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# Subpart D



**SEISMIC  
HAZARDS**

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## INTRODUCTION

Earthquakes and tsunamis are considered seismic hazards. An earthquake is sudden ground motion or trembling caused by an abrupt release of accumulated strain acting on the tectonic plates that comprise the Earth's crust. When an earthquake occurs in the ocean, it may trigger tsunami waves. Earthquakes and tsunamis are more prevalent in the Western States and Pacific Territories.

Although earthquakes in the United States have caused less economic loss annually other hazards such as ground failures and floods, they have the potential to cause great sudden loss because devastation can occur in just minutes.

Tsunami waves can reach heights of 50 ft (15 m) or more. Damaging tsunami events are relatively infrequent, occurring about every 7 years in the high-risk areas of Alaska and Hawaii, flooding inland property up to 1 mi (1.6 km) from the coast.

Seismic hazards often trigger other devastating events: earthquakes cause landslides and fires; earthquake-damaged dams and levees may add to flood risks; and tsunamis can erode shorelines.



*Photo: Red Cross*



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CHAPTER

# 16



# EARTHQUAKES

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## CHAPTER SUMMARY

Although earthquakes have caused much less economic loss annually in the United States than other hazards such as floods, they have the potential for causing great and sudden loss. Within 1 to 2 minutes, an earthquake can devastate part of an area through ground-shaking, surface fault ruptures, and ground failures.

The zone of greatest seismic activity is along the Pacific Coast in Alaska and California. However, the intermountain west, central, and eastern regions have experienced significant earthquakes. Social, physical, and economic impacts may be very long-term. The 1994 Northridge, CA event caused \$20 billion in damage. The average annual loss from earthquakes is estimated at \$1 billion.

According to a recent FEMA estimate, more than 109 million people and 4.3 million businesses in the United States are exposed to some degree of seismic risk. Houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, waterlines, gaslines, and sewer lines all are exposed to damage from earthquakes. While direct deaths and injuries from an earthquake are unlikely, they can occur as an indirect result, when structures collapse.

FEMA and the National Institute of Building Sciences (NIBS) are developing a standardized methodology for estimating potential earthquake losses on a regional basis (Chapter 24). Other cooperative efforts include research into engineering techniques to reduce losses, developing effective means for saving lives and property and limiting social disruptions, and emergency planning. Building codes for rehabilitation of existing buildings and for new buildings have been adopted by several States and local jurisdictions.



Photo: Red Cross



*Photo: Red Cross*

## HAZARD IDENTIFICATION

An earthquake is a sudden motion or trembling caused by an abrupt release of accumulated strain on the tectonic plates that comprise the Earth's crust. The theory of plate tectonics, introduced in 1967, holds that the Earth's crust is broken into several major plates. These rigid, 50- to 60-mi (80- to 96-km) thick plates move slowly and continuously over the interior of the earth, meeting in some areas and separating in others. Velocities of relative motion between adjacent plates range from less than a fraction of an inch to approximately 5 in (13 cm) per year. Although slow by human standards, the velocities are rapid by geologic standards. A movement of 2 in (5 cm) per year adds up to 30 mi (48 km) in only 1 million years.

As the tectonic plates move together they bump, slide, catch, and hold. Eventually, faults along or near plate boundaries slip abruptly when the stress exceeds the elastic limit of the rock, and an earthquake occurs. The ensuing seismic activity and ground motion provoke secondary hazards: surface faulting, ground failure, and tsunamis (Chapter 17).

The great majority of earthquakes strike near continental margins or in areas where large lithospheric plates

collide or move past each other. However, earthquakes can occur within a major plate as evidenced by the major events that occurred in 1811-12 in the vicinity of New Madrid, MO. Other interior areas that have experienced earthquakes include parts of Montana, eastern Idaho, western Wyoming, Utah, and Nevada.

**GROUND MOTION.** Ground motion describes the vibration or shaking of the ground during an earthquake. In general, the severity of ground motion increases with the amount of energy released and decreases with distance from the causative fault or epicenter. When a fault ruptures, seismic waves are propagated in all directions, causing the ground to vibrate at frequencies ranging from 0.1 to 30 Hz. Seismic waves are referred to as P waves, S waves, and surface waves (Hays, 1981).

P (primary) waves, also called compressional or longitudinal waves, propagate through the Earth at a speed of approximately 15,000 mph (39,000 km/h) and are the first waves to cause vibration. They are longitudinal waves, similar in character to sound waves and cause back-and-forth oscillation along the direction of wave travel. The direction of particle motion is the same as the direction of wave propagation (Figure 16-1).

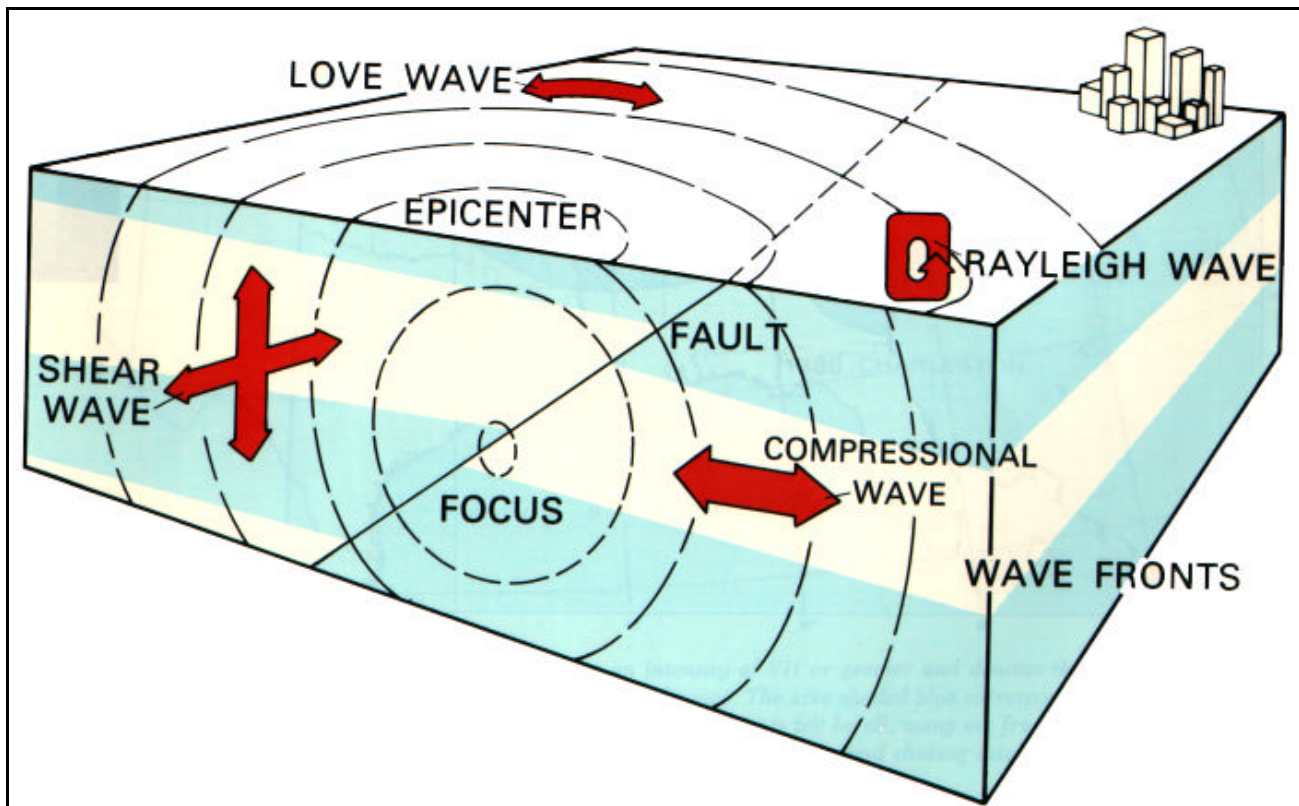


FIGURE 16-1.—Wave fronts: directions of vibrations.

Source: Hays, 1981.



S (secondary or shear) waves are slower and cause structures to vibrate from side to side. Particle motion is back and forth at right angles to the direction of wave travel (Figure 16-1). S waves are the most damaging waves because unreinforced buildings are more easily damaged by horizontal motion than by vertical motion.

Surface waves (Rayleigh waves and Love waves) travel even slower than P and S waves, and propagate along the Earth's surface rather than through the interior. Particle motion is orbital, similar to motion in water waves. Particle motion in Rayleigh waves is elliptical in the vertical plane containing the direction of propagation, and amplitude decreases exponentially with depth. Particle motion in Love waves is horizontal, transverse to the direction of propagation, with no vertical motion. They both produce surface ground shaking, but very little deep motion.

P and S waves mainly cause high-frequency vibrations (greater than 1 Hz), which are more efficient than low-frequency waves in causing low buildings to vibrate. Rayleigh and Love waves mainly cause low-frequency vibrations, which are more efficient than high-frequency vibrations in causing tall buildings to vibrate. Because the amplitudes of low-frequency waves decay less rapidly than high-frequency vibrations as distance from the fault increases, tall buildings located at relatively great distances from a fault (60 mi (96 km)) are sometimes damaged.

**SEISMIC ACTIVITY.** Seismic activity is described in terms of magnitude and intensity. Magnitude ( $M$ ) characterizes the total energy released, and Intensity ( $I$ ) subjectively describes effects at a particular place. While an earthquake has only one magnitude, its intensity varies throughout the affected region.

In 1935, Charles Richter of the California Institute of Technology devised a logarithmic magnitude scale, referred to as the Richter Magnitude Scale, to define local magnitude ( $M_L$ ) in terms of the motion that would be measured by a standard type of seismograph (Wood-Anderson torsion seismograph):

$$M_L = \log A - \log A_0$$

where  $A$  is the maximum amplitude traced by the seismograph (in millimeters), and  $\log A_0$  is a standard value as a function of distance between the seismograph and the epicenter, where the distance is less than 370 mi (600 km).

Several other magnitude scales are in use. For example, body-wave magnitude and surface-wave magnitude are similar to the local magnitude (Richter), but

are a function of measurable parameters of P, S, and surface waves. In technical and scientific applications, it is essential to specify the type of magnitude used rather than resort to or imply a generic "Richter magnitude" (Stover and Coffman, 1993).

On the Richter Scale, magnitude is expressed in whole numbers and decimals. In qualitative terms, an earthquake of 5.0 is a moderate event, 6.0 characterizes a strong event, 7.0 is a major earthquake, and a great quake exceeds 8.0. The scale is open-ended, but the highest magnitude known to have been calculated was approximately 9.5, while the lowest was approximately -3.0 (Stover and Coffman, 1993). On this logarithmic scale each whole number increase in magnitude represents a tenfold increase in measured amplitude. Furthermore, a magnitude 6.0 earthquake generates elastic-wave energy that is approximately 30 times greater than that generated by a magnitude 5.0 earthquake, 900 times ( $30 \times 30$ ) greater than that of a magnitude 4.0 earthquake, and so forth.

The effect of an earthquake on the Earth's surface is called the intensity. In the United States, the most commonly used intensity scale is the Modified Mercalli Intensity Scale (MMI) (Wood and Neuman, 1931). This scale, composed of 12 increasing levels of intensity ranging from imperceptible to catastrophic, is an evaluation of the severity of ground motion at a given location measured relative to the effects of earthquakes on people and property. It provides a convenient way for observers to summarize what happened at different locations (Table 16-1).

Principal earthquakes in the United States from 1568 through 1989 have been described (Stover and Coffman, 1993). To show magnitudes for earthquakes without computed values, a relation was established between magnitude and intensity. This was accomplished by correlating the maximum intensity with the average magnitude of earthquakes in four geographical areas where computed magnitudes and intensities were available: Western United States, Eastern United States, Hawaii, and Alaska. The results of the correlations for the four areas provide an approximate comparison of the two methods for measuring earthquake severity (Table 16-2).

**SURFACE FAULTING.** Surface faulting is the differential movement of two sides of a fracture. While faults occur deep within the Earth, their effects at the surface can be severe. Surface faulting is an obvious hazard to structures built across active faults. In particular, surface faulting can damage railways and highways, and buried infrastructure such as pipelines and tunnels.

TABLE 16-1.—*Earthquake felt intensity: the modified Mercalli Intensity Scale*

MMI	Felt Intensity
I	Not felt except by a very few people under special conditions. Detected mostly by instruments.
II	Felt by a few people, especially those on upper floors of buildings. Suspended objects may swing.
III	Felt noticeably indoors. Standing automobiles may rock slightly.
IV	Felt by many people indoors, by a few outdoors. At night, some people are awakened. Dishes, windows, and doors rattle.
V	Felt by nearly everyone. Many people are awakened. Some dishes and windows are broken. Unstable objects are overturned.
VI	Felt by everyone. Many people become frightened and run outdoors. Some heavy furniture is moved. Some plaster falls.
VII	Most people are alarmed and run outside. Damage is negligible in buildings of good construction, considerable in buildings of poor construction.
VIII	Damage is slight in specially designed structures, considerable in ordinary buildings, great in poorly built structures. Heavy furniture is overturned.
IX	Damage is considerable in specially designed buildings. Buildings shift from their foundations and partly collapse. Underground pipes are broken.
X	Some well-built wooden structures are destroyed. Most masonry structures are destroyed. The ground is badly cracked. Considerable landslides occur on steep slopes.
XI	Few, if any, masonry structures remain standing. Rails are bent. Broad fissures appear in the ground.
XII	Virtually total destruction. Waves are seen on the ground surface. Objects are thrown in the air.

Source: *Pearce and others, 1993.*

The displacements, lengths, and widths of surface faulting vary widely. The differential movement of displacements in the United States has ranged from a fraction of an inch to more than 20 ft (6 m). The length of surface ruptures on land has ranged from less than 1 mi (1.6 km) to more than 200 mi (322 km).

Most fault displacements are confined to a narrow zone ranging in width from 6 to 1,000 ft (2 to 305 m). However, separate subsidiary fault ruptures may occur 2 to 3 mi (3.2 to 4.8 km) from the main fault. The area subject to disruption by surface faulting varies with the length and width of the rupture zone (Hays, 1981).

There are three general types of surface faulting, shown in Figure 16-2 and described below.

- **Strike-Slip Faults** are high-angle fractures in which displacement is horizontal, parallel to the strike of the fault plane. Little or no vertical movement occurs. Instead, these faults are expressed topographically by a straight, low ridge extending across the surface, which commonly marks a discontinuity in various landscapes.
- **Normal Faults** move mainly in the vertical. Rocks above the fault plane move downward relative to those beneath the fault plane. Most normal faults are steeply inclined, usually between 65 and 90 degrees.

TABLE 16-2.—*Relationship between Modified Mercalli Intensity Scale and seismic magnitude*

Western United States	
MMI	Magnitude
V	<5.0
VI	5.0
VII	5.5
VIII	6.0
IX	6.5
X-XII	7.0
Eastern United States	
MMI	Magnitude
VI	<5.
VII	5.
VIII	5.
IX	6.
X-XII	6.5
Hawaii	
MMI	Magnitude
V	<5.5
VI	5.5
VII	6.0
VIII	6.5
IX	7.0
X-XII	7.5
Alaska	
MMI	Magnitude
V	<6.0
VI	6.0
VII	6.5
VIII	7.0
IX	7.5
X-XII	8.0

Source: *Stover and Coffman, 1993*

- **Reverse (Thrust) Faults** are low-angle faults in which the hanging wall moves up and over the fault plane. Movement is predominately horizontal, and displacement can occur for more than 35 mi (56 km). These faults result from crustal shortening and are generally associated with intense folding caused by powerful horizontal compression of the crust.

**EARTHQUAKE-RELATED GROUND FAILURE.** Liquefaction is a physical process that takes place during some earthquakes and may lead to ground failure. Liquefaction is caused when clay-free soil deposits, primarily water-saturated sand and coarse silts, react to vibrations, temporarily lose strength, and behave as viscous fluids. Liquefaction takes place when seismic shear waves pass through a saturated granular soil layer, distort its granular structure, and cause some of the void spaces to collapse. If drainage is limited, the pore-water pressure increases. If it rises to about the pressure caused by the weight of soil, the granular soil behaves like a fluid rather than a solid for a short period of time and deformations can occur.

Generally, the younger and looser the sediment and the higher the water table, the more susceptible a soil is to liquefaction. Liquefaction enhances ground settlement and sometimes generates sand boils. Sand boils are caused by water laden with sediment venting from sub-surface layers in which artesian pore-water pressures develop during liquefaction.

Liquefaction causes three types of ground failure, described below.

- **Lateral Spreads** involve the lateral movement of large blocks of soil as a result of liquefaction of an underlying layer. They generally develop on gentle slopes, most commonly on those between 0.3 and 3 degrees. Horizontal movements commonly are as much as 10 to 15 ft (3 to 5 m). However, where slopes are particularly favorable and the duration of ground shaking is long, lateral movement may be as much as 100 to 150 ft (30 to 50 m). Lateral spreads usually break up internally, forming numerous fissures and scarps.
- **Flow Failures**, consisting of liquefied soil or blocks of intact material riding on a layer of liquefied soil, are the most catastrophic type of ground failure caused by liquefaction. They commonly move scores of feet and up to dozens of miles under certain conditions. Flow failures usually form in loose saturated sand or silts on slopes greater than 3 degrees.
- **Loss of Bearing Strength** occurs when the soil supporting buildings or other structures liquefies. When

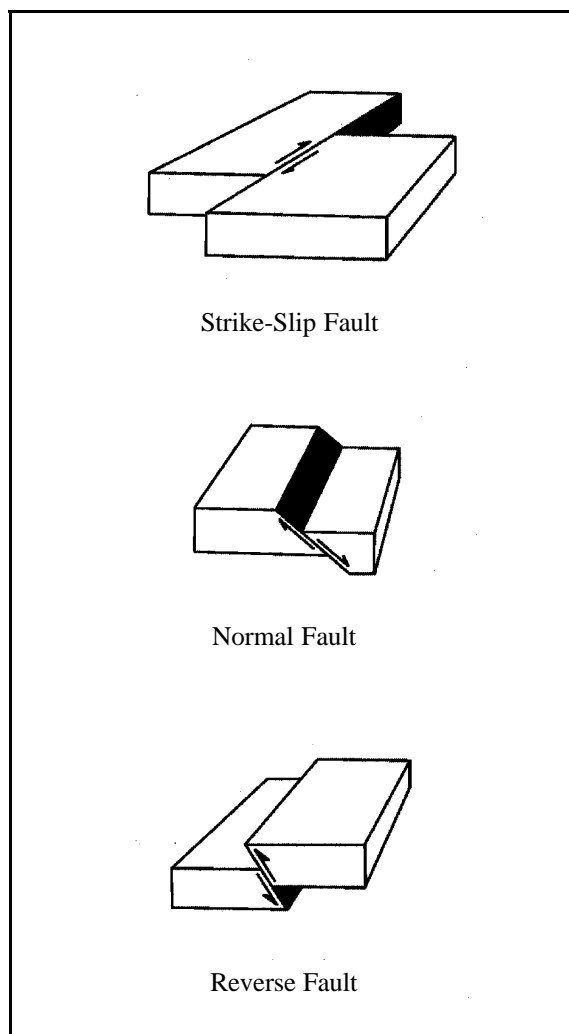


FIGURE 16-2.— Surface faulting.

Source: *Hays, 1981*

large deformations occur, structures settle and tip. The general subsurface geometry required for liquefaction-caused bearing failures is a layer of saturated, cohesionless soil that extends from near the ground surface to a depth equal to about the width of the building.

## RISK ASSESSMENT

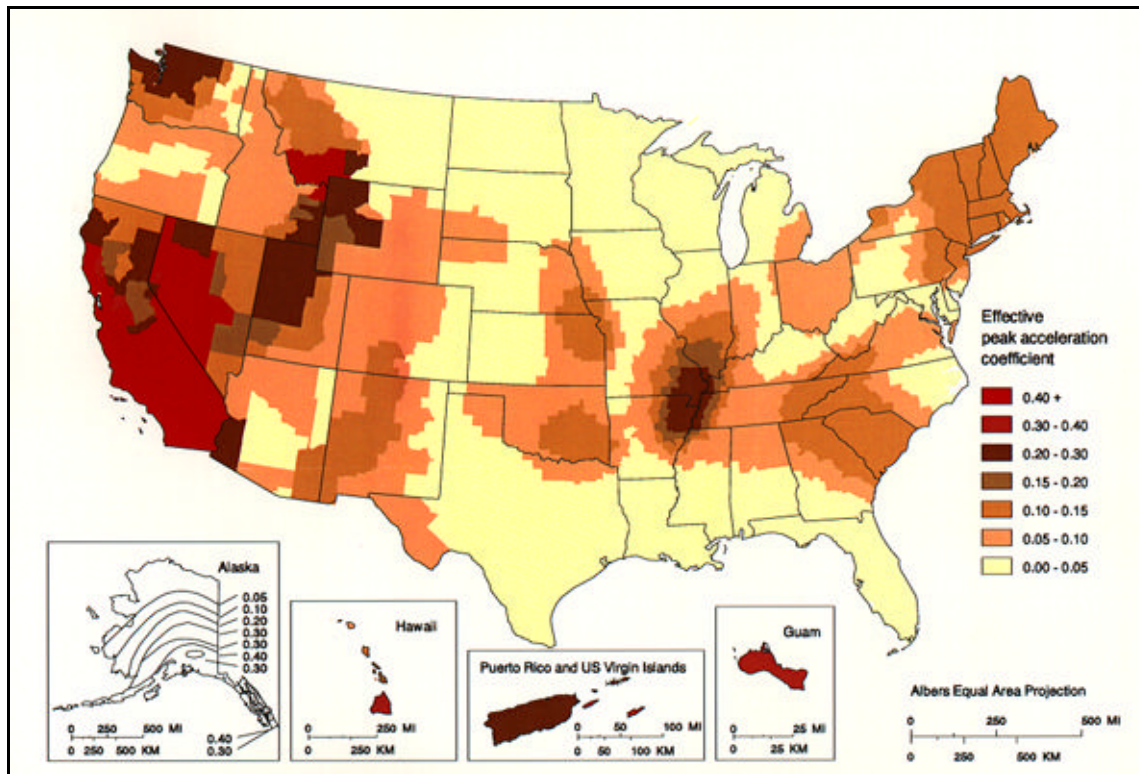
Published probabilistic ground motion maps can be used to assess the magnitude and frequency of seismic hazards. Twelve of these maps are published as part of the 1994 edition of the National Earthquake Hazards Reduction Program's *NEHRP Recommended Provisions* (FEMA-222A, 1994). NEHRP Maps 1 to 4, prepared by the Applied Technology Council, Redwood City, CA, and based on a probabilistic maximum ground acceleration map by Algermissen and Perkins

(1976), were originally published as part of the *Tentative Provisions* in 1978. NEHRP Maps 5 to 12 were developed by USGS.

## PROBABILITY AND FREQUENCY

Algermissen and Perkins (1976) described preparation of a probabilistic maximum ground acceleration map, described below.

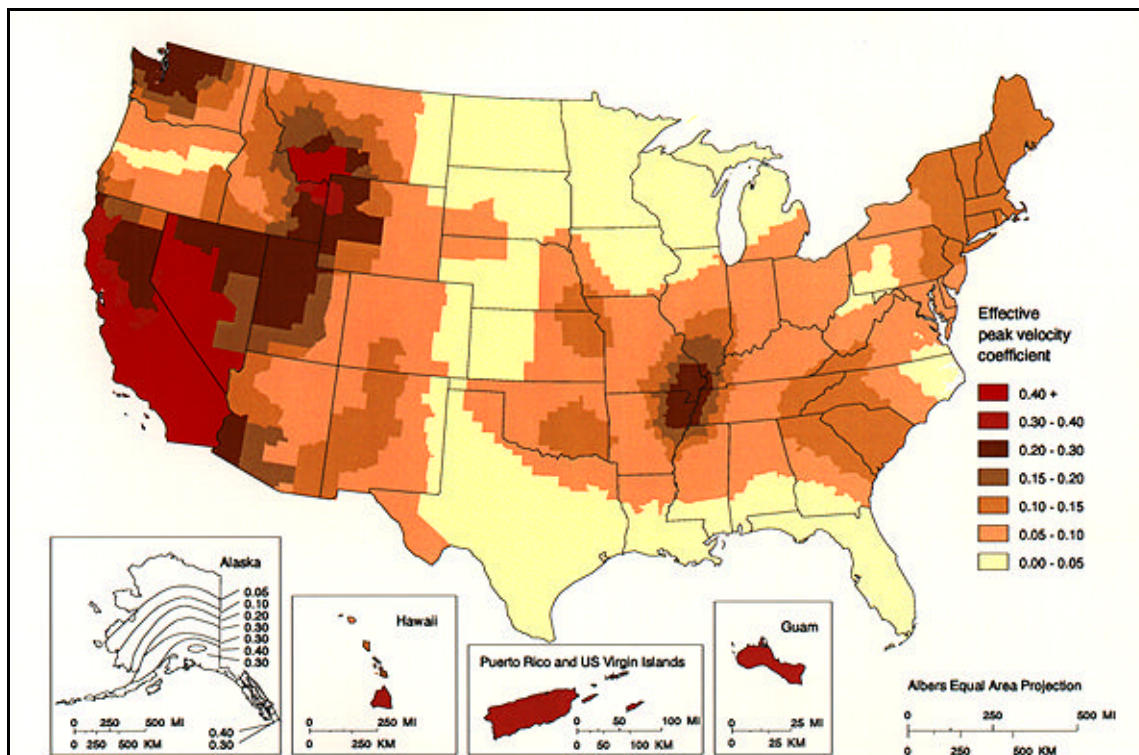
1. Source zones and faults in which, or along which, significant earthquakes (MMI of V or greater, magnitude of 4.0 or greater) can occur were identified and delineated on a map. Spatial occurrence of future earthquakes was assumed to be uniform throughout each source zone. Using historical seismicity, geological, and tectonic information, 71 seismic source zones were identified.
2. For each source zone, the rate at which earthquakes of different magnitudes can occur and the maximum credible magnitudes were estimated. The number of earthquakes per unit time per unit area were related linearly to the magnitude, with coefficients determined from known events in each source zone. Future earthquake occurrences were assumed to have the same general average time rate characteristics as past earthquakes.
3. Acceleration attenuation curves were used to give the intensity of shaking as a function of magnitude and distance from an epicenter. Different attenuation curves were used for the Western and Eastern States.
4. The distribution of acceleration was computed for a number of sites in each source zone. The expected number of times a particular acceleration is likely to occur in a given period of years was determined, and the maximum acceleration in a given number of years corresponding to a given level of exceedance probability was estimated. The probabilistic model assumed that the occurrences of major earthquakes is a Poisson process and that they are independent and identically distributed events. The assumption of a Poisson process results in an exponential probability distribution of the time between occurrences of major earthquakes.
5. The maximum acceleration with a 10-percent chance of being exceeded in 50 years was computed and mapped. The return period for this acceleration is approximately 475 years, or, stated alternatively, there is a 0.21-percent chance of it being exceeded in any given year.



Map 16-1. Spatial variation in the effective peak acceleration coefficient ( $A_a$ ), by county.

Data not available for American Samoa.

Source: *Map 1 in 1994 edition of the "NEHRP Recommended Provisions."*



Map 16-2. Spatial variation in the effective peak velocity coefficient ( $A_v$ ), by county.

Data not available for American Samoa.

Source: *Map 2 in 1994 edition of the "NEHRP Recommended Provisions."*

In developing NEHRP Maps 1-4, two parameters were used to characterize the intensity of ground shaking: effective peak acceleration (EPA), and effective peak velocity (EPV). EPA, which is related to oscillation of buildings, is computed for periods in the range of 0.1 to 0.5 seconds and is generally less than the peak ground acceleration. EPV is computed for approximately 1-second-long periods and is generally greater than peak ground velocity at large distances from major earthquakes.

For the purpose of computing seismic design coefficients, EPA and EPV are replaced by dimensionless coefficients  $A_a$  and  $A_v$ . EPA is equal to  $A_a$  when expressed as a decimal fraction of the acceleration of gravity, such that if  $EPA = 0.2G$ , then  $A_a = 0.2$ .  $A_v$  is equal to EPV divided by 30 (FEMA-223A, 1994).

NEHRP Map 1 (Map 16-1), which shows values  $A_a$  of by county, was developed to avoid operational difficulties associated with having different zones within a single jurisdiction.

NEHRP Map 2 (Map 16-2), which shows values of  $A_v$  by county, was converted to a county-by-county map from the contour map published as NEHRP Map 4, which originates from NEHRP Map 3, a contour map of  $A_a$ .

Algermissen and Perkins (1976) originally developed peak ground accelerations with a 10-percent chance of being exceeded in a 50-year period. However, because the mapped values of  $A_a$  and  $A_v$  (as illustrated in Maps 16-1 and 16-2) were truncated, adjusted, and smoothed, the percent chance of exceedance cannot be estimated precisely, and the risk may not be the same at all locations.

The percent chance of exceedance of  $A_a$  and  $A_v$  in Maps 16-1 and 16-2, is believed to be in the range of 10 to 20 percent for a 50-year period. This would imply that the return period is on the order of 225 to 475 years, or that the percent chance of exceedance in any given year is on the order of 0.44 to 0.21 percent. The use of a 50-year period to characterize the percent chance of exceedance is rather arbitrary for convenience, and does not imply that all buildings are thought to have a useful life of 50 years (FEMA-223A, 1994).

## EXPOSURE

The zone of greatest seismic activity in the United States is along the Pacific Coast in Alaska and California. However, the Central and Eastern States have also experienced seismic activity: the Boston

vicinity (1755); the central Mississippi Valley at New Madrid, MO (1811-1812); Charleston, SC (1880s); and at Hebgen Lake, MT (1959). In 1973, earthquakes were felt in 34 States. All or parts of 39 States lie in regions classified as having major or moderate seismic risk (Hays, 1981).

FEMA recently conducted a study of the number of people and businesses that are exposed to various hazards, including seismic risks of 0.1 percent or greater ( $A_a \geq 0.1$ ). When evaluated by county and State, over 109 million people and 4.3 million businesses may be exposed. The study did not provide information on potential losses from earthquakes.

## CONSEQUENCES

Damages and deaths associated with significant U.S. earthquakes that measured 6.4 and higher on the Richter scale from 1964 to 1994 are summarized in Table 16.3. Different sources report varying values of magnitude, damages, and deaths for these events. In general, the values reported in Stover and Coffman (1993) were used to achieve some measure of consistency.

Recent significant earthquakes have occurred in the Western United States. Losses can be catastrophic, as evidenced by the \$20 billion in damage caused by the 1994 Northridge earthquake where collapse of structures due to ground shaking was a major cause of damage. Hays (1990) estimates that the average annual losses from all U.S. earthquakes are approximately \$1 billion. The average loss from earthquakes measuring 6.4 or greater is approximately \$900 million.

Deaths and injuries from surface faulting are unlikely, but casualties can occur indirectly through damage to structures. Surface faulting, in the case of a strike-slip fault, generally affects a long narrow zone whose total area is small compared with the total area affected by ground shaking. Nevertheless, damage to structures located in a fault zone can be very high, especially where land use is intensive.

A variety of structures have been damaged by surface faulting, including houses, apartments, commercial buildings, nursing homes, railroads, highways, tunnels, bridges, canals, storm drains, water wells, waterlines, gaslines, and sewer lines. Damage to these structures has ranged from minor to very severe. An example of severe damage occurred in 1952 when three railroad tunnels in California were badly damaged. As a result, traffic on a major line linking northern and southern California was stopped for 25 days, despite an around-the-clock repair effort (Hays, 1981).

TABLE 16-3.—*Significant U.S. earthquakes: 1964–1994.*

Location	Date	Magnitude *	Damages (in millions)	Deaths
Prince William Sound, AK	March 27, 1964	8.4	\$311.0	125
Puget Sound, WA	April 29, 1965	6.4	\$12.5	7
San Fernando, CA	February 9, 1971	6.6	\$505.0	65
Island of Hawaii	November 29, 1975	7.2	\$4.1	2
Imperial Valley, CA	October 15, 1979	6.5	\$30.0	0
Coalinga, CA	May 2, 1983	6.4	\$10.0	0
Borah Peak, ID	October 28, 1983	6.5	\$12.5	2
Island of Hawaii	November 16, 1983	6.6	\$7.0	0
Loma Prieta, CA	October 17, 1989	7.1	\$6,000.0	63
Northridge, CA	January 17, 1994	6.7	\$20,000.0	61

\*Sometimes an average of different magnitude types.

Sources: *From Stover and Coffman, 1993; Heliker, 1990; Hays, 1980; FEMA, 1993.*

Damage caused by lateral spreads is seldom catastrophic, but usually is disruptive. For example, during the 1964 earthquake in Alaska, more than 200 bridges were damaged or destroyed by lateral spreading of floodplain soils toward river channels. The spreading deposits compressed bridges over channels, buckled decks, thrust sedimentary beds over abutments, and shifted and tilted abutments and piers (Hays, 1981). A number of major water pipeline breaks occurred during the 1906 earthquake in San Francisco, CA, hampering efforts to fight fires. Thus, rather inconspicuous ground-failure displacements of less than 7 ft (2.2 m) contributed significantly to the overall devastation.

Flow failures can originate underwater or on land. Many of the largest and most damaging flow failures have taken place underwater in coastal areas. For example, large sections of port facilities at Seward, Whittier, and Valdez, AK, were carried away during the 1964 earthquake. These flow failures, in turn, generated large sea waves that overran parts of the coastal floodplain, causing additional damage and casualties.

## RESEARCH, DATA COLLECTION, AND MONITORING ACTIVITIES

**SUSCEPTIBILITY OF LATERAL-SPREAD GROUND FAILURE.** A new methodology to determine the spatial susceptibility of earthquake-induced lateral-spread ground failure (liquefaction) is described by Pike and

others (1994) for a study area along the Monterey Bay coast of central California. Using Probit regression analysis, a regional model was developed to estimate the susceptibility of liquefaction based on age and sand content of the sedimentary deposits, horizontal distance to nearest surface water, and ground slope. The occurrence (or non-occurrence) of liquefaction in 100-m (309-ft) grid cells was identified throughout the study area. The methodology could be used where adequate data on liquefaction are available. Susceptibility has no implications for frequency of occurrence.

**LOSS ESTIMATION METHODOLOGY.** The National Institute of Building Sciences (NIBS), under a cooperative agreement with FEMA, is developing a nationally applicable standardized methodology for estimating potential earthquake losses on a regional basis (Chapter 24). Known as HAZARD U.S. (HAZUS), the method will be used by local, State, and regional officials to plan and prepare for emergency response and recovery, and to stimulate mitigation actions. HAZUS may be used for rapid loss estimations following earthquake events. Pre-disaster assessments may support risk-based allocation of federal resources in the future.

**NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM (NEHRP).** In 1977, the U.S. Congress passed the National Earthquake Hazards Reduction Act (P.L. 95-124). NEHRP, a program to reduce or mitigate the nation's losses from earthquakes, was initiated in June 1978. Fundamental research on earthquake haz-

ards and engineering techniques to reduce losses has been carried out or funded by FEMA, USGS, NIST, and NSF.

Recently, a strategy for a new National Earthquake Program (NEP) to strengthen and extend NEHRP was formulated by the National Earthquake Strategy Working Group (NESW) for the National Science and Technology Council and the White House Office of Science and Technology Policy (NESW, 1995). NEP aims to focus scarce research and development dollars on the most effective means for saving lives and property, limiting social disruptions from earthquakes, coordinating Federal research and development, and supporting emergency planning in other Federal agencies. The objectives are to avoid duplication, ensure focus on priority goals, and cooperate with the private sector and State and local jurisdictions to apply effective mitigation strategies and measures.

Leadership and coordination for NEP is provided by FEMA. FEMA's responsibilities include transfer of research results to the user communities and keeping research focused on the NEP goals.

**PARKFIELD EARTHQUAKE PREDICTION EXPERIMENT.** The San Andreas fault at Parkfield, CA, is one of the most active faults in the United States. Earthquakes of magnitude 6.0 or more occurred in 1857, 1881, 1901, 1922, 1934, and 1966, for an average of 22 years between events. In 1985, USGS published a prediction that the next Parkfield earthquake was expected in a time window centered on 1988, with a 95-percent chance of occurrence by the end of 1992 (Bakun and Lindh, 1985). The National Earthquake Prediction Evaluation Council working group (NEPEC) reviewed the prediction favorably, and USGS located a focused experiment at Parkfield.

The USGS and the State of California have instrumented the Parkfield area with over 20 observational networks, including seismometers, creep meters, borehole strain meters, a two-color laser geodimeter, water wells, and magnetometers. Five networks are monitored in real-time. The experiment has two scientific goals: to record geophysical data before, during, and after the expected earthquake; and to issue a short-term prediction. With the involvement of the State, the experiment took on an important public policy aspect, serving as a test bed for communication between earthquake scientists and public officials (NEPEC, 1994).

Although the predicted earthquake did not occur by 1992, Parkfield still is considered to be more likely to experience a strong (magnitude 6.0) earthquake than any other place in the United States. Several estimates

of the percent chance of occurrence of an event cluster around a value of approximately 10 percent per year. Such a probability is high enough that monitoring of the Parkfield area is continuing.

**SPECTRAL RESPONSE MAPS.** The earthquake maps used to administer building codes have their origin in the Algermissen and Perkins peak acceleration map (1976). Maps of spectral response ordinates at natural periods of 0.3 and 1.0 seconds for a reference site condition were developed in 1994 and are available for the entire United States (Leyendecker and others, 1995). They are for a 10-percent chance of exceedance for exposure times of 50 and 250 years (return periods of approximately 475 and 2,370 years). The spectral response maps are revisions of those first prepared and published in the 1991 *NEHRP Recommended Provisions*. The 1994 revision gives recognition to the increased likelihood of occurrence of large earthquakes on the Cascadia subduction zone off the coast of the Northwestern United States (Leyendecker and others, 1995).

## MITIGATION APPROACHES

Considerable interagency cooperation and research have supported adoption of State and local building codes and regulations designed to reduce losses sustained by new and existing construction due to seismic hazards. The cooperating organizations included ATC, NIST, NSF, ASCE, NIBS, and FEMA.

The emergence of FEMA as the agency responsible for implementing the Earthquake Hazards Reduction Act and NEHRP required the establishment of a mechanism to obtain a broad public and private consensus on recommended improvements for building design and construction regulatory provisions. Following a series of meetings with ASCE, NSF, NIST, and NIBS, the Building Seismic Safety Council (BSSC) was created in 1979 under the auspices of NIBS and is located in Washington, DC.

BSSC was established as an independent, voluntary membership body to deal with the complex regulatory, technical, social, and economic issues involved in developing and promulgating national regulatory provisions. BSSC, which represents all of the needed expertise and all relevant public and private interests (50+ organizations), has improved the seismic safety provisions published by FEMA (FEMA-222A, 1994). BSSC coordinates the activities of 12 technical subcommittees that address technical, social, political, legal, administrative, and regulatory issues.

Two important programs coordinated by FEMA and



supported by many other agencies are the rehabilitation of existing buildings and the seismic safety of new buildings. Many publications provide guidance on mitigation techniques have resulted.

Publications related to rehabilitation of existing buildings include:

- Rapid visual screening of buildings for potential seismic hazards (FEMA-154 and FEMA-155, 1988);
- Techniques for the seismic evaluation and rehabilitation of existing buildings (FEMA-178 and FEMA-172, 1992);
- Typical costs and benefit-cost model for the seismic rehabilitation of existing buildings (FEMA-156, 1994; FEMA-157, 1995; FEMA-227 and FEMA-228, 1992);
- Establishing programs and priorities for the seismic rehabilitation of buildings (FEMA-173 and FEMA-174, 1989);
- Financial incentives for seismic rehabilitation of buildings (FEMA-198 and FEMA-199, 1990); and
- Identification and resolution of issues related to seismic rehabilitation of buildings (FEMA-237, 1992).

Publications related to seismic safety of new buildings include:

- The *NEHRP Recommended Provisions* for seismic regulation for new buildings, including the NEHRP probabilistic ground motion maps (FEMA-222A and FEMA-223A, 1994);
- The *Non-Technical Explanation of the 1994 NEHRP Recommended Provisions* (Building Seismic Safety Council, 1995);
- *Seismic Consideration for Communities at Risk* (Building Seismic Safety Council, 1990);
- Selected readings on societal implications (FEMA-84, 1985);
- Seismic considerations for elementary and secondary schools (FEMA-149, 1990), health care facilities (FEMA-150, 1990), hotels and motels (FEMA-151, 1990), apartment buildings (FEMA-152, 1988), and office buildings (FEMA-153, 1988); and
- Interim guidelines for evaluation, repair, modification and design of steel moment frame structures (FEMA-267, 1995).

## RECOMMENDATIONS

The National Earthquake Strategy Working Group (1995) provided recommendations for a new strategy for earthquake loss reduction. The 1994 *NEHRP Recommended Provisions* includes recommendations for the safe seismic design of new buildings (FEMA-222A and FEMA-223A, 1995). FEMA provided several recommendations for loss-reduction measures (FEMA-200, 1990).

The Applied Technology Council, a nonprofit organization established by the Structural Engineers Association of California to conduct projects, workshops, and seminars in support of structural engineering, especially earthquake-related topics, is developing nationally accepted guidelines for the seismic rehabilitation of buildings. The guidelines will incorporate information from the many publications produced, and will provide recommendations.

Experts on the 12 technical subcommittees of BSSC are evaluating the impacts of adopting the new USGS spectral response probabilistic ground motion maps described by Leyendecker and others (1995).

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CHAPTER

17



# TSUNAMI EVENTS

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## CHAPTER SUMMARY

The tsunami, a Japanese word meaning "harbor wave," occurs most commonly in the Pacific Ocean. Tsunami waves have resulted in significant coastal flooding and damage in the Western States, Alaska, Hawaii, and American Samoa. Events in the Atlantic Ocean and Caribbean Sea have occurred in the vicinity of Puerto Rico and the U.S. Virgin Islands, but are much less frequent.

Tsunamis are large seismic sea waves, usually generated by shallow-focus, underwater earthquakes. A tsunami wave can travel across the ocean at speeds up to 500 mph (800 km/h). Upon hitting a coastline, a wave can cause significant damage to shore protection structures and buildings, severe erosion, extensive inland flooding, and loss of life.

Tsunami events affecting the United States and its territories have been responsible for almost 470 fatalities and hundreds of million dollars in property, infrastructure, transportation, and lifeline damage. The United States has not experienced a major tsunami event since the Great Alaskan Earthquake at Prince William Sound on March 28, 1964. That event killed 10 people and caused more than \$7 million in property damage in Crescent City, CA. It caused 106 fatalities and more than \$84 million in damage in Alaska. The worst tsunami in U.S. history occurred in the Aleutian Islands on April 1, 1946, and was responsible for 159 deaths and \$26 million in damage.

Hawaii is subject to remote-source tsunamis generated by earthquakes throughout the Pacific. The remaining tsunami-prone areas along the coasts of the continental United States, Alaska, Puerto Rico and the U.S. Virgin Islands are affected by locally generated events caused by subduction, underwater landslides, and volcanic activity. Since 1770, more than 46 remote-source generated tsunamis and 18 local tsunamis have been observed along the West Coast.

Hazard identification and risk assessment efforts include detailed mapping of tsunami wave runup and flood inundation limits, as well as related hazards that are expected concurrently with tsunamis. Public education campaigns are important to increase awareness. Mitigation measures include construction of shore-protection structures, land-use planning and building techniques, and relocation of utility lines, water mains, sewer lines, and roadways in immediate impact areas.

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*Photo: Red Cross*

## HAZARD IDENTIFICATION

Tsunamis are large seismic sea waves, impulsively generated by shallow-focus earthquakes. They typically are induced by a rapid, vertical thrust along the subsurface fault line between two tectonic plates of the earth's crust (Camfield, 1994). When a large mass of earth on the ocean bottom impulsively sinks or uplifts, the column of water directly above it is displaced, forming a tsunami wave on the surface. Tsunamis also are caused by volcanic activity and submarine landslides, but these triggering events occur less frequently than earthquakes. Earthquakes may induce landslides that contribute to wave size.

A tsunami wave can travel across the ocean at speeds up to 500 mph (800 km/h), depending on the location and source of the event. A tsunami is relatively unnoticeable until the shoaling effects of the nearshore continental shelf interact with the wave, boosting wave heights to 50 ft (15 m) or more. Astronomical tide levels, resonance in narrowing bays, and concave shoreline features may contribute to increases in wave height. Large tsunami waves have been known to damage and flood areas up to 1 mi (1.6 km) inland.

The height of a tsunami wave will be affected by its interaction with the shoreline. This influence will vary, depending on shoreline geometry (orientation and configuration), existence of submarine canyons, shoaling and refraction of incident waves, and large headland features. When waves reach coastal scarps, heights increase, while the nature of the wave period allows it to bend around obstacles. Coral reefs surrounding islands in the western North Pacific and the South Pacific generally cause waves to break, providing some protection to the islands.

Lander and Lockridge (1989) found the intensity of a tsunami wave to be directly related to:

- Magnitude of the shallow-focus earthquake;
- Area and shape of the rupture zone;
- Rate of displacement and sense of motion of the ocean floor in the source (epicenter) area;
- Amount of displacement of the rupture zone; and
- Depth of water above the rupture zone.

Radiation of a tsunami wave from the source area is directional, with wave periods ranging from 5 to 60 minutes. Long-period waves typically are associated with large-magnitude earthquakes, and smaller magnitude earthquakes generate short-period waves.

A remote-source tsunami may travel for more than 1 hour from its epicenter before it impacts a shoreline. While in deep water, its wave velocity is high. As the tsunami reaches shallow coastal waters, it slows down, its wavelength shortens, and its wave energy increases due to the shoaling effects of the nearshore subbottom. This effect can magnify a 3-ft (1-m) ocean tsunami wave to more than 50 ft (15 m) during coastal runup.

Depending on the reflection at the shoreline, Camfield (1994) reported the interaction of a tsunami with the shoreline could produce standing wave resonance at the shoreline, generation of edge waves by impulse of the incident waves, trapping of reflected waves by refraction, and the possibility of a Mach-stem along the shoreline. When a wave reaches the shoreline, it either breaks on the beach or rushes ashore as a bore-like, abrupt front of water (Lander and Lockridge 1989).

In Alaska, the principal tsunami source zones differ along exposed shorelines. Portions of the North Pacific Ocean coastline of Alaska are subject to tsunamis generated by landslides, tectonic plate movement (subduction), submarine landslides, and volcanic activity. The Aleutian Island coastlines are affected by remote-source earthquakes (Lander, 1994). In the Gulf of Alaska, tsunami waves may be generated by all sources. The coastline along the Bering Sea is not considered threatened by tsunami.

Because of its location in the central North Pacific basin, Hawaii is subject to remote-source tsunami generated by tectonic earthquakes from all Pacific regions. South Pacific seismic activity in the vicinity of American Samoa causes remote-source tsunami events. The remaining tsunami-prone areas along the coasts of the continental United States, Alaska, Puerto Rico and the U.S. Virgin Islands are affected by locally generated events caused by subduction, landslides, and volcanic activity.

The subduction zone off the West Coast is located relatively close to the shoreline, with the Juan De Fuca plate offshore of Oregon and Washington posing a likely source of locally-generated tsunamis. Researchers conducting sediment/soil investigations in the Pacific Northwest found sheets of sand deposited over coastal lowlands at ground elevations of up to 60 ft (18 m) above sea level, suggesting a tremendous tsunami event. Evidence that significant Cascadia subduction-zone tsunamis have occurred over the past 7,000 years has alerted officials to the exposure of coastal communities in the region. Tsunami researchers have predicted a recurrence of an event of this magnitude within the next 50 years (Preuss and Hebenstreit, 1991).



According to the American Samoa Department of Public Safety, TEMCO, draft *Survivable Crisis Management Plan* (1995), the tsunami hazard in American Samoa is primarily due to undersea earthquakes with magnitudes greater than 6.5 on the Richter scale. The abrupt rise of the islands from the ocean floor limits tsunami wave heights at the coastline.

## RISK ASSESSMENT

### PROBABILITY AND FREQUENCY

Since 1770, more than 46 remote-source generated tsunamis and 18 local tsunamis have been observed along the West Coast of the United States. Only the 1964 Prince William Sound Alaskan earthquake-induced event caused significant damage along the West Coast. Other major tsunami events occurred in the region in 1946 and 1957 in the Aleutian Islands, in 1952 on Kamchatka Island, and in 1975 in Hawaii.

Five tsunami hazard zones are identified in USGS Open-File Report 85-533 (USGS, 1985), prepared for the Interagency Committee on Seismic Safety in Construction (ICSSC). The report includes a map of general tsunami hazards for the United States and detailed mapping of hazard zones for the Hawaiian Islands. Map 17-1 reproduces predicted tsunami elevations with a 90-percent chance of not being exceeded in a 50-year period only for the Western United States, Alaska and Hawaii. The data and frequency curves were developed by the USACE Waterways Experiment Station (WES) in Vicksburg, MS, for FEMA Flood Insurance Studies from 1974 to 1980, and for a 1977 report on tsunami-wave elevation frequency of occurrence for Hawaii. The elevations along the Hawaiian shoreline include the combined effects of tsunami and astronomical tides, which are not included in determining hazard zones in other areas.

Coastal topography defines the landward penetration of tsunami wave runup and flood inundation. The elevation with a 1-percent chance of being equaled or exceeded in any given year, also known as the 100-year elevation, varies throughout the Pacific Ocean. Variations are due to differences in shoreline configuration, offshore bathymetry, upland topography, wave type, and proximity to sources of tsunami waves.

The principal tsunami-related risk in the Northwestern United States is considered to be from an offshore, subduction earthquake in the Cascadia fault zone. The last major Cascadia subduction-zone tsunami event, based on sedimentological records, occurred approximately 350 to 600 years ago (Preuss and Hebenstreit, 1991).

Along the coasts of California, Oregon, and Washington, predicted tsunami elevations are lower than the 1-percent-annual-chance coastal storm flood elevations caused by combined extreme wave heights and storm-surge tides. In Hawaii, tsunami wave runup elevations vary from 5 ft to over 20 ft (1.5 to +6 m).

Predicted tsunami elevations for American Samoa, with the exception of the Pago Pago area on Tutuila, are 4 ft (1.3 m), with inundation limits extending only 200 ft (61 m) inland. The 1-percent-annual-chance flood elevation at Pago Pago is approximately 11 ft (3.4 m) and is more associated with tropical cyclones than tsunamis.

In Puerto Rico, the potentially damaging effects of historical tsunami waves are acknowledged throughout the island. However, a return period and 1-percent-annual-chance tsunami elevation cannot be established because historical data are limited and tsunami waves occur infrequently.

### EXPOSURE

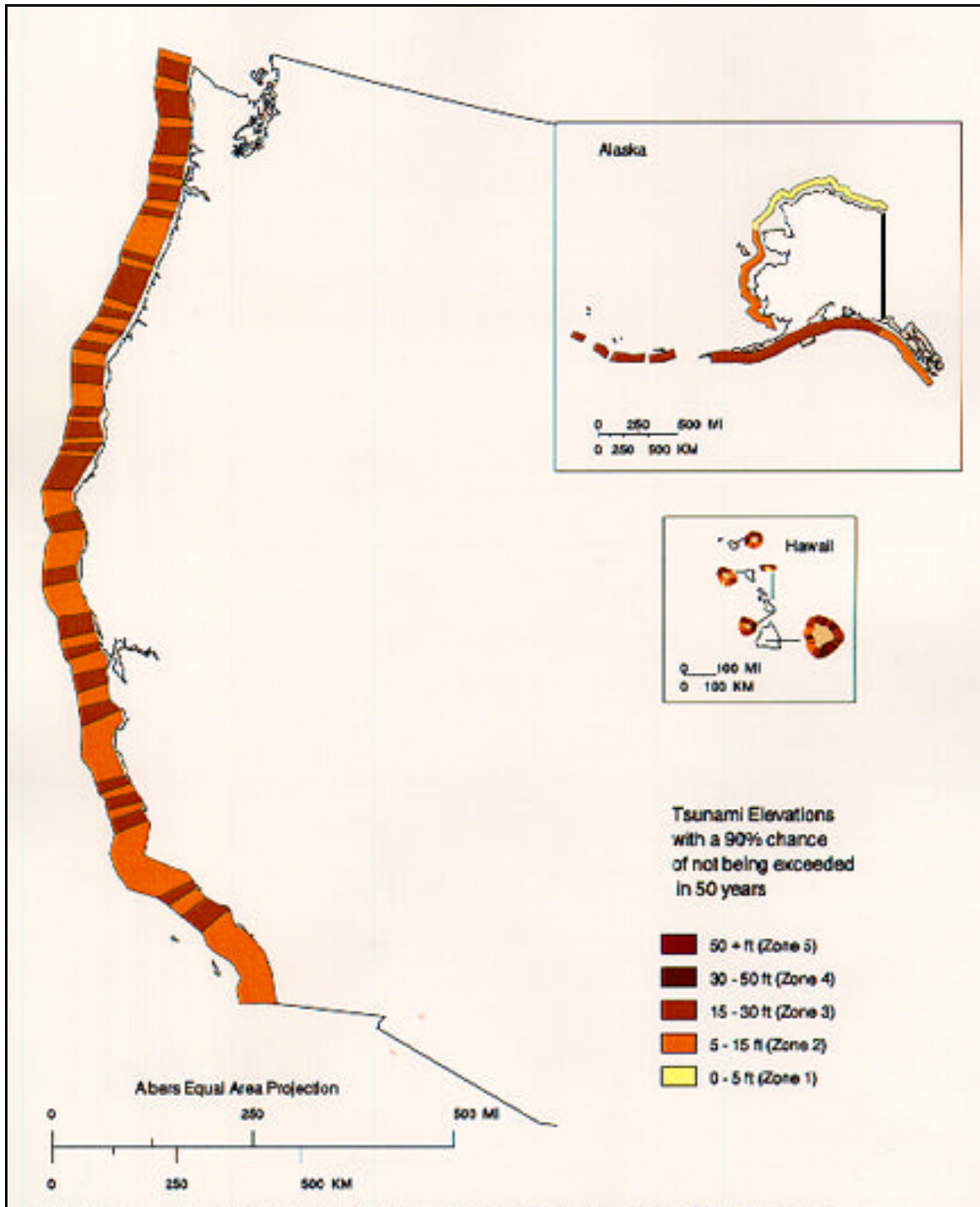
Buildings and infrastructure located in low-lying areas, in close proximity to the Pacific Ocean shoreline, and along the coasts of Puerto Rico and the U.S. Virgin Islands have the greatest exposure to the destructive forces of tsunamis.

Although a subduction-zone tsunami wave event has not occurred in recent history, exposure to potential disaster is high due to the heavily populated coastal area of the West Coast. A subduction-zone earthquake close to the shore could generate a tsunami wave that reaches the shoreline in less than 20 minutes. Thus, warning times would be insufficient to evacuate exposed areas.

During tsunami events affecting American Samoa, the village of Pago Pago on the island of Tutuila has suffered the greatest damage and flooding due to amplification of waves in its triangular bay. Damaging tsunamis occurred in the harbor at Pago Pago in 1917, 1919, 1922, 1952, 1960, and 1976. Comparatively, tropical cyclones cause greater damage throughout the island group than tsunamis.

### CONSEQUENCES

Tsunami events affecting the United States and its territories have been responsible for almost 470 fatalities and hundreds of million dollars in property, structure, facility, transportation, and lifeline damage (Lander and Lockridge, 1989). The high-risk areas of Alaska and Hawaii experience a damaging tsunami about every 7 years. During the past 20 years, tsunamis have not resulted in federally-declared disasters.



Map 17-1. Tsunami elevations with a 90-percent chance of not being exceeded in 50 years, also known as the 475-year return period elevation. Northern Puerto Rico and Virgin Islands (not shown) in Zone 3, southern Puerto Rico in Zone 2. Data not available for Pacific Territories. Source: *Data from U.S. Geological Survey, 1985*

The primary earthquake sources of tsunamis that impact the entire Pacific basin area are the Kamchatka Peninsula, Aleutian Islands, Gulf of Alaska, and coast of South America (Lander and Lockridge, 1989). Although about five tsunami events occur each year in the Pacific basin, only one is large enough to be observed or measured (Lander and others, 1993). A major, destructive tsunami occurs approximately once every 10 years somewhere around the Pacific Ocean.

The Great Alaskan earthquake at Prince William Sound in 1964 measured 9.2 on the Richter scale and generated waves throughout most of the Pacific basin. Several waves hit Crescent City, CA, causing over \$7 million in property damage, flooding, and 10 fatalities (Topozada and others, 1995). The first wave to reach Crescent City was 4.8 ft (1.5 m) high. The fourth wave was the largest, reaching 20.8 ft (6.3 m) and arriving hours after the first wave (Lander and others, 1993).

The 1964 event is the most significant in Alaskan history. The earthquake-generated main wave accounted for two to three dozen of the 106 fatalities attributed to the earthquake. The maximum tsunami wave elevation of approximately 200 ft (61 m) occurred in Valdez Inlet as a result of a local submarine landslide triggered by the earthquake (Lander, 1994). In all, the 1964 earthquake resulted in over \$84 million worth of damage in Alaska.

The magnitude 7.3 earthquake in the Aleutian Islands in 1946, generated a tsunami with wave heights of 55 ft (17 m) in Hawaii. It is considered the worst tsunami in U.S. history, and was responsible for 159 fatalities and \$26 million in damage (Lander and Lockridge, 1989).

The draft *Survivable Crisis Management Plan* for American Samoa reported that the May 22, 1960, tsunami in Pago Pago was the largest ever recorded in the island group. Tsunami wave runup at the end of Pago Pago Bay reached 10 ft (3 m), with a maximum runup elevation measured at 15.5 ft (4.7 m) in the village of Pago Pago. Damage was estimated at \$50,000.

The most significant tsunami to impact Puerto Rico and the U.S. Virgin Islands occurred on November 18, 1867. Triggered by an earthquake in the Anegada Trough between St. Croix and St. Thomas, it reportedly damaged settlements in the Islands and eastern Puerto Rico (Palm and Hodgson, 1993). During another event in 1918, caused by an earthquake off the northwest coast of Puerto Rico, 40 people were killed in western part of the island.

## RESEARCH, DATA COLLECTION AND MONITORING ACTIVITIES

Tsunami research has been conducted primarily by the International Tsunami Information Center at Honolulu, HI; the NWS Pacific Tsunami Warning Center (PTWC) at Ewa Beach, HI; the Alaska Tsunami Warning Center (ATWC) at Palmer, AK; the NOAA National Geophysical Data Center (NGDC) at Boulder, CO; and the NOAA Pacific Marine Environmental Laboratory (PMEL) at Seattle, WA.

Recent research efforts by FEMA, the California Division of Mines and Geology, Scientific Applications International Corporation (SAIC), the Urban Regional Research, and PMEL have focused on land-use planning and understanding the multiple-hazard impacts of a local tsunami event created by a Cascadia subduction zone earthquake.

## MITIGATION APPROACHES

The potential for loss of life and property damage from a tsunami is significant enough to warrant extensive regional planning efforts to prepare pre-disaster response and mitigation plans. Hazard mitigation workshops were conducted by PMEL in 1994 and 1995, and studies were conducted for Grays Harbor, WA (Preuss and Hebenstreit, 1991), Humboldt and Del Norte Counties, CA (Topozada and others, 1995), and Eureka and Crescent City, CA (Bernard and others, 1994). The resulting reports focus not only on the tsunami wave hazard, but also on assessment and integration of related hazards caused by a subduction-zone earthquake, mapping tsunami wave runup and multiple hazard impacts. Coastal community planning needs are addressed.

Key tsunami hazard mitigation concerns are focused on modernization and integration of existing capabilities and use of technological advancements for at-risk coastal communities. The efforts aim to provide effective hazard assessment, warning systems, and educated response to tsunami hazards, including detailed identification and mapping of tsunami wave runup and inundation limits. Warning systems must be real-time monitoring systems in order to provide information necessary to initiate emergency actions.

Public education campaigns are important to increase awareness and understanding of the hazard. They will also be vital to ensuring appropriate response in emergency situations.

Tsunami wave impacts can be mitigated in some areas through construction of shore-protection structures. The most effective means of mitigating damage to buildings are elevation above the flood levels and the use of engineered foundations to resist erosion and scour.

In some cases, the best way to prevent repetitive damage to structures is to acknowledge the risk and demolish or relocate existing buildings out of high-hazard areas. Shore protection structures can be effective in protecting upland property, given sufficient structural integrity, elevation, continuous length, and proper maintenance. Land-use and engineering practices aimed at limiting the exposure of new coastal development will help mitigate tsunami wave damage.

One land-use practice for tsunami wave hazard zones involves landscaping with vegetation capable of resisting and reflecting wave energy, thereby reducing wave height and potential damage. Planned coastal residential developments are also advised to ensure that streets and homes are located perpendicular to the waves to allow wave penetration along a path of least resistance and to reduce the likelihood of debris impact.

Other mitigation measures to reduce damage include relocation of utility lines, water mains, sewer lines, and roadways that in the immediate area of tsunami impacts. Evacuation of residents in tsunami hazard areas is undertaken to prevent loss of life.

## RECOMMENDATIONS

A series of three tsunami hazard workshops were held at NOAA's Pacific Marine Environmental Laboratory (PMEL) between November 1993 and October 1994 to discuss "state-of-the-art" technology and to identify key needs and concerns of the users of NOAA's tsunami warning products. Attendees included 56 tsunami specialists from the fields of science, emergency planning, operations, and education, representing 41 different organizations of local, State, and Federal governments, and universities. The five key States affected by tsunami hazards (Alaska, California, Oregon, Washington, and Hawaii) were represented.

PMEL published the summary and conclusions of the workshops in a March 31, 1995 report to the United States Senate Appropriations Committee (PMEL, 1995). The report included recommendations that addressed three key concerns:

- Tsunami hazard assessment for identification and mapping of tsunami flood-prone areas;

- Tsunami warning systems for real-time monitoring and alerting vulnerable coastal communities and residents; and
- Proper response to the tsunami threat through public education and awareness.

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