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DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

A Review of Information on Seismic Hazards Needed for the Earthquake-resistant Design of Lifeline Systems in the United States

A DRAFT TECHNICAL REPORT OF SUBCOMMITTEE 3,
"EVALUATION OF SITE HAZARDS,"
A PART OF THE INTERAGENCY COMMITTEE ON SEISMIC SAFETY IN CONSTRUCTION

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A Review of Information on Seismic Hazards Needed for the Earthquake-resistant Design of Lifeline Systems in the United States

by

Walter W. Hays

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COMPILED BY
JOYCE A. COSTELLO

Reston, Virginia
1987

FOREWORD

This draft technical report "A Review of Information on Seismic Hazards Needed for the Earthquake-resistant Design of Lifeline Systems in the United States" was developed by Subcommittee 3--Evaluation of Site Hazards, a part of the Interagency Committee on Seismic Safety in Construction (ICSSC). This is the fifth report of the Subcommittee; the other four reports addressed surface faulting, earthquake-induced ground failure, ground motion for the design of large dams, and seismic hazards for earthquake-resistant design. The membership of the Subcommittee during the preparation of this report was:

S. T. Algermissen	U.S. Geological Survey
A. J. Eggenberger	National Science Foundation
John M. Ferritto	Naval Civil Engineering Laboratory
Julius G. Hansen	Department of Labor
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Richard D. McConnell	Veterans Administration
Peter V. Patterson	Department of Agriculture
David M. Perkins	U.S. Geological Survey
Leon Reiter	Nuclear Regulatory Commission
Davis E. White	Department of Housing and Urban Development

The Subcommittee has recommended that this draft technical report be submitted to all concerned agencies with the request that they test its implementation through use in planning, design, contract administration, and quality control, either on a trial or real basis, during 1988 and 1989. Following a period of trial implementation, the Subcommittee plans to review the draft report, revise it as necessary, and then recommend its adoption by ICSSC as part of a manual of standard practice. Comments on this draft are welcomed and should be forwarded to:

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PUBLICATIONS OF SUBCOMMITTEE 3

INTERAGENCY COMMITTEE ON

SEISMIC SAFETY IN CONSTRUCTION

M. G. Bonilla, 1982, Evaluation of Potential Surface Faulting and other Tectonic Deformation, U.S. Geological Survey Open-file Report 82-732 (ICSSC TR-2).

John M. Ferritto, 1982, Evaluation of Earthquake-Induced Ground Failure, U.S. Geological Survey Open-file Report 82-880 (ICSSC TR-3).

E. L. Krinitzsky and W. F. Marcusson III, 1983, Considerations in Selecting Earthquake Motions for the Engineering Design of Large Dams, U.S. Geological Survey Open-file Report 83-636 (ICSSC TR-4).

Walter W. Hays, 1985, An Introduction to Technical Issues in the Evaluation of Seismic Hazards for Earthquake-resistant Design, U.S. Geological Survey Open-file Report 85-371 (ICSSC TR-6).

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ABSTRACT

This report gives an overview of the various types of basic geological and seismological information that are needed when siting and designing lifeline systems in earthquake-prone areas of the United States. Two physical phenomena, permanent ground movements and dynamic ground shaking, are the most important considerations that must be assessed in regional- and urban-scale studies. Although the process of earthquake-resistant design of lifeline systems is complicated, the knowledge base on lifeline engineering has increased significantly since the 1971 San Fernando earthquake.

A REVIEW OF INFORMATION ON SEISMIC HAZARDS NEEDED FOR THE EARTHQUAKE-RESISTANT DESIGN OF LIFELINE SYSTEMS IN THE UNITED STATES

1 INTRODUCTION

Fundamental information on seismic hazards is needed for the earthquake-resistant design of lifeline systems in the United States. The geologic parameters that control the physical characteristics of permanent ground movements and dynamic ground shaking are the two most important physical considerations for design of lifelines. Permanent ground movements (surface fault rupture, liquefaction, landsliding, lateral spreading, compaction, regional tectonic deformation) are more important for the design of buried lifeline systems than the effects of ground shaking; however, dynamic ground shaking can be more important when designing lifeline systems that have buildings and other structures and components above ground and especially when vertical shaking, soil strain, and soil amplification are important considerations.

Lifeline systems include energy (electricity, gas, liquid fuel, steam), water (potable, flood, sewage and solid waste, fire-fighting water), transportation (highways, bridges, railways, airports, harbors, transit), and communications (telephone, telegraph, radio, television, telecommunications, mail, press). These systems collectively provide the essential functions of supply, disposal, transportation, and communication required by an urban community. The well being of the community requires that the lifeline systems continue to function after a damaging earthquake. Lifeline systems also can be characterized in terms of their surface and subsurface spatial distribution, an important consideration in earthquake-resistant design. The distributions include (1) long linear systems covering distances ranging from a few miles to several thousand miles, (2) areal distributions ranging from a few square miles to several tens of square miles, and (3) discrete locations ranging from a "point" to a few hundred feet in size. The spatial distribution of a lifeline system guides the selection of seismic design parameters, for example, the horizontal spatial variation of ground motion can be very significant for long lifeline systems, such as bridges, pipelines, and tunnels, but relatively less important for buildings and lifeline systems having short lateral dimensions. The vertical component of ground motion is very important for some types of lifeline systems; for example, buildings are less sensitive to vertical ground motion than to horizontal ground motion, but bridges, tanks, floor-mounted equipment, and pipelines can be affected significantly by the vertical component of ground shaking because the energy arrives earlier and is always richer in high frequencies than on the horizontal component. Pipelines, tunnels, and waste repositories are sensitive to the depth dependence of ground shaking.

The term "seismic hazards" denotes potential damaging physical phenomena accompanying an earthquake. Each seismic hazard is described below:

1. Surface faulting.--This phenomenon is the offset or tearing of the ground surface by differential movement across a fault during an earthquake. Surface faulting is limited to a linear zone along the surface trace of the fault. Not all earthquakes cause surface faulting. In the Eastern United States, no historic earthquakes, except possibly the 1811-12 New Madrid earthquakes, have caused surface faulting, whereas, in the Western United States, surface faulting has occurred at many locations from earthquakes generally having magnitudes of 5.5 and greater (Bonilla, 1982).

2. Liquefaction.--This is a physical process that always is restricted to areas of saturated cohesionless soils during moderate (magnitudes of 6-7) to large (magnitudes of 7-8) to great (magnitudes of 8 and greater) earthquakes and leads to ground failure. The potential for liquefaction is greatest when seismic shear waves having high values of peak acceleration and long duration pass through a saturated sandy soil, distorting its granular structure and causing some of the void spaces to collapse. The pressure of the pore water between and around the sand grains increases until it equals or exceeds the confining pressure. When this condition occurs, the water soil mixture moves upward and sometimes emerges at the surface. The liquefied soil then behaves like a fluid rather than as a solid for a short time. Although rare, liquefaction can occur at distances of 80-161 kilometers (50-100 miles) from the epicenter of an earthquake and can be triggered by levels of ground shaking as low as Modified Mercalli intensity IV-VI. Liquefaction causes lateral spreads, flow failures, and loss of bearing strength that can damage lifeline systems.

3. Landslides.--This is a downward and outward movement on slopes of rock, soil, artificial fill, and combinations of these materials. If the slope stability is lost, then landslides can be triggered by fairly low levels of ground motion during an earthquake. The factors that control landsliding are those that increase the shearing stress on the slope and decrease the shearing strength of the earth materials.

4. Tectonic deformation.--In its broadest context, this includes tilting, uplift, and downwarping; fracturing, cracking, and fissuring; compaction and

subsidence; and fault creep phenomena occurring before, during, and after the earthquake. Deformation over a broad geographic area covering thousands of square miles is the characteristic feature of a great earthquake; for example, having magnitudes greater than 8.0, such as the 1964 M_W 9.2 Prince William Sound, Alaska, earthquake).

5. Ground motion or ground shaking.--This phenomenon refers to the amplitude, frequency composition, and duration of the horizontal and vertical components of the vibration of the ground produced by body and surface seismic waves arriving at a site, independent of the structure or lifeline systems at the site. The frequency range of interest in earthquake-resistant design is 0.1-20 Hertz (0.05-10 seconds), although higher frequencies may be important for components of lifelines, such as porcelain-mounted equipment in electrical substations. Ground shaking, a force-controlled process, will cause damage to structures, facilities, and lifeline systems unless they are designed and constructed to withstand the shear strains caused by vibrations that coincide with the natural frequencies of structures, facilities, and lifelines. Ground shaking also can trigger permanent ground deformation, such as described in 1 through 4 above. Buried pipelines are especially sensitive to displacement-controlled processes rather than to the force-controlled process of ground shaking, which has the most pronounced effect on buildings and structures located above ground. Peak ground acceleration; response spectra; spectral acceleration, velocity, and displacment; and duration are the parameters used most frequently to characterize ground motion for earthquake-resistant design. Design spectra are broadband and can be either site-independent (applicable for sites having a wide range of local geologic and seismologic conditions) or site-dependent (applicable to a particular site having specific

geologic and seismological conditions). The elastic response spectra typically are anchored at the "zero period" to a value of ground acceleration, which is typically a reduced value of the peak ground acceleration read from a strong motion accelerogram. The two basic problems with use of instrumental peak ground acceleration are short-period acceleration time histories having short duration have very little effect on the elastic response spectra within the period range of 0.1-0.5 seconds and elastic response spectra anchored to the instrumental peak ground acceleration tend to overestimate the actual damage to a structure because the effects of the duration of strong ground motion and the number of cycles of inelastic response are not incorporated. The maximum Modified Mercalli Intensity is used when instrumental ground-motion data are not available. Under certain conditions, the structure or lifeline system can modify the ground motion through the phenomenon of soil-structure or soil-lifeline interaction (Wolf, 1985).

The spatial distribution of horizontal and vertical ground motions is a very important consideration when designing lifeline systems. Also, values of the spectral velocity and displacement are more important than values of spectral acceleration for long linear lifelines, such as long bridges. The depth dependency of ground motion also can be an important design parameter; siting at greater depth can reduce design levels.

2 EARTHQUAKE HAZARDS

An earthquake is caused by the violent and abrupt release of slowly accumulating strain energy along a fault, which is a surface or zone of fracturing within the Earth's crust. When a fault breaks or ruptures, seismic waves are propagated in all directions from the source (Figure 1). As the compressional (P), shear (S), Love, and Rayleigh waves impinge upon the surface of the earth, they cause the ground to vibrate at frequencies ranging from about 0.1 to 20 Hertz. (0.05-10 seconds). Depending on their geometries and the soil system, buildings and lifeline systems are induced to vibrate up and down and side to side as a consequence of the amplitude, spectral compositions, and duration of the ground shaking. Damage takes place if the building or lifeline system is not designed and constructed to withstand permanent displacements and the dynamic forces triggered by these vibrations. P and S mainly cause high-frequency (greater than 1 Hertz) vibrations that are more efficient than low-frequency waves in causing short buildings to vibrate. Rayleigh and Love waves mainly cause low-frequency (less than 1 Hertz) vibrations that are more efficient than high-frequency waves in causing tall buildings to vibrate.

Ground shaking, surface fault rupture, earthquake-induced ground failure, regional tectonic deformation, and, in some coastal areas tsunamis. Each of these hazards can cause economic loss, loss of life, and damage to buildings, facilities, and lifeline systems (Figure 2). Fires and floods also can be triggered by an earthquake. Aftershocks may last several months to a few tens of years, depending on the energy release of the main shock, and can reactivate any or all of these physical phenomena and can cause additional damage, loss, and psychological impact.

Evaluation of earthquake hazards for the earthquake-resistant design of buildings and lifeline systems is a complex task requiring educated guesses regarding the forces and displacement expected to occur (Figure 3).

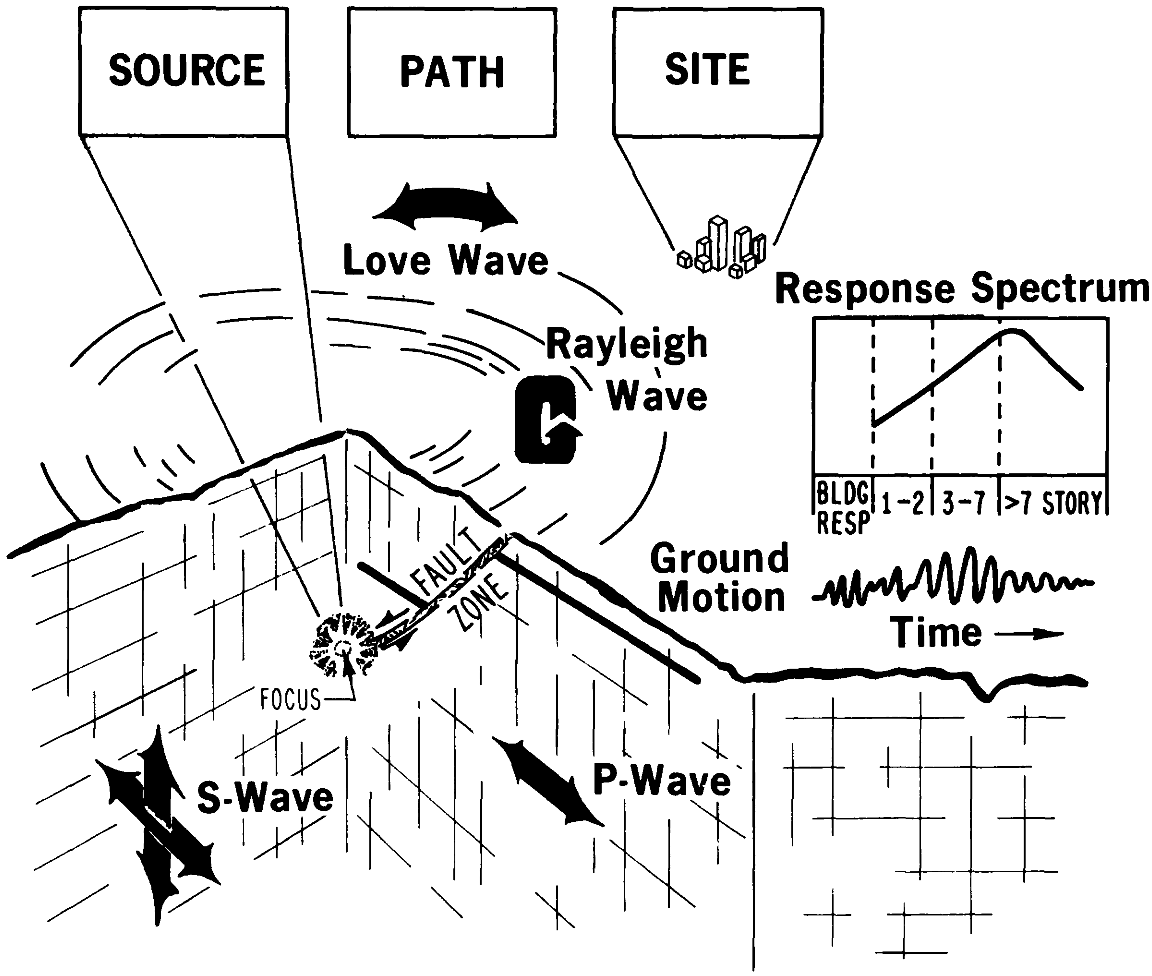


Figure 1. Schematic illustration of the directions of vibration caused by body (P and S) and surface (Rayleigh and Love) seismic waves generated during an earthquake. Evaluation of the ground-shaking and ground-failure hazards critically important for design of lifeline system.

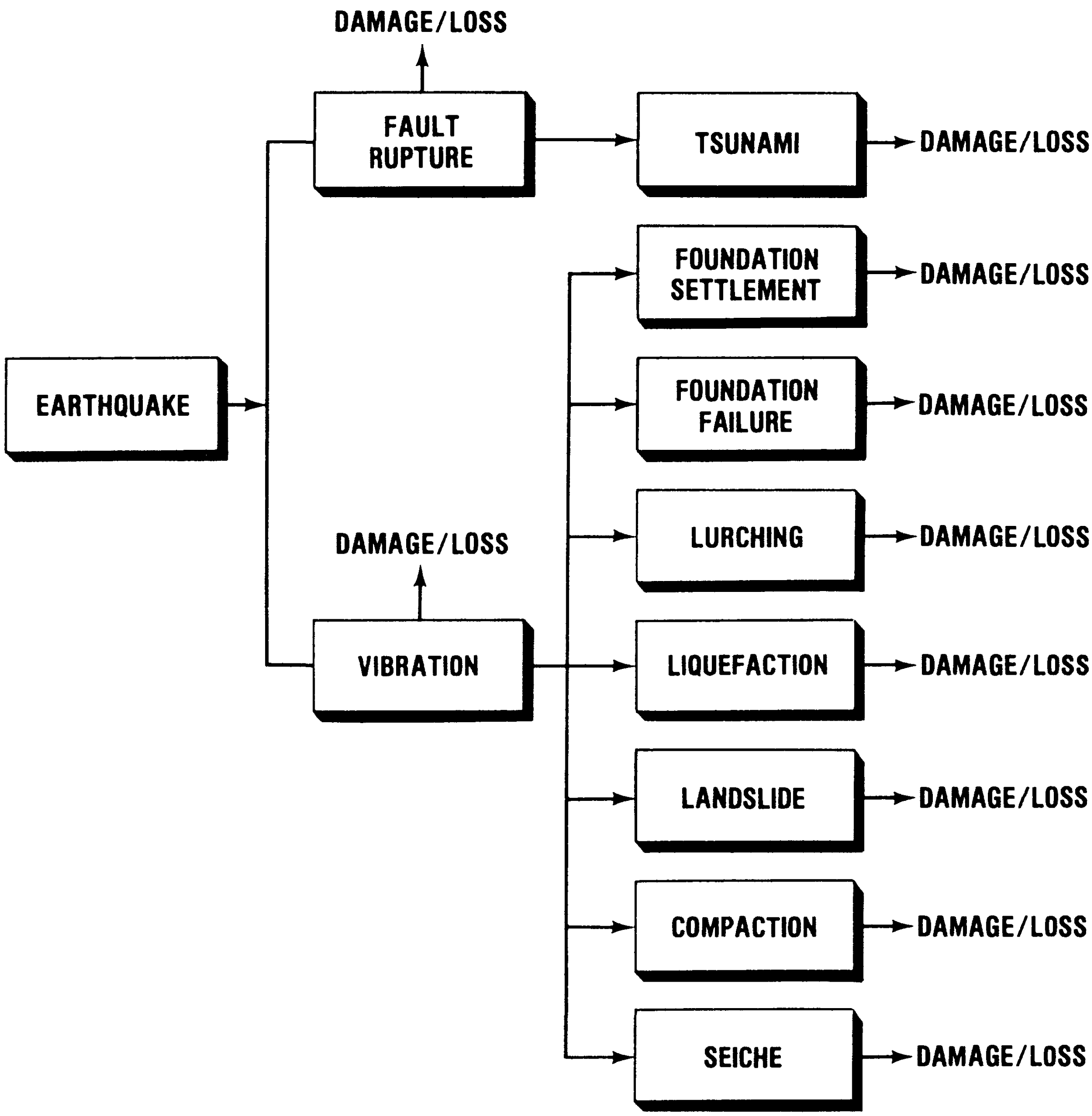


Figure 2. Schematic illustration of the primary and secondary hazards caused by an earthquake. Each hazard can lead to damage and loss of function of a lifeline system.

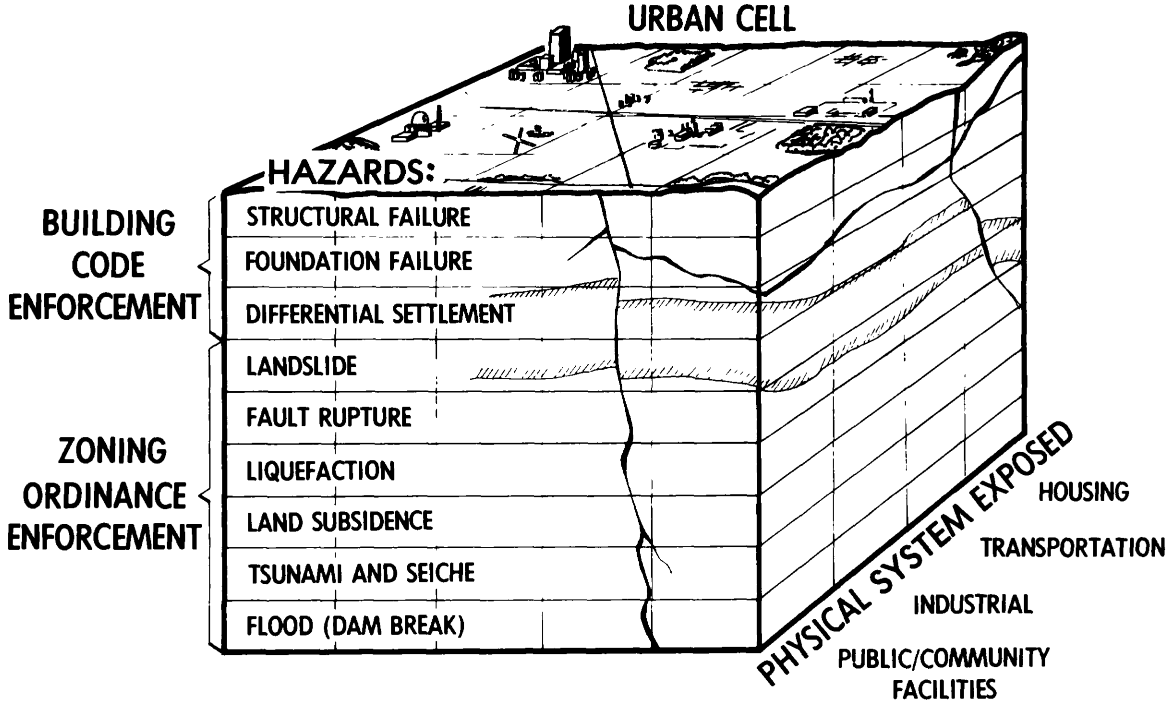


Figure 3. Schematic illustration of an urban community showing the wide range of buildings and lifeline systems requiring earthquake-resistant design and construction.

Scientists and engineers must perform a wide range of technical analyses that are conducted on three scales--global (map scale of about 1:7,500,000 or larger), regional (map scale of about 1:250,000 or larger), and local (map scale of about 1:250,000 or smaller). Global studies give the "big picture" of the tectonic forces. Regional studies establish the physical parameters needed to define the earthquake potential of a region. Local studies define the dominant physical parameters that control the site-specific characteristics of the physical effects. All the studies seek answers to the following technical questions: Where are earthquakes occurring now? Where did they occur in the past? Why are they occurring? How often do earthquakes of a certain size (magnitude) occur? How big (severe) have the physical effects been in the past. How big can they be in the future? How do the physical effects vary spatially and temporally?

The answers to these questions are used to define the seismic design parameters (Figure 4). Although these questions appear to be simple, the answers require considerable research and technical judgment. Data on hazards collected from worldwide earthquakes are used to provide a comprehensive framework of understanding.

Worldwide Data on the Ground-Shaking Hazard - Scientists and engineers throughout the world have recognized and documented the ground-shaking hazard since the 1800's (MacMurdo, 1824; Idriss and Seed, 1968, Seed and Idriss, 1969), showing that site response and structural response, are very important considerations in earthquake-resistant design of buildings and lifeline systems. Important rules derived from past experiences include the following:

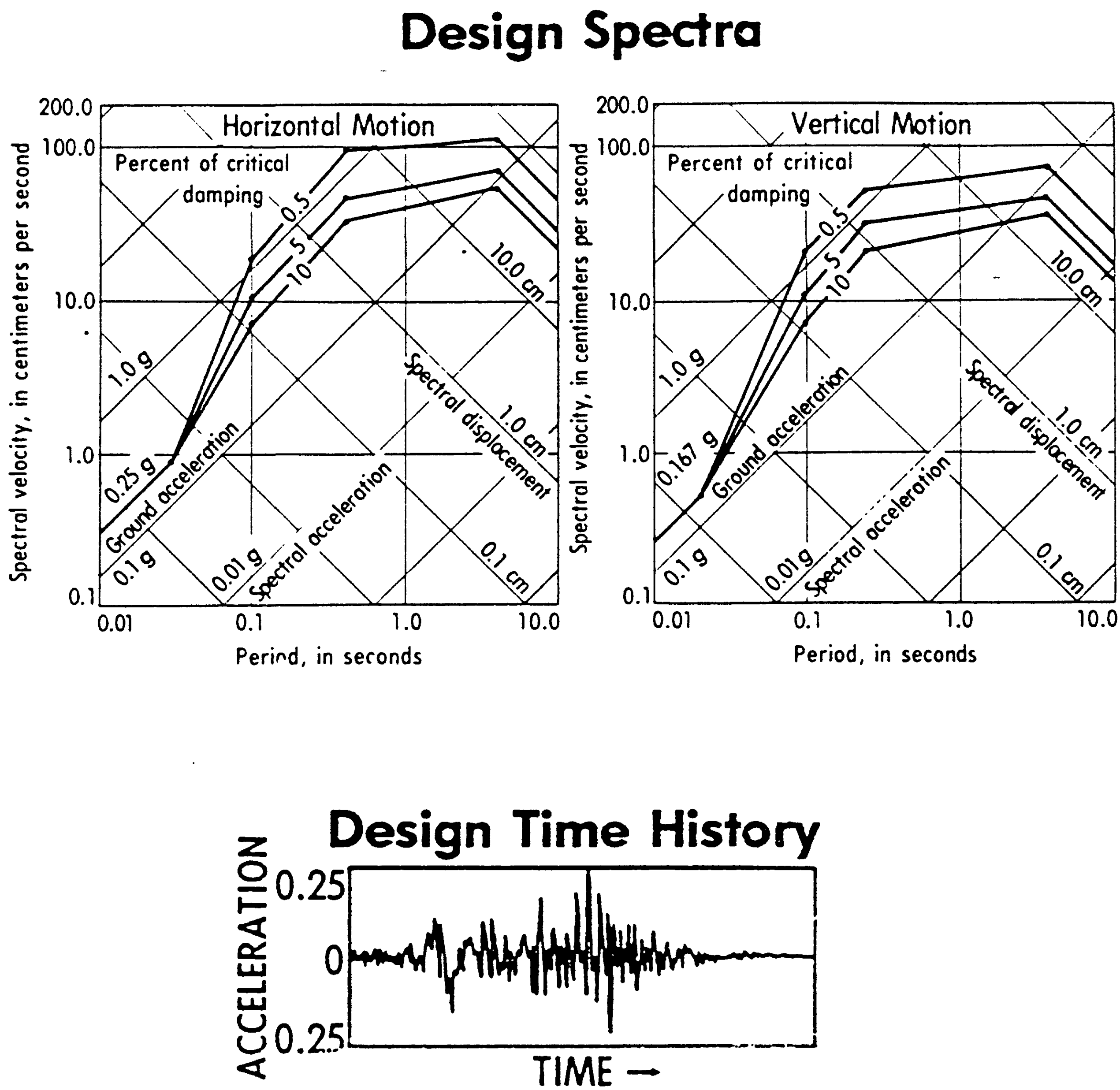
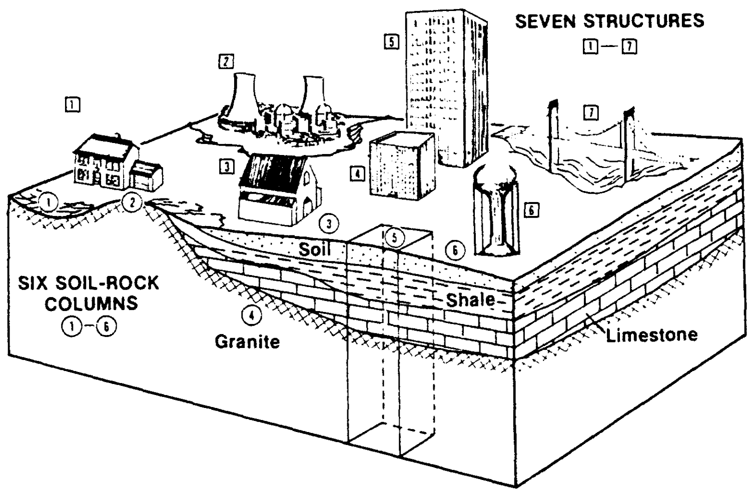


Figure 4. Schematic illustration of the design response spectra and time history used in the design of some lifeline systems and/or buildings and critical facilities.

1. In any city in any earthquake, the characteristics of the earthquake ground motion can vary widely depending on how close one is to the causative fault and the degree of variation in local soil-rock columns.

2. The damage to a structure or lifeline system at a site in an earthquake is complexly related to the dynamic frequency-dependent properties of the earthquake source, the low-pass filtering characteristics of the wave-propagation path, and the band-pass filtering characteristics of the lifeline system and the soil-rock column underlying the structure (Figure 5). The physical parameters that cause the soil-rock column and the structure or lifeline system to vibrate with the same period contribute most to the potential for damage (Yamahara, 1970).

3. The ground motion recorded in an earthquake at a free-field location is the best dynamic representation of how the ground moved. Movement is characterized in terms of the time histories of acceleration, velocity, and displacement; spectral composition (spectral acceleration, velocity, displacement) level of dynamic strain; and duration of shaking. The following physical parameters contribute distinctive frequency-dependent signatures to these ground-motion parameters: source--increasing the magnitude increases the peak amplitudes of all periods (low frequencies) enhancing the long periods (low frequencies); propagation path--the longer paths act like a low-pass filter, attenuating the peak amplitudes of the short periods (high frequencies) more rapidly than the peak amplitudes of the long periods; and site geology--the soil-rock column acts like a band-pass filter, increasing the peak amplitudes of the surface ground motion in a narrow band of frequencies and diminishing it in other period bands (Hays, 1980).



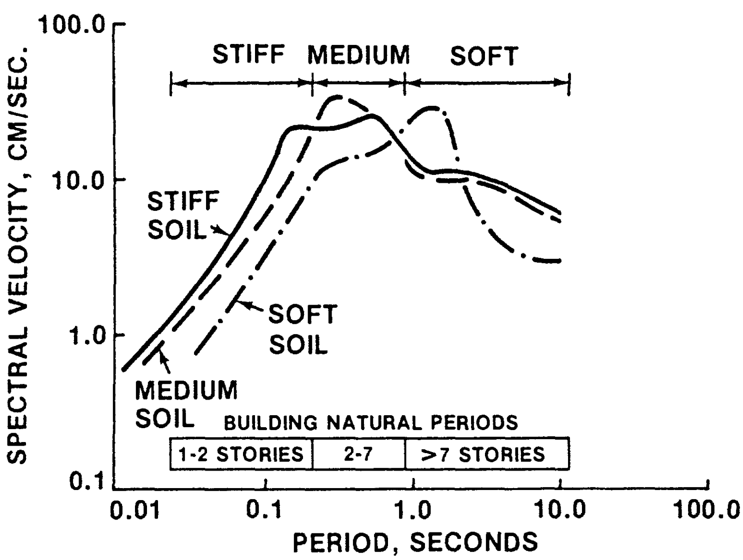


Figure 5. (Top) Schematic illustration showing a soil-rock column underlying seven types of structures. Siting and/or design must consider the physical effects of permanent ground displacements and dynamic ground shaking, which are a function of the earthquake source, the wave propagation paths, and the local site geology.

(Bottom) Schematic illustration showing the critical reasonant periods of soil columns and the fundamental periods of vibration of buildings of various height.

4. The level of dynamic shear strain and its effects on soil properties are a controversial aspect of seismic design. The level of strain induced in the soil column by the ground motion increases as the magnitude increases and decreases as the distance from the earthquake focus increases (Figure 6).

5. The frequency response of the soil-rock column strongly depends on the strain-dependent properties of the soil. Based on the level of dynamic shear strain and the contrast in physical properties of the soil and rock, the soil acts either as an energy transmitter on an energy dissipator. As an energy transmitter, the soil column acts like a band-pass filter, modifying the amplitude and phase spectra of the incident body and surface seismic wave (Murphy and others, 1971) and increasing the duration of shaking (Hays, 1975). As an energy dissipator, the soil column damps the earthquake ground motion, transmitting part of the vibrational energy of the soil column and any structure back into the Earth and permitting vertical side-to-side movement of the structure on its base (Wolf, 1985).

6. Site amplification, which is the frequency- and strain-dependent response of the soil-rock column to body and surface seismic waves, increases the surface ground motion in a narrow band of frequenices that is related to the thickness, shear wave velocity, bulk density, and geometry of the soil column.

7. A structure or other components in a lifeline system also can act like a band-pass filter as it responds to ground motion. The frequency response of the structure or lifeline system can be increased or decreased, depending on the type of structure, the construction materials, the lateral and vertical dimensions, the physical properties of the soil-rock column, and the

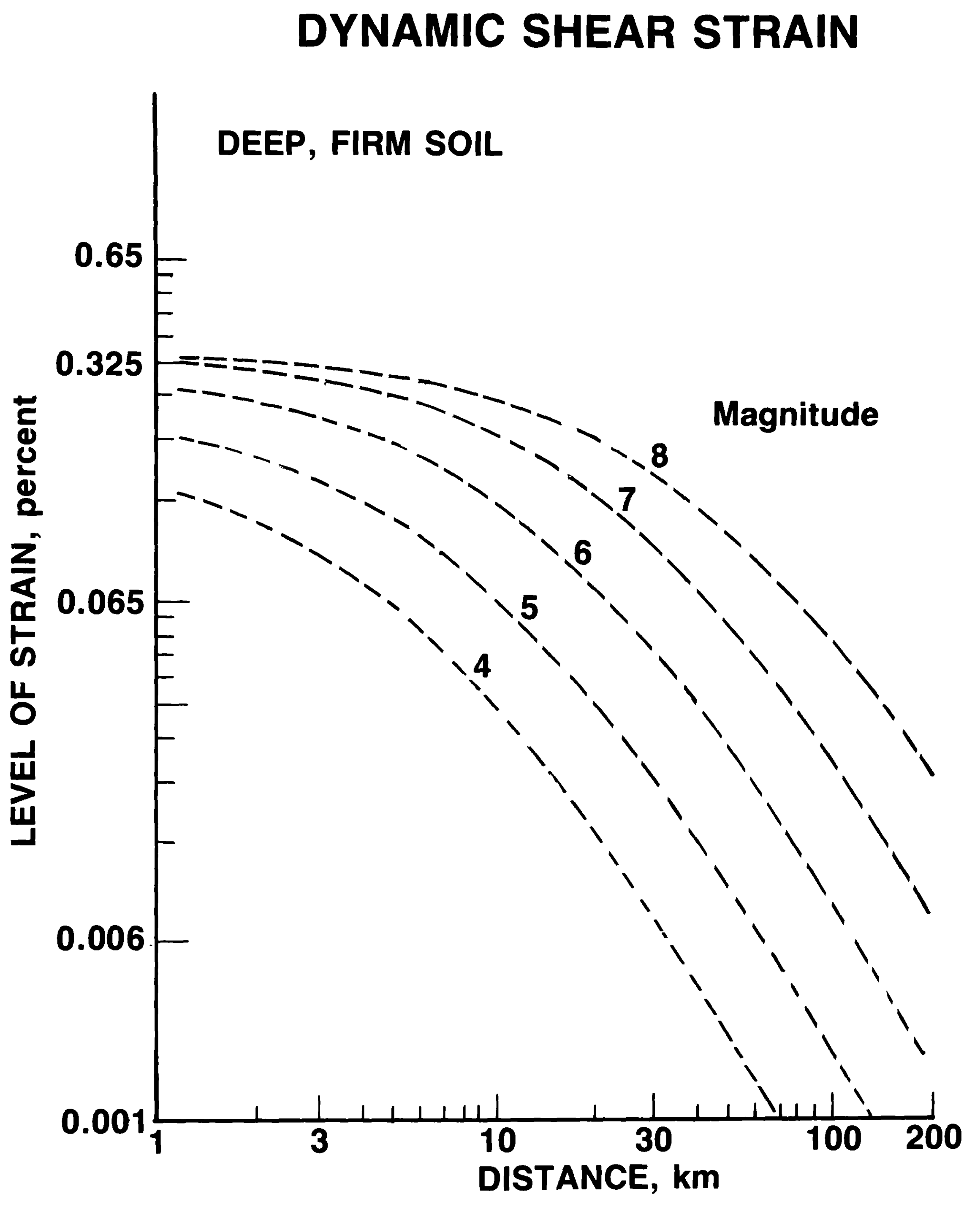


Figure 6. Schematic illustration showing how the dynamic shear strain for a deep, firm soil varies as a function of earthquake magnitude and epicentral distance. The near-surface material has a shear-wave velocity of 200 m/sec

wavelengths and strengths of the incident seismic waves. The worst case occurs when the dominant period of the rock motion, the fundamental natural period of vibration of the structure or lifeline system, and the natural period of the soil column are the same, creating a condition of resonance.

8. The near field is the most complex part of the problem of earthquake-resistant design. Analyses of strong-ground-motion data recorded in the near field; that is, locations within a few widths of the fault zone have been made by a number of investigators (for example, Idriss, 1978; Hays, 1980; Singh, 1985). For the near field, these analyses indicate two things. First, separation of the frequency-dependent effects of the source from the frequency-dependent effects of the soil-rock column is very difficult because the source effects appear to dominate the path and site effects in the near field. Also, the directivity of the source appears to cause most of the large variability in the values of peak ground accelerations, peak ground velocity, peak ground displacement, and spectral velocity observed in the near field (Singh, 1985). Second, a killer pulse, a pulse of approximately 1-second duration that typically does not have the greatest amplitude, but which has the greatest kinetic energy, is generated in some cases in the near field as a consequence of the fling of the fault (Bertero and others, 1978). Phenomena called breakout and stopping phases that are related to the fault rupture also can occur.

9. The spatial variation of the horizontal and vertical ground motion is an important factor that strongly influences the distribution of damage in an earthquake, espeically for lifeline systems. Strong-ground-motion data acquired on the "differential array" in the 1970 Imperial Valley, California,

earthquake showed that the peak amplitudes, spectral composition, and duration of ground shaking can vary widely over horizontal distances of only a few tens of a meters. This degree of variability is an important consideration in the seismic design of buried pipelines and other long linear structures. Data showing how ground motion varies with depth is limited; however, the available data indicate that the level of ground shaking increases with depth and that the spectral composition is related to the thickness and physical properties of the soil column (Hays, 1980; Kennedy and others, 1984).

3 ROLES OF THE GEOLOGIST, SEISMOLOGIST, AND GEOTECHNICAL ENGINEER

The geologist, seismologist, and geotechnical engineer have important roles in providing information that can be correlated with permanent ground movements and dynamic ground shaking. They conduct investigations on all three scales (global, regional, and local) and provide information on plate tectonics, faults, seimsicity, paleoseismicity, earthquake potential, seismic source zones, seismic wave attenuation, bedrock ground-shaking hazard, site-specific characteristics of the soil and rock column underlying or enclosing the lifeline system, and liquefaction and landslide potential.

Plate Tectonics - Each year, several million earthquakes occur throughout the world. Most of these earthquakes occur along the boundaries of about a dozen 80- to 96-kilometers (50- to 60-mile) thick rigid plates or segments of the Earth's crust and upper mantle that are moving slowly and continusously over the interior of the Earth (Figure 7). These plates meet in some areas and separate in others, moving at relative velocities that range from less than 1 centimeter (fraction of an inch) to about 25 centimeters (10 inches) per

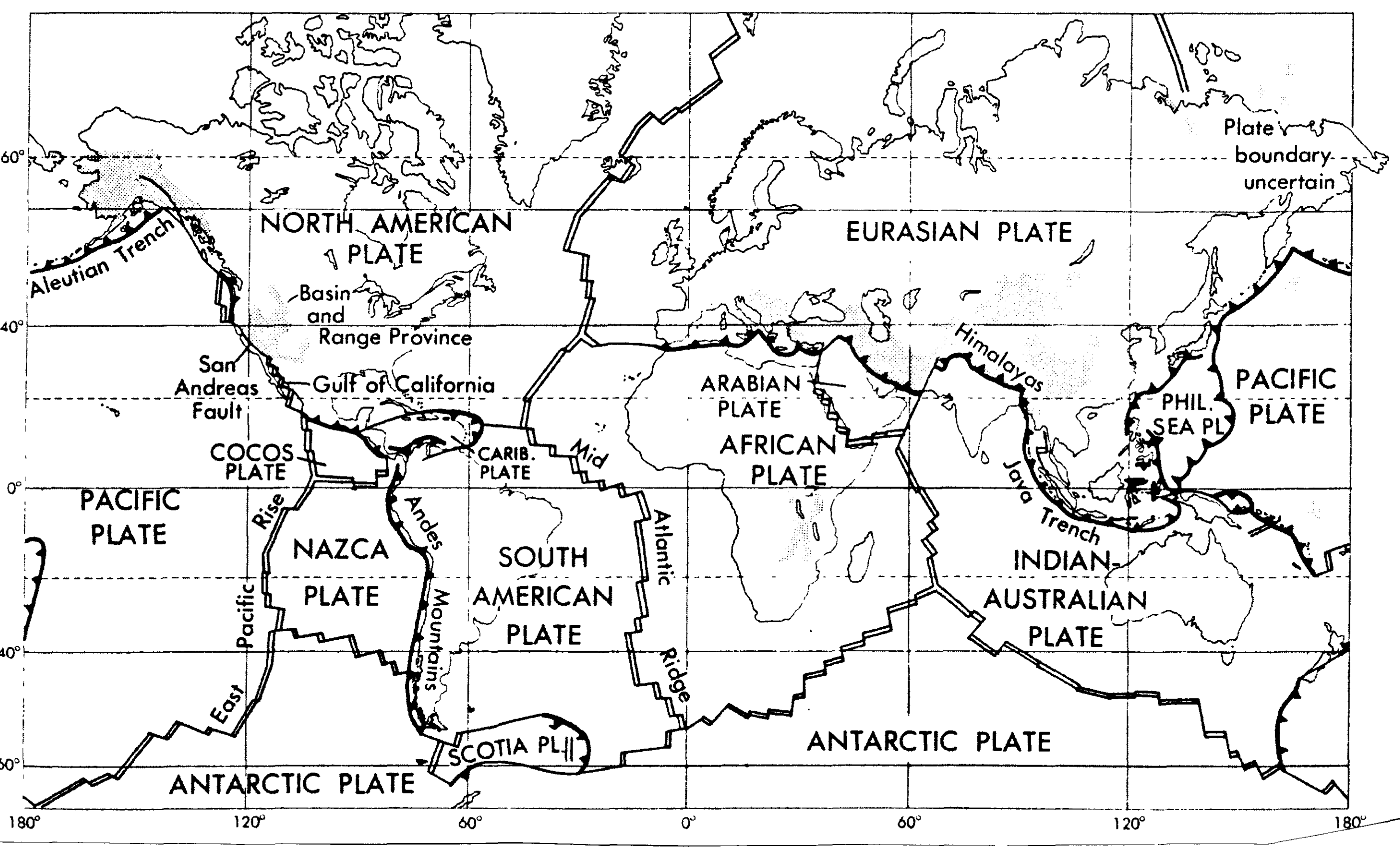


Figure 7. Map showing the major tectonic plates of the world (Figure adapted from many sources and simplified in complex areas). Lifeline systems are exposed to interplate and intraplate earthquakes.

year. Although these velocities are slow, they can add up to more than 50 kilometers (30 miles) in only 1 million years, which is a short time, geologically speaking. As these plates move, strain accumulates at the margins of plates, and, eventually, faults along or near the plate margins slip abruptly, and an earthquake occurs.

Studies of Faults - The study of individual fault systems provides an understanding of where earthquakes are likely to occur, how big they are likely to be, and how often they are likely to take place. The energy released during large to great earthquakes demands that a fault rupture over a significant fraction of its length. Observational data from historic earthquakes throughout the world indicate that even moderate earthquakes having magnitudes of about 6 requires a fault rupture length of 5-10 kilometers (3-6 miles) and that great earthquakes having magnitudes of 8 and greater can have a rupture length of as much as 1,000 kilometers (600 miles). A great earthquake signals that adjustments have occurred in the entire crust of the Earth.

The largest known vertical and horizontal fault displacements observed at the ground surface during historic earthquakes are 11.5 meters (38 feet) during the 1897 Asam earthquake and 9.9 meters (33 feet) during the 1957 Mongolia earthquakes, respectively (Allen, 1984). Geodetic observations suggest that significantly larger displacements may have occurred at depth.

Many faults extending to the ground surface have been identified and studies throughout the world by geologists. Studies of faulting have produced the following general rules (Allen, 1984; Hays, 1980):

1) Rules of Occurrence (Allen, 1984)

- Almost all large earthquakes have occurred on preexisting faults that have had a previous history of earthquake displacements within the recent geologic past, usually within the past few tens of thousands of years.

- Long faults are required to generate large earthquakes.

- Long faults grow from the gradual lengthening and coalescing of small faults that rupture in small to medium earthquakes over a period of milions of years. Thus, a long fault, such as the San Andreas in California, is not born during a single great earthquake in the distant past, but rather is the result of many smaller earthquakes occurring over time.

- If the frequency of movements on a fault during the recent geologic past can be determined, then reliable estimates can be made of how likely the fault is to rupture in a future earthquake during a specific time interval.

2) Rules on Ground-Shaking Characteristics (Hays, 1980)

- The length of the fault and the fraction of the length that ruptures affects the maximum magnitude of the earthquake, the seismic moment, and the duration of shaking. The entire spectral composition is affected, but the low-frequency portion of the response spectrum increases most as the length of the fault rupture (and the magnitude) increases.

- o Although the rupture mechanism of the fault can affect the entire spectrum, it appears to mainly affect the high-frequency portion of the response spectrum and has caused near-field phenomena, such as directivity and focusing. Breakout phases and the killer pulse on the Pacoima dam time histories are examples of the effect of the fault rupture.

- o The level of ground shaking at the location of a building or lifeline system is greatest in the near field, except where the local soil conditions cause amplification of ground motion; for example, the 1985 Mexico earthquake. These cases are rare.

- o The history of the fault rupture (that is, the cycle of fault activity) controls how often earthquakes of a given magnitude recur.

- o Investigations of faults throughout the world have shown that large to great earthquakes have occurred on strike-slip faults (for example, the San Andreas fault) thrust/or reverse faults (for example, the subduction zone beneath southern Chile and the Oued Fodda fault in northern Algeria). Thrust faults, where one block overrides the other block on a shallowly inclined fault plane, are more difficult to recognize and to quantify through paleoseismicity studies than strike-slip or normal faults. A highly active fault, such as the thrust fault marking the subduction zone in southern Cahile, has the potential for generating a great earthquake, on the average, about once every 100 years, whereas other faults, such as the Oued Fodda fault in northern Algeria, have a longer recurrence interval or repeat time, about once every 450 years, for generating a large earthquake, such as the magnitude 7.3 El Asnam earthquake of October 1980. Determination of the activity rate of a fault is a major challenge and important task for the geologist because the activity rate affects the amplitude leel of the seismic design parameters.

o Some geologists classify faults as either "active" or "inactive," based on whether they have moved within a specific period of time, such as in the last few tens of thousands of years. Figure 8 illustrates types of fault classification.

o Geophysical investigations (for example, seismic reflection) are very important in identifying and evaluating the activity of buried faults in onshore and in offshore areas. Buried faults control the "floating earthquake" and are more difficult to quantify than those exposed at the surface.

Seismicity - Studies of the record of historic seismicity provide answers to the questions where, how big, how often, and why. In 1983, S. T. Algermissen produced a comprehensive treatment of the seismicity of the United States. This information is summarized below for each region of the conterminous United States, Alaska, Hawaii, Puerto Rico, and the Virgin Islands. The Modified Mercalli Intensity (MMI) Scale is used as the reference if instrumental data are unavailable to define the magnitude of the surface wave.

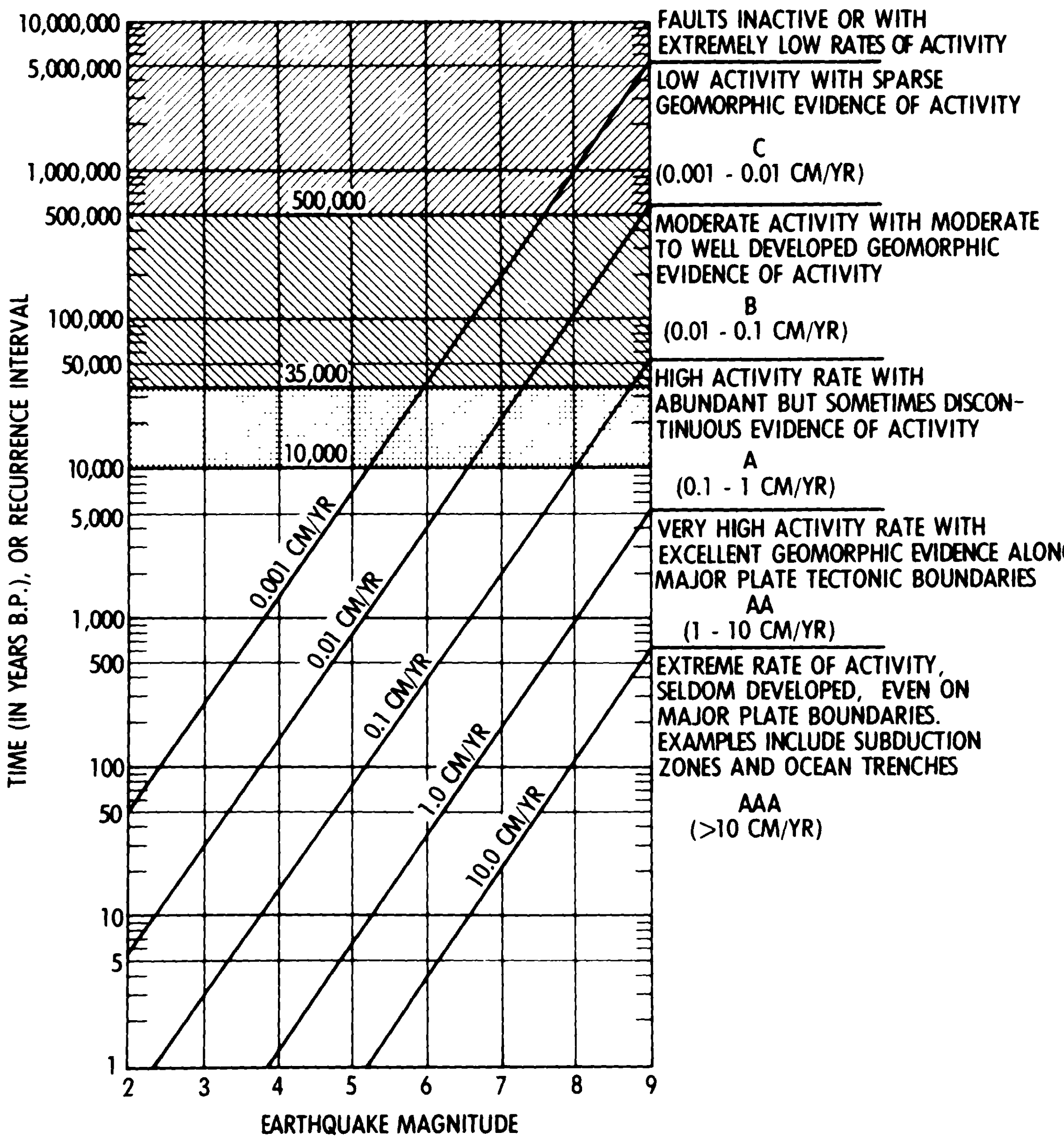


Figure 8. Graph showing earthquake magnitude, slip rate, and recurrence interval of active fault zones throughout the world. (From Slemmons, 1977).

Northeastern Region

The record of earthquakes in the United States (and the Northeast} is believed to have started with the Rhode Island earthquake of 1568. The distribution of earthquakes with respect to the maximum MMI in the northeastern United States, excluding Canada and offshore epicenters, is shown in Table 1.

TABLE 1
IMPORTANT EARTHQUAKES FOR EASTERN CANADA AND NEW ENGLAND
[m_b, MAGNITUDE FROM BODY (P AND S) WAVES. FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
1534 - 1535	St. Lawrence Valley	IX-X	
Jun 11, 1638	St. Lawrence Valley	IX	
Feb 5, 1663	Charlevoix Zone	X	7.0
Nov 10, 1727	New Newbury, Massachusetts	VIII	7.0
Sep 16, 1732	Near Comtreal	VIII	
Nov 18, 1755	Near Cape Ann, Massachusetts	VIII	
May 16, 1791	East Haddam, Connecticut	VIII	
Oct 5, 1817	Woburn, Massachusetts	VII-VIII	
Oct 17, 1860	Charlevoix Zone	VIII-IX	6.0
Oct 20, 1870	Charlevoic Zone	IX	6.5
Mar 1, 1925	Charlevoix Zone	IX	7.0
Aug 12, 1929	Attica, New York	VIII	5.5
Nov 18, 1929	Grand Banks of Newfoundland	X	8.0
Nov 1, 1935	Timiskaming, Quebec	VIII	6.0
Sep 5, 1944	Massena, New York-Cornwall, Ontario	VIII	6.0
Jan 9, 1982	North Central New Brunswick	V	5.7(m_b)

Modified Mercalli Intensity	Number
V	120
VI	37
VII	10
VIII	3

Southeastern Region

The southeastern United States is an area of diffuse low-level seismicity that has not experienced a MMI VII or greater earthquake in nearly 80 years. The largest and most destructive earthquake in the region was the 1886 Charleton earthquake, which caused 60 deaths and widespread damage to buildings. It had an epicentral intensity of X and a magnitude from surface waves (M_S) of approximately 7.7 (Bollinger, 1977). Important earthquakes of the southeastern region are listed in Table 2. The distribution of earthquakes through 1976 in the southeastern region is as follows:

TABLE 2
IMPORTANT EARTHQUAKES OF THE SOUTHEASTERN REGION
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Feb 21, 1774	Eastern VA	VII	
Feb 10, 1874	McDowell County, NC	V-VII	
Dec 22, 1875	Arvonia, VA area	VII	
Aug 31, 1886	Near Charleston, SC	X	7.7
Oct 22, 1886	Near Charleston, SC	VII	
May 31, 1897	Giles County, VA	VIII	6.3
Jan 27, 1905	Gadsden, AL	VII-VIII	
Jun 12, 1912	Summerville, SC	VI-VII	
Jan 1, 1913	Union County, SC	VII-VIII	5.7-6.3
Mar 28, 1913	Near Knoxville, TN	VII	
Feb 21, 1916	Near Asheville, NC	VI-VII	
Oct 18, 1916	Northeastern, AL	VII	
Jul 8, 1926	Mitchell County, NC	VI-VII	
Nov 2, 1928	Western NC	VI-VII	

Modified Mercalli Intensity	Number
V	133
VI	70
VII	10
VIII	2
IX	0
X	1

Central Region

The seismicity of the central region is dominated by the three great earthquakes that occurred in 1811-12 near New Madrid, Missouri. These earthquakes had magnitudes (M_S) ranging from 8.4 to 8.7 and epicentral intensities ranging from X to XII (Nuttli, 1973). About 15 of the thousands of aftershocks that followed had magnitudes greater than M_S = 6. A distribution of earthquakes through 1976 in the central region is given below as well as a listing of the important earthquakes through 1980 (Table 3).

TABLE 3
IMPORTANT EARTHQUAKES OF THE CENTRAL REGION THROUGH 1980
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Dec 16, 1811	New Madrid, Missouri	XI	8.6
Jan 23, 1812	New Madrid, Missouri	X-XI	8.4
Feb 7, 1812	New Madrid, Missouri	XI-XII	8.7
Jun 9, 1838	Southern Illinois	VIII	5.7
Jan 5, 1843	Near Memphis, Tennessee	VIII	6.0
Apr 24, 1867	Near Manhattan, Kansas	VII	5.3
Oct 22, 1882	West Texas	VII-VIII	5.5
Oct 31, 1895	Near Charleston, Missouri	VIII-IX	6.2
Jan 8, 1906	Near Manhattan, Kansas	VII-VIII	5.5
Mar 9, 1937	Near Anna, Ohio	VIII	5.3
Nov 9, 1968	Southern Illinois	VII	5.5
Jul 27, 1980	Near Sharpsburg, Kentucky	VII	5.1

Modified Mercalli Intensity	Number
V	275
VI	114
VII	32
VIII	5
IX	1
X	0
XI	2
XII	1

Western Mountain Region

A number of important earthquakes have occurred in the western mountain region--in the Yellowstone Park-Hebgen Lake area in western Montana, in the vicinity of the Utah-Idaho border, and sporadically along the Wasatch Front in Utah (see Table 4). The largest earthquake in the western mountain region in historic times was the 1959 Yellowstone Park-Hebgen Lake earthquake, which had a magnitude now believed to be in excess of $M_S = 7.3$. The strongest earthquake in 24 years occurred at Borah Peak in Idaho in October 1983; it had a magnitude of $M_S = 7.3$. The distribution of historic earthquakes in the western mountain region is as follows:

TABLE 4
IMPORTANT EARTHQUAKES OF THE CENTRAL REGION THROUGH 1980
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Nov 9, 1852	Near Ft. Yuma, Arizona	VIII	
Nov 10, 1884	Utah-Idaho border	VIII	
Nov 14, 1901	About 50 km east of Milford, Utah	VIII	
Nov 17, 1902	Pine Valley, Utah	VIII	
Jul 16, 1906	Socorro, New Mexico	VIII	
Sept 24, 1910	Northeastern Arizona	VIII	
Aug 18, 1912	Near Williams, Arizona	VIII	
Sept 29, 1921	Elsinore, Utah	VIII	

Sept 30, 1921	Elsinore, Utah	VIII	
Jun 28, 1925	Near Helena, Montana	VIII	6.7
Mar 12, 1934	Hansel Valley, Utah	VIII	6.6
Mar 12, 1934	Hansel Valley, Utah	VIII	6.0
Oct 19, 1935	Near Helena, Montana	VIII	6.2
Oct 31, 1935 (Aftershock)	Near Helena, Montana	VIII	6.0
Nov 23, 1947	Southwestern Montana	VIII	
Aug 18, 1959	West Yellowstone-Hebgen Lake	X	7.1
Aug 18, 1959 (Aftershock)	West Yellowstone-Hebgen Lake	VI	6.5
Aug 18, 1959 (Aftershock)	West Yellowstone-Hebgen Lake	VI	6.0
Aug 18, 1959 (Aftershock)	West Yellowstone-Hebgen Lake	VI	6.0
Aug 18, 1959	West Yellowstone-Hebgen Lake	VI	6.5
Mar 28, 1975	Pocatello Valley, Idaho	VIII	6.1
Jun 30, 1975	Yellowstone National Park	VIII	6.4
Oct 28, 1983	Borah Peak, Idaho	VII	7.3

Modified Mercalli Intensity	Number
V	474
VI	149
VII	26
VIII	22
IX	0
X	1

California and Western Nevada Region

The highest rates of seismic energy release in the United States, exclusive of Alaska, occur in California and western Nevada. The coastal areas of California are part of the active plate boundary between the Pacific and North America tectonic plates. Seismicity occurs over the well-known San Andreas fault system as well as many other fault systems. A number of major earthquakes have occurred in this region (Table 5). The following generalizations can be made: (1) the earthquakes are nearly all shallow, usually less than 15 kilometers in depth, (2) the recurrence rate for a large (M_S greater than 7.8) earthquake on the San Andreas fault system is about every 100 years, (3) the recurrence rates for large earthquakes on single fault segments in the Nevada seismic zone are believed to be in the order of thousands of years, and (4) most of the major earthquakes have produced surface faulting. Excluding offshore earthquakes, the distribution in California and western Nevada is given below:

TABLE 5
MAJOR EARTHQUAKES OF CALIFORNIA AND WESTERN NEVADA
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Dec 21, 1812	Santa Barbara Channel	X	
Jun 10, 1836	Hayward fault, east of San Francisco Bay	IX-X	
Jun 1838	San Andreas fault	X	
Jan 9, 1857	San Andreas fault, near Fort Tejon	X-XI	
Oct 21, 1868	Hayward fault, east of San Francisco Bay	IX-X	
Mar 26, 1872	Owens Valley	X-XI	
Apr 19, 1892	Vacaville, California	IX	
Apr 15, 1898	Mendocino County, California	VIII-IX	
Dec 25, 1899	San Jacinto, California	IX	
Apr 18, 1906	San Francisco, California	XI	8.3
Oct 3, 1915	Pleasant Valley, Nevada	X	7.7
Apr 21, 1918	Riverside County, California	IX	6.8
Mar 10, 1922	Cholame Valley, California	IX	6.5
Jan 22, 1923	Off Cape Mendocino, California	(IX)	7.3
Jun 29, 1925	Santa Barbara Channel	VIII-IX	6.5
Nov 4, 1927	West of Point Arguello, California	IX-X	7.3
Dec 21, 1932	Cedar Mountain, Nevada	X	7.3
Mar 11, 1933	Long Beach, California	IX	6.3
May 19, 1940	Southeast of El Centro, California	X	7.1
Jul 21, 1952	Kern County, California	XI	7.7
Jul 6, 1954	East of Fallon, Nevada	IX	6.6
Aug 24, 1954	East of Fallon, NV	IX	6.8
Dec 16, 1954	Dixie Valley, Nevada (2 shocks)	X	7.3
Feb 9, 1971	San Fernando, California	XI	6.4
Oct 15, 1979	Imperial Valley, California	IX	6.6
May 2, 1983	Coalinga, California	VIII	6.5

Modified Mercalli Intensity	Number
V	1,263
VI	487
VII	170
VIII	40
VIII-IX	2
IX	8
IX-X	3
X	5
X-XI	2

Washington and Oregon Region

This region is charcterized by a low to moderate level of seismicity independent of the active volcanism of the Cascade Range. With the exception of plate interaction between the North American and Pacific tectonic plates, no clear relation is known between seismicity and geologic structure. From the list of important earthquakes that occurred in the region (Table 6), the two most recent damaging earthquakes in the Puget Sound area (M_S = 6.5 in 1965; M_S = 7.1 in 1949) occurred at a depth of 60-70 kilometers. Currently, researchers are speculating that a great earthquake could occur as a consequence of the interaction of the Juan de Fuca and the North American tectonic plates. The distribution of earthquakes in the Washington and Oregon region is given below:

TABLE 6
IMPORTANT EARTHQUAKES OF WASHINGTON AND OREGON
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_o)	Magnitude (Approx. M_S)
Dec 14, 1872	Near Lake Chelan, Washington	IX	(7.0)
Oct 12, 1877	Cascade Mountains, Oregon	VIII	
Mar 7, 1893	Umatilla, Oregon	VII	
Mar 17, 1904	About 60 km northwest of Seattle, Washington	VII	
Jan 11, 1909	North of Seattle, Washington near Washington-British Columbia	VII	
Dec 6, 1918	Vancouver Island, BC	(VIII)	7.0
Jan 24, 1920	Straits of Georgia	(VII)	
Jul 16, 1936	Northern Oregon, near Freewater	VII	(5.7)
Nov 13, 1939	Northwest of Olympia (Depth of focus about 40 km)	VII	(5.8)
Apr 29, 1945	About 50 km southeast of Seattle, Washington	VII	
Feb 15, 1946	About 35 km north northeast of Tacoma, Washington (Depth of focus 40-60 km)	VII	6.3
Jun 23, 1946	Vancouver Island	(VIII)	7.2
Apr 13, 1949	Between Olympia and Tacoma, Washington (Depth of focus about 70 km)	VIII	7.1
Apr 29, 1965	Between Tacoma and Seattle, Washington (Depth of focus about 59 km)	VIII	6.5

Modified Mercalli Intensity	Number
V	150
VI	57
VII	8
VIII	3
IX	1

Alaska Region

The Alaska-Aleutian Island area is one of the most active seismic zones in the world. The Queen Charlotte Island-Fairweather fault system marks the active boundary in southeastern Alaska where the Pacific plate slides past the North American plate. The entire coastal region of Alaska and the Aleutians have experienced extensive earthquake activity (Table 7) even in the relatively short (85 years) time period for which the seismicity is well known. The most devastating earthquake in Alaska occurred on March 28, 1964, in the Prince William Sound. This earthquake, which recently has been assigned a moment magnitude of 9.2, also probably was the largest historical earthquake in the region. It caused 114 deaths, principally as a consequence of the tsunami that followed the earthquake. The regional uplift and subsidence covered an area of more than 77,000 square miles. The distribution of earthquakes in Alaska in terms of magnitude (M_S) is as follows:

TABLE 7
MAJOR EARTHQUAKES OF ALASKA
[From Algermissen (1983)]

Date	Location	Magnitude (Approx. M_S)
Sep 4, 1899	Near Cape Yakataga	8.3
Sep 10, 1899	Yakutat Bay	8.6
Oct 9, 1900	Near Cape Yakataga	8.3
Jun 2, 1903	Shelikof Straight	8.3
Aug 27, 1904	Near Rampart	8.3
Aug 17, 1906	Near Amchitka Island	8.3
Mar 7, 1929	Near Dutch Harbor	8.6
Nov 10, 1938	East of Shumagin Islands	8.7
Aug 22, 1949	Queen Charlotte Islands, Canada	8.1
Mar 9, 1957	Andreanof Islands	8.2
Mar 28, 1964	Prince William Sound	8.4
Feb 4, 1965	Rat Islands	7.8

M_S	Number
5.0-5.9	757
6.0-6.9	344
7.0-7.9	63
Greater than or equal to 8.0	11

Hawaiian Islands Region

The seismicity in the Hawaiian Islands is related to the well-known volcanic activity and is associated primarily with the island of Hawaii. Although the seismicity has been recorded for about 100 years, a number of important earthquakes have occurred since 1868 (Table 8). Tsunamis from local, as well as distant, earthquakes have impacted the islands; some tsunamis had wave heights of as much as 55 feet. The distribution of earthquakes in terms of maximum MMI is given below:

TABLE 8
EARTHQUAKES CAUSING SIGNIFICANT DAMAGE IN HAWAII
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_0)	Magnitude (Approx, M_S)
Apr 2, 1868	Near south coast of Hawaii	X	
Nov 2, 1918	Mauna Loa, Hawaii	VII	
Sep 14, 1919	Kilauea, Hawaii	VII	
Sep 25, 1929	Kona, Hawaii	VII	
Sep 28, 1929	Hilo, Hawaii	VII	
Oct 5, 1929	Honualoa, Hawaii	VII	6.5
Jan 22, 1938	North of Maui	VIII	6.7
Sep 25, 1941	Mauna Loa, Hawaii	VII	6.0
Apr 22, 1951	Kilauea, Hawaii	VII	6.5
Aug 21, 1951	Kona, Hawaii	IX	6.9
Mar 30, 1954	Near Kalapana, Hawaii	VII	6.5
Mar 27, 1955	Kilauea, Hawaii	VII	
Apr 26, 1973	Near northeastern coast of Hawaii	VIII	6.3
Nov 29, 1975	Near northeastern coast of Hawaii	VIII	7.2
Nov 16, 1983	Near Mauna Loa, Hawaii		6.6

Modified Mercalli Intensity	Number
V	56
VI	9
VII	9
VIII	3
IX	1
X	1

Puerto Rico and the Virgin Islands Region

The seismicity in Puerto Rico and the Virgin Islands region is related to the interaction of the Caribbean and the North American tectonic plates. The Caribbean plate is believed to be nearly fixed while the North American plate is moving westward at the rate of about 2 centimeters per year. Earthquakes in this region are known to have caused damage as early as 1524-28. During the past 120 years, major damaging earthquakes have occurred in 1867 and 1918; both earthquakes had tsunamis associated with them. The distribution of earthquakes affecting Puerto Rico is given below in terms of maximum MMI; Table 9 lists damaging earthquakes in Puerto Rico and the Virgin Islands region.

TABLE 9

DAMAGING EARTHQUAKES ON OR NEAR PUERTO RICO
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Apr 20, 1824	St. Thomas, Virgin Islands	(VII)	
Apr 16, 1844	Probable north of Puerto Rico	VII	
Nov 28, 1846	Probably Mona Passage	VII	
Nov 18, 1867	Virgin Islands	VIII (also tsunami)	
Mar 17, 1868	Location uncertain	(VIII)	
Dec 8, 1875	Near Arecebo, Puerto Rico	VII	
Sep 27, 1906	North of Puerto Rico	VI-VII	
Apr 24, 1916	Possibly Mona Passage	(VII)	
Oct 11, 1918	Mona Passage	VIII-IX (also tsunami)	7.5

Modified Mercalli Intensity	Number
V	24
V-VI	4
I	5
VI-VII	1
VII	6
VIII	2
VIII-IX	1

Paleoseismicity - Recently, geologists have developed field techniques to determine the dates of prehistoric earthquakes on some faults and to extend the record of seismicity as far back in time as 15,000 years or more. These techniques involve trenching and geotechnical dating (usually with the carbon-14 method) of buried strata that immediately predates and postdates a fault offset. The application of these techniques is called a "paleoseismicity" study. The basic principles of paleoseismicity studies are as follows:

- o Prehistoric earthquakes cause cumulative surface deformation, which manifests itself as stratigraphic and topographic displacements.

- Some of displacements can be identified by trenching. A trench having a depth of only 5 meters (16 feet) along the San Andreas fault zone can exhibit deformation from earthquakes during the past 2,000 years (Sieh, 1978).

Three basic levels of evidence are the objectives in trenching. They are as follows:

- Evidence of significant crustal strain can be isolated at discrete surface locations.

- Earthquake-generating fault movements duplicate the near-surface pattern of deformation.

- Datable near-surface materials around a fault are preserved for longer periods of time than the recurrence intervals of major fault movements.

Because several prehistoric earthquakes likely are to be represented in a single exposure in a trench, the geologic relations can be very complex. Optimal bracketing of the time of the earthquake requires dating of the oldest unbroken postearthquake strata and the youngest deformed preearthquake strata.

Useful geologic evidence for paleoseismicity has been developed from stratigraphic and geomorphic evidence within active fault zones in the Western United States (Sieh, 1978; Schwartz and Coppersmith, 1984). These relations provide estimates of the displacements and repeat times of individual paleoseismic events. In the Eastern United States, paleoseismicity studies also are beginning to produce useful results. Late Holocene (less than 10,000 years B.P.) prehistoric earthquakes have been recognized in the New Madrid, Missouri, region on the basis of discrete ages of liquefaction, two features that probably occurred in the past 2,000 years (Russ, 1982). Recently, three large pre-1886 earthquakes that occurred in the past 7,500 years have been recognized in Hollywood, South Carolina, on the basis of studies of liquefaction features (Obermeier, 1985).

Studies of Earthquake Potential - Once faults and other tectonic features have been identified, their potential for generating earthquake is determined. The procedure for assessing earthquake potential includes the following:

1. Selection of the physical characteristics that enable tectonic features to be differentiated,

2. Comparison with other tectonic featurs having specific physical characteristics, and

3. Assessment of the probability that a tectonic feature exhibits a particular combination of physical characteristics favorable for generating earthquakes.

Figure 9 shows a matrix that can be used to assess the earthquake potential of a tectonic feature. All the available information is used to infer the physical characteristics as accurately as possible. The following types of questions are asked:

RECENT STRAIN	GEOLOGIC REACTIVATION	LOW STRENGTH OR CHANGE IN STRENGTH	ASSOCIATED SEISMICITY: MODERATE-TO-LARGE EARTHQUAKES				SMALL EARTHQUAKES ONLY				NO SEISMICITY			
		GEOMETRY RELATIVE TO STRESS/ SENSE OF SLIP	FAVORABLE		UNFAVORABLE		FAVORABLE		UNFAVORABLE		FAVORABLE		UNFAVORABLE	
		LOCAL STRESS AMPLIFICATION	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
YES	YES	YES												
		NO												
	NO	YES												
		NO												
NO	YES	YES												
		NO												
	NO	YES												
		NO												

Figure 9. Example of matrix containing basic criteria used to evaluate the earthquake potential of a tectonic feature (from Electric Power Research Institute, 1984).

- o Has historical seismicity been associated with the tectonic feature? Does evidence exist of recent crustal strain?

- o Does evidence exist for reactivation of a tectonic feature along preexisting zones of weakness?

- o Does evidence exist showing that the tectonic features are located along preexisting zones of weakness?

- o Does evidence exist showing that the tectonic feature amplifies the local stress above the ambient level because of structural complexities?

- o Do the tectonic features have low crustal strength or do they exhibit spatial and temporal changes in crustal strength?

The first two factors, association of the tectonic feature with historical seismicity and evidence for recent crustal strain, seem to be the most diagnostic and can be interpreted to indicate that the earthquake potential is high or low depending on what relations are observed.

Studies of Seismogenic Zones - The geologist and seismologist integrate their information to define seismogenic source zones, a region having spatially homogeneous characteristics of earthquake recurrence rates and maximu magnitude. Delineation of seismic sources requires the integration of data on seismicity, paleoseismicity, and the tectonic framework. Figure 10 illustrates the basic source models--line source, area source, collection of line sources, and an areas source encompassing a collection of line sources.

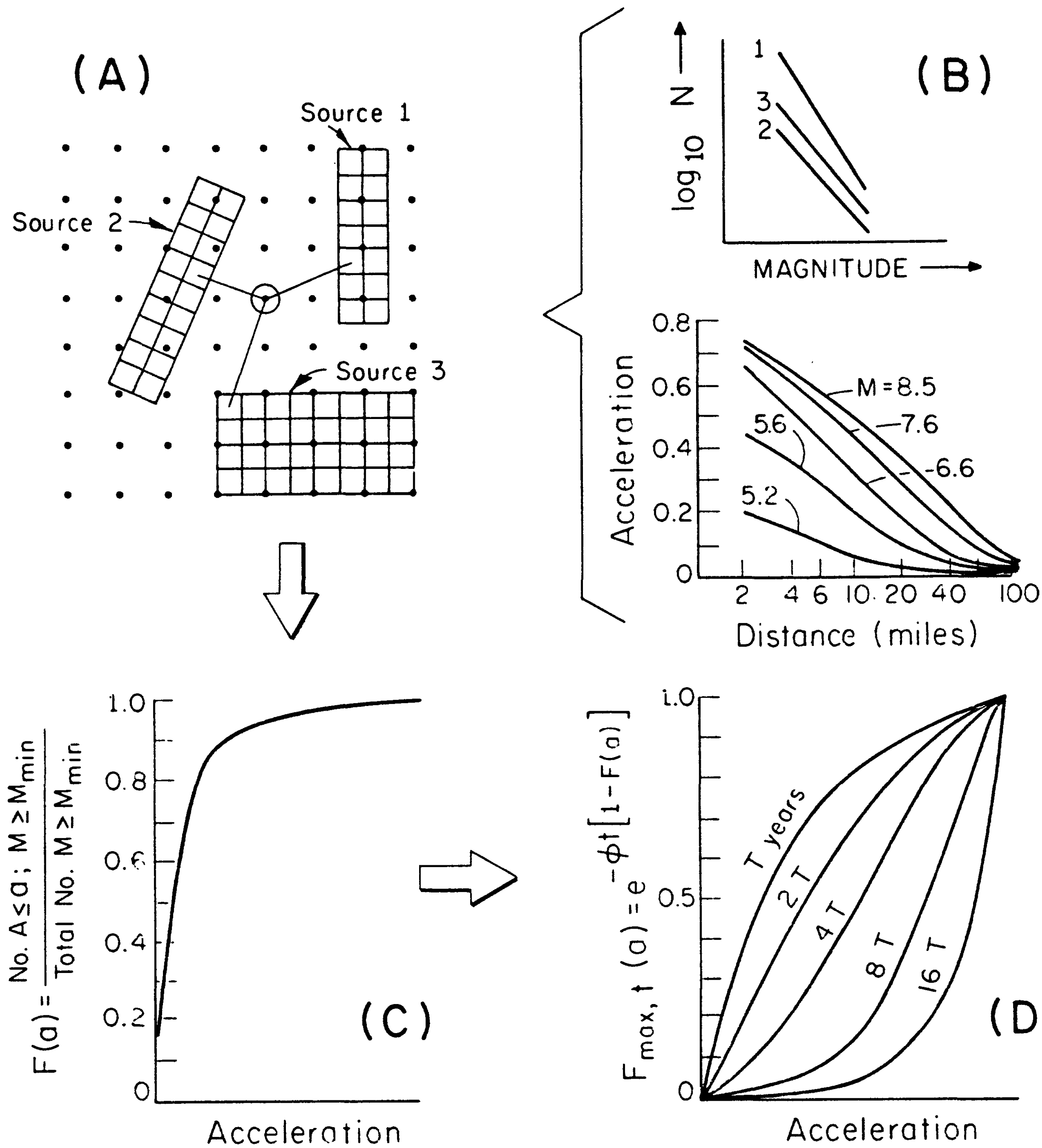


Figure 10. Schematic illustration of types of seismogenic zones and how they and other information are modeled in probabilistic analyses. Sources can be modeled as points, lines, areas, and combinations of all three.

The following general rules are utilized:

- o A line source model is used when earthquake locations are constrained along an identified fault or fault zone.
- o An area source is used when the seismicity occurs uniformly throughout a region.
- o A set of line sources is used to model a large zone of deformation where earthquake rupture occurs randomly but with a perferred orientation.
- o An area source encompassing a collection of line sources is used when large events are assumed to occur only on identified active faults and smaller events are assumed to occur randomly within the region.

Study of Seismic Wave Attenuation - The geologist, seismologist, and geotechnical engineer work separately or collectively to define the regional seismic wave attenuation function. The attenuation function is difficult to define (Hays, 1980). One of the most important factors in precise specification of the level of spatial variation of the design earthquake ground motion precisely is knowledge of how body and surface waves attenuate from the source in various geographic regions of the United States. Research on seismic wave attenuation has proceeded slowly because it is very difficult to quantify the physical parameters of the crust and upper mantle causing attenuation. Also, the present strong-ground-motion data are limited geographically to California, and few empirical data exist elsewhere to define the effects of such path parameters as the natural anisotrophy and inhomogeneity of the Earth and the loss mechanisms (geometrical spreading, absorption, scattering). However, one fact has emerged clearly from comparison of isoseismal maps of earthquakes in the Eastern and Western United States--seismic waves attenuate much more rapidly in the Western United States than in the Eastern United States (Figure 11).

Bedrock Ground-Shaking Hazard - To evaluate the ground-shaking hazard at a site, the basic data on seismicity, paleoseismicity, earthquake potential, seismogenic zones, and seismic wave attenuation are integrated and utilized in either a deterministic or a probabilistic methodology. Bedrock is used as the reference if soils data are limited. When the deterministic approach is used to evaluate the ground-shaking hazard, the seismic design parameters are estimated for earthquakes of specific magnitudes occurring at specific distances from a construction site or lifeline system. The value of magnitude is typically the maximum magnitude that is judged capable of occurring in a seismogenic zone. When the probabilistic method is used, the probability of exceedance of different levels of ground motion in a given exposure time is calculated, considering the occurrence of earthquakes of all possible magnitudes and all possible distances from the site of a building or a lifeline system. The procedure is illustrated schematically in Figure 10.

The maps shown in Figures 12-15 describe the beckrock ground-shaking hazard in the conterminous United States in terms of peak horizontal bedrock ground acceleration and velocity. These maps take into account the differences in rate of seismicity, the geologic characteristics of seismogenic zones, and the rates of seismic wave attenuation in the Eastern and Western united States. The maps are from Algermissen et al. (1982). In Figure 12, the ground-shaking

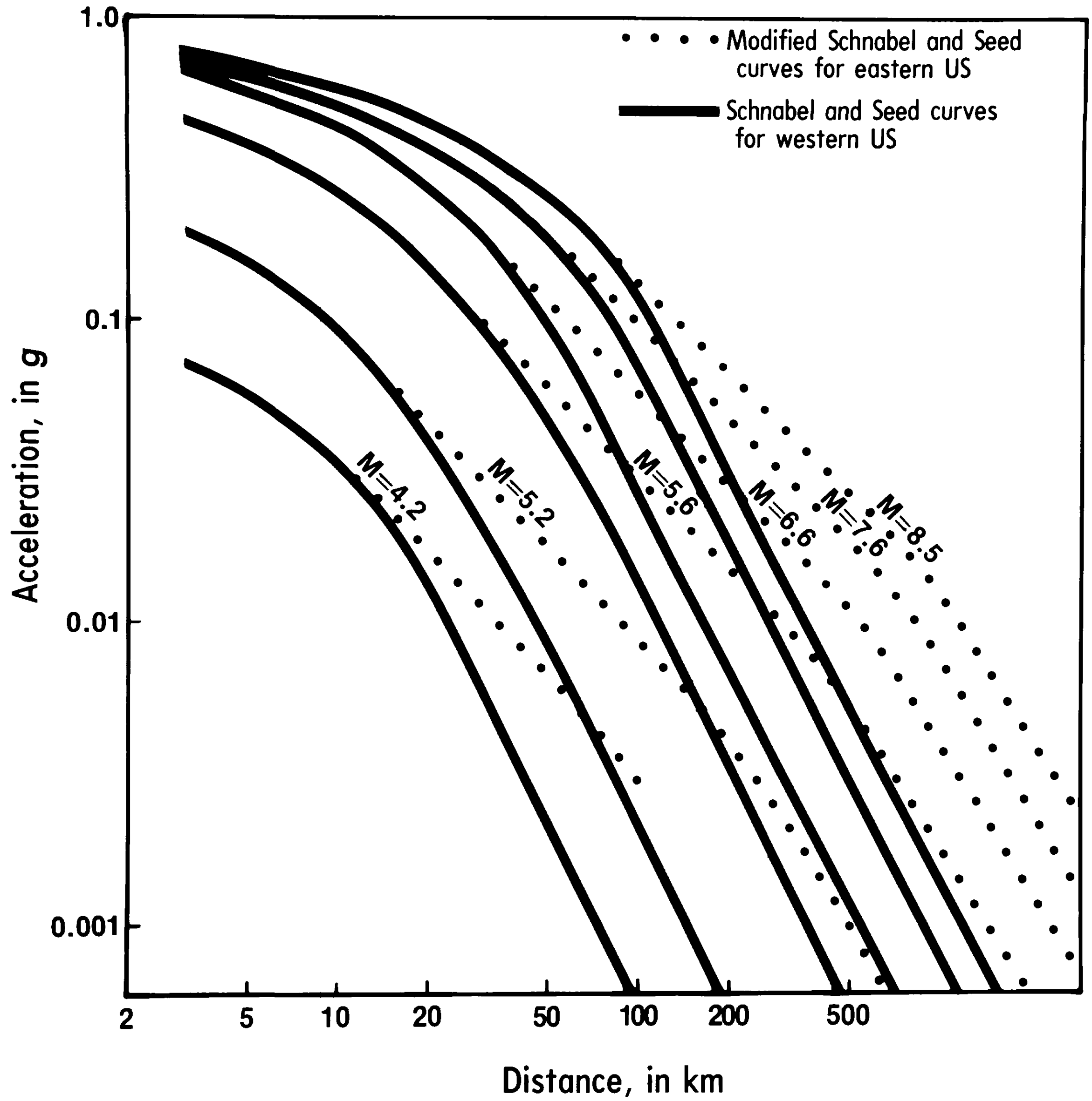


Figure 11. Graph showing differences in rates of bedrock seismic-wave attenuation in the western (Schnabel and Seed, 1973) and eastern (Algermissen and Perkins, 1976) United States.

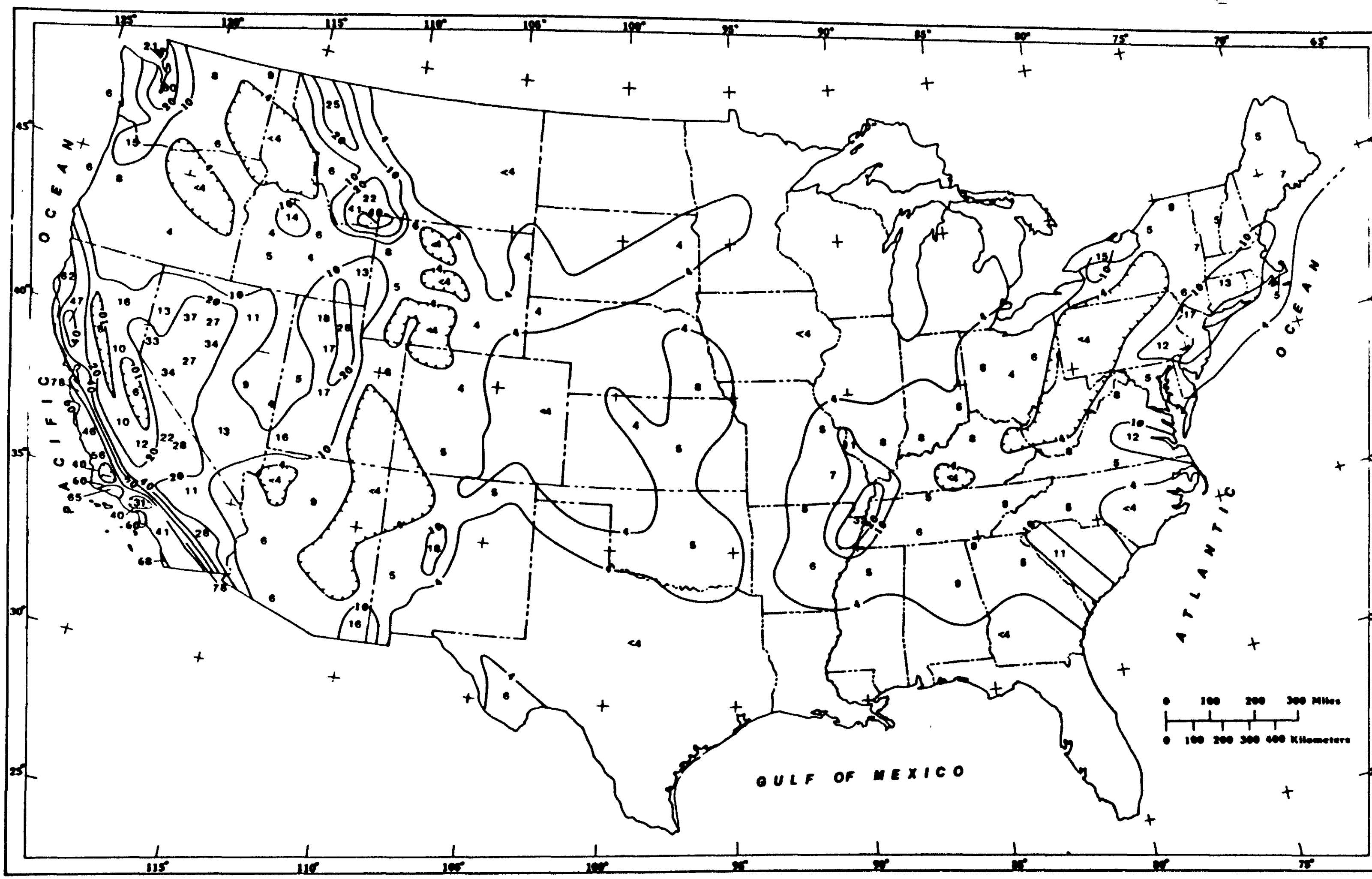


Figure 12. Map showing maximum levels of peak horizontal bedrock acceleration expected in the United States in an exposure time of 50 years with a 90 percent probability of nonexceedance. (Algermissen et al, 1982)

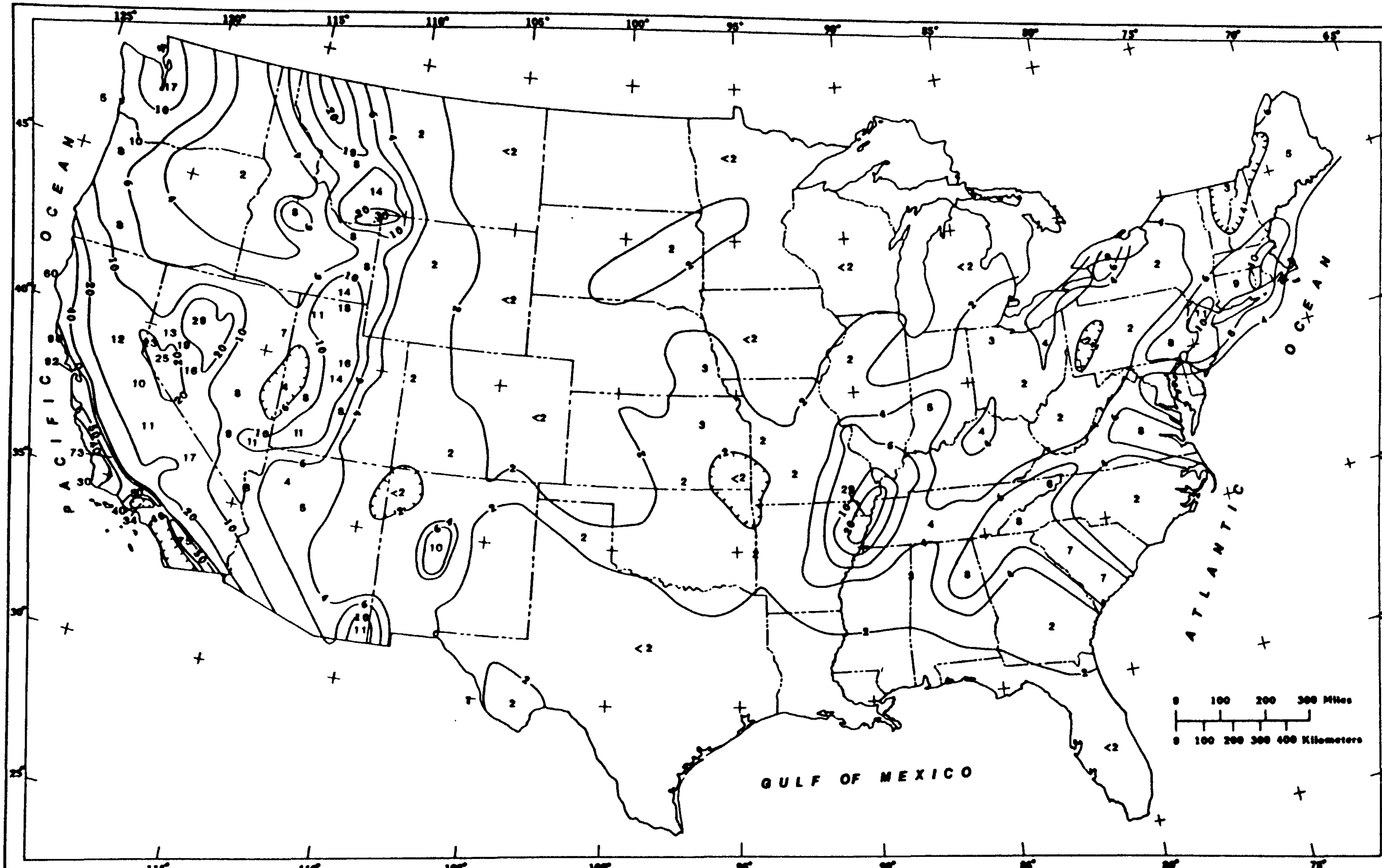


Figure 13. Map showing maximum levels of peak horizontal bedrock velocity expected in the United States in an exposure time of 50 years with a 90 percent probability of nonexceedance. (Algermissen et al, 1982)

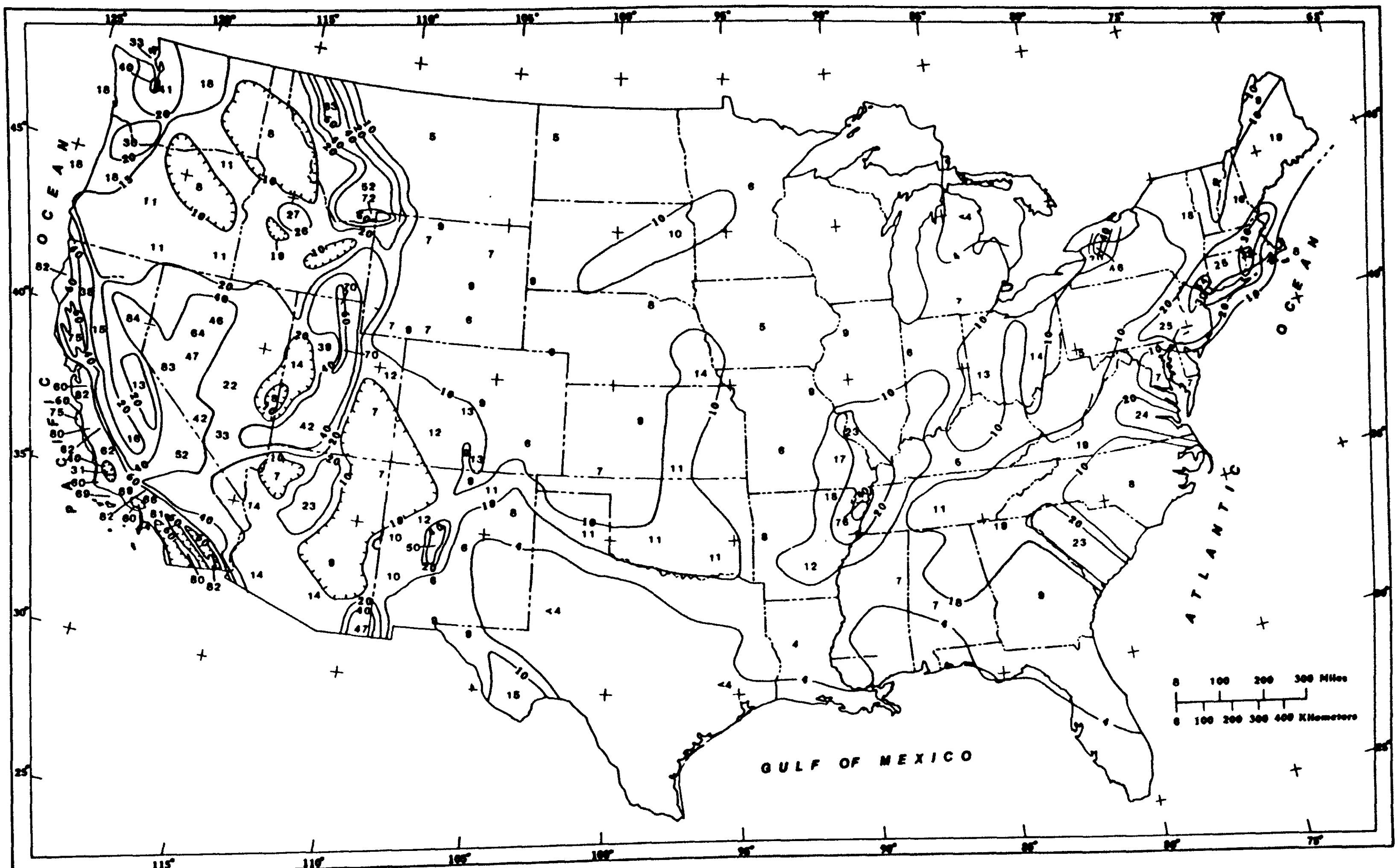


Figure 14. Map showing maximum levels of peak horizontal bedrock acceleration expected in the United States in an exposure time of 250 years with a 90 percent probability of nonexceedance. (Algermissen et al, 1982)

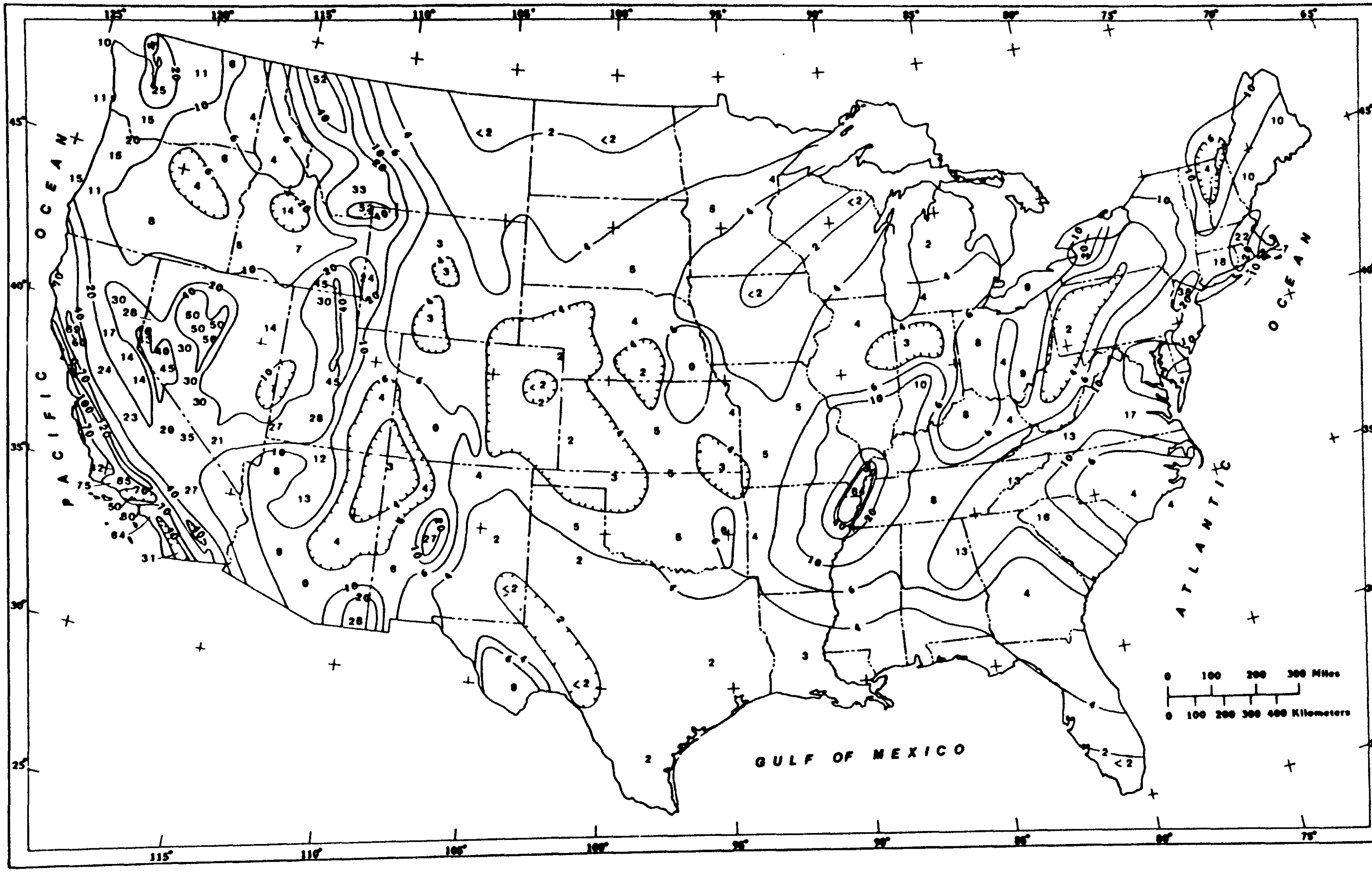


Figure 15. Map showing maximum levels of peak horizontal bedrock velocity expected in the United States in an exposure time of 250 years with a 90 percent probability of nonexceedance. (Algermissen et al, 1982)

hazard is depicted in terms of contoured values of the peak horizontal gorund accelration expected in a 50-year exposure time at sites underlain by bedrock. The values of peak acceleration shown by the contours have a 90 percent probability of nonexceedance (10 percent probability of exceedance) in 50 years. Such a map is useful for selecting seismic design parameters for ordinary buildings or lifelines; that is, buildings or lifeline systems having a useful life of about 50 years. Maps of acceleration for longer exposure times, such as 250 years (Figure 13), may be used when siting critical structures, such as hospitals,or critical lifelines, such as a communication center, that have about the same useful life but that are required to remain functional after an earthquake. Consideration of exposure times longer than 250 years may be required in the case of large dams, nuclear powerplants, and waste repositories (and certain lifeline systems) even though the useful life may be as short as 40 years (as in the case of a nuclear powerplant) or as long as several thousand years as in the case of high-level radioactive waste repositories). The values of peak bedrock acceleration and velocity can be used to estimate the smooth response spectra (Hays, 1980). The effects of local soil amplification are considered below (See, 1975).

<u>Studies of Site Amplification</u> - These studies define the seismic design parameters more precisely and help to quanitify the spatial variability of ground shaking. Experience and data have shown that strong contrasts between the soil and rock in the shear-wave velocity between the near-surface soil and underlying rock comprising the upper 30-60 meters (100-200 feet) can cause the gorund motion to be increased in a narrow range of frequencies. The peak amplitudes, spectral composition, and duration of shaking can be incrased significantly when the velocity contrast is a factor of 2 or more and the

thickness of the soil column is as little as 10-30 meters (30-100 feet). Scientists and engineers still are working to resolve technical issues that center mainly on the question of whether linear ground response occurs at high levels of peak ground acceleration and (or) dynamic shear strain (Murphy and West, 1974; Hays, 1983; Kennedy and others, 1984). All researchers agree, however, that the propagation path and the local soil-rock column contribute significantly to spatial variability of ground motion.

Study of the Potential for Liquefaction and Landslides - Liquefaction is restricted to certain geologic and hydrologic environments, mainly areas where sands and silts were deposited in the last 10,000 years and where ground water is within 10 meters (30 feet) of the surface. As a general rule, the younger and looser the sediment and the higher the water table, the more susceptible a sandy soil is to liquefaction (Figure 16).

Liquefaction causes three types of gorund failures--lateral spreads, flow failures, and loss of bearing strength. Liquefaction also enhances ground settlement. Lateral spreads develop on gentle slopes (between 0.3 and 3 degrees) and can have horizontal movements of 3-5 meters (10-15 feet), but, where slopes are particularly favorable and the duration of ground shaking is long, lateral spreads can move as much as 30-45 meters 9100-150 feet). During the 1964 Prince William Sound, Alaska, earthquake, lateral spreads caused damage to more than 200 bridges. Lateral spreads in the 1906 San Francisco earthquake caused extensive damage to pipelines, reducing the city's capability to fight the fires that broke out after the earthquake.

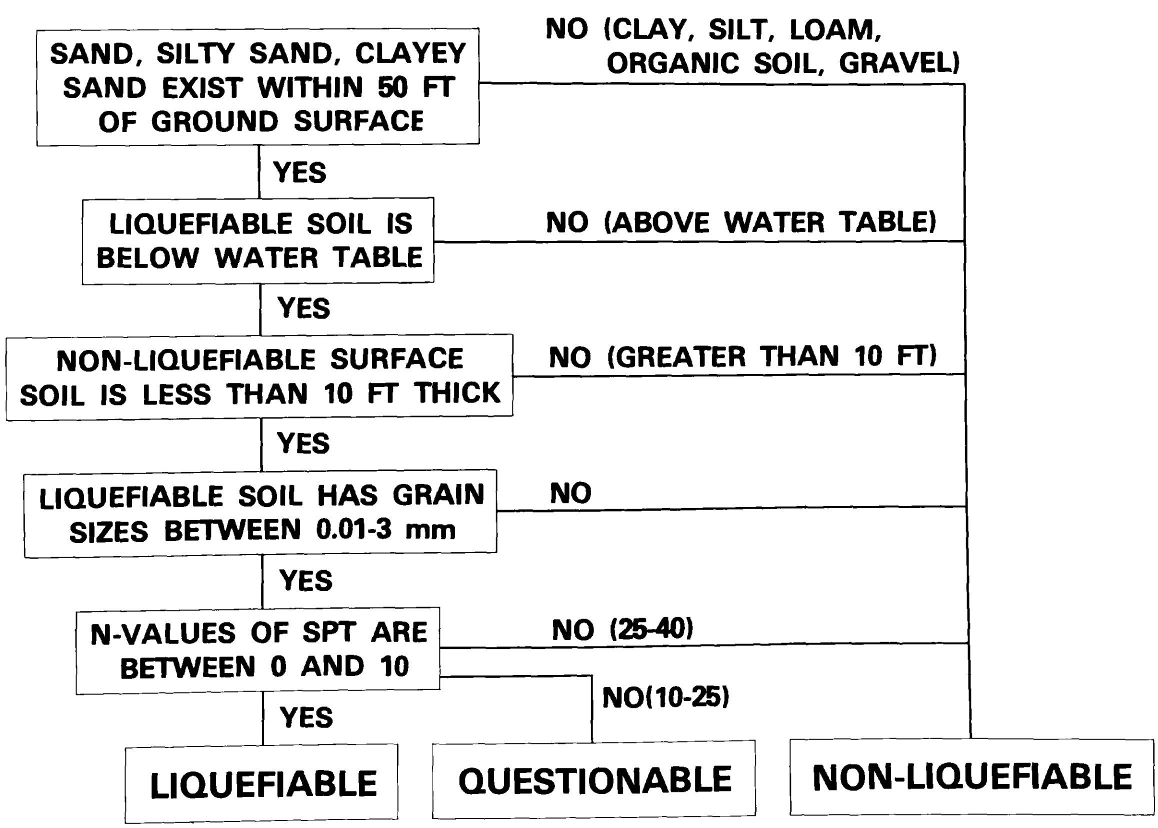


Figure 16. Flow diagram that can be used when evaluating the potential for liquefaction at a site. SPT denotes the Standard Penetration Test. Buried lifelines are especially susceptible to liquefaction.

Flow failures, consisting of soil and blocks of intact material riding on a layer of liquefied soil, are the most catastrophic types of ground failure caused by liquefaction. These failures commonly move several tens of feet and, if geometric conditions permit, several tens of miles. Flows travel at velocities as great as many tens of miles per hour. Flow failures usually form in loose saturated sands or silts on slopes greater than 3 degrees.

Flow failures can originate either underwater or on land. Many of the largest and most damaging flow failures have taken place underwater in coastal areas; for example, submarine flow failures carried away large sections of port facilities at Seward, Whittier, and Valdez, Alaska, during the 1964 Prince William Sound, Alaska, earthquake. These flow failures, in turn, generated large sea waves that overran parts of the coastal areas, causing additional damage and casualties. Flow failures on land have been catastrophic, especially in other countries, for example, the 1920 Kansu, China, earthquake induced several flow failures of as much as 1 mile in length and breadth, killing an estimated 200,000 people.

Past experience has shown that several types of landslides have taken place in conjunction with earthquakes. The most abundant types of earthquake-induced landslides are rock falls and slides of rock fragments that form on steep slopes. Although less abundant, shallow debris slides, which form on steep slopes, and soil and rock slumps and block slides, which form on moderate to steep slopes also take place. Large earthquake-induced rock avalanches, soil avalanches, and underwater landslides can be very destructive. One of the most spectacular examples occurred during the 1970 Peruvian earthquake when a single rock avalanche triggered by the earthquake killed more than 18,000 people. The 1959 Hebgen Lake, Montana, earthquake triggered a similar, but less spectacular, landslide that formed Erthquake Lake and killed 26 people. Many loess slopes failed during the 1811-12 New Madrid, Missouri, earthquakes.

Evaluation of the landslide potential in a region requires identification and careful analysis of the physical properties of the site that correlate with the failure process. All landslides involve the failure of earth materials under shearing stress. Initiation of the failure process is related directly to the following factors: parameters that contribute to an increase in shear stress and those that contribute to a decrease in shear strength.

Actions for reducing damage due to landslides include avoidance, engineering techniques to stabilize the landslide-prone area, zoning to regulate design, and construction.

Loss of Bearing Strength - When the soil supporting a building or some other structure liquefies and loses strength, large deformations cn occur within the soil, allowing the structure to settle and tip. The most spectacular example of bearing-strength fialures took palce during the 1964 Niigata, Japan, earthquake. During the event, several four-story buildings of the Kwangishicho apartment complex tipped as much as 60 degress. Most of the buildings were later jacked back into an upright position, underpinned with piles, and reoccupied.

Soils that liquefied at Niigata typify the subsurface geometry required for liquefaction-caused bearing failures--a layer of saturated, cohesionless soil (sand or silt) extending from near the ground surface to a depth of about the width of the building.

4 CONCLUSIONS AND RECOMMENDATIONS

Although the literature on lifeline earthquake engineering has grown considerably sinece the 1971 San Fernando, California, earthquake (the primary triggering event for lifeline earthquake engineering), many aspects of earthquake-resistant design for lifelines are still in the research phase. Research programs are focusing on the following topics:

1. A probabilistic representation of the two categories of seismic hazards, permanent ground movements and dynamic ground shaking that are most important in guiding the selection of appropriate seismic design parameters. The engineer needs explicit information and answers to the questions--where, how big, why, how often, and how do the effects vary in space and time.

2. Knowledge of the range of forces, displacements and frequencies of vibration generated by permanent ground displacements and dynamic ground shaking in earthquakes of various magnitudes. The engineer needs to know the sensitivity of each lifeline system to the various force- and displacement-controlled excitations to select the most appropriate seismic design paramters.

3. Empirical, analytical, and experimental data showing how the characteristics of permanent ground movements and dynamic ground shaking cause damage to a lifeline system. The engineer needs to know what the cause and

effect relations are for each lifeline system. Such knowledge comes from postearthquake investigations, strong-ground-motion arrays, computer modeling, testing of scale models, and laboratory and field experiments.

The research topics identified above are vitally important to the field of lifeline earthquake engineering. Research results are needed now to improve the capability of urban communities located in earthquake-prone areas throughout the Nation to build lifeline systems that will remain functional after the inevitable, potentially damaging earthquake occurs. These results are needed for design and construction of new lifeline systems as well as for guidance in the repair and strengthening of existing lifeline systems.

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6 GLOSSARY

Accelerogram. The record from an accelerometer showing acceleration as a function of time. The peak acceleration is the largest value of acceleration on the accelerogram.

Acceptable Risk. A probability of occurrences of social or economic consequences due to earthquakes that is sufficiently low (for example in comparison to other natural or manmade risks) as to be judged by authorities to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions.

Active fault. A fault is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future. This active state exists independently of the geologists' ability to recognize it. Geologists have used a number of characteristics to identify active faults, such as historic seismicity or surface faulting, geologically recent displacement inferred from topography or stratigraphy, or physical connection with an active fault. However, not enough is known of the behavior of faults to assure identification of all active faults by such characteristics. Selection of the criteria used to identify active faults for a particular purpose must be influenced by the consequences of fault movement on the engineering structures involved.

Attenuation. A decrease in seismic signal strength with distance which depends on geometrical spreading and the physical characteristics of the transmitting medium that cause absorption and scattering.

Attenuation law. A description of the average behavior of one or more characteristics of earthquake ground motion as a function of distance from the source of energy.

b-value. A parameter indicating the relative frequency of earthquakes of different sizes derived from historical seismicity data.

Capable fault. A capable fault is a fault whose geological history is taken into account in evaluating the fault's potential for causing vibratory ground motion and/or surface faulting.

Design earthquake. A specification of the ground motion at a site based on integrated studies of historic seismicity and structural geology and used for the earthquake-resistant design of a structure.

Design spectra. Spectra used in earthquake-resistant design which correlate with design earthquake ground motion values. A design spectrum is typically a broad band specturm having broad frequency content. The design spectrum can be either site-independent or site-dependent. The site-dependent spectrum tends to be less broad band as it depends at least in part on local site conditions.

Design time history. One of a family of time histories used in earthquake-resistant design which produces a response spectrum enveloping the smooth design spectrum, for a selected value of damping.

Duration. A description of the length of time during which ground motion at a site exhibits certain characteristics such as being equal to or exceeding a specified level of acceleration such as 0.05g.

Earthquake hazards. Natural events accompanying an earthquake such as ground shaking, ground failure, surface faulting, tectonic deformation, and inundation which may cause damage and loss of life during a specified exposure time. See earthquake risk.

Earthquake risk. The probability that social or economic consequences of earthquakes, expressed in dollars or casualties, will equal or exceed specified values at a site during a specified exposure time.

Earthquake waves. Elastic waves (P, S, Love, Rayleigh) propagating in the Earth, set in motion by faulting of a portion of the Earth.

Effective peak acceleration. The value of peak ground acceleration considered to be of engineering significance. It can be used to scale design spectra and is often determined by filterng the ground-motion record to remove the very high frequencies that may have little or no influence upon structural response.

Epicenter. The point on the Earth's surface vertically above the point where the first fault rupture and the first earthquake motion occur.

Exceedence probability. The probability (for example, 10 percent) over some exposure time that an earthquake will generate a level of ground shaking greater than some specified level.

Exposure time. The period of time (for example, 50 years) that a structure or facility is exposed to earthquake hazards. The exposure time is sometimes related to the design lifetime of the structure and is used in seismic risk calculations.

Fault. A fracture or fracture zone in the Earth along which displacement of the two sides relative to one another has occurred parallel to the fracture. See Active and Capable faults.

Focal depth. The vertical distance between the earthquake hypocenter and the Earth's surface.

Ground motion. A general term including all aspects of motion; for example, particle acceleration, velocity, or displacement; stress and strain; duration; and spectral content generated by an earthquake, a nuclear explosion, or another energy source.

Intensity. A numerical index describing the effects of an earthquake on the Earth's surface, on man, and on structures built by him. The scale in common use in the United States today is the Modified Mercalli scale of 1931 with intensity values indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are summarized below.

I. Not felt--or, except rarely under specially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body of striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink or clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practially all, outdoors by many or most; outdoors direction estimated. Awakened many or most. Frightened few--slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes and glassware to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors and shutters abruptly. Pendulum clocks stopped, started or ran fast, or slow. Move small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees and bushes shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees and bushes shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Move furnishings of moderately heavy kind.

VII. Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows and furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches and trunks broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls, cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changes level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures, remained standing. Destroyed large well-built bridges by the wrecking of supporting piers or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipelines buried in each completely out of service.

XII. Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

Liquefaction. The primary factors used to judge the potential for liquefaction, the tranformation of unconsolidated materials into a fluid mass, are: grain size, soil density, soil structure, age of soil deposit, and depth to ground water. Fine sands tend to be more susceptible to liquefaction than silts and gravel. Behavior of soil deposits during historic earthquakes in many parts of the world show that, in general, liquefaction susceptibility of sandy soils decreases with increasing age of the soil deposit and increasing depth to ground water. Liquefaction has the potential of occurring when seismic shear waves having high acceleration and long duration pass through a saturated sandy soil, distorting its granular structure and causing some of the void spaces to collapse. The pressure of the pore water between and around the grains increases until it equals or exceeds the confining pressure. At this point, the water moves upward and may emerge at the surface. The liquefied soil then behaves like a fluid for a short time rather than as a soild.

Magnitude. A quantity characteristic of the total energy released by an earthquake, as contrasted to intensity that describes its effects at a particular place. Professor C. F. Richter devised the logarithmic scale for local magnitude (M_L) in 1935. Magnitude is expressed in terms of the motion that would be measured by a standard type of seismograph located 100 km from the epicenter of an earthquake. Several other magnitude scales in addition to M_L are in use; for example, body-wave magnitude (m_b) and surface-wave magnitude (M_S), which utilize body waves and surface waves, and local magnitude (M_L). The scale is theoretically open ended, but the largest known earthquakes have had M_S magnitudes near 8.9.

Region. A geographical area, surrounding and including the construction site, which is sufficiently large to contain all the geologic features related to the evaluation of earthquake hazards at the site.

Response spectrum. The peak response of a series of simple harmonic oscillators having different natural periods when subjected mathematically to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variations of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping.

Return period. For ground shaking, return period denotes the average period of time or recurrence interval between events causing ground shaking that exceeds a particular level at a site; the reciprocal of annual probability of exceedance. A return period of 475 years means that, on the average, a particular level of ground motion will be exceeded once in 475 years.

Risk. See earthquake risk.

Rock. Any solid naturally occurring, hard, consolidated material, located either at the surface or underlying soil. Rocks have a shear-wave velocity of at least 2,500 ft/sec (765 m/s) at small (0.0001 percent) levels of strain.

Seismic Microzoning. The division of a region into geographic areas having a similar relative response to a particular earthquake hazard (for example, ground shaking, surface fault rupture, etc.). Microzoning requires an integrated study of: 1) the frequency of earthquake occurrence in the region, 2) the source parameters and mechanics of faulting for historical and recent earthquakes affecting the region, 3) the filtering characteristics of the crust and mantle along the regional paths along which the seismic waves travel, and 4) the filtering characteristics of the near-surface column of rock and soil.

Seismic zone. A generally large area within which seismic design requirements for structures are uniform.

Seismotectonic province. A geographic area characterized by similarity of geological structure and earthquake characteristics. The tectonic processes causing earthquakes are believed to be similar in a given seismotectonic province.

Source. The source of energy release causing an earthquake. The source is characterized by one or more variables, for example, magnitude, stress drop, seismic moment. Regions can be divided into areas having spatially homogeneous source characteristics.

Strong motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or in earthquake-resistant design of structures.