Reducing Earthquake Losses

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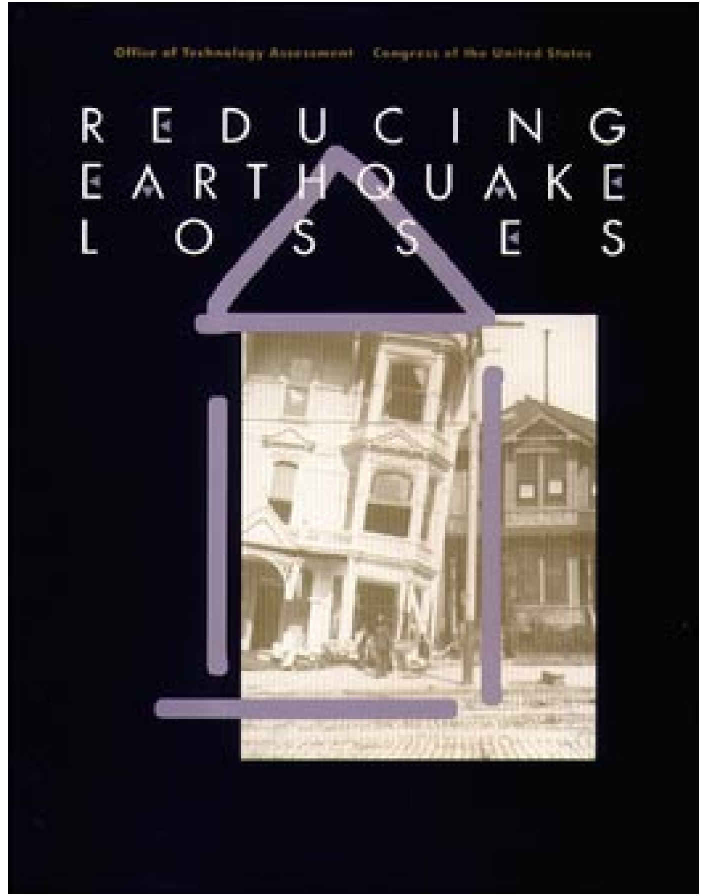

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Foreword

Much of the nation is at risk for earthquakes. Although considerable uncertainty remains over where and when future earthquakes will occur, there is general consensus that earthquakes will strike the United States in the next few decades, causing at a minimum dozens of deaths and tens of billions of dollars in losses.

Recent congressional hearings on the nation's earthquake program—the National Earthquake Hazards Reduction Program (NEHRP)—revealed some dissatisfaction with the program, yet little agreement on problems or solutions. The House Committee on Science, Space, and Technology (now the Committee on Science) and its Subcommittee on Science (now the Subcommittee on Basic Research) asked the Office of Technology Assessment to review the nation's efforts to reduce earthquake losses, and to provide options for improving these efforts.

This Report assesses the state of the knowledge, identifies key future challenges in each of the three components of earthquake risk reduction—earth science, engineering, and implementation—and offers policy options to improve federal efforts. The Report concludes that, since its beginning in 1977, NEHRP support of efforts to better understand earthquake risk and find ways to reduce it have advanced our knowledge considerably, although many significant uncertainties remain. However, there is a large gap between knowledge and action—many known technologies and practices are just not used. In addition, NEHRP suffers from a lack of specific goals, making progress difficult to measure. Policy options for improving federal efforts include changes in the specific activities supported by NEHRP, changes in the management and operations of the program, and extension of federal activities into areas in which NEHRP is not currently active.

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Note: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

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Executive Summary

The 1994 Northridge, California, earthquake caused dozens of deaths and over $20 billion in losses. In 1995 an earthquake in Kobe, Japan, killed more than 5,000 and resulted in losses of well over $100 billion. These disasters show the damage earthquakes can inflict. Although future losses are uncertain, there is general agreement that **damaging earthquakes will strike the United States in the next few decades, causing at the minimum dozens of deaths and tens of billions of dollars in losses.**

Since 1977, the federal government has had a research-oriented program to reduce earthquake losses. This program—the National Earthquake Hazard Reduction Program (NEHRP)—has made significant contributions toward improving our understanding of earthquakes and strategies to reduce their impact. However, much of the United States remains at risk for significant earthquake losses. Risk-reduction efforts lag far behind the knowledge base created by research; this lag, or "implementation gap," reflects the limitations of NEHRP's information-based strategy for encouraging nonfederal action. NEHRP also suffers from a lack of clear programmatic goals.

THE EARTHQUAKE THREAT

Much of the United States is seismically active. Risks vary widely from region to region:

- The greatest likelihood of repeated economic losses due to earthquakes is in the coastal regions of California, where moderate earthquakes are frequent and population densities are high. California, in addition, faces a lower probability of larger, very damaging earthquakes.
- The Pacific Northwest has experienced rare but very large earthquakes in the past; the timing of future earthquakes in this region of the country is uncertain.
- Quakes in the section of the Intermountain West running from southern Idaho and western Montana through Utah and Nevada can endanger communities historically unprepared for any seismic activity.
- The central United States (chiefly, the region near the intersection of Missouri, Kentucky, Tennessee, and Arkansas) and sections of the eastern United States have experienced infrequent earthquakes in the past. Future occurrences are very uncertain, but if and when they do occur, losses could be quite high as these areas are largely unprepared.

The primary hazard associated with earthquakes is ground shaking, which damages and destroys buildings, bridges, and other structures. Ground shaking also causes liquefaction, landslides, and other ground failures that endanger structures. This damage and destruction has both short- and long-term implications. In the short term, people are killed and injured by falling buildings and other objects. The fires associated with earthquakes are often difficult to fight because water pipes have been broken and roads have been blocked by debris. In the long term, the costs of repair or replacement, coupled with the loss of customers and employees (e.g., due to impassable roads), can force businesses and industries to close. Local governments may be forced to cut services to cover the costs of infrastructure repair. And if reductions in the supply of housing lead to higher rents, there may be increased homelessness.

THE U.S. POLICY RESPONSE TO DATE

The federal government currently responds to the earthquake threat with a number of policies and programs. Its primary effort is the National Earthquake Hazard Reduction Program (NEHRP), established in 1977 to "reduce the risks of life and property from future earthquakes in the U.S...." The program combines the efforts of four federal agencies:

- the U.S. Geological Survey (USGS),
- the National Science Foundation (NSF),
- the Federal Emergency Management Agency (FEMA), and
- the National Institute of Standards and Technology (NIST).

NEHRP's original charter included wide-ranging provisions for earthquake prediction, earthquake control, and vigorous implementation of seismic safety knowledge. In practice, however, the program has centered on the performance and dissemination of science and engineering research. Thus, 64 percent of the NEHRP budget goes (via USGS and NSF) to research in the earth sciences, and another 14 percent supports engineering research; the remaining 22 percent of the budget goes to "implementation" activities such as technical translation, education, and outreach.

NEHRP: PROGRESS AND PROBLEMS

NEHRP-sponsored research has yielded an impressive list of accomplishments. Although past accomplishments do not ensure future ones, it is clear that **NEHRP has led to significant advances in our knowledge of both earth science and engineering aspects of earthquake risk reduction.** For example, NEHRP-supported research led to recognition of the seismic risk in the Pacific Northwest, and NEHRP funding helped develop the knowledge base that now makes it possible to design and construct new buildings that are unlikely to collapse in earthquakes. Although NEHRP is principally a research program—over 75 percent of its funds are directed toward research—it has made some contributions to the implementation of earthquake mitigation, as well. Thus, for example, we now have model building codes that reflect a national consensus on new building seismic design, as well as several interdisciplinary centers that work to translate research results into useful information for decisionmakers.

Despite these successes, however, earthquakes continue to cause massive losses in the United States. The 1994 Northridge earthquake caused more than $20 billion in losses, and scenarios of possible future U.S. earthquakes suggest that thousands of casualties and tens or even hundreds of billions of dollars in losses may occur. Although there is no consensus on what level of loss is acceptable,[1] **there is clearly a significant remaining exposure to earthquake damage—due in large part to a failure to implement known technologies and practices.** Many communities, especially in California, have taken steps to reduce earthquake losses, but there still remains a large gap between what current knowledge says could be done and what actually is done.

The failure to implement known technologies and practices, or "implementation gap," is a direct result of NEHRP's approach to reducing earth-

[1] Although no losses would seem desirable, achieving zero losses would be either impossible or impractically expensive.

quake losses. NEHRP's approach can be thought of as supplying information on earthquake risks and possible countermeasures to those who may wish to mitigate. By supplying this information, the program hopes to motivate individuals, organizations, and local and state governments toward action while providing guidelines on how to proceed. This approach implicitly assumes that the interest or incentive for mitigation is sufficient for people to act on such information. However, the current paucity of mitigation activities suggests that individuals, organizations, and local and state governments lack sufficient incentives for mitigation. Whether or not the federal government should play a role in ensuring that there are sufficient incentives for mitigation is a sensitive policy question. In any case, **NEHRP's approach of supplying information alone clearly limits the program's impact.**

NEHRP faces serious operational problems as well. Numerous congressional reports and expert review panels have noted that **NEHRP lacks clear and workable goals and strategies.** Although NEHRP's authorizing legislation does set broad overall objectives for the program, actual NEHRP spending by the four participating agencies does not suggest any unified multiagency agreement on specific goals, strategies, or priorities. In the absence of a multiagency consensus on NEHRP goals and strategies, each of the four participating agencies (USGS, NSF, FEMA, and NIST) has developed a portfolio of NEHRP activities that reflects its own agency mission and priorities. In addition, the lack of agreement on goals and strategies makes it difficult to judge the impact or success of the overall program, since there are few criteria by which to measure performance.

POLICY OPTIONS

OTA has identified several policy options that Congress could consider to improve federal efforts to reduce earthquake losses. Three general types of policy options are discussed:

- One type of option involves changes in the specific research and other activities that NEHRP undertakes. OTA identifies key research and implementation needs that NEHRP could address within its current scope.
- The second type of option involves management and operational changes in NEHRP. Such changes could make NEHRP a more efficient, coordinated, and productive program.
- The third type of option includes changes to federal disaster assistance and insurance, regulation, and financial incentives. Such changes are outside the current scope of NEHRP and would represent a significant change in direction for the program. However, **such changes are necessary to yield major national reductions in earthquake risk.**

CHANGES IN SPECIFIC ACTIVITIES OF NEHRP

Earth Science Research

Decisions about what earth science research to support should be made in the context of the goals of the earthquake program. If Congress would like NEHRP to reduce earthquake losses in the short term and also to focus on implementing known technologies and practices, then the earth science research portfolio should favor more applied, short-term work such as microzonation, ground motion mapping, and hazard assessment. In contrast, if Congress views NEHRP as a program for reducing earthquake hazards over the long term, it would be appropriate to retain the current focus on basic earth science research.

Earthquake Engineering Research

A new structure that meets current seismic building codes will be very resistant to collapse due to earthquakes. The construction of buildings that are resistant to collapse is a great technical accomplishment in which NEHRP played a considerable role. Since this has been achieved, it is time to consider moving some resources to the next research challenge—reducing earthquake-related structural, nonstructural, and contents damage.

Much of the risk of both structural failure and nonstructural and contents damage lies in existing structures, which do not incorporate current codes and knowledge. Relatively few of these structures have been retrofitted to reduce risk; and where retrofits have been performed they have often been expensive, complex, and of uncertain benefit. More research is needed to improve retrofit methods.

Implementation

One of NEHRP's most promising implementation activity is to directly assist communities in their efforts to understand earthquake risk and to devise mitigation options. Analytic tools to estimate likely losses in the event of a future earthquake and to predict the likely benefits of mitigation would be of great help to communities.

FEMA currently has several programs intended to promote implementation of known mitigation technologies and practices. Very few of these programs have been evaluated carefully in the past, leaving current program planners with little guidance as to what works, what does not, and why. All mitigation programs should be evaluated carefully, and the results should be used to improve, refocus, or—if necessary—terminate programs.

In addition to direct support for implementation, NEHRP also supports some research into the behavioral, social, and economic aspects of mitigation. Further research of this type could improve our understanding of some key issues that currently hinder mitigation.

MANAGEMENT AND OPERATIONAL CHANGES

NEHRP spending by the four participating agencies suggests a loosely coordinated confederation of agencies with no overarching agreement on specific goals, strategies, or priorities for NEHRP. One policy option is for FEMA, as the lead agency, to work with other NEHRP agencies and with the professional earthquake community to come up with specific goals and priorities for NEHRP. Defining overarching goals for NEHRP would not be easy and would have to address the difficult issue of acceptable risk. Yet it is necessary for NEHRP to move beyond a loose confederation of four agencies. Congress could require FEMA to report on progress toward defining and meeting specific goals for NEHRP. Since FEMA has no explicit budgetary or other control over the other agencies that participate in NEHRP, Congress may wish to provide oversight to ensure that all these agencies work toward defining and meeting the agreed-on goals.

The continuing congressional dissatisfaction with FEMA's management and coordination of NEHRP has led some to consider transferring lead agency responsibility from FEMA to another agency. OTA's finding that implementation is emerging as NEHRP's key challenge, however, suggests that, of the four principal NEHRP agencies, FEMA appears to be the most appropriate lead agency. FEMA has the most direct responsibility for reducing losses from natural disasters; it is in direct contact with state, local, and private sector groups responsible for reducing earthquake risks; it has a management rather than research mission; and it coordinates regularly with other agencies in carrying out its mission. The other NEHRP agencies are principally involved in research and therefore may find it difficult to develop the strong implementation component necessary to lead the program. One policy option would be for Congress to allow FEMA to continue as lead agency but to provide frequent oversight to ensure that lead agency responsibilities are carried out.

BEYOND THE CURRENT NEHRP

Congress could consider other policy options that go beyond the scope of the current NEHRP. These include using federal disaster assistance as an incentive for mitigation, an increased federal role in disaster insurance, increased regulation, and greater use of financial incentives to promote mitigation. These policy options have the potential to significantly increase implementation of seismic safety knowledge—something NEHRP, in its current form, is unlikely to accomplish. However, these options would likely require new legislation and would be a significant departure from current policy. They would also be quite controversial.

In considering these options, a central issue is: **What is the appropriate role of the federal government in mitigation?** Some argue that increased investment in mitigation by the federal government would save money by reducing future disaster outlays. Others argue that the very existence of federal disaster assistance programs creates disincentives for mitigation. Still others argue that mitigation tools, notably land-use planning and building regulation, are state and local issues in which an increased federal role is inappropriate. These arguments involve different political and philosophical beliefs; OTA does not attempt to resolve them but rather suggests that policymakers consider the policy options in light of their own beliefs.

Insurance and disaster assistance can be a vehicle for mitigation, as well as a disincentive against mitigation, depending on how the program is structured. Congressional decisions as to the fate of hazards insurance legislation will involve many issues, most of which are beyond the scope of this report. With respect to mitigation, however, it is clear that insurance can be a strong incentive for earthquake mitigation—if the cost of insurance reflects the risk. In addition, social science research suggests that individual mitigation decisions are not made on an economically rational cost-benefit basis but are considerably more complex. Insurance programs should recognize these complexities.

One policy option, largely outside the scope of NEHRP as currently defined, would be for the federal government to take a stronger position on implementation via regulation. In the current policy environment, regulation in the form of building codes is the most widely used mitigation tool, but it is performed at the state or local level. The federal government plays only an indirect role by providing technical support for code development and implementation. In addition, Executive Order 12699 (issued January 5, 1990) requires that new buildings constructed with federal assistance meet current codes. A more aggressive policy option would be to require states and localities to adopt model building codes, or demonstrate a minimum level of code enforcement, as a condition for receiving federal aid. Nonstructural mitigation efforts could be advanced through an executive order addressing this problem in federal buildings.

Summary and Policy Options 1

Earthquakes have caused massive death and destruction, and potentially damaging earthquakes are certain to occur in the future. Although earthquakes are uncontrollable, the losses they cause can be reduced by building structures that resist earthquake damage, matching land use to risk, developing emergency response plans, and other means. Since 1977, the federal government has had a research oriented program to reduce earthquake losses—the National Earthquake Hazards Reduction Program (NEHRP). This program has made significant contributions toward improving our understanding of earthquakes and strategies to reduce their impact. Implementing action based on this understanding, however, has been quite difficult.

This chapter provides an introduction to earthquakes: a summary of the earthquake hazard across the United States, a review of the types of losses earthquakes cause, a discussion of why earthquakes are a congressional concern, and an introduction to *mitigation*—actions taken prior to earthquakes that can reduce losses when they occur. The federal policy response to date, NEHRP, is then described and reviewed. Finally, specific policy options for improving federal efforts to reduce future earthquake losses are presented.

INTRODUCTION TO EARTHQUAKES

■ When and Where Earthquakes Occur

Many parts of the United States are subject to earthquakes, which occur when stress accumulates in underground rocks. This buildup of stress typically reflects the slow but continuous motion of the earth's outermost rocky layers, large sections of which drift about the globe as moving *tectonic plates*. Where adjacent plates collide or grind against one another, rocks are highly stressed, and this stress is released in sudden shifts in the earth's surface. As a result, plate boundaries are the primary breeding ground for earthquakes.

One such boundary lies in California, where two major plates slide against one another along the San Andreas fault. Stresses along this and associated faults make California subject to frequent and sometimes powerful earthquakes. In the north of the state, detailed earth science research suggests **a 67 percent probability of one or more earthquakes of magnitude 7[1] or greater in the San Francisco Bay area by 2020.[2]** To the south, where hazard assessments are less certain due to the geologic complexity of the Los Angeles region, a recent report estimates **an 80 to 90 percent probability of a magnitude 7 or greater earthquake in southern California before 2024**.[3]

The colliding of adjacent plates produces extremely powerful earthquakes along the Alaskan coast, one of which severely damaged the city of Anchorage in 1964. A similar earthquake threat has recently been recognized in the Pacific Northwest states of Oregon and Washington: according to a 1991 study, **a great earthquake (magnitude 8 to 9) is possible in the Pacific Northwest; magnitude 6 to 7 earthquakes have occurred in this area in the past and are likely to occur in the future**.[4]

Other parts of the United States are also seismically active—due not to plate collisions, but to other processes not well understood. **Regions experiencing damaging earthquakes in the recent past include parts of the Intermountain West (i.e., sections of Utah, Idaho, Wyoming, Montana, and Nevada); the Mississippi Valley region of the central United States (centered on an area north of Memphis, Tennessee); and cities on the Atlantic seaboard (notably Charleston, South Carolina, and Boston, Massachusetts).** (See figure 1-1.) Earthquakes in these regions (called *intraplate* earthquakes because they occur far from current plate boundaries) are infrequent but potentially powerful.

Earthquake Effects

Earthquakes can cause deaths, injuries, and damage to buildings and other structures, and may inflict a wide range of longer term economic and social losses as well.[5] Although estimating future losses is very uncertain (see box 1-1), there is general agreement that in the next 50 years or so **one or more damaging earthquakes will occur in the United States, resulting in at least hundreds of deaths and tens of billions of dollars in losses**. Larger events, involving thousands of deaths and hundreds of billions of dollars in losses (such as that seen in the 1995 earthquake in Kobe, Japan), are also possible, although scientific uncertainty makes it difficult to estimate their likelihood.

The primary hazard associated with earthquakes is ground shaking, which can damage or destroy buildings, bridges, and other structures. Figure 1-2 shows expected ground motions from

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[1] A magnitude 7 earthquake is one large enough to cause serious damage. For comparison, a magnitude 5 will cause slight damage, and a magnitude 8 or greater can cause total damage. See chapter 2 for a discussion of earthquake magnitude scales.

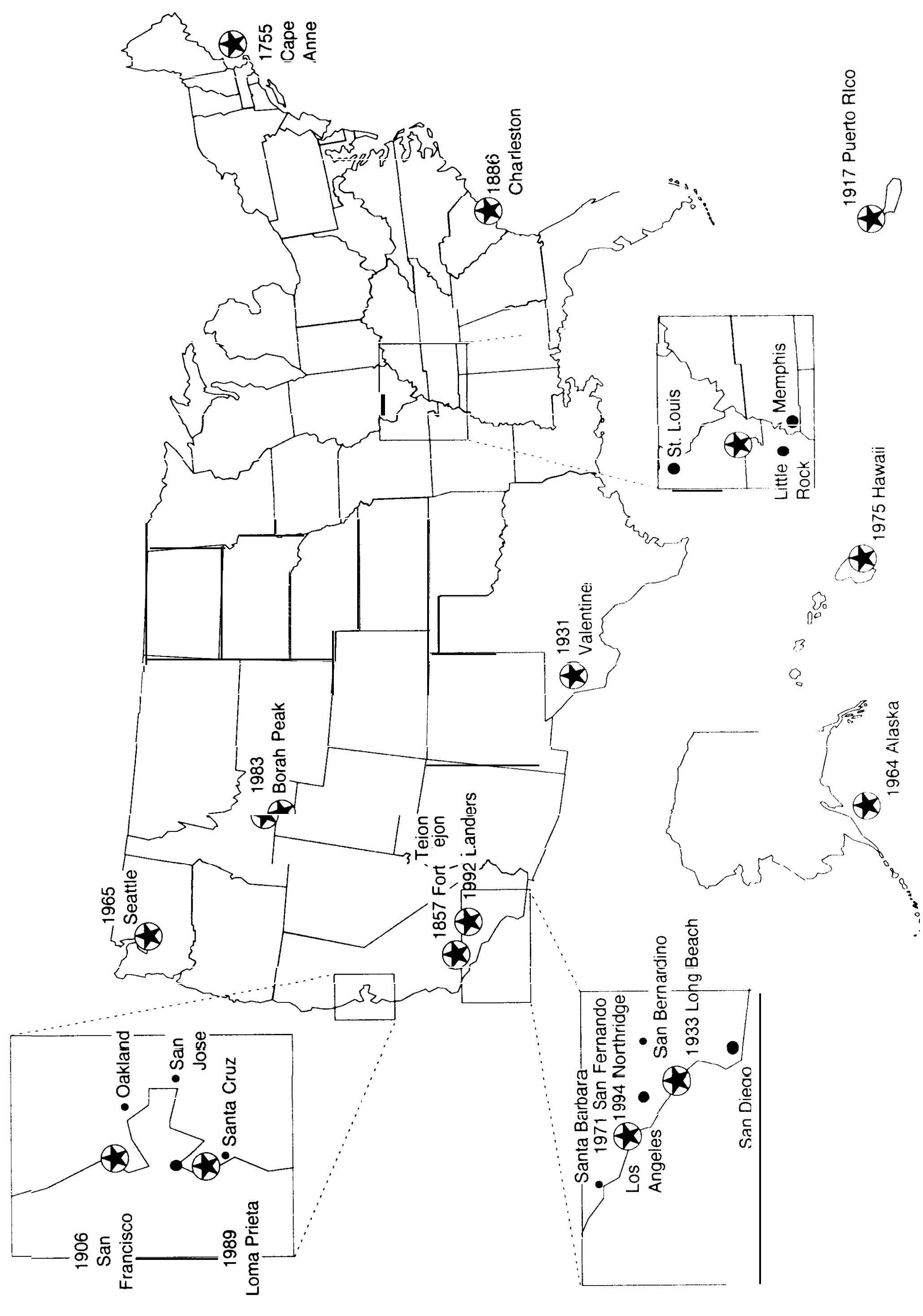
[2] Working Group on California Earthquake Probabilities, *Probabilities of Large Earthquakes in the San Francisco Bay Region, California*, U.S. Geological Survey Circular 1053 (Washington, DC: U.S. Government Printing Office, 1990).

[3] Working Group on California Earthquake Probabilities, "Seismic Hazards in Southern California: Probable Earthquakes, 1994-2024," *Bulletin of the Seismological Society of America*, vol. 85, No. 2, April 1995, p. 379.

[4] Kaye M. Shedlock and Craig S. Weaver, *Program for Earthquake Hazards Assessment in the Pacific Northwest*, U.S. Geological Survey Circular 1067 (Washington DC: U.S. Government Printing Office, 1991), p. 1.

[5] *Damage* generally refers to the direct physical effects of earthquakes, while *losses* include all the societal effects including deaths, injuries, direct financial costs, indirect costs (such as those resulting from business interruptions), and social impacts such as increased homelessness.

FIGURE 1-1: Recent Selected Significant Earthquakes in the United States



NOTE: Not to scale

SOURCE: Office of Technology Assessment, 1995, based on U.S. Geological Survey

BOX 1-1: Loss Estimation

Dependable estimates of likely losses from earthquakes would be useful in developing appropriate policies for earthquake mitigation—for example, by allowing comparisons with other threats to life and property. Unfortunately, the huge uncertainties in the location, timing, and magnitude of earthquakes themselves; in the response of the built environment to earthquakes; and in the inventory of structures that might be damaged make estimating future losses very difficult. '

Despite these difficulties, some estimates of future losses have been made. The results of several such studies are summarized here to provide a sense of the probable range of such losses. These studies cannot be compared, since they examine different geographical areas and different types of losses. As a group, however, they give some indication of the expected scale of future losses A 1992 study for the property Insurance industry estimated losses for several geographic areas, including sections of California, the Pacific Northwest, and the central United States. Total losses due to building damage for a magnitude 7.8 earthquake on the northern section of the San Andreas fault near San Francisco, for example, were estimated at $35.2 billlon.[2] This does not include public sector losses, such as those due to damaged schools or bridges. Another study estimated both dollar losses and fatalities for scenario earthquakes in California and in the central United States. For the larger earthquakes (magnitude 7.5 or greater), losses were on the order of tens of billions of dollars and fatalities in the thousands.[3]

Much more dramatic results can be seen from attempts to predict damages from worst-case earthquakes-great earthquakes that strike close to population centers. A repeat of the 1906 magnitude 8.3 earthquake in San Francisco could cause 2,000 to 6,000 deaths.[4] A repeat of the 1811 central U S earthquake could cause more than $100 billion in damage due to ground motion [5]

An alternate method for arriving at an overall sense of future earthquake damage IS to examine the damage caused by past earthquakes. As shown in the table below, U.S. earthquakes since 1900 have, in total, resulted in about 1,200 deaths and $40 billion in damage. However, extrapolating from historical earthquake damages IS problematic for several reasons"

- All else equal, damage will Increase over time as both population and urbanization Increase—especially in the western United States, which has experienced rapid population growth in recent years
- The recent historical record shows no major earthquakes in the eastern United States, although such earthquakes have occurred and may occur again.

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[1] According to a National Academy of Sciences report, "even using the best of today's methods and the most experienced expert opinion, losses caused by scenario earthquakes can only be estimated approximately Overall property loss estimates are often uncertain by a factor of 2 to 3, and estimates of casualties and homeless can be uncertain by a factor of 10 " National Research Council, *Estimating Losses from Future Earthquakes* (Washington, DC National Academy Press, 1989), p 3

Although loss estimation methods are still relatively crude and hampered by lack of data, recent technological advances suggest that loss estimation may soon be a more useful and accurate policy analysis tool The rapid development of computer hardware and software-specifically the ability to store large amounts of data on CD-ROMs or tapes, and the availability of software that can make sense of these data—has made it possible to manage detailed databases of all structures in specific geographic areas Geographical information systems are now being used in combination with probabilistic ground motion data to yield useful forecasts of likely and worst-case earthquake damages The Federal Emergency Management Agency, for example, IS supporting the development of a computer-based loss estimation tool that would be available to city planners and emergency managers on their desktop computers

[2] Risk Engineering, Inc. , "Residential and Commercial Earthquake Losses in the U S ," prepared for the National Committee on Property Insurance, Boston MA, May 3, 1993 Zero-deductible assumption "Loss" does not reflect deaths or injuries

[3] R Litan et al , "Physical Damage and Human Loss The Economic Impact of Earthquake Mitigation Measures, " prepared for The Earthquake Project, National Committee on Property Insurance, February 1992 Base-case scenarios, without mitigation Expected losses do not include deaths or injuries.

[4] See "'Repeat' Quakes May Cause Fewer Deaths, More Damage, " *Civil Engineering,* November 1994, pp. 19-21

[5] National Academy of Sciences, *The Economic Consequences of a Catastrophic Earthquake,* Proceedings of a Forum, Aug. 1 and 2, 1990 (Washington, DC National Academy Press, 1992), p 72

BOX 1-1 (cont'd.): Loss Estimation

Major U.S. Earthquakes, 1900-94

Year	LoCaliforniation	Deaths	Damages (million $1994)
1906	San Francisco, California	700	6,000
1925	Santa Barbara, California	13	60
1933	Long Beach, California	120	540
1935	Helena, Montana	4	40
1940	Imperial Valley, California	8	70
1946	Aleutian Islands, Alaska	n/a	200
1949	Puget Sound, Washington	8	220
1952	Kern County, California	12	350
1952	Bakersfield, California	2	60
1959	Hebgen Lake, Montana	28	n/a
1964	Anchorage, Alaska	131	2,280
1965	Puget Sound, Washington	8	70
1971	San Fernando, California	65	1,700
1979	Imperial County, California	n/a	60
1983	Coalinga, California	0	50
1987	Whittier Narrows, California	8	450
1989	Loma Prieta, California	63	6,870
1992	Petrolia, California	0	70
1992	Landers, California	1	100
1993	Scotts Mills, Oregon	n/a	30
1993	Klamath Falls, Oregon	2	10
1994	Northridge, California	57	20,000
TOTAL		1,225	39,160

KEY n/a = not available

SOURCE Office of Technology Assessment, 1995

- Some argue that in certain regions, more and larger earthquakes should be expected in the future.[6]
- A single event can influence the data significantly. More than half the deaths since 1900 occurred in just one incident—the 1906 San Francisco earthquake, while about half of the total dollar damages were from the 1994 Northridge event. This demonstrates the "lumpiness" of earthquakes: the deaths and losses occur not in regular intervals, but in large and catastrophic single events.
- On the other hand, new buildings meeting current seismic codes are much more resistant to structural failure than old buildings, which should help to reduce fatalities.

The uncertainties both in projecting losses and in extrapolating historical data make predicting future losses difficult. It is generally agreed, however, that in the next 50 years or so, damaging earthquakes WIII occur in the United States, resulting in at least hundreds of deaths and tens of billions of dollars in losses. Larger events, involving thousands of deaths and hundreds of billions of dollars in losses, are possible, although less likely.

[6] J Dolan et al., "prospects for Larger or More Frequent Earthquakes in the Los Angeles Metropolitan Region," *Science*, vol 267, Jan 13, 1995, pp 199-205

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Failure of the ground itself can make an otherwise sound building unusable.

future earthquakes in the United States. Ground shaking can also cause liquefaction, landslides, subsidence, and other forms of ground failure that can endanger even the best-built structures, and moreover may generate coastal tsunamis (great surges of water popularly known as tidal waves).

The damage and destruction wrought by earthquakes has both short- and long-term implications. In the short term, people are killed and injured by collapsing buildings and falling debris. The fires that can result may be difficult to fight due to broken water pipes and roads blocked by debris. In the long term, the costs of repair or replacement coupled with the loss of customers and employees (e.g., due to impassable roads) can force businesses and industries to relocate or close. Local governments may be forced to cut services to cover the costs of infrastructure repair, and housing rents can increase (due to reductions in supply), leading to increased hopelessness.

Deaths

A single earthquake can cause thousands of deaths and tens of thousands of injuries. In just the last decade—1980 to 1990-earthquakes killed almost 100,000 people worldwide. About two-thirds of these deaths occurred in just two catastrophic earthquakes-over 25,000 deaths in Armenia[6] in 1988 and 40,000 in Iran in 1990.[7]

The historical record of U.S. earthquake fatalities is less unfortunate. Since 1900, about 1,200 people have died in U.S. earthquakes (see box 1-l). Most of these earthquakes occurred in regions that were, at the time, sparsely populated. Thus, the low fatality figures for earthquakes from 1900 to 1950 are not surprising. However. even those quakes occurring since 1950 in heavily populated areas of California have had relatively low fatalities, due largely to the fact that many buildings and other structures in California are built to resist seismic collapse.[8] Casualties from future earthquakes are uncertain. One estimate found that a repeat of the 1906 San Francisco earthquake would cause 2,000 to 6,000 deaths;[9] another study found that a large earthquake striking the New Madrid region of the central United States would result in 7,000 to 27,000 deaths.[10]

Most deaths in earthquakes occur when structures collapse. In Armenia, for example,

6 L. Wyllie, Jr., President, Earthquake Engineering Research Institute, personal communication, May 11, 1995.

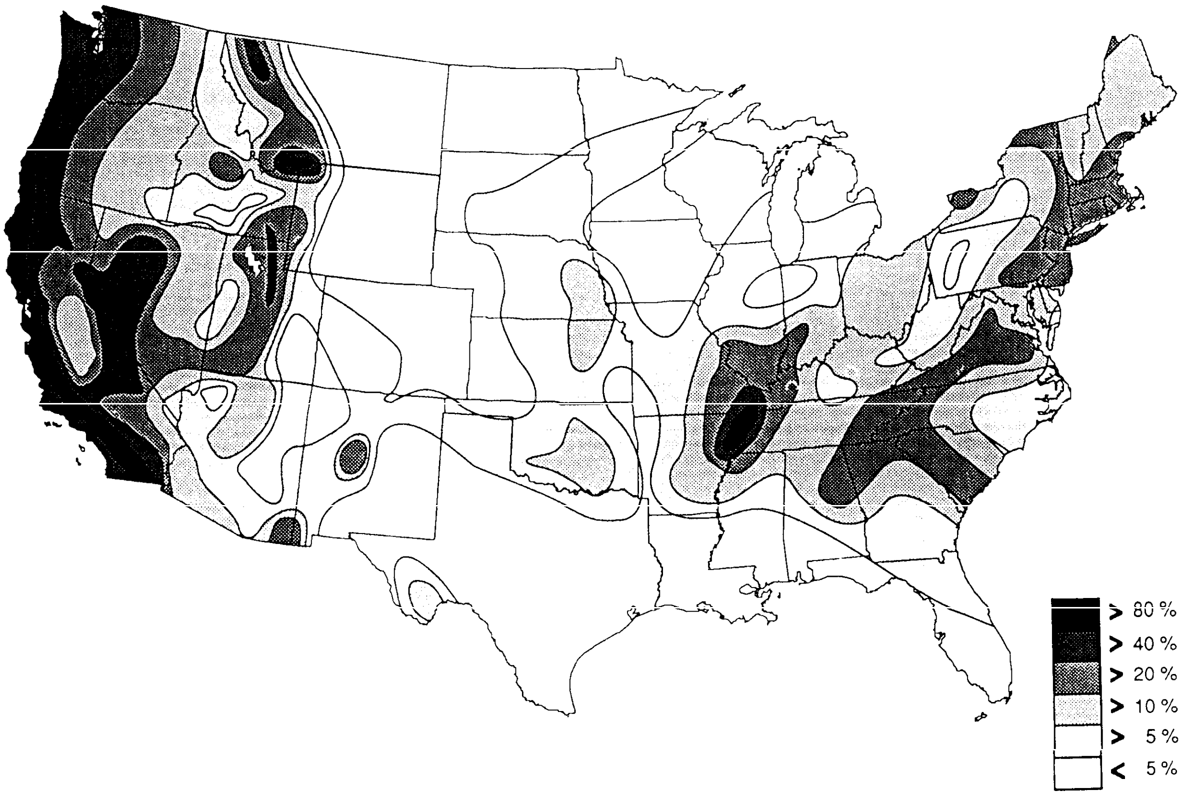
7 B. Bolt, *Earthquakes* (New York, NY: W. H. Freeman and Co., 1993), pp. 272-273.

8 There is an element of luck here as well. The Loma Prieta earthquake, for example, struck during the world series baseball game when roads were relatively empty. Fatalities would have been in the hundreds, perhaps higher, if traffic had been at more typical weekday levels.

9 See "'Repeat' Quakes May Cause Fewer Deaths, More Damage," *Civil Engineering,* November 1994, pp. 19-21.

10 National Academy of Sciences, *The Economic Consequences of a Catastrophic Earthquake,* proceedings of a Forum, Aug. 1 and 2, 1990 (Washington DC: National Academy Press, 1992), p. 68.

FIGURE 1-2: U.S. Seismic Haz



NOTE Map shows expected ground acceleration as a percentage of gravitational acceleration (1 OOYO = 1 0 G) This expected acceleration is for O 3-second period shaking and has a 10% probability of being exceeded in 50 years

SOURCE Off Ice of Technology Assessment, 1995, based on U S Geological Survey

most of the deaths were caused by people being crushed under collapsing buildings. Nearly all of the deaths in the 1989 Loma Prieta earthquake were due to structural collapse.[11] The second major cause of death in earthquakes is fire. In the 1923 Tokyo earthquake, for example, many of the 143,000 deaths were caused by the firestorms that occurred after the quake.[12]

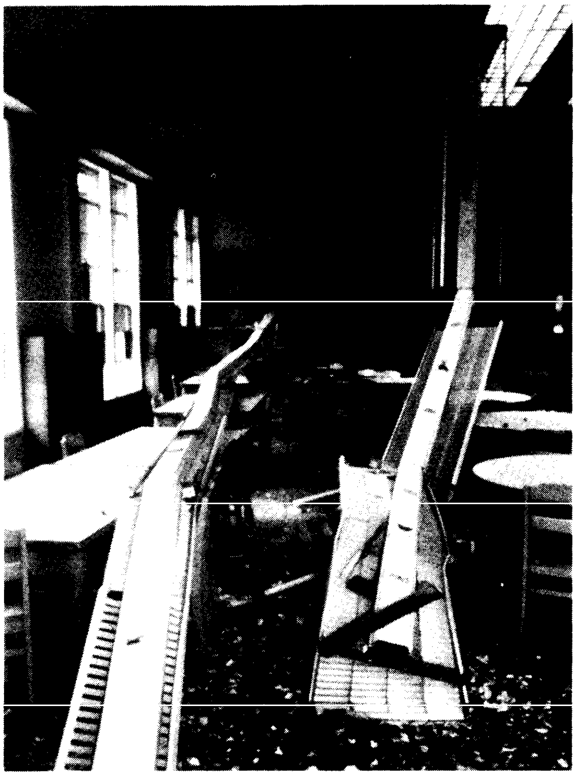
Injuries

In a typical earthquake, many more buildings are damaged than are destroyed. It is this damage to buildings and their contents that causes most injuries. In the 1989 Loma Prieta earthquake, for example, 95 percent of the injuries did not involve structural collapse.[13] These injuries are caused by

[11] M, Durkin and C. Thiel, "Improving Measures To Reduce Earthquake Casualties," *Earthquake Spectra*, vol. 8, No. 1, February 1992, p. 98.

[12] Bolt, see footnote 7, pp. 219, 27"

[13] Durkin and Thiel, see footnote 11



EARTHQUAKE ENGINEERING RESEARCH INSTITUTE

Earthquake injuries are often the result of shifting contents

falls, getting struck by falling or overturned objects, or getting thrown into objects. For example, bookcases and file cabinets can tip over, tumbling books onto people and knocking over other objects, and lighting fixtures and ceiling tiles can come down on people's heads.

Damage to Buildings

Earthquakes can cause four types of damage to buildings: 1) collapse—tile destruction of an entire building, with the death of most of its occupants; 2) structural damage, which leaves the building standing but still unsafe; 3) nonstructural damage to walls, water pipes, windows, and so forth; and 4) damage to contents. The costs of such damage are borne by the building owners and, if the building is insured, by the insurance industry. As discussed later, these costs are in turn shared in many cases by the federal government through disaster assistance programs.

Damage to Lifelines

Lifelines—transportation, energy, water, sewer, and telecommunications systems—are often damaged by earthquakes. These systems can be very expensive to repair; yet even those costs may be dwarfed by the costs of service interruptions. In the short term, interruptions in water supply can cause a city to bum down, and breaks in key transportation links can block access by emergency vehicles. As with buildings, the costs of repair typically fall on the owner (which for many lifelines is the state or local government), the insurance industry if the system is insured, and the federal government through disaster assistance programs.

Other Costs

In addition to deaths, injuries, and damage to buildings and lifelines, earthquakes also cause losses of a different sort. These losses, sometimes called "economic," "indirect," or "social," include the following:

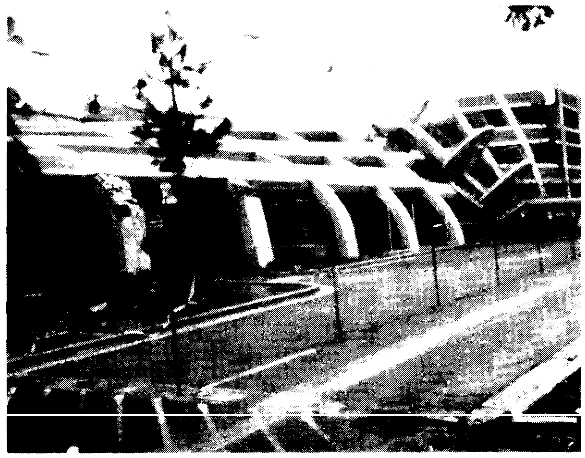
- People cannot get to work when a transportation system is damaged; as a result, businesses must close or reduce their services.
- Basic services such as energy and communications are interrupted, making economic activity difficult or impossible.
- Small business with limited access to capital often cannot survive the combination of loss of business and capital requirements to repair damage.

However, there are those who benefit from earthquakes as well. A severe earthquake is typically followed by a large inflow of money from the government. Construction and associated businesses, such as building materials and architectural firms, experience large increases in business. Housing vacancy rates go down.

The net longer-term economic effects of earthquake are not clear. As a recent review noted,". . . no systematic research has been conducted on the overall economic effects of a major disaster on the public sector, much less on trying to project these impacts for a future catastrophic earthquake. . . .”[14] Clearly, an earthquake has *distributional* impacts (e.g., damaged businesses lose and construction companies gain), but the net effects are difficult to measure.

Social losses

Often missing from attempts to measure the effects of earthquakes are very real social losses. Low-income housing, which is often concentrated in older buildings that are less resistant to seismic damage, may be the most severely affected, leading to increases in hopelessness and dislocation. Communities faced with the huge costs of repairing earthquake-induced damage to public property maybe forced to reduce other services. Housing rents may increase (because of a reduction in supply), resulting in hardship for low-income households. The trauma of seeing one’s home or livelihood threatened or destroyed can be severe. Damaged structures may be left unrepaired for years, creating an eyesore and detracting from a sense of community.



J. DEWEY U.S. GEOLOGICAL SURVEY

The 1994 Northridge, California, earthquake caused extensive damage to this parking garage.

SAN FRANCISCO CHRONICLE

Nonstructural damage can be very costly and disruptive.

■ Congressional Interest in Earthquakes

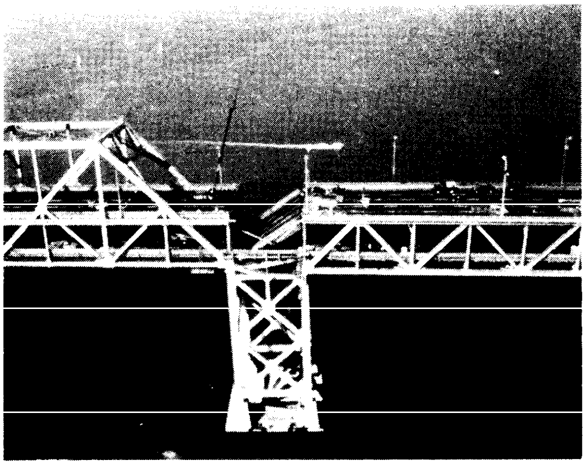
The large and continuing losses from earthquakes are of concern to Congress for several reasons. The federal government has long assumed some responsibility for responding to disasters that are beyond the abilities of individuals and local governments to manage. Earthquakes can easily overwhelm state and local disaster response capabilities, and without federal support, many more people would suffer great personal and financial pain. In recent years, however, the financial costs of federal earthquake relief have been very high. In two recent U.S. earthquakes-Loma Prieta (1989) and Northridge (1994)—Congress passed supplemental appropriations bills to help pay for the losses. For Northridge, this bill totaled about $10 billion (although not all of it was to be spent on the Northridge quake).[15] Future earthquakes may well receive the same response from Congress—a large supplemental appropriation that strains the federal budget and aggravates the deficit. Since the U.S. government pays much of the costs of earthquakes, it is in the government’s financial interest to understand what these costs are due to and how they could be reduced.

In addition to the intermittent large supplemental appropriations to cover some of the costs of earthquakes, the federal government currently spends about $100 million annually on NEHRP—

[14] National Academy of Sciences, see footnote 10, p. 5.

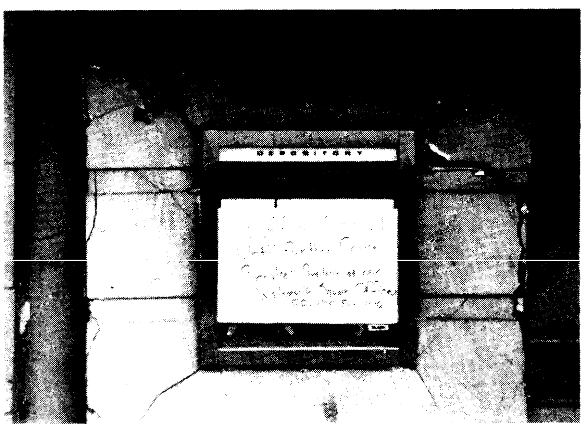
[15] “Disaster Relief: A Trial Run for the Deficit Battle,” *Congressional Quarterly,* Feb. 12, 1994, p. 319.

CALIFORNIA DEPARTMENT OF TRANSPORTATION



The San Francisco-Oakland Bay Bridge was damaged in the 1989 Loma Prieta earthquake.

U.S. GEOLOGICAL SURVEY



Earthquakes often disrupt business services such as banking.

the national program intended to reduce earthquake losses (NEHRP is discussed in detail below). Congressional oversight of this program is needed to ensure that this money is well spent.

The federal government's own property—federal buildings and federally sponsored or supported highways, dams, and other projects—is also at risk from earthquakes. About 40 percent of federal buildings and employees are located in seismically active areas, and about 15 percent are located in areas of high or very high seismic hazard.[16] A recent General Accounting Office report found that, "agencies' efforts to reduce building vulnerability have been limited."[17] Reducing this vulnerability is in the federal government's interest.[18]

Mitigation: Reducing the Losses

Although earthquakes are unavoidable and uncontrollable, much of the losses they cause are not. Numerous technologies and practices are available that can sharply reduce damage and casualties from earthquakes. Some of these are already in use—largely in California, which leads the nation in earthquake mitigation. However, many technologies are underutilized due to lack of incentives, lack of information, and other barriers (discussed in chapter 4).

Mitigation *measures (i.e.,* actions) include:

- incorporating seismic design features into new buildings and lifelines;
- retrofitting existing buildings and lifelines to improve resistance to seismic forces;
- securing nonstructural components so that they do not fall or become sources of injury in an earthquake;
- matching land use to the hazard; and
- developing response plans that ensure the availability of fire, ambulance, and other resources as needed.

There are numerous *tools,* or levers, to promote these measures, including:

- building codes that set minimum seismic requirements for new construction;
- land-use regulations that steer inappropriate development away from dangerous areas (e.g., prohibiting residential construction in landslide-prone areas);

[16] U.S. Congress, General Accounting Office, "Federal Buildings: Many Are Threatened by Earthquakes, but Limited Action Has Been Taken," GAO/GGD-92-62, May 1992.

[17] Ibid.

[18] The federal government has taken some steps, including the signing of two executive orders, to reduce the risk in federal buildings

- provision of information such as detailed ground motion maps to decisionmakers;
- public education programs;
- financial incentives, such as insurance, that promote the use of mitigation measures; and
- research, to better define the risk and improve methods to reduce it.[19]

Clearly, mitigation can save lives and reduce losses. The relatively low fatalities in the two recent California earthquakes, for example, are due largely to the fact that for many years California has had a building code that requires the use of seismic design principles in new building construction. However, mitigation has its challenges as well; these are summarized below.

Knowledge Gaps and Uncertainties

Although considerable progress has been made in defining the earthquake hazard and in understanding how to design structures to reduce the chances of collapse, much remains unknown; these uncertainties make mitigation more difficult. Key knowledge and understanding gaps include:

- the earthquake hazard outside California—the probabilities, magnitudes, and resulting ground motions of potentially damaging earthquakes;
- how to design buildings to minimize structural and nonstructural damage (as distinguished from minimizing the chances of collapse);
- low-cost and effective ways to retrofit existing structures to reduce earthquake damage; and
- the costs and benefits of mitigation.

Information Access

Decisionmakers may not have access to the latest information, or current knowledge may not be available in a useful and understandable form. For example, structural engineers may not be trained in the latest thinking on seismic design, and homeowners may not know that gas water heaters should be secured to the wall. Similarly, city planners and land-use zoning officials may not have accurate and readily understandable risk maps showing which areas of the city are susceptible to earthquake-induced liquefaction or landslides.

Costs, Benefits, and Incentives

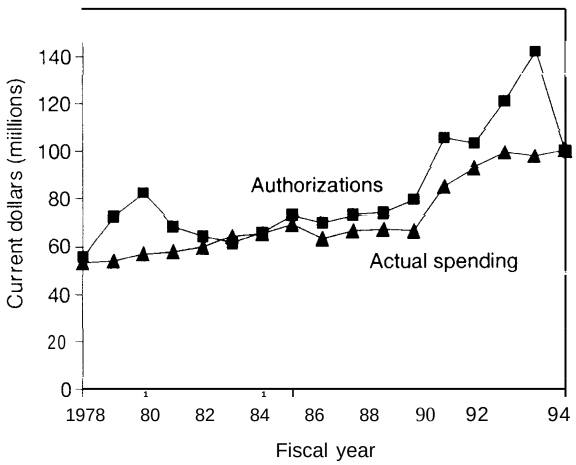
The use of mitigation technologies and practices increases upfront (initial) costs. These costs can be calculated with reasonable certainty, and they can be considerable. For example, the estimated cost to seismically retrofit buildings at one campus of the University of California is $500 million.[20] The benefits of mitigation—avoided damage—occur in the future and are, like earthquake risk, uncertain. Forecasting the benefits of mitigation in just one building requires information on future earthquake timing, effects, damage without mitigation, and reduction in damage due to mitigation. These are all uncertain, and this uncertainty makes it very difficult to determine the net benefits (i.e., benefits minus costs) of mitigation. Although there is general agreement in the professional community that greater mitigation would have positive net financial benefits (i.e., benefits would exceed costs), this can be difficult to demonstrate due to the numerous uncertainties.

Even when mitigation clearly provides positive net benefits, many individuals and institutions demand rapid paybacks from investments (i.e., they heavily discount future returns) and are less likely to invest in mitigation since its benefits are long term. For example, if a building owner expects to own a building for only a short time, he or she may see the probability of an earthquake in that time period as low and therefore not justifying

[19] The earthquake *hazard* is ground shaking, liquefaction, and other natural phenomena that cannot be controlled; while the *risk* is the potential for losses and *can* be controlled.

[20] C. Ingham and T. Sabol, "A Comprehensive Seismic Program: The Experience at UCLA," in *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering,* July 10-14, 1994, Chicago, IL (Oakland, CA: Earthquake Engineering Research Institute, 1994), vol. 3, p. 842.

FIGURE 1-3: NEHRP Authorizations and Actual Spending, 1978-94



SOURCE Office of Technology Assessment, 1995, based on NEHRP budget data

mitigation. In addition, the costs and benefits of mitigation may fall on different groups. For example, if an individual believes that an insurance company or the federal government is likely to pay for earthquake damage, there is less financial incentive to mitigate.

POLICY RESPONSE TO DATE: FOCUS ON NEHRP

The federal government currently responds to the earthquake threat with a number of policies and programs. Its primary effort is NEHRP, established in 1977 to "reduce the risks of life and property from future earthquakes in the U.S. . . ."[21] This program combines the efforts of four federal agencies—the U.S. Geological Survey (USGS), the National Science Foundation (NSF), the Federal Emergency Management Agency (FEMA), and the National Institute of Standards and Technology (NIST)—in an effort to reduce earthquake risk through research, development, and implementation.

This Office of Technology Assessment (OTA) report was prepared in response to a request by the House Committee on Science for use in reauthorizing the NEHRP program. Therefore, it focuses on NEHRP. However, the federal government has a number of other policies and programs for addressing earthquakes. Although these are largely response and recovery programs, they have some effect on mitigation. The principal federal disaster program is the Robert T. Stafford Disaster Relief and Emergency Assistance Act,[22] which authorizes the President to issue major disaster or emergency declarations, sets eligibility criteria, and specifies the types of assistance that federal agencies may offer. In the event of a presidentially declared disaster, the region becomes eligible for a number of programs, many of which are operated by FEMA. In the case of large disasters such as the 1989 Loma Prieta and 1994 Northridge earthquakes, Congress passed supplemental appropriations bills to fund FEMA and other agencies' disaster response programs.

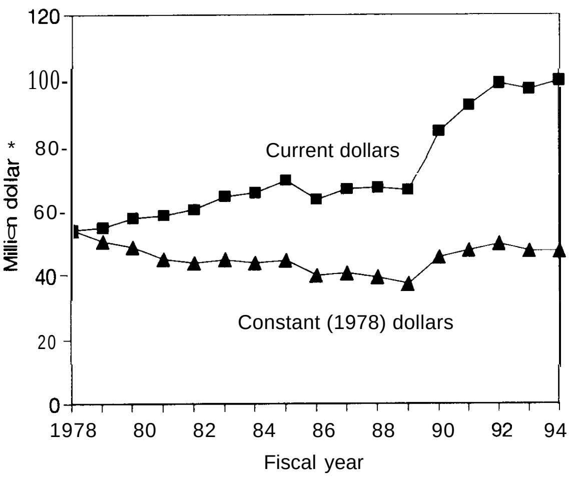
A number of federal agencies have earthquake mitigation research and implementation programs that deal with specific earthquake risks faced by these agencies. The Department of Veteran's Affairs, the Department of Energy, the Department of Defense, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and others conduct a wide range of earthquake-related research and mitigation (see appendix B).

Two recent executive orders address the earthquake risk in federal buildings. Executive Order 12699 (signed January 5, 1990) directs federal agencies to incorporate seismic safety measures in new federal buildings; Executive Order 12941 (signed December 1, 1994) establishes standards

[21] Public Law 95-124, Oct. 7, 1977, as amended.

[22] 42 U.S.C. 5121 *et seq.*

FIGURE 1-4: NEHRP Spending in Current and Constant Dollars, 1978-94



SOURCE Office of Technology Assessment, 1995, based on NEHRP budget data.

for use by federal agencies in evaluating and retrofitting existing federal buildings.

■ Brief Description of NEHRP[23]

The National Earthquake Hazards Reduction Program was enacted on October 7, 1977, and has been amended several times. The original law provided authorizations only for USGS and NSF. Amendments in 1980 established FEMA as the lead agency, and extended authorizations to FEMA and to NIST. Amendments in 1990 clarified agency roles and set congressional reporting requirements.

NEHRP actual spending has, in most years, been considerably lower than that authorized (figure 1-3) and has decreased in constant (real) dollars (figure 1-4).

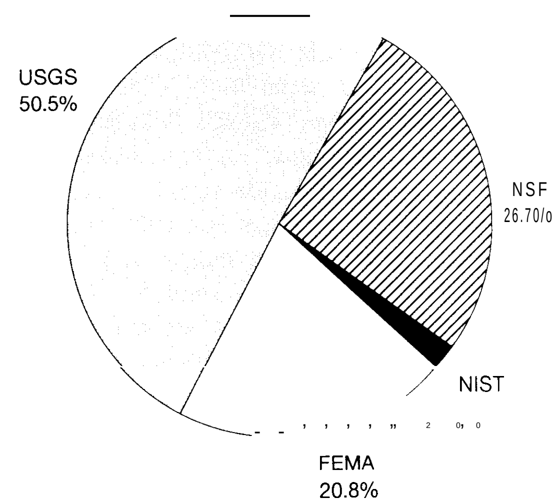
There is no NEHRP agency or central office. Rather, NEHRP is a program in which four federal agencies—USGS, NSF, FEMA, and NIST—participate. **Almost two-thirds of NEHRP funds go for earth science research—via** USGS and NSF earth science programs (see figure 1-5). Fourteen percent is used for engineering research, and 21 percent is used by FEMA, mostly for implementation programs. (See figure 1-6 for data on how agency funding has changed over time.)

U.S. Geological *Survey*

USGS accounts for about half of NEHRP funding—$49.9 million in fiscal year 1994. The majority of USGS activities related to earthquakes are under the agency's Earthquake Hazards Reduction Program, whose stated goals are:

- understanding the earthquake source;
- determining earthquake potential;
- predicting the effects of earthquakes: and
- using research results .24

FIGURE 1-5: NEHRP Spending by Agency, 1994



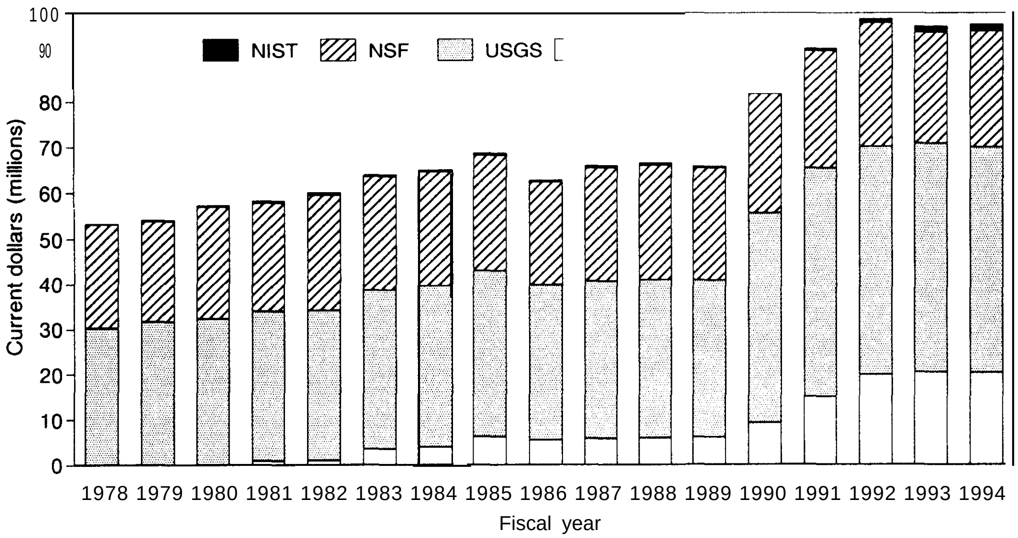
KEY USGS = U S Geological Survey, NSF = National Science Foundation, FEMA = Federal Emergency Management Agency, NIST = National Institute of Standards and Technology

SOURCE Office of Technology Assessment, 1995, based on NEHRP budget data

23 See appendix A of this report for a detailed history of NEHRP.

24 Robert A. Page et al., *Goals, Opportunities, and Priorities for the USGS Earthquake Hazards Reduction Program. U.S.* Geological Survey Circular 1079 (Washington, DC: U.S. Government Printing Office, 1992), pp. 1-2.

FIGURE 1-6: NEHRP Spending by Agency, 1978-94



KEY: USGS = U.S. Geological Survey, NSF= National Science Foundation, FEMA = Federal Emergency Management Agency, NIST = National Institute of Standards and Technology.

SOURCE: Office of Technology Assessment, 1995, based on NEHRP budget data.

More than two-thirds of its NEHRP funding is used internally-to support USGS scientists in regional programs, laboratory and field activities, national hazards assessment projects, and seismic network operations. The remainder is spent as grants to outside researchers for specific projects. In general, the internal work focuses more on applying knowledge to describe hazards, while the external program emphasizes expanding and strengthening the base of scientific knowledge.

National Science Foundation

NSF accounts for about 27 percent of NEHRP funding, 11 percent for earth science research and 16 percent for engineering research.

NSF awards grants directly to researchers for the study of earthquake sources, active tectonics, earthquake dating and paleoseismology, and shallow crustal seismicity.[25] The program also supports a university consortium for seismological research and a southern California earthquake research center. Instrument-based seismology, tectonics, and geodesy received the bulk of the funding (together, about 90 percent) in recent years; paleoseismology and microzonation efforts, in contrast, constituted about 5 percent of the overall budget for individual awards.

The NSF earthquake engineering budget can be divided into four major areas: support for the National Center for Earthquake Engineering Research (NCEER) in Buffalo, New York; geotechnical research (e.g., liquefaction and soil response); structural and mechanical research (e.g., active control systems and design methodologies); and socioeconomic and planning research (e.g., cross-cultural hazard response studies and investigations of code enforcement).

25 James Whitecomb, Director, Geophysics Program, National Science Foundation, personal communication, Nov. 21, 1994.

TABLE 1-1: Major Budget Components of FEMA, FY 1993

Area	Approximate annual budget (million $)	Examples
Leadership	1,3	User needs assessment. Small-business outreach program NEHRP plans, reports, and coordination.
Design and construction standards	5.0	Manual for single-family building construction. Preparation of seismic design values. Technical support for model codes.
State and local hazards reduction program	6.1	Grants to states and cities for mitigation programs, Grants to multistate consortia.
Education	1.1	Training in use of NEHRP provisions. Dissemination of information on retrofit techniques.
Multihazard studies	1.7	Loss estimation software development. Wind-resistant design techniques.
Federal response planning	0.9	Urban search and rescue National federal response.

SOURCE Federal Emergency Management Agency, Office of Earthquakes and Natural Hazards, "Funds Tracking Report, " 1993

Federal Emergency Management Agency

FEMA is the lead agency of NEHRP and has responsibility for both overall coordination of the program and implementation of earthquake mitigation measures.[26] FEMA's activities in NEHRP are summarized in table 1-1.

National Institute of Standards and Technology

NIST's role in NEHRP has been largely in applied engineering research and code development. NIST's funding under NEHRP has been relatively low—less than $1 million annually until the 1990s—s0 its NEHRP-related activities have been modest in size and scope. Current NEHRP-related work is varied and includes:[27]

- applied engineering research, such as testing of building components;
- technical support for model code adoption of the NEHRP Recommended Provisions;[28]
- technology transfer (support of conferences and meetings for engineering research); and

26 This description of FEMA activities draws on Federal Emergency Management Agency, *Building for the Future,* NEHRP FY *1991-92* Report to Congress (Washington, DC: December 1992); Federal Emergency Management Agency, *Preserving Resources Through Earthquake Mitigation,* NEHRPFY 1993 -94 Report to Congress (Washington, DC: December 1994); and Federal Emergency Management Agency, Office of Earthquakes and Natural Hazards, "Funds Tracking Report, FY 1993," 1993.

27 Information drawn from Federal Emergency Management Agency, *Preserving Resources Through Earthquake Mitigation, see* footnote 26.

28 The recommended provisions are a resource document used by model code developers.

TABLE 1-2: Examples of NEHRP-Sponsored Contributions

Earth science	Understanding the potential for great coastal earthquakes in the Pacific Northwest.
	Ability to determine earthquake locations and magnitudes instantaneously.
	Long-term, probabilistic forecasts of earthquakes for the San Francisco Bay region.
	Instrumental recordings of liquefaction during strong ground shaking.
	Availability of a strong-motion database.
	Improved understanding of fault behavior and ground motion propagation.
	Paleoseismology.
	Understanding of the role of local soil conditions in influencing ground motion.
Engineering	Improved techniques for nonlinear analysis of building components and structures.
	Advances in analytical and modeling techniques that permit seismic structure design on Inexpensive computers.
	Improved understanding of how structures behave under earthquake-reduced stress—leading to better building codes in areas such as bracing systems for steel structures.
	Advances in new technologies, such as base Isolation and active control.
	Better reliability and risk assessment techniques for lifelines and structures.
	Improved disaster response planning from social science research that sheds light on, for example, cultural differences in perceptions of disaster.
Implementation and technology transfer	NEHRP provisions adopted by model codes.
	Handbooks for seismic retrofits.
	Information centers (information services at the National Center for Earthquake Engineering Research at the State University of New York at Buffalo, the Earthquake Engineering Research Center at the University of California, and the Natural Hazards Center at the University of Colorado).
	Executive orders covering new and existing federal buildings.
	Multistate consortia.

SOURCES Robert A Page et al , *Goals, Opportunities, and Priorities for the USGS Hazards Reduct/on Program,* U.S. Geological Survey Circular 1079 (Washington, DC U S Government Printing Off Ice, 1992), p 5, and National Science Foundation, "Directions for Research in the Next Decade, " Report on a Workshop, June 1983

- international cooperation (support of meetings and exchange programs with other countries).

NEHRP CONTRIBUTIONS AND CHALLENGES

Contributions

NEHRP **has led to significant advances in our knowledge of both earth science and engineering aspects of earthquake risk reduction (see** table 1-2). For example, NEHRP has contributed to the following accomplishments: the seismic risk in the Pacific Northwest is better understood, structures can be built that are unlikely to collapse in an earthquake, and improved computer-based structure design tools are available. Although NEHRP is principally a research program, it has contributed to the implementation of earthquake mitigation as well. For example, we now have model building codes that reflect a national consensus on new building seismic design, as well as several interdisciplinary centers that work to translate research results into useful information for decisionmakers.

Despite these successes, however, earthquakes still cause massive losses in the United States. The 1994 Northridge earthquake caused more than $20 billion in losses, and scenarios of possible future U.S. earthquakes suggest that thousands of casualties and tens or even hundreds of billions of dollars in losses may occur. Although there is no consensus on what level of loss is acceptable,[29] there is clearly a significant remaining exposure to earthquake damage—due in large part to a failure to implement known technologies and practices. Although many communities, especially in California, have taken steps to mitigate earthquake losses, a large gap still exists between what current knowledge says could be done and what actually is done. **Addressing this implementation gap is NEHRP's greatest challenge**.

Implementation Gap

When NEHRP began in 1977, the enabling legislation contained a number of objectives, including educating the public, ensuring the availability of earthquake insurance, and promoting seismic building codes and seismic considerations in land-use policy. However, actual funding was authorized only for USGS and NSF, to be used for earthquake-related research. Although in later years some funding was authorized for implementation activities by FEMA, NEHRP has remained largely a research program. Currently, about 75 percent of the NEHRP budget is used for research.

This historical focus on research can be understood in part by recognizing that NEHRP was founded at a time of great scientific optimism. Newly discovered principles of plate tectonics (see chapter 2) had led to great insights into earthquake mechanisms and many believed that short-term earthquake prediction would soon become a reality. This prediction capability was thought sufficient to motivate widespread mitigation action. Therefore, NEHRP was given neither regulatory teeth nor significant financial incentives to promote mitigation. Instead, the program aimed to develop a body of knowledge from which local and state authorities and the private sector would draw. Since then, however, prediction has proved more elusive than originally thought, and the original role of NEHRP as a source of knowledge from which decisionmakers would eagerly draw is now seen by many as insufficient, due to the lack of regulations or incentives to implement the knowledge. This has contributed to the current situation of an implementation gap.

Examples of this implementation gap include the following:

- An assessment of California's mitigation status found, "we still have many earthquake-vulnerable buildings . . . it's now possible to avoid seismically hazardous areas and build earthquake-resistant structures, but too often the information needed is not used."[30]
- Many states in moderate risk areas do not have state seismic codes.[31]
- In those states that do have codes, many counties are not even aware of their existence.[32]
- Even when codes are adopted, they may not cover all buildings—for example, they may exempt single-family dwellings.[33]
- A recent study concluded, "Even in California, many localities consider seismic risks in only the most rudimentary manner."[34]

[29] Although no losses would seem desirable, achieving this would be either impossible or impractically expensive.

[30] California Seismic Safety Commission, *California at Risk*, 1994 Status Report, SSC 94-01 (Sacramento, CA:1994), p. 1.

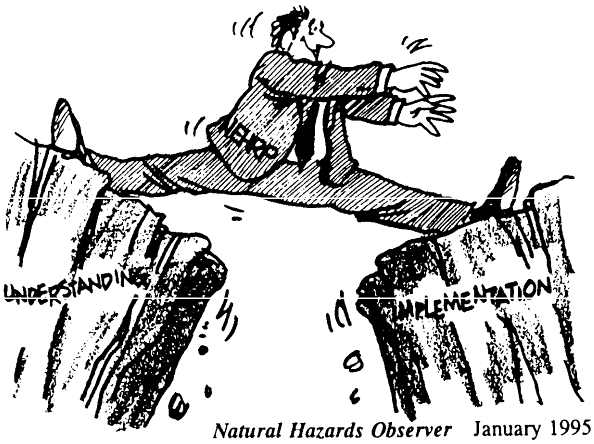
[31] R. Olshansky, "Earthquake Hazard Mitigation in the Central United States: A Progress Report," in *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, July 10-14, 1994, Chicago IL (Oakland, CA : Earthquake Engineering Research Insitute, 1994), p. 991.

[32] Ibid.

[33] The building code in Paducah, Kentucky, for example, exempts single-family dwellings; unanchored foundations are common. VSP Associates, Inc., "State and Local Efforts To Reduce Earthquake Losses," contractor report prepared for the Office of Technology Assessment, December 1994, p. III-9.

[34] P. Berke and T. Beatley, *Planning for Earthquakes* (Baltimore, MD: Johns Hopkins University Press, 1992).

ROB PURIM, NATURAL HAZARDS OBSERVER, JANUARY 1995



Natural Hazards Observer January 1995

The gap between knowledge (understanding) and implementation can be daunting

If NEHRP continues along a similar path—a focus on research, with a relatively small effort to promote implementation[35]—then we will likely see advances in earthquake-related earth science and engineering continue to outpace the implementation of new knowledge.

■ Additional Challenges

The implementation gap is a key issue for NEHRP. However the program faces several additional challenges as well. These include a lack of specific goals and strategies, differing expectations by different groups, tensions between basic and applied research, and the inherent limitations of NEHRP's information-only approach to earthquake mitigation.

Goals and Strategies

In recent years, NEHRP has been criticized for its lack of concrete goals and strategies:

- A 1991 study found that, "federal agency descriptions of NEHRP . . . do not provide much sense of an overall strategy."[36]
- In hearings for the 1993 reauthorization. witnesses commented, "[NEHRP's] fragmented, four-agency structure has contributed to an inability to define program and budgetary priorities and achieve realistic, well-coordinated goals."[37]
- A 1993 congressional report accompanying NEHRP reauthorization legislation noted. "long-standing concerns about NEHRP—[including] lack of an overall strategic plan."[38]

Although the NEHRP authorizing legislation sets broad overall objectives for the program, actual NEHRP spending by the agencies involved does not suggest any unified multiagency agreement on specific goals, strategies, or priorities. In the absence of clear goals and strategies, each agency's NEHRP activities have evolved into a portfolio that reflects that agency's missions and priorities, rather than strong multiagency agreement. In addition, this lack of agreement on goals and strategies makes judging the impact or success of the overall program difficult, since there are few criteria by which to measure performance.

Differing Expectations

Different groups have different expectations from NEHRP. In the absence of clear goals and strategies, these differing expectations make allocating NEHRP's scarce resources difficult.

The earth science research community is concerned with the state of knowledge of earthquakes. In its view, earthquakes are a poorly understood natural phenomenon. Thus, better understanding of earthquakes—why and how they

35 Currently NEHRP, through FEMA, does have some programs to promote implementation, but these are generally quite small. For example, FEMA's program to support state and local mitigation efforts is funded at about $6 million annually or, given 39 states that face a reasonable seismic risk, at about $150,000 per state.

36 P. May, "Addressing Public Risks: Federal Earthquake Policy Design," *Journal of Policy Analysis and Management*, vol. 10, No. 2, p. 270.

37 U.S. *Congress,* House Committee on *Science,* Space, and Technology, Subcommittee on Science, hearing, Sept. 14, 1993, p. 20.

38 U.S. *Congress,* House Committee *on Science,* Space, and Technology, "Earthquake Hazards Reduction Act Reauthorization," Nov. 15. 1993, p. 6.

occur, and when and what type of earthquakes are likely to occur in the future—is an important component of reducing earthquake losses. This community would like NEHRP to be a source of funding for research and data collection that could, in the long term, help reduce such losses.

The engineering research community is concerned with how the built environment—buildings, bridges, dams, and so forth—is damaged in earthquakes and how these structures should be built so as to reduce losses. It sees the need for improvement in the current understanding of structural response to earthquakes, and considers engineering research an important component of reducing earthquake losses. Much like the earth science research community, this group is concerned with the amount of funding NEHRP can provide for research.

State and local government officials concerned with earthquakes, in contrast, would like NEHRP to provide products to help them reduce risk. State highway agencies, for example, would like technical assistance in prioritizing and conducting retrofits of highway bridges. City planners would like detailed maps showing liquefaction and landslide potential to help determine where and how to guide development. Local code enforcement officials would like software to help determine code compliance. Emergency managers would benefit from methods to ensure that critical facilities (such as hospitals and emergency communication systems) survive earthquakes.

The practicing engineering and design community would like NEHRP to provide information on the earthquake-related issues it faces: how to design safe buildings at low cost, what specific types of ground motion to expect and when, and what levels of retrofit protection to provide.

The public generally is unaware of or uninterested in NEHRP; however some individuals concerned with reducing earthquake risk have needs that could be met by the program. Some large companies and institutions have risk managers whose responsibilities include earthquakes; these individuals would like tools to help them reduce risk, such as information on expected ground motion and likely damage, and methods for retrofit prioritization. Electric and gas utilities would like technical assistance in determining risk, and in prioritizing and conducting retrofits. Some regions have community and grassroots groups concerned with earthquake risks; these groups would like pamphlets, workbooks, and other material to help inform the public. The media are often interested in information after an earthquake: how big was the earthquake, where was the epicenter, and what is the probability of significant aftershocks?

These different perspectives on NEHRP's function—each valid and sincere in its own right—pull the program in different directions. These pulls—between research versus implementation, basic versus applied research, and earth science versus engineering—complicate the allocation of NEHRP's finite resources, and can only be resolved through the setting of clear program goals.

Tensions Between Basic and Applied Research

NEHRP currently supports a range of research, from basic studies on how faults move to applied work in testing building components. (See appendix B for a full description of NEHRP's research and development (R&D) portfolio.) Tension exists over the appropriate levels of support for these different activities. Some argue that certain pressing short-term needs, if met, would yield significant social benefits. Others point out that basic research is required to continue to advance the knowledge base and that this work will not be done without federal support.

It is useful to recognize that the distinction between "basic" and "applied" is better seen as a continuum and that work at all levels is potentially useful. In addition, across this continuum runs the need for data collection, which can also demand significant R&D resources.

Information Alone Has Its Limits

NEHRP's approach to reducing earthquake losses can be thought of as supplying information on earthquake risks and possible countermeasures to those who may wish to mitigate. By supplying this information, the program hopes to motivate individuals, organizations, and local and state governments toward action while providing guidelines on how to proceed. This approach implicitly assumes that the interest or incentive for mitigation is sufficient for people to act on such information. However, the frequent lack of mitigation activity often reflects not a lack of information, but a lack of interest or incentives to take action. **Information alone will not result in widespread implementation**. Whether or not the federal government should play a role in ensuring that there are sufficient incentives for implementation is a sensitive policy question that is discussed below. In any case, NEHRP's approach of supplying only information limits the program's impact.

POLICY OPTIONS

NEHRP reauthorization offers an opportunity for Congress to consider what it wants to accomplish with NEHRP and how it wishes the program to proceed. A key decision is whether to maintain the current federal role of research sponsor and information provider or to change the federal role through, for example, changes in federal disaster policy, insurance, or regulation. As discussed above, **NEHRP has had numerous research accomplishments and has made significant contributions to earthquake knowledge; it has become clear that taking action based on this knowledge is a key challenge for the future**. Significant changes in the federal role could potentially help close this knowledge-implementation gap. However, increasing the federal role would be controversial. Furthermore, doing so would represent a significant shift in NEHRP and would require the participation of additional congressional committees.

Three types of policy options are discussed here:

1. **Specific activities undertaken by NEHRP**. The Office of Technology Assessment (OTA) identifies key research and implementation needs that NEHRP could address within its current scope. Addressing these while maintaining the current portfolio would require increased funding.
2. **Management and operational changes in NEHRP**. These could allow NEHRP to be a more efficient, coordinated, and productive program.
3. **Changes to federal disaster assistance and insurance, regulation, and financial incentives**. These would be necessary if Congress decides that the federal government should take greater responsibility for the implementation of NEHRP-produced knowledge. They are outside the current scope of NEHRP and would represent a significant change in direction for the program.

NEHRP Portfolio Changes

NEHRP currently supports earth science research, engineering research, and implementation support and promotion. In each of these areas OTA has identified specific topics needing further attention.

Earth Science Research

Earth science research can help to reduce earthquake-caused deaths, injuries, and other losses by:

- narrowing the uncertainty of when and where large earthquakes will occur;
- estimating, as accurately as possible, the expected ground motions, ground failure, and other effects that will occur in future earthquakes; and
- developing maps of these seismic hazards for use by engineers, land-use planners, and emergency managers.

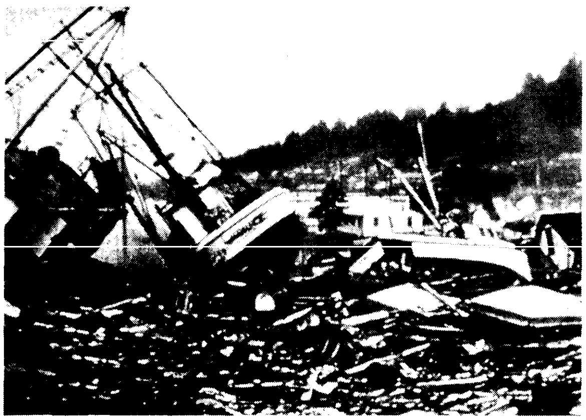
Historically, NEHRP has focused on basic research that contributes primarily to the first objective and, to a much lesser degree, on disseminating research results to the public. In large part, this is due to the absence of clear goals or strategies for the program, an issue discussed in greater detail in a following section. Without consensus on programmatic goals, NEHRP's earth science R&D portfolio has been strongly influenced by the values and concerns of the agencies supporting it—NSF and USGS—both of which have strong research orientations. Basic research into fundamental earth processes (e.g., how do earthquakes begin and propagate) dominates the research supported by NSF under NEHRP. USGS supports research that is generally more applied than that of NSF (e.g., developing and distributing detailed maps showing expected ground motions), but conducts and sponsors some basic research as well. With NEHRP funding, NSF and USGS also support seismic monitoring networks and other data collection efforts related to earthquake research and seismic hazard assessment.

If Congress views NEHRP's earth science activities as primarily a means of providing long-term benefits (e.g., enhancing fundamental understanding of earth processes such that uncertainties in the timing, location, and magnitude of future earthquakes can be reduced), retaining the current concentration in more basic research would be appropriate. This work has yielded new insight into, for example, the relationship between plate deformation and earthquakes, the mechanics of fault rupture, and the sources of some intraplate quakes. In time, this research may narrow the uncertainties in future earthquake location, timing, and effects.

Today, however, knowledge of seismic hazards in many U.S. metropolitan areas remains very limited. Outside of coastal California and a few other cities (e.g., Salt Lake City, Memphis, Portland, and Seattle), assessing and mapping earthquake hazards is proceeding very slowly. If Congress believes that NEHRP should now place more emphasis on near-term applications of data and research results to risk assessment (e.g., microzonation), then NEHRP's earth science portfolio should include a greater share of activities that meet these goals.

MS HARRY A SIMMS, SR

Tsunamis are an infrequent but dangerous result of undersea earthquakes.



NOAA/EDIS

Tsunamis can cause major damage.

Engineering Research

Knowledge of how to design and build structures to reduce earthquake-induced losses has improved tremendously. However the problem is far from solved. The 1994 Northridge earthquake occurred in the area of the United States that is probably the most well prepared; nevertheless, the quake caused dozens of deaths and more than $20 billion in losses. Scenarios of future earthquakes suggest that large losses are likely.

Greater use of existing knowledge, practices, and technologies could reduce these losses. For example, the collapse of the 1-880 elevated highway in the 1989 Loma Prieta earthquake, which caused the deaths of 42 people, could have been prevented with the use of known retrofit technologies.[39] The implementation (or lack thereof) of these technologies to date has been determined

[39] U.S. Congress, Genera] Accounting office, "Loma Prieta Earthquake: Collapse of the Bay Bridge and the Cypress Viaduct," GA@ RCED-90- 177, June 1990, p. 2.

STEINBRUGGE COLLECTION, EERC

Many older buildings are vulnerable to structural collapse.

largely by economic, behavioral, institutional, and other factors—not by the state of current knowledge.

Nevertheless, additional. knowledge could have several benefits. First, although our understanding of how to build new structures to resist seismic damage is good, it is far from perfect (e.g., the steel weld failures in modem buildings in the Northridge earthquake, discussed in chapter 3). Second, most of the financial losses in recent earthquakes were not due to building collapse. Rather, they resulted from structural, nonstructural, and contents damage—areas that could benefit from further research. Third, much of the casualty risk lies in existing structures, and retrofit methods are just now being refined and standardized. More research into improving retrofits could reduce this risk. Fourth, to the extent that the upfront costs of mitigation reduce implementation, research that reduces these costs could lead to greater implementation.

New buildings

A new building that meets current seismic building codes will be very resistant to collapse due to earthquakes. This is a great technical accomplishment in which NEHRP played a considerable role. Since this has been achieved, it is time to consider moving some resources to the next research challenge: **reducing structural, nonstructural, and contents damage.** Possible areas of research include:

- data collection and analysis of structural, nonstructural, and contents damage from recent earthquakes;
- analytical methods to measure and predict such damage;
- guidelines for designing lighting, electrical, water, and other systems so as to minimize seismic damage;
- building codes that address structural, nonstructural, and contents damage; and
- new technologies—notably active and passive control (see chapter 3)—that can reduce this damage.

Existing buildings

Much of the risk of both structural collapse and nonstructural and contents damage lies in existing buildings, which do not incorporate current codes and knowledge. Relatively few of these buildings have been retrofitted to reduce risk, and where retrofits have been performed they have often been expensive, complex, and of uncertain benefit. Although NEHRP has made progress in understanding and improving retrofits (e.g., through FEMA's existing buildings program), more research is needed to improve retrofit methods.

The first area of research for existing buildings should be to better understand their vulnerability. Laboratory and field experiments, and collection and analysis of data on how buildings respond in earthquakes, are needed. Improved tools to determine risk in existing buildings—such as nondestructive evaluation techniques—are needed as well. A second area is **the development of low-cost standardized retrofit techniques.** Standardized methods, such as those contained in codes for new construction, would reduce costs and could allow for multiple levels of safety to account for different risk preferences. A third research area is to **extend retrofits to nonstructural and contents damage reduction.**

Lifelines

Lifelines are expensive to repair, and service interruptions, which are at best inconvenient and at times deadly, may result in large economic losses. The lack of an accepted national standard for the design and construction of lifelines raises costs and reduces performance. Although the 1990 NEHRP reauthorization directed that FEMA and NIST work together to develop a plan for developing and adopting design and construction standards for lifelines by June 30, 1992, as of May 1995 no such plan had been submitted to Congress.

Much of the life safety risk associated with lifelines lies in existing facilities. Research is needed to develop methods to better determine the risks in existing facilities, to prioritize retrofits, and to reduce retrofit costs. Low-cost, easy-to-use procedures to analyze lifelines for weak links would help to ensure their continued function in earthquakes.

Implementation of Mitigation

NEHRP supports mitigation several ways: through technical support of state and local efforts, through research to better understand the implementation process, and through knowledge transfer efforts. Some promising directions that could improve these activities are discussed below.

Perhaps the most promising implementation activity is to directly assist communities in their efforts to understand earthquake risk and to devise mitigation options. In particular, **it is critical that communities be given analytic tools to estimate likely losses in the event of a future earthquake and to predict the likely benefits of mitigation**. At present, it is difficult to quantify these basic parameters, and this absence inhibits vigorous action at all mitigation levels. Fortunately recent advances in computers—and specifically in geographical information systems—suggest that it will soon be possible to provide local decisionmakers with highly detailed and specific information on seismic risks, even on a specific building level. FEMA is now supporting an effort to make these regional loss estimation tools available to local governments. This is a promising direction that could reduce considerably the uncertainty in risk. These tools often require large amounts of detailed data on local land-use patterns and building stock; communities need help in defining data needs and collecting data as well. User training may also be needed.

Better evaluation of FEMA implementation programs is needed. Very few of these programs have been evaluated carefully in the past, leaving current program planners with little guidance as to what works, what does not work, and why. All mitigation programs should be evaluated carefully, and the results should be used to improve, refocus, or—if necessary—terminate programs.

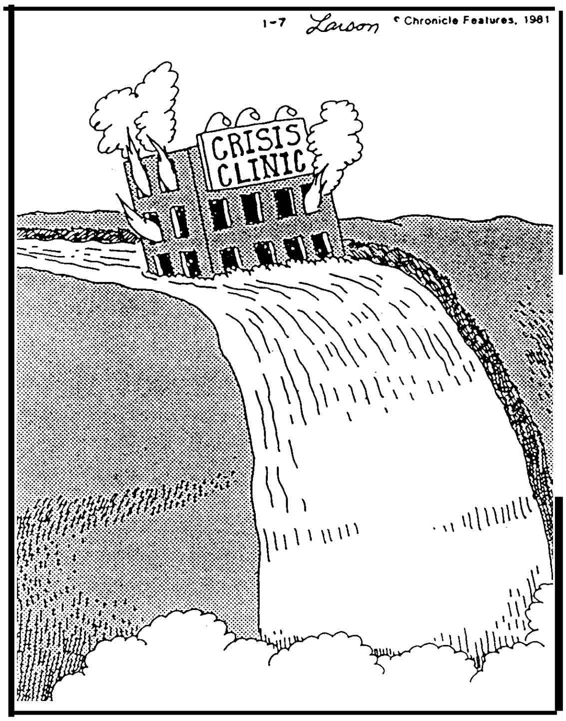
Because individual local "advocates" can play a powerful role in fostering and maintaining community interest in mitigation, efforts to create or assist advocates are potentially quite useful. The federal government can support advocates by identifying and working closely with them to ensure their access to the latest mitigation information and analysis tools.

Media and public outreach activities can have a powerful indirect effect. The more publicity there is concerning earthquakes, the more likely that advocates will arise and act. Public interest in earthquakes largely depends on how recently a major quake last occurred, so preparing outreach materials to take advantage of disaster "windows" is a prudent measure. The advantage of this outreach is that it is relatively inexpensive and can be very effective.[40]

To complement activities on the seismic front, efforts could be made to incorporate seismic implementation into a larger "all-hazards" framework. Much of the nonstructural preparation

[40] The disadvantage is that in places where destructive seismic activity is extremely infrequent (e.g., the U.S. east coast), these windows are rarely open.

THE FAR SIDE By GARY LARSON



Some areas of the US. are threatened by a variety of natural hazards. (The Far Side cartoon by Gary Larson is reprinted by permission of Chronicle Features, San Francisco, CA. All rights reserved).

required for seismic mitigation (e.g., predisaster emergency planning) is useful in the event of fire, flood, wind storm, or other natural disasters, and can thus gain in political and economic attractiveness when viewed in a larger context.

In addition to direct support for implementation, NEHRP also supports some research into the behavioral, social, and economic aspects of mitigation. Further research of this type could improve our understanding of some key questions that currently hinder mitigation. Examples of specific questions that NEHRP could address include the following:

- How do financial and other incentives affect mitigation behavior? To what extent is insurance and the expectation of federal disaster relief currently a disincentive for mitigation?
- How is NEHRP-generated information (e.g., hazard maps and building seismic response data) used by the mitigation community? How should this information be presented to ensure its appropriate and productive use?
- How well have NEHRP-supported information and technology transfer efforts worked? What contributed to their successes and failures, and what does this suggest for future efforts?

The answers to these questions could help improve the next generation of NEHRP-supported implementation programs.

The four NEHRP agencies have put increasing effort into "knowledge transfer"—institutions and procedures that promote the delivery of useful information to decisionmakers. For example, NEHRP funds several "centers" that emphasize matching research to user needs and ensuring research results are provided in a useful form to decisionmakers. NEHRP also supports several information services that provide research results to interested users, as well as multistate consortia that coordinate state activities and facilitate communication between researchers and users.

The implementation gap discussed above suggests that these efforts be continued and expanded. Options for expansion include increasing funding for knowledge transfer programs, requiring utilization plans for applied research projects, and establishing formal utilization criteria for evaluating applied research proposals.[41] All such efforts should be evaluated carefully and regularly.

Allocating NEHRP Funding

Current NEHRP funding is about $100 million annually. The ideal method to determine appropriate funding levels would be to consider the costs and benefits of future NEHRP spending. Although the direct costs are clear—simply the pro-

41 A detailed discussion of options for increasing the use of applied research can be found in Applied Technology Council, *Enhancing the Transfer of USGS Research Results into Engineering Practice, ATC-35* (Redwood City, CA: 1994).

jected funding—the benefits are not. Much of NEHRP funding is for research, and the results of research—greater understanding—are not easily quantified. NEHRP's spending for implementation should be somewhat easier to evaluate. However, as noted above, past implementation programs have not been evaluated in a systematic way; thus there is little guidance on the likely benefits of future spending. **Improved evaluation would provide guidance for deciding funding levels and allocations**.

NEHRP spending, both in allocation and in total, should reflect national priorities. Basic conceptual earth science research enhances our understanding and will likely, in the long term, translate into better mitigation. Engineering research can produce more immediate benefits. Implementation programs, such as FEMA's state and local grants, can have immediate impacts. The current NEHRP portfolio is tilted strongly toward earth science research: 64 percent of NEHRP spending is under USGS and NSF earth science. If Congress would like NEHRP to emphasize improving basic knowledge, and thus provide longer term societal benefits, then the present mix is appropriate. If, however, Congress would like NEHRP to produce more immediate societal risk reduction, then a tilt toward engineering and implementation would be appropriate.

Structural and Operational Changes

Policy options related to the structure and operations of NEHRP include changes to improve program coordination, changes in the lead agency, and improvements in cross-agency coordination.

Program Coordination

Overall program coordination and the selection and role of the lead agency in NEHRP have been problematic since the program began.[42] Initial NEHRP legislation directed the President to select a lead agency, and the 1980 reauthorization designated FEMA as the lead agency. Since then, evaluations of and hearings on NEHRP have often criticized FEMA's management and coordination of the program. Examples of this criticism include:

- a 1983 General Accounting Office report that noted, "FEMA needs to provide stronger guidance and direction";[43]
- the Senate report accompanying the 1990 reauthorization that noted, "the need to improve coordination of the agencies in the program";[44]
- hearings for the 1993 reauthorization in which witnesses commented on, "the diffusion of responsibility inherent in four different federal agencies attempting to implement NEHRP"; [45]
- a 1993 congressional report that noted, "insufficient coordination among the [NEHRP] agencies to shape a unified, coherent program."[46]

Coordination is difficult to measure. OTA's meetings and discussions with NEHRP agencies, and its reviews of NEHRP activities, did not uncover any glaring examples of poor coordination. NEHRP staff in each agency were aware of activities in other agencies; they had frequent informal contact with each other and made efforts to keep one another informed of changes and findings. FEMA has produced congressionally mandated

[42] See David W. Cheney, Congressional Research Service, "The National Earthquake Hazard Reduction Program," 89-473 SPR, Aug. 9, 1989; U.S. Congress, General Accounting Office, "Stronger Direction Needed for the National Earthquake Program," GAO/RCED-83-103, July 1983; and VSP Associates Inc., "To Save Lives and Protect Property," Report for the Federal Emergency Management Agency, FEMA-181, July 1989.

[43] General Accounting Office, see footnote 42, p. 7.

[44] U.S. Congress, Senate Committee on Commerce, Science, and Transportation, National Earthquake Hazards Reduction Program Reauthorization Act, Report 101-446, (Washington, DC: Aug. 9, 1990), p. 3.

[45] House Subcommittee on Science, see footnote 37.

[46] House Committee on Science, Space, and Technology, "Earthquake Hazards Reduction Act Reauthorization," see footnote 38.

reports and plans that describe the NEHRP programs in detail.

As discussed above, however, actual NEHRP spending by the agencies does not suggest any overall multiagency agreement on specific goals, strategies, or priorities, but suggests instead a loosely coordinated confederation of agencies. **In the absence of clear goals and strategies, each agency's NEHRP activities reflect that agency's missions and priorities rather than a strong multiagency agreement**. This lack of agreement on goals and strategies also makes it difficult to judge the impact or success of the overall program, because there are no criteria by which to measure performance. In OTA's view, **coordination must be preceded by agreement on specific goals and priorities—and such agreement is largely lacking**.

One policy option is for FEMA, as lead agency, to work with the NEHRP agencies and the professional earthquake community to come up with specific goals and priorities for NEHRP. An example of such a goal is to have 80 percent of new building construction incorporate the seismic knowledge represented in today's model codes by 2005. Defining such goals would not be easy and would have to address the difficult issue of acceptable risk. Congress could require FEMA to report on progress toward defining and meeting these goals. Since FEMA has no explicit budgetary or other control over the other agencies that participate in NEHRP, Congress may wish to provide oversight to ensure that all these agencies work toward defining and meeting the agreed-on goals.

The Lead Agency

The continuing congressional dissatisfaction with FEMA's management and coordination of NEHRP has led some to consider transferring lead agency responsibility from FEMA to another agency. OTA's finding that implementation is emerging as NEHRP's key challenge, however, suggests that, of the four principal NEHRP agencies, FEMA appears to be the most appropriate lead agency. FEMA has the most direct responsibility for reducing losses from natural disasters; it is in direct contact with state, local, and private sector groups responsible for reducing earthquake risks; it has a management rather than research mission; and it coordinates regularly with other agencies in carrying out its mission. The other NEHRP agencies are principally involved in research and, therefore, may find it difficult to develop the strong implementation component necessary to lead the program. In addition, FEMA has recently shown a stronger commitment to mitigation, as evidenced by its proposed National Mitigation Strategy.[47] One policy option would be to allow FEMA to continue as lead agency, but to provide frequent oversight to ensure that lead agency responsibilities are met.

Coordinating with Non-NEHRP Agencies

Although NEHRP is the government's central earthquake program, a significant fraction of federal spending on earthquake mitigation occurs not within the four NEHRP agencies, but in other agencies that both sponsor research and implement earthquake mitigation. The Department of Veterans Affairs, the Department of Energy, the Department of Defense, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and other federal agencies conduct a wide range of earthquake-related research and mitigation (see appendix B). Although there is no unified federal earthquake budget, federal non-NEHRP earthquake spending probably far exceeds the $100 million NEHRP budget.[48] Despite this wealth of activity, there are few formal structures for coordinating non-

[47] The National Mitigation Strategy, under development by FEMA, is an effort to increase attention on mitigation as a means to decrease demand for disaster response resources.

[48] The last budget data were for the period ending in 1987. Cheney, see footnote 42, p. 20.

NEHRP federal efforts.[49] Improved coordination across all agencies would be useful. For example, it could allow one agency to serve as a demonstration site for a technology developed with NSF funding, or enable agencies to share data on ground motion or retrofit techniques.

Ensuring multiagency coordination is challenging. The first step in doing so could be to promote a thoughtful combination of improved information sharing and incentives for coordination. Examples might include:

- establishing a "Federal Agency Earthquake Activities" home page on the Internet, hosted by FEMA;
- sharing employees across agencies (e.g., a NIST seismic design researcher could spend one month as a "visiting scholar" to assist the Department of Veterans' Affairs in retrofitting hospitals); and
- encouraging agencies implementing seismic technologies to communicate with NSF- and NIST-funded researchers working on these technologies, to ensure their appropriate use or to demonstrate new and innovative approaches.

More aggressive actions to ensure multiagency coordination include:

- requiring the NEHRP lead agency to maintain a database with information on all federal agency earthquake-related activities, and to make this database available electronically to agencies and to state and local governments;
- requiring all agencies with earthquake activities to participate in the goal-setting process proposed above; or
- requiring the submission of an annual budget laying out all earthquake-related agency activities.

Beyond the Current NEHRP

Congress could consider other policy options that are outside the scope of NEHRP as currently designed. This section discusses three areas in which policy change could be considered: insurance and federal disaster relief, regulation, and incentives.[50] The policy options discussed here have the potential to significantly increase implementation—something NEHRP, in its current form, is unlikely to accomplish. However, these options would likely require new legislation and would be a significant departure from current policy. They would also be quite controversial.

In considering these options, a central issue is **what is the appropriate role of the federal government in disaster mitigation?** Some argue that increased investment in mitigation by the federal government would save money by reducing future disaster outlays. Others argue that the very existence of federal disaster assistance programs creates disincentives for mitigation. Still others argue that mitigation tools, notably land-use planning and building regulation, are state and local issues in which an increased federal role is inappropriate. These arguments involve different political and philosophical beliefs. OTA does not attempt to resolve them.

Insurance and Federal Disaster Assistance

The issue of insurance and federal disaster assistance—and specifically, what role, if any, the federal government should play in earthquake insurance (or natural hazards insurance in general)—is complex and contentious. Several bills to set up a comprehensive federal disaster insurance program were introduced in the 103d Congress (none were passed), and others have been or are

[49] Many federal agencies participate in a multiagency group known as the Interagency Committee on Seismic Safety in Construction, set up to establish and implement standards for federal construction and retrofit. Some agencies also participate in the Subcommittee on Natural Disaster Reduction, under the National Science and Technology Council.

[50] Much of this section applies to federal policy toward other natural disasters as well, such as floods, hurricanes, and tornadoes.

expected to be introduced in the 104th Congress. Other bills propose changes in federal disaster assistance; for example, one bill proposes giving states financial responsibility for natural disasters. Congressional interest in disaster insurance is motivated largely by the recent string of natural disasters in the United States, and the fact that, in fiscal years 1992 to 1994, Congress passed $10.8 billion in supplemental appropriations for natural disasters.[51]

Among the issues involved in this debate are:

- **Equity.** Is it "fair" for natural disaster losses to be covered by the U.S. Treasury? To what extent should those at risk pay for their own losses? Should the federal government pay for the noninsured and underinsured? Should natural disaster insurance be required for those at risk?
- **Insurance industry financial health.** Can the insurance industry survive a series of large disasters? Should the federal government have a formal mechanism to provide secondary insurance to the industry?
- **Mitigation.** What is the relationship between insurance or disaster assistance and mitigation?
- **Appropriate roles.** What are the appropriate roles of the federal government, state regulators, and the private insurance industry in natural disaster funding?

The following discussion focuses on the relationship between insurance or disaster assistance and mitigation. Readers interested in other aspects of insurance are referred elsewhere.[52]

Insurance and disaster assistance can be a vehicle for mitigation, as well as a disincentive against mitigation, depending on how the program is structured. At its simplest, an insurance program—whether private or public—can simply require mitigation as a condition of insurance. For example, the federally subsidized national flood insurance program requires, as a condition of receiving insurance coverage, that the lowest floor of a new structure be above the base flood level.[53] In the case of earthquakes, insurance might require a basic level of seismic safety, or might not be offered for structures built in high-risk areas such as landslide-prone hills. This approach is complicated by the fact that relatively few residences are covered by earthquake insurance; requiring mitigation would most likely further reduce this number. One solution is a *mandatory* insurance program, where owners of structures at risk are required to purchase insurance. Structures in high-hazard flood areas, for example, are required to have insurance if federal loans or grants were involved in building or buying the structure.[54]

Insurance can also promote mitigation by having rates reflect risk.[55] Much as drivers who have had accidents pay more for automobile insurance, structures that are located in high-risk areas or that do not incorporate accepted seismic design principles can be charged more (or be subject to higher deductibles or lower coverage limits) for earthquake insurance. This approach is limited by the fact that earthquake insurance is voluntary and

[51] For comparison, the total supplemental appropriations from 1974 to 1991 was $4.4 billion. U.S. Congress, Congressional Research Service, "FEMA and Disaster Relief," 95-378 GOV, Mar. 6, 1995, p. 10.

[52] See, e.g., U.S. Congress, Congressional Research Service, "Natural Hazard Risk and Insurance: The Policy Issues," 94-542E, July 5, 1994; U. S. Congress, Congressional Budget Office, "The Economic Impact of a Solvency Crisis in the Insurance Industry," April 1994; Federal Emergency Management Agency and Department of the Treasury, "Administration Policy Paper: Natural Disaster Insurance and Related Issues," Feb. 16, 1995.

[53] The base flood level is the elevation at which there is a 1 percent chance of flooding in a given year. U.S. Congress, General Accounting Office, "Flood Insurance: Financial Resources May Not Be Sufficient To Meet Future Expected Losses," GAO/RCED-94-80, March 1994, p. 11.

[54] Ibid.

[55] Earthquake risk is often very uncertain. Development of risk estimation tools as discussed above would be helpful in setting insurance rates as well.

often not purchased. Large rate increases would presumably further decrease the number of structures (especially high-risk ones) covered by earthquake insurance. Again, making earthquake insurance mandatory would address this, but it raises fundamental questions about individual responsibility and the role of government.

Insurance can work against mitigation as well. In our present system, most structures do not have earthquake insurance. In recent earthquakes, losses have been covered in part from the U.S. Treasury via supplemental appropriations. This can be considered a form of insurance in which the premiums are the federal taxes paid by all. In this form of insurance, there is no relationship between premiums and risk. Similarly, insurance in which there is no connection between either premiums, or the availability of insurance, and risk can work against mitigation through what is known as “moral hazard.” In this situation, appropriate mitigation measures are not taken because of the belief that insurance will cover losses in any case.

The issue of moral hazard is especially relevant to earthquakes. One commonly held belief is that current federal disaster policy is a disincentive for property owners to purchase private earthquake insurance. If one believes that the federal government will cover one’s losses in the event of an earthquake, then in theory it would not be economically rational to pay for private insurance. This argument is sometimes used to explain the surprisingly low fraction of California homeowners who purchase earthquake insurance—currently about 25 percent.[56]

Evidence from surveys, however, suggests that the relationship between mitigation and expected federal aid is somewhat more tenuous than commonly thought:

> Most homeowners said they do not anticipate turning to the federal government for aid should they suffer losses . . . we hypothesize that most homeowners in hazard-prone areas have not even considered how they would recover should they suffer flood or earthquake damage . . . the (survey) results suggest the people refuse to attend to or worry about events whose probability is below some threshold.[57]

This evidence suggests that the low rate of insurance ownership in California could be explained in part by a general lack of interest in low-probability events such as earthquakes, not simply by the expectation of federal aid.[58]

Congressional decisions as to the fate of hazard insurance legislation will involve many issues, most of which are beyond the scope of this report. With respect to mitigation, however, clearly **insurance can be a strong incentive for earthquake mitigation—if the cost of insurance reflects the risk**. In addition, social science research suggests that individual mitigation decisions are not made on an economically rational cost-benefit basis but are considerably more complex. Federal insurance programs should recognize these complexities.

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[56] H. Kunreuther et al., “On Shaky Ground?” *Risk Management*, May 1993, p. 40.

[57] H. Kunreuther, *Disaster Insurance Protection* (New York, NY: John Wiley and Sons, 1978), pp. 236-238. More recently, “There is little empirical evidence suggesting that individuals are *not* interested in insurance because they expect liberal disaster relief following a disaster.” H. Kunreuther, “The Role of Insurance and Regulations in Reducing Losses Hurricanes and Other Natural Disasters,” *Journal of Risk and Uncertainty*, forthcoming.

[58] Some argue that high premium costs and high deductibles contribute to the low levels of insurance ownership as well. Earthquake premiums in California prior to the Northridge earthquake were typically $2 per $1,000 of coverage per year, with a 10 percent deductible. U. S. Congress, Congressional Research Service, “A Descriptive Analysis of Federal Relief, Insurance, and Loss Reduction Programs for Natural Hazards,” 94-195 ENR, Mar. 1, 1994, p. 106.

Regulation

A key challenge to earthquake mitigation is its voluntary nature: people are often unwilling to invest time and money to prevent unknown, uncertain, or unlikely future damage. NEHRP relies mostly on a supply-side approach to mitigation: it makes available information and technical expertise, and leaves the decision of adoption to the state, local government, or individual.

One policy area, largely outside the scope of NEHRP as currently defined, would be for the federal government to take a stronger position on implementation via regulation. In the current policy environment, regulation in the form of building codes is the most widely used mitigation tool, but it is performed at the state or local level. The federal government plays largely an indirect role by providing technical support for code development and implementation. A more aggressive policy option would be to require states and localities, as a condition for receiving federal aid, to adopt model building codes or demonstrate a minimum level of code enforcement. Nonstructural mitigation could be advanced through an executive order addressing this problem in federal buildings.

Arguments in favor of increasing the federal role in requiring the use of seismic mitigation measures include:

- The federal government pays much of the costs of seismic losses through disaster relief; it would be economical to require some reasonable level of mitigation.
- The information and behavioral barriers to mitigation are great. It may be less expensive to regulate than to attempt to overcome these barriers with public information or incentive programs.
- There are many precedents for regulations to protect public safety and property. Examples include safety and performance requirements for consumer goods (e.g., seat belts and bumpers for cars) and safety standards for services (e.g., safety training for airline pilots and flammability limits for airplane cabins).
- Regulation is usually simpler and less expensive (in terms of direct government outlays) than most other policy options (e.g., R&D, financial incentives, or improved consumer information).
- The losses resulting from a damaged or destroyed structure can be considered an externality (defined as a cost to society not captured in the market price of a good), because some costs are paid by society as a whole through disaster assistance programs. As such, the price of structures should be raised to a level reflecting their true cost to society. (Strictly speaking, this is an argument for market intervention, not necessarily for regulation.)

There are, as well, a number of arguments *against* increasing the federal role in requiring the use of seismic mitigation measures, including:

- Regulation of buildings and construction is currently a state and local issue, not a federal one. Any federal role beyond that of providing information could be considered an infringement on state and local rights.
- Current levels of mitigation reflect individual and market preferences. Regulation would impose costs and investments that would otherwise not be made.
- The inherent inflexibility of regulations may result in mitigation investments that increase net societal costs.[59]
- Regulation is not a cure-all—many individual mitigation actions, such as not putting heavy books on the top of bookshelves, cannot realistically be regulated.

Evaluation of these arguments is a political, not a technical, decision. *If* Congress does decide

[59] Not all mitigation is financially prudent (an extreme example might be requiring a building used exclusively for storage to provide a high level of life safety).

to pursue a regulatory approach, then a much better understanding of the costs and benefits of mitigation would be needed to set these regulations at an appropriate level.

Financial Incentives

NEHRP currently relies on information, along with a modest amount of technical support, to promote mitigation. A policy direction that, like regulation, is outside the scope of the current NEHRP, would be the use of financial incentives to promote mitigation. These could take the form of rewards for greater mitigation (e.g., tax credits or low-interest loans) or punishments for insufficient mitigation (e.g., taxing buildings not meeting code, or reducing disaster assistance to those who did not mitigate).

Among the advantages of such an approach are:

- It retains some flexibility and freedom of choice, since participation is voluntary.
- It can be structured so as to require no net federal spending (e.g., by using a combination of taxes and grants).
- As mentioned above, as long as the public pays for disaster relief, the losses resulting from a collapsed structure can be considered an externality (i.e., a cost to society that is not captured in the market price of a good). As such, the price should be raised to a level reflecting the true cost.

Disadvantages include:

- The administrative costs of such a system could be high.
- The response of the market to financial incentives is not well known; it may be that very large subsidies (or penalties) are needed to change behavior.
- As with regulation, the benefits of mitigation are often difficult to quantify. Thus, incentives for increased mitigation may mean more money poorly spent.

A decision as to what, if any, financial incentive should be used to promote mitigation is, like the decision to regulate, largely a political and not a technical decision. Financial incentives can promote mitigation. However, the behavioral response to such incentives is not well understood. Thus, such incentive programs should be thought out carefully and tested on a pilot scale before full-scale implementation.

Understanding Seismic Hazards 2

Earthquakes remind us that the earth is continually changing, sometimes with disastrous consequences for its inhabitants and for the relatively fragile structures built atop its outermost layer. Our understanding of the seismic hazard (i.e., the potential for earthquakes and related effects) has improved significantly in the last two decades, largely through research supported by the National Earthquake Hazards Reduction Program (NEHRP). This improved knowledge of the seismic hazard can in turn be applied to better estimation of the potential impact on specific communities. For example, earthquake-related research and development (R&D) to date has yielded detailed information on historical and estimated future ground motions that earthquake engineers now use for research, design, and building code development.

Federal support for earthquake-related R&D in the earth sciences is concentrated in programs directed by both the National Science Foundation and the U.S. Geological Survey (USGS) under the aegis of NEHRP; other federal agencies conduct related research as well (see appendix B). Since focused efforts began, there have been many achievements in earth sciences. However, the complexity of the task of understanding earthquake phenomena means that significant uncertainties remain about the timing and location of future damaging earthquakes and the exact nature of their effects.

This chapter reviews the current knowledge of earthquake phenomena and of seismic hazards across the United States. It then outlines the role of basic and applied earth science R&D in meeting information needs for the nation's earthquake loss mitigation program, and provides examples of research efforts needed to address knowledge gaps.

EARTHQUAKES

An "earthquake" technically refers to trembling or strong ground shaking caused by the passage of seismic waves through the earth's rocky interior. These waves arise from phenomena as varied as explosions,[1] volcanic eruptions, or quarry blasts, but the source most commonly associated with the term is the fracturing, or *faulting,* of rocks deep underground through the action of powerful geologic forces.

Seismic waves radiate away from a rupturing fault in the same way that ripples in a pond spread outward from a splashing pebble. These waves die away with distance from the initial source, so that very distant or very deep earthquakes are of relatively little concern. Like pond ripples, the waves can bounce and bend around obstacles to produce intricate patterns. Because the structure of the earth is far more complicated than the surface of a pond, what happens when seismic waves reach the earth's surface can be exceedingly complex.

Efforts to assess risks to U.S. communities posed by future earthquakes rest on the ability to estimate where and when earthquakes will occur and to quantify, where possible, what will happen when earthquake-generated seismic waves hit the earth's surface. (Figure 2-1 illustrates seismicity that has occurred in the United States.) Specific questions addressed by current earth science research include:

- What causes a particular fault to rupture?
- How do seismic waves propagate through the earth?
- How do seismic waves and local geology interact to produce strong ground motions[2] or damage to the earth's surface?

Two distinct methods of evaluating the severity of an earthquake are: 1) calculating its *magnitude,* and 2) estimating its *intensity.* The magnitude of an earthquake is related to the amount of seismic energy released at the quake's source; it is based on the amplitude of the seismic waves recorded on seismographs. Earthquake magnitude calculations also take into account the effects of distance between the recording instrument and the source of the waves, and the type of instrument itself.[3]

The magnitude scale most widely used for many years is the Richter magnitude scale, introduced in 1935 by Charles Richter and Beno Gutenberg. A strong earthquake, for example, would have a Richter magnitude (M) of 6.0 to 7.0, while a great earthquake such as the 1906 earthquake beneath San Francisco would measure above M8. Although it is open-ended, the Richter scale does not accurately measure large earthquakes on faults with a great rupture length.[4] To better quantify the severity of great quakes, scientists have developed the moment magnitude scale. The moment magnitude (Mw) measures the total seismic energy released, which is a function of rock rigidity in the fault, the area of rupture on the fault plane, and the amount of slip. These scales are compared in table 2-1.

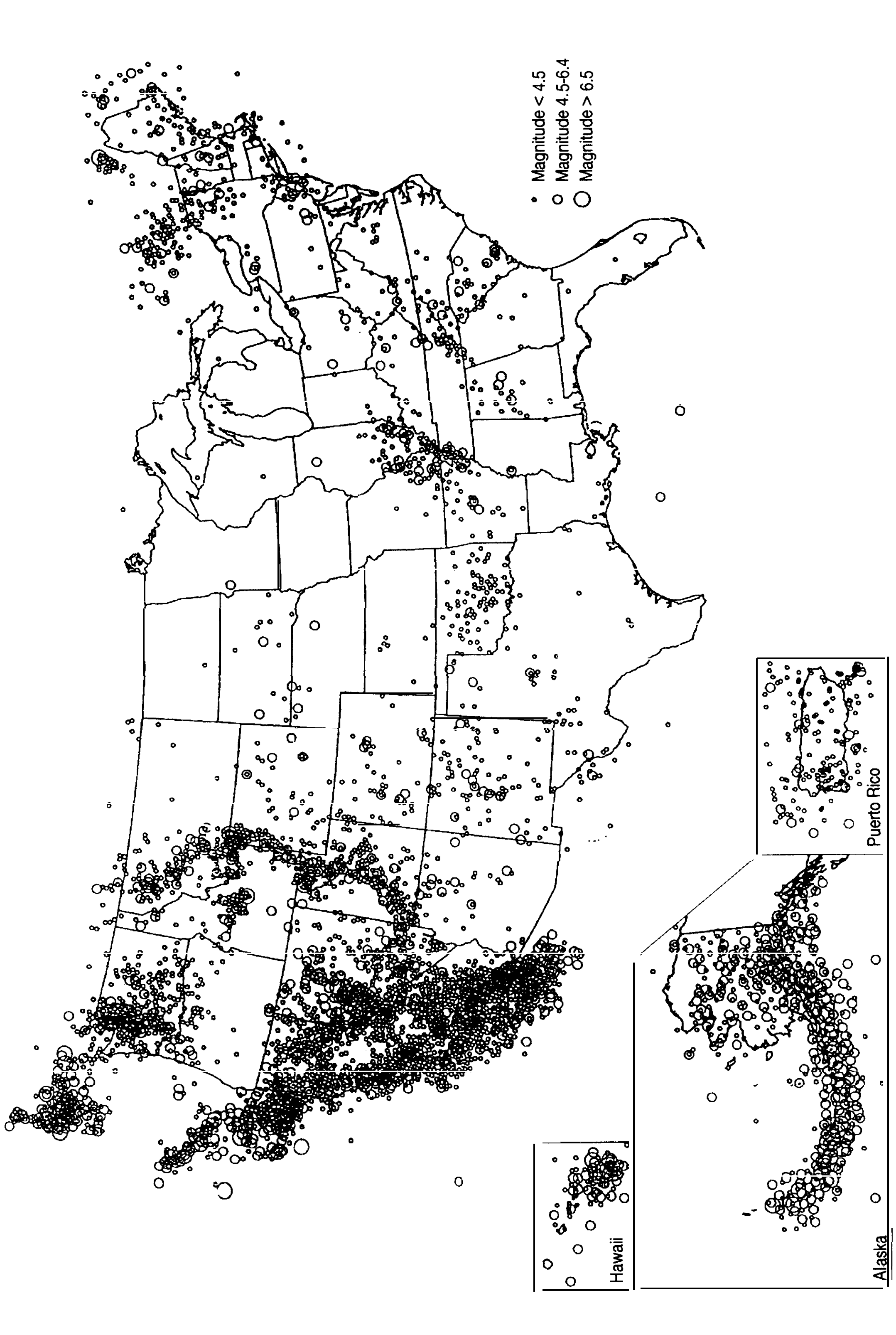
In contrast to magnitude, an earthquake's *intensity* is a highly subjective measure. For many years the Modified Mercalli Intensity (MMI) scale, developed in 1931, has been used to describe the relative strength of ground shaking experienced at a particular location. Seismologists assign intensity using the 12-increment scale that reflects the effects of shaking on people, damage to the built environment, and changes in the natu-

[1] Nuclear explosions, for example, generate seismic waves that can be detected at great distances by earthquake-monitoring networks.

[2] Strong motions are energetic ground displacements that cause damage to buildings and other structures.

[3] U.S. Geological Survey, "The Severity of an Earthquake," brochure, 1990. This report adopts the classification for quakes of different strengths as follows (M=magnitude): moderate, M5-6; strong, M6-7; major, M7-8; and great, M>8.

[4] Much of the energy of a large earthquake is transmitted via long-wavelength seismic waves, the frequency of which is too low to factor into calculations of earthquake magnitude.



SOURCE: U.S. Geological Survey, National Earthquake Information Center.

TABLE 2-1: Comparison of Richter and Moment Magnitudes for Selected Quakes

Earthquake	Richter magnitude	Moment magnitude
Chile, 1960	8.3	9.5
Alaska, 1964	8.4	9.2
New Madrid, Missouri, 1812	8.7	8.1
Mexico, 1985	8.1	81
San Francisco, California, 1906	8.3	77
Loma Prieta, California, 1989	7.1	7.0
Kobe, Japan, 1995	6.8	69
San Fernando, California, 1971	6.4	6.7
Northridge, California, 1994	6.4	6.7

SOURCE: Rick Gore, "Living with California's Faults," *National Geographic, vol.* 187, No. *4*, April 1995, p 10

ral environments Table 2-2 provides an abbreviated description of the MMI scale.

Continuing research has illuminated both the basic setting for earthquakes and their hazardous effects. These two topics set the stage for understanding the seismic hazards that exist in different areas of the country.

Geologic Setting for Earthquakes

The overall framework that guides the discussion of earthquake occurrence is the theory of plate tectonics, a large-scale picture of the earth's basic workings originally set forth in the 1960s and 1970s.[6] In this conceptual framework, the rocks making up the outer layers of the earth are broken into a patchwork of ever-shifting tectonic plates (see figure 2-2). Some of these plates are enormous—the rocks underlying much of the Pacific Ocean, for example, lie on a single 10,000-km-wide Pacific Plate—whereas others may span only a few hundred kilometers. What distinguishes a plate, however, is that it moves as a cohesive body across the surface of the earth.[7] As a plate moves, it grinds or knocks against its neighbors; this plate-to-plate interaction produces the majority of the world's earthquakes.

With a few significant exceptions, identifying the most likely breeding ground for darnaging earthquakes is thus synonymous with finding the boundaries of tectonic plates. The two types of plate boundaries associated with damaging earthquakes in the United States are subduction zones and strike-slip faults. In addition, there are intraplate earthquakes, whose origins are less well understood[8] (see box 2-l).

Earthquake Effects at the Earth's Surface

Besides knowing where and when earthquakes might occur, those interested in reducing earth-

5 "Quake Intensity," *Earthquakes and* Volcanoes, vol. 24, No. 1, 1993, p. 42.

15 It should be noted that many of the data that supported the theory's development were derived from pre-NEHRPefforts (e.g., Department of Defense mapping of seafloors, and global seismic monitoring aimed at detecting nuclear testing in the former Soviet Union).

7 This motion is slow—usually on the order of a few centimeters or less per year. Over millions of years, however, it can carry continents from the equator to the poles, rip landmasses apart, or assemble disconnected land fragments into continents.

8 Intraplate quakes, which can strike deep within a plate's interior, are relatively rare. There are also earthquakes associated with mountain-building and active continental deformation far inland from plate boundaries. One theory is that such activity in western states reflects the presence of a diffuse plate boundary stretching from the Pacific coast to the front ranges of Utah, in which case earthquakes in the Intermountain West are not "intraplate" quakes at all. This report adopts the convention that the North American Plate ends near the Pacific coast and that earthquakes in the Intermountain West are intraplate events.

TABLE 2-2: Modified Mercalli Intensity Scale and Corresponding Effects

MMI	Description
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings.
Iv	During the day, felt indoors by many, outdoors by few. At night, some awakened.
v	Felt by nearly everyone; many awakened. Some dishes, windows broken; a few instances of cracked plaster; unstable objects overturned
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Chimneys, factory stacks, columns, monuments, and walls fall.
Ix	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb, damage great in substantial buildings.
x	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked Rails bent.
XI	Few masonry structures remain standing, Bridges destroyed,
XII	Damage total Lines of sight and level distorted. Objects thrown upward into the air.

SOURCE: U.S. Geological Survey, "The Severity of an Earthquake," brochure, 1990.

quake losses are concerned with what effects an earthquake might have on nearby communities. Earthquake engineers, for example, desire quantitative assessments of expected ground motion or deformation in order to evaluate the likely impact on buildings or lifelines.[9]

Ground Shaking

Contrary to the popular image in Hollywood movies or the more spectacular literary accounts, the earth generally does not open up and swallow buildings during earthquakes. Cracks and fissures do occasionally break the earth's surface. However, they are secondary effects of the most damaging earthquake phenomenon—strong ground shaking caused by seismic waves.

Analogous to sound waves,[10] seismic waves can be produced at different frequencies (corresponding to the pitch of a musical note) and at different amplitudes (corresponding to volume). Large earthquakes (which involve big motions on big faults) tend to produce larger amplitude, lower frequency waves. In reality, however, all earthquakes produce a complex suite of different waves of varying amplitudes and frequencies.

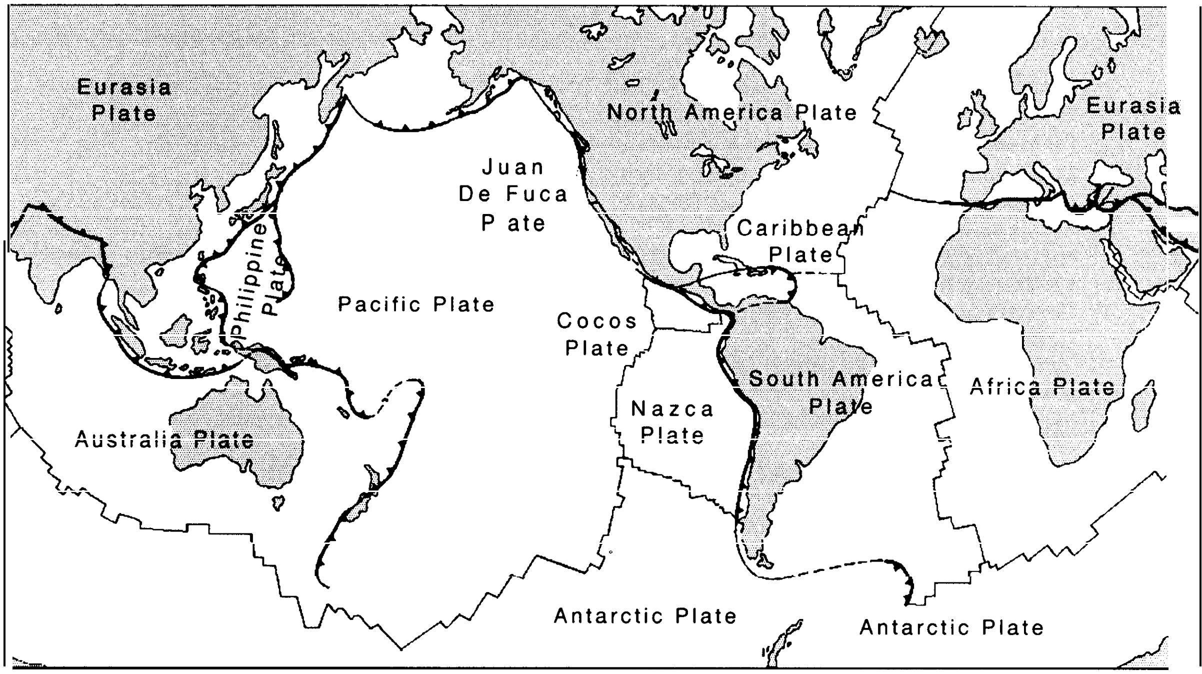
The damage done to structures and their contents depends on the characteristics of the ground motion. The shaking may be up and down, side to side, or some complex combination of the two. There may be a short flurry of rapid, energetic motions followed by rolling or swaying motions that last several seconds or more. Higher frequency accelerations[11] primarily affect shorter, stiffer structures; repetitive, lower frequency motions pose a special threat to very tall or flexible structures. Displacements produced by very large amplitude

[9] *Lifelines* are roads, bridges, communication systems, utilities, and other essential infrastructure. See chapter 3.

[10] One type of seismic wave, the *P-wave,* is in fact an underground sound wave.

[11] Acceleration is commonly expressed as a fraction of the strength of earth's gravity, *g*. A vertical acceleration of more than 1 *g* can actually throw objects in the air.

FIGURE 2-2: World's Major Tectonic Plates



SOURCE: Office of Technology Assessment, 1995, based on Bruce A. Bolt, *Earthquakes (New* York, NY: W.H. Freeman and Co , 1993), p 36

waves can stretch or twist structures beyond their engineering limits. The frequency, energy content, and duration of shaking are not related simply to earthquake size, but also to distance from the fault, direction of rupture, and local geology, including soil conditions.

Increasingly, earth scientists have applied state-of-the-art R&D to determining what sort of ground acceleration and displacement is to be expected in different earthquake regions. Such estimates require knowledge (or prediction) of what waves are originally generated by the earthquake (which implies an understanding of exactly how earthquakes occur) and of how these waves decay, grow, or combine as they travel through the earth. The latter requires geophysical and geological mapping of the rocks between the earthquake and the area of concern.

Because softer soils and clay tend to amplify ground motions, compared with those experienced on bedrock, research has also been directed at how seismic waves interact with surficial and near-surface materials to enhance ground shaking. A dramatic example of the effects of localized geology was the 1985 Mexico City earthquake; ground motions there were significantly enhanced at periods of several seconds compared with those at hard-rock sites closer to the quake source[12] (see box 2-2).

12 Thomas H. Heaton and Stephen H. Hartzell, "Earthquake Ground Motions," Annual Review *of Earth Planetary Science,* vol. 16, 1988, p. 124.

BOX 2-1: Geologic Settings for Earthquakes

Subduction Zones

In Alaska and the Pacific Northwest, the overriding of the North American continent over the various plates of the Pacific Ocean has led to the formation of *subduction zones,* a type of plate boundary that generally produces very large earthquakes. In a subduction zone, the layers of rock making up an oceanic plate move toward a landmass and, in the resulting collision, are forced down into the earth's deep interior. In the Pacific Northwest, this collision is responsible for the presence of the region's coastal mountains, for the volcanic activity that has produced the Cascade Mountain Range, and—most significantly—for the potential for major earthquakes to occur where the subducting plate is stuck, or locked, against the overriding continent. In most cases, this is at depths of 15 to 45 km (1 O to 30 miles).

Earthquakes in subduction zones generally reflect the presence of *thrust faults* ---fractures in the earth that allow one rock mass to slide toward and over its neighbor, The seismic waves thus generated shake the ground upward and downward as well as forward and back. Because the faults allow for vertical motions, subduction zone earthquakes can lead to the uplift or subsidence of local landmasses, over time flooding coastal areas or leaving them high and dry. If the earthquake occurs offshore beneath the ocean (the plate boundary in a subduction zone generally lies underwater and out of sight), the vertical motion of the sea bottom can send a surge of water (a *tsunami*) racing toward vulnerable seaside communities. Finally, since subduction zones are typically mountainous (because of all the vertical fault motion), strong subduction temblors can set off major landslides, avalanches, or mudflow.

Strike-Slip Plate Boundaries

A very different type of plate interaction is at work in California and southeast Alaska. Here, the Pacific Plate (on which Baja California and the westernmost sliver of the North American continent rest) slides sideways against the North American Plate in a motion known geologically as *strike-slip.* On a strike-slip boundary, there is very little up-and-down motion, most earthquake waves are side to side, and seismic activity does not raise mountains or produce tsunamis in the way it does in a subduction zone.

In the case of California, the seam between the North American and Pacific Plates is the San Andreas fault, a long and distinct scar in the earth's surface that runs beneath San Francisco, through central California, and southward toward Mexico through the desert east of Los Angeles. [1] There is another strike-slip plate boundary fault off the coast of southeast Alaska. Earthquakes occur along these faults primarily because relative motion, or *slip,* along either fault is not continuous over time or distance. That is, the fault is locked most of time, so that no slip occurs. The inexorable movement of the tectonic plates, however, causes stress to build along the fault until, for poorly understood reasons, one or more segments of the fault rupture, releasing the stored-up energy in an earthquake.

In California, most of the slip between the North American and Pacific Plates occurs along the San Andreas fault or in the immediate vicinity. Some deformation of the plate edges also occurs many miles from the primary fault, leading to stress-relieving earthquakes on strike-slip faults located on either side of the San Andreas. An example is the 1992 Landers earthquake (M7.3). The largest U.S. earthquake in 40 years, it occurred in a relatively sparsely populated area several miles northeast of Los Angeles.

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[1] A continuous narrow break in the earth's crust, the entire fault zone is more than 800 miles long and extends at least 16 km beneath the earth's surface. Sandra E Schulz and Robert E. Wallace, The *San Andreas Fault,* prepared for the U.S. Geological Survey (Washington, DC. U.S. Government Printing Office, 1993), pp. 3-4.

(continued)

BOX 2-1 (cont'd.): Geologic Settings for Earthquakes

A pronounced bend in the San Andreas north of the Los Angeles area effectively locks the motion of the tectonic plates, contributing to vertical deformation and setting the stage for earthquakes on downward-dipping faults hidden from view beneath the earth's surface. The 1971 San Fernando and 1994 Northridge quakes both ruptured such "blind" thrust faults,

Intraplate Earthquakes

Although more than 90 percent of the world's earthquakes occur on plate boundaries, damaging earthquakes have also occurred in areas far from plate edges. *Intraplate* earthquakes, which though uncommon can be sizable, seem to reflect processes that are a topic of current tectonic and geophysical research Possible explanations include: 1) dynamic interactions between the earth's stiff exterior layers and its deeper, more flowing mantle; 2) a continent's adjusting to evolving plate boundary geometries (the Basin and Range Province of Nevada, for example, is stretching east-west following the disappearance of a subduction zone that once lay to the west); or 3) the interaction between zones of weakness within a plate and stresses transmitted across the plate from its boundaries,

The regions of the United States in which future intraplate earthquakes are most likely to occur are the Intermountain West and central United States, although parts of the Atlantic seaboard are also susceptible.[2] Compared with interplate earthquakes, uncertainty over the origin, likelihood, severity, and characteristics of intraplate quakes is very high, Improved understanding can come only through further basic earth science research.

[2] The eastern coast of North America, while marking the edge of the continent, is not a plate boundary North America is joined directly to the rocks underlying the western half of the Atlantic Ocean, and the eastern boundary of the North American Plate lies in the middle of the Atlantic.

SOURCE Office of Technology Assessment, 1995

Other Effects

The shaking caused by seismic waves, in addition to directly damaging structures, can also affect the earth's surface in ways equally detrimental (or more so) to the built environment. Ground failure, as these effects are often called, has several different facets:

- liquefaction, whereby shaking transforms a water-saturated soil or sediment into a thick, quicksand-like slurry;
- ground rupture, in which shaking opens up fissures and cracks in the soil;
- surface faulting, in which an earthquake fault reaches the surface of the earth and produces vertical or horizontal *offsets* of material astride the fault;
- landslides or avalanches; and
- damaging water waves (e.g., tsunamis and seiches).[13]

[13] *Fast-moving* surges of water that travel across the ocean, *tsunamis* form a steep wall of water when entering shallow water along shorelines. The local wave height and run-up length are affected by the topography of the seafloor and continental shelf and by the shape of the shoreline—tsunamis with crests as high as 25 meters have devastated parts of Japan. Bruce A. Bolt, *Earthquakes (New* York, NY: W.H. Freeman and Co., 1993), pp. 148, 151. Tsunami generation is not fully understood, and may result more from the absolute motion of material at an earthquake fault than from the ground shaking from seismic waves. *Seiches are* earthquake-generated surges of water on lakes and enclosed bays.

BOX 2-2: Mexico City Earthquake

On September 19, 1985, Mexico City experienced the effects of an M8.1 quake that occurred in a subduction zone 350 km away Strong shaking caused extensive damage, killed thousands of people,[1] and left many more thousands homeless Most of the damage was confined to areas of the city built on soft, water-saturated soils

Key factors in the devastating losses Included:

- the long duration of shaking,
- local soil conditions that amplified seismic energy and produced extensive liquefaction,
- poor overall configuration and significant irregularities in the distribution of buildings mass, strength, and stiffness, and
- poor quality control of building materials.

Rupture on the segment of a subduction zone known as the Michoacan gap produced approximately 1 5 minutes of shaking with a roughly two-second period. (Higher frequency motions were damped over the distance between the earthquake's focus and Mexico City.)

Liquefaction was widespread, and soil-structure interaction increased the structural response of many multistory buildings to a period that coincided with the long-period motion produced by the quake. The effects of this resonance Included drift, deformation, and pounding between buildings

[1] The official count is 4,596 lives lost, although other estimates areas high as 20,000

SOURCE: Applied Technology Council and Earthquake Engineering Research Institute, *Proceedings of the Workshop for Utilization of Research on Engineering and Socioeconomic Aspects of the* 1985 *Chile and Mexico Earthquakes, ATC-30* (Redwood City CA Applied Technology Council), 1991

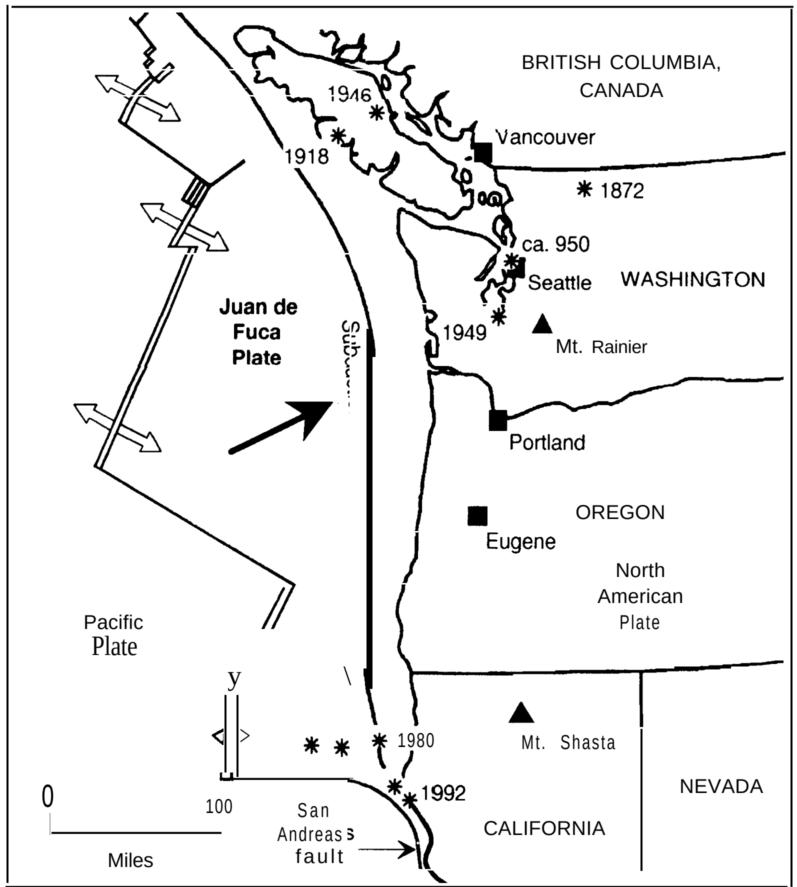
Like strong ground shaking, ground failure is strongly dependent on the surface and near-surface geology. Areas adjacent to waterways and developed with artificial fill are particularly susceptible to liquefaction, as seen in the Marina district in San Francisco during the 1989 Loma Prieta earthquake and in the 1995 Hyogoken-Nanbu earthquake that struck Kobe, Japan. Lateral spreading (in which surface layers are transported laterally over liquefied soils) ruptured water and sewer lines in the Kobe quake. The shaking produced by the 1994 Northridge, California, quake and its aftershocks caused thousands of landslides in nearby mountains.

SEISMIC HAZARDS ACROSS THE UNITED STATES

Earthquake researchers use an understanding of the basic setting for earthquakes and knowledge of prior earthquakes to assess seismic hazards and relate these to affected communities. Earthquake hazards vary widely across the country, from high in Alaska and the West Coast to low (but not zero) in much of the eastern United States. There is a continuum of earthquake risk,[14] as well: where heavy urbanization exists and frequent damaging earthquakes are expected, the risk is very high (e.g., in the San Francisco Bay or Los Angeles

[14] *Seismic hazard* is the potential for an earthquake and related effects to occur. *Seismic risk* is the likelihood for casualties, damage to the built environment, or other losses to occur as a result of earthquakes.

FIGURE 2-3: Tectonic Setting and Significant Earthquakes in the Pacific Northwest



NOTE * indicates earthquakes of magnitude greater than 7

SOURCE Office of Technology Assessment, 1995, based on U S Geological Survey

areas). In the Pacific Northwest, the seismic risk stems from the potential for infrequent but large to great earthquakes and from the region's status as a relative newcomer to mitigation (i.e., fewer steps have been taken to reduce risk). Likewise, central and eastern areas of the United States face the threat of significant earthquakes over very long intervals; the low frequency of damaging seismic events in recent history has contributed to the more limited implementation of mitigation measures than in the West, despite the vulnerability of many population centers (e.g., New York City or Boston) to even moderate shaking. The following sections describe current knowledge of earthquake hazards in different regions of the United States.

Pacific Northwest

The coastal area stretching from Alaska's western Aleutian Islands to the states of Washington and Oregon is at risk for both moderate and enormously powerful earthquakes. This area encompasses the growing metropolitan areas of Seattle, Portland, and Anchorage, as well as cities on Canada's west coast. Estimates of possible earthquake magnitudes in the region range as high as magnitude 9 (see figure 2-3).

The convergence of tectonic plates creates a high likelihood of seismic activity. For this reason, Alaska frequently experiences potentially damaging earthquakes, but due to its relatively low population density the impact is smaller than in more developed areas. In 1964, the second largest quake of this century struck Alaska, uplifting sections of the ocean floor and causing extensive damage to the Anchorage area. The Mw9.2 quake also caused a tsunami that led to further loss of life and damage in Alaska and in the northern California coastal town of Crescent City.

If such a temblor occurred further south, it could affect coastal communities from Vancouver, British Columbia, to northern California. However, off the coasts of Oregon and Washington, there have been no quakes of this size during recorded history. Awareness of this particular seismic threat was low until evidence of tsunami deposits and changes in coastal elevation, gathered in large part through NEHRP, revealed that great subduction zone earthquakes had occurred in the past. Based on tsunami records from Japan, the most recent may have been in the year 1700.[15]

Moderate-to-large crustal earthquakes in Oregon and Washington have been relatively infrequent, but the risk to population centers is significant. A major quake struck the Cascades of northern Washington in 1872;[16] the Puget Sound region experienced quakes of magnitudes 7.1 and 6.5 in this century;[17] and as recently as March 1993, a M5.6 temblor rocked the Oregon capital city of Salem.[18]

Uncertainty remains over how likely or how severe future events may be. Research into this question, much of it involving the modeling of geophysical processes in the region, is active and growing, and may eventually remove much of this uncertainty. In the meantime, complementary research into paleoseismology (the study of early historic or prehistoric earthquake activity based on geologic evidence) seeks to refine estimates of the timing and magnitude of previous subduction zone and crustal quakes. Besides indicating that prehistoric, devastating tsunamis occurred, the geologic record also suggests that a major earthquake took place 1,100 years ago directly beneath what is now downtown Seattle.[19]

California

A combination of high population density, heavy levels of urbanization, and the relatively frequent occurrence of moderate to great earthquakes makes California a state with very high seismic risk. Other areas in the United States may experience equally severe earthquake disasters, but the likelihood is lower.

For many years it was thought that the earthquake hazard in California stemmed primarily from the great San Andreas fault system, which accommodates the sliding of the North American continent sideways against the Pacific Plate. Several M8+ earthquakes have occurred along the San Andreas, including the great 1906 San Francisco Earthquake. The long-awaited "Big One" is ex-

[15] Kenji Satake et al., "A Possible Cascadia Earthquake of January 26, 1700, as Inferred from Tsunami Records in Japan," *Geological Society of America 1995 Abstracts with Programs*, vol. 27, No. 5, 1995, p. 76.

[16] Reported effects indicate that its magnitude was approximately 7.4, probably the largest during recorded history for that area. Thomas Yelin et al., *Washington and Oregon Earthquake History and Hazards*, U.S. Geological Survey Open File Report 94-226B (Denver, CO: National Earthquake Information Center, 1994), p. 7.

[17] The quakes took place in 1949 (M7.1) and 1965 (M6.5); both deep quakes (depths of 54 to 63 km), they caused several deaths and significant damage. Linda Lawrance Noson et al., *Washington State Earthquake Hazards*, Information Circular 85 (Olympia, WA: Washington Department of Natural Resources, 1988), p. 21.

[18] Six months later, a pair of strong quakes occurred a little more than two hours apart near Klamath Falls, in the southern part of the state. Shallow crustal quakes like these have also occurred in the Portland area. Yelin et al., see footnote 16.

[19] Ibid., p. 9.

ROBERT E. WALLACE, U.S. GEOLOGICAL SURVEY

Looking northwest along the San Andreas fault, the seam between the North American and Pacific Plates, in the Carnzo Plain (central Ca//forn/a)

pected to involve rupture of the fault's southern section.

A more recently recognized danger is the likelihood of future moderate-to-large earthquakes occurring on lesser known or even unsuspected faults adjacent to or directly underneath major metropolitan centers (see figure 2-4). The quake beneath Northridge in January 1994 revealed all too well the hazardous potential of blind thrust faults in the Los Angeles area.[20]

The danger of these blind thrust systems is a combination of the size of their associated earthquakes and their proximity to urban centers. Because an earthquake's damaging effects tend to decrease rapidly with distance, the physical separation between the San Andreas and a metropolitan center such as Los Angeles allows policy makers to prepare the built environment against a lesser amount of damage than sheer earthquake magnitude might seem to warrant. However, if a fault capable of producing earthquakes is close by, then its proximity allows even a moderate event to inflict more damage than might result from the long-awaited "Big One."[21]

In northern California, the geometric complexity of the San Andreas fault system that prevents North America from sliding cleanly against the Pacific Plate causes the San Andreas to branch off into a series of smaller faults that run in a north-south direction along the east side of San Francisco Bay (see figure 2-5). In addition to the 1906 San Francisco and 1989 Loma Prieta earthquakes, the Bay Area has experienced 20 other moderate to great earthquakes in the last 160 years.[22]

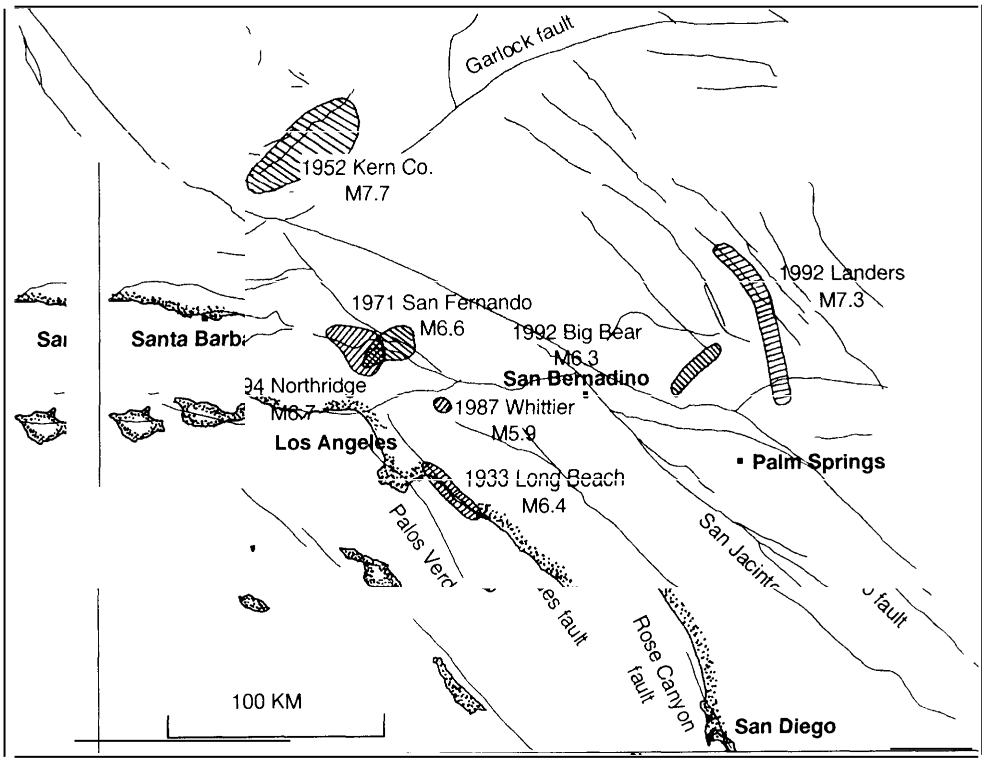
Because of these and other findings from recent research, the true earthquake hazard in California remains uncertain, and future estimates may well be subject to upgrading. As of 1990, **the estimated likelihood of major (M7+) earthquakes stands at 67 percent over 30 years in the San**

[20] Seismograph and strong-motion instrument data recorded during and after the Northridge earthquake indicate larger ground motions than have typically been observed or reflected in engineering design in California. The aftermath of the quake included realization that improved knowledge of the system of blind thrust faults lying beneath the Los Angeles area and environs would be useful for targeting mitigation efforts. While oil company studies are a good source of information about subsurface structure, the mapping rarely extends to depths where earthquakes initiate.

[21] It appears that one such fault, the Elysian park blind thrust fault, lies directly beneath downtown Los Angeles.

[22] Association of Bay Area Governments, 'The Bay Area Is Earthquake Country," Internet, address http: //www.abag.ca.gov/bay area/eq - maps; doc/text l.html#background, citing Jeanne B. Perkins and John Boatwright, *The San Francisco Bay Area--On Shaky Ground* (Oakland, CA: Association of Bay Area Governments, April 1995).

FIGURE 2-4: Earthquake Source Zones for Selected Significant Events in Southern California



NOTE: Shaded areas represent rupture zones for earthquakes shown

SOURCE U S Geological Survey, 1995

Francisco Bay area.[23] Studies of the potential for liquefaction and ground failure that would result from shaking on the San Andreas and its neighbors across the Bay are continuing,[24] as are investigations of local fault structures.

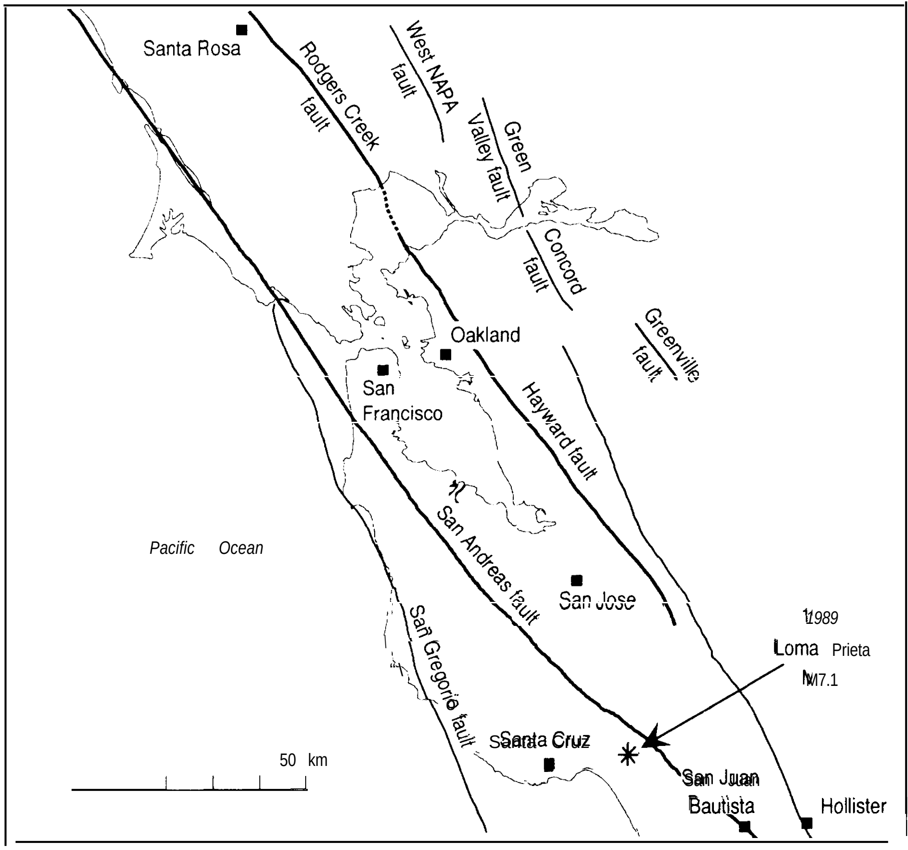
The 30-year probability of a major earthquake in southern California, estimated in 1994, is 80 to 90 percent (this estimate reflects both San Andreas and blind thrust hazards for the urban corridor from San Bernardino through Los Angeles to Santa Barbara).[25] Scientists have also noticed a historical deficit in the size or number of earthquakes expected for southern California;

[23]The primary fault structures evaluated for the assessment were nearby segments of the San Andreas fault and the neighboring fault system east of the bay, which consists of the Hayward and Rodgers Creek faults. Working Group on California Earthquake Probabilities, *Probabilities of Large Earthquakes in the San Francisco Bay Region, California,* U.S. Geological Survey Circular 1053 (Washington, DC: U.S. Government Printing Office, 1990), p. 31.

[24]This is an area of cooperation between USGS and the California Division of Mines and Geology, the state agency responsible for mapping special hazard zones.

[25]Working Group on California Earthquake Probabilities, "Seismic Hazards in Southern California: Probable Earthquakes, 1994-2024," *Bulletin of the Seismological Society of America,* vol. 85, No. 2, April 1995, p. 379; USGS and SCEC Scientists, "The Magnitude 6.7 Northridge, California, Earthquake of 17 January 1994," *Science,* vol. 266, Oct. 21, 1994, p. 396.

FIGURE 2-5: Primary Faults in the San Francisco Bay Area



SOURCE U S Geological Survey, 1995

geologic and geodetic data indicate that too few earthquakes have occurred to account for strain accumulation.[26] Whether this points to bigger quakes or to more frequent quakes is still under discussion in the scientific community.

Intermountain Seismic Belt

A region not commonly associated with seismic hazards—yet nevertheless under considerable risk—is the Intermountain Seismic Belt. Stretching from southern Idaho and western Montana down through southwestern Utah and Nevada, this area includes the urban center of Salt Lake City, Utah, and other rapidly growing communities in the Intermountain West (e.g., Boise, Idaho, and Reno, Nevada).

Earthquakes here do not stem from the plate collisional processes of the Pacific Northwest or from the sideways sliding of adjacent plates seen in California. Rather, they arise from intraplate deformation of the North American continent associated with the uplift of the Rocky Mountains

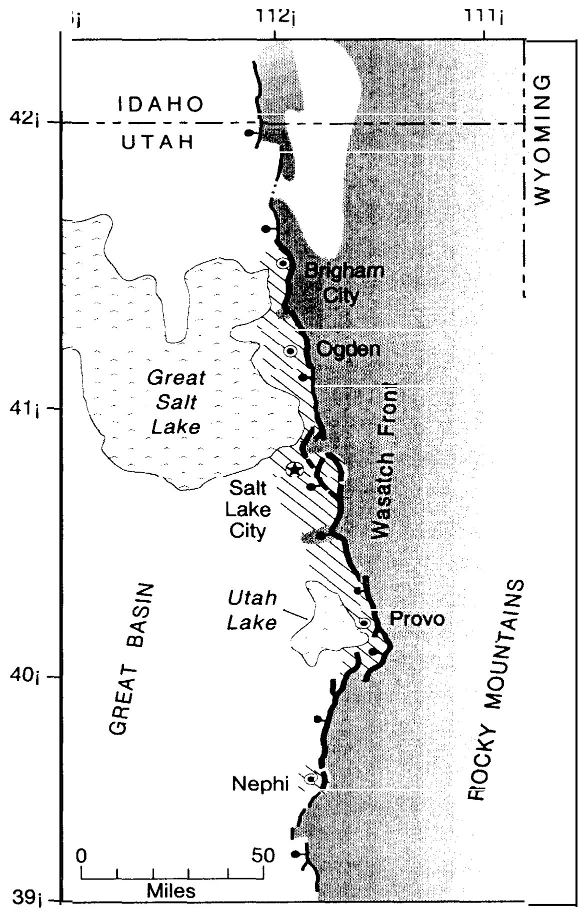
26 James F. Dolan et al., "Prospects for Larger or More Frequent Earthquakes in the Los Angeles Metropolitan Area." *Science*, vol. 267, Jan. 13, 1995, p. 203; and Working Group on California Earthquake Probabilities, see footnote 25.

and the east-west stretching of the Basin and Range Province. Because this region lies within the interior of the North American Plate and far from the active deformation, collision, and sliding experienced at the plate edges, damaging earthquakes are relatively rare. However, since these earthquakes reflect active mountain-building processes in the continental interior, when they do occur, they can be sizable (M7 or higher).

Even though the maximum earthquake magnitudes in this region appear to be less severe than those projected or observed in the Pacific Northwest or California, the potential for disaster exists simply because the scarcity of historic earthquakes has led to a relatively low level of preparedness. General settlement of the area did not begin until the 1840s; in the intervening years, there have been no large quakes near the region's few urban centers. Consequently, damaging earthquakes have generally been less of a public concern than is the case in California. The region's last major quakes were in Montana in 1959, when several people were killed by landslides, and southern Idaho in 1983.

Awareness of the threat to Utah's metropolitan corridor grew as a result of a major NEHRP project to study the Wasatch Front, which is formed by the uplift of the Rocky Mountains along a long, north-south fault zone—the Wasatch fault zone (see figure 2-6). The research showed that major earthquakes *have* occurred in the past, with paleoseismic evidence suggesting a roughly 400-year recurrence along the most urbanized part of the Wasatch fault zone.[27] In 1991, **the probability of a** M7+ **earthquake anywhere along the Wasatch was estimated to be 13 percent over a 50-year period.**[28] An earthquake of that size anywhere along the fault zone will be felt throughout

FIGURE 2-6: Wasatch Fault Zone



NOTE: Thick line designates the Wasatch fault About 80 percent of Utah's population, or nearly 16 million people, are at risk to movement of the fault.

SOURCE: U.S. Geological Survey, 1995

the system, and is likely to damage structures in the closest cities.[29]

Although a major earthquake in a California city would cause considerable damage and loss of life, an occurrence in less-prepared Utah could be

[27] Michael N. Machette et al., "Paleoseismology of the Wasatch Fault Zone: A Summary of Recent Investigations, Interpretations, and Conclusions," USGS Professional Paper 1500-A, November 1990, p. A55. Led by USGS and the Utah Geological and Mineral Survey, the project was completed in the early 1990s; seismic hazard and risk assessment continues today under state and local authorities.

[28] S. Nishenko, "Probabilistic Estimates for the Wasatch Fault," in *Proceedings of the National Earthquake Prediction Evaluation Council,* June 11-12, 1991, Alta, Utah, USGS Open File Report 92-249 (Washington, DC: U.S. Geological Survey, 1992), pp. 16-19.

[29] Kaye Shedlock, U.S. Geological Survey, Earthquake and Landslide Hazards Branch, personal communication, Apr. 15, 1995.

far worse.[30] Moreover, continued population growth in the region will likely lead to urbanization in areas relatively untargeted (until recently) by earthquake researchers; this raises the possibility of additional damage in areas currently unaware of their seismic hazard.

Central United States

A series of three great earthquakes occurred between December 1811 and February 1812 near New Madrid, Missouri, opening chasms in the earth, destroying the scattered settlements in the region, and causing sections of the Mississippi River to temporarily reverse and flow backward. Although there were no modern seismographic instruments available then to record the quakes' magnitudes, the level of destruction witnessed places these events among the most powerful ever.[31]

The challenge to the earth science community has therefore been to determine the likelihood of future damaging earthquakes in this region, and to decide whether the great New Madrid earthquakes were a geophysical fluke or the offspring of geologic conditions specific to the region.[32] In many respects, this task has been more difficult to perform than is generally the case in the western United States, because earthquakes in the central and eastern United States cannot be accounted for by classic plate tectonic theory. Compounding this difficulty is an observational problem caused by the presence of the Mississippi. Sediments carried by the river and deposited overland during floods over the eons have blanketed the region with kilometers of mud, sand, clay, and soil that effectively hide potential earthquake faults from view.[33]

About a decade ago, a major success was achieved in the identification of a geologic structure that appears tied to the region's earthquakes. This structure, the Reelfoot Rift, is a buried series of faults and anomalous rock formations formed 500 million years ago when tectonic forces tried but failed to split North America in two.[34] The rifting event in effect drew a wounding scar through the more-or-less contiguous landmass of the central and eastern United States. It is this singular zone of weakness (identified through geophysical surveys) that may account for the New Madrid earthquakes (see figure 2-7).

Thus, it appears that seismicity in this area is tied to a particular geologic structure, and is not expected to recur randomly elsewhere (see figure 2-7). However, scientists have also learned that any earthquakes that do occur in the eastern half of the United States will be felt far more widely than

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30 A 1976 USGS study, for example, projected 14,000 fatalities in the event of a major Wasatch Front event. The Salt Lake area has since upgraded its seismic zone status and implemented hazard assessment and mitigation projects.

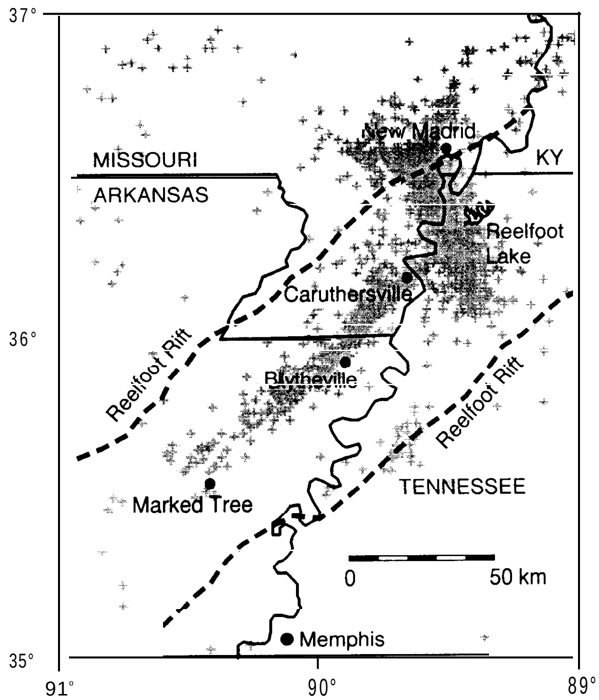
31 With MMI of XI and XII, these temblors were the largest to occur within the coterminous United States; the 1812 quake was felt throughout an area of 5 million square kilometers. For comparison, the great San Francisco earthquake of 1906 had an MMI of XI and registered 8.3 the Richter scale. William Atkinson, *The Next New Madrid Earthquake: A Survival Guide for the Midwest* (Carbondale and Edwardsville, IL: Southern Illinois University Press, 1989), p. 22; and Bolt, see footnote 13, pp. 5, 270, 277.

32 The former conclusion would suggest that a repeat might occur virtually anywhere in the United States; the latter, although disquieting to local residents, at least confines the likely region of future devastation.

33 Although the deep sedimentary cap precludes direct observation of the faults, sedimentation facilitates paleoseismic work, and some information about the region's tectonic structures can be inferred by its topography. Geologic evidence indicates that three large earthquakes have occurred in the New Madrid area over the last 2,400 years, a recurrence rate comparable to that for the Wasatch fault or many reverse faults in California. Robert Yeats, Department of Geosciences, Oregon State University, personal communication, May 7, 1995; and see Keith I. Kelson et al., "Multiple Late Holocene Earthquakes Along the Reelfoot Fault, Central New Madrid Seismic Zone," *Journal of Geophysical Research*, forthcoming, January 1996.

34 Robert M. Hamilton and Arch C. Johnston (eds.), *Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake*, U.S. Geological Survey Circular 1066 (Washington, DC: U.S. Government Printing Office, 1990), p. 9. At the time, North America was joined to Eurasia and Africa. Following the failure of the Reelfoot Rift, the landmass farther east split to form the proto-Atlantic Ocean.

FIGURE 2-7: New Madrid Seismic Zone



NOTE: Shaded area shows region of intense liquefaction in 1811 to 1812 earthquakes, small hatches represent seismicity during 1974 to 1991, and heavy dashed lines indicate boundaries of the Reelfoot Rift.

SOURCE U S. Geological Survey, 1995

quakes that occur west of the Rockies (see box 2-3).

Given the potentially far-flung and devastating effects of a major earthquake in the central United States, it is critical that earthquake severity and timing estimates are refined to the point that regional policymakers know the need and time scale for action. Unfortunately, uncertainties for the region remain substantial. Although the presence of the Reelfoot Rift provides an explanation for the siting of earthquakes, it does not by itself predict their occurrence. At present, there is no clear consensus on what mechanism causes tectonic stress in the region to build up to the point of an earthquake. In the absence of a conceptual tectonic model, the best guide to future earthquake activity in this region lies in the record of past earthquakes. This record suggests a recurrence of moderate quakes every 60 to 90 years (the last moderate event was in 1895).[35] **The probability of an M6.3 quake before 2040 is 86 to 97 percent; of an M8.3 quake, 2.7 to 4 percent.**[36]

Furthermore, outside the immediate New Madrid Seismic Zone, the characteristics of the source zones in the central (and eastern) United States are poorly known. The region is virtually devoid of identifiable active faulting,[37] and geologic studies of seismogenic features are in the reconnaissance stage. Although current levels of seismicity indicate a low hazard, NEHRP-supported studies have provided evidence of several major quakes in the Wabash Valley area (southern Indiana and Illinois) over the last 20,000 years.

Eastern United States

The Pacific Northwest, California, Intermountain West, and central United States have constituted the primary earthquake concerns in this country because the likelihood and potentially devastating effects of damaging earthquakes are known with greatest certainty in these regions. However. other parts of the country are also at risk (although the hazards are more uncertain) and may come more to the forefront with continued research and understanding. These regions include the Atlantic seaboard, which has experienced rare but moderately damaging earthquakes centered near Charleston, South Carolina; Boston, Massachu-

35 Atkinson, see footnote 31, p. 1; and ibid., P. 8.

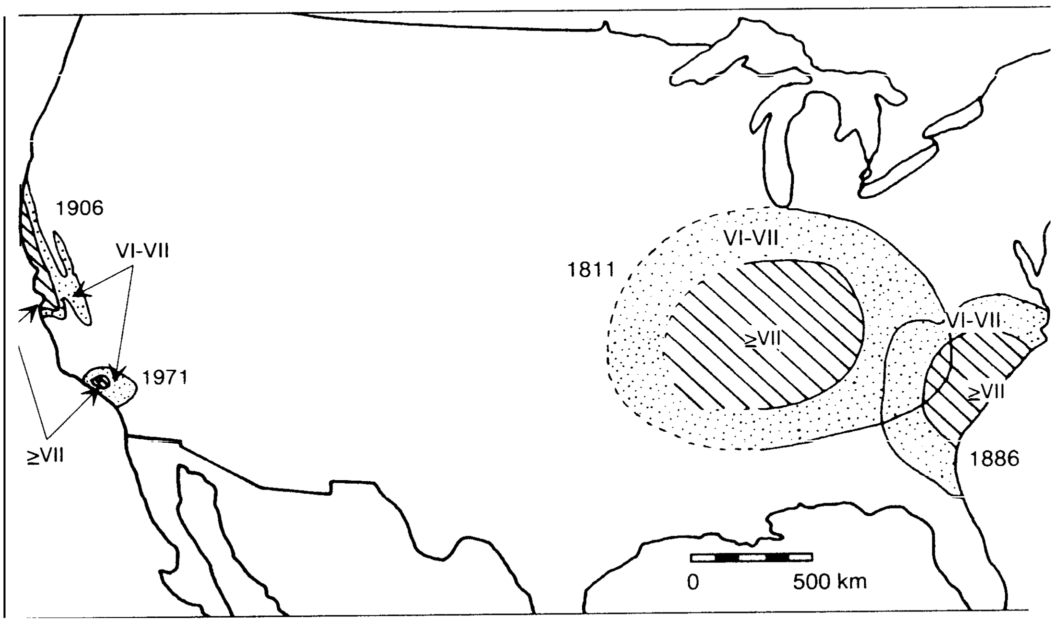
36 Hamilton and Johnson (eds.), see footnote 34.

37 Arch c. Johnston and susan J. Nava, seismic Hazard Assessment in the Central United States," Proceedings *of ATC-35 Seminar* on *New Developments in Earthquake Ground Motion Estimation and Implications for Engineering Design Practice, ATC-35-1,* Applied Technology Council (cd.) (Redwood City, CA: Applied Technology Council, 1994), p. 2-7. An exception is the Meers Fault in Oklahoma, which has geologic expression indicative of previous strong earthquakes but very low modem seismicity.

BOX 2-3: Relative Impact Areas for Eastern and Western Earthquakes

The two halves of the North American continent have very different tectonic histories. East of the Rockies, the North American landmass has held together (the abortive Reelfoot Rift notwithstanding) for a good part of the last billion years, and the tectonic plate material is strong In contrast, the continent west of the Rockies has experienced repeated breakup, reassembly, uplift, compression, extension, and shear—heating and weakening it Seismic waves radiating from a western earthquake therefore diminish more rapidly as they pass through fractured and heated rock, so that a major earthquake along the San Andreas can have relatively moderate effects on the distant Los Angeles basin. East of the Rockies, however, seismic waves are far less weakened as they radiate through hard, cold, strong rock, and even a moderate quake has the potential for destruction over a wide geographic range.[1]

Relative Impact Areas for Severe Earthquakes in Western and Eastern United States



NOTE: Figure shows areas of Modified Mercalli Intensity of VI and VII for two great earthquakes (New Madrid, Missouri, in 1811 and San Francisco, California, in 1906) and two major damaging earthquakes (Charleston, South Carolina, in 1886 and San Fernando, California, m 1971). Potential damage area corresponds to intensity VII and greater, an area of roughly 250,000 square miles for the New Madrid earthquake

SOURCE Off Ice of Technology Assessment, 1995, based on R Hamilton and A Johnston (eds.), *Tecumseh's Prophesy Preparing for the Next New Madrid Earthquake,* U S Geological Survey Circular 1066 (Washington, DC U S Government Printing Office, 1990) pp. 6, 12;O. W. Nuttli, "The MISSISSIPPI Valley Earthquakes of 1811 and 1812—Intensltles, Ground Motion, and Magnitudes" *Bulletin of the Seismological Society of America,* vol 63, 1973, pp. 227-248, and D W Rankin (ed.), "Studies Related to the Charleston, South Carolina, Earthquake of 188&A Preliminary Report, " U S Geological Survey Professional Paper 1028, 1977

[1]The 1812 New Madrid shock was felt in Boston, Canada, Georgia, and at least as far west as Kansas and Nebraska Moderate ground shaking was felt over an area of nearly 1 million square miles, in contrast to some 60,000 square miles in the 1906 San Francisco quake. William Atkinson, *The Next New Madrid Earthquake: A Survival Guide for the Midwest* (Carbondale and Edwardsville, IL Southern Illinois University Press, 1989), p 18

SOURCE Office of Technology Assessment, 1995 setts; and northward toward the Saint Lawrence Valley.

Puerto Rico and the U.S. Virgin Islands are at risk from earthquakes in the Caribbean's subduction zone. In 1917, Puerto Rico suffered a major earthquake (M7).

Limiting Factors in Assessing Seismic Hazards

Damaging earthquakes have occurred in many parts of the United States, and several metropolitan areas are located in regions of moderate to very high seismic hazards (see table 2-3). Over the last quarter of a century, understanding of these hazards has increased considerably. In the past five years, advanced instrumentation and computer-based analytic tools have revolutionized earth science research and laid the groundwork for new hazard estimation capabilities.

Despite the many achievements to date, uncertainties still plague our ability to characterize seismic hazards. Engineers desire better information on the types of ground shaking expected for a given area so that methods for analyzing and improving a structure's seismic resistance can be enhanced. Likewise, planners and emergency managers would greatly benefit from improved knowledge of which areas in a city are likely to be hardest hit by future earthquakes. Factors that limit our knowledge of faults capable of producing earthquakes, of how often quakes occur on them, and of their likely effects include the following:

- The historical and instrumental records are very short compared with the time scales on which earthquakes are generated, particularly east of the Rockies.
- Most quakes begin rupturing 10 km or more beneath the surface of the earth: although some earthquake phenomena and causative factors are observed directly in surface faulting and geodetic strain, other information must be inferred from seismological and other data.
- Detailed mapping of the structural features that influence earthquake damage has been completed in only a small portion of the United States.
- There are few records of strong ground motions in close proximity to fault ruptures, and data on crustal deformation and stress are likewise sparse.

Such challenges to our understanding of seismic hazards and progress toward the long-term goal of accurately predicting earthquakes will likely be more readily surmounted in the future, given the present confluence of new tools, trained scientists, and expanded databases. These advances stem from work in the earth sciences supported by NEHRP and from other federal, state, local, and international activities.

EARTHQUAKE-RELATED RESEARCH IN EARTH SCIENCE

The preceding sections outlined some of the substantial progress made by the earth science community in achieving a basic understanding of the earthquake problem. This understanding has made it possible for policymakers to identify future trouble spots and to take preventive action. Current knowledge of seismic hazards in different regions, however, has not reached the point where scientists and policymakers are no longer surprised by earthquakes and their effects. Scientific uncertainties for much of the country remain high enough to discourage the implementation of oftentimes costly mitigation measures. Under NEHRP, earth science researchers seek to reduce these uncertainties and to make available much needed information for the implementation of seismic risk reduction policies, practices, and technologies. This section discusses current research efforts that address the primary knowledge gaps.

Objectives

The objectives of current earthquake-related earth science include:

- identifying the regions of potential risk;
- producing or refining estimates of future earthquake location, timing, and severity;
- highlighting special geologic hazards that may accompany future events (e.g., landslides, tsunamis, unusual ground shaking); and

TABLE 2-3: Summary of U.S. Earthquake Hazards

Area	Frequency/probability of return	Comments on tectonic framework
Alaska	Since 1900, one M8 or larger quake every 13 years, one M7+ quake every year, and several moderate to large quakes every year.	Subduction zone along Aleutian Islands, Alaskan Peninsula, and southern Alaska. Frequent strong intraplate seismicity. Damaging quakes also possible on strike-slip Queen Charlotte fault in southeast Alaska.
Pacific Northwest	90-year return period for a M7.5.	Shallow crustal quakes, massive subduction zone quakes possible offshore, and quakes within subducted plate deep beneath Puget Sound.
Northern California	67 percent chance of a M7 or greater earthquake in the San Francisco Bay area by 2020.	Primary faults: strike-slip San Andreas and Hayward/Rogers Creek faults on the east side of the bay; quakes on local blind thrust faults also possible, Northern California coast subject to quakes with several sources: northern segment of the San Andreas, Cascadia subduction zone, and inland crustal quakes.
Southern California	80-90 percent probability of a M7 or greater earthquake before 2024 in greater Los Angeles area.	Extensive rupture of strike-slip San Andreas possible, and moderate-to-large quakes also likely on secondary fault systems, Extensive buried thrust fault system beneath the Los Angeles basin as a result of compressional terrain Faults near Los Angeles' and San Diego's port facilities pose a similar threat as the fault that ruptured near Kobe, Japan, in 1995.
Hawall	Frequent seismicity associated with volcanic activity; last major quake (M7.1) in 1975.	Repeatedly struck by tsunamis; landslide potential high,
Intermountain West	*30* percent chance of major quake anywhere along Utah's Wasatch fault zone in the next 100 years. Growing population centers elsewhere in Intermountain Seismic Belt also susceptible to damaging earthquakes.	Mountain-building region; normal faulting with large vertical offsets possible from Utah northward through Idaho and into Montana.
Central United States	40-63 percent probability of recurrence of M = 6+ quake in New Madrid Seismic Zone before 2005, 86-97 percent probability before 2040, approximately 250-year return period for a M7.6 or greater	Abundant seismicity in New Madrid Seismic Zone, linked to rifted margin; dispersed seismicity elsewhere in the region not linked to specific faults,
Northeast	300-year return period estimated for a M7 Last moderate quakes in New York area in 1944 and 1985.	"Stable" plate interior, with zone of relatively high seismicity from Adirondacks up through St Lawrence Valley; dispersed seismicity elsewhere. Several large earthquakes scattered throughout region since 1600s, primarily in Canadian provinces,
Southeast	Charleston, South Carolina, struck by large quake (M6.7) in 1886. High concentration of seismicity in eastern Tennessee	Tectonic origin for seismicity in eastern United States unclear
Puerto Rico and U.S. Virgin Islands	Last major quake in 1917; estimated 70-year return period.	Subduction zone where the Caribbean Plate meets the North American and South American Plates

SOURCES: Working Group on California Earthquake Probabilities, Probabilities of large *Earthquakes in the San Francisco Bay Region, California,* U.S. Geological Survey Circular 1053 (Washington, DC U S Government Printing Office, 1990), Working Group on California Earthquake Probabilities, "Seismic Hazards in Southern California. Probable Earthquakes, 1994 to 2024, " *Bulletin of the Seismological Society of America,* vol *85, No 2,* April 1995, pp. 379-439; R. Hamilton and A Johnston (eds.), *Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake,* U.S. Geological Survey Circular 1066 (Washington, DC U.S. Government Printing Office, 1990); K Shedlock and C Weaver, *Program for Earthquake Hazards Assessment in the Pacific Northwest,* U S Geological Survey Circular 1067 (Washington, DC: U.S. Government Printing Office, 1991), and Christine A Powell et al , "A Seismotectonic Model for the 300-Kilometer-Long Eastern Tennessee Seismic Zone, " *Science,* vol 264, Apr. 29, 1994, pp. 686-688

- supporting scientific and engineering applications of earthquake data and theories.

Meeting these objectives and resolving some of the unknowns laid out in the first half of this chapter requires continued effort in several research disciplines. This work ranges from exploratory research into details of earthquake sources to applying new computational techniques toward predicting ground failure or tsunami development. **Earth science research and data collection efforts have been—and will continue to be—essential to the development and selection of mitigation options appropriate to a particular region's seismic risk.**

For the discussion that follows, earthquake-related research is grouped into two broad areas: 1) basic research into the fundamental processes that govern earthquake timing, location, and severity; and 2) research applied toward predicting the effects of earthquakes, which in turn supports engineering analyses, land-use planning, and emergency response.

Foretelling Earthquake Timing, Location, and Severity

The general theory of plate tectonics, while identifying where earthquakes should occur over the long term, does not itself give clear warning of earthquake likelihood or timing. This stems from the difference between geologic time, which spans thousands or millions of years, and the time scales that are appropriate for public policy. Plate tectonics suggests that if we were to wait several millennia, we would expect earthquakes to occur essentially everywhere along a plate boundary. What it does not tell us is which specific parts of that boundary will become active in the next few years or decades. Moreover, plate tectonics does not easily explain why earthquakes should occur far from plate boundaries (as they do east of the Rockies), and rising evidence suggests that the theory is generally inadequate to describe the large-scale tectonic behavior of continental masses.[38]

To specify which part of a plate boundary is likely to break in the near future, researchers must go beyond the large-scale workings of the basic plate tectonic model and identify how general plate tectonic movements are translated into local earthquakes. This quest entails a host of separate research endeavors, the chief of which are regional tectonic studies, including geodetic studies; fundamental seismological research and monitoring; and paleoseismology. The following sections describe these research areas.

Regional Tectonic Studies

Regional tectonic studies seek to determine how large-scale plate motions produce finer scale patterns of stress and deformation (e.g., uplift and compression of the earth's surface) in potential earthquake zones. If earthquake-causing buildup of tectonic stress can be correlated with the occurrence of tectonic deformation, areas of potential danger can be identified even in the absence of historical seismicity through observing changes in stress. Such an identification would be particularly useful in regions such as the Pacific Northwest where major earthquakes have been historically infrequent.

Tectonic studies also seek to identify hidden structures that are capable of producing earthquakes (e.g., Los Angeles' blind thrust faults) through a combination of remote geophysical techniques and onsite geologic mapping.[39] For example, scientists have studied how the relation-

[38] Current indications are that the thinner oceanic parts of the earth's surface act more plate-like (i.e., they are rigid and strong) but that continents behave in a more complex fashion. For example, the Basin and Range Province of Nevada is stretching in an east-west direction (generating low-level seismicity in the process), while the central and eastern parts of the country seem to consist of strong rigid blocks criss-crossed with weaker scars from ancient tectonic activity.

[39] Methods of imaging subsurface geology and seismogenic structures include analysis of the passage of seismic waves through the earth, and local changes in the earth's magnetic and gravitational fields. When combined, the data reveal variations in material properties or rock types that point to the presence of faults.

BOX 2-4: Geodetic Techniques

Japan initiated the first geodetic monitoring program at the turn of the 20th century, many decades before a similar program was established in the United States.[1] Today, both countries have implemented state-of-the-art observation systems intended to reveal strain and stress accumulation from ongoing tectonic processes. Although geodetic measurements are now made in many areas, in only two areas—the San Andreas strike-slip fault zone and the subduction zone along the southern coast of Japan—are there sufficient data to attempt to reconstruct the entire quake-loading cycle.[2]

Very Long Baseline Interferometry and Global Positioning System

The paucity of data stems in part from the logistics of geodetic measurement techniques, which for years required laborious field surveys. However, the availability of highly accurate clocks and digital telecommunications systems has brought significant advances to the field during the last decade or so. Very Long Baseline Interferometry (VLBI) and, later, Global Positioning System (GPS) satellites have allowed expanded observation of crustal deformation and measurement of slip rates with greater accuracy.[3] GPS-based techniques in particular offer speedier calculations of relative distances and thus deformations. Other technical advantages of GPS systems are: absence of line-of-sight constraints, simultaneous determination of vertical and horizontal position, and a useful interstation range from hundreds of kilometers to less than one kilometer.[4]

Regional networks of continuously recording GPS receivers are operating in Japan and California to monitor strain for earthquake research and forecasting. Deployment of portable stations after an earthquake allows scientists to observe post-seismic deformations; these data complement data from seismographs concerning the depth, orientation, and amount of fault slip.[5]

[1] Christopher H. Scholz, *The Mechanics of Earthquakes and Faulting (New* York, NY: Cambridge University Press, 1990), p 223

[2] Ibid., p 227.

[3] VLBI uses radio waves from distant quasars as sources of ranging signals. GPS satellites broadcast time-stamped position data at two different frequencies, allowing for correction of signal delays caused by the earth's atmosphere and thus Improved resolution

[4] Robert A. Page et al., *Goals, Opportunities, and Priorities for the USGS Earthquake Hazards Reduction Program,* USGS Circular 1079 (Washington, DC: U.S. Government Printing Off Ice, 1992), p 9

[5] University Navstar Consortium, *Geoscientific Research and the Global Positioning System. Recent Developments and Future Prospects* (Boulder, CO: 1994), pp. 3-4. The University Navstar Consortium (UNAVCO) provides information, support, and scientific infrastructure to principal investigators making use of GPS satellites for earth science and related research.

ship between primary tectonic features such as the Reelfoot Rift and the continental interior's overall stress regime may serve to localize seismicity in the New Madrid area.[40] Such research may also help to explain the spatial and temporal earthquake clustering that has been observed in the United States and other parts of the world.

Geodetic Studies

A number of technologies (see box 2-4) are used to observe and measure tectonic deformation. These geodetic studies provide part of the raw material for tectonic studies and serve as intermediate checkpoints for earthquake forecasts based on

[40] A current hypothesis is that most stable continental quakes occur through the reactivation of relatively young rift faults that break the integrity of the continental crust. John Adams and Peter W. Basham, "New Knowledge of Northeastern North American Earthquake Potential," ATC-35-1, p. 3-7, citing Coppersmith et al., *Methods for Assessing Maximum Earthquakes in the Central and Eastern United States: EPRI Project 2556-12,* Working Report (Palo Alto, CA: Electric Power Research Institute), 1987; and A.C. Johnston, "The Seismicity of 'Stable Continental Interiors'" *Earthquakes at North Atlantic Margins: Neotectonics and Postglacial Rebound, S.* Gregerson and P.W. Basham (eds.) (Dordecht, Netherlands: Kluwer Academic Publishers, 1989), pp. 299-327.

BOX 2-4 (cont'd.): Geodetic Techniques

Synthetic Aperture Radar Imagery

An even more recent departure from established ground-based geodetic measurement techniques is the use of remote sensing to produce detailed images of deformation fields. Microwave signals generated by synthetic aperture radar (mounted on aircraft or satellites) and reflected off the ground are processed to estimate displacement.[6] Unlike most geodetic techniques, a surveyed network need not be in place prior to an earthquake-satellite images collected at regular intervals can capture co-seismic displacements without advance knowledge of an earthquake's location.[7] Other advantages of Synthetic Aperture Radar imagery include more dense spatial sampling and better precision than previous space imaging techniques.

Laser Interferometry

Near Parkfield, California, the U.S. Geological Survey has been using a two-color laser distance measuring instrument (geodimeter) to observe relative movement in the vicinity of the San Andreas fault. The two-color geodimeter measures distances to a precision of 0.3 to 1.0 mm for ranges between 1 and 9 km.

In-fault Measurements

A number of instruments placed at various depths in an active fault zone also help to reveal ongoing deformation either directly (eg., through creepmeters and strainmeters) or indirectly (e.g., through changes in water level or pore pressure). Creepmeters continuously monitor fault movement within a few meters of fault zones to characterize the rate and nature of fault slip. They can detect changes of about 0.1 mm. Borehole volumetric strainmeters can detect changes of 10 parts per billion (1 inch in 1,600 miles) for signals with periods of several weeks and, for higher frequency signals, can detect even smaller changes.

[6] William Prescott, "Seeing Earthquakes from Afar," *Nature,* vol. 364, July 8, 1993, pp. 100-101.

[7] Didier Massonnet et al., "The Displacement Field of the Landers Earthquake Mapped by Radar Interferometry," *Nature,* vol 364, July 8, 1993, p 138

SOURCES: Office of Technology Assessment and U.S. Geological Survey, 1995.

models of regional tectonics. For example, geodetic data are used to infer rates of regional plate motion that, along with seismologic or geologic evidence of fault locations, can provide estimates of the hazard from these faults.[41] Important data are also obtained from strain measurements at depth (e.g., through borehole monitoring of porosity).

The advent of space-based geodetic techniques, such as Very Long Baseline Interferometry, Satellite Laser Ranging, and most recently, surveys using the Global Positioning System (GPS), has revolutionized this field of study.[42] With these newer techniques, it is possible to directly observe crustal deformation, which may ac-

[41] USGS and SCEC Scientists, see footnote 25, p. 395.

[42] The first two technologies were developed under the aegis of the National Aeronautics and Space Administration's (NASA) Crustal Dynamics Project, a program aimed at directly measuring the relative velocities of tectonic plates on a global scale; the original geoscientific applications of GPS stemmed from this work. University Navstar Consortium, *Geoscientific Research and the Global Positioning System: Recent Developments and Future Prospects* (Boulder, CO: 1994), p. 1. Today, under NASA's Mission to Planet Earth Program, space-based geodetic technology development and research continues.

celerate the development of reliable earthquake forecasting.

Fundamental Seismological Research

To better understand how stresses in the earth eventually lead to the rupturing of a fault and the production of an earthquake, scientists monitor earthquakes via global and regional seismic networks (coordinated systems of sophisticated seismic listening and measuring devices, known as *seismometers*; see box 2-5) and compare the seismology data collected with results from theoretical and laboratory models of earthquake generation.

Questions central to seismological research include the following:

- How does an earthquake initiate?
- What determines whether a growing earthquake becomes large, moderate, or small?
- Can a prenascent earthquake telegraph its future birth and characteristics to attentive observers?
- How does an earthquake affect tectonic stress in a region (e.g., does it simply alleviate stress and thus reduce the likelihood of an imminent recurrence, or can an earthquake create distortions in the regional stress field that set off nearby followers)?

The advent of faster, more powerful computers has aided in understanding the processes by which crustal stresses lead to earthquakes at any given location. Using seismological data, researchers now model how fractures initiate and propagate as a result of mechanical properties (e.g., frictional strength) and stress changes at each point on the fault. In addition, three-dimensional models of ruptures along segmented faults are being developed to study what stops earthquakes and thereby to estimate their magnitudes.[43]

Another effort to understand what controls earthquake faulting involves laboratory studies of the physical properties of earth materials and physical conditions at the earthquake source, the interactions between rock and fluid in the fault, and nucleation and instability mechanisms.[44] The objective is to improve tools for interpreting observations of seismic and geodetic data in terms of earthquake processes and conditions at the source.

Paleoseismology

On most faults, the time between similar large earthquakes is much longer than the period over which modern instruments have observed earthquakes and geodetic changes. Even in regions where recorded history spans thousands of years, such as the eastern Mediterranean or north-central China, contemporary observers often could not correlate earthquakes with specific faults.[45] Thus our knowledge of how often faults can produce damaging earthquakes is very limited.

To learn whether or not earthquakes consistently rupture the same segment of a fault in the same way (i.e., act as a characteristic earthquake) or follow a regular time pattern, it is necessary to extend the modern record back long enough to encompass several similar earthquakes on the same fault. This need led to the development of paleoseismology, a relatively new field of earth science. Researchers seek and examine evidence of sudden coastal subsidence or uplift; fault displacement revealed by shallow excavations; and deposits related to liquefaction, tsunamis, or other seismically induced processes. In many cases, paleoseismic events can be dated by radiocarbon and other techniques, although typically not with as much precision as historical events.[46]

With funding from NEHRP, this type of data collection has accelerated in the past 15 years. Paleoseismology has been particularly useful in as-

[43] Ruth Harris, U.S. Geological Survey, Menlo Park, personal communication, Nov. 4, 1994.

[44] James Dieterich, U.S. Geological Survey, Menlo Park, personal communication, Nov. 4, 1994.

[45] This section is drawn from Robert Yeats, Department of Geosciences, Oregon State University, personal communication, May 7, 1995.

[46] Kenneth A. Geottel, Goettel & Horner, Inc., personal communication, May 7, 1995.

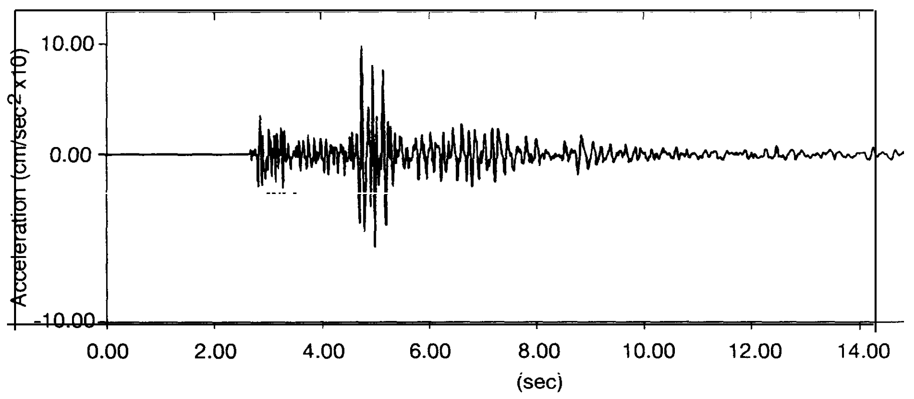
BOX 2-5: Seismic Monitoring

Seismic monitoring serves several purposes: it allows determination of the location of significant earthquakes in support of emergency response and public information; it enables nuclear test ban verification; and it supports research directed at improving basic understanding of tectonics and earthquake phenomena,

In the 19th century, knowledge of major seismicity was for the most part limited to earthquakes felt on the continents.[1] The installation and operation of seismometers in many countries, along with extensive cooperation in exchanging data, have since permitted knowledge and illustration of global patterns of seismicity, The 1960s witnessed the establishment of a global network of seismic stations (largely with nuclear monitoring in mind); at the same time, several regional seismic networks were established in the United States. As of 1994, there were more than 1,400 permanent seismographic stations maintained by regional networks [2]

Two primary classes of seismometers exist today: 1) 1960s-generation equipment that provides data in limited frequency and amplitude ranges, largely because of analog transmission constraints; and 2) new generation broadband, high-dynamic range instruments available since 1985. The advanced instruments and digital telemetry now enable improved representation of the phase and energy spectra of seismic waves, essential to ground motion and earthquake processes research. With constrained resources, however, there are tradeoffs between increasing the quality or the quantity of instruments Likewise, there is tension between providing funding for the operation and maintenance of stations and performing research with the available data.

Seismogram of Northridge Aftershock



NOTE: Vertical component of acceleration recorded in the San Fernando Valley from a magnitude 45 aftershock of the 1994 Northridge earthquake

SOURCE: U.S. Geological Survey, 1995.

[1] Bruce A. Bolt, *Inside the Earth" Evidence from Earthquakes* (San Francisco, CA W H Freeman and Co , 1982), p 54

[2] Council of National Seismic System, "CNSS Seismic Networks and Data Centers" internet address http://www. geophys.washington.edu/CNSS/cnss.sta.html, May 11, 1995 CNSS was begun at a meeting in Denver in February 1993 by representatives from most of the U.S. regional seismic networks and the National Seismic Network to help coordinate efforts to record and analyze seismic data in the United States As of spring 1995, 27 institutions had formally joined the council

(continued)

BOX 2-5 (cont'd.): Seismic Monitoring

National Seismic Network

In the late 1980s, the Nuclear Regulatory Commission decided to withdraw support for its networks, located primarily in eastern states, The U.S. Geological Survey proposed to establish the National Seismograph Network (NSN), a 150-station network of modern digital stations distributed throughout the country, to enable uniform monitoring of significant quakes and provide data for research into a variety of earthquake problems. To date, 23 NSN broadband seismic stations have been installed in the eastern United States, with nine more stations planned. In the western United States, 16 NSN broadband stations are operating, and seven more are planned. Installation of an additional 10 to 15 cooperative NSN stations is possible over the next few years for the continental United States.[3]

NSN is not intended to perform the monitoring and research functions of the existing regional networks, Rather, it leverages their capabilities with technology for recording broadband, high-dynamic range, three-component seismic data in real time and with low telemetry costs. In addition, NSN provides standardized data manipulation procedures and a communications network that interconnects regional networks[4]

[3]Harley Benz, U S Geological Survey, personal communication, May 11, 1995

[4]Thomas H. Heaton et al., "National Seismic System Science Plan, " U S Geological Survey Circular 1031 (Washington, DC: U.S. Government Printing Office, 1989), pp. 21-22

SOURCE Office of Technology Assessment, 1995

sessing earthquake potential in regions that have not been struck by a major earthquake during recorded history, such as the Salt Lake City metropolitan corridor, the San Andreas fault in southeastern California, and the Cascadia subduction zone in the Pacific Northwest. It has also helped to reduce uncertainty about the frequency of major quakes in the central United States, and to enhance knowledge of historic earthquakes in the San Francisco Bay area.[47]

Earthquake Forecasting and Prediction

A longstanding objective of efforts to understand basic geological and seismological processes is a reliable means of predicting earthquakes.[48] The simplest model of the earthquake cycle is that strain accumulates, is released in an earthquake, and accumulates again—initiating another cycle. The average length of the cycle for a certain type of quake at a given location is called the recurrence interval, which is used to roughly estimate the time of the next earthquake. To determine this interval, scientists rely on seismic monitoring and paleoseismology to obtain relationships for magnitude and recurrence.

Historical seismicity and paleoseismology show, however, that there is great variability in the timing, location, and magnitude of earthquakes. The variations in earthquake characteristics on a single fault segment or the clustering of several

[47]In spite of the fact that *paleo* means ancient, paleoseismologists study both prehistoric and historical earthquakes-in areas having short historic records, there may be only one example of an earthquake on a given fault. Carol Prentice and Andrew Michael, U.S. Geological Survey, Menlo Park, personal communications, June 5, 1995.

[48]This report distinguishes between forecasting and prediction as follows: the former refers to estimates of earthquake potential or timing over a period of many decades; the latter encompasses estimates of earthquake occurrence on shorter time scales (e.g., imminent—a few seconds or minutes; short-term-several minutes to days or weeks; and intermediate-term-up to several years).

TABLE 2-4: Comparable Seismic Zones

U.S. region	International counterpart
New Madrid Seismic Zone and eastern United States	Australia, peninsular India
California	New Zealand, northeastern Iran, Mongolia, Turkey, Venezuela
Intermountain West	North-central China, Aegean region of Greece and western Turkey
Pacific Northwest	Southwest Japan, southern Chile

SOURCE Robert Yeats, Department of Geosciences, Oregon State University, personal communication, May 7, 1995

earthquakes in time indicate that the simple model is not sufficient for many applications. Some areas exhibit greater variability than others; typically, these are regions of more complex geology and plate interaction. Several U.S. metropolitan centers are located in such regions (e.g., Los Angeles, San Francisco, and cities in the Pacific Northwest).

To improve on the simple earthquake model requires a better understanding of the processes through which tectonic stress leads to individual earthquakes. This entails developing models of earthquake generation and relating these models to things we can observe in the earth (some of which may turn out to be earthquake precursors). Therefore, current efforts at earthquake prediction combine historical seismological and paleoseismological data with models of earthquake generation, and correlate the results with measurements of geophysical phenomena.

Forecasts

In a few regions of the country, scientists have gathered enough data to permit long-term earthquake forecasts; these are often expressed as the probability that a certain size earthquake will occur within the next few decades, either for a single fault (e.g., the southern San Andreas or Wasatch) or for a region with several hazardous faults (e.g., the San Francisco Bay area).[49] Such probabilistic assessments have been important in analyzing a region's seismic hazard, and directly support land-use planning and building code development.[50]

Because individual earthquakes repeat so infrequently and because there is variability between events, these forecasts are subject to considerable uncertainty. We can develop and test improved models more rapidly if we also look outside the United States for data, especially to other parts of the world that have similar geologic settings and have had large historical earthquakes. Table 2-4 lists these areas and their international counterparts.

Prediction

In theory, prediction could stem from improvements to the probabilistic forecasting method—that is, through reducing uncertainties in the assessment of earthquake characteristics and timing to permit more precise estimates. But variability in earthquake events is not the only source of uncertainty; the probabilistic method is also hampered in areas where quakes are very infrequent or have poor surface expression, and where geophysical and geodetic data are sparse. Intraplate quakes, in particular, tend to have very long recur-

[49] A probabilistic forecasting model, for example, incorporates the regional stress field, rate of crustal deformation in the vicinity Of the fault, and strain accumulation with seismologic and geologic data.

[50] Estimates of earthquake potential are also used in deterministic assessments of seismic hazards (i.e., the calculation of strong ground motions for a specific earthquake scenario and site); these are frequently used in building design and the construction of seismically resistant structures.

rence times (e.g., thousands of years), and few have surface expression.

Thus earthquake prediction may hinge on interpreting certain warning signs rather than enhancing current models of the seismic cycle. As a first step, it is essential to verify whether or not such signs exist. Box 2-6 discusses research questions related to earthquake prediction.

Foretelling Earthquake Effects

In addition to determining earthquake potential, an equally important task for the earth science community is to give planners and engineers precise information on what earthquakes will actually do to the earth's surface that threatens the built environment. Earth science R&D with more immediate application to mitigation has historically been overshadowed by the basic research disciplines, but is now receiving increased emphasis (a breakdown of funding levels is given in appendix B). This applied research is of great importance for two reasons.

First, because earthquake effects on the earth's surface are complex, improving the seismic resistance of lifelines, buildings, and their contents requires detailed knowledge of the physical forces they will encounter. Second, the initial expenses of some mitigation measures are such that at-risk communities may have difficulty implementing them. The use of broad-brush, regionwide mitigation measures is often constrained by political and economic concerns (see chapter 4). Research that can identify locations of extreme danger and areas of relative safety can thus allow communities to target limited resources to where they will do most good.

This work includes the fields of strong-motion studies and seismic zonation (and its subset, microzonation).[51] Its objective is to examine—and quantify where possible—how seismic waves interact with particular aspects of local geology and geography to produce potentially damaging effects, including ground shaking, soil amplification, liquefaction, and tsunamis. The following discussion explains related studies and their applications in more detail.

General Ground Shaking

To design buildings and other structures that resist seismic damage, the engineering community requires quantitative estimates of the accelerations, velocities, and displacements that will occur in future earthquakes. Producing such estimates requires knowledge of:

- future earthquake magnitude;
- the location, orientation, and size of the likely earthquake fault;
- the attenuation characteristics of geologic material lying between the earthquake location and the area of concern (to determine how rapidly seismic waves decay with distance from the epicenter); and
- the general soil characteristics of the region.

This work is partly theoretical and partly empirical; it typically involves the correlation of laboratory predictions with data recovered from strong-motion seismometers in real-world earthquakes[52] (see box 2-7). Useful data can also be obtained by temporary regional-scale seismic networks deployed in an earthquake's aftermath to record the effects of aftershocks.

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[51] *Strong-motion studies* focus on the shaking effects that seismic waves impose on the earth's surface, while *zonation* is a broader field that incorporates such indirect earthquake hazards as landslides and tsunamis, as well. *Microzonation* is hazard assessment on the scale of a town or city block.

[52] Strong-motion devices differ from traditional seismometers in that they can record the strong, violent ground motions from a nearby earthquake without failing or going off-scale (traditional observatory-grade seismometers are sensitive instruments designed to detect the faint tremors from distant seismic events and cannot handle strong shocks). Gathering strong-motion data has thus historically meant the deployment of specialized instruments for the task. However, recent technical developments have allowed some modern seismometers to function both as strong-motion instruments and as observatory devices, and they are increasingly used in many of the newest seismic networks.

BOX 2-6: Earthquake Prediction

To date, programs directed at predicting earthquakes have had mixed success, The central questions include: 1) are there specific physical conditions that Indicate the location, timing, and size of future earthquakes; 2) are current research programs adequately designed to capture and permit assessment of potential precursors?

- **Is there a recognizable pattern to earthquakes?**

Through statistical analysts of worldwide earthquake occurrences, one can estimate the frequency of different magnitude quakes across the globe. The monitoring of global seismicity also makes it clear that certain areas are much more prone to quakes than others—90 percent of the world's earthquakes occur on the boundaries of large tectonic plates

Along a single plate boundary, however, there can be considerable variability in the size and frequency of significant earthquakes. For example, parts of the San Andreas fault accommodate the relative motion of the North American and Pacific Plates without earthquakes (i.e., through aseismic slip); other sections of the fault have experienced several large or major quakes during recorded history. In general, intraplate earthquake sources and processes are even less well known Thus, a better understanding of the relationships among plate tectonics, regional stresses, and earthquake sources is needed.

- **Is an earthquake's size "known" at the time of its initiation?**

Scientists are making progress in understanding earthquake genesis and growth, although there IS not yet consensus on whether the eventual magnitude of the quake is random or somehow programmed into the surrounding rock, Recent observations of earthquake sources using advanced seismographic instruments, however, show that earthquakes Initiate with a distinctive seismic nucleation phase and that the size and duration of the nucleation phase appear to scale with the eventual size of the earthquake. ' These new and somewhat controversial results suggest that conditions favoring the growth of large, potentially destructive earthquakes are fundamentally different from those that lead to more common, smaller events, If so, careful geologic and geophysical monitoring might someday detect the conditions that signal the imminent risk of a large earthquake.

Local geology (and topography) may also have a role in whether larger, less frequent quakes (or smaller, more frequent ones) are to be expected on a fault [2] Advanced models of rupture propagation, additional geophysical data, and additional seismological data from newer broadband, high-dynamic range instruments will likely aid in understanding how surficial and subsurface fault characteristics affect rupture and maximum magnitude.

- **Does the state of stress that causes an earthquake to initiate and a fault to rupture betray itself through characteristic signals?**

The standard approach to developing a prediction capability hinges on the earth's providing recognizable signals of impending quakes. Ideally, much as we have come to associate certain symptoms with the onset of a cold, scientists could detect reliable Indicators of an earthquake's occurrence in advance of the event itself.

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1 W L Ellsworth and G C Beroza, "Seismic Evidence for an Earthquake Nucleation Phase, " Science, VOI 268, 1995, p 851

2 Scientists look for the presence of rough patches in the fault (asperities) through analysis of seismograms, physical separation (e.g., step-overs) between fault segments, or other geologic barriers to the spread of the rupture zone

(continued)

BOX 2-6 (cont'd.): Earthquake Prediction

Theoretical and laboratory studies indicate there should be a preliminary phase prior to rupture. Potential earthquake precursors include: foreshocks (as material starts to fail under the extreme stress or strain), changes in the groundwater table (these occur when water-bearing pores in the rock start to deform under the stress) and other hydrologic or hydrothermal phenomena, deformation of the earth's surface, changes in the rock's electrical conductivity or magnetic properties, and changes in seismic wave properties through the area in question. In the past, such phenomena have been observed in the field, but not consistently.[3]

Broad efforts to Identify potential precursors are being pursued in China, Japan, and the former Soviet Union through extensive monitoring of seismicity, crustal deformation, and a variety of other phenomena. Chinese scientists were able to predict the 1975 M7.4 quake in Haicheng and the August 1976 M7.2 Songpan earthquake.[4] However, they were unable to predict the July 1976 Tangshan earthquake (M7.8), which killed hundreds of thousands. In Japan, public warning was achieved for the 1978 Izu-Oshima earthquake (M7).[5] Japan's monitoring and prediction program focuses primarily on the region surrounding Tokyo, which has the highest seismic risk. The Kobe locale, assigned a very low hazard, received little prediction attention.

It is important to note that Japan's monitoring program is directed at subduction zone earthquakes and may not be applicable to the strike-slip boundary on the U.S. West Coast.[6]

Earthquake Prediction in the United States

The first U.S. effort directed at earthquake prediction was located near the central California town of Parkfield, adjacent to the San Andreas fault. The Parkfield prediction experiment was begun in 1985 after analysis of previous earthquake occurrences on a particular fault section indicated that a repeat event would occur near the end of the decade.[7] The expected "characteristic earthquake" did not happen within the prediction window.

Further analysis showed that, while the successive repeat of similar (but not identical) quakes might be expected on individual fault sections, the amount of time between them may be highly variable Confidence in predictions based on estimations of recurrence intervals has decreased; scientists are more sanguine about the possibility of identifying one or more of the "red flags" described above.[8]

Today, the Parkfield experiment operates 21 instrument networks to record pre-earthquake phenomena (e.g. strain transients, electromagnetic signals); five of these networks are monitored in real time Ten additional networks are in place to record strong ground motion, co-seismic slip, and liquefaction [9]

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[3] Paul Silver, Department of Terrestrial Magnetism, Carnegie Institution, personal communication, Apr 5, 1994

[4] Cinna Lomnitz, *Fundamentals of Earthquake Prediction (New* York, NY: John Wiley & Sons, Inc., 1994), pp. 22, 29-30 Some argue that the Haicheng quake was easy to predict because there were many foreshocks the day before the main shock

[5] Evelyn Roeloffs and John Langbein, "The Earthquake Prediction Experiment at Parkfield, California, " AGU *Reviews of Geophysics,* vol. 32, No 3, August 1994, p 315

[6] The Japanese program has also been the subject of much criticism for its expense, lack of openness, and lack Of results. See, e g , Robert J Geller, "Shake-up for Earthquake Prediction, " *Nature, vol. 352, No. 6333,* July 25, 1991, pp. 275-276

[7] Parkfield has experienced moderate quakes six times since 1857. In 1985, on the basis of this sequence, the recurrence interval for M6 quakes near Parkfield was estimated to be about 22 years, and it was estimated with 95 percent confidence that another similar event would occur before 1993 Roeloffs and Langbein, see footnote 5, p. 315, citing W.H. Bakun and A G Lindh, "The Parkfield, California, Earthquake Prediction Experiment, " *Scier_rce,* vol. 229, 1985, pp. 619-624.

[8] Silver, see footnote 3

[9] Roeloffs and Langbein, see footnote 5.

BOX 2-6 (cont'd.): Earthquake Predic

Assessing Prediction Feasibility

For prediction to be feasible, however, scientists must be able not only to recognize the red flags, but also to determine the relationship between these precursors and succeeding earthquakes. In addition, the red flags must have some predictive power; that is, there must be a sound correlation between their occurrence and the subsequent occurrence of significant earthquakes.[10]

According to some scientists, while the current monitoring program at Parkfield may yield useful data for that specific spot, it is not comprehensive enough to verify whether or not prediction is feasible. Instead, they advocate a more extensive program to monitor multiple types of potential precursors throughout the San Andreas fault zone. New observation techniques (e. g., space-based geodetic surveys and Imagery of crustal deformation) could provide the necessary broad coverage and complement in situ monitoring and fault studies.

Given the complexity of such an undertaking, as well as the relative infrequency of damaging U.S. earthquakes, results from this effort might not be expected for another few decades.

10 silver, see footnote 3

SOURCE Off Ice of Technology Assessment, 1995.

Early Warning

Advances in seismometers and telecommunications, along with automated analysis of earthquake events, may soon permit early warning of seismic waves capable of producing strong ground motion. Because electronically transmitted information travels at a much faster rate than seismic waves travel through the earth, realtime warning of severe shaking approaching a populated area or lifelines will be possible given monitoring systems that can automatically determine a quake's location and magnitude and estimate the strong-motion characteristics within a few seconds.[53] Early warning systems hold the potential for automated response during an earthquake and more rapid, effective response after the shaking stops.

Amplification Effects

Engineers and planners within specific communities also must be aware of the possibility of localized, unusually high amounts of ground shaking. These "hot spots" can result from simple soil amplification, in which the presence of soft soils and sediments at the earth's surface significantly increases the amplitude of passing seismic waves (see figure 2-8).

The collection of ground motion records from recent large California quakes and their aftershocks, as well as from recent events in Mexico and Japan, has aided in understanding site effects in these areas.[54] However, records for other areas of the United States are very limited. In addition, significant geotechnical modeling is still needed

53 Post-earthquake notification systems have been operating in southern California since 1991 and in northern California since 1993. System operators expect to achieve early warning capabilities within a few years.

54 Stephen Hartzell, U.S. Geological Survey, Earthquake and Landslide Hazards Branch, personal communication, Oct. 20, 1994.

BOX 2-7: Strong Motion Record

Beside the seismometer, another essential tool for defining the impact of a quake is the strong-motion accelerograph, typically housed in or near buildings, dams, and other critical engineered structures. *Strong motion* is used to mean ground motions that are sufficiently large to cause damage to structures; a strong-motion accelerograph is intended to record these large motions without signal saturation. The data generally are used for engineering purposes and, until recently, the instruments were usually triggered only by events of a minimum magnitude (e.g., M4.5 for local events or higher for distant quakes).

The development of regional seismographic networks began in the 1960s in response to the need to learn more about the distribution of seismicity with areas of recognized earthquake hazards. Because the primary objective of their implementation was the construction of a catalog of earthquake activity with high spatial resolution, the seismometers were adjusted to record smaller, more numerous earthquakes. This, combined with the use of analog data telemetry to meet high sample rate requirements and an emphasis on high-frequency ground motions, limited the effective dynamic range of the monitoring networks. As a result, the recording of strong ground motions was largely sacrificed.

Now, digital strong-motion instruments are being Integrated into seismic observatories that record both weak and strong ground motions.

The majority of strong-motion networks are located in the western states; with these instruments, scientists and earthquake engineers have obtained a fairly extensive strong-motion data set for the southwestern United States. Few records exist for other parts of the country and, more importantly, there are no near-field records from damaging quakes in U.S. urban centers. This means that scientists and engineers still lack empirical knowledge of the effects of earthquakes that occur directly beneath densely populated areas. [1]

[1] The 1994 Northridge quake occurred in a largely suburban area, and its largest motions were focused toward less populated areas The ground motions in downtown Los Angeles produced by a quake on the buried Elysian Park thrust fault, for example, would likely be much larger than those experienced above the source of the Northridge quake Likewise, the 1989 Loma Prieta quake occurred several miles from heavily populated centers in the San Francisco Bay area.

SOURCE: Office of Technology Assessment, 1995, based on Thomas H. Heaton et al , "National Seismic System Science Plan," U S Geological Survey Circular 1031 (Washington, DC: U.S. Government Printing Office, 1989)

to address several facets of site response, including soil properties, stratigraphy, and ground motions that occur in the immediate vicinity of a fault.[55]

Other factors in unusual ground shaking are: 1) basin effects, in which sedimentary basins (large, bowl-shaped deposits of river or lake-borne sands, soils, and clays, on which most of the country's urban centers are built) trap, accumulate, and amplify passing seismic waves (see box 2-8); and 2) ridge effects, in which topographic features such as hills and valleys can focus seismic waves together in the manner of a lens.[56]

[55] Examples are: nonlinear response of soft, weak soils; deep basin response; deep cohesive sites and shallow, stiff soils; two- and three-dimensional topographic and stratigraphic effects; and near-field motions and spatial incoherence. Ray Seed, Earthquake Engineering Research Center, University of California, Berkeley, personal communication, Nov. 3, 1994.

[56] Amplification and basin effects were largely responsible for the unusual amount of devastation wrought in the Mexico City earthquake of 1985, as well as for damage to the Marina District of San Francisco in the 1989 Loma Prieta quake. Ridge effects in the Loma Prieta event are thought to have been responsible for vertical accelerations in excess of 1 g in certain severely damaged neighborhoods.

Predicting amplification effects is in theory straightforward, since the scientific principles involved are well understood. However, accurate estimates require detailed knowledge of local geology (which typically demands a special effort), as well as specific predictions of the future earthquake's source characteristics (i.e., fault rupture characteristics and the consequent nature of the initial seismic waves).

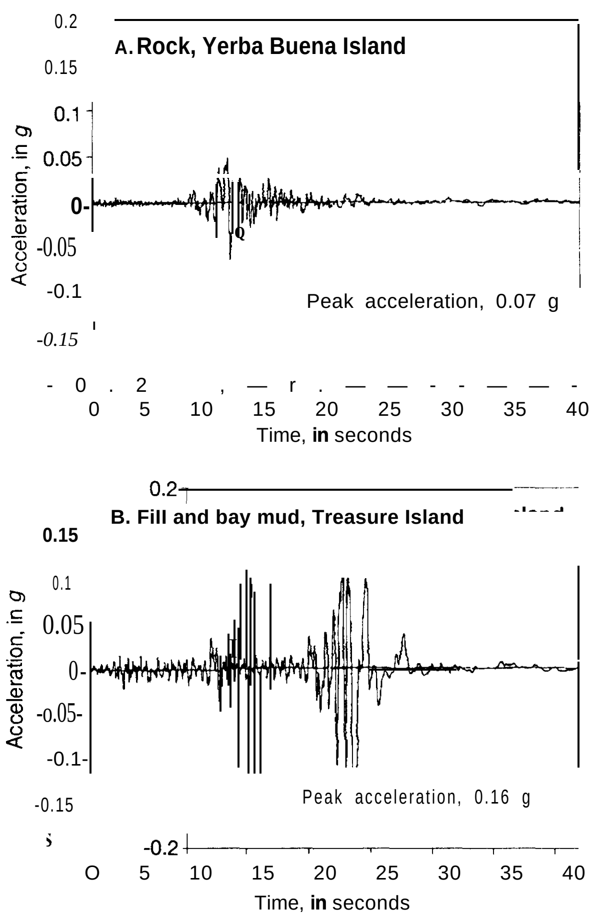
Ground *Failure*

Combining knowledge of the potential for strong shaking and of local geology and soil conditions yields an improved capability to identify the potential for liquefaction, landslides, and other forms of ground failure. When water-saturated soils and sediments turn into a quicksand-like slurry during extended shaking, they lose the ability to bear loads, thus causing even seismically resistant buildings and structures to fail at the foundation. Lateral spreading or permanent ground displacement also can cause great damage to buried utilities or port facilities. These phenomena are of particular concern to planners and local policymakers, because sites prone to such failure may require extraordinary preventive measures or relegation to less vulnerable forms of land use.

Geographical Information System (GIS) tools have been increasingly utilized in assessing these hazards and in analyzing related risks to special facilities or structures. Primarily a research tool today with respect to earthquake hazards, GIS-based maps can be readily converted to a larger educational-or policy—tool as well.[57]

In addition, systems have been proposed for both northern and southern California that will incorporate knowledge of a quake's location, size, and faulting mechanism into preexisting databases on shallow soil structure and the built environment.[58] Their objective is to quickly map the zones with most severe ground motion, which will indicate where emergency managers should look for the most damage and should direct response teams.

FIGURE 2-8: Effects of Local Geological Conditions on Ground Motion



NOTE" Recorded horizontal ground motion (east-west direction) from the 1989 M7.1 Loma Prieta earthquake,

SOURCE: U.S. Geological Survey, 1995

Tsunamis and Seiches

In addition to knowledge of the hazardous effects described above, coastal communities also require warnings of the possibility of tsunamis and

57 Arthur C. Tarr, U.S. Geological Survey, Earthquake and Landslide Hazards Branch, personal communication, Oct. 21, 1994.

58 Barbara Romanowicz, Seismic Research Center, University of California, Berkeley, personal communication, Nov. 3, 1994.

BOX 2-8: Basin Effects

Most of the large urban areas in the United States have developed on sediment-filled basins, which can strongly modify the ground motion from an earthquake.[1] It is believed that the shape and material properties of a sedimentary basin allow it to focus and collect seismic waves.[2] The result is large-amplitude surface waves that reverberate long after the rupture itself has ceased. Until recently, however, models of the earth's structure and wave propagation could not represent these conditions.

Under NEHRP, the U.S. Geological Survey is applying new three-dimensional modeling techniques to the case of complex propagation effects for the San Bernardino Valley east of Los Angeles, through which the San Andreas fault passes. The simulated effects include high ground velocities in localized portions of the basin, which could pose significant risk to structures with natural periods of one second or longer (e.g., buildings of 10 or more stories, some highway overpasses, and elevated pipelines).[3] Similar studies are under way for the San Francisco Bay area and Washington State's Puget Sound region.

[1] Stephen Hartzell, U.S. Geological Survey, Earthquake and Landslide Hazards branch, personal communication, Oct 20, 1994

[2] Thomas H, Heaton and Stephen H. Hartzell, "Earthquake Ground Motions," *Annual Review of Earth Plantary Science,* vol. **16, 1988,** p. 127, citing J A. Rial, "Caustics and Focusing Produced by Sedimentary Basins, Applications of Catastrophe Theory to Earthquake Seismology," *Geophysical Journal of the Royal Astronomical Society, vol.* 79, 1984, pp 923-38.

[3] Arthur Frankel, "Three-Dimensional Simulations of Ground Motions in the San Bernardino Valley, California, for Hypothetical Earthquakes on the San Andreas Fault," *Bulletin of the Seismological Society of America, vol. 83, No.* 4, August 1993, p 1021

SOURCE. Off Ice of Technology Assessment, 1995.

seiches. Research into these hazards-which seeks to understand why they are generated by some earthquakes and not others—blends the scientific fields of seismology and oceanography. Such research has a considerable international component (although tsunamis and seiches do take place in the United States, considerably more experience has been gained by Japan and other countries of the far Pacific Rim) and is frustrated by the unusual physical characteristics of the phenomena. Tsunamis, for example, exist in the open ocean as extremely fast, extremely broad, but extremely low waves that can pass beneath ships completely undetected.[59] Given these characteristics, specialized tsunami detection equipment is necessary both for research and for establishing early warning systems for coastal communities.[60] The National Oceanic and Atmospheric Administration operates the U.S. tsunami warning system.

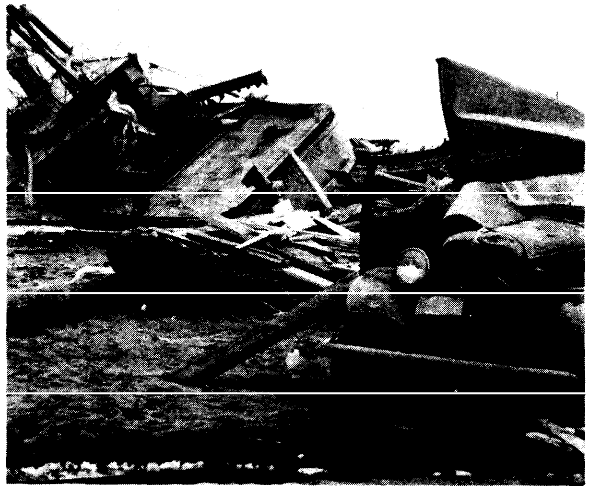
A common thread in all these applied research efforts is that they require collaboration between specialists in the traditional seismic research community and practitioners in other earth science and engineering disciplines. Moreover, the work cannot be accomplished purely through theory or lab-

[59] The danger of tsunamis is that, although extremely low in the open ocean (only inches high), they are long enough to contain a considerable amount of water (tsunami waves can stretch a hundred miles crest to crest), and fast enough to propel that water far inland. Speeds of hundreds of miles per hour are common. In a damaging tsunami strike, the incoming wave slows down as it approaches land. As it slows, the back of the wave catches up with the front, the wave height builds to many tens of feet, and the wave ultimately washes ashore as a huge surge of water.

[60] Because tsunami waves are so broad and low, their detection in the open ocean requires devices akin to tide gauges (i.e., instruments that can detect the passage of an open-ocean tsunami amid normal wind-driven waves).

oratory experiments; gathering detailed geologic information on each region or locality of interest requires a concerted effort.[61]

For example, the U.S. Geological Survey prepares maps of seismic hazards on national and regional scales, using a variety of data sources and modeling techniques (see figure 2-9). Maps of expected ground shaking are converted by the engineering community into design maps that reflect current engineering analyses; they form the foundation for model seismic codes. In addition, regional hazard maps support state and local land-use planning efforts, and can pinpoint areas where further study is warranted.


STEINBRUGGE COLLECTION, EARTHQUATE ENGINEERING RESEARCH CENTEI

Valdez, Alaska, waterfront after tsunami caused by 1964 Good Friday earthquake.

SUMMARY AND KEY FINDINGS

Earthquake hazards vary widely across the United States. The most active seismic regions in the United States are Alaska and California; their high seismic it y stems from proximity to the boundaries between shifting segments of the earth's crust. However, few parts of the United States are immune to quake hazards. Significant earthquakes have occurred in the Pacific Northwest, in the central United States, and along the east coast.

Earth science research, in which NEHRP has played a key role, has advanced significantly our understanding of U.S. seismic hazards. It is now possible to estimate the likelihood of future earthquakes for a few areas (the San Francisco Bay and greater Los Angeles areas, where many years of study have helped to reduce uncertainties; Utah's Wasatch fault zone; and the New Madrid Seismic Zone). In the near future, scientists maybe able to do the same for other regions of the United States.

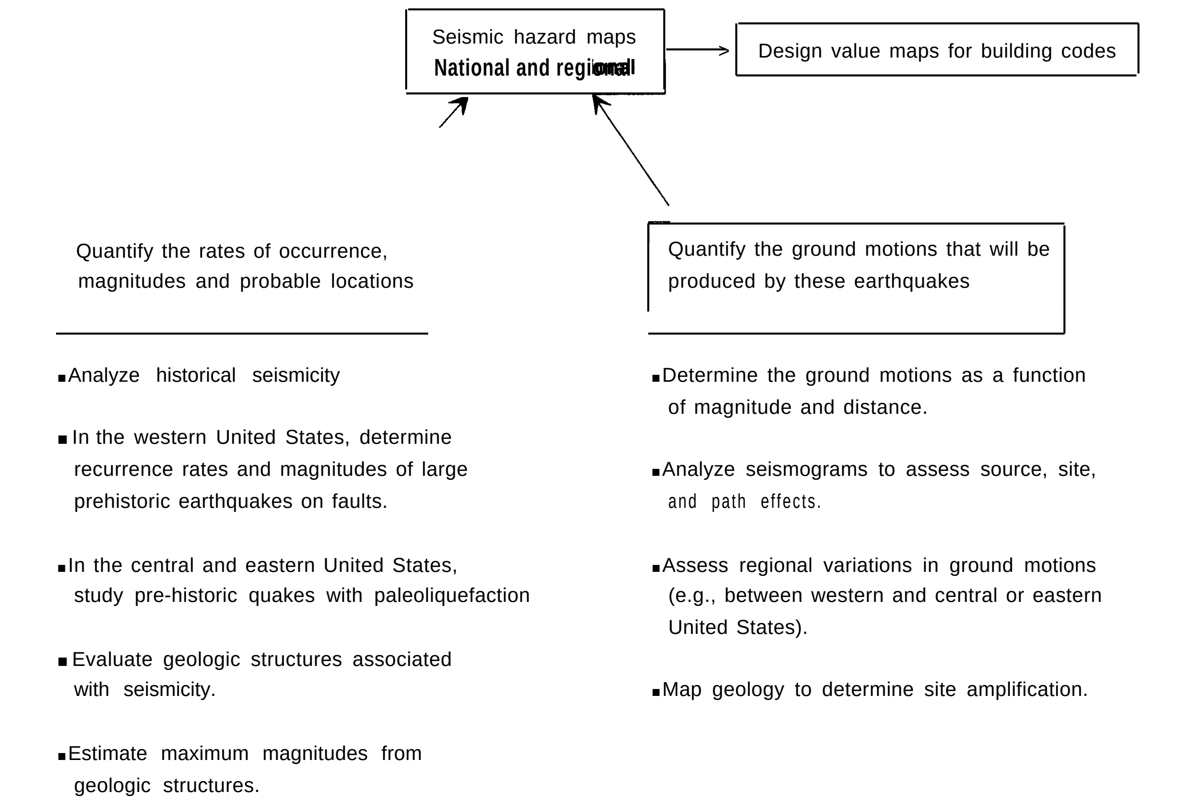
The importance of local soil conditions and other factors that influence the type and degree of damage an earthquake can cause (e.g., soil amplification and landslides) are now recognized and better understood. It is now possible to produce detailed maps showing specific hazards resulting from local soils, and provide more detailed and accurate expected ground motion information for use in building design and model code development. Within a few years, researchers expect to be able to provide real-time warnings of approaching strong shaking.

Despite the numerous advances, however, significant uncertainties and knowledge gaps remain. Scientists are far from able to determine the specific time, location, and magnitude of future earthquakes. Among the key unknowns are questions about the constitutive properties of faults, the interactions of different fault systems, and the mechanisms of rupture. Additionally, in many areas of the country, the location of faults capable of producing damaging earthquakes is still not known, nor is the likelihood of these earthquakes or the extent of their hazardous effects.

There are many societally useful directions for future earthquake-related earth science research. A key issue is how to strike the appropriate balance between types of research efforts and among different geographical areas, given both financial and time constraints. As with many research-in-

[61] The effort to gather such information (i.e., geologic and geophysical mapping) is often carried out for other purposes by USGS and by private concerns such as the petroleum and mineral exploration industries. The oil and mineral industries are very competitive; companies are often understandably hesitant to make data gathered at considerable expense available to competitors.

FIGURE 2-9: Seismic Hazard Map Development Process



SOURCE U S. Geological Survey, 1995.

tensive efforts, it is difficult to quantitatively assess the value of different activities; determining the balance between applied research directed at near-term results and longer term research is a political, not merely a scientific, challenge. Even within the earth science community, tension exists over how to divide resources between expanding the fundamental understanding of quake phenomena and concentrating on mapping hazardous site conditions in areas where damaging seismicity has already occurred.

Decisions on how to allocate earth science research funds should be made in the context of the goals of the earthquake program (discussed in chapter 1). However, several research areas clearly deserve attention:

- **Microzonation.** To better assess the overall risk posed to inhabitants and the built environment, analysis of the potential for strong shaking or ground failure is needed on finer scales. This requires not only the application of improved models of earthquake potential and expected shaking, but detailed mapping of near-surface geology and site conditions. Such microzonation studies have been completed in only a few areas of the United States. Thus, we have an incomplete picture of the probability of significant hazards near populated areas or critical facilities for all but the most intensely studied zones (i.e., the San Francisco Bay area and greater Los Angeles region). Additional emphasis should be placed on microzonation in urban areas and around critical facilities where long-duration, strong shaking is expected.

- **Earthquake potential.** New technologies and practices have enabled significant additions to the body of knowledge required to understand the potential for earthquakes in different areas. Paleoseismology permits more reliable estimates of the magnitude and dates of prior earthquakes, especially in areas where damaging earthquakes have very long recurrence times. This information is essential to gauging the likelihood of future damaging events within a decades-long time frame.
- Satellite-based geodetic techniques have revolutionized the observation and modeling of crustal deformation, which contributes to assessments of crustal stress and strain. This information supports long-term forecasts of earthquake potential. In addition, further enhancements to the scope and accuracy of these techniques could provide the foundation for new imaging methods that, akin to weather forecasting, facilitate reliable earthquake prediction.
- **Geographic focus.** Because of its frequent damaging earthquakes, California is the test bed for the development of many current theories and techniques. However, some of these may not be readily adapted to the Pacific Northwest or to the central and eastern United States. Additional research and data collection specific to these latter areas should be considered to determine what distinguishes the nature of the hazards and to support the application of existing tools.
- **International focus.** Fortunately for those who experience damaging earthquakes, the events are few and far between. This leaves the scientific community at a disadvantage, however, with respect to opportunities to incorporate data into the seismic record and evaluate theoretical models of seismic phenomena. Field investigations and analyses of data from earthquakes that occur outside our borders are crucial to understanding similar U.S. seismic hazards (e.g., subduction and intraplate quakes that have occurred here rarely).
- **Knowledge transfer.** It is essential to maintain efforts to make new knowledge and tools readily available to potential users. In recent years, the earth science research community and NEHRP research agencies have put increased emphasis on knowledge transfer to professionals and the general public. These efforts, although difficult to evaluate, are crucial to ensuring that research results help to accelerate the pace of earthquake mitigation throughout the country.

The Built Environment 3

Earthquake hazards exist throughout the United States. The primary hazard associated with earthquakes is ground shaking, which damages and destroys buildings, bridges, and other structures. Ground shaking also causes liquefaction, landslides, and other ground failures that also damage and destroy structures. This damage can cause massive immediate financial losses, casualties, disruptions in essential services such as water and electricity, and severe long-term economic and social losses. Although the location, timing, and magnitude of future earthquakes are uncertain, there is little doubt that potentially damaging earthquakes will strike U.S. metropolitan areas in the next few decades.

Although earthquakes are unavoidable, the losses they cause are not. This chapter reviews technologies and practices to reduce the societal losses[1] of earthquakes. The focus is on *the built environment*—the buildings, bridges, pipelines, and other structures that bear the brunt of earthquake damage. The chapter first discusses deaths and injuries from earthquakes, focusing on what causes them and how they can be reduced. This is followed by a discussion of buildings—how they are damaged by earthquakes, and what technologies and practices are available to increase the seismic resistance of both new and existing buildings. Technologies for reducing damage to lifelines, such as bridges, water and sewer systems, and energy systems, are then reviewed. Finally,

[1] *Damage* refers to the direct financial costs of earthquakes. *Losses* denotes all of the societal effects of earthquakes, including deaths, injuries, direct financial costs, indirect costs (e.g., those resulting from business interruptions), and social impacts such as increased homelessness. Reducing damage by strengthening the built environment will reduce losses as well.

TABLE 3-1: Major Earthquakes Worldwide, 1980-90

Yea	oca on	Magn ude	Dea hs
1980	Algeria	7.7	3,500
1980	Italy	7,2	3,000
1981	Iran	6.9	3,000
1981	Iran	7.3	1,500
1982	Yemen	6.0	2,800
1983	Japan	7.7	107
1983	Turkey	6.9	1,342
1985	Chile	7.8	177
1985	Mexico	7.9	9,500
1986	El Salvador	5.4	1,000
1987	Colombia, Ecuador	7.0	1,000
1988	Nepal, India	6.6	1,450
1988	Burma, China	7.0	730
1988	Armenia	7.0	25,000
1989	West Iran	5.8	90
1989	U.S.—California	7.0	63
1989	Australia	5.6	13
1990	Iran	7.7	40,000+
1990	Philippines	7.8	1,700
TOTAL			~96,000

SOURCE: Bruce A. Bolt, *Earthquakes (New* York, NY: W. H. Freeman and Co., 1993), pp. 272-273,

the chapter discusses key research needs for ensuring that the built environment is well protected from future earthquake damage.

CASUALTIES

Deaths

A single earthquake can cause thousands of deaths and tens of thousands of injuries. As shown in table 3-1, in just 11 years-1980 to 1990-earthquakes killed almost 100,000 people worldwide. About two-thirds of these deaths occurred in just two catastrophic earthquakes-25,000 in Armenia in 1988 and 40,000 in Iran in 1990.

The historical record of U.S. earthquake fatalities is less unfortunate. About 1,200 people have died in U.S. earthquakes since 1900 (table 3-2). Most of these earthquakes occurred in regions that were, at the time, sparsely populated; so the low fatality figures for 1900 to 1950 earthquakes are not surprising. However, even those earthquakes occurring since 1950 in heavily populated areas of California have had relatively low fatalities, largely because many of its buildings and other structures are built to resist seismic collapse.[2]

Casualties from future earthquakes are very uncertain. In California, most deaths from future earthquakes will likely be caused by the collapse of older, seismically vulnerable structures. One estimate found that a repeat of the 1906 San Francisco earthquake would cause 2,000 to 6,000 deaths.[3] In the Pacific Northwest and the eastern United States, the potential for large numbers of deaths may be higher than in California. Although the probability of a major earthquake is relatively low, the building stock is more vulnerable, as even new structures often do not use known technologies and practices to reduce seismic damage.[4] One study found that a large earthquake striking the New Madrid region of the central United States would cause 7,000 to 27,000 deaths.[5]

Deaths that occur in earthquakes are due largely to the collapse of structures. In Armenia, most of the deaths were caused by people being crushed under collapsing concrete buildings. All but one of the deaths in the Loma Prieta earthquake were

[2] There is an element of luck here as well. The Loma Prieta earthquake, for example, struck during the World Series baseball game when the roads were relatively empty. Fatalities would have been in the hundreds, perhaps higher, if traffic levels were at more typical weekday levels.

[3] See "'Repeat' Quakes May Cause Fewer Deaths, More Damage," Civil *Engineering,* November 1994, pp. 19-21.

[4] As noted in chapter 1, many states in lower risk areas do not have or do not enforce seismic building codes for new construction.

[5] National Academy of Sciences, *The Economic Consequences of a Catastrophic Earthquake,* Proceedings of a Forum, Aug. 1 and 2, 1990 (Washington DC: National Academy Press, 1992), p. 68.

TABLE 3-2: Major U.S. Earthquakes, 1900-94

Year	Location	Deaths	Damages (million $1994)
1906	San Francisco, California	700	6,000
1925	Santa Barbara, California	13	60
1933	Long Beach, California	120	540
1935	Helena, Montana	4	40
1940	Imperial Valley, California	8	70
1946	Aleutian Islands, Alaska	n/a	200
1949	Puget Sound, Washington	8	220
1952	Kern County, California	12	350
1952	Bakersfield, California	2	60
1959	Hebgen Lake, Montana	28	n/a
1964	Anchorage, Alaska	131	2,280
1965	Puget Sound, Washington	8	70
1971	San Fernando, California	65	1,700
1979	Imperial County, California	n/a	60
1983	Coalinga, California	0	50
1987	Whittier Narrows, California	8	450
1989	Loma Prieta, California	63	6,870
1992	Petrolia, California	0	70
1992	Landers, California	1	100
1993	Scotts Mills, Oregon	n/a	30
1993	Klamath Falls, Oregon	2	10
1994	Northridge, California	57	20,000
TOTAL		1,225	39,160

KEY: n/a = not available.

SOURCE: Office of Technology Assessment, 1995.

due to structural failure.[6] Other earthquakes generally show the same pattern: people are killed in earthquakes when structures collapse. The second major cause of death in earthquakes is fire. In the 1923 Tokyo earthquake, for example, many of the 143,000 deaths were caused by the firestorms that occurred after the earthquake.[7]

Further reductions in fatality levels will come largely from incorporating seismic design principles into new construction (this is not done in many areas of the United States), retrofitting existing structures to improve their seismic resistance, and ensuring adequate fire and emergency response.

Injuries

Earthquake-related injuries, in contrast to deaths, often result from nonstructural damage. Damages

[6] M. Durkin and C. Thiel, "Improving Measures To Reduce Earthquake Casualties," *Earthquake Spectra,* vol. 8, No. 1, February 1992, p. 98.

[7] Bruce A. Bolt, *Earthquakes* (New York, NY: W. H. Freeman and Co., 1993). PP. 2197271.

[8] This report uses *retrofitting* to mean adding seismic resistance features, such as bracing, to an existing building to reduce the damage if an earthquake occurs. Some reports use the term *rehabilitation* instead.

TABLE 3-3: Injuries from the Loma Prieta Earthquake, 1989

Source	Percent of Injuries
Hit by falling object	13
Hit by overturning object	11
Thrown into object	18
Fall-related injuries	27
Strained taking evasive action	7
Structural collapse	5
Other	19

SOURCE: M. Durkin and C. Thiel, "Improving Measures To Reduce Earthquake Casualties, " *Earthquake Spectra,* vol. 8, No. 1, February 1992, p 99.

can occur, and people in or near buildings can be injured, even when there is no structural failure. In Loma Prieta, for example, 95 percent of the injuries did not involve structural collapse (table 3-3). These injuries were caused by falls, being struck by falling or overturned objects, or being thrown into objects.

Some simple, low-cost measures that can reduce these injuries include anchoring bookcases to walls, using chains to secure books in bookcases, securing kitchen appliances to the floor, bolting computers to desks, and tying lights to ceilings.

DAMAGE TO BUILDINGS

When the ground moves in an earthquake, the basement and the first floor will move with it. The top floor, or in a multistory building the upper floors, however, tend to stay put because a building is not perfectly rigid. The movement of the bottom of the building relative to the top puts great stress on the walls. The stress and resulting damage vary depending on the building itself. A simple wood house on a concrete foundation maybe knocked off its foundation in an earth quake, because the foundation moves with the ground but the house is left behind. A three-story brick building can be turned into a pile of rubble because the bricks are not rigidly attached to each other; the walls collapse outward leaving the floor unsupported. A tall steel-framed building may show little or no damage, because steel bends and sways to absorb the movement of the lower floors.[9]

The most dramatic, widely feared, and best understood type of damage is *collapse* (also called structural failure)-destruction of an entire building by an earthquake, often killing most of its occupants. A second type of damage is *structural damage*— broken or twisted beams, failure of structural members, and other damages that leave a building standing but often unsafe. In some cases costs of repair approach those of replacement. *Nonstructural damage+ racks* in walls, broken water pipes, broken windows—is rarely life-threatening but is often dauntingly expensive to repair. A final type of damage is *contents damage*--computers sliding off desks, pictures knocked off the wall, dishes smashed, merchandise tossed off shelves in stores, and so on. A useful rule of thumb is that contents are typically worth about 50 percent of the cost of the building

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Earthquakes can severely damage buildings.

[9] However, the 1994 Nothridge earthquake resulted in unexpected damage to steel buildings, which is discussed later in this chapter.

TABLE 3-4: Expected Damage to New Buildings That Meet Seismic Codes

Magnitude 6.0-6.5	Magnitude 7.5-8.0	Damage (percent of buildings)			
Distance to fault (miles)		Minor only	Nonstructural	Structural	Collapse
30	50	10-40	1-5	<1	0
5	40	35-45	10-30	<5	<1
1	30	25-40	20-40	3-10	<2
—	3	5-25	40-70	10-30	<5

NOTE: These estimates are for new buildings that meet the 1991 Uniform Building Code; they do not apply to existing building stock.

SOURCE: Adapted from Earthquake Engineering Research Institute, "Expected Seismic Performance of Buildings," February 1994, p. 15.

itself.[10] Therefore, damage to contents, although rarely life-threatening, can be a significant expense and can cause many injuries as well.

After an earthquake, one typically finds many buildings with nonstructural damage and progressively fewer buildings with greater damage. The degree of damage tends to increase as one moves closer to the fault (see table 3-4).

The type and amount of building damage caused by an earthquake depend on several factors. Liquefaction, in which the soil loses its ability to support weight, can cause a building to sink or topple. Ground-shaking damage will vary depending on the magnitude and frequency of the shaking. In general, long, slow ground movement is more damaging to taller buildings because the ground movement is closer to the building's natural frequency. In contrast, short, rapid ground movements are generally more damaging to shorter buildings. The design and materials used in the building are important as well. Buildings with carefully designed bracing, reinforcements in concrete columns, tightly connected walls and floors, and other seismic design features can ride out even large earthquakes; but those designed without consideration of seismic forces are likely to be damaged. Finally, the material used in construction (e.g., unreinforced masonry, wood, and steel) has a strong influence on a building's response to an earthquake (see box 3-l).

New Construction

Incorporating seismic considerations into the design and construction of buildings is much less expensive than attempting to retrofit an existing structure. Furthermore, if new construction incorporates such features, eventually all buildings will have them as older buildings are demolished. This section reviews the state of the knowledge of designing new buildings to resist seismic forces. The principal tool that determines the seismic performance of new buildings—building codes—is discussed, and several promising new technologies are reviewed.

State of *the Knowledge*

Numerous technologies and practices for new construction can reduce dramatically the risk of structural failure. These range from relatively simple design features, such as avoiding the use of soft stories (i.e., large open spaces in the first

10 Risk Engineering, Inc., "Residential and Commercial Earthquake Losses in the U.S.," report prepared for the National Committee on Property Insurance, Boston MA, May 3, 1993, p. 2.

BOX 3-1: Building Materials and Earthquakes

Unreinforced Masonry

Among the most dangerous buidings in an earthquake are those built of unreinforced masonry (URM). These buildings are dangerous for two reasons 1) the floors and roof are often not strongly attached to the walls and therefore the walls tend to collapse outward in an earthquake, and 2) the walls are often not strong enough to absorb the shear forces experienced in an earthquake (masonry is very weak in tension, meaning it has little resistance to being pulled apart). A relatively mild earthquake can turn a URM building into a pile of rubble quite easily. URM is also one of the least expensive building techniques—leading to the unfortunate outcome that lower income groups are often hardest hit by earthquakes. URM buildings are dangerous both to occupants and to those nearby, who can be hit by falling masonry. For example, eight people were killed by falling bricks in the Loma Prieta earthquake, all were killed outside a URM building.1

Concrete and Reinforced Masonry

A second type of building—made with reinforced masonry (in which steel reinforcing bars are used for strengthening), concrete frames, or precast concrete—can be dangerous as well, although less so than those built from URM. Concrete frame buildings—typically built in the 1950s to 1970s—are often large, multistory commercial or office buildings. Even when these buildings have walls to absorb some of the stress of an earthquake (called shear walls), the frame itself can fail. Precast concrete is often used for single-story warehouse, light industrial, or commercial buildings. The concrete panels can simply fall away from the building in an earthquake, due to inadequate connections between roof, floors, and walls,

Wood

Wood is often used as a structural material in single-family residences. It is the preferred construction material for smaller buildings in high earthquake risk areas because, unlike concrete, it is flexible and can bend without breaking. In an earthquake, a wood frame building will typically sway and bend, but will not fail. It is rare for a wood frame building to suffer structural collapse in an earthquake. However, wood residences can be damaged, sometimes severely, by an earthquake. Unanchored wood houses sitting on concrete foundations can be knocked off their foundations, Short walls (called cripple walls) that provide support between the floor and the ground can tip, moving the house off the foundation and severing gas lines and utility wires. These dangers can be reduced at reasonable cost by, for example, bolting houses to foundations and bracing cripple walls.

[1] California Seismic Safety Commission, *The Commercial Property Owner's Guide to EQ Safety, SSC 93-01* (Sacramento, CA January 1993), p, 8,

floor) in apartment buildings, to the use of complex computer models to assist in the design and location of structural members in a large office building. Although considerable uncertainties exist in building performance under seismic stress, [11] it is generally agreed that **the knowledge exists to** design and construct buildings that are unlikely to collapse in an earthquake. Years of research have yielded a knowledge base that, *if applied properly,* would result in buildings that are unlikely to collapse in an earthquake. However such knowledge may not always be applied

[11] Examples include the steel weld issue (see box 3-1), and recent modeling suggesting that large buildings maybe vulnerable to collapse from large ground motions. T. Heaton et al., "Response of a High-Rise and Base-Isolated Buildings to a Hypothetical Mw 7.0 Blind Thrust Earthquake," Science, vol. 267, Jan. 13, 1995, pp. 206-211.

BOX 3-1 (cont'd.): Building Materials and Earthquakes

Steel

Steel has long been considered the ideal material for large buildings in high earthquake risk areas. It is extremely strong, durable, flexible, and ductile (i.e., it will bend slowly, rather than snap, if overstressed). A steel-framed building is very unlikely to fail structurally from ground shaking in an earthquake. However, faith in steel as a structurally sound material was shaken by the 1994 Northridge earthquake. In this quake, more than 100 steel-framed buildings—including some under construction—exhibited a severe and costly vulnerability not seen before: the steel beams themselves cracked at or near where they were welded to steel columns. Although none of these buildings collapsed, repair will be very expensive. Furthermore, these buildings were built to modern design standards. Presumably if they are rebuilt to these standards they will be susceptible to the same damage if they are subjected to the same shaking forces. This unexpected vulnerability has international Implications because large buildings all over the world are similarly built, and are presumably just as vulnerable to this type of damage.

What has become known as the steel-weld problem refers, in most cases, to cracks in steel supporting members at or near welds that joined horizontal beams and vertical columns. In tall buildings, these beams and columns are the backbone of the building. The discovery of cracks in these members usually leads to immediate evacuation due to fear of structural collapse. This problem was discovered in a few buildings in routine post-earthquake inspections; as awareness of the problem spread, cracks were found in more than 100 buildings. Since these cracks were in most cases found only by tearing down walls or other covering material, many were not discovered until inspectors went looking for them.

There is as yet little agreement on why these failures occurred. Fears of financial liability have made all parties sensitive to placing or accepting responsibility. Among the possible reasons raised are poor welding quality, poor steel quality, improperly designed connections, and inherent limitations of the beam-column design.

The first proposed technical fix was to reinforce the welds; however, tests of these reinforced welds showed that they too would fail in a major earthquake.[2] A second reinforcing method appears to perform better in preliminary testing, but costs three times as much as a standard connection.[3] Efforts to find effective and affordable solutions are continuing.

[2] "Weld Test Failures Shock L.A,," *Engineering News-Record,* June 13, 1994, p 9.
[3] "Test Results Kick Off More Debate on Steel, " *Engineering News-Record,* Sept 19, 1994, p. 8

properly because of lack of training, costs, and other reasons (these issues are discussed in chapter 4).

There are numerous examples of the ability to build structures that can resist seismic collapse. In the 1989 Loma Prieta earthquake, "well-designed and well-constructed buildings performed well."[12] In the 1994 Northridge earthquake, damage was most severe in older and poorly engineered buildings.[13] The 1995 earthquake in Kobe, Japan,[14] also suggests that current designs can yield build-

[12] National Research Council, *Practical Lessons from the Loma Prieta Earthquake* (Washington DC: National Academy Press, 1994), p. 70.

[13] J.D. Goltz (ed.), National Center for Earthquake Engineering Research, "The Northridge, California Earthquake of January 17, 1994: General Reconnaissance Report," Technical Report NCEER-94-0005, Mar. 11, 1994, p. 3-19.

[14] This earthquake is sometimes called the Hyogo-Ken Nanbu earthquake to denote the three regions involved.

ings unlikely to collapse. Although the earthquake caused massive losses and more than 5,000 deaths, new structures reflecting current building codes performed quite well.[15]

Our knowledge and implementation of technologies and practices to reduce *nonstructural* and contents damage is poor. Very little research has been done in these areas, and building codes are for the most part directed at protecting life safety by avoiding structural damage.[16] An analysis of residential insurance claims from recent California earthquakes found little correlation between the age of a building and the claim amount: newer buildings, although much less likely to collapse, were just as vulnerable to nonstructural damage.[17]

Building Codes

The knowledge of how to construct new buildings to avoid structural failure is laid out in building codes—detailed documents that summarize consensus design principles. Building codes are the most important policy lever for incorporating seismic considerations into new buildings; some of their key features and constraints are summarized here. A detailed discussion of building codes may be found in chapter 4.

In the United States, the local political jurisdiction typically regulates the design and construction of new buildings through the use of building codes. These codes are intended to ensure the health and safety of occupants. The codes typically set requirements for structural soundness, fire safety, electrical safety, and in some areas, seismic resistance as well. Most local building codes are based on model codes. The three national model codes are: the Uniform Building Code, which has been adopted in part by much of the western United States; the Building Officials and Code Administrators code, generally used in the northeast United States; and the Southern Building Code Congress International, adopted in the southeastern United States. The seismic provisions of these three model codes are based in part on what is known as the NEHRP (National Earthquake Hazards Reduction Program) Provisions.[18] These NEHRP Provisions are produced by an independent organization (the Building Seismic Safety Council) with NEHRP funding.

Codes have strengths and weaknesses that should be recognized. First, building codes are consensus documents. They are the results of negotiation and discussion among interested parties, and they reflect a balance of safety, first-cost, performance uncertainty, and other concerns. Second, codes are intended to provide a minimum, not an optimal, performance level. Although codes are unfortunately often taken as prescriptive, they are intended to define a minimum acceptable level of safety. Third, codes are technologically conservative. The process for updating and modifying codes is complex and time consuming. The result is that new technologies and practices can take years to make it into the model codes. From there, many more years are often necessary before a new model code is adopted by localities. Fourth, codes are intended primarily to prevent structural collapse. They have few requirements for nonstructural damage

[15] See, e.g., National Science Foundation, “Modern Buildings Fared Well in Kobe Quake, According to Preliminary Report,” press release, Feb. 23, 1995; and “Kobe High-Rise Rebuilding on Hold,” *Engineering News-Record*, Feb. 20, 1995, p. 12. This second reference reports on a post-earthquake survey in Kobe that found more than one-third of pre-1971 buildings were unsafe, while only 6 percent of buildings meeting current codes were unsafe.

[16] “The primary intent (of the Uniform Building Code seismic provisions) is to protect the life safety of building occupants and the general public.” Earthquake Engineering Research Institute, *Expected Seismic Performance of Buildings* (Oakland, CA: February 1994), p. 6.

[17] Confidential insurance industry data.

[18] “Two Model Codes Stiffen Protection,” *Engineering News-Record*, Jan. 6, 1992, p. 7.

TABLE 3-5: Costs of Seismic-Resistant Features in New Buildings

Building type	Number of cases	Estimated change in construction costs (percent)
Low-rise residential	9	0.7
High-rise residential	12	3.3
Office	21	1.3
Industrial	7	0.5
Commercial	3	1.7
Average	—	**1.6**

SOURCE: S Weber, National Institute of Standards and Technology, "Cost Impact of the NEHRP Recommended Provisions on the Design and Construction of Buildings," 1985, p. 1-11,

or for protecting contents. Finally, they generally apply only to new construction.[19]

Costs of Incorporating Seismic Provisions in New Construction

The cost of incorporating seismically resistant features into new buildings is frequently raised as a barrier to greater use of these features, especially in lower risk areas. These costs are heavily dependent on the design, location, and features of the building, as well as the local costs of labor and materials. Several studies have tried to estimate these costs through the use of representative case study buildings. These studies found that **incorporating seismic resistance features into new buildings increases construction costs by about 1 to 2 percent.**

One study by the National Institute of Standards and Technology estimated the costs of complying with the NEHRP Provisions, relative to building to the existing code. The study found an average increase in *construction* costs of 1.6 percent (see table 3-5).[20] A separate study estimated these costs for new single-family residential buildings. This study found that the costs of complying with the NEHRP Provisions, relative to existing practice, varied from O (some houses did not need any changes) to 1.6 percent of construction costs.[21] As in the previous study, these costs would be higher as a percentage of structural costs and lower as a percentage of total costs.

New Technologies

The traditional method of designing a building to resist seismic damage is by strengthening the structure. Although this is often effective at reducing the chances of structural collapse, significant nonstructural and contents damage can still result.[22] Furthermore, it is difficult and expensive to retrofit existing buildings to make them suffi-

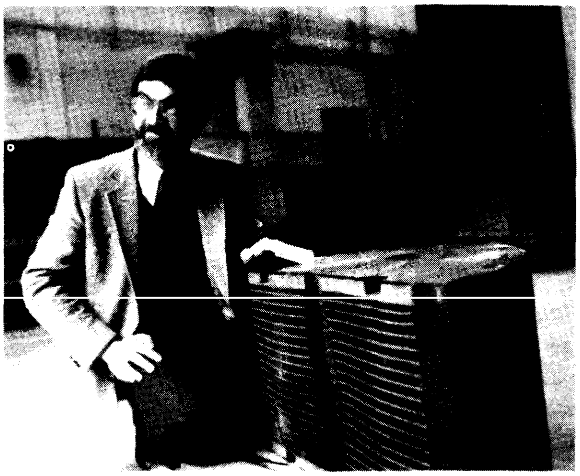
[19] It is possible, however, to have building codes apply when existing buildings are extensively modified or expanded.

[20] S. Weber, National Institute of Standards and Technology, "Cost Impact of the NEHRP Recommended Provisions on the Design and Construction of Buildings," 1985, p. 1-11. The choice of denominator in such an estimate is crucial. Construction costs include structural, material, labor, and all other costs associated with actual construction. They do not include land, site development, and other nonconstruction costs. Costs as a percentage of structural costs would be three to four times higher; as a percentage of total costs they would be roughly half of those shown in table 3-5.

[21] NAHB Research Center, "Estimated Cost of Compliance with 1991 Building Code Seismic Requirements," prepared for the Insurance Research Council, Oak Brook IL, August 1992, p. 3.

[22] The contents of a building are typically worth about half as much as the building itself. Risk Engineering, Inc., see footnote 10, P. 2.

BRUCE COOK



A base isolator cut in half to show its construction.

ciently strong to withstand a major earthquake. Two new technologies that may be able to reduce damages in both new and existing buildings—base isolation and active control systems—are reviewed here, promising information technologies are discussed in box 3-2.

Base isolation

Rather than the usual method of stiffening a building to resist seismic damage, base isolation in effect disconnects the building from the ground. This allows the ground to move underneath the building while the building stays relatively still. If successful, base isolation can protect both the building and its contents. There are two principal techniques for base isolation:

1. Installing rubber or rubber and steel pads, called elastomeric bearings, between the building and the ground: when the ground moves in an earthquake, the bushing bends and gives; the building, however, stays relatively still.
2. Using a bearing and a concave surface: the building's columns are attached to a bearing or other low-friction material, which in turn sits in a concave surface. In an earthquake, the concave surface (which is attached to the ground) slides around while the building stays still.

There are currently at least 30 base-isolated buildings in the United States, and more than 65 in Japan.[23] Applications of base isolation include new buildings such as the Foothill Communities Law and Justice Center in southern California, opened in 1986, which uses 98 rubber bearings; retrofits to existing buildings such as the U.S. Court of Appeals in San Francisco, originally built in 1905; and other structures such as a water tower in Seattle and art objects in the J.P. Getty Museum in Malibu, California.

Key questions of base isolation are:

- How well does it protect buildings and their contents?
- How does its cost compare to conventional techniques?

Computer modeling and laboratory testing of base isolation suggest that it works quite well. Laboratory tests of a base isolation system built to protect a large statue indicate that the system reduces accelerations 35 to 45 percent at the top of the statue.[24] Computer modeling of a base isolation retrofit to a historic brick tower in Seattle predicted a 75 percent reduction in base shear.[25] A much better test of base isolation would be its performance during a real earthquake. Although no base-isolated structures in the United States have yet experienced a large earthquake, several have been exposed to moderate ground shaking in recent years. Although data are still sparse, it ap-

[23] D. Trummer and S. Sommer, Lawrence Livermore National Laboratory, "Overview of Seismic Base Isolation Systems, Applications, and Performance During Earthquakes," UCRL-JC-1 15114, August 1993, p. 2.

[24] W. Haak, "Base Isolation System for Large Scale Sculptural Works of Art," in *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering,* July 10-14, 1994, Chicago IL, vol. 1 (Oakland, CA: Earthquake Engineering Research Institute), p. 590.

[25] D. Bleiman et al., "Seismic Retrofit of a Historic Brick Landmark using Base Isolation," in *Proceedings of the Fifth U.S. National conference on Earthquake Engineering, see* ibid., p. 616.

BOX 3-2: Earthquake Notification and Early Warning Systems

Additional tools in the mitigation of seismic risks are post-earthquake notification and early warning systems (EWS). Notification systems use automated analysis of seismic data to estimate earthquake location, magnitude, and the geographic distribution of potentially damaging ground motion within minutes of a quake's occurrence. Because electronic signals travel faster than seismic waves through the earth, EWS can warn of approaching ground motion. Initial applications of future EWS include automated shut off of valves and opening of firehouse doors; these actions impose low to moderate costs if the warning is a false alarm. Should 30 to 60 seconds of warning be available, more applications are possible, including turning off computers or halting manufacturing processes and initiating personal safety precautions in schools, homes, or offices.

Development of Earthquake Notification Systems and EWS in California

In 1988, the California Division of Mines and Geology (CDMG) studied earthquake warning systems and their potential benefits and costs in California. The agency concluded that, with existing technologies and knowledge of earthquake hazards, construction of an EWS in California would not be justifiable on a cost-benefit basis.[1]

Within three years of this report's release, however, the California Institute of Technology (Caltech) and the U.S. Geological Survey (USGS), Pasadena—with the participation of local governments and the private sector—began providing automated broadcasts of southern California earthquake magnitude and location in near real time. Today, the Caltech-USGS Broadcast of Earthquakes (CUBE) system disseminates this Information to the scientific community, public officials, electric utilities, and railroad operators via pagers, electronic access to the Southern California Earthquake Data Center at Caltech, and direct phone lines. Another notification system, the Rapid Earthquake Data Integration (REDI) system, has been operating in northern California since 1993. It uses data from University of California at Berkeley and USGS, Menlo Park, seismographic stations located throughout northern and central California.

Factors contributing to the change of heart toward implementing EWS included:

- The National Research Council issued a report that delineated the benefits of real-time analysis of seismological data.[2]
- There were rapid advances in seismic data digitizers and sensors and satellite telecommunications capabilities.

[1]See Richard Holden et al., *Technical and Economic Feasibilityofan Earthquake Warning System in California, Special* Publication 101 (Sacramento, CA, California Department of Conservation, Division of Mines and Geology, March 1989).

[2]See National Research Council, Committee on Seismology, *Real-Time Earthquake Monitoring: Ear/y Warning and Rapid Response* (Washington, DC: National Academy Press, 1991)

(continued)

pears that base isolation systems reduced large accelerations yet had little effect on small accelerations.[26] In one study in Japan, two identical buildings, one with base isolators and one with conventional technology, were built side by side in an active seismic area. The building with base isolators experienced, on average, about 75 percent lower acceleration than the conventional building during a series of moderate earthquakes.[27] There is some evidence, however, that

[26]Trummer and Sommer, see footnote 23, p. 3.

[27]T. Kuroda et al., Argonne National Laboratory, "Comparison of Seismic Response of Ordinary and Base-Isolated Structures," ANL/CP—75357, 1992.

BOX 3-2 (cont'd.): Earthquake Notification and Early Warning Systems

- Increased attention was given to the earthquake threat, facilitated by the 1989 Loma Prieta earthquake in the San Francisco Bay area and the 1992 Landers earthquakes in southern California.
- There was improved perception by the private sector and local governments of the usefulness of ground-motion information and early warning.[3]

REDI and CUBE coordinate to provide complete statewide coverage and to automatically notify the state Office of Emergency Services, Department of Transportation, CDMG, utilities, telecommunications providers, and transportation companies of significant events. Second, strong-motion estimates (for earthquakes of magnitude 5.5 or greater) are broadcast via the paging system and maps of strong-motion distribution are made available on the Internet. After initial source data and strong-motion estimates are released, the systems automatically calculate the seismic moment and moment tensor for the earthquake. This helps to determine which fault planes are involved, to refine magnitude calculations, and to better characterize rupture processes that determine the degree of severe shaking.[4]

Future Directions

Besides developing EWS capabilities, goals for the existing notification systems include reducing analysis time and developing quick damage assessment capabilities to aid in emergency response and aftershock preparedness. For example, university and government researchers are working to include soil amplification and other site effects, and to integrate building inventories into the systems in order to rapidly estimate zones of highest damage and casualties.

In a similar vein, work is under way to develop an automated rapid damage assessment capability intended to alleviate much of the uncertainty, delays, and inaccurate information associated with traditional post-quake intelligence gathering.[5] Data on the built environment are being collected and vulnerability assessment software is being developed that will accept CUBE and REDI data and predict both damage areas and overall impact.

[3] Egill Hauksson, Seismological Laboratory, California Institute of Technology, personal communication, June 28, 1995

[4] Lind Gee, Selsmographic Station, University of California at Berkeley, personal communication, June 28, 1995

[5] Ronald T Eguchi et al , "Real-Time Earthquake Hazard Assessment in California: The Early Post-Earthquake Damage Assessment Tool and the Caltech-USGS Broadcast of Earthquakes, " paper presented at the Fifth U S National Conference on Earthquake Engineering, July 10-14, 1994, Chicago, Illinois, p. 2.

base isolation systems as currently designed may be overwhelmed by large earthquakes that produce very large ground displacements.[28]

The costs of base isolation are not well known. A commonly used estimate is that base isolation adds about 5 percent to the construction costs of a new building. One cost analysis of a new building in southern California found that base isolation would be about 6 percent cheaper than conventional design, with much of the savings coming from eliminating the need for measures to protect computers and other sensitive equipment.[29]

[28] Heaton et al., see footnote 11.

[29] S. Sommer and D. Trummer, "Issues Concerning the Application of Seismic Base Isolation in the DOE," in *Proceedings* of the Fifth U.S. *National Conference on Earthquake Engineering, see* footnote 24, p. 603.

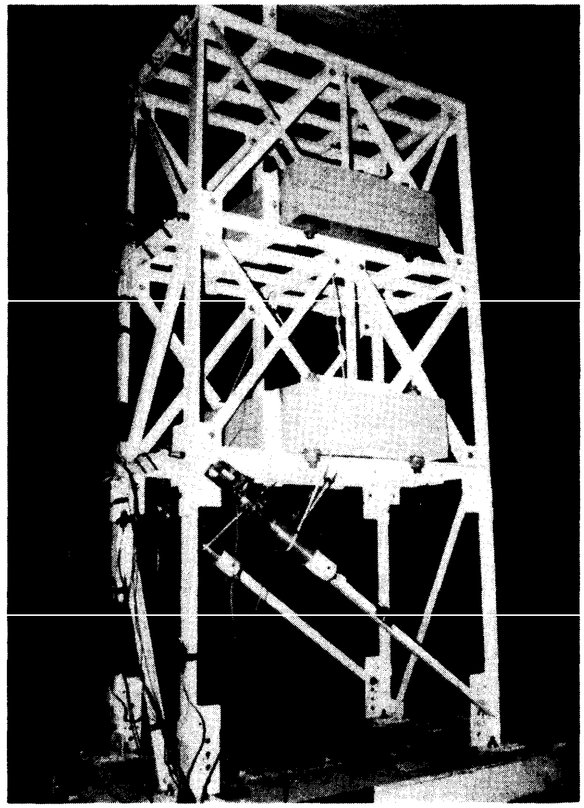
Another study found the life-cycle costs of base isolation to be comparable to conventional technology.[30]

Although these studies suggest that the costs of base isolation are competitive with conventional design, costs are still uncertain. Most applications to date of base isolation have been in buildings where noncost attributes are crucial: experimental buildings, historic retrofits where major interior renovations were impossible, and buildings where continuance of building function after an earthquake was critical.

Active control systems

Another approach to minimizing earthquake damage is the use of active control systems, which detect earthquakes and respond to them. Although many ideas for active control are still at the conceptual stage, some are beginning to be applied in buildings. Perhaps the simplest example of active control is the use of a large weight on the top of a building; the weight is computer-controlled to move so as to counteract the earthquake-induced sway of a building. This technique, known as "active mass damping," is already used in some tall buildings, including the John Hancock Building in Boston, to reduce occupant discomfort from wind-induced building sway.[31] Such a system has been installed in an office building in Japan to resist seismic damage.[32]

A more advanced approach is the use of "active tendons' '-electronically controlled actuators that can be instructed to shake the frame of a building so as to minimize earthquake-induced movement. These systems, although still far from commercial application, have the potential to reduce both structural and contents damage by minimizing building movement in an earthquake. They could in theory be used in both new and retrofit applications. An active tendon system has been installed in an experimental building in Tokyo, Japan.[33]



Active control systems being tested.

Issues affecting the development and use of these systems include:

- Cost. Most systems to date have been experimental and designed with little attention to cost. The costs of commercial systems are as yet unknown.

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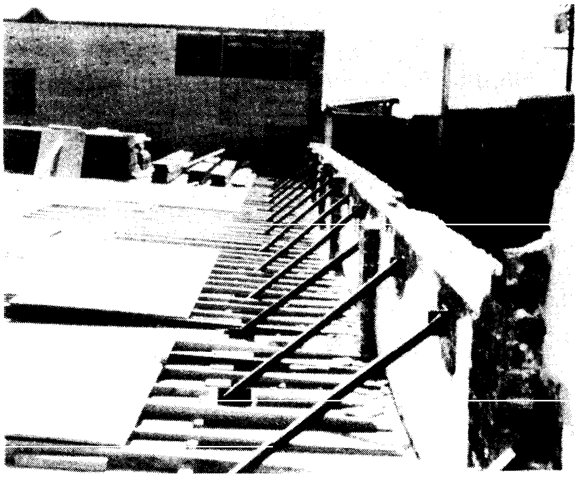
[30] S. Pyle et al., "Life-Cycle Cost Study for the State of California Justice Building," in *Proceedings of Seminar on Seismic lsolation, Passive Energy Dissipation, and Active Control,* ATC 17- I (Redwood City, CA: Applied Technology Council, 1993), p. 58.

[31] V. Vance, Langley Research Center, "Active Control of Buildings During Earthquakes," NASA Technical Memorandum, December 1993, p. 3.

[32] "Structures Tuned to the Rhythm of a Quake," *New Scientist,* Feb. 16, 1991, p. 33.

[33] Vance, see footnote 31, p. 5.



Bracing parapets can reduce damage and injuries.

- *Reliability.* These systems will be inactive most of the time, but must work properly when called on. Reliability is critical, and ensuring it will increase cost.
- *External energy requirements.* Active systems require energy, and energy systems can be interrupted in an earthquake. If energy storage is needed, costs will increase.
- *Potential for future applications.* Since a well-designed building is likely to avoid structural damage in all but the largest earthquakes, the value of active control systems will be largely in their ability to reduce nonstructural and contents damage. This value has not been well-quantified.

■ Existing Buildings

Most buildings in existence today were constructed before our current understanding of how to build them to reduce seismic damage. These older structures were built to earlier, less stringent building codes. This section reviews technologies and practices for reducing earthquake damage in existing buildings. It discusses the costs of doing so and some associated policy issues.

State of the Knowledge

Our understanding of how to retrofit existing buildings to improve their seismic performance has improved in recent years, due in part to NEHRP-sponsored programs, yet numerous knowledge gaps and uncertainties remain. Retrofitting is a more difficult task than new building design for several reasons: the original plans of the building may be missing or inaccurate; it maybe necessary to allow the building to remain occupied while it is being retrofitted; owners may want to preserve the appearance of a building (e.g., exterior seismic braces may be unacceptable); and, as always, costs are a concern. Designing retrofit methods that can overcome these obstacles is a continuing challenge.

There are generally agreed-on principles that can guide retrofitting. For example, typical steps to reduce damage include bracing parapets; improving connections among walls, floors, and roofs; strengthening the walls themselves; adding structural framing to support exterior walls; and modifying the building design to reduce asymmetry (symmetric buildings are generally stronger). Work to refine these techniques is ongoing. Its goal is to develop a set of comprehensive guidelines on seismic retrofitting of existing buildings.[34]

Costs of Retrofit

The costs of retrofitting buildings to improve seismic resistance are uncertain, but are generally much higher than incorporating seismic design into new construction. The uncertainty is due to several factors: seismic retrofits are often done in conjunction with other building improvements, such as appearance and fire safety, which makes it

[34]The Federal Emergency Management Agency has published a number of related guidebooks and reports, and plans to complete retrofit guidelines in 1997.

difficult to separate the cost of seismic actions alone;[35] buildings and retrofit techniques differ widely, leading to wide variations in costs; and there is little agreement on the appropriate level of retrofit (i.e., the level of safety a retrofitted building should provide).

Unreinforced masonry (URM) buildings have received the most retrofit attention since they are often the buildings at greatest risk for life safety. Costs of URM retrofits are typically $7 to $18 per square foot.[36] To put these costs in perspective, typical construction costs for new masonry buildings are $40 to $70 per square foot.[37] Combining these estimates yields a range of 10 to 45 percent, with a midpoint of 23 percent: that is, **retrofit of URM buildings typically costs about 23 percent as much as new construction** (although costs will vary considerably). When this is compared with the 1 to 2 percent additional cost of incorporating seismic design into new construction (discussed above), it is clear that retrofitting is much more expensive.[38]

Other Retrofit Issues

Few buildings in the United States have been retrofitted to improve seismic performance, even though they represent a significant risk.[39] Why are retrofits so difficult to implement? Part of the answer is their high cost. As noted above, retrofits of URM buildings typically cost about 23 percent as much as new construction, and costs of retrofits for other building types are comparably high. Perhaps more important, however, is that these retrofits offer little in the way of near-term market benefits (which are typically a function of size, location, amenities, and so forth). Not surprisingly, therefore, the retrofits that have occurred have been largely in response to regulations requiring them (chapter 4 discusses these issues in more detail).

A second issue complicating retrofits is determining the appropriate level of safety. Increased safety comes at an increased cost. For new buildings, the minimum safety level is set by the building code. There is however no such generally accepted code for existing buildings (although guidelines are now available),[40] and requiring them to meet the same safety levels as new buildings would be extremely expensive.

A third issue is how well retrofits work. Data on retrofit performance in earthquakes are rare; however, there is some evidence that retrofitted URMs

[35] Performing a seismic retrofit may “trigger” other code requirements, such as fire safety upgrades.

[36] Much of the variation can be explained by the level of seismicity to which the building is retrofitted and by the size of the building (larger buildings have lower retrofit costs per square foot). Retrofit costs for non-URM buildings are in the same range—for example, retrofitting precast concrete tilt-up walls is estimated to cost $5 to $19 per square foot. Federal Emergency Management Agency, *Typical Costs for Seismic Rehabilitation of Existing Buildings*, 2nd Ed., FEMA 156 (Washington, DC: December 1994), pp. 1-15 to 1-18.

[37] OTA estimate, based on Federal Emergency Management Agency, *Typical Costs for Seismic Rehabilitation of Existing Buildings*, vol. 2, FEMA 157 (Washington, DC: September 1988), p. 3-72.

[38] Retrofitting, although more expensive than incorporating seismic considerations into new construction, can still be a worthwhile investment if the risk is high (e.g., in an area with a high probability of a damaging earthquake or in a critical building such as a hospital).

[39] For example, a 1994 review of California’s seismic risk found, “we still have many earthquake-vulnerable buildings. . . .” California Seismic Safety Commission, “California at Risk,” 1994 Status Report, SSC 94-01, p. 1. In the central United States, some states have just begun to identify hazardous structures. R. Olshansky, “Earthquake Hazard Mitigation in the Central United States: A Progress Report,” in *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, see footnote 24, p. 992.

[40] These guidelines, known as the Uniform Code for Building Conservation (UCBC), are intended not to ensure life safety but to decrease seismic risk. For example, 15 to 25 percent of *retrofitted* URMs located near the epicenter of a major earthquake are expected to collapse in a moderate earthquake. Earthquake Engineering Research Institute, see footnote 16, p. 16. In addition, as noted above, FEMA is working to develop comprehensive retrofit guidelines.

did not perform as well as hoped.[41] Evaluation of retrofit methods is clearly needed.

One major technical issue that makes such retrofits difficult is the analysis of existing buildings. Deciding on a retrofit technique requires an understanding of the strengths and weaknesses of the building as it stands. For many older buildings, however, the original plans are not available; the building has been modified several times since its original construction; and structural details of the building are hidden by nonstructural components. Some work has been done by the National Institute of Standards and Technology (NIST) in applying nondestructive testing techniques, such as sensors that can detect reinforcing rods in concrete, to seismic retrofit problems. The Federal Emergency Management Agency (FEMA) has also sponsored research into "rapid screening methods"—methods to quickly estimate a building's seismic hazard without performing a detailed engineering analysis. These are promising research directions.

DAMAGE TO LIFELINES

Lifelines (i.e., bridges, mass transit systems, overpasses, roads, electric and gas supply systems, water and sewer systems, and telecommunication networks) are often damaged by earthquakes. Much of what has been discussed about buildings applies to lifelines as well:

- most fatalities associated with lifelines are caused by structural collapse;
- the knowledge of how to build new lifeline facilities to minimize structural collapse is available, although this knowledge, for economic or other reasons, may not be used;
- much of the remaining life safety risk lies with existing facilities; and
- existing facilities can be retrofitted, but the costs are high.

There are, however, some key ways in which lifelines differ from buildings. The most important difference is **the high cost of outage**. If a building is damaged, only the functions in that building are lost. If a lifeline is interrupted—even for a brief time—the costs can be massive. The most extreme example would be loss of a water supply system after an earthquake, which occurred in San Francisco in 1906, leading to massive fires. In the longer term, interruptions in water or sewer service can lead to public health problems, breaks in key transportation links can snarl commuting, and the loss of natural gas systems can force otherwise undamaged businesses to close. Thus "success" in lifeline seismic design is often defined as retaining functionality rather than simply reducing damage.

The second major difference is that **lifelines are usually owned and operated by public agencies** (exceptions are electricity and natural gas supply systems, which in most areas are owned and operated by publicly regulated, privately owned companies). Therefore, responsibility for their continued operation, and decisions about their earthquake resistance, often lie entirely with the government.

Bridges

Bridges, overpasses, and elevated highways are often damaged by earthquakes, and the costs of damage to these critical lifelines are high. Catastrophic failure can result in many deaths. Of the 63 deaths in the 1989 Loma Prieta earthquake, for example, 42 were caused by the collapse of one elevated highway.[42] Repair of damaged bridges can be very expensive: the reconstruction of the

[41] For example, many retrofitted masonry structures suffered severe damage in the Northridge earthquake. Goltz, see footnote 13, p. 3-36.

[42] M. Durkin, "Improving Earthquake Casualty and Loss Estimation," paper presented at the Earthquake Engineering Tenth World Conference, Balkema, Rotterdam, 1992, p. 559.

Santa Monica Freeway in Los Angeles, which was damaged in the Northridge earthquake, cost $29.4 million.[43] Also, interruption of transport services can disrupt the local economy; the 1989 Loma Prieta earthquake caused the partial collapse of the San Francisco-Oakland Bay Bridge, which disrupted the passage of 243,000 vehicles per day.[44]

Bridges can be damaged in several ways, including:

- They can simply be "unseated." Sections of bridges typically sit on horizontal supports, called seats; if the support moves far enough in an earthquake it can simply drop the bridge section.
- The columns holding up sections of a bridge may collapse under the lateral (side) forces caused by an earthquake.
- The soil providing support for a bridge may settle or shift.

Known technologies and practices can do much to reduce the risk of major damage to or collapse of bridges. The primary constraint is the high cost of implementing these technologies and practices, especially when such long-term investments must compete with other public investments for scarce capital.

New Construction

Like buildings, bridges built to current standards of seismic resistance have performed quite well in recent earthquakes. In the Loma Prieta earthquake, only one of the 100 bridges damaged was designed after 1972, when seismic design requirements were revised significantly.[45] Similarly, the two major freeway collapses in the 1994 Northridge earthquake—the Santa Monica Freeway and the I5-SR14 interchange—were due primarily to the failure of supporting columns designed and built before 1971.[46] A total of seven highway bridges collapsed in the 1994 Northridge earthquake; none were built to current codes.[47] The elevated highway that collapsed during the 1995 quake in Kobe, Japan, did not incorporate current knowledge on designing columns to resist seismic damage.[48]

Some design features in new bridges that resist seismic damage include: using continuous spans and thereby eliminating joints that can separate and collapse, using longer seat widths that allow for more horizontal movement without unseating, improving soil strength to avoid liquefaction, designing all bridge components for horizontal loads, and confining (wrapping) columns.[49]

Retrofits

About 345,000 bridges in the United States were built before 1970, with little or no consideration of seismic resistance.[50] Although not all of these are located in areas of seismic concern, retrofitting these bridges remains a major technical, financial, and policy challenge.

Much of the bridge retrofit activity in the United States has been in California. The 1971 San Fernando earthquake in southern California

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[43] "Quake-Damaged Freeway Reopening Ahead of Time," *New York Times*, Apr. 12, 1994, p. A12. About half the cost was a bonus to the contractor for early completion.

[44] U.S. Geological Survey, "The Loma Prieta, California, Earthquake of October 17, 1989—Fire, Police, Transportation, and Hazardous Materials," 1553-C, 1994, p. C18.

[45] National Research Council, see footnote 12, p. 169.

[46] J. Cooper et al., "The Northridge Earthquake," *Public Roads*, summer 1994, p. 32.

[47] I.G. Buckle, National Center for Earthquake Engineering Research, "The Northridge, California Earthquake of January 17, 1994: Performance of Highway Bridges," Technical Report NCEER-94-0008, Mar. 24, 1994, p. 1-1.

[48] Earthquake Engineering Research Institute, *The Hyogo-Ken Nanbu Earthquake*, Preliminary Reconnaissance Report (Oakland, CA: February 1995), p. 44.

[49] Cooper et al., see footnote 46, p. 34.

[50] Ibid.

damaged more than 60 bridges, and led both to revision of standards for new bridge construction and to an ambitious bridge retrofit program. Retrofitted bridges performed very well in the 1989 Loma Prieta earthquake: 350 bridges retrofitted with hinge restrainers were in the area impacted by the quake, and none were damaged.[51] Similarly, retrofitted bridges performed very well in the 1994 Northridge earthquake.[52] Although some hinge restrainers failed, no steel-jacketed column retrofits showed signs of distress.[53]

The technical knowledge of how and what to retrofit is good, but not faultless. The 1989 Loma Prieta earthquake caused the partial collapse of the San Francisco Bay Bridge; this bridge had been retrofitted in the 1970s, and the section that collapsed was not considered vulnerable.[54]

In addition to determining the best technologies and practices for bridge retrofits, funding these retrofits remains a major challenge. The I-880 elevated highway that collapsed in the Loma Prieta earthquake, killing 42 people, was scheduled for retrofit but had not been because of budget limitations.[55] A General Accounting Office survey of state bridge retrofit activity found that very few states had retrofitted their bridges; limited funding was identified as a major barrier.[56]

Water and Sewer Systems

Ground motion and ground failure due to earthquakes can cause water and sewer pipes to break; this can be especially dangerous if fire follows an earthquake. Also, since almost all of these pipes are underground, repair is expensive and time consuming. The 1989 Loma Prieta earthquake caused 748 water supply pipeline breaks; the total cost of repairs was in the tens of millions of dollars.[57] This earthquake also severely damaged San Francisco's auxiliary water supply system.[58] The 1987 Whittier Narrows earthquake caused 17 major water supply pipeline breaks, with the result that water pressure in the system was at half its usual level for two days following the earthquake.[59] The loss of water supply contributed to the severity and duration of fires in the 1995 Kobe, Japan, earthquake.

Recent experiences with the performance of water systems in earthquakes suggest several design principles to reduce future disruptions. The Loma Prieta and Northridge experiences point to the importance of redundancies in water supply systems. In the Loma Prieta earthquake, liquefaction in the South of Market area of San Francisco caused a break in a major pipeline of the city's backup water supply system. Fortunately, other backup systems, including cisterns and a fire boat, were available. Water supply systems should build in redundancies (e.g., multiple pipelines and independent power supplies for pumping) to reduce the probability of the system's being disabled from the loss of any one component. In the Northridge earthquake, a number of water leaks resulted from the breakage of pipes and valves

[51] National Research Council, see footnote 12, p. 168.

[52] Cooper et al., see footnote 46, p. 32.

[53] Buckle, see footnote 47, p. 1-1.

[54] U.S. Congress, General Accounting Office, *Loma Prieta Earthquake: Collapse of the Bay Bridge and the Cypress Viaduct*, GAO/RCED-90-177 (Washington, DC: June 1990), p. 5.

[55] Ibid., p. 2.

[56] U.S. Congress, General Accounting Office, *The Nation's Highway Bridges Remain at Risk from Earthquakes*, GAO/RCED -92-59 (Washington, DC: January 1992), p. 13.

[57] National Research Council, see footnote 12, pp. 138, 146.

[58] "Keeping Lifelines Alive," *Civil Engineering*, March 1990, p. 59.

[59] A. Schiff, "The Whittier Narrows, California Earthquake of October 1, 1987—Response of Lifelines and Their Effect on Emergency Response," *Earthquake Spectra*, vol. 4, No. 2, 1988, p. 344.

where they connect to water tanks. Use of flexible connections that would allow differential movement of pipes and tanks would reduce such leaks. A $17-million evaluation and retrofit of Seattle's water supply system found that elevated water tanks were among the most vulnerable components of the system.[60] Ensuring that such tanks have sufficient anchors and braces will reduce the chances of collapse.

Electricity Systems

In recent earthquakes in the United States, the damage to electricity systems has been relatively minor. Redundancies in transmission and distribution systems, coupled with the inherent flexibility of wires (i.e., compared to rigid pipes), suggests that electricity is not the most vulnerable lifeline. In the Loma Prieta earthquake, several electrical switchyards were moderately damaged.[61] In the Northridge earthquake, about 2 million customers lost electrical power due mainly to substation problems; however, most service was restored within a day.[62]

Fortunately most critical facilities that use electricity—such as hospitals, telecommunications systems, and computer facilities—have backup electricity-generating facilities. However, since most backup systems such as batteries and on-site generators are designed to supply limited power for only a short time (typically hours or tens of hours), longer term electricity system damage can be a serious problem.

Natural Gas Systems

Natural gas is transported through underground pipelines, which are vulnerable to fracture in earthquakes. Resulting natural gas leaks are a dangerous fire and explosion hazard. In the Northridge earthquake, a broken natural gas transmission pipeline caused a fire that destroyed five houses.[63] Analysis of the performance of natural gas transmission pipelines in California earthquakes found that most damage could be traced to pre-1930 welds, which were generally of poor quality. Pre-1930 pipes had a damage rate 100 times that of post-1930 pipes.[64] Modern pipes with high-quality welds are still vulnerable to ground deformation, but are very resilient to damage from traveling ground waves.

Although modern natural gas transmission systems generally perform quite well in earthquakes, leaks and other problems in the distribution system and at or near the service connection are common. In the 1987 Whittier Narrows earthquake, for example, there was only one leak in the transmission system (due to a cracked cast iron pipe) but there were 1,400 leaks on customer property. Three-quarters of these resulted from failures at appliance connections, primarily water heaters.[65] In the Loma Prieta earthquake, the natural gas transmission system was undamaged, but the distribution system suffered extensive damage. Repairs in many cases were made by inserting flexible plastic piping into damaged cast iron pipes.[66] In the Northridge earthquake, 120 mobile

[60] W. Anton et al., "Seattle Plays It Safe," *Civil Engineering*, August 1992, p. 39.

[61] National Research Council, see footnote 12, p. 142.

[62] Goltz (ed.), see footnote 13, p. 4-11.

[63] Ibid., p. 4-21.

[64] T. O'Rourke and M. Palmer, National Center for Earthquake Engineering Research, "The Northridge, California Earthquake of January 7, 1994: Performance of Gas Transmission Pipelines," Technical Report NCEER-94-0011, May 16, 1994, pp. 2-32, 2-35.

[65] Schiff, see footnote 59, p. 348.

[66] National Research Council, see footnote 12, p. 140-141.

homes were destroyed by fires triggered by natural gas valve leaks.[67]

ACCOMPLISHMENTS AND NEEDS OF FEDERALLY SPONSORED RESEARCH

Accomplishments

Considerable progress has been made in understanding how the built environment is affected by earthquakes and how structures can be designed to reduce structural failure. **NEHRP has done much to expand our knowledge of earthquake engineering**. Although a rigorous evaluation of NEHRP has not been undertaken (and would be very difficult, since much of NEHRP involves research, which is inherently difficult to evaluate), there are numerous examples in which NEHRP-funded programs have had considerable societal benefits.

A 1993 workshop defined some key contributions made to earthquake engineering by the National Science Foundation's funding of research under NEHRP. These include:

- advances in analytical and modeling techniques, permitting seismic structure design on inexpensive computers;
- improved understanding of how structures behave under earthquake-induced stress, which has led to better building codes in such areas as bracing systems for steel structures;
- advances in new technologies such as base isolation and active control;
- better reliability and risk assessment techniques for lifelines and structures; and
- improved disaster response planning from social science research that sheds light, for example, on cultural differences in perceptions of disaster.[68]

NEHRP-funded work by NIST, although a small fraction of total program funding, has also addressed some key applied earthquake engineering problems. Examples include testing of base isolation systems, development of methods to evaluate the strength of existing buildings, and evaluation of building retrofit techniques.[69] Additional relevant NIST activities include, for example, development of seismic standards for existing federal buildings and management of a United States-Japan annual meeting on earthquake engineering.

Implementation of this knowledge is a continuing concern; yet there are successes here as well. For example, development of the NEHRP Provisions, a resource document for model codes, and their adoption by model code agencies, is a significant accomplishment. Retrofitting of existing buildings is still a difficult and expensive task, yet FEMA's work in this area has made some progress toward consensus on methods and costs.

These examples of NEHRP successes are not the result of a thorough evaluation of that program, nor do past successes ensure future contributions. However, it is clear that NEHRP has made a significant contribution to improving understanding of how to build structures that will resist seismic damage. (A more detailed description of the current activities of NEHRP agencies can be found in appendix B.)

Future Needs

Knowledge of how to design and build structures so as to reduce earthquake-induced damage has improved considerably. However, the problem is far from solved. The 1994 Northridge earthquake occurred in probably the most well-prepared area of the United States. Nevertheless, it caused 57

[67] Goltz (ed.), see footnote 13, p. 6-5.

[68] National Science Foundation, "Directions for Research in the Next Decade," Report on a Workshop, June 1993.

[69] Richard N. Wright, Director, Building and Fire Research Laboratory, National Institute of Standards and Technology, testimony at hearings before the Senate Committee on Commerce, Science, and Transportation, Subcommittee on Science, Technology and Space, May 17, 1994, on NEHRP reauthorization.

deaths and about $20 billion in losses. Scenarios of future earthquakes across the United States suggest that large losses are likely.

Greater use of existing knowledge, practices, and technologies could reduce these losses. For example, the 1989 collapse of the I-880 elevated highway in Oakland, which resulted in 42 deaths, could have been prevented with the use of known technologies. The implementation (or lack thereof) of these technologies to date has been determined largely by economic, behavioral, institutional, and other factors, not by the state of the knowledge (these issues are addressed in chapter 4).

Nevertheless, improved knowledge could have several benefits. First, although current knowledge of how to build new structures to resist seismic damage is good, it is far from perfect (consider the steel weld failures in new buildings in the Northridge earthquake). Second, many of the financial losses in recent earthquakes resulted from nonstructural and contents damage—areas that have received little research attention. Third, much of the risk of fatalities lies in existing structures, and retrofit methods are still not well developed. Research into improving retrofits could reduce this risk. Fourth, to the extent that economic factors influence implementation, research to reduce costs could lead to greater implementation.

New Buildings

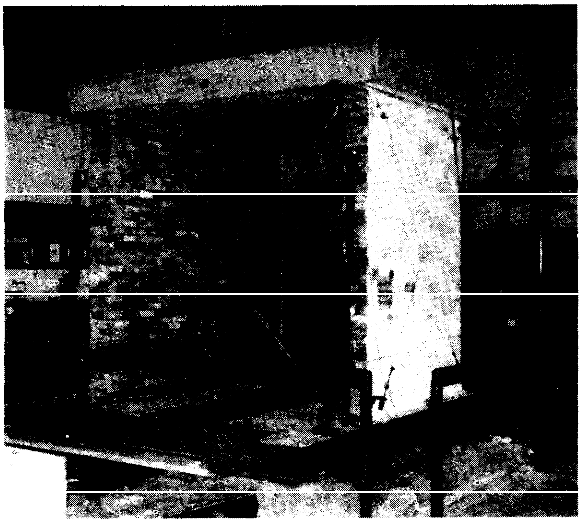
Buildings constructed to comply with today's codes are meeting the goal of providing life safety. Building collapses have been limited largely to older buildings designed to earlier codes. This is a major success, for which NEHRP gets some credit: years of research, and a concerted effort to ensure that the results of this research are incorporated into codes, have resulted in effective new building codes that, if properly applied, will yield a building that is unlikely to suffer structural collapse.

However, several crucial areas of new building seismic design are still not well understood. A new building meeting today's code, although unlikely to suffer structural collapse, will likely suffer expensive nonstructural and contents damage in a major earthquake. This does not indicate inadequate or faulty construction or design. Rather, it reflects the fact that codes are intended primarily to protect life safety by preventing structural collapse and typically have few or no requirements to limit nonstructural or contents damage.[70] It is time for new building seismic engineering research to consider the next problem: **reducing nonstructural and contents damage**. Possible areas of research include:

- data collection and analysis of nonstructural and contents damage from recent earthquakes;
- how to design and build structures to avoid or minimize expensive nonstructural failures such as cracked walls, broken sprinkler systems, and collapsed chimneys;
- analytical methods to measure or predict such damage;
- guidelines for lighting, electrical, water, and other systems design and installation to minimize seismic damage;
- expanding building codes to address nonstructural and contents damage; and
- considering technologies—notably active and passive control—that can reduce these damages.

The major surprise of the 1994 Northridge earthquake was the failure of steel welds. These failures occurred in new buildings and in buildings under construction. Although none of these buildings collapsed, repairing this damage will be very expensive. Since it is not yet clear why such damage occurred or how to prevent it, repairs may

[70] "The primary intent [of the Uniform Building Code seismic provisions] is to protect the life safety of building occupants and the general public." Earthquake Engineering Research Institute, see footnote 16, p. 6.


NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

Testing of URM retrofit methods

not prevent the recurrence of this problem. Researcg is needed to better understand what caused this failure and how steel frames should be designed, assembled, and modified (in existing buildings) to prevent it from happening again.[71]

Existing Buildings

Much of the risk of collapse and resulting fatalities lies in existing buildings, which do not incorporate current codes and knowledge. Few of these buildings have been retrofitted to reduce risk, and such retrofits have sometimes been expensive, complex, and of uncertain benefit. Additional research is needed to improve understanding of how to best reduce the risk in existing buildings.[72]

The first area of research for existing buildings should be to **better understand the vulnerability of existing buildings.** It is commonly recognized that URM buildings are unsafe. However, for other types of buildings (e.g., precast concrete framed buildings or reinforced masonry buildings), the risk is less well known. Laboratory and field experiments, and collection and analysis of data on how buildings respond during earthquakes, are needed. Improved tools to determine risk in existing buildings—such as nondestructive evaluation techniques—are needed as well. A second area is **the development of low-cost standardized retrofit techniques.** Many retrofits to date have been expensive and have required extensive site-specific design and analysis. Standardized methods, such as those contained in codes for new construction, would reduce costs. These methods could also allow for multiple levels of safety to accommodate different risk preferences. A third research area is to **extend retrofits from structural damage reduction to nonstructural and contents damage reduction.** The bulk of damage to buildings in recent California earthquakes has been nonstructural and contents damage; retrofit methods to reduce this damage could be very beneficial.

Lifelines

Lifelines are expensive to repair if damaged in an earthquake, and service interruptions are at best inconvenient and at times deadly. Like buildings, lifeline facilities built to current design knowledge generally behave quite well in earthquakes. However, the lack of an accepted national standard for the design and construction of lifelines raises costs and reduces performance. The 1990 NEHRP reauthorization directed FEMA and NIST to work together to develop a plan for creating and adopting design and construction standards for lifelines. The legislation directed the agencies to submit this plan to Congress by June 30, 1992. Although some work has been done on the plan, as of this writing it had not yet been submitted to Congress.

Much of the life safety risk associated with lifelines lies in existing facilities. Research is needed to develop methods to better determine the risk in

[71] Fema is currently using supplemental appropriations funds, passed after the Northridge earthquake, to sponsor research and development related to the steel weld problem.

[72] FEMA has an existing buildings program that is addressing some of the issues noted here.

existing facilities, to develop methods to prioritize retrofits, and to develop standardized retrofit methods that can reduce retrofit costs. A goal of preserving functionality, rather than simply minimizing damage, is often appropriate for lifelines. The development of low-cost, easy-to-use procedures to analyze lifelines for weak links would help to ensure their continued function in earthquakes.

Implementation 4

From earth science comes knowledge of earthquake hazards; from engineering, an understanding of how to prepare structures against them. For this knowledge and understanding to actually reduce earthquake losses, however, it must be put into effect. This process, the transformation of research results into real-world measures that will reduce loss of life and property, is referred to as *implementation*.

Implementation can take a number of forms. It can mean the incorporation of engineering lessons into the building practices of a seismically vulnerable region, land-use planning to restrict development of unusually dangerous ground, emergency planning to ensure service or business continuity in the aftermath of a major temblor, or informational outreach programs to inform potential earthquake victims of risks and preventive measures. It is a complex, multifaceted process involving many different players working at many different levels, and as such it is inherently challenging.

In many respects, implementation is the chief bottleneck hindering seismic mitigation efforts in the United States. Research in the earth sciences and engineering has already provided much of the knowledge base needed to prepare against earthquakes: we have a good idea of where earthquakes can occur (at least for the more seismically active areas); we have a sense of their potential severity and probable effects; and where we choose to prepare, we can significantly reduce the likelihood of massive destruction and loss of life. The problem is that we do not always choose to prepare. Despite mounting evidence that truly devastating earthquakes can occur in heavily populated regions of the central United States, Intermountain West, and U.S. East Coast, these regions remain highly vulnerable to future earthquake losses.

Moreover, where we do choose to act (most notably in the state of California), we have focused on issues of life safety and remain vulnerable to devastating economic loss.

These problems—a general lack of earthquake mitigation in many seismically hazardous regions (particularly outside California), and a surprising economic vulnerability in even the best-prepared communities—have drawn attention to how the implementation of seismic mitigation might best be improved.

The emphasis in the National Earthquake Hazards Reduction Program (NEHRP) has traditionally been on the front end of the implementation process (i.e., the gathering and dissemination of research knowledge and recommendations), with the actual execution largely left to state and local authorities, private organizations, and private individuals. As a result, implementation might be improved through better coordination and tailoring of front end efforts to the needs of nonfederal implementers. Alternatively, one might desire to complement existing efforts by having the federal government play a more active implementation role through incentives, insurance, or regulation. All such efforts require an understanding of how the implementation process works, who the chief players are, what their relations are to NEHRP and to each other, and what incentives or disincentives influence their desire or ability to act. Those seeking to improve mitigation efforts in the United States must therefore consider the following:

- How does implementation work in the ideal and in practice?
- What underlying factors reduce implementation success?
- What activities or measures have the greatest impact on implementation success?

These questions are considered in turn. The next section, "The Implementation Process," examines the basic workings of implementation and identifies difficulties that arise in the execution of mitigation measures. Following that, "Factors Affecting Implementation" sets these difficulties in the context of larger motivational problems that complicate the widespread and thorough adoption of mitigation programs. Finally, the section "How Matters Might Be Improved" identifies earth science, engineering, and direct implementation measures that might improve mitigation adoption and execution.

THE IMPLEMENTATION PROCESS

The Voluntary Nature of Earthquake Mitigation

From the perspective of the federal government, the implementation of earthquake mitigation measures is an essentially voluntary process. Federally supported research gives warning of likely earthquake hazards while suggesting possible technical countermeasures, and concerned nonfederal entities decide whether to incorporate those suggestions into state, local, or private hazard reduction schemes.

The origins of this approach lie partly in the unusual scientific climate surrounding NEHRP's conception (a point addressed later) and partly in matters of constitutional authority. That is, although federal funds can guide the course of research, the application of research results takes place primarily through land-use decisions and building codes—authority over which is constitutionally ceded to the states—and through action by individuals and nongovernmental organizations.

To explain in more detail, the essential goals of mitigation are to ensure that buildings and other structures do not collapse, that lifelines and services continue to function, that individuals and organizations are aware of risks and appropriate responses, and (a more recent concern) that economic losses are minimized. The basic tools to accomplish these goals are:

1. building codes for new construction in seismically hazardous areas;
2. retrofit or demolition programs and guidelines to reduce or remove the risk of potentially hazardous older construction;

3. land-use planning or zoning measures to prevent development on particularly dangerous ground (e.g., fault scarps and landslide zones), or to limit such development to nonessential, less vulnerable uses;
4. actions by individuals or nongovernmental groups to reduce nonstructural hazards (e.g., anchoring office equipment), or to initiate measures (land-use, retrofit, seismic-safety standards) beyond those recommended by the government;
5. structural, organizational, or emergency response measures to ensure lifeline survivability; and
6. the collection, processing, and dissemination of information on earthquake risk, mitigation alternatives, and earthquake response to at-risk individuals and organizations.

Of these tools, the first three (which have the greatest impact on reducing catastrophic building collapse and major loss of life) are building and land-use issues, while the fourth is, by definition, private. The federal government has some influence on lifeline survivability via authority over utilities and transportation (and of course on direct federal construction), but its basic role in implementation is currently focused on the last measure—collecting, processing, and disseminating information.[1] This handling of information serves two functions: one is to motivate nonfederal entities toward action by making clear both the risks and the potential losses; the other is to facilitate action by translating research results into readily usable forms (e.g., by incorporating engineering theories into ready-to-use model building codes).

Approaches to Implementation

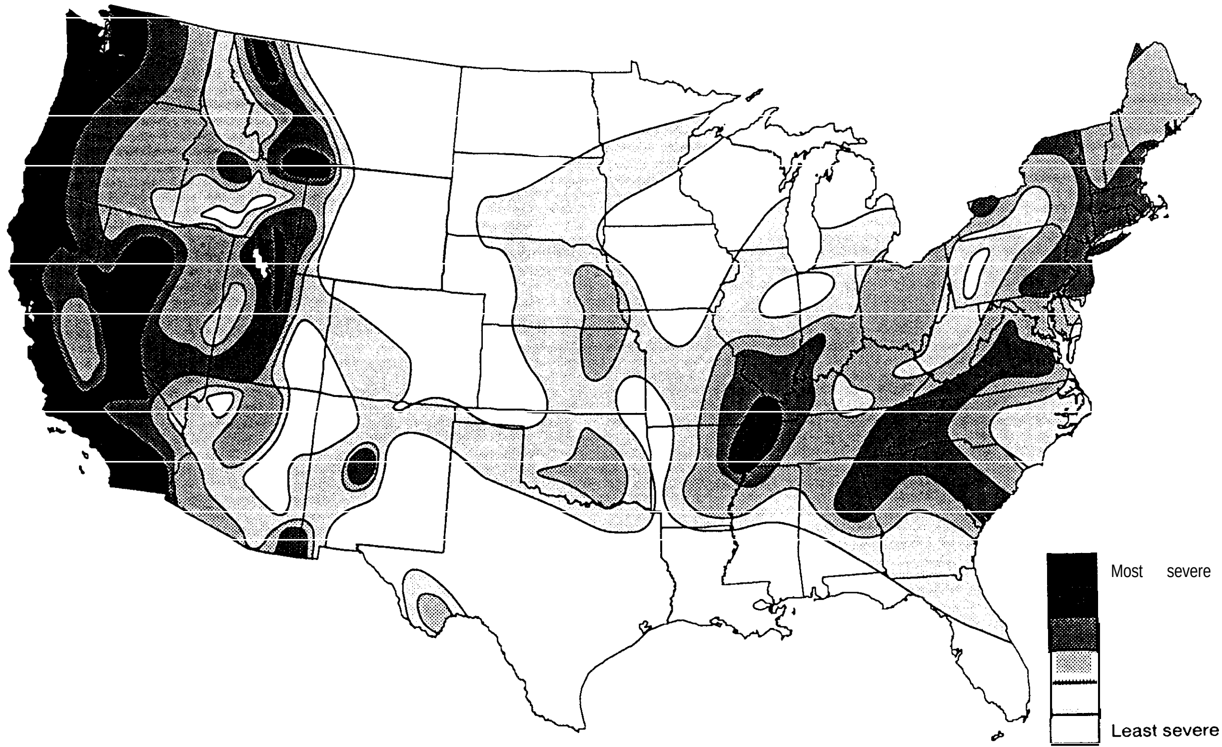
With federal agencies currently playing a primarily informational role, authorities in the state, local, and private sectors are faced with devising their own plans for putting hazard reduction into effect. Because different parts of the country vary in their geology, hazard awareness, economics, political climate, and mitigation history, these plans show a wide range of approaches:

- The overall approach can be regulatory, incentive- or insurance-based, or built on outreach and the media.
- Action can be initiated by states, localities, professional and technical associations, or the private sector.
- In some instances (e.g., hospitals and schools in California), the state takes a direct role in mandating preventive measures. Alternatively, the state can issue voluntary guidelines for local jurisdictions, or it can set performance standards that local authorities must attain.
- Considerable discretion is commonly left to local governments. Where state activity is weak, local authorities sometimes take the lead (indeed, localities in even the most active states are free to adopt more stringent measures than required).
- Finally, important mitigation decisions can be made at a nongovernmental level by regional or local utilities, private businesses, professional societies such as those guiding the training and practice of engineers, organizations governing particularly sensitive institutions such as museums and laboratories, and private individuals.

Despite the variety of mitigation approaches, some common themes recur. In deciding whether and how to guard against earthquake hazards, communities, organizations, and individuals will generally seek to:

1. assess the local level of seismic hazard and local vulnerability to that hazard,
2. decide what changes should be made to the existing and future built environment while ensuring that the benefits of such changes outweigh the costs, and

[1] The federal role could be larger, and options for making it so are presented in chapter 1. However, this discussion reflects the federal role as it currently exists.



OFFICE OF TECHNOLOGY ASSESSMENT, 1995, BASED ON U.S. GEOLOGICAL SURVEY

A community's first step in assessing earthquake risk is to consult large-scale seismic hazard maps; here, the severity of future ground shaking is shown for the continental U.S.

3. devise regulatory, financial, insurance-based, or cooperative tools to put those changes into effect.

Although simple in concept, these steps—particularly the first-are not straightforward to execute. To illustrate the difficulties that arise, the remainder of this section examines how a hypothetical (and unusually thorough) community might approach each of the above steps. For clarity's sake, each step is presented in sequence, with the assumption that conscious, rational thought governs every phase of the process. In the real world, communities or individuals will likely deal with steps simultaneously or in varying sequences, perhaps making decisions on the basis of less-than-formal deliberations; however, the basic problems that arise are the same whether the decisionmaking process is explicit or implicit.

■ Assessing Hazard, Risk, and Vulnerability

Assessing Overall Hazard—Seismic Hazard Maps

As a first step, this hypothetical community will examine U.S. Geological Survey (USGS) seismic hazard maps[2] to gain a sense of the overall danger. Of concern are:

- the frequency of seismic activity and the likelihood of activity within a future time window,
- the most likely severity of future events, and
- the severity of the worst-case event.

All three points are subject to considerable uncertainty, and all have an impact on the scope and character of the desired mitigation action.

The first point reflects the immediacy of the earthquake threat and can determine the choice of implementation tools. If a community can reason-

[2] There are many types of seismic hazard maps. See chapter 2 for more details.

ably expect a damaging quake several hundred years from now[3]—by which time most or all of its current building stock will have already been replaced—then seismic codes for new construction might suffice for future protection. However, if a major seismic event is expected within the next few years or decades (i.e., within the lifetime of many existing buildings), prudence may dictate more drastic measures such as building retrofit or demolition and replacement. The difficulty is that situations are rarely so straightforward. Because earthquake likelihood is commonly expressed as a probabilistic estimate (i.e., there is a percentage chance of an event during some future time interval) and because building lifetimes vary widely, communities must judge the impact of an uncertain future event on an evolving building stock. As a result, communities must balance the risk of overmitigation (e.g., by tearing down or retrofitting structures that would never have experienced an earthquake) against that of mitigating too slowly and being caught unprepared.

Apart from issues of urgency is the question of earthquake severity: should one prepare for the worst-case scenario, or for the most-likely? The geologic stresses that lead to seismic activity (see chapter 2) can be released by earthquakes of many different sizes, and those preparing for them must choose from a range of predicted calamities. This choice creates problems for those trying to justify the expense of mitigation, for over- and underpreparation can both waste money: overpreparation is expensive for obvious reasons, while an expensively but inadequately prepared building can still be destroyed at a a total loss.

Assessing Risk in Detail

It is tempting to stop the assessment process at the level of the seismic hazard map—knowing the predicted zone of devastation surrounding future earthquakes, one could in theory simply require that all structures within the zone be built to seismically resistant standards.

Real-world costs however make a broad-brush approach impracticable on two counts:

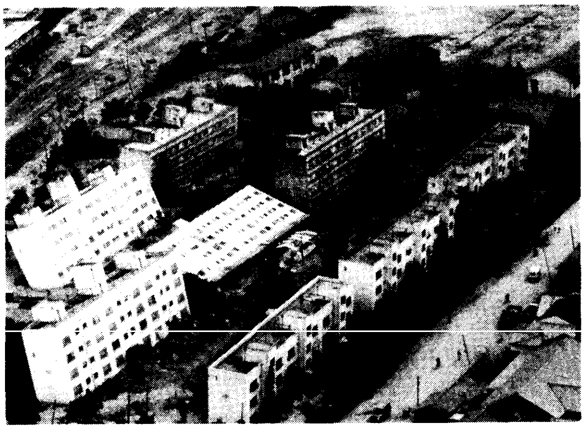
1. In many regions (particularly east of the Rockies) scientific uncertainties mean that enormous portions of the seismic map are marked as potentially hazardous. A broad-brush mitigation strategy can therefore prepare a widespread area for a future earthquake that, if and when it occurs, might strike but a small fraction of the region.[4]
2. Even if predicted earthquake locations are tightly constrained, a broad-mitigation strategy can still be undesirable. Within the general area affected by an earthquake, quirks of local geography and geology will make some localities much more dangerous than others (see chapter 2); these quirks are largely ignored in the preparation of seismic maps. Applying an average level of mitigation to the entire area will thus tend to overprepare some localities while underpreparing others.

For practical and economic reasons, a community will therefore wish to focus its efforts on locations where devastation is most likely. Places subject to ground failure, seismic energy amplification, and other earthquake-related effects (see chapter 2) can experience the bulk of a region's earthquake damage and will call for special attention (or sole attention, if the commitment to mitigation is weak). Because the typical seismic

[3] Such an expectation can never be certain, for there is a certain probability that an earthquake can occur at any time; however, a community in a seismically inactive region may judge its near-term earthquake risk to be too low to warrant drastic action.

[4] This form of overpreparation is particularly troublesome where earthquakes are infrequent, in which case many of the region's buildings will never experience an earthquake during their lifespans.

STEINBRUGGE COLLECTION, EERC



Earthquake-reduced ground failure (liquefaction) can endanger even the most well-constructed buildings (Niigata, Japan, 1964).

hazard map predicts only the average severity of ground shaking that would occur on an average piece of land, the community will likely have to conduct its own study of local geologic conditions. This sort of "microzonation" assessment is typically far beyond the technical capability of a local government, and although some metropolitan regions have been studied through state efforts or because of special interest on the part of earth scientists, a community will generally have to hire a geotechnical firm to perform the work.

Assessing Vulnerability: Inventory and Damage Estimation

Although one might expect the damage pattern in a community to coincide with the pattern of maximum ground shaking (subject to the microzonation effects noted above), the damage a given building experiences in an earthquake will depend on its design, the type and quality of its construction, and how the building reacts to the particular ground motion characteristics of the earthquake (see chapter 3). Hence, it is not enough to know the local geology and geophysics-one must also estimate how the building stock will respond. Such an estimate requires an accurate inventory of the local building stock and predictive tools relating earthquake damage to building type.

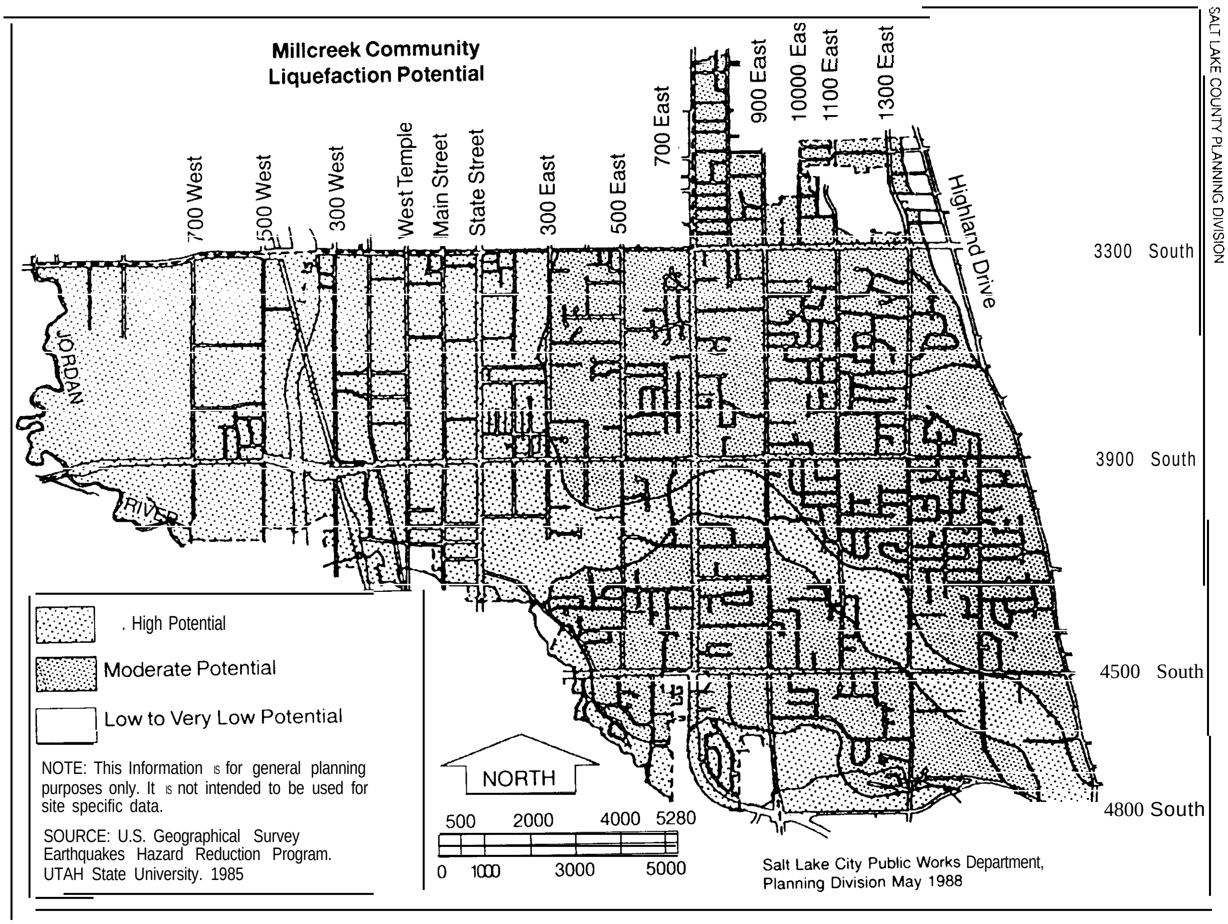
Unfortunately, most communities do not possess workable building inventories. Inventories may simply not exist, they may be outdated, or they may be expressed in terms that are of little use for mitigation (e.g., an inventory developed for tax or urban planning purposes might classify buildings according to function while including nothing about their construction).

A concerned community will therefore probably conduct a building survey to learn what buildings it has, what condition they are in, and where vulnerable structures are located. Again, this is not a straightforward task, particularly when it comes to the most worrisome older structures. That is, it is generally not enough to simply walk down a street and note down what buildings stand along it: a given "old building" might be made of unreinforced masonry; reinforced masonry; or some hybrid, much modified arrangement of wood, stone, metal, or concrete. Therefore, a judgment on its construction and vulnerability may require physical inspection by a specialist.[5]

Finally, having determined its building inventory, the community must relate that inventory to what it knows of the earthquake hazard and come up with an estimate for likely future losses. Ideally, this estimate will include economic loss and casualty figures broken down by building type and geography. Again, such an estimate is not straightforward, because the relation between earthquake damage and building design or construction is as yet poorly understood. However, if it can be done, such an estimate will allow a community to target those areas in which it is most vulnerable, and expend less of its resources in areas that are more robust.

Earthquake loss estimates thus function as a mitigation tool of singular importance. By reducing mitigation costs while increasing the likely

[5]The technical expertise requied for such an inventory suggests a possible avenue for federal implementation assistance.



Detailed risk assessment requires the preparation of small-scale seismic zonation maps, in which local geologic dangers are matched to features of the built environment. Here, the potential for liquefaction in a Utah community is over/am on a map 01 city streets.

benefits, a quantitative loss estimate can increase the effectiveness of current mitigation efforts while making it much more likely for as yet undecided communities to act. Unfortunately, although work is progressing on this front, reliable, consistent estimates are extremely difficult to obtain.[6]

The Office of Technology Assessment (OTA) notes an exceptional lack of quantitative information on expected earthquake losses in specific urban areas of the United States. Loss estimates have been made for certain regions (most notably, metropolitan areas in California), but variations in methodology, scope, assumptions, and even terminology make interpreting or comparing their results difficult. Further lacking are comprehensive data showing the change in expected losses that would result from mitigation--data essential to judging the cost-effectiveness of different mitigation measures. Indeed, many at-risk communities (particularly smaller urban centers in areas outside of California) have little more than a sense

[6]The Federal Emergency Management Agency, under NEHRP, is sponsoring the development of a computer-based loss estimation tool that could allow communities to estimate risk and prioritize risk reduction efforts.

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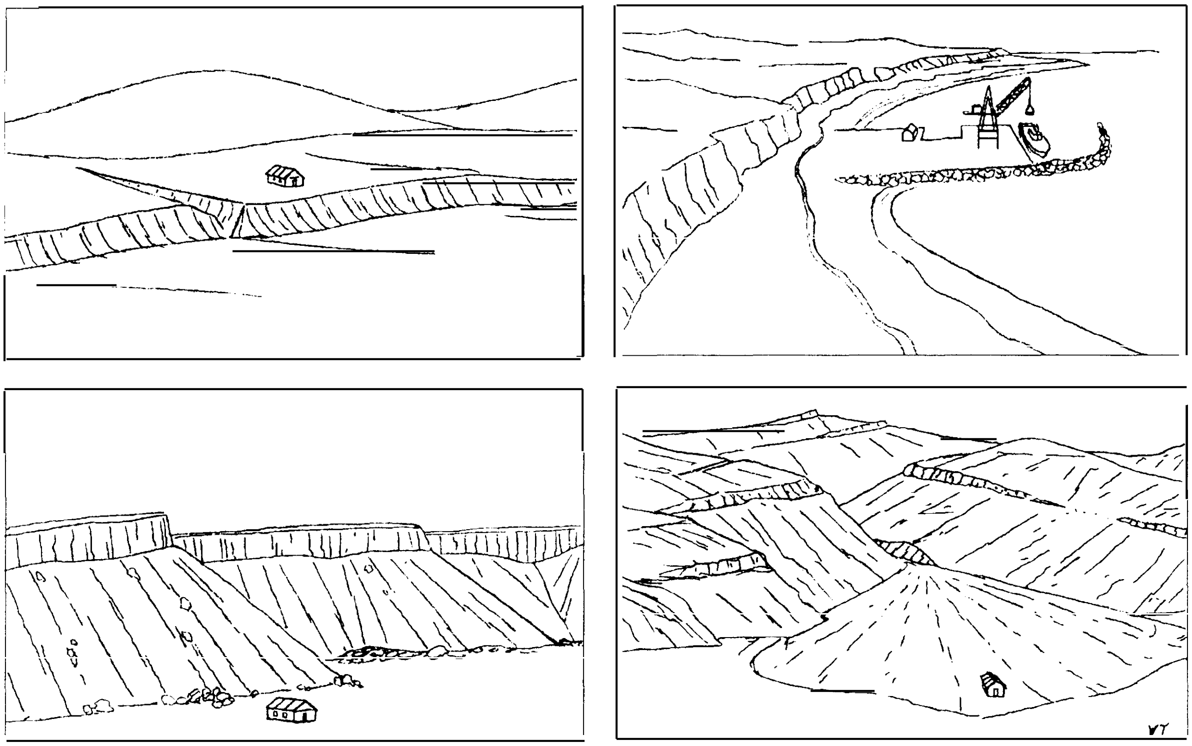


Land-use planning measures are best employed where local geologic conditions create unusually severe hazards (e.g., clockwise from upper left: fault scarps; landfills and land reclaimed from the sea; outwash and alluvial fans; unstable slopes).

that some sort of disaster might happen sometime in the future, and that some sort of preventive action should be taken. Missing are hard data on what are the expected losses, and in what functional and geographic areas will they occur. Without such data, communities can only guess how to respond.

■ Modifying the Built Environment

Having assessed the risk as well as it can, a community has a choice of mitigation tools with which to proceed. Possibilities include:

- land-use planning and zoning,
- building codes for new construction,
- retrofit or demolition of older construction, and
- systems-related, small-scale, and private activity (including emergency planning).

Although each of these has an impact on both life safety and economic loss, the first three tend to affect life safety issues, while the fourth is more directed toward economic damage.

Land-Use Planning and Zoning

The simplest and most drastic mitigation option is to avoid building things where earthquake hazards are expected. However, such an option is also the least used, and in practice land-use planning generally entails not the outright banning of development, but the tailoring of land use to forms less susceptible to earthquake damage.

Abolishing development on hazardous ground is most acceptable when the risk is clear, the alternatives are poor, and the geographical extent of the expected damage is limited. For earthquakes, circumstances meeting these criteria are relatively rare. The presence of a historically active surface fault rupture offers a possible candidate, in that the likelihood of future fault movement is evident, the engineering options are nonexistent (few structures can resist being torn in two, regardless of their construction), and the most damaging geologic effects occur in a tightly constrained area immediately adjacent to the fault.

However, even where conditions seem right, strict land-use measures such as development bans rarely appear as a mitigation tool. The history of earthquake disasters shows no end of instances where major structures have been built along known faults, even in seismically aware California (e.g., the stadium of the University of California at Berkeley sits atop the Hayward Fault), and with relatively rare exceptions (e.g., the "Faultline Park" in Salt Lake City), such measures are generally unpopular.

The roots of this unpopularity lie in the geographic nature of the earthquake phenomenon. Unlike floods, which typically strike clearly defined parts of floodplains and coasts, the primary earthquake hazard—ground shaking---can be distributed over an area so broad that general development bans become impractical (clearly one cannot halt construction in all of Los Angeles). Even local bans in places of obvious fault rupture or ground failure are often thwarted by a variety of socioeconomic objections (e.g., earthquake faults possess a perverse ability to create potentially valuable real estate with spectacular views). Moreover, typical seismic recurrence intervals of a lifetime or longer mean that bans must be maintained through years or decades of seismic inactivity.

The more likely use of land-use planning is thus in a milder form in which development on dangerous land, though permitted, is restricted to its less vulnerable forms. Thus, for example, a community might identify an undeveloped parcel of land that is subject to liquefaction or landslide, and limit construction to single-story, low-occupancy dwellings, or perhaps to noncritical industrial uses such as warehousing (such is one effect of California's Alquist-Priolo Act, see box 4-1). In this way, land-use planning is used not to prevent earthquake damage outright, but to reduce its direct and indirect impacts. Alternatively, a community might designate high-risk areas as sites requiring special geologic and engineering consideration before building can proceed (as in Utah's Salt Lake County Natural Hazards Ordinance, see box 4-2), thereby ensuring that vulnerably sited structures are more seismically resistant than the norm.

PHILIP R. BERKE

Areas of extreme earthquake hazard-such as this fault scarp in Utah—are often attractive locations for development.

Building Codes for New Construction

With land-use planning reserved for special cases, a concerned community will commonly turn to the most broad-based of mitigation tools—the incorporation of seismic provisions in building codes. By using codes to effect seismically resistant construction, a community can replace the bulk of its building stock over time with one less vulnerable to damage and collapse. Because the approach does not restrict or modify land-use patterns, and because it is relatively inexpensive when applied strictly to new construction (see chapter 3), it can be more politically palatable than a broad-based land-use planning approach.[7] For all these reasons, building codes are perhaps the most popular of implementation options, and are often (erroneously) thought of as the sole tool of mitigation.

[7] In some situations, land-use planning measures can be more politically acceptable than are broad-based building codes (as is the case in Salt Lake County, Utah.). However, such measures are adopted because they are *extremely* limited in geographic scope, and thus affect a relatively small number of buildings and structures.

BOX 4-1: Land-Use Planning in California: The Alquist-Priolo Act

The classic use of land-use planning to combat seismic hazards is California's Alquist-Priolo Act of 1972, This ordinance, which applies to the local government permit process for new construction, seeks to prevent structures from being built atop active earthquake faults. Its origins lie in the historical prevalence of active fault rupture (see chapter 2) in major California earthquakes, and reflects a belief that buildings and structures cannot be engineered to be resistant to fault motion. In concept, the act represents land-use planning in its purest form, and practical details of the act therefore illustrate basic problems in implementation.

The basic form of the Alquist-Priolo is as follows: the State of California, through its Division of Mines and Geology, identifies active faultlines and defines the land on and immediately adjacent to the faultlines as "Special Study Zones. " These zones are typically 600 feet to a quarter mile wide, with the width reflecting the degree of uncertainty over fault location and the amount of secondary fracturing of the ground on either side of the main fault. Those wishing to build within a study zone must submit a licensed geologist's report detailing the existence of active faults near the building site. If an active fault is found, buildings must be '(set back" from the fault (the amount of setback ranging from 10 to 50 feet, depending on the nature of the fault). In this manner, buildings are not sited where they are not expected to survive.

Though the Alquist-Priolo is straightforward in concept, practical matters of execution somewhat weaken its impact. The philosophical justification for the act is the government's responsibility to safeguard human life, and the legislation is therefore targeted at occupied structures. Structures occupied less than 2,000 person-hours per year are therefore exempt—an exemption that leaves out most lifeline system components (also exempt are single-family dwellings of wood frame construction, which though not resistant to fault motion, are less likely than other building types to fail in a lethal fashion). In addition, local expertise in geologic matters is required for successful implementation, as direct review authority over the required geologic reports is left to local governments.

Finally, the Alquist-Priolo contains a purely informational component, whereby a buyer of property that lies in a Special Study Zone is supposed to be informed of that fact. This provision of the act has been found to be largely ineffective in influencing buyer behavior.

SOURCE: Robert Reitherman, "The Effectiveness of Fault Zone Regulations in California, " *Earthquake Spectra,* vol 8, No 1 (Oakland, CA Earthquake Engineering Research Institute, 1992), pp. 57-78

Seismic codes, however, are not a panacea. In practice, their use involves a number of decisions and tradeoffs that can collectively reduce their impact:

- Seismic building codes do not govern every aspect of a community's building stock, but typically focus on specific parts of specific building types (thus ignoring certain aspects of building damage and economic loss).
- Codes cannot serve as a substitute for seismic engineering expertise, and indeed require skill and judgment on the part of their executors.
- Elements of the code adoption process (the steps that translate a seismic engineering recommendation into a specific code at the local level) often reduce code performance from the engineering ideal.
- Effective local enforcement of the code is crucial for reducing risk.

These points are discussed in turn.

Code coverage and philosophy

Although in theory codes can be written so that all buildings in a community are completely built to seismically resistant standards, in practice their application is more selective. Because the application of building codes involves a cost in money and effort, prioritization is necessary, and not all buildings and not all parts of buildings are treated equally.

BOX 4-2: Land-Use Planning in Utah: The Salt Lake County Natural Hazards Ordinance

A region subject to infrequent but potentially sizable earthquakes, the Salt Lake County of northern Utah (an area containing metropolitan Salt Lake City and some 40 percent of Utah's total population) uses land-use planning measures to reduce the impact of future damaging earthquakes. The intent of these measures is not to safeguard the general population, but to reduce the vulnerability of the built environment in unusually hazardous areas. This approach in part reflects the historical lack of seismic activity in the region and the consequent low public awareness of earthquakes and earthquake hazards: while broad-based mitigation measures such as new-construction building codes have engendered active regional opposition (because of feared mitigation costs), geographically limited land-use decisions—which are typically made by a small number of governmental and professional individuals—are less visible to the general public and hence inspire less controversy.

The centerpiece of the county's mitigation strategy is the Salt Lake County Natural Hazards Ordinance of 1989. Significantly, this ordinance does not treat earthquakes in isolation. Instead, seismic concerns are tied in with other natural hazards such as flood, landslide, and avalanche. This tactic allows the less common hazards--of which earthquakes are perhaps the rarest—to be handled by the same procedures that govern the most common, a move that further reduces opposition to the measure while minimizing additional implementation cost.

In outline, the ordinance works as follows: geologic and microzonation studies (some funded through the National Earthquake Hazards Reduction program (NEHRP) and the U.S. Geological Survey) are used to identify particularly dangerous "hazard zones. " Those seeking to develop sites within those zones can be required to prepare a special engineering geology study delineating ***all*** of the local natural hazards and explaining how the hazards will be dealt with (the nature of the hazard zone and the Intended use of the site dictate whether a study is called for). The study must then be reviewed by the county geologist, the Utah Geological Mineral Survey, and the Forest Service (in cases of avalanche threat), following which final approval must be obtained by the county's planning commissions.

The hallmark of this ordinance is extreme flexibility-a flexibility cited by county planning staff as crucial to the measure's success. With one exception (no buildings can be placed astride an active fault), the ordinance does not require any specific mitigation action. Developers are therefore free to develop their own mitigation tactics, be it through land-use measures like fault setbacks or through some engineering response. This flexibility is another factor favoring public acceptance of the ordinance, and is felt appropriate to the region's often complicated geology.

In turn, a flexible ordinance requires scientific and technical expertise on the part of county officials tasked with reviewing the engineering geology studies (and further demands that reviewers actively use their authority to halt unsatisfactory projects). Earlier incarnations of the ordinance were felt to suffer in effectiveness because this expertise was lacking. In this light, a critical contribution was made to regional mitigation efforts through NEHRP funding of a County Geologist Program from 1985 to 1988 This program, which placed a geologist on the staff of the Salt Lake County Planning Department to improve the geologic review process, was deemed so successful that the county chose to maintain the position following the expiration of federal funding.

SOURCES: Philip R. Berke and Timothy Beatley, *Planning for Earthquakes: Risks, Politics, and Policy (Baltimore,* MD The Johns Hopkins Universty Press, 1992), pp 40-62; and Carlyn E. Orians and Patricia A. Bolton, *Earthquake Mitigation Programs in Ca//forn/a, Utah, and Washington* (Columbus, OH: Battelle Human Affairs Research Centers, 1992), pp. 59-60, 69-70

SAN FRANCISCO CHRONICLE

Nonstructural damage-which most building codes do not address-can be considerable.

First and foremost, the seismic portion of a building code typically deals only with the building's so-called structural components (i.e., the frames, columns, beams, and load-bearing walls whose failure can lead to building collapse and consequent loss of life). Moreover, the structural components are not necessarily intended to survive a strong earthquake unscathed: if the component is damaged but does not collapse, the code is considered to have done its job. In other words, a code-complying building can "survive" an earthquake (i.e., not collapse and kill people) and still end up a shambles inside and out. This structural emphasis is in part philosophical, since the original intent of seismic codes is to safeguard human life. However, it also reflects a realization that greater levels of building protection entail greater construction costs.

Besides making a distinction between structural and nonstructural components, building codes distinguish in terms of building use. In general, structures that serve critical functions (e.g., hospitals) or house large numbers of people (e.g., schools) are held to a higher standard than are less important, more thinly occupied buildings. These distinctions again reflect the life safety focus of most codes and the great cost of more broad-based mitigation.

Because current codes are thus directed toward life safety, they have only an indirect impact on reducing economic loss. For one thing, the function or occupancy of a damaged building has little direct bearing on its cost of repair or replacement, and a focus on high-occupancy or critical facilities can leave vulnerable many less critical but costly structures. In addition, nonstructural building components such as stairwells, interior walls, ceilings, plumbing, and fixtures can be both dangerous and expensive in their own right (see table 4-l).

Concerns over earthquake-induced economic losses have led some to propose that the focus of seismic building codes be broadened to encompass more than issues of strict life safety. Overall damage reduction could then be pursued through the targeting of nonstructural as well as structural building components, or through the specification of minimum levels of post-earthquake building "functionality." In principle, such changes could be accomplished—although at some additional cost. As noted in chapter 3, however, the knowledge base for this is not yet well developed, and there is the chance that increased code complexity will cause its own problems (e.g., by perhaps aggravating already formidable problems in code enforcement).

Codes: no substitute for knowledge of seismic engineering design

Although a great deal has been learned in recent years about the design and construction of earthquake-resistant structures, most buildings are in fact designed by local architects and engineers far removed from the cutting edge of research. Some way must therefore be found to transfer knowledge and experience from the researcher to the practicing designer.

When resources are abundant, the knowledge transfer process can be direct. If the expense is warranted, one can require that a proposed structure be subjected to rigorous seismic engineering analysis by specialists in seismic design—that is, knowledgeable individuals with a professional obligation to stay abreast of developments in their field. Such an approach has the advantage of directly exposing the design process to individuals

TABLE 4-1: Nonstructural Building Elements Typically Unregulated by Seismic Codes

Exterior elements	Cladding, veneers, glazing, infill walls, canopies, parapets, cornices, appendages, ornamentation, roofing, louvers, doors, signs, detached planters.
Interior elements	Partitions, cellings, stairways, storage racks, shelves, doors, glass, furnishings (file cabinets, bookcases, display cases, desks, lockers), artwork.
Mechanical, electrical, and plumbing elements	Heating, ventilation, air conditioning equipment, elevators, escalators, piping, ducts, electric panel boards, life-support systems, fire protection systems, telephone and communication systems, motors, emergency generators, tanks, pumps, boilers, light fixtures.
Contents	Electronic equipment, data-processing facilities, medical supplies, blood bank inventories, hazardous and toxic materials, museum and art gallery displays, office equipment.

SOURCE: H.J. Lagorio, *Architectural and Nonstructural Aspects of Earthquake Engineering* (Berkeley, CA University of California at Berkeley, Continuing Education in Engineering, Extension Division, July 1987)

well versed in seismic principles, and is one often applied to major structures such as skyscrapers or nuclear powerplants.

The drawback of the engineering analysis approach is, of course, cost. Cost considerations are such that most buildings in the United States are constructed without the direct input of a seismic engineering specialist, and many of the smaller, more mundane structures (e.g., single-family dwellings) are "unengineered'' -that is, designed without any formal engineering input. For such buildings, seismic knowledge transfer can be accomplished through a code. Larger structures are governed by code guidelines that lead nonseismic engineers and architects through the design process; for smaller buildings, the codes offer specific, written requirements for how structures should be built. Such codes, which attempt to incorporate seismic design principles into buildings too small or inexpensive to warrant the involvement of a licensed structural engineer, in theory would require no specialized seismic engineering knowledge. That is, a competent builder or architect unversed in seismic engineering should, by following the code, be able to produce a structure that will not fall down in an earthquake.

In practice, however, the application of codes by competent but seismically unversed individuals will not always be successful. The reason for this failure is the need for flexibility within a building code. That is, although it is possible to write a "cookbook" code that unambiguously spells out exactly how a building should be built, such a code would be unworkable because:

- Successful results are most likely when the overall design of the building is of a type anticipated by the code writer—if the building is innovative or somehow out of the ordinary, the code may simply not apply.
- More fundamental] y, a cookbook code does not allow architects and engineers the flexibility to overcome the many unique obstacles that arise in designing buildings and structures.

Because of these concerns, building codes are written so as to give latitude for interpretation while providing some guidance for the inexperienced. Thus it is possible for the seismically inexperienced to rigorously follow a code, cookbook fashion, but still arrive at a vulnerable design.

In short, real-world variety in building design and construction requires that building codes be flexible, and this flexibility in turn requires that judgement be exercised in code execution. Thus building codes can work as intended only when working designers and building officials pos-

sess an adequate understanding of seismic design and engineering.

Code adoption process

The preceding discussion presupposes that seismic building codes are actually used in the design and construction of new buildings. How well a code works, however, is of little import if the code is never used. Local and state jurisdictions have considerable discretion over the content of their building codes, and many at-risk areas of the country have chosen to incorporate seismic codes only in part or not at all. The politics and economics of code adoption can thus have a greater impact on seismic safety than do technical issues of code performance.

The process of code adoption is as follows:

- The fruits of research sponsored by NEHRP and other organizations are distilled into a collection of reference documents, most notably:[8]
  1. *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, Federal Emergency Management Agency (informally referred to as the NEHRP Recommended Provisions);
  2. *Minimum Design Loads for Buildings and Other Structures, ASCE-7-93*, American National Standards Institute; and
  3. *Recommended Lateral Force Requirements and Tentative Commentary, Blue Book*, Structural Engineers Association of California.
- These documents, which give suggestions for the stress or force levels that a building must withstand, along with "detailing requirements" that specify the design and construction of critical joints and structural elements, are not building codes. They are instead recommendations that may be incorporated by regional code organizations into idealized "model codes," the most well-known of which is the Uniform Building Code (UBC) of the International Committee Conference of Building Officials, which is used by much of the western United States. (Other model codes include the Southern Building Code Congress International used by southeastern states, and the Building Officials and Code Administrators code used in the northeast United States.)
- Although a model code such as the UBC is in fact a real building code, it does not directly govern the construction of any buildings. Instead, state or local authorities may choose to incorporate it wholly or partly into the codes actually used within their jurisdictions.

There are thus a number of hurdles to be overcome between the creation of a seismic code provision and its implementation. At the highest level, that of the recommended provisions, considerable effort is made to maximize the provision's cost-effectiveness and political acceptability. A successful effort will enhance the provision's acceptability and hence its chances for eventual adoption, but the necessary changes have the effect of making codes minimal, rather than optimal, requirements. At the intermediate level, model code organizations may pick and choose among the recommended provisions in order to meet their members' economic and political concerns. At the end-use level, states and localities will apply their own criteria as well in adopting the model code. **The result can be a wide gap between a NEHRP provision and an actual state or local code**.

Code enforcement: a continuing problem

Finally, the existence of a local building code does little good if it is ignored when the building is designed, and code compliance in a building plan is similarly irrelevant if the actual construction of the building bears little relation to the design. These failings do not imply dishonesty or malicious intent. Simple calculation errors at the de-

[8] Henry J. Lagorio, *Earthquakes: An Architect's Guide to Nonstructural Seismic Hazards* (New York, NY: John Wiley & Sons, Inc., 1990), p. 246.

sign stage, for example, can result in a weakened building, and construction elements such as plywood shear walls can be rendered useless by sloppy nailing. To guard against these and other failings, **a community concerned with seismic safety must invest resources into code enforcement.**

Building code performance therefore requires that plans and the actual construction process be checked by competent inspectors. Unfortunately, few data exist on the performance of local plan- or code-checkers, but anecdotal evidence from California's Northridge earthquake and from Florida's Hurricane Andrew suggest that problems of code execution and compliance result in significant economic losses.[9] The problem is poorly documented but broadly recognized, and represents an area in which improved performance can have benefits beyond simple seismic safety (e.g., improved code enforcement has the potential to lessen losses from wind and fire as well).

In summary, building codes for new construction, although relatively popular and potentially powerful, are no silver bullet: they generally cover only structural collapse, they still require some level of seismic engineering knowledge in order to work well, they might not reflect the latest thinking as captured in model codes or NEHRP provisions, and they must be enforced.

Retrofit or Demolition of Existing Structures

Despite the problems that can beset code implementation, building codes for new construction remain a powerful tool for improving the safety of the built environment. However, when a community has a substantial older urban core and the risk of an earthquake is immediate, the codes may work too gradually. Since the average new building will typically stand for 50 to 100 years before replacement, a community can expect about 1 to 2 percent of its building stock to be replaced each year (more, if the community is expanding and flourishing; less, if it is economically stagnant). Thus if a damaging earthquake strikes within a few decades of a code's adoption, large parts of the building stock will be caught unprepared. A concerned community might therefore consider the most unpopular and contentious of mitigation measures—retrofitting or demolishing vulnerable existing structures (i.e., older structures that do not comply with the latest version of the code).

The unpopularity of this option is manifold. One problem is cost: unlike the case of new construction, in which code compliance adds some 1 to 2 percent to the total building cost, a retrofit/demolition plan can entail enormous expense. Retrofitting an unreinforced masonry building, for example, will generally cost one-quarter the price of a new building (and can in some cases cost much more),[10] while demolition and replacement will of course cost full building value. Such expenditures understandably instill resistance on the part of building owners or anyone else who must bear the expense. In addition, the money spent is not necessarily recouped in the event of an earthquake: retrofits are primarily intended to prevent building collapse, and in some instances a retrofitted building can be just as vulnerable to expensive nonstructural and contents damage as an unmodified structure.

In addition to economic issues, there are considerable objections based on quality-of-life and demographic concerns. Unreinforced masonry buildings, potentially the most dangerous existing buildings, are structures that form much of the urban core of many U.S. cities. They are often prized for two very different reasons: 1) they can embody much of the architectural heritage and character of a city, and 2) they tend to provide most of the low-cost housing used by lower income groups. Demolition is therefore unpopular from both an

[9] Although current life safety-oriented codes cannot eliminate economic losses, they do—by preserving the structural integrity of buildings—have an often significant impact on direct economic losses.

[10] See chapter 3, "Damage to Buildings," for references and assumptions.

architectural and a housing point of view, while retrofits can lead to rent increases that drive away the original residents. For these reasons alone, city planners may hesitate to take such action, particularly where (as in the central United States) there is great uncertainty about the timing of future earthquakes.

Private, Small-Scale, and Systems Preparation

The three mitigation tools discussed above—land-use planning and zoning, new construction building codes, and retrofit and demolition programs—primarily affect the structural integrity of the built environment. If the primary concern is to reduce loss of life, these tools may suffice. However, they are not enough to curtail major economic losses in the event of a damaging earthquake.

Recent experience (e.g., the 1989 Loma Prieta and the 1994 Northridge quakes) has shown that structural collapses, although spectacular and newsworthy, are by no means the only source of earthquake-related losses. Economic losses also stem from business interruptions; loss of records and computer databases in the service economy; disruption of roadways, utilities, and other lifelines; and widespread, noncatastrophic damage to residential and commercial structures throughout the earthquake region. Although it is difficult to quantify the effect of these losses (particularly in the case of indirect economic damage), their significance is suggested by one estimate of direct residential losses in future earthquakes. This estimate implies that catastrophic building failure, which is what codes and retrofits are designed to prevent, will be responsible for less than one-tenth of California's future bill for direct earthquake losses.[11] Even neglecting the potentially significant issue of indirect losses (i.e., those pertaining to the disruption of business and services), we thus find that traditional mitigation tools of land-use planning, retrofits, and building codes can be largely undirected at reducing the economic impact of a major earthquake.

To mitigate against economic damage, a community must therefore encourage a varied assortment of measures that are collectively referred to in this report as "private, small-scale, and systems preparations." These are measures adopted primarily by individuals, corporations, and utilities to reduce the economic losses caused by various nonstructural failures. The distinction between these measures and structural tools is somewhat arbitrary (e.g., structural building codes can help reduce nonstructural damage, and lifeline-related losses ultimately stem from the failure of bridges, dams, and other structures). However, as a group the measures are ones requiring motivation, careful thought, and tailoring of strategy by individual end users, and as such are not well suited to broad-brush, mandated approaches.

Examples of such measures are:

- Encouraging individual developers and building owners to adopt design and construction techniques that exceed code requirements. As noted earlier, codes serve as a minimum standard, and future structural and nonstructural damage might be averted if a structure is built to a higher level of performance.
- Developing, *before* a damaging earthquake, contingency plans for rerouting traffic, dispatching emergency crews, establishing alternative water, power, and supply sources, and otherwise taking action to reduce post-earthquake indirect losses. Such activity, which requires considerable time, expertise, and coordination, can be taken by both governmental and private entities.
- Motivating individuals, businesses, and organizations to systematically identify their own earthquake vulnerabilities and to take appropriate action. These actions can range from securing bookshelves and waterheaters by homeowners, to elaborate efforts on the part of

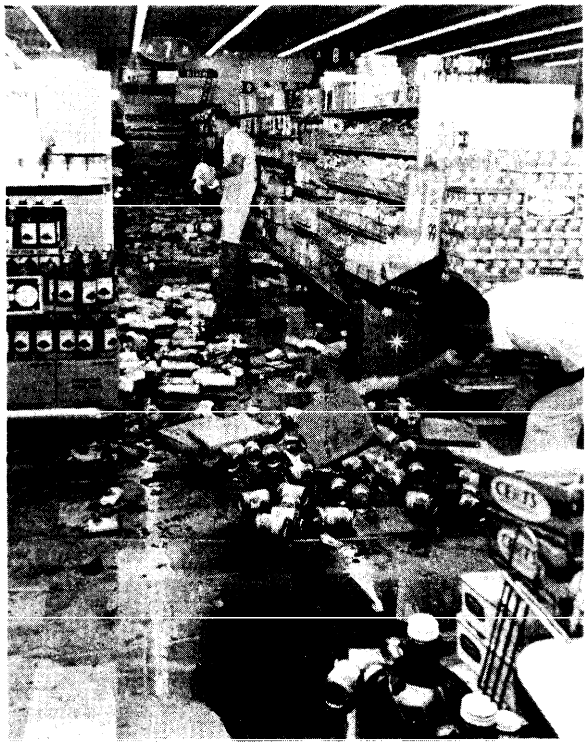
[11] Risk Engineering, Inc., "Residential and Commercial Earthquake Losses in the U.S.," report prepared for the National Committee on Property Insurance , May 1993, p. 17.

businesses, hospitals, schools, museums, and utilities to establish redundancies of power, services. computer databases, and the like.

Success in these efforts can work greatly to reduce the damage, injuries, and general chaos that may accompany earthquakes. The difficulty is that such efforts require diligent action on different fronts by different players, many of whom may care little about mitigation. Complicating matters is that most of these efforts require for their success that other measures be successful as well. For example, computer backups do little good if the computer resides in a building that collapses, and a single unsecured water heater can set an otherwise diligent neighborhood ablaze. Success thus depends on the community possessing a broad, active, and sustained level of public interest in mitigation.

■ Devising and Fostering Action

Once a community has decided on its choice of mitigation measures, it must put those measures into effect. The simplest action is to require (through regulation or mandate) that certain steps be taken. Such an approach, however, risks alienating the affected constituency (particularly in cases such as building retrofit or demolition, where high mitigation costs might be borne by a small group of individuals). Thus, in practice, many communities have chosen to develop alternative implementation strategies using financial or zoning incentives for mitigation, or (more weakly) through notices and disclosure laws warning potential renters or buyers of a building's noncompliance. Experience has generally shown that for success to be achieved, implementation schemes must be tailored to the particular political, socioeconomic, and geological conditions of a specific at-risk community, and that great pains must be taken to involve (as much as is possible) a broad-based constituency. Some possible approaches are illustrated in boxes 4-1 through 4-4. One potentially powerful implementation tool—the use of insurance to encourage the adoption of



Many earthquake losses cannot be eliminated through codes or other governmental measures, but require that individuals take steps to prepare.

seismic mitigation—is not discussed because of a lack of historical experience.

FACTORS AFFECTING IMPLEMENTATION

In the preceding section, some of the practical difficulties that arise in putting mitigation tools into effect are discussed. This section focuses on several underlying issues that more fundamental y influence implementation success.

■ Basic Problems

Communities interested in mitigation can encounter many frustrations in determining their level of seismic risk, in estimating their vulnerability to that risk, in assessing the short- and long-term economic consequences of mitigation, and in putting mitigation tools into effective action. Such difficulties arise even in the relatively straightforward process of improving life safety

BOX 4-3: Seismic Retrofit in Los Angeles, California

After California's San Fernando earthquake of 1971, in which buildings of unreinforced masonry (URM) construction experienced substantial damage, the nearby city of Los Angeles began considering ways of safeguarding its own URM building stock. Action was initiated in February 1973, via a city council motion to study the feasibility of seismic "building rehabilitation, " but eight years would pass before the landmark Los Angeles Seismic Ordinance finally became law. The twists and turns on the road to this ordinance—and the at times surprising impact it has had on local land-use patterns—illustrate some of the issues that can arise in the implementation of seismic retrofit programs.

Initial Action

Seismic retrofit action in Los Angeles was prompted by the San Fernando experience, by the 1971 passage of an earthquake hazards reduction ordinance in nearby Long Beach, and by the recognition that the city possessed many thousands of old, potentially vulnerable URM structures, many of which were extremely densely occupied. Concerns centered on life safety issues, with little priority given to minimizing earthquake-induced economic losses, and early attention focused on high-density, public-assembly buildings such as churches and movie theaters. This philosophy of targeting a select group of high-vulnerability structures quickly ran afoul of such community groups as architectural historians, who feared the demolition or visual modification of many of the city's historical landmarks, and groups such as the Association of Motion Picture and Television Producers, which felt that seismic ordinances would force the bankruptcy and closure of many marginal theaters (particularly since the proposed ordinances were combined with compliance requirements for structural, electrical, and fire safety codes from which the buildings had hitherto been exempt).

Vigorous community opposition to the proposed ordinances therefore led to the holding of public and city council meetings from 1974 through 1976. Following these meetings, it was decided to target only the most potentially catastrophic buildings: pre-1 934 URM assembly buildings that could contain over 100 occupants in the assembly areas. Because of continued concern over the financial implications of seismic retrofit (contemporary estimates placed retrofit costs at amounts comparable to the cost of an entirely new building), recommendations were also made that the retrofits be in part publicly funded by federal and state grants (for which lobbying efforts were initiated), low-interest loans, or tax incentives.

Work on establishing forms of financial assistance proceeded through 1976, but progress was Impeded by a combination of legal and engineering difficulties. One problem was that governmental assistance to churches or other sectarian-use buildings was deemed unconstitutional; another was a growing realization that very little was known about the true costs of seismic retrofit.

After three years without progress, an interim proposal in October 1976 suggested that the 14,000-odd buildings to be targeted by the eventual ordinance be prominently signposted as seismically hazardous By posting such information, the city hoped to invoke market forces for mitigation (by reducing market demand for vulnerable structures) before the start of seismic retrofit. This information-based proposal was strongly attacked by a host of citizen groups, among them the Hollywood Chamber of Commerce, apartment house owners, owners of commercial properties, and private attorneys. All expressed outrage and concern over possible effects on rents, property taxes, insurance rates, real estate sales, bank financing for renovations, lost jobs, and local economic development. Faced with this overwhelming opposition, the city tabled the proposal and redirected its efforts to the core components of the ordinance.

BOX 4-3 (cont'd.): Seismic Retrofit in Los Angeles, California

At this point in the controversy, studies were commissioned to determine the economic and social impacts of different proposals. Key issues included the breadth of the eventual ordinance (e.g., it was decided early on to cover a wide range of commercial and private building types, but to exempt single-family residences); the amount of time a building owner would be given to comply, the rapidity with which the program would be phased in and the prioritization given to different buildings and building types; and the type, availability, and impact of different financial assistance schemes. By 1978, these studies had identified specific concerns for the city council to address, among them: a continued lack of accurate retrofit cost estimates; a real possibility of substantial insurance premium hikes in the region, a significant likelihood of rent increases that would displace low-income residents; an insufficient municipal tax base for financial assistance (Proposition 13 had recently been passed); and an expectation that some businesses displaced during retrofitting would leave the city entirely.

Final Passage

With most of the concerns identified in the studies of 1977 to 1979 revolving around the economics of seismic rehabilitation, a breakthrough eventually occurred when three old URMs were found to stand in the path of a street-widening program. The city was persuaded to donate the three buildings for tests on the true costs of seismic retrofits. These tests, which were completed by 1980, showed retrofit costs to represent only about 20 percent of replacement costs—far less than had previously been suggested—and in so doing significantly weakened the economic objections to the proposed ordinance.

At last, after more lengthy debate, a seismic safety ordinance was formally adopted by the city on January 7, 1981—almost a decade after the initial impetus of the 1971 San Fernando earthquake. In its final form, the ordinance targeted all commercial URM structures and all residential URM buildings housing five or more dwelling units. After being notified by the city, owners of targeted buildings would have three years in which to bring their structures up to standard (this standard represents some 50 to 70 percent of the 1980 Los Angeles requirements for new construction). Buildings not brought up to standard would be demolished. To ease the impact on building owners and to facilitate bureaucratic execution, the ordinance allowed a one-year compliance extension should wall anchors (see chapter 3) be installed within the first year, and used a staggered notification schedule based on building type. Essential and high-risk facilities were to be targeted first, with lower risk structures to be dealt with later; as a result, some owners of low-risk buildings were not to receive official notification until 1988.

Impact of the Ordinance

From a seismic mitigation viewpoint, the Los Angeles Seismic Ordinance can be viewed as a success. Though the process has been more protracted than proponents might wish, a seismically vulnerable urban core is being prepared against the near-certainty of future earthquakes in the region. Should a damaging earthquake strike Los Angeles in the near future, it is extremely probable that many lives will have been saved by this measure. However, the ordinance has also generated side effects. Most notable has been the loss of low-cost housing, arising from owners raising rents in an attempt to recover out-of-pocket retrofit expenses. In addition, architectural and historic preservation has suffered-not because of building demolition (generally forbidden by historic building codes), but because of partial demolition, the removal of architectural ornamentation, and the filling in of windows.

(continued)

BOX 4-3 (cont'd.): Seismic Retrofit in Los Angeles, California

Perhaps the most surprising development has been a change in the overall appearance of some URM-lined streets, a change stemming from an unexpected interaction between seismic and fire safety regulations: noncompliance with existing fire safety codes has led many URM owners to close the upper floors (thus avoiding the cost of code compliance), and bring to compliance only the higher rent street level for use by commercial establishments (this partial vacancy is possible because fire safety codes need apply only to the occupied parts of a building). Because seismic retrofit must be applied to entire buildings—which means that vacant, nonproductive floors must be strengthened along with floors that are actually occupied—many of these URM owners have chosen to remove the upper floors entirely, leaving behind only single-story structures. Aside from aesthetic considerations, such removal further reduces the potential low-cost housing stock within the city's urban core.

WILLIAM SPANGLE AND ASSOCIATES, INC.

An unexpected side-effect of the Los Angeles seismic retrofit program was the partial demolition and conversion of multistory buildings into low, single-story structures

SOURCES: Daniel J. Alesch and William J. Petak, *The Politics and Economics of Earthquake Hazard Mitigation* (Boulder, CO, University of Colorado Behavioral Science, 1986), pp. 57-82; and Martha B Tyler and Penelope Gregory, *Strengthening Unreinforced Masonry Buildings in Los Angeles: Land Use and Occupancy Impacts of the L.A. Seismic Ordinance* (Portola Valley, CA William Spangle and Associates, Inc., 1990)

through building codes. When the goal is to reduce economic losses—which requires a much more comprehensive effort by both governmental and nongovernmental entities—the uncertainties are even greater.

Given these uncertainties, it is perhaps not surprising that many communities have encountered diffilculties in implementation. The problems are not insuperable in California-where earthquakes are frequent and severe enough to foster a desire for action—but even there one finds substantial variations in preparedness among different communities, and substantial difficulties persist in areas of retrofit and private or organizational activity. Outside California, matters are generally worse: in many hazardous regions, a relative lack of historical seismic activity produces a consequent lack of concern, so that even basic mitigation efforts languish.

■ Administrative Difficulties

In response to this inactivity, NEHRP has sponsored social science research on how and why communities act or fail to act. This research has shown that a number of forces conspire to weaken community will. Some of the difficulties stem from poor experience with existing mitigation ef-

BOX 4-4: Voluntary Retrofit in Palo Alto, California

While several communities in southern California have attempted mandatory retrofit and demolition programs to reduce the seismic vulnerability of urban centers (see box 4-3), the northern California city of Palo Alto has recently introduced a wholly voluntary, information- and incentive-based seismic retrofit program that is showing some early signs of success.

The origins of Palo Alto's voluntary program lie in two failed attempts at introducing mandatory, Los Angeles-style requirements. The first, a 1982 proposal targeting 250 unreinforced masonry, tilt-up (see chapter 3), and other vulnerable structures, succumbed to strong opposition from affected building owners and tenants. Following the defeat of this ordinance, the Palo Alto city council formed a broad-based citizen's Seismic Hazard Committee representing a range of public and private interests. This committee was intended to devise a second hazard mitigation plan that would reflect the concerns of the general community. However, the creation of the committee had the effect of greatly heightening community awareness of local seismic risk and hazard, with the consequence that the second proposal (in 1983) was far stronger than the first. This, too, went down in defeat—in part because of an inflexible retrofit timetable, and in part because proponents of the measure were hampered by extreme uncertainties regarding building vulnerability and the potential economic impacts of the ordinance. In light of these uncertainties, it was suggested that a voluntary program be instituted, one that would allow building owners to judge whether retrofit was economically justified, and one that would permit flexibility of approach and timing.

In 1986, a seismic ordinance was therefore passed in which no buildings were mandated for retrofit or demolition. The provisions of this ordinance areas follows: at-risk structures (particularly those with high occupancy) are identified and their owners given official notification. Following notification, building owners are required to contract with a structural engineer to evaluate building vulnerability and to suggest appropriate engineering fixes. Owners do not have to carry out the suggestions; however, they are required to inform building occupants in writing that an engineering study has been performed and that the results have been publicly filed with the city. In concert with the city's relatively high level of seismic awareness (fostered by the high education level of the citizenry, the work of the Seismic Hazard Committee, the presence of well-placed mitigation advocates within the local government, and extensive media coverage of earthquake disasters elsewhere), this notification is intended to affect rental and real estate prices in the city's highly competitive market. A March 1988 review of the program suggested that this market incentive is working as planned. To further increase the incentive, the city has also offered a zoning bonus, in which seismically upgraded buildings are allowed greater floor areas than is otherwise the norm. This bonus (again in concert with the city's strong economic health) also appears to be effective, to the extent that building owners who are unaffected by the program have sought (unsuccessfully) to obtain the bonus by having their own buildings included.

SOURCE: Philip R Berke and Timothy Beatley, *Planning for Earthquakes: Risks, Politics, and Policy* (Baltimore, MD: The Johns Hopkins University Press, 1992), pp. 63-81.

forts, which can suffer at the state and local level from:

- a lack of scientific and technical information in a form that local governments and private industry can easily use;
- overly stringent reporting, oversight, and approval requirements; and
- tasks that require more staff resources than are available (typically, implementation duties are assigned to but one or two persons in a state office).[12]

[12] VSP Associates, Inc., "State and Local Efforts To Reduce Earthquake Losses: Snapshots of Policies, Programs, and Funding," report prepared for the Office of Technology Assessment, Dec. 21, 1994.

More fundamentally, existing state and local efforts can suffer from a lack of hard information on earthquake risks and potential impacts. A recent survey of state activities has shown that **across the risk spectrum, studies of historical earthquake activity and assessments of current vulnerability are the two types of information essential to raising awareness, understanding, and commitment to seismic safety.[13]**

The Role of Advocates

Despite the difficulties that beset state and local mitigation efforts, considerable progress has been made by a number of concerned communities.[14] In many instances, this progress arises from the presence of well-placed mitigation "advocates"—energetic, often exceptional individuals in state or local government who adopt and push the cause of mitigation. Such advocates do not work in isolation. Rather, they can act as catalysts for action in communities where local political and socioeconomic conditions are conducive. Although their presence is not essential for action to occur, advocates can have an impact completely out of proportion to their numbers. Indeed, a number of cities owe the bulk of their mitigation progress to a handful of such individuals.[15]

Political Will

The importance of individual advocates, however, points out a larger problem besetting NEHRP: earthquake mitigation advocates (successful or not) are generally in the position of encouraging activity for which there is little initial enthusiasm. This reality has stern implications for efforts to reduce earthquake-related economic losses. While a few well-placed advocates can help convince governments to adopt building codes or land-use planning, they are less likely to create the groundswell of public action needed to substantially curtail future economic losses.

OTA's review of the implementation process has shown that effective mitigation depends on competent, committed action by a host of different individuals. This need is especially apparent in the case of private, small-scale, or systems-related efforts, which require that people design and implement their own mitigation schemes. Yet it is also true for the relatively straightforward use of building codes (i.e., an effective building code, adopted in full by the state or local authority, interpreted by engineers trained in seismic design principles, and enforced by experienced plan and code checkers working with the support of the local community) (see figure 4-1). To some extent, the many players in the chain can be persuaded or forced into action (at least for a while), but as a whole, implementation is greatly enhanced if there is an evident and sustained political will to support mitigation. Such is often not the case in the United States.[16]

Perceived and True Danger of Earthquakes

Nonfederal support for seismic mitigation suffers in part from the relation between earthquake risk and geography. At the federal level, interest in earthquake mitigation is sustained by a high prob-

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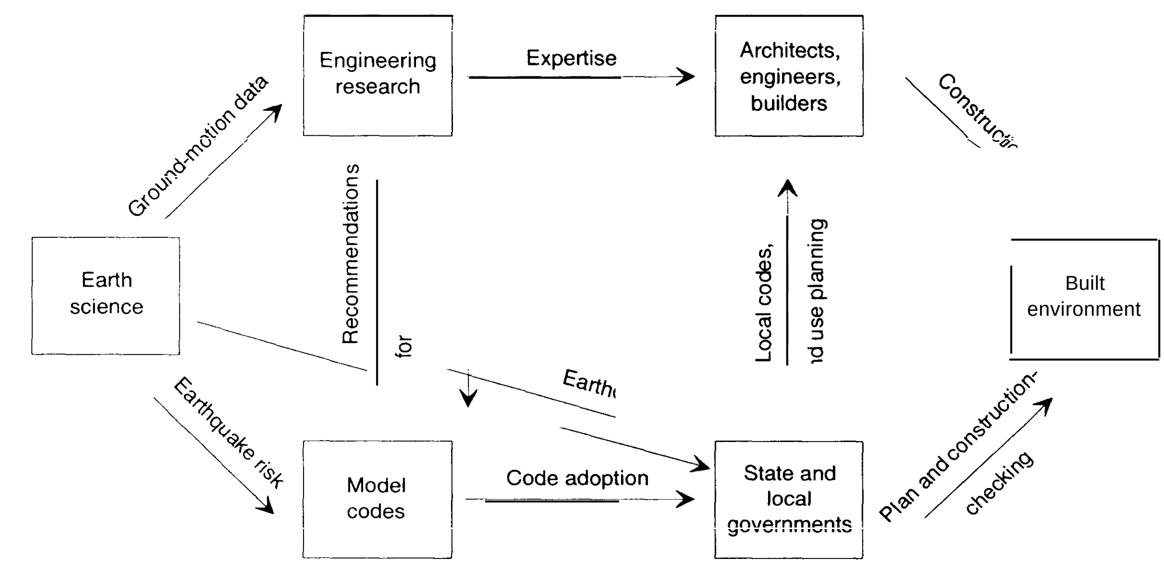
[13] Ibid.

[14] The report prepared for OTA indicates that California, Kentucky, Missouri, Utah, Arkansas, Washington, and Oregon devote particular attention to the formulation, adoption, and implementation of major policies. Ibid.

[15] Joanne M. Nigg," Frameworks for Understanding Knowledge Dissemination and Utilization: Applications for the National Earthquake Hazards Reduction Program," *A Review of Earthquake Research Applications in the National Earthquake Hazards Reduction Program: 1977-1987*, Walter W. Hays (ed.) (Reston, VA: U.S. Geological Survey, 1988), pp. 13-33; Philip R. Berke and Timothy Beatley, *Planning for Earthquakes: Risk, Politics, and Policy* (Baltimore, MD: The Johns Hopkins University Press, 1992), pp. 32-34; and U.S. Geological Survey, *Applications of Knowledge Produced in the National Earthquake Hazards Reduction Program: 1977-1987*, Open File Report 88-13-B (Reston, VA: 1988), pp. 20-22.

[16] Peter H. Rossi et al., *Natural Hazards and Public Choice: The State and Local Politics of Hazard Mitigation* (New York, NY: Academic Press, 1982), pp. 40, 71.

FIGURE 4-1: Implementation Steps and Key Players for the Application of Seismic Codes



NOTE Steps and players will differ for other types of mitigation measures

SOURCE Off Ice of Technology Assessment, 1995

ability of damaging seismic activity occurring within federal jurisdictional borders. To the extent that California bears the largest share of the country earthquake hazard, California state interest in earthquakes is also reasonably strong (it is not coincidental that California's mitigation efforts frequently surpass those of the federal government). For the rest of the country, however, the risk[17] of earthquake activity in any one state is considerably less than the nationwide risk borne by the federal government, and everywhere the local risk declines further when one considers the smaller governmental or organizational units. At the extreme is the plight of the individual building owner in a region such as the Northeast. This individual owns a structure that might never experience a damaging earthquake. If an earthquake occurs, the building may or may not collapse. If it does collapse, it is not certain that retrofitting would have saved it.

In short, while the federal government may have a legitimate interest in encouraging all building owners in the country to consider retrofits (on the assumption that at least some of those retrofits will do some good), an individual owner may see very little reason to embark on a costly action whose benefits are long term and uncertain. The owner lack of interest maybe based on a very rational analysis of costs and benefits, but can also be influenced by the short time horizon frequently observed in analyses of consumer decisionmaking (sometimes expressed as a high consumer discount rate), an influence that has been well documented in issues of energy efficiency,[18] and which has relevance to hazard mitigation.[19]

[17] *Risk* is used here as total exposure or potential for damage in an earthquake.

[18] See, e.g., U.S. Congress, Office of Technology Assessment, *Building Energy Efficiency,* OTA-E-518 (Washington, DC: U.S. Government Printing Office, May 1992), chapter 3.

[19] H. Kunreuther, "The Role of Insurance and Regulations in Reducing Losses from Hurricanes and Other Natural Disasters," *Journal of Risk and Uncertainty,* forthcoming.

With perceived risk at the individual level often very low, one can attempt to increase it through skillful use of the media and educational outreach. That the media can have significant impact on earthquake awareness is unquestioned, and history has shown that extensive media coverage in the aftermath of a damaging earthquake creates a temporary "window of opportunity" for rapid mitigation progress.[20] The importance of these windows—and the unpleasant reality that mitigation progress can easily stall after the window closes[21]—has prompted research on how one may best create a permanent perception of risk. Results have thus far been mixed—for example, some studies show that people already overestimate the risk of rare events such as earthquakes,[22] while others suggest that low probability risks tend to be ignored.[23]

Role of NEHRP

Given the general lack of sustained public support for mitigation, why does NEHRP depend so heavily on the unforced adoption of mitigation measures by nonfederal entities? In large part this dependence stems from the scientific circumstances that surrounded the program's birth. In broad terms, NEHRP was created during a period of optimism over the practicability of accurate earthquake prediction, and its original program mission (which specifically cites prediction as a goal) reflects that optimism. At the time of NEHRP's founding, the earth sciences had just emerged from a sweeping and profound revolution, one comparable to Darwin's theory of evolution in its scope, impact, and ramifications. This revolution was the advent of modern plate tectonic theory—a conceptual picture of the world that, through the 1960s and early 1970s, succeeded in tying together a host of previously unexplained and seemingly unrelated phenomena from across the earth sciences. Seismology—the study of earthquakes and earthquake-related phenomena—played an integral role in the development of plate tectonic theory; in turn, plate tectonics offered a simple unifying framework for understanding why, when, and where earthquakes should occur. The decade of the 1970s was thus one of extraordinary excitement in the earth sciences, and in this climate it was felt that short-term earthquake prediction, if not just around the corner, was at least conceivable, and that steady improvements in long-range earthquake forecasting would come with research.

The significance of this optimism from a policy standpoint is that it favors a mitigation strategy in which federal incentives for action are perceived as unnecessary. As we have seen, uncertainties in the timing, location, and severity of future earthquakes hinder both the acceptance and the execution of mitigation programs by nonfederal entities. Successful earthquake prediction, in removing this uncertainty, improves matters by providing a clear motivation for action and by delineating the intensity and geographic scope of the necessary mitigation, thereby constraining the cost.

In effect, a vastly refined foreknowledge of how, when, and where earthquakes occur can arguably be used to create both the desire and the expertise for the implementation of mitigation measures. In keeping with this philosophy, NEHRP was given neither regulatory teeth nor the authority to provide substantial incentives for mitigation. Instead, the program was intended to create a font of knowledge from which nonfederal

[20] U.S. Geological Survey, see footnote 15, pp. 27-28.

[21] Berke and Beatley, see footnote 15, p. 178.

[22] Andrew Coburn and Robin Spence, *Earthquake Protection* (Chichester, England: John Wiley & Sons, 1992), p. 315.

[23] Daniel J. Alesch and William J. Petak, *The Politics and Economics of Earthquake Hazard Mitigation* (CO: University of Colorado, Institute of Behavioral Science, 1986), p. 142; and Dennis S. Mileti et al., "Fostering Public Preparations for Natural Hazards: Lessons from the Parkfield Earthquake Prediction," *Environment*, vol. 34, No. 3, April 1992, p. 36.

authorities and the private sector would eagerly draw.

Although it is debatable whether NEHRP would have attained its societal goals even with widespread success in earthquake prediction (given the implementation difficulties discussed above), the fact is that prediction is not likely in the near future. This development is not the fault of the program. In fact, it is NEHRP-sponsored research that has begun to reveal just how complex, unpredictable, and variable earthquakes and their effects really are. Because of NEHRP we now know far more about earthquakes and far more about the structures and techniques that can withstand them. However, with this understanding comes a better appreciation of how deep and stubborn are the remaining uncertainties—uncertainties that work against the nonfederal adoption of mitigation measures.

HOW MATTERS MIGHT BE IMPROVED

The preceding sections have shown that implementation difficulties hinder both the adoption and the execution of seismic mitigation programs; these difficulties largely reflect the economic and political cost of mitigation as seen against a backdrop of uncertain seismic hazard and vulnerability. In the current NEHRP structure, federal activities to promote mitigation consist largely of outreach, media, and educational programs; such efforts may be expanded, or they may be supplemented by more aggressive implementation tactics (see chapter 1). Here, OTA suggests a range of directions that can improve mitigation efforts.

The implementation needs of California are largely different from those of the rest of the country. Within California, continual seismic activity in a heavily urbanized state has led to significant public and governmental awareness of earthquake risks and hazards. This awareness has resulted in California leading the country in mitigation and preparedness efforts. Because California already has in place a basic mitigation framework of new building codes, selective policies of land-use planning, and active public outreach programs through schools and the media, the main implementation issue is execution, rather than adoption. That is, although some adoption problems remain (notably, the retrofit of "pre-code" buildings that do not comply with the latest building standards), for the most part one can concentrate on expanding and optimizing the mitigation efforts that are already in play.

In contrast, regions outside California display a broad spectrum of mitigation activity, ranging from encouraging progress in some communities of the Pacific Northwest, to low or nonexistent activity in many parts of the East Coast, central United States, and Intermountain West. For some of these areas, earthquake severity and timing are such that seismic concerns are reasonably seen as low priority (e.g., Boston). In others, potentially high risks are masked by relatively short histories of urban settlement and a relative absence of frequent, moderate-level seismic activity (e.g., the Intermountain West). In concert with the extreme levels of scientific uncertainty that seem to surround non-California earthquakes, these factors have greatly inhibited the adoption of many mitigation measures.

Thus, in basic terms, one would hope to improve program *execution* in California while encouraging program *adoption* elsewhere. Efforts to achieve these aims can be made in each of the three NEHRP components: earth science, engineering, and implementation.

Earth Science Research Measures

Earth Science: Reducing Loss of Life

Earth science research efforts that can improve life safety in future earthquakes fall into two broad categories: basic research that will reduce the likelihood of "surprises" in the future size, location, and timing of severely damaging earthquakes (and in so doing, increase the likelihood that mitigation measures are adopted); and more directed, microzonation-style studies to identify localized troublespots. Both categories are of use throughout the country, although their roles vary subtly according to geography.

In areas where implementation is currently weak (i.e., much of the country outside of California), reductions in loss of life (and economic losses) require that seismic building codes and other mitigation measures be adopted by at-risk communities. **Because great uncertainties over earthquake location, severity, and timing act as a disincentive to action, the earth science priority here is for basic research that can better zero in on when, where, and how strongly an earthquake will strike**. This research must not only delineate where earthquakes are likely to occur (information that increases the perceived benefit of mitigation), but also identify areas of relative safety (which reduces the geographic extent—and thus cost—of mitigation).

Where there exists some degree of interest in seismic mitigation, the potential importance of microzonation-style research grows. In localities where the earthquake danger is recognized, such research allows communities to sidestep opposition to broad-based mitigation by narrowly targeting exceptionally hazardous sites (this is the approach taken by Utah's Salt Lake County Natural Hazards Ordinance, discussed in box 4-2). More mitigation-friendly locales will likely use such research to help prioritize efforts in seismic retrofit and demolition; to identify situations in which land-use planning is the most effective implementation option (i.e., places where no reasonable amount of engineering can overcome the effects of catastrophic liquefaction, landslides, or tsunamis); and to optimize building code provisions for the characteristics of future ground motions.[24]

Earth Science: Reducing Economic Losses

Although the importance of earth science research for life safety is clear, its role in minimizing economic loss is somewhat less so. This uncertainly stems from our lack of understanding of the true sources of earthquake economic loss.

On the one hand, successful earth science research can reduce future economic losses in those regions where mitigation activity is relatively weak. Where mitigation measures are hampered by uncertainty over risk and hazard, refined earthquake forecasts can encourage their adoption. In addition, microzonation research can allow otherwise reluctant communities to direct their efforts to geographically limited locales, thus fostering adoption where there would otherwise be none. In both cases, research can lead to loss reduction through the encouragement of basic mitigation activity.

In regions where mitigation measures are already in place, however, continued earth science research plays a more uncertain role. Because such regions typically experience high seismic activity (e.g., southern California), sheer prudence dictates that basic seismic research and ground-motion studies be continued so as to reduce the likelihood of major surprises in earthquake location and severity (surprises that can leave even a diligent community unprepared for a future calamity). However, in the absence of such surprises, there is the possibility that continued research will beget diminishing returns. At issue is the true source of earthquake economic losses: if the bulk of such losses stem from episodes of major damage, then refined earthquake and microzonation forecasts can reduce losses by permitting better targeting of vulnerable structures (particularly if the research is directed toward lifeline survivability). However, if the majority of earthquake losses stem ultimately from moderate-to-minor ground-shaking damage distributed over a wide area, then efforts to pinpoint local trouble spots (as well as to refine estimates of earthquake timing and location) will not address the major source of economic loss. **Uncertainty over the true origins of earthquake-induced economic**

[24] Damage in the 1994 Northridge quake indicates that even moderate earthquakes can subject buildings to stresses far greater than have been expected, and one must assume that larger quakes possess a similar potential. Credible ground-motion estimates, derived from microzonation-style modeling and from data collected in actual events, are therefore essential to writing effective building codes. However, such estimates will be of use only if actively transmitted to the engineering community in a manner that recognizes the need for codes to be stable over time.

losses therefore impede discussions of earthquake loss reduction, and remain an important avenue for social science research.

Engineering Research Measures

Engineering Measures: Reducing Loss of Life

From an implementation perspective, improved life safety can arise from engineering research if retrofit costs are brought down, and if better tools are devised to assess building vulnerability.

Particularly in California, where new construction is reasonably well handled by codes,[25] measures to save lives will center on older structures, particularly buildings of unreinforced masonry. Although many factors inhibit the systematic retrofitting of URMs and other noncomplying structures, a major obstacle to retrofit action is simply cost. Successful research into more cost-effective retrofit techniques—particularly if the techniques can be shown to reduce post-earthquake repair bills dramatically—can therefore make retrofit programs more palatable both to local policymakers and to building owners.

Opposition to retrofit programs can be further reduced if it can reliably be determined what buildings do *not* need to be retrofitted. For example, not all URM structures display the same vulnerability to earthquake damage, and a means of distinguishing the most vulnerable from the least can permit a more selective targeting of structures. Ongoing efforts to develop an analytic means of making such distinctions can therefore enhance program effectiveness while reducing the number of affected building owners and occupants.

Engineering Measures: Reducing Economic Losses

As noted above, current building codes focus on structural issues while giving little attention to nonstructural and contents damage. Because the latter kind of damage can generate most of the economic losses that accompany damaging earthquakes, research into effective, low-cost methods of reducing such damage might yield substantial rewards.

It is unclear, however, how to best incorporate nonstructural and contents damage concerns into current building codes. One difficulty is that such damage is often hard to proscribe in the language of a prescriptive code (e.g., a code cannot easily specify what steps a computer software company must take to safeguard its data and records, nor can it order individuals how to arrange furniture, bookshelves, or cooking equipment). Because of this limitation, one approach could be to replace prescriptive building codes with performance-based standards (i.e., codes that provide great flexibility of execution while requiring minimum standards of seismic performance). Such an approach has been adopted with some success in the construction of California hospitals, which are required to maintain functionality in the aftermath of a damaging earthquake (however, these codes are somewhat controversial in their need for painstaking execution). By defining design options appropriate to different levels of safety or performance, engineering research may increase the odds that performance-based codes attain a wider use.

A second approach to reducing economic losses would be to concentrate on the indirect effects of earthquake damage. In particular, because the federal government maintains some authority over lifeline systems (e.g., transportation and energy), a potentially significant avenue for economic loss reduction lies in the "hardening" (i.e., strengthening and introducing redundancy) of lifelines and vital response systems to reduce indirect losses and improve post-earthquake recovery. Such a move would be assisted by research into measures such as the preservation of potable and firefighting water systems, or the use of automatic shutoff devices on natural gas lines.

[25] Subject to the limitations noted in this chapter, including problems of enforcement and limited coverage of economic damage.

Direct Measures To Improve Implementation

More direct efforts to improve implementation will primarily involve education and outreach, technical assistance to nonfederal governments and organizations, and social science research into the nature of implementation bottlenecks. These efforts can be applied to the current implementation framework, or as preparation for a more vigorous federal mitigation role.

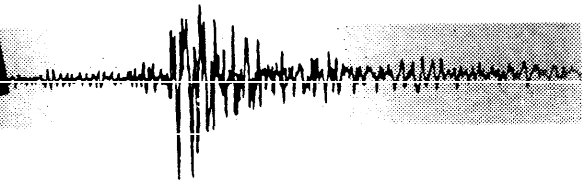
Actions that may assist implementation within the current framework include the following:

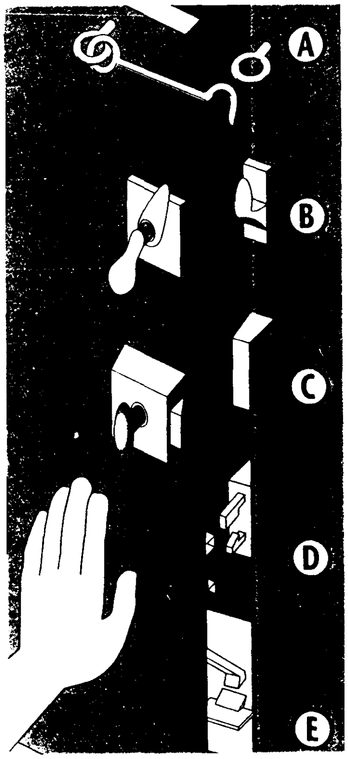
- Because individual local advocates and concerned professional organizations can play a powerful role in fostering and maintaining community interest in mitigation, efforts to create or assist advocates are of great potential impact. The federal government can assist advocates in this area by: ensuring that advocates have access to the latest information and educational materials on earthquake risks, supporting community activities as funding permits, or supplying direct technical and educational assistance to local or state governments.
- The more publicity there is concerning earthquakes, the more likely it is for individuals to become advocates. Thus media and public outreach activities can have a powerful indirect effect, both in fostering the appearance of advocates and in creating a supportive environment in which they may act. Public interest in earthquakes generally depends on how recently a major quake has occurred, but preparing outreach materials to take advantage of disaster windows is a prudent measure. Such outreach is relatively inexpensive and potentially productive, although in places where destructive seismic activity is extremely infrequent (e.g., the U.S. east coast), it is unlikely to create a surge of local activity.
- Research into the political and social science of mitigation success and failure can assist implementation by identifying stumbling points (e.g., factors hindering code enforcement) in the implementation process. Such research will not likely be undertaken without federal support.
- Perhaps the most promising implementation activity is to assist communities in their efforts at understanding risk, vulnerability, costs, benefits, and mitigation options. Workshops, conferences, and forums have been and will continue to be useful in disseminating such information, but strong efforts should be made to assign hard numbers to the predictions. In particular, communities must be given analytic tools for estimating likely losses in the event of a future earthquake, and credible means must be developed to predict the likely benefits of mitigation. At present, it is difficult to quantify these basic parameters, and it is this absence that perhaps most inhibits vigorous action at all mitigation levels.[26]
- In addition to supplying such informational assistance to at-risk communities, the federal government might wish to offer more direct technical aid. This aid can take the form of supplied expertise (e.g., mitigation efforts in the Salt Lake County of Utah were greatly enhanced by a three-year federal grant for hiring an in-house county geologist—see box 4-2), or through programs to assist in the education and training of engineers and design professionals in the principles of seismically resistant construction.
- To complement activities on the seismic front, efforts can be made to incorporate seismic implementation into a larger “all-hazards” framework. Much of the nonstructural preparation required for seismic mitigation (e.g., predisaster emergency planning) is useful in the event of fire, flood, wind storm, or other natural disasters, and can thus gain in political and eco-

[26] The Federal Emergency Management Agency is currently supporting development of a computer-based tool to assist communities in loss estimation, a promising endeavor that may considerably aid future implementation efforts.

HUMBOLDT EARTHQUAKE EDUCATION CENTER

What To Do Right Now To Prepare:





LATCHES

For manv residents of the North Coast a large financial Ioss will come if the doors of kitchen cabinets are shaken open, throwing contents to the floor. A few dollars spent now can prevent most of that loss.

In choosing a latch, consider looks and ease of use, The standard hook and eye(A) is an inexpensive and secure latch, but you may not close it every time you enter the cabinet because it takes extra effort to do so. A child-proof catch (E) prevents a door from opening more than an inch or two. These catches close automatically, but they require an extra action every time you open the door.

Some standard types of secure latches mount on the surface of the door (B, C). Latches are available that mount inside the door (D), hold the door firmly shut and open by being pushed gently inward. These are marketed under names such as push latch, touch latch, or pressure catch. If you cannot find these latches, ask your hardware dealer to order them for you.

Protect Your Belongings

Falling objects and toppling furniture can be dangerous and expensive to replace or repair.

- Move heavy items, such as pictures, mirrors or tall dressers, away from your bed.
- Secure tall furniture and bookcases with lag bolts to wall studs. Add lips to shelves to prevent costly items from sliding off. Be sure adjustable shelves cannot slide off their supports.
- Put latches on cabinet doors, especially at home in your kitchen and at work or school laboratories
- Fasten heavy or precious items to shelves or tables. Secure file cabinets, computers, televisions and machinery that may overturn during an earthquake.
- Store potentially hazardous materials such as cleaners, fertilizers, chemicals, and petroleum products in appropriate containers and in sturdy cabinets fastened to the wall or floor.
- In your office, be sure heavy objects are fastened to the building structure and not just to a movable wall. Ask a carpenter or an electrician to determine whether light fixtures and modular ceiling systems are securely fastened.
- Be sure your water heater is fastened to the wall studs and that all gas heaters and appliances are connected to the gas pipe through flexible tubing. If you use propane gas, be sure the storage tank is secured against overturning and sliding.
- Secure your wood stove to wall or floor studs. Make sure you have a fire extinguisher close at hand.
- Check with your school officials to be sure they have taken similar precautions.

6

Outreach and education materials, such as this pamphlet on safeguarding household effects, can both foster and guide mitigation efforts.

nomic attractiveness when viewed in a larger context.

- Lastly, consideration can be given to making NEHRP less of a purely voluntary, information-driven program by attaching strong incentives for action and regulatory or economic penalties to inaction (e.g., through changes in federal disaster relief or insurance). These options, which are discussed in chapter 1, can also act as a tool for enforcement (e.g., by using premortgage inspections to ensure building code compliance).

All of the above efforts require insight into the many political, economic, social, and practical forces that shape the implementation process. It should be reemphasized that the current understanding of these forces is by no means complete. Social science research into the behavior of communities and individuals is thus of considerable importance—all the more so if substantial changes to current policy are being considered (e.g., the possible use of mandatory earthquake insurance to foster seismic mitigation). Ongoing NEHRP-funded social science research has already illuminated many of the factors affecting implementation within the current NEHRP framework; this effort might profitably be strengthened or extended. In particular, substantial social science knowledge gaps remain that hinder efforts to improve NEHRP. Chief among these are the following:

- How might individuals respond to financial incentives (such as insurance) for implementation?
- Does the current de facto insurance framework (federal disaster assistance) inhibit state, local, and private implementation efforts, and if so, to what extent?
- Where do the true bottlenecks occur in the enforcement process for seismic building codes (e.g., to what extent does the trouble lie in onsite building inspection, in plan checking at the design stage, or in unexpected variability in construction practices and standards)?
- Will different parts of the country respond differently to proposed implementation strategies, and if so, what regional variations are to be expected?

Successful research into these matters will greatly improve action within the current implementation framework, and will be critical to any efforts at extending program scope.

Appendix A: The National Earthquake Hazards Reduction Program

A

The 1964 Alaska and 1971 San Fernando, California, earthquakes increased public awareness of U.S earthquake risks and led to numerous task forces, reports, and proposals for establishing a federal earthquake program. Then, in the mid-1970s, a number of events led to the growing momentum for federal legislation:

- China successfully predicted a major earthquake before it occurred, saving at least tens of thousands of lives.
- China and Guatemala suffered large and damaging earthquakes.
- The "Palmdale" bulge, a section of the San Andreas fault showing uplift, was identified.
- Various expert panels and committees released reports on earthquakes, some of which stated or implied that the United States was behind China, Japan, and Russia in its commitment to and understanding of earthquake prediction.
- There was considerable optimism in the scientific community that earthquake prediction was feasible. For example, a National Academy of Sciences report recommended that the United States make a national commitment to a long-term earthquake prediction program.[1]
- The President's Commission on Science and Technology put together a panel that produced a report (commonly known as the Newmark-Stever report) laying out a preliminary plan and budget for a federal earthquake program.

EARTHQUAKE HAZARDS REDUCTION ACT

Various bills to establish a federal earthquake program were introduced in Congress in the early and mid-1970s. However, none were enacted until 1977, when the Earthquake Hazards Reduction Act[2] was passed. Several aspects of the original legislation are worthy of note. First, it was developed and enacted in an era of great optimism about the potential for earthquake prediction—that is, accurate short-term forecasts of the location, magnitude, and timing of earthquakes. The legislation reflects this, for example, stating:

[1] National Research Council, *Predicting Earthquakes: A Scientific and Technical Evaluation—with Implications for Society* (Washington, DC: National Academy of Sciences, 1976), p. 3.

[2] Public Law 95-124, Oct. 7, 1977.

> A well-funded seismological research program in earthquake prediction could provide data adequate for the design of an operational system that could predict accurately the time, place, magnitude, and physical effects of earthquakes.[3]

Second, although the bill listed a number of nonresearch objectives, including public education and code development, much of the original legislation was directed toward research. For example, the bill authorized agency appropriations only for the U.S. Geological Survey (USGS) and the National Science Foundation (NSF), to conduct or fund earthquake-related research. Third, the legislation did not make clear how the nonresearch objectives were to be implemented. Instead, responsibility for implementation was given to the President, who was charged with developing an implementation plan. Thus, the program began with immediate activity by two relatively strong research organizations, USGS and NSF, but without a clearly defined implementation component and without a lead agency.

The President's implementation plan,[4] sent to Congress in 1978, gave much of the responsibility for implementation to a "lead agency," although just *which* agency was not specified. Other federal agencies were given specific tasks, including participation in a multiagency task force that was to develop design standards for federal projects. Executive Order 12148, dated July 20, 1979, designated the then newly created Federal Emergency Management Agency (FEMA) as the lead agency.[5]

REAUTHORIZATION HISTORY

The National Earthquake Hazards Reduction Program (NEHRP) has been reauthorized eight times since its inception (see table A-1); however, only two of these reauthorizations made significant changes to the program. The 1980 reauthorization[6] established FEMA as the lead agency, and extended NEHRP authorizations to FEMA and to the National Bureau of Standards (now the National Institute of Standards and Technology, NIST).

The 1990 reauthorization (Public Law 101-614) made several substantial changes. The Senate report accompanying the final bill noted several congressional concerns with NEHRP, including,

> . . . the slow and, in the view of many experts, inadequate application of research findings to earthquake preparedness; . . . the need to improve coordination of the agencies in the program and define better their roles; . . . the need to update and broaden the scope of the [NEHRP].[7]

In response to these and other concerns, the following major changes were made:

- references to earthquake prediction and control were downplayed;
- program objectives were clarified and expanded, for example, education, lifeline research, earthquake insurance, and land-use policy;
- the role of FEMA as lead agency was clarified and defined, for example, program budgets, written program plans, reports to Congress, a

[3] Ibid., sec. 2(4).

[4] Executive Office of the President, "The National Earthquake Hazards Reduction Program," June 22, 1978.

[5] U.S. Congress, General Accounting Office, "Stronger Direction Needed for the National Earthquake Program," GAO/RCED-83-103, July 26, 1983, p. 2.

[6] Public Law 96-472, Oct. 19, 1980.

[7] U.S. Congress, Senate Committee on Commerce, Science, and Transportation, *NEHRP Reauthorization Act,* Report 101-446 (Washington, DC: Aug. 30, 1990), p. 3.

TABLE A-1: Reauthorization H

Public Law number	Date of passage	Provided reauthorization for fiscal years	Significant changes or additions
95-124	Oct. 7, 1977	1978, 1979, 1980	Defined and initiated program. Authorized funds for U.S. Geological Survey and National Science Foundation only. Directed President to select lead agency for implementation.
96-472	Oct. 19, 1980	1981	Defined Federal Emergency Management Agency (FEMA) as lead agency. Authorized funds for FEMA and National Bureau of Standards (now National Institute of Standards and Technology).
97-80	Nov. 20, 1981	1982	None.
97-464	Jan. 12, 1983	1983	None.
98-241	Feb. 22, 1984	1984, 1985	None.
99-105	Sept. 30, 1985	1986, 1987	None.
100-252	Feb. 29, 1988	1988, 1989, 1990	None.
101-614	Nov 16, 1990	1991, 1992, 1993	Eliminated some references to prediction consequences and to earthquake control. Clarified objectives of National Earthquake Hazards Reduction Program, emphasizing implementation. Required seismic regulations for new federal buildings, and the adoption of seismic regulations for existing federal buildings. Clarified agency roles.
103-374	Oct. 20, 1994	1994, 1995, 1996	None.

SOURCE Off Ice of Technology Assessment, 1995

comprehensive education program, and grants to states;

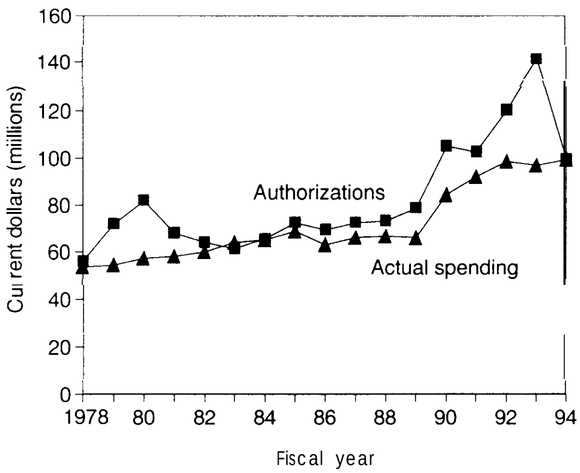
- the roles of USGS, NSF, and NIST were clarified (but not altered significantly); and
- the President was required to ensure that federal agencies issue seismic safety regulations for new buildings, and adopt seismic standards for existing federal buildings lacking adequate seismic resistance.

The 1994 reauthorization made no substantive changes in NEHRP, however the hearings and language in the report accompanying HR 3485 out of the House Committee on Science, Space, and Technology (now the Committee on Science) provide some insight into congressional views of and concerns with NEHRP. The report stated:

> The [House Science, Space, and Technology] Committee is concerned about the effectiveness of the NEHRP. Recent hearings have raised long-standing concerns about NEHRP—lack of an overall strategic plan; insufficient coordination among the agencies to shape a unified, coherent program; insufficient application of results of NEHRP research to limit losses; and inadequate emphasis on research to mitigate earthquake damage.[8]

[8] U.S. Congress, House Committee on Science, Space, and Technology, "Earthquake Hazards Reduction Act Reauthorization," Report 103-360, Nov. 15, 1993, p. 6.

FIGURE A-1: NEHRP Authorizations and Actual Spending, FY 1978-94



SOURCE: Office of Technology Assessment, 1995

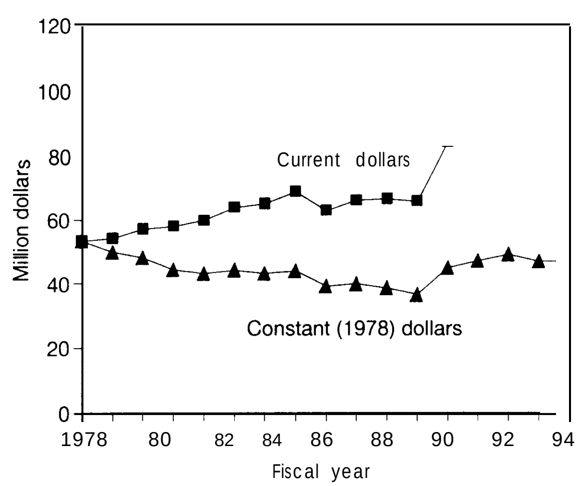
The Committee took two steps to address these concerns: first, members of the House of Representatives sent a letter to the President requesting an executive branch review of NEHRP. The executive branch review was given to the White House Office of Science and Technology Policy, which as of August 1995 had not yet issued their findings. Second, the Committee sent a letter to the director of the congressional Office of Technology Assessment (OTA) requesting that OTA "review Federal efforts to reduce earthquake damage." This report is OTA's response to that request.

BUDGET

As for all federal programs, the budget process for NEHRP involves two separate congressional processes, authorizations, and appropriations. NEHRP's authorizations give permission to the agencies to spend up to the amount authorized for the activities discussed in the legislation. The appropriations process, however, provides the actual funding to do the work. For NEHRP, as for almost all government programs, authorizations and appropriations are under separate committees of Congress. As NEHRP is a relatively small component of the agency budget, the congressional appropriations committees generally do not directly specify the amount of money to be spent on NEHRP activities. Instead, each agency determines its own budget priorities in conjunction with the Office of Management and Budget, and submits this budget (which specifies NEHRP spending levels) in the President's annual budget request. The appropriations committee, in turn, either accepts this overall budget level or sets it at a different level.

In the past, NEHRP authorizations have usually exceeded the actual spending (see figure A- 1). Actual spending has increased in current dollars, but has decreased overall in constant dollars (see figure A-2).

FIGURE A-2: NEHRP Spending, FY 1978-94 (in current and constant dollars)



SOURCE Office of Technology Assessment, 1995

Appendix B: Agency Efforts in the Current NEHRP

B

Four agencies—the National Science Foundation (NSF), the U.S. Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), and the National Institute of Standards and Technology (NIST)—have specific responsibilities within the National Earthquake Hazards Reduction Program (NEHRP). Figure B-1 shows the division of NEHRP funding among the principal agencies. This appendix describes each agency's current NEHRP efforts and outlines earthquake-related activities by other federal agencies that are outside the formal NEHRP framework.

U.S. GEOLOGICAL SURVEY

USGS receives the largest share of NEHRP funds—about $50 million in FY 1994, accounting for more than half of all NEHRP spending. In recent years, USGS has used its NEHRP funds to pursue four goals:

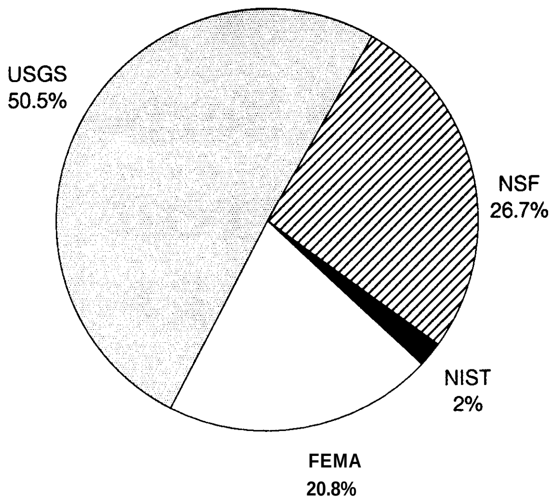
- understanding what happens at the earthquake source,
- determining the potential for future earthquakes,
- predicting the effects of earthquakes, and
- developing applications for research results.[1]

Supporting efforts span a wide range of activities, from research into basic earthquake processes to mapping expected ground motions for use in building design codes. More than two-thirds of NEHRP funding is used internally—to support USGS scientists in regional programs, laboratory and field activities, national hazards assessment projects, and seismic network operation. The remainder is spent as grants to outside researchers for specific projects. In general, the internal work focuses on applying knowledge to describe hazards, while the external program emphasizes expanding and strengthening the base of scientific knowledge.

Three specific aspects of U.S. Geological Survey's NEHRP-related work are discussed below: the geographic focus of the work, efforts made at

[1] Robert A. Page et al., *Goals, Opportunities, and Priorities for the USGS Earthquake Hazards Reduction Program*, U.S. Geological Survey Circular 1079 (Washington, DC: US Government Printing Office, 1992), pp. 1-2.

FIGURE B-1: NEHRP Spending by Agency, FY 1994



KEY: FEMA = Federal Emergency Management Agency; NIST = National Institute of Standards and Technology; NSF = National Science Foundation; USGS = U.S. Geological Survey.

SOURCE: Office of Technology Assessment, 1995, based on NEHRP budget data.

improving technology transfer, and the post-earthquake investigation program.

■ Geographic Focus

Concentrated for years primarily in California, USGS research and hazard assessment activities expanded in the mid- 1980s to include a multiyear effort to fully characterize seismic hazards along the Wasatch fault zone in Utah. Beginning in 1991, USGS divided a substantial portion of its resources among four regions where the earthquake hazard is most severe: southern California, northern California, the Pacific Northwest, and the central United States[2] (see table B-l). A regional coordinator is responsible for coordinating all aspects of the program with state and local agencies, engineering groups, county emergency managers, and planners.[3] Although California still receives the bulk of the funding set aside for regional studies, USGS has shifted toward a more national program. The most noticeable remaining gap in coverage is metropolitan areas in the Northeast that have significant seismic risk (e.g., Boston and New York City).

■ Technology Transfer

USGS has several programs intended to promote the use of agency-produced knowledge and tools. Examples include the following:

- USGS works with the California Division of Mines and Geology (a state agency) to develop geographical information systems for use in studying high seismic risk regions of the state.
- USGS supports the Southern California Earthquake Center (SCEC). SCEC is a multidisciplinary effort to catalog and quantify regional earthquake hazards and to transfer this information to the mitigation community. It is described further under NSF activities.
- With FEMA, USGS has assisted in establishing the Coordinating Organization for Northern California Earthquake Research and Technology (CONCERT). With members from government agencies and private sector organizations, CONCERT provides a framework for members to exchange ideas and hold public workshops. Their objective is more effective transfer of new technologies and research results to the region's engineering community.
- USGS encourages the exchange of ideas and expertise between "sister cities" with similar seismic risks. One of the first such exchanges

[2] The Pacific Northwest refers to northernmost California, Oregon, Washington, and Alaska; the central United States include Indiana, Illinois, Missouri, Kentucky, Tennessee, Arkansas, and Mississippi. Craig Weaver, Acting USGS NEHRP Coordinator, personal communication, May 9, 1995.

3 Along with three discipline coordinators (who oversee geographically based studies outside the four primary regions, laboratory and theoretical studies, and the national seismic network system), the four regional coordinators oversee peer review panels that advise USGS on funding priorities. Ibid.

TABLE B-1: USGS Spending Under NEHRP, FY 1995

Program element	FY 1995 spending (million dollars)		
	Internal	External	Total
Northern California	7,096.7	1,830.0	8,926.7
Southern California	5,385.2	1,900,0	7,285.2
Pacific Northwest	2,434.2	1,316,1	3,750.3
Central United States	1,853.6	1,000.5	2,854.1
National and international	2,772.1	1,067.2	3,839.3
Seismic networks	5,040.0	2,620.0	7,660.0
Earthquake process and theory	2,491.3	919.8	3,411.1
Southern California Earthquake Center		1,200.0	1,200.0
Other	7,870.0	2,118.4	9,988.4
Total	34,943.1	13,972.0	48,915.1

NOTE Other includes miscellaneous administration and program assessments.

SOURCE: Office of Technology Assessment, 1995, based on detailed U.S. Geological Survey budget data

involved hazard planners and engineers from Watsonville, California, and their counterparts in Anchorage, Alaska. Other sister-city meetings are planned.

- USGS operates the National Earthquake Information Center (NEIC) in Golden, Colorado. NEIC has three main missions: 1) to determine, as accurately and rapidly as possible, the location and magnitude of damaging earthquakes; 2) to collect and distribute seismic data for use in research; and 3) to pursue research into locating and understanding earthquakes. In support of these missions, NEIC distributes a number of products (see table B-2).

  USGS makes earth science data and maps available over the Internet. For example, data centers in northern and southern California provide maps of recent regional earthquakes, the location of and data from geodetic and seismic monitoring stations, and links to other Internet sites with related data or topics. Other information is becoming increasingly available for use by researchers, educators, and the public.

Future Directions

NEHRP achievements in recent years include increased awareness on the part of state and local officials, engineering associations, and other private sector organizations of earthquake hazards and risks. According to USGS, these groups have become more sophisticated as to what they need next from NEHRP. To better serve their needs, USGS has redesigned the major elements of its FY 1996 NEHRP effort as follows:

- assessing national and regional earthquake hazard and risk,
- assessing major urban area earthquake hazard and risk,
- understanding earthquake processes,
- providing national real-time earthquake hazard and risk assessment, and
- providing national geologic hazards information services.[4]

[4] Ibid.

TABLE B-2: National Earthquake Information Center Products

Title	Description
Quick Epicenter Determinations	Very preliminary list of significant quakes, compiled daily and available for computer access by telephone line.
Preliminary Determination of Epicenters	Initial locations prepared and distributed weekly to those contributing data to the NEIC; also published in a monthly listing available via the Superintendent of Documents in Washington, DC.
Earthquake Data Report	Monthly publication that provides additional, more detailed Information for seismologists on a data exchange basis.
Other products	CD-ROMs, maps, and an annual book of U.S. earthquakes.

SOURCE U S Geological Survey, National Earthquake Information Center, 1994 *Guide to Products and Services* (Golden, CO 1994)

Post-Earthquake Investigations

The 1990 NEHRP reauthorization[5] directed USGS to establish a post-earthquake investigation program, to study and learn lessons from major earthquakes. USGS has supported post-quake work for both U.S. and non-U. S., major earthquakes. This work has allowed USGS to collect perishable data on aftershocks and earthquake-induced damage.

After the Northridge earthquake in 1994, Congress passed a supplemental appropriations bill that, in part, funded USGS to install a seismic monitoring system that can better measure strong ground motions. This system will improve the ability to provide real-time information on earthquake size, location, and likely effects.

NATIONAL SCIENCE FOUNDATION

NSF receives about one-quarter of the NEHRP funding. Its NEHRP spending is in two distinct areas: fundamental earth science, and engineering and social science research. The earth science research, overseen by the Earth Sciences Division in the Directorate for Geosciences, accounts for 11.4 percent of NEHRP funds in FY 1994. The engineering and social science research in the Earthquake Hazard Mitigation Program within the Directorate for Engineering accounts for 15.6 percent of NEHRP funds. Figure B-2 provides funding trends in current dollars for both areas.

Earth Science Research

NSF uses NEHRP resources to support earthquake-related earth science research through two main channels: direct grants to researchers and support for various university consortia, including the Incorporated Research Institutions for Seismology (IRIS) and the Southern California Earthquake Center (see table B-3). In addition, using non-NEHRP funds, NSF supports the University Navstar Consortium (UNAVCO) that provides technical assistance and equipment to investigators for geodetic studies and other earth science research.

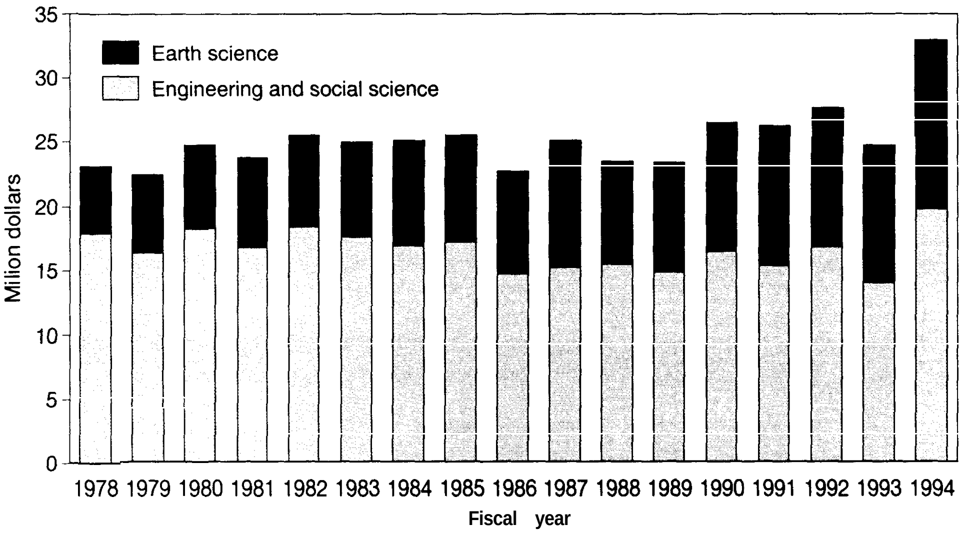
Direct Grants

NSF awards research grants directly to investigators for the study of earthquake sources, active tectonics, earthquake dating and paleoseismology, and shallow crustal seismicity.[6] For FY 1990 to 1994, instrument-based seismology, geodesy, and other tectonics received the bulk of the awards (on

[5] Public Law 101-614, Nov. 16, 1990.

[6] James Whitcomb, Director, Geophysics Program, National Science Foundation, personal communication, Nov. 21, 1994.

FIGURE B-2: NSF Spending Under NEHRP, FY 1978-94



SOURCE Office of Technology Assessment, 1995, based on National Science Foundation budget data

the order of 90 percent); paleoseismology and microzonation efforts, in contrast, comprised about 5 percent of the overall budget for direct grants (see table B-4).

Incorporated Research Institutions for Seismology

IRIS is a university-based consortium that supports research in seismology by providing facilities for instrumentation and for data collection, archiving, and distribution. IRIS is supported by NSF (in part with NEHRP funds) and by the Air Force Office of Scientific Research.

IRIS, in partnership with USGS, is building a multiuse global network of modem, digital seismograph stations. According to IRIS, the Global Seismographic Network supports NEHRP by enabling detailed assessments of the frequency of earthquakes around the world and of their anticipated ground motions. In 1994, 20 new stations were added to the network, bringing the total to 72.[7]

Through PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere), IRIS provides portable instrumentation and support facilities for the study of seismic sources and earth structure. Under development is the Rapid Array Mobilization Program, intended to support rapid deployment of instruments in the field immediately after a large earthquake or volcanic event.[8]

Another significant function of IRIS is the Data Management System, which tracks the operation of the stations and archives the data. In addition, the IRIS Data Management Center (in Seattle, Washington) makes available via the Internet these data, customized data products, and a number of other historical data sets.

[7]Incorporated Research Institutions for Seismology, 1994 *Annual Report* (Arlington, VA: 1994), p. 5.

[8]Incorporated Research Institutions for Seismology, 1992 *Annual Report* (Arlington, VA: 1992), p. 18.

TABLE B-3: NSF Earth Science Spending, FY 1994

Element	Spending (million dollars)
Direct grants	$4,3
incorporated Research Institutions for Seismology	3.6
Southern California Earthquake Center	3.3
Total	**$11.2**

SOURCE: Office of Technology Assessment, 1995, based on detailed National Science Foundation budget data

TABLE B-4: Allocation of NSF Investigator Awards in Earth Science, FY 1990-94

Research area	Award totals (thousand dollars)	Percentage of overall awards
Seismology	$10,450	48.3
Tectonics		
Geodesy	3,763	17.4
Nongeodetic	4,966	22.9
Paleoseismology	711	3.3
Microzonation	383	1.8
Tsunami	305	1.4
Other	1,077	5.0
Total NSF grants	$21,655	100,0

NOTES: Other includes support for workshops, travel, and conferences. The total does not include staff salary and expenses.

SOURCE. Off Ice of Technology Assessment, based on 1994 National Science Foundation geosciences award data

Southern California Earthquake Center

SCEC serves as the focal point for regional studies of earthquake hazards and risk mitigation measures. The principal institutions involved are: University of Southern California; University of California-Los Angeles, San Diego, and Santa Barbara; California Institute of Technology; and Columbia University.

The center has a multidisciplinary outlook that promotes earthquake hazard reduction by defining when and where damaging earthquakes will occur in southern California, calculating expected ground motions, and communicating this information to the practicing engineering community and the public. Products include conditional probabilities for major faults, maps of seismotectonic source zones and regional probabilistic seismic hazards, assessments of the implications of recent patterns of seismicity in the greater Los Angeles area, and up-to-date earthquake source databases.

SCEC also supports the operation of a seismic network and several data centers. In addition, the center has facilitated installation of a comprehensive crustal strain monitoring network using the Global Positioning System (GPS). This is intended to provide improved hazard estimation from regional strain rates and increased understanding of post-quake deformation patterns.

TABLE B-5: NSF Earthquake Engineering Budget (excluding NCEER), FY 1994

Area	Budget (thousand dollars)	Research examples
Geotechnical	$2,621	Liquefaction, tsunamis.
Structural	2,722	Active controls, repair and rehabilitation.
Architectural and mechanical systems	2,719	Active controls, hazard evaluation.
Earthquake systems integration	2,567	Planning, social science.
Total	$10,629	

NOTE: Including the $4 million awarded to the National Earthquake Engineering Research Center (NCEER), the total FY 1994 National Science Foundation engineering budget was $14.629 million.

SOURCE: Office of Technology Assessment, 1995, based on National Science Foundation detailed budget data.

Principal support comes from NSF (SCEC is an NSF Science and Technology Center) and USGS; SCEC is also supported by FEMA, the California Department of Transportation, and the City and County of Los Angeles.

University Navstar Consortium

UNAVCO maintains a standardized GPS equipment pool and data archiving center. One of the primary applications of geodetic measurements to earthquake research is the comparison of contemporary plate velocities and the rates of intraplate and plate boundary zone deformation with geological and geophysical observations and models.[9] Space-based techniques have revolutionized geodetic studies; they offer significant improvements over surface techniques in several applications.

Earthquake Engineering

The NSF earthquake engineering budget for FY 1994 was $14.6 million. It includes $4 million for the National Center for Earthquake Engineering Research (NCEER); the remainder is divided among four major research areas (see table B-5).

National Center for Earthquake Engineering Research

NCEER, located in Buffalo, New York, was established in 1986 with a five-year, $25-million grant from NSF.[10] This grant was renewed in May 1991 for five more years and $21 million. Additional funds for the center are provided by the State of New York and by various institutions.[11] The center mission is to "advance engineering, planning and preparedness to minimize the damaging effects that earthquakes have."[12] As summarized in

9 University Navstar Consortium, FY 95-99 Proposal (Boulder, CO: n.d.), p. 7. Besides earthquake-related research, UNAVCO staff collaborate with the National Aerobatics and Space Administration, the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration, the Federal Aviation Administration, and university investigators in projects related to solid earth dynamics, climate, and meteorology.

10 The decision to award this grant to the State (University of New York at Buffalo, instead of to a competing bid from California researchers, was a controversial one. The story of this battle is told in VSP Associates, Inc., "To Save Lives and Protect Property," final report prepared for the Federal Emergency Management Agency, Nov. 1, 1988, appendix C.

11 For example, the total NCEER budget in 1993-94 was $11.5 million: $4.0 million from NSF, $3.0 million from the Federal Highway Administration for research into the seismic vulnerability of the national highway system, $2.0 million from the state of New York, and $2.5 million from other sources. National Center for Earthquake Engineering Research, *Program Overview 1992-94* (Buffalo, NY: 1994), p. 30.

12 Ibid., p. 1.

TABLE B-6: Research Funded by NCEER, 1993-94

Area	Funding (thousand dollars)	Examples
Seismic hazard and ground motion	$384	Ground motion and site response, seismic zonation.
Geotechnical engineering	375	Liquefaction and lifelines,
Structures and systems	1,025	Retrofit methods, lifeline system analysis,
Risk and reliability	344	Development of risk-based design criteria,
Intelligent and protective systems	826	Base isolation, hybrid control systems,
Socioeconomic Issues	600	Insurance and mitigation relationships, estimating damage with geographical Information systems, hazard perception,
Implementation activities	446	Workshops, education and training.

SOURCE: Office of Technology Assessment, 1995, based on unpublished National Center for Earthquake Engineering Research (NCEER) budget data

table B-6, the research portfolio supported by NCEER ranges from geotechnical engineering to socioeconomic issues.[13]

Geotechnical

NSF-sponsored work on geotechnical engineering includes studies of liquefaction, tsunamis, the response of soils to earthquakes, and the response of structures to ground motion. This research is, for the most part, applicable to all structures, including new and existing buildings and lifelines.

Structural

NSF-funded efforts in structures and earthquakes include support of research in active and hybrid control systems, design methodologies, seismic behavior of components such as reinforced concrete frames or precast panels, and lifeline design. A significant fraction of the research in this category is in the area of "structural control"—the use of active or hybrid intelligent control systems to reduce seismic damage in structures.

Architectural anti Mechanical Systems

Much of the work in architectural and mechanical systems looks at specific building components such as composite walls and reinforced concrete frames. As in the structural category, active or hybrid controls are a significant topic, accounting for almost one-third of the funding in this category.[14]

Earthquake Systems Integration

Behavioral, social science, planning, and similar research is funded in earthquake systems integration. Issues addressed include code enforcement, decisions to demolish or repair a building, information transfer, and international comparisons of mitigation.

[13] For further information, see National Center for Earthquake Engineering Research, *Research Accomplishments 1986-1994 (Buffalo, NY:* September 1994).

[14] Research into *structural control, active control, hybrid control,* or similar phrases accounts for 32 percent of funding in the architectural and mechanical areas. Source is NSF detailed budget data.

FEDERAL EMERGENCY MANAGEMENT AGENCY

FEMA has two distinct roles in NEHRP: 1) as lead agency, FEMA is charged with overall coordination of the program; and 2) it also has responsibility for implementation of earthquake mitigation measures.

History

FEMA's role in NEHRP can best be understood by looking at how its role has evolved over time. When NEHRP was founded in 1977, the legislation called for a lead agency but did not specify what agency was to take that role. FEMA was given lead agency status by executive order in 1979. This was confirmed by Congress in the NEHRP reauthorization for 1981,[15] which also provided an explicit authorization for FEMA spending on earthquakes.

In the early years of its NEHRP activities, FEMA functioned primarily as a coordinator rather than as a strong leader or director. A 1983 U.S. General Accounting Office (GAO) report criticized FEMA's leadership, noting that FEMA had not carried out several responsibilities assigned to it in the legislation. GAO found that "FEMA could better prepare the United States for a major earthquake by more aggressively implementing the [NEHRP] act's requirements and providing stronger guidance and direction to Federal agencies."[16] In 1987, an expert review committee, assembled to assist in NEHRP planning and review, noted that "serious questions were raised regarding FEMA's performance in its assigned role."[17] The committee recommended the creation of an oversight commission, with some budget authority for NEHRP activities.

The 1990 NEHRP reauthorization contained extensive reference to FEMA's role in NEHRP. Although there was not a clear change in FEMA's role, the legislation specifically directed FEMA to:

- prepare an annual NEHRP budget for review by the Office of Management and Budget,
- prepare a written NEHRP plan for Congress every three years,
- operate a program of state grants and technical assistance, and
- ensure appropriate implementation of mitigation measures.

According to the Senate report accompanying the legislation, the intent of this language was in part to separate FEMA's leadership function from its operational (implementation) role.[18]

The 1993-94 reauthorization hearings suggest that concerns over coordination and implementation continue. In the Senate hearings, a senator asked of the witnesses, "Has coordination among the four NEHRP agencies improved?"[19] In the House hearings, a representative asked, "Is the program doing enough to ensure application of its findings?"[20]

[15] Public Law 96-472, Oct. 19, 1980.

[16] U.S. General Accounting Office, "Stronger Direction Needed for the National Earthquake Program," GAO/RCED-83-103, July 26, 1983, pp. i,ii.

[17] Federal Emergency Management Agency, "Commentary and Recommendations of the Expert Review Committee 1987," p. xiii.

[18] U.S. Congress, Senate Committee on Commerce, Science, and Transportation, *National Earthquake Hazards Reduction Program Reauthorization Act*, Report 101-446 (Washington, DC: Aug. 30, 1990), p. 12.

[19] U.S. Congress, Senate Committee on Commerce, Science, and Transportation, Subcommittee on Science, Space, and Technology, hearing, May 17, 1994, p. 4.

[20] U.S. Congresss, House Committee on Science, Space, and Technology, Subcommittee on Science, hearing, Sept. 14, 1993, p. 2.

TABLE B-7: FEMA Major Budget Components, FY 1993

Area	Approximate budget (million dollars)	Examples
Leadership	$1.3	User needs assessment.
		Small-business outreach program.
		NEHRP plans, reports, and coordination.
Design and construction standards	5.0	Manual for single-family building construction.
		Preparation of seismic design values.
		Preparation of NEHRP Provisions.
State and local hazards reduction	6.1	Grants to states and cities for mitigation programs.
		Grants to multistate consortia.
Education	1.1	Training in use of NEHRP Provisions.
		Dissemination of information on retrofit techniques,
Multiple hazards	1.7	Loss estimation software development.
		Wind-resistant design techniques,
Federal response planning	0.9	Urban search and rescue.
		National federal response.

SOURCE: Federal Emergency Management Agency, Office of Earthquakes and Natural Hazards, "Funds Tracking Report," Nov. 9, 1993,

Current Activities

FEMA currently conducts a broad range of activities under its NEHRP mandate.[21] Table B-7 lists the FY 1993 budget and examples of activities for each of six core areas of effort.

Leadership

According to the 1994 NEHRP report to Congress,[22] recent activities under FEMA's leadership function include:

- preparation of NEHRP plans and reports to Congress,
- assessment of user needs,
- support of earthquake professional organizations,
- arranging interagency meetings,
- support of problem-focused studies—specific issues of concern to the earthquake community, and
- outreach programs for small businesses.

Design and Construction Standards

FEMA contributes to the development of practices and standards to reduce seismic risk in both new and existing structures. Examples include sponsoring the development of the *NEHRP Provi-*

[21] This section draws on Federal Emergency Management Agency, *Building for the Future,* NEHRP FY 1991-1992 Report to Congress (Washington, DC: December 1992); Federal Emergency Management Agency, *Preserving Resources through Earthquake Mitigation,* NEHRP FY 1993-1994 Report to Congress (Washington, DC: December *1994);* and Federal Emergency Management Agency, Office of Earthquakes and Natural Hazards, "Funds Tracking Report, FY 1993," 1993,

[22] Federal Emergency Management Agency, *Preserving Resources through Earthquake Mitigation, see* footnote 21.

sions (a synthesis of design knowledge for adoption by model codes),[23] development of handbooks for retrofitting existing buildings, and support of an earthquake testing and research facility at the University of Nevada.

State and Local Hazards Reduction Program

States and local governments bear primary responsibility for implementing plans and technologies to increase the resilience of communities toward seismic hazards and thus minimize the long-term effects of earthquakes. Through its State and Local Hazards Reduction Program, FEMA provides grants to states, local governments, and multistate consortia to support their earthquake mitigation activities. Of the 43 states and territories[24] with low to very high degrees of seismic hazard, 28 participate in one manner or another in the FEMA program. Seventeen of these states joined NEHRP at its inception in 1977.

Activities funded by FEMA grants vary, but typically involve education, outreach, code adoption, training, and similar implementation activities. Indiana, for example, used FEMA funding to develop a brochure on techniques to measure risk in existing buildings, North Carolina used FEMA funding to update its building code to include seismic provisions, and Arizona conducted public awareness and education workshops.[25]

Financial Requirements

Current cost-sharing regulations are that FEMA provides 100 percent of the first year's funding; 25- and 35-percent in-kind matches are required for years two and three; and a 50-percent cash match from states is necessary for the following years.[26] The effects of the matching requirement vary greatly among states. Participation by some states appears to decline after reaching the 50-percent cash threshold; others have declined to participate at all because of the cash requirement.

For example, of the six states in the highest risk category, only Wyoming does not formally participate in NEHRP. Wyoming indicated that fourth-year financial requirements (i.e., 50-percent cash match) precluded such involvement. However, it does participate in NEHRP-related activities and belongs to the Western States Seismic Policy Council.

Program Elements

The five primary matching fund program elements are: Leadership and Program Management; Fundamental Research and Studies; Hazard Mapping, Risk Studies, and Loss Estimation; Hazard Mitigation; Preparedness and Response/Recovery Planning; and Information and Education. In addition, there is a "Special Projects and Other Programs" category. Under the latter, for example, New York State established in 1990 an Earthquake Lifelines Project to assess earthquake hazards, analyze lifeline vulnerability to support mitigation efforts, inform and educate the public, and provide training.

Typically, state efforts in the mitigation category relate to bridge safety analysis and reinforcement. New Jersey's activities under this program, however, also include a Prudent Business Practices program that encourages businesses to educate their employees and customers about seismic risks. At least nine states have activities in all NEHRP matching fund program areas.[27]

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[23] Building and Seismic Safety Council, *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*, 1991 Ed., prepared for Federal Emergency Management Agency (Washington, DC: January 1992).

[24] Including Guam, Puerto Rico, and the U.S. Virgin Islands.

[25] Examples from Federal Emergency Management Agency, *Building for the Future*, see footnote 21.

[26] VSP Associates, Inc., "State and Local Efforts To Reduce Earthquake Losses: Snapshots of Policies, Programs, and Funding," report prepared for the Office of Technology Assessment, Dec. 21, 1994.

[27] Arkansas, California, Kentucky, Mississippi, Missouri, Nevada, New Jersey, New Mexico, and Tennessee.

Regional Efforts

Three regional organizations play important roles in supporting individual states' seismic safety efforts: the Western States Seismic Policy Council, founded in 1977; the Central United States Earthquake Consortium (CUSEC), established in 1985; and, most recently, the Northeastern States Earthquake Consortium. CUSEC is the only one of the three groups that receives federal funds. These groups typically facilitate the exchange of information among states; provide a convenient mechanism for holding meetings and training sessions; act as an "issue network" by helping to forge state views on NEHRP priorities and programs; and, because of their administrative flexibility, can often do more things for their member states than individual state procedures allow.[28]

Education

FEMA supports a number of educational activities, including a course on post-earthquake reconstruction, a natural hazards information center, and dissemination of information on existing building retrofits.

With funding from USGS and NSF as well as FEMA, the Natural Hazards Research and Applications Information Center in Boulder, Colorado, serves as a national clearinghouse for information on the economic loss, human suffering, and social disruption caused by earthquakes, floods, hurricanes, tornadoes, and other natural disasters.

Multi-Hazard Assessment and Mitigation

Some FEMA activities in NEHRP address multiple hazards. For example, FEMA recently supported work on wind-resistant designs for buildings. Also under this heading is FEMA's support of the development of a loss estimation computer tool for use by cities and states in earthquake planning.

Federal Response Planning

FEMA has primary responsibility for preparing the federal government for national emergencies. FEMA activities include carrying out exercises, getting agencies to agree on emergency response plans, and supporting regional operating centers. FEMA has also supported urban search and rescue teams.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

NIST's role in NEHRP has been largely in applied engineering research and code development. The agency's funding under NEHRP has been low—less than $500,000 annually until the 1990s—so its NEHRP-related activities have been modest in size and scope. Current NEHRP funding is approximately $1.9 million.

Funding History

The initial NEHRP legislation did not provide explicit authorization for NIST (then the National Bureau of Standards), but NIST did receive some funding in the early years of NEHRP. The 1980 NEHRP reauthorization bill specifically authorized NIST as one of the four key NEHRP agencies, and these authorizations have continued in subsequent bills. In recent years, NIST's budget for earthquake-related activities has expanded due to contributions from other federal agencies, as well as a small contribution from the private sector. In FY 1994, for example, NIST received an additional $1.5 million from the Northridge supplemental appropriations for a total NIST earthquake-related budget of nearly $3.6 million.[29]

[28] Examples include securing out-of-state consulting assistance and paying honoraria and invitational travel so that speakers can participate in training conferences.

[29] Richard N. Wright, Director, Building and Fire Research Laboratory, National Institute of Standards and Technology, testimony at hearings before the Senate Committee on Commerce, Science, and Transportation, May 17, 1994, table 1.

Activities

NEHRP's initial legislation and subsequent amendments did not define a specific role for NIST. In the 1980s, NIST's activities were "exclusively focused on the studies of performance of buildings through in-house experimental and analytical research."[30] The 1990 NEHRP reauthorization defined NIST's role as follows: "The National Institute of Standards and Technology shall be responsible for carrying out research and development to improve building codes and standards and practices for structures and lifelines."[31]

Increased funding since 1990 has allowed NIST to expand into new areas. Its current NEHRP-related work includes:[32]

1. Applied engineering research:
   - preparation of guidelines for testing and evaluation of seismic isolation systems,
   - development of design provisions for precast concrete connections and for seismic strengthening of concrete frame buildings,
   - testing of masonry walls to determine shear capacity, and
   - development of improved methods to predict the effects of ground motion on lifelines.
2. Code development and distribution, including technical support for model code adoption of the NEHRP Provisions.
3. Technology transfer (e.g., support of conferences and meetings for engineering research).
4. International cooperation, including technical and financial support for various meetings and exchange programs with other countries.

OTHER RELATED FEDERAL AGENCY ACTIVITIES

Several federal agencies in addition to the four primary NEHRP agencies spend many millions of dollars in earthquake mitigation. These efforts include evaluating the seismic safety of facilities and improving their seismic resistance, conducting earthquake-related research and development, and other efforts.[33] Although detailed agency spending data are not available, this non-NEHRP federal spending on earthquake-related research and development on upgrading the seismic resistance of facilities probably exceeds the $100 million spent annually by the four primary NEHRP agencies.[34] The contributions of many non-NEHRP agencies are summarized in table B-8.

[30] Riley Chung, National Institute of Standards and Technology, personal communication, June 30, 1994.

[31] Public Law 101-614, sec. 5b5, Nov. 16, 1990.

[32] Federal Emergency Management Agency, *Preserving Resources through Earthquake Mitigation*, see footnote 21.

[33] David W. Cheney, Congressional Research Service, "The National Earthquake Hazards Reduction Program," 89-473SPR, Aug. 9, 1989.

[34] The last budget data were for the period ending 1987. Ibid., p. 20.

TABLE B-8: Summary of Federal Earthquake-Related Activities

Agency/department	Examples
National Aerobatics and Space Administration (NASA)	NASA conducts research and development (R&D) in basic earth processes. Its space-based geodesy program has enabled important advances in monitoring and characterizing crustal deformation and strain before, during, and after seismic events
National Oceanic and Atmospheric Administration (NOAA)	NOAA provides real-time tsunami warnings for the United States and its possessions and territories; the warnings are issued from two centers, located in Alaska and Hawaii. In addition, NOAA's seafloor mapping and monitoring of marine earthquakes support improved understanding of offshore earthquake hazards and the reduction of tsunami risk. NOAA also disseminates earthquake and tsunami data through the National Geophysical Data Center.
Department of Energy (DOE)	DOE has conducted earthquake hazard research related to nuclear powerplants and waste disposal. DOE has upgraded the seismic resistance of many of its facilities, including its national laboratories and nuclear weapons production facilities. As part of its nuclear energy research programs, DOE has also studied ways to Improve the seismic safety of new reactor designs.
Nuclear Regulatory Commission (NRC)	In the past, NRC has sponsored seismographic networks in the eastern United States to aid in analyzing seismic risks to nuclear powerplants. The commission has also conducted engineering research related to improving the seismic resistance of nuclear powerplants and waste disposal facilities.
Department of Defense (DOD)	DOD has a seismic safety program to ensure appropriate seismic safety of its facilities, and conducts seismic R&D with applications to other government and privately owned infrastructure. The Army Corps of Engineers, for example, addresses the seismic safety of dams. DOD also operates seismic stations for nuclear test monitoring and supports seafloor research (by the Office of Naval Research).
Department of Transportation (DOT)	DOT conducts seismic research in advanced earthquake-resistant design, construction, and retrofit of highway bridges through the American Association of State Highway and Transportation Officials specifications and guides of recommended practice, assesses DOT facilities to prevent interruption of vital functions; and provides immediate response after major earthquakes.
Bureau of Reclamation, Department of the Interior	The bureau is the lead technical agency for Interior's Safety of Dams Program. In addition to dam modifications, it conducts seismotectonic studies, operates three seismic networks in Colorado and Wyoming, and operates strong-motion instruments at dams and other critical facilities.
Department of Veterans Affairs (VA)	Since 1971, the VA has undertaken the seismic strengthening of its hospitals in areas of moderate and high seismic hazard.
Department of Housing and Urban Development (HUD)	HUD funds earthquake studies related to disaster response, damage assessment, and mitigation; conducts seismic risk assessments for HUD-assisted properties; develops seismic safety standards for such properties, as well as for manufactured housing; and provides major rebuilding and emergency housing assistance to earthquake-stricken communities.
Centers for Disease Control and Prevention (CDC), Department of Health and Human Services	CDC conducts research on the health impact of natural and technological disasters in order to develop strategies to prevent or reduce future disaster-related health problems.

SOURCES: Office of Technology Assessment, based on David W. Cheney, Congressional Research Service, "The National Earthquake Hazards Reduction Program, " 89-473SPR, Aug. 9, 1989; and unpublished Office of Science and Technology Policy material, For a further description of earthquake programs in these and other contributing federal agencies, see Federal Emergency Management Agency, *Preserving Resources Through Earthquake Mitigation,* FY 1993-94 NEHRP Report to Congress (Washington, DC: December 1994), pp. 131-170

Appendix C: International Earthquake Programs

C

Devastating earthquakes have been experienced all around the globe, at times with astounding loss of life (see table C-1). Figure C-1 illustrates recent world seismicity. Future occurrences of potentially damaging quakes are inevitable. As a result, many countries have mounted extensive research and development, hazard assessment, and disaster response programs related to earthquake hazards and seismic risk.

A comprehensive discussion of the many international mitigation programs and their achievements is beyond the scope of this report. Instead, this appendix briefly describes efforts under way in a few countries whose seismicity and mitigation practices may shed light on related U.S. efforts. It also outlines the framework that exists for cooperation and coordination among nations in understanding earthquake hazards and mitigating seismic risk.

To summarize, both Japan and China have sizable earthquake research and mitigation programs. Unlike the United States, however, the predominant focus of Japan's efforts is seismic monitoring and research applied toward predicting great earthquakes.

New Zealand also has a collection of efforts similar in scope, if not scale, to the U.S. national effort. One major difference is the inclusion of a government-sponsored earthquake insurance program and a move toward mitigating economic disruption along with threats to life safety. Several other countries have significant research programs or relevant data. For seismological or paleoseismological data from intraplate earthquakes, China and Australia are sources.[1] Russia, China, and Japan have data on potential earthquake precursors; Japan also has strong-motion data from subduction zone earthquakes and results from tsunami studies. In addition, Canada and the United States exchange data and analyses regarding seismic hazards in the west and east (e.g., subduction zone quakes in the Pacific Northwest and intraplate quakes in the northeastern United States).

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[1] Few earthquakes that occur in relatively stable regions of continents have surface expression. Of the 11 historic intraplate earthquakes that have produced surface ruptures, five occurred in Australia since 1968. Michael Machette and Anthony Crone, "Geologic Investigations of Australian Earthquakes: Paleoseismicity and the Recurrence of Surface Faulting in the Stable Regions of Continents," *Earthquakes & Volcanoes*, vol. 24, No. 2, 1993, p. 74.

TABLE C-1: Selected Significant Earthquakes Worldwide

Location	Year	Magnitude	Impact
Northern China	1556	—	800,000 killed
Lisbon, Portugal	1755	—	60,000 killed, fire
San Francisco, California	1906	8.3	700 killed, fire
Messina, Sicily	1908	7.5	160,000 killed
Tokyo, Japan	1923	8.3	140,000+ killed, fire
Assam, India	1950	8.4	30,000 killed
Chile	1960	Mw 9.5	5,700 killed, 58,000 homes destroyed, tsunami
Alaska	1964	Mw 9.2	131 killed, tsunami
Northern Peru	1970	7.7	67,000 reported killed
Guatemala	1976	7.5	23,000 killed
Tangshan, China	1976	7.9	240,000-650,000 killed
Northern Iran	1978	7.7	25,000 killed
Mexico City	1985	8.1	10,000+ killed
Armenia	1988	6.8	55,000 killed
Loma Prieta, California	1989	7.1	63 killed, $5 billion to $10 billion damage
Northern Iran	1990	7.7	40,000 killed
Flores, Indonesia	1992	7.5	2,500 killed
Latur, India	1993	Mw 6.2	9,750 deaths
Northridge, California	1994	6.8	57 killed, more than $20 billion damage
Kobe, Japan	1995	6.8	5,500+ killed, more than $200 billion losses
Sakhalin Island, Russia	1995	Mw 7.0	Approximately 2,000 killed

NOTE: A significant earthquake is one that registers a magnitude of 6,5 or more, or one that causes considerable damage or loss of life On average, 60 significant earthquakes take place around the world each year. Mw representsmoment magnitude, a measure of the total seismic energy released

SOURCE: Office of Technology Assessment, based on Bernard Pipkin, *Geology and the Environment* (St Paul, MN: West Publishing Co , 1994), and references cited therein; and William Ellsworth, U S Geological Survey, Menlo Park, personal communication, June 14, 1995

The United States is actively involved in several cooperative programs established to share expertise and data. Joint research and technology transfer projects have been especially useful to the spread of seismic zonation practices around the world.[2] (In a similar vein, technology transfer from Japan to Chile has been integral to the latter nation's advances in earthquake mitigation, for example, in tsunami studies.[3])

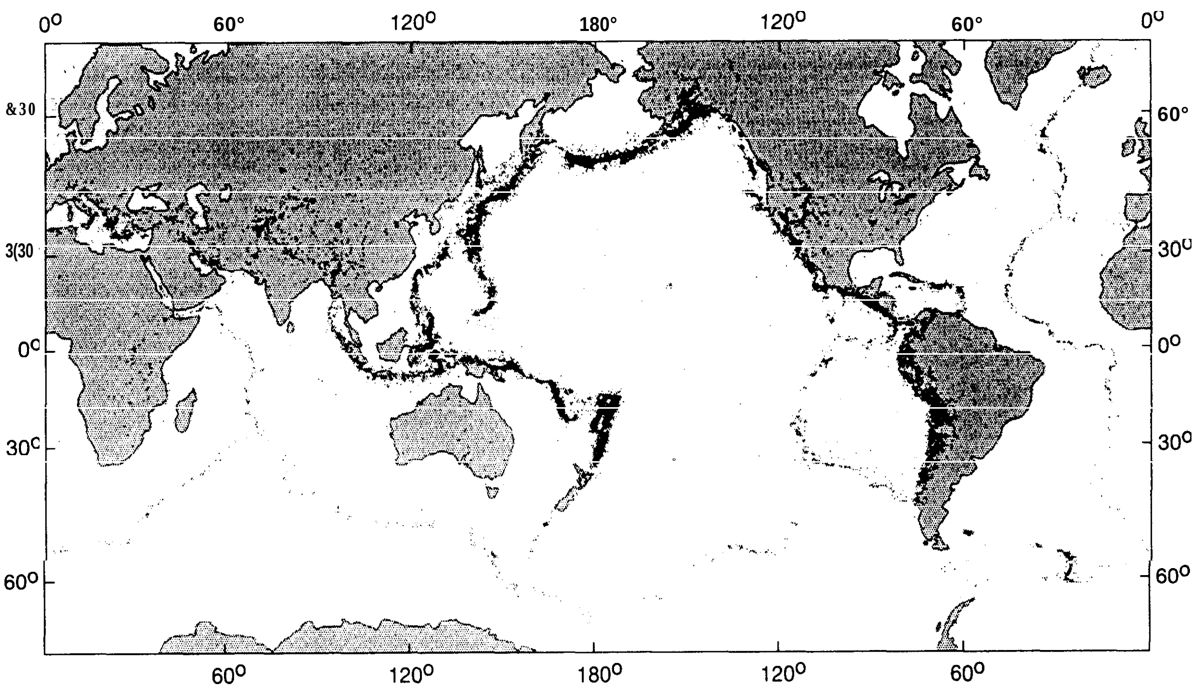
AUSTRALIA

Australia, a relatively stable continent far removed from the earth's plate boundaries, received

[2] Seismic zonation is the division of a geographic region into smaller areas or zones that are expected to experience the same relative severity of an earthquake hazard (e.g., ground shaking or failure, surface faulting, tsunami wave runup). Based on an integrated assessment of the hazard, built, and policy environments, resulting zonation maps provide communities with a range of options for ensuring resilience to earthquakes and sustainable development. U.S. Geological Survey, *Proceedings of the Fourth International Forum on Seismic Zonation,* July 14, 1994, Chicago, IL, and Aug. 30, 1994, Vienna, Austria, Open File Report 94-424 (Reston, VA: n.d.), appendix B, p. 1.

[3] See Maria Ofelia Moroni, "Technology Transfer on Earthquake Disaster Reduction Between Japan and Chile," *Bulletin of the International Institute of Seismology and Earthquake Engineering,* vol. 27, 1993, pp. 199-211. In 1960, a tsunami that originated off the coast of Chile caused nearly 1,000 deaths in that country and much destruction in Japan as well.

FIGURE C-1: Epicenters of 30,000 Earthquakes, 1961-67



SOURCE Office of Technology Assessment, 1995, adapted from F Press and R Siever, *Earth,* Second Edition (San Francisco, CA: W.H. Freeman and Company, 1978), p. 412.

a wake-up call with respect to urban earthquake hazards when a magnitude 5.6 (M5.6) earthquake struck Newcastle in December 1989. It resulted in about $2.86 billion (U. S.) in losses and 13 deaths.[4] The disaster led to increased studies of the region's intraplate quakes and a national program in seismic zonation.

The Australian Geological Survey Organization, in coordination with various state geological surveys and universities, conducts the national program in earthquake monitoring. With funding from the federal agency Emergency Management Australia and state governments, the Center for Earthquake Research in Australia (CERA) has completed seismic zonation maps for four of the largest cities (Sydney, Newcastle, Melbourne, and Brisbane and its environs). Maps for other urban areas are in progress.[5]

According to CERA, the outcomes of this mapping program have practical applications in many areas, including seismic code formulation, emergency management, and community education.[6]

[4] John M.W. Rynn, "The Potential To Reduce Losses from Earthquakes in Australia, " D.I. Smith and J.W. Handmer (cd.), *Australia's Role in the International Decade for Natural Disaster Reduction,* Resource and Environmental Studies No. 4, Journal of the Australian National University Center for Resource and Environmental Studies, 1991, p. 9.

[5] For a description of initial efforts, see John M.W. Rynn, "Mitigation of the Earthquake Hazard Through Earthquake Zonation Mapping: The Program for Urban Areas in Australia," *Proceedings of the Workshop Towards Natural Disaster Reduction,* June 27-July 3, 1993, Okinawa, Japan, S. Herath and T. Katayama (eds.) (Tokyo, Japan: International Center for Disaster-Mitigation Engineering, July 1994), pp. 115-136.

[6] John Rynn, Center for Earthquake Research in Australia, personal communication, June 7, 1995.

TABLE C-2: Canadian Organizations Involved in Earthquake Mitigation

Organization	Description	Activities
Geological Survey of Canada (GSC)	Agency of the Ministry of Natural Resources Canada	Seismic and strong-motion monitoring, hazard estimation; international cooperation.
National Research Council (NRC)	Established within the Ministry of Industry, Science and Technology	The agency's Canadian Commission on Building and Fire Codes promulgates the National Building Code.
Canadian National Committee on Earthquake Engineering	Committee with representation from GSC, NRC, and the private sector.	Develops seismic provisions for the National Building Code, advises the Canadian Commission on Building and Fire Codes, and provides advice to private industry on matters related to seismic hazard assessment for specific projects.
Emergency Preparedness Canada	Agency within the Ministry of Defence	Earthquake preparedness and response planning.

SOURCE Off Ice of Technology Assessment, based on Peter Basham, Geological Survey of Canada, personal communication, Nov 24, 1994

Collaboration between Australia and other countries (e.g., neighboring developing nations in the South Pacific, countries in Southeast Asia, and South America, as well as the United States) is rapidly increasing.

CANADA

Canada has experienced several large, damaging earthquakes during its recorded history. Seismicity along its west coast is relatively well understood in terms of plate boundary convergence offshore. The sources of intraplate earthquakes in eastern Canada are less well known, but may be related to compressional stresses acting on localized zones of weakness in the crust.[7] Table C-2 shows the primary agencies and organizations participating in Canada's earthquake mitigation effort. According to the Geological Survey of Canada (GSC), it is the only federal agency concerned with seismological aspects of earthquake loss reduction, and the only Canadian agency with expertise in seismic hazard assessment.[8]

Canada's primary earthquake-related research goals are to: 1) understand the causes and effects of earthquakes well enough to be able to assess seismic hazards accurately throughout the country, and 2) improve knowledge of earthquake-resistant design and construction in order to provide an adequate level of protection against future earthquakes. Currently, a major research program is underway to produce new zoning maps for trial use, modification, and formal adoption in the year 2000 National Building Code of Canada. The existing code was adopted in 1985 and is based on

[7] Dieter Weichert et al., "Seismic Hazard in Canada," *The Practice of Earthquake Hazard Assessment*, International Association of Seismology and Physics of the Earth Interior (Denver, CO: U.S. Geological Survey, 1993), p. 46.

[8] Unless noted otherwise, the material in this section is drawn from Peter Basham, Acting Director, Geophysics Division, Geological Survey of Canada, personal communication, Nov. 24, 1994.

probabilistic analyses of peak acceleration and peak velocity.[9] According to GSC, relatively little effort is devoted to microzonation, although some efforts have been undertaken as university research projects.

CHINA

Strong intraplate earthquakes frequently occur throughout China, which lies in the southeast part of the Eurasian plate. The seismicity is thought to be related to forces from the Pacific Plate to the east and the Indian Ocean Plate to the southwest. China's historic earthquake record extends back thousands of years; from 1831 B.C. to A.D. 1989, 17 great earthquakes, 126 major quakes, and almost 600 large earthquakes took place.[10] Because of their typically shallow depth and since relatively little building stock has been designed to resist shaking, severe damage and casualties are likely in the country's densely populated areas from large earthquakes (i.e., having magnitudes of 6 and higher).[11]

The Chinese government has a three-pronged effort to address seismic risks. Earthquake prediction, resistance, and emergency relief responsibilities are accorded to the State Seismological Bureau, the Ministry of Construction, and the Ministry of Civil Affairs, respectively.[12] A unified program is being assembled by the Chinese Ten-Year Committee, in cooperation with United Nations International Decade for Natural Disaster Reduction[13] (see table C-3.)

Prediction

The large-scale development of an earthquake prediction capability began after the 1966 Xingtai earthquake (M7.2), which resulted in 8,000 deaths.[14] Over the last couple of decades, a number of earthquake-monitoring systems have been set up in China's major seismic areas. The national network consists of six regional telemetry networks, 12 local radio telemetry networks, and 10 digital seismographic stations.[15] Data from these monitoring systems, and from other observations, support research in detecting precursors and correlating them with large earthquakes.

In 1975, hours before a M7.4 quake struck Haicheng, a series of foreshocks prompted residents to construct earthquake huts (temporary shelters adjacent to their homes) and local authorities to issue a warning of a major quake.[16] Even with these precautions, more than 1,000 people were killed. Without these measures, a much larger percentage of the 3 million people living in Haicheng might have died inside collapsed buildings.[17] However the Chinese prediction system has predicted earthquakes that did not occur and has failed to predict some that did. Several months after the Haicheng

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[9] With seven zones, the 1985 edition maps have a finer subdivision of zoning in moderate-risk areas and additional zones in the high-risk areas relative to the previous edition (1970). P.W. Basham et al., "New Probabilistic Strong Seismic Ground Motion Maps of Canada," *Bulletin of the Seismological Society of America*, vol. 75, No. 2, April 1985, p. 563.

[10] Xiu Jigang, "A Review of Seismic Monitoring and Earthquake Prediction in China," *Tectonophysics*, vol. 209, 1992, p. 325. See chapter 2 for description of earthquake severity scales.

[11] Ma Zongjin and Zhao Axing, "A Survey of Earthquake Hazards in China and Some Suggested Countermeasures for Disaster Reduction," *Earthquake Research in China*, vol. 6, No. 2, 1992, p. 241.

[12] Wang Guozhi, "The Function of the Chinese Government in the Mitigation of Earthquake Disasters," *Earthquake Research in China*, vol. 6, No. 2, 1992, p. 254.

[13] Ibid.

[14] Zongjin and Axing, see footnote 11, p. 243.

[15] The six regions covered are Beijing, Shanghai, Chengdu, Shenyang, Kunming, and Lanzhou. Ibid.; and William Bakun, U.S. Geological Survey, Menlo Park, personal communication, June 15, 1995.

[16] Cinna Lomnitz, *Fundamentals of Earthquake Prediction* (New York, NY: John Wiley & Sons, Inc., 1994), pp. 24-26.

[17] Bruce A. Bolt, *Earthquakes* (New York, NY: W.H. Freeman and Co., 1993), p. 194.

TABLE C-3: Earthquake Efforts by the People's Republic of China

Organization	Description	Activities
Ministry of Construction (MOC), Office of Earthquake Resistance	Established in 1967, MOC is concerned with emergency response, technical codes and standards, development of International cooperation, and education and training in earthquake engineering.	Funds proposals in earthquake resistance research for buildings and engineering structures; seismic response research for special works, structures, and equipment; strong-motion observation,
State Seismological Bureau	Established in 1971, the bureau is responsible for central management of earthquake monitoring, prediction, and scientific and engineering research.	Plans and administers national seismological programs; conducts International cooperation and exchange programs in earthquake studies; performs field studies of societal responses to earthquake hazards and events. The bureau's Institute of Engineering Mechanics plays a key role in earthquake engineering research at the government level.
National Natural Science Foundation of China, Department of Architectural Environment and Structural Engineering	Supports research in basic theory, technical advances, and earthquake hazard mitigation.	Funds projects in hazard assessment; soil-structure interaction; structural dynamic response; seismic resistance of lifelines; base Isolation and structural control; and earthquake site investigation and aseismic experimental technology.
Ministry of Energy, Science and Technique Development Foundation of Power Industry	Established in 1989 by the China Association of Power Enterprises in affiliation with the Ministry of Energy,	Awards grants to researchers and technological workers for studies related to hydroelectric, thermoelectric, and electric systems.

SOURCE: U.S. Panel on the Evaluation of the U.S.-P.R.C. Earthquake Engineering Program, National Research Council Commission on Engineering and Technical Systems, *Workshop on Prospects for U.S.-P.R.C. Cooperation on Earthquake Engineering Research* (Washington, DC: National Academy Press, 1993), pp. 8-10,

quake, a M7.8 quake struck Tangshan, apparently without warning. Hundreds of thousands were killed.[18]

Seismic Zonation and Building Codes

In 1957, China adopted its first earthquake intensity scale, a 12-level scale similar to the Modified Mercalli Intensity scale, and initially focused its mitigation efforts on buildings in the highest hazard areas. In 1992, using data from recent earthquakes and geophysical studies, China promulgated a new edition of its seismic intensity zoning map. The Chinese zoning map reflects both subjective measures of intensity and probabilistic analyses of ground motion expected from future earthquakes. Grade 9 on the Chinese intensity scale is roughly equivalent to Zone 4 of the 1988 Uniform Building Code.[19]

The first seismic code was promulgated in China in 1974.[20] The Tangshan earthquake prompted

[18] The Official estimate is approximately 250,000 deaths; however, unofficial estimates suggest that over 800,000 may have been killed.

[19] The Unifom Building Code is one of three U.S. model codes on which state and local seismic codes are based. See chapter 3.

[20] Hu Shiping, "Seismic Design of Buildings in China, '' *Earthquake Spectra,* vol. 9, No. 4, 1993, p. 704. The first draft, in 1957, was based on the Soviet code.

BOX C-1: Japan's Earthquake Prediction Program

Six agencies participate in Japan's earthquake prediction program. The Japan Meteorological Agency (JMA) collects seismological data and oversees Japan's prediction efforts. The Earthquake Assessment Committee, consisting of six eminent seismologists, is responsible for analyzing potentially anomalous data and reporting to the director of JMA a verdict of: 1) imminent danger, or 2) no danger.[1]

The Geodetic Council of Japan acts as an advisory body to the Ministry of Education, Science and Culture with respect to earthquake prediction, and oversees development of five-year program plans. Other agencies revolved in the prediction effort include the Maritime Safety Agency, the Geographical Survey Institute, the Geological Survey of Japan, and the National Research Institute for the Earth Sciences and Disaster Prevention (part of the Science and Technology Agency).[2]

Now in its sixth five-year plan, the program has both harsh critics, which include an increasing number of Japanese scientists, and staunch defenders. Limited access to data, opportunity costs for other areas of earthquake research, and the program's narrow focus on the Tokyo region are among the motivations for criticism.

[1]Robert J. Geller, "Cash Falling Through the Cracks," *The Daily Yomiuri,* May 12, 1994, p. 6. The two options are designated *black* and *white* verdicts, respectively. A *gray* verdict, or statement of intermediate probability, IS not permitted.

[2]Robert J. Geller, "Shake-up for Earthquake Prediction," *Nature,* vol. 352, No. 6333, July 25, 1991, pp. 275-276

SOURCE Off Ice of Technology Assessment, 1995

revision of this code; the effort was completed in 1978. The present code, promulgated in January 1990, was revised from the 1978 version by the China Academy of Building Research, along with other professionals.[21]

JAPAN

The Eurasian, Philippine Sea, Pacific, and North American Plates all converge in the vicinity of Japan. The relative movement of these plates causes Japan to experience strong to great earthquakes frequently, as well as face the threat of volcanic activity and tsunamis. The largest earthquakes have originated in the subducted Philippine Sea and Pacific Plates, although the havoc wreaked on Kobe by the 1995 Hyogoken-Nanbu earthquake reveals the hazard posed by shallow crustal quakes to densely populated cities.

Japan has a multipronged government program to address its many seismic risks. Unlike the United States, however, earthquake prediction is a primary focus of Japan's efforts to reduce losses from earthquakes.

■ Prediction

With spending on the order of $100 million per year-a figure that does not include salaries-Japan's prediction program receives funding comparable to the entire U.S. National Earthquake Hazards Reduction Program (NEHRP). Initiated in 1963, it is one of Japan's largest and oldest research projects[22] (see box C-l).

Pursuant to the 1978 Large-Scale Earthquake Countermeasures Act, 10 regions have been designated for special monitoring. The Kanto-Tokai Observation Network, for example, continuously

[21] Ibid., p. 705.

[22] Y. Ishihara, Office of Disaster Prevention Research, Japanese Science and Technology Agency, personal communication, June 16, 1995.

monitors crustal movements using more than 250 seismometers, strainmeters, and tiltmeters. In addition, 167 Global Positioning System stations operate in this area.[23]

The most recent five-year plan for the prediction program, adopted in 1993, continues intensive observation of the Tokai region, which is expected to experience the effects of a great earthquake on the nearby Suruga Trough.[24] Scientists hope to detect the onset of the quake by monitoring seismicity, strain, and crustal deformation. Previous major quakes on the Suruga and Nankai Troughs were preceded by rapid crustal uplift.

Building Codes and Engineering

Early in this century, Japan established one of the first seismic design codes based on the performance of certain buildings in Tokyo during the 1923 Great Kanto earthquake.[25] The years since then have seen many advances in earthquake engineering research, seismic codes, and construction practices, because of investment on the part of both the government and the private sector.

The most recent code went into effect in 1981.[26] The Japanese seismic design code differs from the current U.S. guidance document for building codes (i.e., the NEHRP Provisions[27]) in that it calls for a two-stage design process. The first phase follows an analysis approach similar to that used in the NEHRP Provisions; it is intended to preclude structural damage from frequent, moderate quakes. The second phase is an explicit assessment of the building's ability to withstand severe ground motions.[28] Design forces used in Japan also are typically significantly larger than in the United States. As a result, Japanese buildings tend to be stronger and stiffer than their U.S. counterparts, and will likely suffer less damage during moderate or severe shaking.[29]

Japanese construction companies annually spend a considerable amount on research and development, including testing of scaled building models in large in-house laboratories and research into passive and active control technologies. One result is that new technologies for seismic protection have been incorporated into new buildings at a faster rate than in the United States.[30]

The government's engineering research facilities include a large-scale earthquake simulator operated by the National Research Institute for the Earth Sciences and Disaster Prevention and used by other agencies. Future evaluation of the seismic performance of the built environment will likely be aided by the large set of strong-motion data obtained from the Hyogoken-Nanbu quake in January 1995; the data set includes near-fault re-

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[23] Ibid.

[24] Dennis Normile, "Japan Holds Firm to Shaky Science," *Science*, vol. 264, June 17, 1994, p. 1656.

[25] The United States adopted its first code shortly thereafter, in 1927.

[26] The Building Standard Law, proposed in 1977. For a description of Japan's seismic design methods, see Andrew Whittaker et al., "Evolution of Seismic Design Practice in Japan and the United States," *The Great Hanshin Earthquake Disaster: What Worked and What Didn't?* SEAONC Spring Seminar Series, Engineering Implications of Jan. 17, 1995, Hyogoken-Nanbu Earthquake, May 25, 1995 (San Francisco, CA: Structural Engineers Association of Northern California, 1995), pp. 5, 10.

[27] Building Seismic Safety Council, *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings* (Washington, DC: 1991).

[28] Whittaker et al., see footnote 26. Exemptions to this second phase of design are permitted only for buildings less than 31 meters in height and having the requisite materials and configuration. Andrew S. Whittaker, Earthquake Engineering Research Center, University of California at Berkeley, personal communication, May 29, 1995.

[29] Whittaker, ibid.

[30] David W. Cheney, Congressional Research Service, "The National Earthquake Hazards Reduction Program," 89-473 SPR, Aug. 9, 1989, p. 35.

cords that reflect rupture directivity and other effects encountered in the immediate vicinity of the fault.[31]

Response and Recovery

Within the National Land Agency, the Disaster Prevention Bureau was established in 1984 to develop disaster countermeasures through coordination with various ministries and agencies. The countermeasure framework has three primary parts: 1) making cities more disaster resistant, 2) strengthening disaster prevention systems (e.g., tsunami warning systems) and raising awareness, and 3) promoting earthquake prediction. One related effort has been to set up the Disaster Prevention Radio Communications Network to link agencies at the federal, prefectural, and municipal levels.[32]

The primary responsibility for disaster response rests with local-level governments that must ensure adequate water, food, and medical supplies. As witnessed in the 1995 disaster, however, Kobe's capabilities were overstretched, and some argue that mechanisms for federal intervention were inadequate. Whether or to what degree Japan's earthquake research, mitigation, and response programs will change as a result of the Kobe disaster is not yet clear. It must be noted that the intensive monitoring programs intended to support Japan's prediction capability cover but a small portion of the nation.

MEXICO

Off the western coast of Mexico, the North American Plate overrides the Cocos Plate. Historically, the Cocos Plate is the most active in the Western Hemisphere. This subduction zone has generated almost 50 earthquakes greater than magnitude 7 in this century, including the M8.1 quake that caused extensive damage and loss of life in Mexico City in 1985.[33]

Mexico currently has a national network of nine broadband seismic instruments linked by satellite, plus a number of regional networks.[34] Six additional broadband stations will be installed in 1995, one of them through a cooperative project with the U.S. Geological Survey.[35] Since late 1987, the National University's Geophysics Institute has operated a nine-station, short-period seismic network in the earthquake-prone state of Guerrero.

To record and assess severe shaking, strong-motion instruments are located throughout the Mexico City area. In cooperation with some U.S. universities and the Japan International Cooperation Agency, arrays of digital strong-motion networks are also operated in Guerrero.

Seismic zonation maps (e.g., maps of maximum Modified Mercalli Intensity, and peak acceleration and velocity) have been incorporated into the Mexican Building Code since the 1960s. In the 1985 quake, many high-rise buildings in an area of the city underlain by a former lake bed collapsed or were severely damaged. These buildings could not withstand the resonance effects induced by the long-period, long-duration shaking that occurred on soft soils. Microzonation has since been completed in the portions of Mexico City most susceptible to seismic wave amplification and liquefaction.[36] Other cities (e.g., Acapulco and

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[31] Earthquake Engineering Research Institute, *The Hyogo-Ken Nanbu Earthquake: January 17, 1995*, preliminary reconnaissance report (Oakland, CA: February 1995), p. 6.

[32] Disaster Prevention Bureau, Earthquake Disaster Countermeasures Division, *Earthquake Disaster Countermeasures in Japan* (Tokyo, Japan: National Land Agency, 1993), pp. 17-18.

[33] Bernard W. Pipkin, *Geology and the Environment* (St. Paul, MN: West Publishing Co., 1994), pp. 83-35. The earthquake catalog of the Geophysics Institute, National University of Mexico, contains 48 major quakes.

[34] U.S.Geological Survey, see footnote 2, p. 31.

[35] Ramón Zúñiga, Geophysics Institute, National University of Mexico, personal communication, June 12, 1995.

[36] U.S. Geological Survey, see footnote 2.

Guadalajara) have recently been included in the microzonation efforts. Based on recently collected data, new zonation maps are being prepared for Mexico as an extension of the Canadian-funded Seismic Hazard in Latin America and the Caribbean Project.[37]

NEW ZEALAND

New Zealand is located astride the boundary between the Australian and Pacific Plates; it is cut and deformed by many active faults and folds.[38] Not surprisingly, New Zealand has both an active research program in earthquakes and a longstanding effort to improve the seismic resistance of its built environment. In 1991, the nation adopted an integrated approach to natural hazards management, of which earthquake mitigation is a major part. Subject to certain constraints in the Resource Management Act of 1991 and Building Act of 1991, regional and local authorities are responsible for controlling land use and construction for the purpose of avoidance or mitigation of specific hazards.[39]

■ Research

The primary institutions conducting earthquake-related research include the Institute of Geological and Nuclear Sciences (IGNS), the Engineering Schools of Auckland and Canterbury Universities, and the Institute of Geophysics at Victoria University in Wellington. The latter has teaching and research programs in seismology, including seismic microzonation. Additional research is conducted by earth science departments in other universities and by some private civil engineering consultants.[40]

IGNS has six programs, funded at $27 million (U.S.) per year, which span the fields of geology, seismology, and engineering seismology.[41] For example, IGNS is currently pursuing a research program titled "Improvements to Earthquake Resistant Design" whose primary objectives are: improved modeling of strong ground motions; enhanced models of the effects of large earthquakes on buildings, other structures, and the natural environment; and improved antiseismic practices and technologies.[42]

The Earthquake Commission (EQC), which provides earthquake insurance for domestic property and contents, also funds approximately $340,000 (U.S.) of research per year. EQC, which administers the Natural Disaster Fund on behalf of the government, is the primary provider of natural disaster insurance to residential property owners.

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[37] Zúñiga, see footnote 35. The Canadian International Development Research Agency funds the Seismic Hazard Project, now in its final phase. The project has two major components: 1) establish a uniform catalog of earthquakes for Mexico, Central and South America, and the Caribbean; and 2) develop probabilistic seismic hazard maps for this region. The Panamerican Institute of Geography and History, Organization of American States, oversees the multinational effort. James Tanner, Seismic Hazard in Latin America and the Caribbean Project, personal communication, June 16, 1995.

[38] Russ Van Dissen and Graeme McVerry, "Earthquake Hazard and Risk in New Zealand," *Proceedings of the Natural Hazards Management Workshop*, Wellington, NZ, Nov. 8-9, 1994 (Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited, 1994), p. 71.

[39] See Christine Foster, "Developing Effective Policies and Plans for Natural Hazards Under the Resource Management Act," in *Proceedings of the Natural Hazards Management Workshop*, see footnote 38, pp. 34-35. One result of the recent legislation is increased demand on the part of regional and local authorities for seismic hazard and risk analyses.

[40] Unless noted otherwise, this section is drawn from personal communications with Warwick D. Smith, Chief Seismologist, New Zealand Institute of Geological and Nuclear Sciences, and John Taber, Institute of Geophysics, Victoria University of Wellington, Dec. 1, 1994.

[41] The Ministry of Research, Science and Technology provides the New Zealand government with policy advice, including recommended funding levels for different areas of research. Earthquake-related research is funded under the Earth Science and Construction categories, or *outputs*. The Foundation for Research, Science and Technology allocates monies for research programs within each output.

[42] A quarter of the program's funding comes from industrial sources. Description of the IGNS Program, "Improvements to Earthquake Resistant Design," provided by Don McGregor, Chief Scientist, New Zealand Ministry of Research, Science and Technology, personal communication, Jan. 17, 1995.

As of 1996, however, owners of nonresidential property will have to seek private coverage for buildings and their contents.

Roughly 25 percent of New Zealand's earthquake research is currently directed at microzonation. This work is included in both the Foundation for Research, Science, and Technology and EQC programs, and is also sponsored by regional and local governments.

Implementation

Under New Zealand's Resource Management Act, regional, district, and city councils are responsible for identifying and mitigating the effects of natural hazards. The councils exercise their duties with respect to earthquake hazards through zoning and microzoning, and by enforcing the New Zealand Building Code. This code is written in performance terms and was published in 1992, after preparation under the supervision of the Building Industry Authority. There were previous seismic loading requirements in building standards and other control documents dating back to 1935. The code requires building owners to maintain their buildings so that they continue to meet the earthquake resistance requirements that existed at the time the building was erected. In some of the more earthquake-prone areas, territorial authorities have required upgrading of older buildings to address possible seismic weaknesses that can be recognized.[43]

The New Zealand National Society for Earthquake Engineering is a nongovernmental organization with approximately 600 members, mostly civil engineers. The society plays a leading role in communication among parties interested in earthquake research, hazard and risk assessment, and mitigation via engineering solutions. Likewise, the Building Research Association maintains close ties with building control officials and manufacturers, who together expedite the introduction of research results into practice.[44]

Until recently, the main thrust of earthquake mitigation efforts in New Zealand was preventing building collapse and minimizing the hazard for occupants. However, this risk was considered to be less severe than for many other countries,[45] and today the reduction of economic disruption is receiving greater emphasis. Increasing the efficiency of restoration of infrastructure and lifelines is a primary consideration.[46]

For example, local councils in Wellington and later Christchurch established engineering exercises to coordinate efforts to sustain lifelines. They focused on the interdependence of these lifelines in urban areas to assess ways in which weakness might be identified and mitigated.[47]

RUSSIA

Microzonation of the largest cities in Russia and the former Soviet Union began in the 1950s, and seismic zonation maps were incorporated into the State Engineering Codes as early as 1957.[48]

Today, the primary institutions and organizations involved in Russia's earthquake efforts are:

[43] Gerald Rys, Assistant Chief Scientist, New Zealand Ministry of Research, Science and Technology, personal communication, July 4, 1995.

[44] John Duncan, Research Director, Building Research Association of New Zealand, personal communication, Jan. 17, 1995.

[45] Reasons include: 1) ongoing implementation of simple antiseismic measures based on early colonial experiences in severe earthquakes, and 2) the fact that the majority of New Zealanders live in single-dwelling, typically wood-framed structures.

[46] Smith and Taber, see footnote 40.

[47] Interdependence relates to the effect of the outage of one utility service (e.g., power) on the time required by another service to recover. The lifeline effort also designated *critical areas*—that is, where a number of lifelines are vulnerable in one location (e.g., a bridge carrying water, gas, and power in addition to traffic). David Brundson, "Reducing Community Vulnerability to Earthquakes: The Value of Lifeline Studies," in *Proceedings of the Natural Hazards Management Workshop*, see footnote 38, p. 10.

[48] U.S. Geological Survey, see footnote 2.

the Ministry of Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Hazards; the Interdepartmental Commission for Seismic Monitoring; and the Russian Academy of Sciences. Russia operates several seismic and strong-motion monitoring stations. However, nearly all are still equipped with analog instruments and transmission methods that limit the quantity and quality of data. The number of stations in operation has decreased in recent years due to lack of funding.[49]

In 1994, the Russian government approved the establishment of a new program to develop a federal system of seismological networks and earthquake prediction, with several objectives:

- seismic hazard assessment,
- prediction of strong earthquakes based on comprehensive analysis of geophysical and geodetic precursors,
- epicentral seismological observations,
- strong-motion data for improvement of seismic resistant design and construction,
- implementation of mitigation measures in areas where strong earthquakes are expected in order to evaluate their effectiveness, and
- development of methods for predicting human-triggered seismicity and for minimizing seismicity induced by mining or reservoirs.

The means to these ends include modernization of observation stations, data transfer and storage techniques, and improved coordination of the efforts of many ministries and agencies. As of late 1994, however, the government had not allocated any financial resources to implement the program.[50]

VEHICLES FOR COOPERATION AND COORDINATION

A number of organizations and other mechanisms foster the international exchange of ideas and practices in the area of earthquake research, mitigation, and response. For example, the U.S. Geological Survey (USGS) and the National Science Foundation (NSF) maintain close working relationships with Japan in earthquake seismology.[51] In addition, for many years, the United States and Japan have held joint workshops under the auspices of the United States-Japan Panel on Wind and Seismic Effects (see box C-2). The United States has established and renewed scientific protocols with the People's Republic of China, and with Russia and other members of the Commonwealth of Independent States. Cooperation between the United States and Taiwan, and between Latin American states, is ongoing, and there are many such efforts with other countries.

Japan also has established cooperative exchanges with many countries, as have some other nations (e.g., Canada and France). There are multilateral forums as well—notably the United Nations International Decade for Natural Disaster Reduction (IDNDR), established in 1990 to promote mitigation and cooperation worldwide.[52] Over the years, several regional programs have

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[49] According to one reviewer, the disastrous Sakhalin Island earthquake of May 1995 illustrates the decline of Russia's earthquake program: the seismic monitoring network had been shut off, there was apparently no plan to retrofit the apartment buildings that collapsed, and the emergency response effort suffered from a shortage of resources. William L. Ellsworth, U.S. Geological Survey, Menlo Park, personal communication, June 14, 1995.

[50] Yu S. Osipov, President of the Russian Academy of Sciences, letter to V.F. Shumeiko, Chairman of the Federation Council of the Federal Assembly of the Russian Federation, Nov. 1, 1994, in "The Shikotan Earthquake of October 4(5), 1994," *Russia's Federal System of Seismological Networks and Earthquake Prediction*, Information and Analytical Bulletin, Special Issue No. 1, November 1994.

[51] Federal Emergency Management Agency et al., "National Earthquake Hazards Reduction Program: Five-Year Plan for 1992-1996," September 1991, p. 91.

[52] The IDNDR sought, in part, to promote: the integration of hazard reduction policies and practices into the mainstream of community activities; funding of additional research into the physical and social mechanisms of natural hazards and the disasters they precipitate; and elimination of constraints on the use of scientific and technical knowledge. National Research Council, *The U.S. National Report to the IDNDR World Conference on Natural Disaster Reduction,* Yokohama, Japan, May 23-27, 1994 (Washington, DC: National Academy Press, 1994), p. 1.

BOX C-2: United States-Japan Panel on Wind and Seismic Effects

The panel consists of 16 U.S. agencies, led by the National Institute of Standards and Technology, and six Japanese agencies. Over the years, the panel has:

- held 25 annual technical meetings for prompt exchange of research findings,
- conducted more than 40 workshops and conferences on such topics as the repair and retrofit of structures,
- conducted cooperative post-earthquake investigations in Japan and in the United States,
- hosted visiting Japanese researchers and provided access for U.S. researchers to unique Japanese facilities, and
- organized cooperative research programs on steel, concrete, masonry, and precast concrete structures.

SOURCE. Richard Wright, Director, Building and Fire Research Laboratory, National Institute of Standards and Technology, testimony at hearings before the Senate Committee on Commerce, Science, and Transportation, Subcommittee on Science, Technology, and Space, May 17, 1994, p. 31

been established, including projects in the Balkans, countries adjacent to the Mediterranean Sea, and central and South America.[53]

In general, there is extensive cooperation with respect to the collection and sharing of earthquake data. With the Global Seismographic Network (GSN), earthquake source data are collected from and distributed to Europe, Latin America, Asia, and Australia.[54] The Global Geodetic Network uses high-resolution, space-based geodetic techniques to monitor crustal motion and deformation around the world. It is supported by NSF, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration, and by agreements with some 45 countries to exchange data and coordinate activities.[55]

Post-earthquake investigations are another important means of collectively assessing the physical and societal impacts of damaging earthquakes and spurring further progress in mitigating against seismic risks. The Post Earthquake Evaluation Program, initiated in 1992 by USGS, the United Nations Educational, Scientific and Cultural Organization, and the Open Partial Agreement on Major Hazards of the Council of Europe, has the following objectives:

- create a mechanism for sharing information,
- strengthen interdisciplinary and interorganizational interfaces,
- increase the worldwide capacity for post-earthquake investigations, and
- foster the adoption of prevention, mitigation, and preparedness measures.[56]

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[53] Participating and sponsoring organizations include USGS, the U.S. Agency for International Development, the United Nations Educational, Scientific and Cultural Organization, and national governments. U.S. Geological Survey, see footnote 2, p. 11.

[54] Established by the Incorporated Research Institutions for Seismology (IRIS) and jointly operated with the USGS Albuquerque Seismological Laboratory, the University of California at San Diego's International Deployment of Accelerometers group, and other member universities, the GSN is a rapidly expanding network of high-quality seismographs installed around the world for the purposes of earthquake and nuclear test monitoring and related research. In addition to data from the GSN, the IRIS Data Management Center has recently begun collecting data from international seismic networks operated by the Federation of Digital Seismic Networks.

[55] Office of Science and Technology Policy unpublished material.

[56] U.S. Geological Survey, see footnote 2, p. 42.

D Appendix D: Acronyms

Caltech	California Institute of Technology
CDMG	California Division of Mines and Geology
CONCERT	Coordinating Organization for Northern California Earthquake Research and Technology
CUBE	Caltech-USGS Broadcast of Earthquakes
CUSEC	Central United States Earthquake Consortium
EWS	Early Warning Systems
FEMA	Federal Emergency Management Agency
GIS	Geographical Information System
GPS	Global Positioning System
IRIS	Incorporated Research Institutions for Seismology
M	magnitude
MMI	Modified Mercalli Intensity
Mw	moment magnitude
NCEER	National Center for Earthquake Engineering Research
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
NSN	National Seismograph Network
PASSCAL	Program for Array Seismic Studies of the Continental Lithosphere
R&D	research and development
REDI	Rapid Earthquake Data Integration
SAR	synthetic aperture radar
SCEC	Southern California Earthquake Center
UBC	Uniform Building Code
UNAVCO	University Navstar Consortium
URM	unreinforced masonry
USGS	U.S. Geological Survey
VLBI	Very Long Baseline Interferometry

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