their likely impact on the built environment. They give a scientific basis for changing community earthquake risk management policies and practices--the only way to reduce earthquake risk (Figure 1).

At present, geologists and seismologists can answer the question "where?" with a high level of confidence, but the state-of-the-art for answering the questions "how big?" or "how severe?" and "when?" is not as advanced. The state-of-the-art is based on the results of detailed studies of individual active fault systems using trenching, age dating, boreholes, strain and stress measurements, geophysical surveys, GPS measurements, and geologic mapping. The greatest problem, however, is that it is still not clear which geologic structure(s) caused some of the large- and great-magnitude earthquakes.

An assessment of the earthquake hazard (i.e., specification of the severity, temporal and spatial distribution, and probability of the occurrence of physical phenomena accompanying an earthquake) and risk (i.e., the chance of loss from these phenomena) is a complex task (Hays, 1991). Each assessment requires multidisciplinary investigations on national, regional, urban, and local scales. Both types of assessments are described below.

EARTHQUAKE HAZARD ASSESSMENT

Under the auspices of the National Earthquake Hazards Reduction Program (NEHRP) (enacted in October 1977, Public Law 95-124), earth scientists and engineers are working together to study: 1) plate tectonics; 2) faults; 3) seismicity,

Reduction Of Community Vulnerability

Built Environment
• Location, value, exposure, and vulnerability of buildings and lifelines at risk from earthquake physical effects (hazards) which can cause damage, failure, loss of function, release of hazardous materials, injuries, and deaths.

Hazard Environment	Policy Environment
• Physical effects such as: ground shaking; liquefaction; landslides; surface fault rupture; tectonic deformation; fires, and flood waves from seiche, tsunami, and dam break generated in an earthquake and the aftershock sequence; each potentially impacting people and the built environment in different ways.	• Social, technical, administrative, political, legal, and economic forces which shape a community's policies and practices for: earthquake risk management (i.e., prevention, mitigation, preparedness, prediction and warning, intervention, emergency response, and recovery), public awareness, training, education, and insurance.

Figure 1.--Essential factors for reducing community vulnerability to earthquakes.
historic earthquakes in the Eastern United States.

seismic sources zones, and earthquake potential; 4) soil response, and 5) ground shaking and ground failure. These studies are described below.

Studies of Plate Tectonics

Geologists and seismologists study plate tectonics on global and regional scales to answer the question, "Why are earthquakes occurring?" Each year, about 12 million earthquakes occur throughout the world. Most of these earthquakes occur along the boundaries of about a dozen 80 to 96 km (50 to 60 miles) thick rigid plates or segments of the Earth's crust and upper mantle. These plates are moving slowly and continuously over the interior of the Earth. They converge in some areas and diverge in others, moving at a relative velocity between plates that ranges from less than a cm (fraction of an inch) to about 25 cm (10 inches) per year. Although these plate velocities appear to be slow, they can add up to more than 50 km (30 miles) in only 1 million years, a short time geologically. As these plates move, strain accumulates until eventually, faults along or near the plate margins slip abruptly, producing an earthquake. Most of the world's earthquakes occur along the Circum Pacific. Alaska, California, and the Puget Sound-Portland area are located along the North American-Pacific plate margin and are the most earthquake prone parts of the United States. Intraplate earthquakes also occur in the Intermountain seismic belt, the New Madrid seismic zone, and the Charleston, South Carolina area.

Studies of Faults

Faults extending to the ground surface such as the San Andreas (a strike slip fault system) and the Wasatch fault (a normal fault system) are easy to identify and geologists and geophysicists have studied these faults and other like them to gain an understanding of fault mechanics. Those faults that do not extend to the surface such as the subduction zone thrust faults in Puget Sound, Washington; Alaska; Puerto Rico; and the buried fault systems in the New Madrid seismic zone in the Central United States and in the Charleston, South Carolina area are much more difficult to study. Collectively, these studies provide an understanding of where, how big, and how often earthquake are likely to occur. These answers provide a scientific basis for earthquake risk management policies and practices for construction sites near active fault zones.

Studies of Seismicity, Seismic Source Zones, and Earthquake Potential

Seismologists use networks of instruments in each earthquake prone area of the Nation to study earthquake activity (Figure 2) and to provide answers to the questions where, how big, how often, and why. Once seismically active faults and tectonic features in a region have been identified as a seismogenic source and characterized in terms of parameters such as maximum magnitude, recurrence rate, and seismic history, their potential for generating future earthquakes can be assessed and incorporated in hazard maps and risk assessments.

Figure 2.--Map showing locations of past notable earthquakes in the United States.

Although the exact mechanisms that produced some of the tectonic earthquakes in the Eastern United States are still in doubt, more than 100 discrete seismic sources have been delineated and characterized on the basis of seismicity and geologic structure. The correlation of earthquake potential with fault slip is clear along the Pacific plate margin, especially in California , but it is unclear at intraplate locations in the Eastern United States, especially in the New Madrid seismic zone of the Central Mississippi Valley and the Charleston, South Carolina area.

In August 1990 following the 1989 Loma Prieta earthquake, the U.S. Geological Survey's Working Group on Earthquake Probabilities reissued a 1988 report on the probability of magnitude 7 or larger earthquake in California within the next 30 years. It concluded that the probability is 60 percent in Southern California and 67 percent in the San Francisco Bay region.

Defining the earthquake potential in the Central Mississippi Valley region and Charleston, South Carolina region is a difficult scientific problem. Each region has low to moderate seismicity and a low annual probability for the recurrence of damaging earthquakes like those that struck the Mississippi Valley region in 1811-1812 and Charleston in 1886; the recurrence intervals are not only much longer but also more difficult to quantify.

Studies of Soil Response

The United States has many sites which have the geologic characteristics for soil-structure resonance. This phenomenon will occur unless an effort is made to prevent siting of structures on soils which will vibrate at the fundamental period of the structure. It is well known that the earthquake source generates seismic waves having a broad frequency spectrum; the path acts like a low-pass filter, attenuating the short period waves more rapidly than the long period waves. The soil column acts like a band pass filter, enhancing the periods that fall in a narrow spectral band and reducing those outside this band. A building also acts like a band pass filter, and when the period of the soil and the building are the same, damaging soil-structure resonance will happen, as it did in Mexico City during the 1985 Mexico earthquake and in San Francisco and Oakland during the 1989 Loma Prieta earthquake.

Studies of Ground Shaking and Ground Failure

Geologists, seismologists, and geotechnical engineers use portable and fixed arrays of strong motion instruments and a variety of field and laboratory techniques to learn all they can about ground shaking and ground failure both during and after an earthquake. When a fault breaks or ruptures, seismic waves are propagated in all directions from the earthquake source. As the compressional (P), shear (S), Love, and Rayleigh waves impinge upon the surface of the earth, they cause the soil and rock to vibrate at frequencies ranging from about 0.1 to 20 hertz (0.05-10 seconds). Ground shaking is elastic, and depending on the geometry and physical properties of the underlying or enclosing rock and soils, structures are induced to vibrate elastically and inelastically as a consequence of the amplitude, frequency composition and duration of the ground shaking. However, permanent ground displacements are inelastic; that are caused by surface fault rupture, liquefaction, landsliding, lateral spreading, compaction, or regional tectonic deformation.

EARTHQUAKE RISK ASSESSMENT

Risk assessments involve scientific, societal, and economic considerations (Figure 3). The main factors are: a) the location of buildings, facilities, and lifeline systems within a community, b) their exposure to the physical effects of an earthquake, and c) their vulnerability (i.e., potential loss in value) when subjected to these physical effects. Risk assessments result in a statement of the economic losses, deaths and injuries, and loss of function expected when a specific physical effect (e.g., ground shaking) strikes a given region, local jurisdiction, site, or structure. When the spatial and temporal characteristics of the physical effects are fully integrated with a community's existing inventory of buildings, facilities, and lifeline systems, the chance of loss can be determined. Risk assessments can be used to: identify hazardous geographic areas, groups of buildings, or lifelines; aid in the development of emergency response plans; evaluate overall economic impact on the Nation; formulate general strategies for land use plans or building codes).

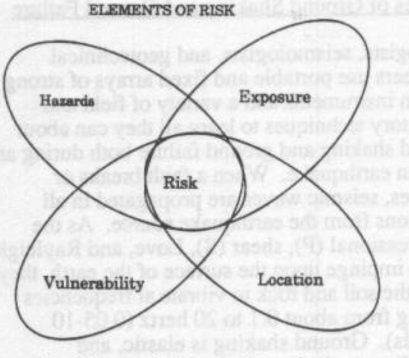

Figure 3.--Schematic illustration of elements involved in a risk assessment.

The physical effects (i.e., earthquake hazards) can damage or destroy buildings and lifeline systems (e.g., bridges, dams, pipelines, utility systems, tunnels, rapid transit) in urban centers and cause socioeconomic impacts over a broad geographic regions. Within a minute or less economic losses can reach several tens of billions of dollars. Ground shaking can trigger liquefaction (i.e., a temporary loss of bearing strength at locations underlain by young, loosely compacted, water-saturated sand deposits) and landslides (i.e., falls, topples, slides, spreads, and flows of rock and/or soil on unstable slopes). Some earthquakes will also generate surface fault rupture where, depending on the magnitude or amount of mechanical energy released at the initial rupture zone, the fault can propagate upward, and break the surface. Surface fault rupture, liquefaction, and landsliding cause permanent displacements, which can be especially damaging to underground lifeline systems. Regional tectonic deformation (i.e., changes in elevation over a broad geographic region) is a characteristic of great-magnitude earthquakes (i.e., those having magnitudes of 8 or greater). Tsunamis (i.e., long-period ocean waves generated by the sudden vertical displacement of a submarine earthquake) can generate flood waves that can destroy ports and harbors and buildings at coastal locations far from and close to the earthquake source. Tsunamis generated by submarine earthquakes have impacted Alaska, the Pacific coast, Hawaii, Puerto Rico, and the Virgin Islands. Seiches (standing waves induced in lakes and harbors), dam failures, and fires can also be induced by an earthquake. Aftershocks (i.e., smaller magnitude earthquakes, following the main shock) can occur for several months to years, repeating and worsening the physical effects described above, depending on their magnitude, proximity to the urban center building or lifeline or site, and the incipient damage state of the remaining structures.

Future earthquakes in either Northern or Southern California as well as the New Madrid seismic zone could cause economic losses that exceed $100 billion and kill and injure several thousand people (State of California, 1990).

EARTHQUAKE RISK MANAGEMENT

The term risk management suggest that earthquake risk can be controlled within limits set by the community. Community decisionmakers and professionals have to adopt and implement policies and practices that improve mitigation, preparedness, emergency response, and recovery. In many cases the existing capability within the community may be inadequate to carry out some or all of these risk management strategies. In those cases technology transfer is required to bridge the gap between research and practice. Mitigation refers to those actions that reduce the demands placed on the community by the natural hazard and/or that protect the community's capability. Preparedness refers to those actions that anticipate and reduce the demands and/or enhance and protect the community's capability. It includes prediction and warning. Emergency response refers to those actions that define the demands and/or manage and reallocate the community's capability. Recovery refers to those actions that stabilize the physical and social demands and/or actions that restore and improve community capability quickly. A disaster occurs when increased or extraordinary demands are made on the community and/or there is inadequate capability or a decrease in the community's capability to cope with the increased demands.

Through technology transfer, planners, emergency managers, medical service specialists, architects, engineers, and scientists can increase the capabilities they need for reducing the risk from natural hazards in their community. Urban planners plan the way groups of engineered and non-engineered buildings and lifelines systems will be combined to form streets and ultimately the urban center. Health care specialists and emergency managers organize the human and material resources of the community for emergency response and recovery. Architects design individual buildings, focusing mainly on the building configuration, non-structural elements, and occupant safety. Engineers, architects, and scientists work together to ensure that new buildings and lifeline systems will meet the requirements of the local building and land use regulations and withstand the physical effects of the earthquake.

Past earthquakes throughout the world have shown that communities are vulnerable to earthquakes because planners, architects, and engineers fail to adopt and implement policies and practices which experience has shown will make buildings and lifelines systems less vulnerable (Hays, 1993; State of California, 1990; EERI, 1989a and 1989b, 1986). A community benefits most from changes in policies and practices which enhance:

- Emergency preparedness and disaster recovery planning.
- Avoidance of the physical phenomena,
- Wise use of the land,
- Adoption and enforcement of building and zoning regulations,
- Reduction of vulnerability,
- Coordinated planning, siting, design, and construction practices,
- Modification of the characteristics of ground shaking and ground failure, and
- Prediction and warning.

Each of these applications is discussed below.

Emergency Preparedness and Disaster Recovery Planning

Emergency managers need realistic scenarios of what to expect and what to do in a damaging earthquake (Der Heide, 1989). These scenarios are the technical basis for emergency response plans and, in the case of a disaster that overwhelms the response capability of the community, disaster recovery plans. From past earthquakes, emergency managers have learned that a damaging earthquake will not only expose all of the flaws in policies and practices for siting, design, and construction of buildings and lifeline systems in the urban center but will also exhibit the weak elements of the emergency response and recovery plans. The most realistic response plans are based on the following assumptions:

- The earthquake will strike without warning at the "worst" time of the day and season of the year.
- Physical effects observed in past earthquakes having the same magnitude and location as the scenario earthquake will be repeated. (Note: Case histories of past earthquakes should be studied in detail to define the range of possible emergency response needs.)
- Ground shaking and ground failure will cause the greatest damage, social impacts, and loses. Fire, flooding from dam breaks or debris dams, and aftershocks should be expected to complicate the emergency response.
- The oldest and most densely populated parts of the urban center will suffer the greatest damage, highest losses, and the greatest

number of casualties and injuries. The poor and elderly will be severely impacted. Homelessness will be a major problem.

- The short-term physical, emotional, and social impacts on the populace will be varied and complex. Families will be separated, people will be trapped in collapsed buildings and highway structures, utilities will suffer outages, and huge traffic jams will be typical.
- Movement into and away from damaged areas will be hampered for days to weeks due to debris, damage to transportation systems, ongoing search and rescue operations (in the first few days), and postearthquake investigations (which can extend from weeks to months).
- Communications will be disrupted for hours to weeks and some communities may be isolated for several weeks. Coordination within and between organizations should be expected to be flawed.

To facilitate disaster recovery, the plans should be developed before the disaster in order to resolve issues that keep recurring in postearthquake recovery throughout the world. Some of the planning assumptions are:

- The political pressures will be very great because of the desire to restore the urban center and community services to normal quickly.
- Assessment of damage will be a top priority, but experienced people to make the assessments will be in short supply.
- Inspection and posting of "red" (unsafe, do not enter), "yellow" (caution in entering), and "green" (safe to enter) tags on buildings will be a critically important task charged with emotion and political pressures.
- Removal of debris will be a complicated task while search and rescue operations are underway and an urgent task during reconstruction.
- Rebuilding to improve the seismic safety of the urban center can be divisive politically; therefore, improved building and zoning regulations should be devised and adopted in advance.

Avoidance

The least expensive and most logical risk management strategy is avoidance. Planners should take the lead in identifying those locations in an urban center that are most susceptible to physical effects such as ground shaking, ground failure, surface fault rupture, and tsunami wave runup, and promote physical planning practices that avoid these hazards. Whenever possible, for example, physical plans should avoid locating buildings and lifeline systems:

- On soils having the same fundamental period of vibration as that of the building or lifeline system.
- In configurations where they will hammer or pound adjacent structures.
- On unstable soils susceptible to liquefaction and landslides.
- In locations subject to surface fault rupture, tectonic deformation, and flooding from tsunami wave runup, or a dam failure.

Wise Use of the Land

The local government, which adopts and enforces land-use measures and building regulations, always achieves earthquake risk reduction because it controls the only optional factor that governs destructiveness of an earthquake. The community has no options regarding control of: (1) the magnitude or energy release of the earthquake, and (2) the proximity of the earthquake source to the urban center. But it can control the extent to which land-use planning and building regulations have been implemented in the urban center to mitigate the effects of ground shaking, ground failure, surface fault rupture, and tsunami wave runup when the earthquake strikes.

Adoption and Enforcement of Building and Zoning Regulations

Planners, architects, and engineers have an important role in the adoption and enforcement of building and zoning regulations. Experience in past earthquakes has shown that economic loss, loss of life, and injuries are lower in urban centers that adopt and enforce seismic design provisions of a building code or urban development plans that consider the types and density of land use in areas prone to strong ground shaking, ground failure, surface faulting, or tsunami wave runup through zoning ordinances.

Reduction of Vulnerability

Damage and loss of function in a large city or capital city can be very disruptive to the State, adjacent States, and possibly the Nation. The capital is usually the headquarters and center for decisionmaking; political, administrative and cultural leadership; banks, insurers, and developers; and newspapers, radio, and television; and foreign embassies. Planners, architects, and engineers can reduce the vulnerability of existing development by application of structural and nonstructural measures in essential facilities such as schools, hospitals, and other buildings.

Coordinated Planning, Siting, Design, and Construction Practices

Planners, architects, and engineers have learned from earthquakes throughout the world that physical planning practices should be integrated with siting, design, and construction practices if buildings and lifeline systems are to withstand the physical effects of ground shaking and ground failure with a high degree of reliability.

Modification of the Characteristics of Ground Shaking and Ground Failure

Planners, architects, and engineers should work together to resolve problems associated with important new or existing civic, historical, or cultural buildings determined to be vulnerable to ground shaking or ground failure. For example, they can use base isolation technology to reduce ground shaking levels, and engineering methods to remediate soils and sites prone to liquefaction or landslides.

Prediction and Warning

Planners and emergency managers should collaborate with scientists who are monitoring pre-earthquake phenomena in order to predict the time, place, magnitude, and probability of occurrence of damaging earthquakes. At present, because the science of earthquake prediction is young, only intermediate- and long-term forecasts are feasible (i.e., a few years to a few decades). Planners and emergency managers should utilize the information contained in warnings associated with intermediate and long-term predictions to improve physical plans and emergency response and disaster recovery.

CONCLUSIONS

Under the auspices of NEHRP, continuing efforts are being made to keep the inevitable future earthquake from becoming a disaster (Figure 4). The emphasis is on improving earthquake hazard and risk assessments, transferring technology for earthquake risk management, and reducing the risk in every earthquake prone area of the United States. A technology base (i.e., information, knowledge, and know how) for earthquake risk management now exists, therefore, it is a matter of continuing the transfer of required technology to practitioners and fostering its implementation at the local level to change policies and practices.

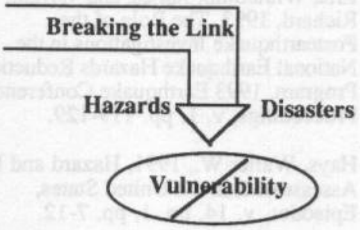

Figure 4--The goal of many communities throughout the world during the 1990's is reduction of community vulnerability to earthquakes (i.e., eliminates flaws in siting, design, and construction).

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