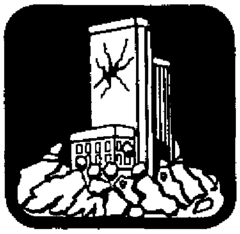


Earthquakes

James W. Stratton, M.D., M.P.H.
California Department of Health Services

Introduction

An earthquake of great magnitude is one of the most destructive events in nature. In our everyday world in which the earth seems so unyielding, it is hard to imagine a force so great that it can shake the ground into standing waves several feet high; snap tree trunks in two; spill rivers and lakes over their banks; turn highways into strips of broken rubble; liquify alluvial soils and send spurts of sand and water into the air; tear open fissures in the earth more than 160 km (100 miles) long; generate seismic sea waves that can race across thousands of miles of open ocean at 700 km/hour (420 miles/hour) and still generate tidal waves up to 30 meters in height; send millions of cubic meters of rock, mud, and debris crashing down hillsides 160 km from the epicenter of the earthquake; and destroy virtually every structure in a city. Such force is hard to imagine, perhaps, on the scale of human endeavor, but easier to understand when viewed from a geologic perspective. The forces that generate great earthquakes are the same forces that generate continents, thrust ancient sea beds upward into great mountain ranges, and fold and break the earth's crust. When this enormous pent-up energy is suddenly released, the impact can mean disaster.

The United States has been relatively fortunate in terms of earthquake-related casualties—so far. On the scale of a human lifetime, earthquakes may seem somewhat random and unpredictable; however, on a geologic time scale, a major earthquake in a heavily populated urban area is inevitable. When a great earthquake eventually does strike one of our major urban centers, the destructive result is entirely predictable—a major catastrophe.

Factors Affecting Earthquake Occurrence and Damage

Natural factors

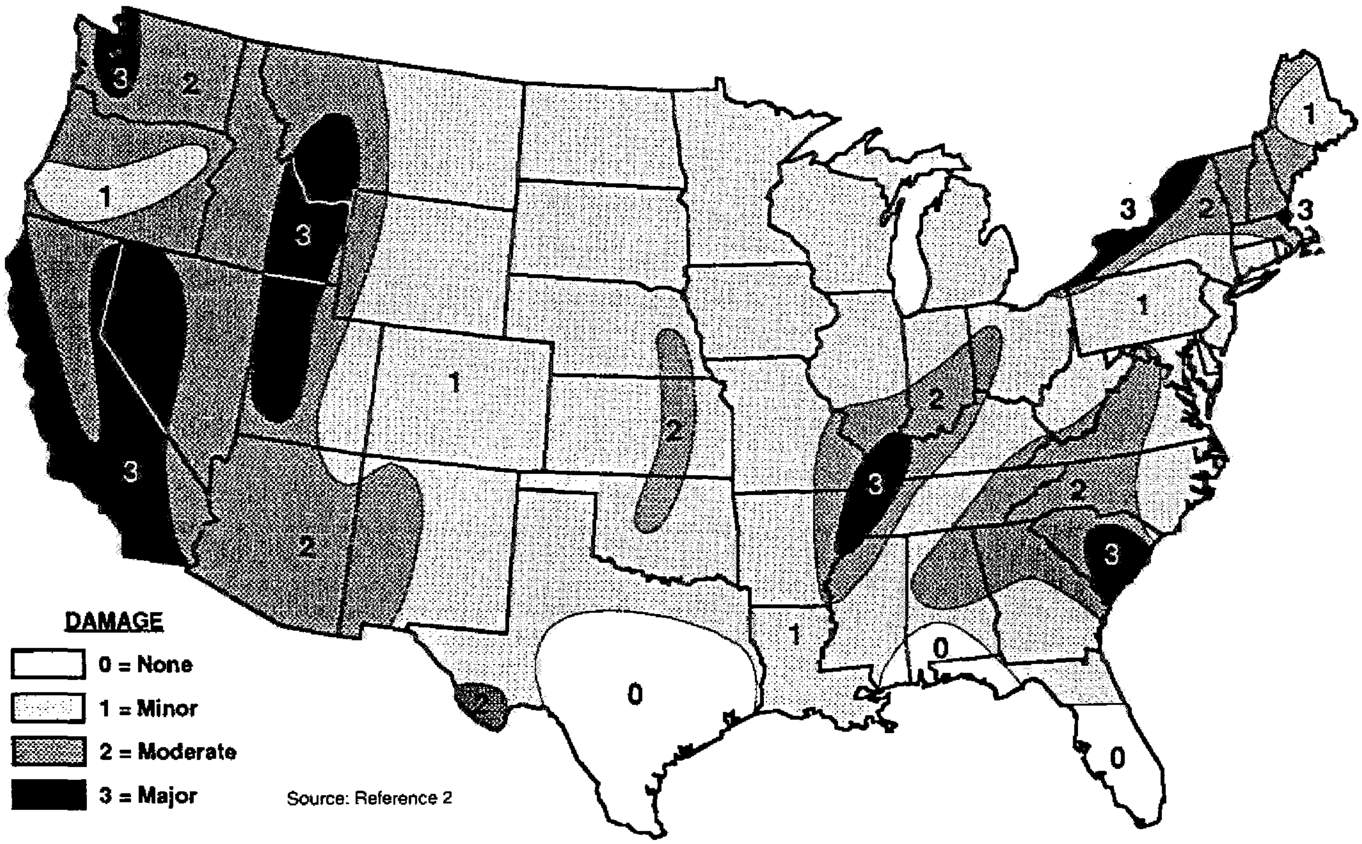
Geophysical factors. Plate tectonics, caused by the collision of the Pacific Plate with the North American Plate, generate most of the seismic disturbances along the Pacific West Coast and Alaska, particularly along the San Andreas Fault in California. Major fault lines exist where these two plates have collided. Forces build up as the two plates attempt to move with respect to one another, both laterally and vertically. Earthquakes occur when the adhesions along the fault give way, releasing pent-up energy. These large and inexorable forces are responsible for the band of seismic activity that extends along the Pacific rim to South America and to Japan. The rapid relative movement of these two plates contributes to the generally high rate of seismic activity. The relatively shallow depth of the San Andreas Fault (10-15 km below the earth's surface) adds to the perceived intensity of earthquakes along this fault.

Other areas of the United States have also been quite seismically active (Figure 1). Areas in which major earthquakes are probable include the Rocky Mountains, the upper Mississippi River and Ohio River valleys, South Carolina, and the area bounded by the eastern Great Lakes and New England. Alaska, Hawaii, Puerto Rico, and the Virgin Islands are all active seismic areas.In fact, throughout the United States, only a few Gulf Coast states are considered at very low risk.

Damaging earthquake forces are propagated as a series of compression waves (pushing and pulling in the direction of wave travel), shear waves (both side-to-side and vertical motion), and more complex waves with an elliptical or rolling motion. Waves travel outward from a fault at about 3-5 km/second, depending on the properties of the wave and the material through which it travels. Destructive ground shaking occurs at wave frequencies from about 0.1-30 Hertz (Hz) (cycles per second). High-frequency waves (>1 Hz) are more efficient at vibrating low buildings than are low-frequency waves, which are more likely to vibrate tall buildings. Low-frequency waves travel greater distances with less attenuation and can cause damage at great distances from the fault. Side-to-side motion is usually the most destructive because unreinforced buildings are less able to withstand it.

Depending on the properties of the earthquake and the local geology, natural and human-made structures are subjected to both vertical and horizontal wave motions that can set up destructive oscillations (swaying back and forth). A multistory building, for instance, acts as an inverted pen-

FIGURE 1. Seismic risk map for conterminous United States



dulum that oscillates at a certain frequency and amplitude (intensity) depending on its height, inertia, and structural characteristics. Seismic waves of the same frequency as the natural frequency of the building reinforce these oscillations and increase the damage. That the natural frequency of oscillation is a function of height explains why two buildings of similar construction but of different heights may experience substantially different degrees of damage.

Magnitude and intensity are two measures of the strength of an earthquake. Magnitude, the measure of physical energy released, is commonly calculated on the Richter scale, a logarithmic scale (to the base 10) of wave amplitudes (wave height as recorded on a seismometer, an earthquake-measuring instrument). On this scale, the recorded amplitude of a magnitude 8.0 earthquake is 10 times that of a 7.0 earthquake and 100 times that of a 6.0 earthquake. Recorded wave amplitude is related to the physical energy released in such a way that the energy released in a magnitude 8.0 earthquake is 31 times greater than the energy released in a magnitude 7.0 earthquake (1). Although the scale is open-ended, the strongest earthquake recorded to date has been of magnitude 8.9.

Intensity is measured by the perceived impact of the earthquake forces on the geologic strata through which the force is transmitted, as well as the direction and the amplitude of the seismic wave forces when they reach the surface. The most commonly used scale for intensity is the Modified Mercalli (MM) Intensity Scale (1), which ranges from barely perceptible earthquakes at MM I to near total destruction at MM XII. It is sobering to review the more intense categories on the Modified Mercalli scale:

CATEGORIES

V. Felt by nearly everyone; damage to contents and structures uncommon but possible.

VI. Felt by all; many frightened and run outdoors; damage slight.

VII. Everybody runs outdoors; damage negligible to buildings seismically well-designed and constructed; slight to moderate to ordinary structures; considerable damage to poorly built or badly designed structures.

VIII. Damage slight in well-designed, considerable in ordinary, and great in poorly built structures; chimneys, monuments, walls, etc., fall.

IX. Damage considerable to well-designed structures, and great (including partial or complete collapse) in other buildings; buildings shifted off foundations; underground pipelines disrupted.

X. Some well-built wooden structures destroyed; most masonry and ordinary structures destroyed; railroad tracks bent; landslides common; water spills over banks of streams, lakes, etc.

XI. Few, if any, masonry structures remain standing; bridges are destroyed; broad fissures open in the ground; underground pipelines are completely out of service; earth subsides.

XII. Damage is total; waves are seen propagating along surface of the ground; nearly impossible to stand; objects thrown up into the air.

The Richter and the MM scales do not correspond one-to-one. Two earthquakes that have the same given intensity on the MM scale may be several orders of magnitude apart on the Richter scale. Conversely, earthquakes of relatively modest magnitude may be quite intense in certain areas. In general, though, earthquakes of magnitude 6 correspond to MM intensities VII-VIII (moderate to major damage); magnitude 7, to MM IX-X (major damage the rule); and magnitude 8+, to MM XII (major to total damage certain).

The intensity of an earthquake is more germane than its magnitude to public health consequences. Intensity scales also allow comparisons with earthquakes that occurred before to the development of seismic monitoring instruments. The destruction that an earthquake causes is a function of its intensity and the resistance of structures to seismic damage.

Topographic factors. Topographic factors substantially affect the impact of earthquakes. The areas most susceptible are the outfall areas for landslides, mudslides, avalanches, and rock falls; low-lying areas susceptible to seismic sea waves (tsunamis or tidal waves) or floods from ruptured dams; and areas constructed on alluvial soils or landfill, both of which tend to liquify and exacerbate seismic oscillations

Meteorologic factors. Meteorology plays only a minor direct role in the events that initiate earthquakes. However, it can substantially affect the secondary effects of earthquakes. High tides and high water levels from storm runoff exacerbate the impact of seismic sea waves. Water saturation of soils increases the likelihood of both landslides and avalanches and of earthen dams to fail, as well as increasing the probability of soil liquefaction during seismic shaking. Earthquake-induced failure of dams when streams are near flood stage would be catastrophic. If housing is substantially damaged, rain or subfreezing temperatures would be, at the least, a nuisance and could contribute substantially to morbidity and mortality.

Human-Made Factors

Structural factors. The single greatest risk for humans is from the collapse of structures. Human behavior has a substantial impact on how well designed and how carefully constructed these structures are, and, more importantly, whether they are built on or near seismically active faults. Ignorance, denial, expedience, and the all-too-familiar tendency to cut corners all weigh in the decision to locate structures in seismically unsafe areas and the failure to construct them using the proper aseismic techniques.

Technologic factors. The fire that followed the 1906 San Francisco earthquake caused more damage than the earthquake itself. Our modern industrial cities are laden with chemical and petroleum products that could contribute substantially to fire hazard as well as to the generation of toxic products of combustion and pyrolysis. In a major earthquake, underground pipelines carrying fuel, natural gas, and the city water supply can be expected to be disrupted. Immediate, widespread fires are also expected, along with impaired means to fight them. Industrial storage facilities for hazardous materials might leak and could cause widespread contamination of surface and groundwater, in addition to potential release of toxic vapors. Polychlorinated biphenyl-containing electrical equipment, if subjected to fire and pyrolysis, could cause substantial contamination by benzo-p-dioxins and dibenzofurans. Failure of a nuclear power plant resulting from seismic activity could lead to widespread contamination by radioactive materials.

Artificial causes of earthquakes. Three human activities have been known to induce earthquakes: a) filling large water impoundments, b) deep well injection, and c) underground explosions of nuclear devices. Some have speculated that nuclear detonations along a fault may release strain in a controlled fashion and prevent a major earthquake, but the potential liability of such an experiment gone awry has proved daunting for even the most intrepid seismic investigators.

Historical Overview of Major Damaging Earthquakes

Time Patterns

The science of predicting earthquakes is still in its infancy. Although some major earthquakes have been presaged by foreshocks, changes in groundwater and geothermal activity, and even animal behavior, most major earthquakes have occurred suddenly and without warning.

While the major earthquake event appears to occur somewhat randomly, periodicity has been observed along major faults. The two major San Andreas Fault zones in northern and southern California have had a major event on average every 140-150 years. Because it has now been 130 years since the magnitude 8.3 Ft. Tejon earthquake along the southern San Andreas Fault in 1857, the probability of a Ft. Tejon-sized event is thought to be greater than 1% per year, with a 40% risk over the next 30 years. In contrast, the northern San Andreas Fault, which had a major release in 1906, experienced no earthquakes greater than magnitude 5 until 1955. This latter part of the San Andreas fault has had an upsurge in seismic activity in the last few years, which some seismic experts believe increases the probability of a major earthquake. Activity along the fault will doubtless increase in frequency and severity until the next major event, with southern California the most likely site.

The south coast of Alaska and the Aleutian Islands is one of the most seismically active areas in the world, with nine earthquakes from 1938 to 1979 of magnitude 7.4 or greater. The 1964 Prince William Sound earthquake of magnitude 8.3 is the second strongest earthquake of the 20th century and one of the most violent earthquakes ever recorded, releasing seismic energy equivalent to the current total annual energy consumption in the United States. Several areas of apparent unrelieved strain along the tectonic plate boundary are likely sites of future major earthquakes. The repeat intervals along the plate boundary average 50-100 years.

The eastern United States has considerably less activity than the area west of the Rocky Mountains, but a damaging earthquake occurs about every 25 years and a great earthquake, every 50-100 years. A series of three great earthquakes (estimated magnitude 8.6, 8.4, and 8.7) all of intensity XII occurred over a 3-month period in 1811-1812 near New

Madrid, Missouri. Although little loss of life occurred in the then sparsely populated area, the earthquakes were felt over most of the United States east of the Rocky Mountains and caused destruction for hundreds of miles. The New Madrid fault system is less well studied than the San Andreas system, but New Madrid-sized earthquakes may recur at 600- to 700-year intervals. Enough strain may have developed to produce a magnitude 7.6 earthquake, which would be damaging over 200,000 square miles. Charleston, South Carolina, experienced a magnitude 6.8 (intensity X) earthquake in 1886 that killed 83 people and was felt over most of the United States east of the Mississippi River. The specific fault responsible has not been identified, but similar geologic conditions exist over much of the mid-Atlantic seaboard with uncertain probabilities of damaging earthquakes. The lower probability of major earthquakes in the East needs to be balanced against the greater population densities, less stringent seismic codes, and the fact that earthquakes in the East exert damaging effects over a much wider area for an event of a given magnitude.

Trends over Time

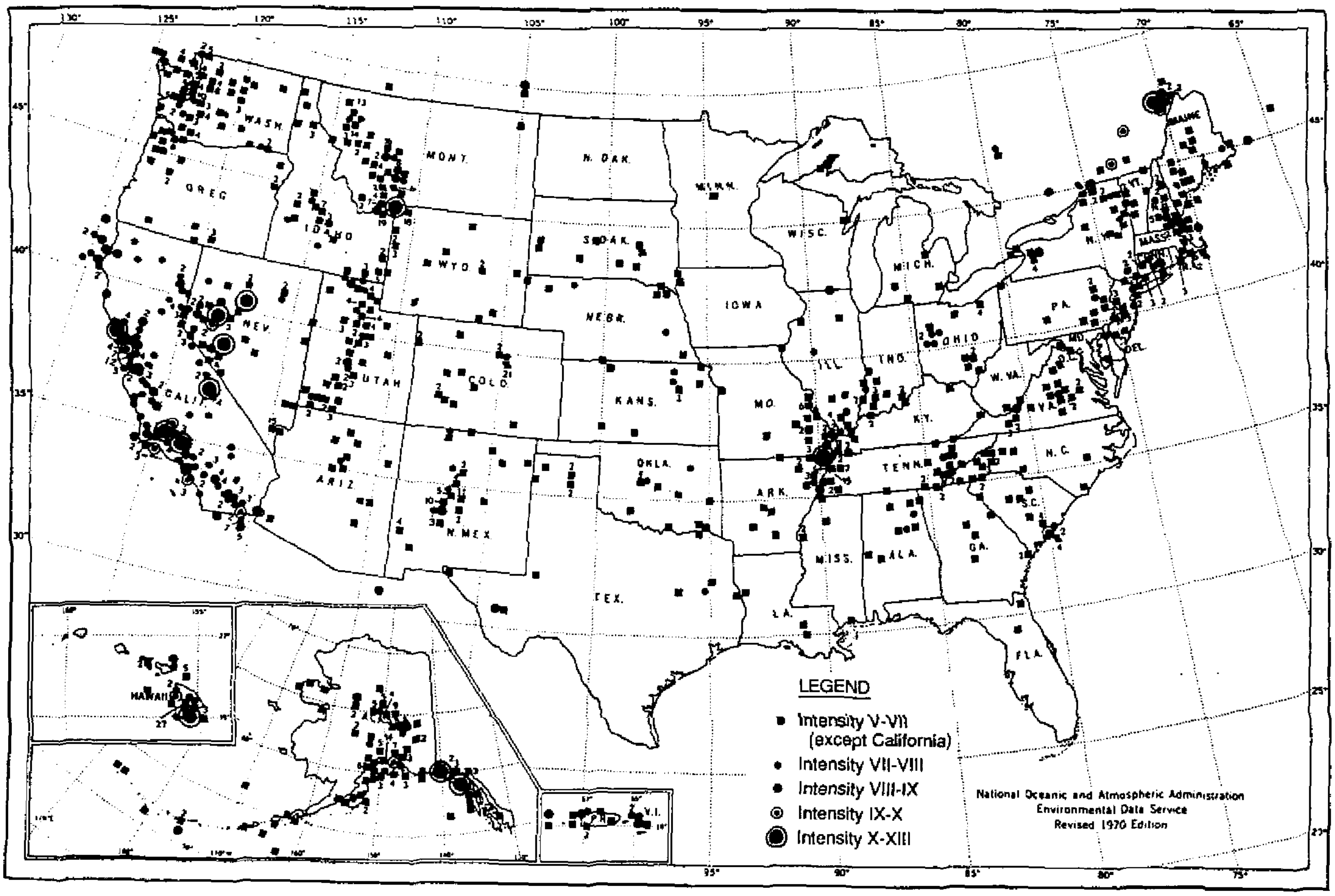
At present we have only a rough idea of the probability of a major earthquake's occurring in a given area during a given interval of time. There is no reason to believe that earthquakes are either increasing or decreasing in frequency or intensity. However, the population at risk has dramatically increased in seismically active areas. Aside from restricting population growth in these areas (a measure usually ignored), the only practical way to control earthquake hazards is to develop and enforce effective seismic safety codes and to phase out older structures that do not meet the codes.

Geographic Areas at Risk

Earthquakes occur on a geologic time scale as a result of forces set in motion millions of years ago. Current areas of high seismic activity will continue to be at high risk for the foreseeable future. The earthquake history of the United States has been described in some detail in a compendium (2). The compendium's graphic descriptions of the effects of a major earthquake are riveting. With the exception of colonial records in the Northeast that date back to 1638, the historical record of U.S. earthquakes is scarcely 2 centuries old, a very small period of observation on the geologic time scale. The zones of various levels of seismic risk are shown in Figure 1. The locations of the epicenters of significant earthquakes through 1970 are shown in Figure 2 and for the years 1971-1980 in Figures 3a and 3b. Approximately 90% of the seismic activity in the contiguous United States occurs in California and western Nevada.

Earthquakes often occur in association with active volcanoes, sometimes triggered by magmatic flow and sometimes releasing pressure that allows magmatic intru-

FIGURE 2. Epicenters of significant earthquakes, United States, 1970



Earthquakes (intensity V and above) in the United States through 1970.

FIGURE 3A. Epicenters of significant earthquakes, conterminous United States, 1971-1980

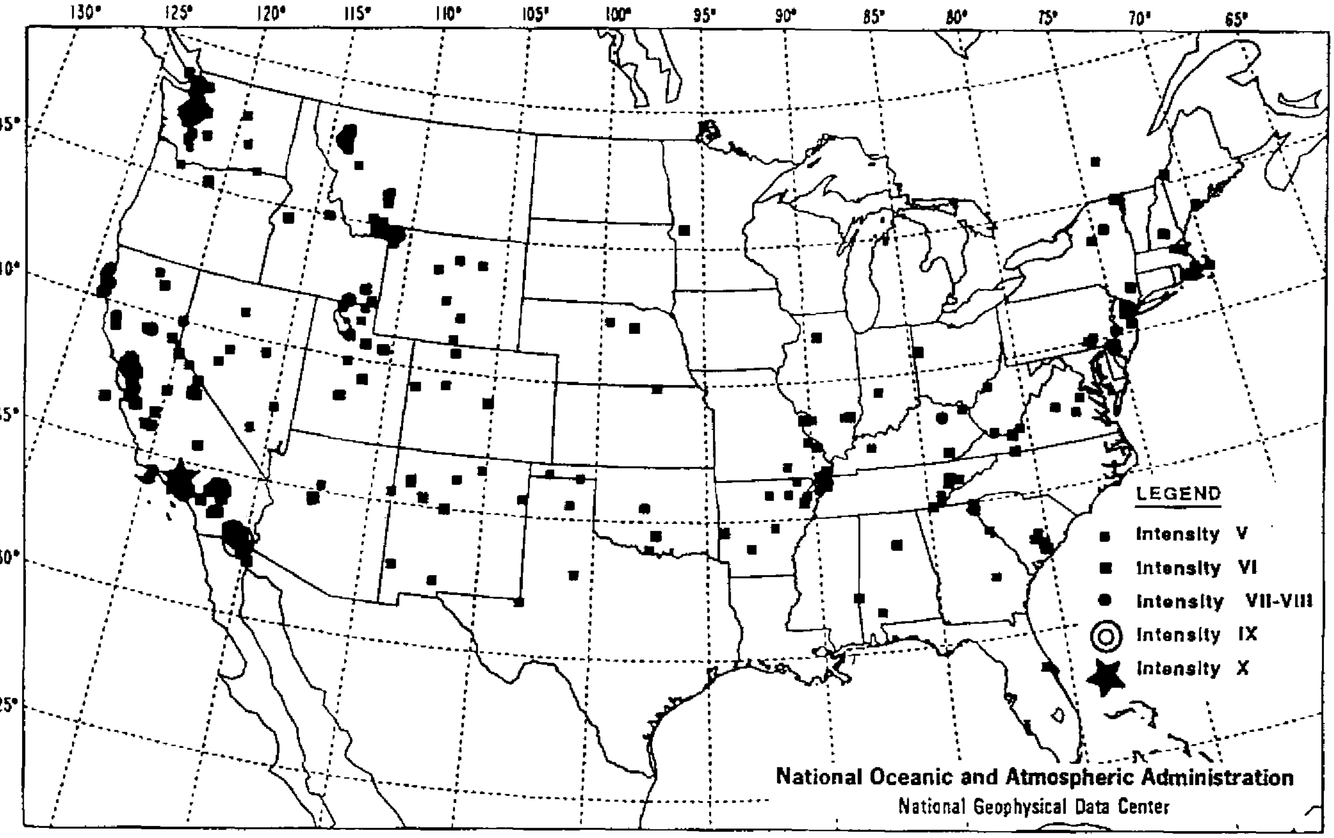
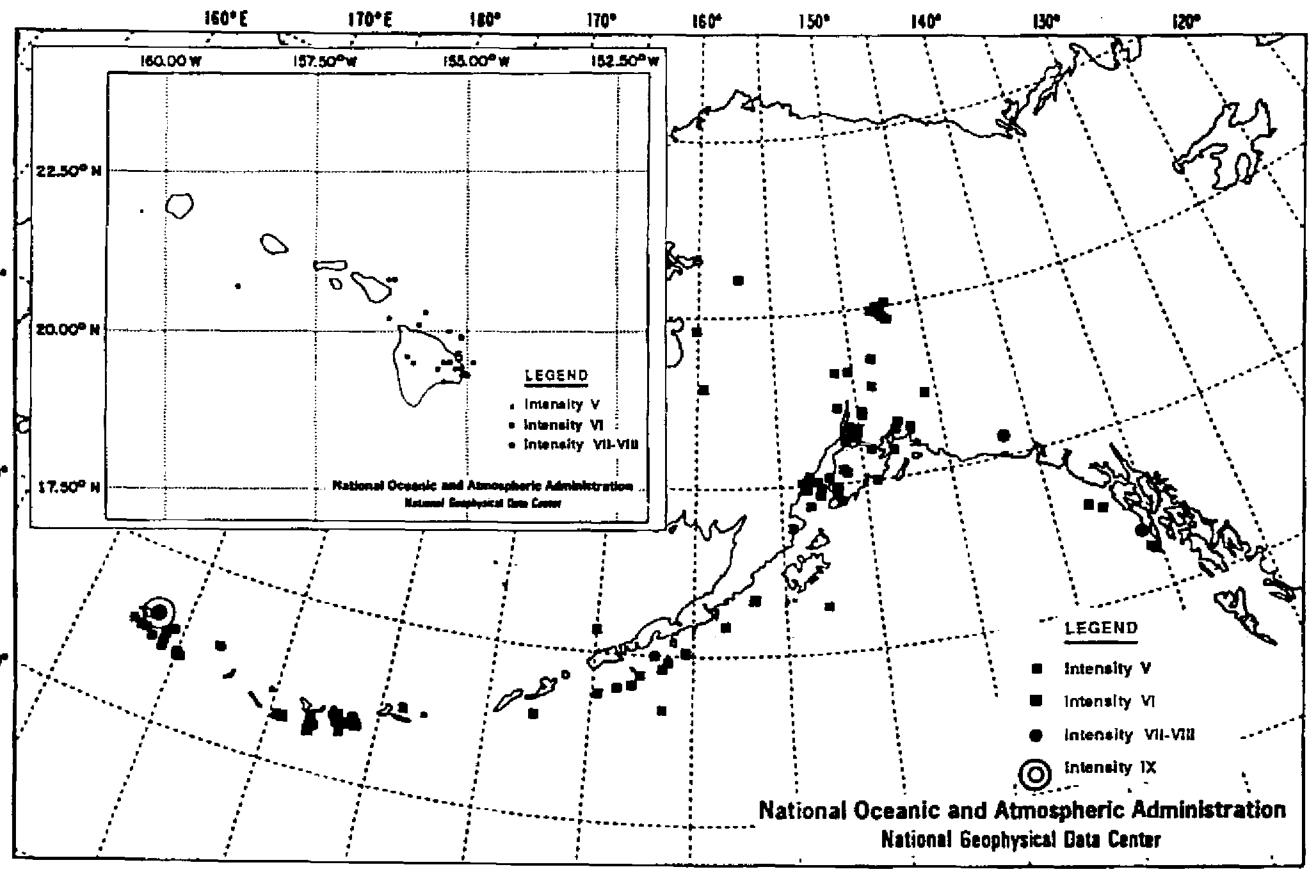


FIGURE 3B. Epicenters of significant earthquakes, Alaska and Hawaii, 1971-1980



sion. The so-called harmonic tremors associated with actual magmatic flow are generally not damaging. Relatively severe earthquakes can immediately precede or accompany volcanic eruption and can contribute to devastating mudslides.

Earthquake Morbidity and Mortality Risk Factors

Approximately 1,600 deaths attributed to earthquakes have been recorded in the United States since colonial times. More than 1,000 of these deaths have occurred in California, including 700 in the 1906 San Francisco earthquake (Table 1). As a cause of death, hurricanes, floods, and tornadoes have each exceeded this relatively modest total. However, there is little cause for complacency. Population growth in areas of high seismic risk has greatly increased the number of people at risk since the last earthquake of great magnitude struck. Populated areas in other parts of the world have suffered great loss of life from catastrophic earthquakes, e.g., Guatemala 1976 (22,778), Peru 1970 (52,000), Japan 1923 (142,807), and China 1976 (665,000). A single great earthquake in one of our cities could result in exceeding the death toll associated with all the natural disasters ever experienced in the United States.

In contrast to the rich and prolific literature on earthquake engineering and earthquake geology, little detailed epidemiologic information on earthquake morbidity and mortality is found in the scientific literature. Most reports are limited to fairly general summary statistics on deaths and injuries or to anecdotal descriptions of disaster medical relief, but some laudable exceptions exist. While we can speak relatively confidently of the major hazards associated with earthquakes, few earthquakes have been the subject of detailed epidemiologic study.

Trauma caused by partial or complete collapse of human-made structures is the overwhelming cause of death and

TABLE 1. Selected fatal earthquakes in the United States, 1811-1987

Date			Location	Magnitude	Deaths	Dollor loss (in millions)
16	Dec	1811	New Madrid, Mo.	8.6	few	NR*
23	Jan	1812	New Madrid, Mo.	8.4	few	NR
07	Feb	1812	New Madrid, Mo.	8.7	few	NR
08	Dec	1812	San Juan Capistrano, Calif.	6.8	40	NR
09	Jan	1857	Ft. Tejon, Calif.	7.9	1	NR
21	Oct	1868	Hayward, Calif.	6.8	6	NR
26	Mar	1872	Owens Valley, Calif	7.8	27	NR
31	Aug	1886	Charleston, S.C.	6.8	83	NR
19	Apr	1892	Vacaville, Calif.	6.8	1	NR
25	Dec	1899	San Jacinto & Hemet, Calif.	6.7	6	NR
18	Apr	1906	San Francisco, Calif.	8.3	700	500
22	Jun	1915	El Centro, Calif.	6.3	6	1
21	Apr	1918	San Jacinto & Hemet, Calif.	6.8	1	NR
11	Oct	1918	Mona Passage, P.R	7.5	116	29
29	Jun	1925	Santa Barbara, Calif.	6.3	13	8
29	Jun	1926	Santa Barbara, Calif.	5.5	1	NR
06	Jun	1932	Humboldt County, Calif	6.4	1	NR
11	Mar	1933	Long Beach, Calif.	6.3	15	40
19	Oct	1935	Helena, Mont.	6.2	2	19
31	Oct	1935	Helena, Mont.	6.0	2	6
19	May	1940	Imperial Valley, Calif.	6.7	9	33
01	Apr	1946	Unimak Island, Alaska	7.4	173	90
13	Apr	1949	Olympia, Wash.	7.0	8	80
25	Jul	1952	Kern County, Calif.	7.7	12	150
22	Aug	1952	Bakersfield, Calif.	5.8	2	30
21	Dec	1954	Eureka, Calif.	6.6	1	6
23	Oct	1955	Walnut Creek, Calif.	5.4	1	3
09	Jul	1958	Lituya Bay, Alaska	7.9	5	NR
18	Aug	1959	Hebgen Lake, Mont.	7.1	28	26
27	Mar	1964	Prince William Sound, Alaska	8.4	131	1,020
29	Apr	1965	Seattle, Wash.	6.5	7	28
09	Feb	1971	San Fernando, Calif.	6.8	65	900
29	Nov	1975	Kalapana, Hawaii	7.2	2	5
01	Oct	1987	Whittier, Calif.	5.9	9	350

*Not reported.

Source: Data compiled from references 2, 20, 21, 22, and 23. Some dollar amounts are historical figures, while others were adjusted to 1979 dollars by the authors of reference 20.

injury in most earthquakes. Rockslides, snow avalanches, and landslides are important threats in hilly and mountainous areas. Tsunamis can cause great loss of life by inundating low-lying coastal areas. Transportation casualties can occur from train derailments, collapse of bridges and highway overpasses, and capsizing of boats by seismic sea waves. Indirect hazards include post-earthquake fires, hazardous chemical and radiation release, electrocution, injury during rescue or clean-up operations, acute myocardial infarction and exacerbation of other chronic diseases, anxiety and other mental health problems, respiratory disease from exposure to dust and asbestos fibers from rubble, and flooding from the broken dams. Infectious epidemics after earthquakes have generally been conspicuous by their absence, despite popular concern. Some of these earthquake-related hazards are worth exploring in more detail.

Direct Hazards

RISK FACTORS RELATED TO STRUCTURAL COLLAPSE

Poor design and materials. Unreinforced masonry (including adobe) is the most hazardous building material and can be expected to fail in even moderate earthquakes. In addition to being structurally weak, masonry is doubly hazardous because of its weight and potential for causing injury when falling. Catastrophic failure of "modern," medium-rise, concrete-slab buildings from collapse of their supports has been well described, e.g., the 1964 Anchorage (3) and 1971 San Fernando (4) earthquakes, and played a prominent role in damage associated with the 1985 Mexico City earthquake.

Buildings can be designed to various levels of seismic security. At a minimum, they should be designed so that the occupants can survive, even if the building is irreparably damaged At the next level of design, the building remains functional even though damaged (an important design criterion for hospitals and other public works that must be able to operate after an earthquake). Structures meeting the most stringent level of design will withstand an earthquake with little or no damage.

Unfortunately, most of our older buildings and many of our newer ones fail to meet even the minimum standard for earthquake-proofing. The principal design flaw in most construction is its inability to withstand lateral forces, usually compounded by weak materials that fail under the seismic load. Although there has been much progress in engineering design, seismic safety is still an inexact science. The Olive View Medical Center, newly constructed to seismic codes, was destroyed by the 1971 San Fernando earthquake 1 month after its dedication (5)

Poor construction. Good design required by seismic codes can be negated if builders cut corners on materials and construction technique. Rigorous enforcement of building codes can prevent shoddy and below-code-level work.

Falling objects. Heavy furniture, appliances, bookshelves, equipment, and objects placed high can fall and cause injury unless secured. Because chimneys are particularly vulnerable to failure, persons exiting buildings during seismic shaking should avoid the potential path of falling brick

Dust from rubble. Heavy dust has been reported immediately after earthquakes and for a considerable time afterward (6). For trapped victims, heavy dust can be a life-threatening hazard (7). Dust has hampered rescue and clean-up operations by causing eye and respiratory-tract irritation. Anecdotal accounts from the 1985 Mexico City earthquake report that rescue workers finally resorted to full-face respirators, equipment that will probably be in short supply after a major earthquake. Commercial and school construction in the United States is often heavily laden with asbestos, which will likely pulverize if subjected to collapse. The asbestos and other particulate matter in the dust could pose both subacute and chronic respiratory hazards to rescue and clean-up personnel, depending on the characteristics and toxicity of the dust.

RISK FACTORS FOR OCCUPANTS

A study of housing-related earthquake injuries in a Guatemalan village of principally adobe construction showed that the young and the elderly were at highest risk of injury and death (8). The youngest child, who usually slept with the mother, tended to share the more favorable mortality risk of the parents. Women of all ages were found to have a higher rate of serious injury. Other than age of the adobe bricks, no structural features seemed to relate to injury rates in adobe housing. Occupants of non-adobe housing fared much better. Large family size was found to relate to increased rate of injury.

An ambitious study conducted after the 1980 earthquake of 3,619 villagers in southern Italy, in contrast to the Guatemalan study, found no differences in injury or death rates by age or sex (9). Despite these well-documented findings in Italy, the consensus in the literature is that the very young, the elderly, and the chronically ill are at somewhat higher risk of death or injury in earthquake disasters. Lack of mobility to flee collapsing structures, inability to withstand trauma, and exacerbation of underlying disease are all plausible reasons for believing that these groups are more vulnerable.

In the Italian study, entrapment requiring assistance to escape was the most important risk factor (death rate was 35.0% for trapped versus 0.3% for untrapped persons), but entrapment was also strongly correlated with the degree of structural damage. Interestingly, death and injury rates were similar for those inside the home and those outdoors at the time of the quake, but were twice as high for those in bars and dancing places. Occupants of upper floors fared less well than ground-floor occupants. Those who ran from the building during the quake fared better than those who did not.

A number of important observations were made about the source, timing, and outcome of injuries. All the deaths and injuries that occurred in the first 48 hours after the earthquake were due to structural collapse. Virtually all injuries (97%) occurred immediately or within 30 minutes of the quake. Survival among the trapped fell off rapidly with time, with 88% alive Day 1, 35% alive Day 2, 9% alive Day 3, and no survivors among 77 bodies extricated on Day 4 on (10). Of all the trapped who were extricated alive, 333 (94%) were rescued during the first 24 hours. People living alone tended to be extricated later, possibly because they did not have family members to rescue them; they also had a higher fatality rate. However, their homes tended to be more heavily damaged. Nearly all the people who died (95%) were trapped and died before rescue. The probability of survival after being freed was high. After the first 48 hours the survival rate for the injured was the same as for the uninjured. Investigators concluded that substantial reduction in mortality could be attained only by improving rescue rates within the first 48 hours.

Behavior of occupants. Does standing in a doorway or crawling under a desk really improve chances of survival? Can people think to take evasive action when their world is disintegrating around them and they have but a few seconds to react?

Anecdotal reports suggest that some people may be too stunned or frightened to think rationally or even to move (11). Other anecdotal reports suggest the efficacy of moving to a protected area such as a doorway or under a desk, but behavior of occupants during and immediately after an earthquake has been poorly studied. From the 1985 Mexico City earthquake, anecdotal reports of little islands of concrete slab perched on the tops of childrens' school desks while the rest of the ceiling had collapsed to the floor suggest that earthquake drills might be worthwhile. The real question, of course, is whether the children would have been able to get under the desks in time to prevent injury if the school had been occupied.

Earthquakes, although sudden, are usually not instantaneous. There are often a few seconds to react before the shaking reaches maximum intensity, raising the possibility of taking evasive action to escape injury. In the best-documented study report identified, 118 employees of a county office building in Imperial County, California, were studied after a magnitude 6.5 earthquake damaged their building (12). The period of strong shaking lasted 8 seconds. The investigators had an unusual opportunity to study behavior of occupants because everyone survived and because completing the questionnaire was required by all employees. Of the 118 office workers, 37% got under a desk, 15% stood in a doorway, 37% stayed where they were, 3% went into a main corridor, 2% left the building, 8% dodged falling objects, and 14% did something else. Of interest is that 30% of the desks under which people sought refuge moved away during the shaking. The occupants attributed their actions as follows: 18% to previous drills in elementary school, 27% to fire and bomb drills in the building, and 25% to experience with previous earthquakes (multiple responses permitted). Because no major building components collapsed onto the workers, the efficacy of their actions is hard to judge.

Injury of occupants. An extensive earthquake planning scenario has been developed for a magnitude 8.3 earthquake along the San Andreas Fault (13). The emergency-medical-services part of the scenario anticipates up to 25,000 deaths and up to 100,000 seriously injured (14). Most planning scenarios call for a ratio of 3.0-3.5 injuries/fatality, but victims trapped in collapsed structures may have a fatality rate high enough to decrease the ratio of injured survivors. The problems anticipated for an urban industrial area obviously involve more than the straightforward lacerations (52%), contusions (27%), and fractures (19%) caused by structural collapse in the Italian villages (9). The conditions in the southern California scenario are anticipated to be 27% surgical, 23% orthopedic injuries, 15% major medical/cardiac, 10% neurosurgical, 10% shock (as the primary problem), 6% severe burns, 5% smoke and toxins, and 5% psychiatric.

Chronic sequelae of neurologic injury, especially spinal-cord injuries, can be expected. A rate of 1.5 cases of paraplegia/1,000 injured was observed after the Guatemalan earthquake (15). Amputations and other chronic orthopedic conditions can be expected.

After a magnitude 6.7 earthquake in Athens, Greece, a 50% increase in cardiac deaths was observed for the first 3 days, peaking on the third day (16). The authors attributed the increase to psychological stress because no increases in other causes of death (including trauma) were seen. This study of death certificates, however, did not allow the examination of alternative hypotheses such as the effects of exertion from clean-up activities.

ROCKSLIDES, SNOW AVALANCHES, AND LANDSLIDES

It is not practical to try to construct buildings that will withstand a landslide or similar insult. The only reasonable alternative is to exercise due care and discretion in locating structures well away from potential areas of impact. One interesting report from a magnitude 7.2 earthquake on Guadalcanal in 1977 suggests that people might escape slides by running uphill where the apex of the slide is narrower (17). Although there were no housing-related deaths (due to the light construction of housing), there were 12 deaths from landslides, primarily in the terraced garden areas of logged hillsides. Landslide was the dominant feature in an earthquake in the Kansu Province of China that killed 100,000 in 1920 (18).

TSUNAMIS

Low-lying areas along seacoasts and around bays and harbors are at risk of inundation by seismic sea waves, which the Japanese call tsunamis (for "harbor wave"). A tsunami can be directly propagated by crustal motion during earthquakes or by landslides, including underwater landslides. Tsunamis can travel enormous distances at 300-600 mph with very little loss of energy. Wave heights in deep ocean water may be only a few feet and pass under ships with little disturbance, but in shallow coastal waters wave heights can reach 100 feet with devastating impact on local shipping and shoreline areas. Successive crests may arrive at intervals of 10-45 minutes for several hours.

The Pacific Coast is at greatest risk from tsunamis, primarily from earthquakes in South America and the Alaska/Aleutian Island region. The 1964 Alaska earthquake generated tsunamis up to 20 feet in height along the coasts of Washington, Oregon, and California and caused extensive damage in Alaska and Hawaii. The death toll from these tsunamis was 122 compared with nine from the earthquake itself. Tsunamis are the leading earthquake-related problem in Hawaii.

The Japanese have historical accounts of tsunamis dating back to A.D. 684 and have constructed breakwaters and other counter-tsunami measures (19). It would be prudent to place no residential construction in tsunami-impacted areas and only necessary commercial structures at the shoreline, e.g., docking facilities and wharfs. Prompt evacuation of low-lying areas should be a priority disaster-response effort when a warning is issued by the National Oceanic and Atmospheric Administration's tsunami warning network headquartered in Hawaii. Tsunamis generated by nearby earthquakes, however, may give little or no warning, making mortality a function of population density in the low-lying areas.

Public Health Implications of Earthquakes

Prevention and Control Measures

Primary prevention of earthquakes is obviously impossible, but much can be done to prevent the adverse consequences of an earthquake. Given the usual longevity of our buildings, most buildings in the United States, including virtually all construction on the West Coast, can be expected to be subjected to a least one episode of strong shaking. The major determinants of death and injury will already be in place at the moment the earthquake strikes. Disaster response in the aftermath of an earthquake, though important, can affect only a fraction of the adverse outcomes.

The challenge for our society is that more than 90% of what needs to be done must have been done well in advance of the earthquake and involves a conscientious investment in seismic safety year after year, often without interim earthquakes locally to remind us of the necessity to maintain the effort. With great earthquakes occurring in any one area on geologic cycles of 50-150 years or more, it is essential to develop the long view toward seismic safety. However, adopting and maintaining the long view is not an approach for which our local planning commissions and our democratic processes are noted. Public health and disaster-response officials need to join in the effort to develop and maintain an effective seismic safety-planning and enforcement program.

PRIMARY PREVENTION OF EARTHQUAKES

Although we can neither prevent earthquakes nor set off small ones to prevent big ones, we should take earthquakes into consideration before undertaking activities known to precipitate earthquakes, such as making deep well injections, filling water impoundments, and discharging underground nuclear explosives.

AVOIDANCE OF CONSTRUCTION IN AREAS OF HIGH SEISMIC RISK

Avoiding unnecessary residential and commercial construction on or near active faults and in areas subject to tsunamis, slides, and soil liquefaction is technically a secondary prevention measure for earthquakes, but a primary prevention measure for earthquake-related injuries. Areas of high seismic risk have been fairly well delineated, and the information should be available to local planners and developers. From a public health point of view, it is preferable to avoid construction in areas of high risk rather than to rely on seismic construction design to withstand the hazard, particularly since there have been some spectacular failures of supposedly "earthquake-proof" design.

In the last 20 years in San Francisco, for example, a veritable forest of high-rise buildings has been constructed, and there is considerable commercial pressure to extend the downtown area onto areas of landfill and bayfill. Despite the fact that these designs have not been subjected to the ultimate empirical test of a strong earthquake, the existence of the current buildings is used to argue that further construction is justified. Major metropolitan areas can be and have been built in the intervals between great earthquakes, especially in California. Due caution in site selection is in order for what is, in essence, an experiment in seismic design and construction on a grand scale.

DEVELOPMENT AND ENFORCEMENT OF SEISMIC SAFETY CODES

Land-use codes and building construction codes appropriate to the level of seismic risk should be developed and rigorously enforced. Aseismic design is an evolving science, and codes need to be updated periodically to reflect what has been learned from building performance during actual earthquakes Particular attention should be paid to areas in the East and in the upper Mississippi River valley, where actual risk may be higher than perceived and where, consequently, local codes may not be adequate. How and when and at what expense older buildings should be brought up to code is a major public health issue since these buildings are likely to be the most vulnerable. Because structural collapse is the single greatest threat to life, seismic construction should be the number-one earthquake priority for most communities In addition to the attention given homes, schools, and office buildings, due care should be given to industrial facilities with flammable, explosive, or toxic threats and so-called lifeline facilities such as hospitals, power plants, municipal waterworks, and transportation centers. Although often beyond the purview of building codes (or any reasonable hope of enforcement), heavy furniture, appliances, and objects placed where they could fall or be thrown about should be secured to prevent them from striking people in the event of an earthquake.

PREDICTION OF EARTHQUAKES

If earthquakes and damaging aftershocks could be predicted reliably, many lives could be saved by evacuating unsafe structures. Many earthquake predictions must necessarily be couched in terms of days or weeks or longer. It is doubtful that evacuations could be maintained for any but the most imminent of predictions, and even then, not for very long. Tsunami prediction, although better developed than earthquake prediction, can sometimes result in false alarms. More disturbing, however, is that many people react to tsunami warnings by going to the waterfront to "watch the waves come in," ignorant of the true potential for disaster.

DRILLS FOR EVASIVE ACTIONS DURING EARTHQUAKES

Despite the relative lack of data on efficacy of occupant behavior, it seems worthwhile for individuals to practice taking evasive actions (such as standing in a doorway, crawling under a desk, or quickly running outside), particularly since they will have just a few seconds to act when an earthquake strikes.

PLANNING SCENARIOS FOR EARTHQUAKES

Relative chaos is likely to prevail immediately after a major earthquake. Area residents, cut off from the outside, will initially have to rely on self-help. They can best help themselves and others if they have already worked out the scenario and practiced the necessary skills. First-aid skills should be taught. How medical triage facilities will be set up and tied in with the existing hospital and emergency medical services networks should be decided. Strategies for rescuing trapped victims with available equipment should be developed. Response scenarios for toxic hazards should be thought out in advance, because specialized technical expertise is unlikely to be available to responders after an earthquake.

DISASTER RESPONSE TO EARTHQUAKES

Disaster response to earthquakes is more akin to medical treatment than to prevention, but some aspects of the response may be likened to tertiary prevention in that they seek to stem further injury and to control the secondary effects of the earthquake. Prompt rescue should improve outcome. Early treatment of injured persons should lessen sequelae. Provision of adequate food, water, and shelter should especially help persons in vulnerable age groups and those with pre-existing disease. Effective environmental-control measures should prevent secondary environmental health problems. Identification and control of long-term hazards (e.g., asbestos in rubble) should reduce chronic effects.

Surveillance

EARLY RAPID ASSESSMENT OF IMPACT

Because rapid rescue of trapped victims and prompt treatment of persons with life-threatening injuries can improve outcome, early rapid assessment of the extent of damage and injuries is needed to help mobilize resources and direct them as they are most needed. Unfortunately, the very factors likely to cause large numbers of injuries are also likely to disrupt communications and transportation and to damage medical-care facilities. Public health officials need to establish in advance how the impacted areas will be surveyed. For instance, a helicopter fly-over to assess damage according to a predetermined sampling grid (rather than a nonsystematic survey or anecdotal field reports) would likely yield a more accurate estimate of damage and potential injuries.

SURVEILLANCE OF INJURIES AT MEDICAL TRIAGE CENTERS

Triage centers should designate someone to organize surveillance of injuries, collect data, and see that the data are tabulated and reported to disaster-response health officials. In addition to collecting adequate information on the location and severity of the injury and disposition of each patient, the surveillance team should attempt to record a permanent point of contact for individuals outside the disaster impact area so that follow-up studies and/or surveillance efforts can find them, even if earthquake damage results in their not returning to their previous addresses. Depending on the urgency of the situation, some information can be collected on the spot about how an injury was sustained. Collecting good basic data at the outset will both provide decision makers with accurate data on injuries and form the basis for learning lessons applicable to the next earthquake.

SURVEILLANCE OF SEARCH AND RESCUE

Much can be learned from the position and circumstances of trapped victims, including persons who have died. Ideally, search and rescue teams should have surveillance forms to record important information about building type, address, nature of collapse, degree of dust, fire or toxic hazards, location of victims, nature and severity of injuries and other factors. Victims pronounced dead at the scene should be tagged with an identification number so that the medical examiner's data can later be linked to the search and rescue surveillance form. Surveillance of search and rescue activities should be used to direct resources to sites where the most good can be done in the first 24-48 hours, the most critical time.

SURVEILLANCE OF DISEASE

Rumors and fears of epidemics generally circulate in the aftermath of disasters, and earthquakes are no exception. Health officials should be prepared to recommend appropriate sanitary precautions and to dispel unfounded rumors and inaccurate information. They should set up a disease surveillance mechanism appropriate to the circumstances and provide regular reports to disaster-response officials. Unusually high incidence of disease should be investigated and control measures implemented. Outbreaks of infectious disease generally have not followed earthquakes in other countries and are unlikely to occur in the United States.

DETAILED FOLLOW-UP EPIDEMIOLOGY

Few earthquakes have been adequately studied epidemiologically, with the exceptions previously noted. It is vital that plans for follow-up epidemiology be developed before an earthquake occurs so that initial surveillance data collected will allow proper follow-up. Disaster-response officials need to be convinced to invest time and resources in the initial surveillance effort, even though their attention is likely to be focused on emergency medical services and disaster relief. Without this investment, the opportunity to learn many lessons useful for future earthquakes may be lost. Again, it is important to take the long view toward the certainty that earthquakes will recur and set aside the resources to study these natural experiments when they occur.

DISSEMINATION OF INFORMATION

Telephone service is likely to be disrupted in the impact area of an earthquake. Police, fire, and many emergency-service organizations maintain radio networks, which public health officials will need to use. Radio and television news crews often arrive at the scene of a disaster with sophisticated communications equipment. Public health organizations should work out scenarios for various information-dissemination contingencies before an earthquake occurs. The electronic news media can be an effective vehicle for health advisories, tsunami warnings, and updates on casualties and relief efforts. Ideally, public officials should work out media guidelines for information dissemination so that all parties will know what to expect when the disaster strikes. Epidemiologists should be aware that computer modems allow radio transmission of digital data. With the appropriate power supplies and information-dissemination devices, data from triage centers might be sent to a central collection point, facilitating surveillance.

Research Needs

Many of the deficiencies in our earthquake public health database have been noted. The most pressing research needs from a public health point of view involve the following areas:

1. Prediction of earthquakes and damaging aftershocks.

2. Prediction and appropriate hazard warnings for tsunamis.

3. Aseismic construction techniques, especially retrofitting of older buildings.

4. Epidemiology of earthquake-related injuries, including whether occupant behavior makes a difference in avoiding injuries.

5. Improved techniques for locating and rescuing trapped victims rapidly.

6. Rapid assessment techniques immediately after earthquakes to allow appropriate allocation of relief efforts.

7. Improved assessment of the potential threat of toxic releases and other nontraditional earthquake hazards that are a function of our modern industrial cities.

8. Improved assessment of the hazard represented by dust and appropriate control measures.

Summary

A major earthquake in one of our urban areas ranks as the largest potential natural disaster for the United States. Most of what can be done to mitigate injuries must have been done before the earthquake occurs. Because structural collapse is the single greatest hazard, priority should be given to seismic safety in land-use planning and in the design and construction of buildings. We need to improve prediction methods for earthquakes and tsunamis. Earthquake-disaster-response planning should concentrate on the rescue and care of trapped or injured victims as quickly as possible. Careful attention should be paid to accurate surveillance and the epidemiologic follow-up of earthquake disasters. Because of the relatively long time between major earthquakes, the public health community faces a special challenge in effectively communicating the hazard and the necessity to plan and take action before an earthquake occurs. It is inevitable that a major earthquake will strike one of our cities again, and we must be prepared.

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