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U.S. GEOLOGICAL SURVEY

An Introduction to Technical Issues in the Evaluation of Seismic Hazards for Earthquake-resistant Design

by

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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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FOREWORD

This draft technical report "An Introduction to Issues in the Evaluation of Seismic Hazards in Earthquake-resistant Design" was developed by Subcommittee 3, "Evaluation of Site Hazards," a part of the Interagency Committee on Seismic Safety in Construction (ICSSC). This is the fourth report of the Subcommittee; the other three reports addressed surface faulting, earthquake-induced ground failure, and selection of ground motions for the design of large dams. The membership of the Subcommittee during the preparation of this report was:

S. T. Algermissen	U.S. Geological Survey
Riley Chung	National Bureau of Standards
John M. Ferritto	Naval Civil Engineering Laboratory
William H. Hakala	National Science Foundation
Julius G. Hansen	Department of Labor
Walter W. Hays	U.S. Geological Survey
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Peter V. Patterson	Department of Agriculture
David M. Perkins	U.S. Geological Survey
Leon Reiter	Nuclear Regulatory Commission
Lawrence Salomone	National Bureau of Standards
Kuppusmay Thirumalai	National Science Foundation
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 1985 and 1986. 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 the author:

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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).

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AN INTRODUCTION TO TECHNICAL ISSUES IN THE EVALUATION OF SEISMIC HAZARDS FOR EARTHQUAKE-RESISTANT DESIGN

ABSTRACT

This report is one of a series recommending procedures for evaluating the seismc hazards of ground shaking, surface fault rupture, tectonic deformation, and earthquake-induced ground failure at Federal construction sites. These reports are issued for a period of trial use and comment by Federal agencies. The purpose of this report is to introduce earth scientists, architects, engineers, policy recommenders, and policymakers to the technical issues that arise in the evaluation of seismic hazards for earthquake-resistant design. The scope includes: 1) identification of the technical issues that must be addressed when evaluating seismic hazards in order to determine WHERE? WHY? HOW BIG? HOW OFTEN? WHAT ARE THE PHYSICAL EFFECTS? AND WHAT ARE THE OPTIONS FOR DESIGN TO WITHSTAND THESE EFFECTS? 2) specification of the technical issues that need resolution in order to eliminate controversy and to clairfy selection of the appropriate seismic-design parameters, related to amplitude, spectral composition, and duration, 3) discussion of the steps that can be taken to ensure an adequate margin of safety (conservatism), and 4) citation of the sources of data and the basic literature references. Three recommendations are made: 1) each Federal agency shall establish the level of acceptable risk for their structures and facilities using either deterministic or probabilistic methodologies, 2) each Federal agency shall attempt to resolve technical issues by acquiring the appropriate data or performing analyses to limit the range of possible hypotheses, and 3) when a tecnnical issue cannot be resolved, the Federal agency shall introduce an appropriate level of conservatism in the seismic design.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This report was prepared by Subcommittee 3, "Evaluation of Site Hazards," a part of the Interagency Committee on Seismic Safety in Construction (ICSSC). ICSSC was created in 1978 and has two primary objectives: 1) to stimulate and coordinate earthquake hazards reduction activities within the Federal Government, and 2) to create a common set of criteria, guidelines, standards, and codes which Federal agencies can use to evolve a standard practice that will improve the seismic safety of existing and new Federal construction. Through ICSSC's activities, the Federal Government has an opportunity to establish a standard practice for evaluating seismic hazards throughout the Nation, an important part of the process of earthquake-resistant design.

This report is one of a series of reports recommending procedures for evaluating seismic hazards at new construction sites as well as for existing structures and facilities. These reports are issued for a period of trial use and comment by Federal agencies before being adopted by ICSSC and recommended as standard practice by agencies involved in Federally funded, assisted, and regulated construction. The objective of this report is to give earth scientists, architects, engineers, policy recommenders, and policymakers a consistent understanding of the technical steps that are involved in the evaluation of seismic hazards and the selection of seismic-design parameters for use in the earthquake-resistant design of various Federal structures and facilities (Figures 1-4).

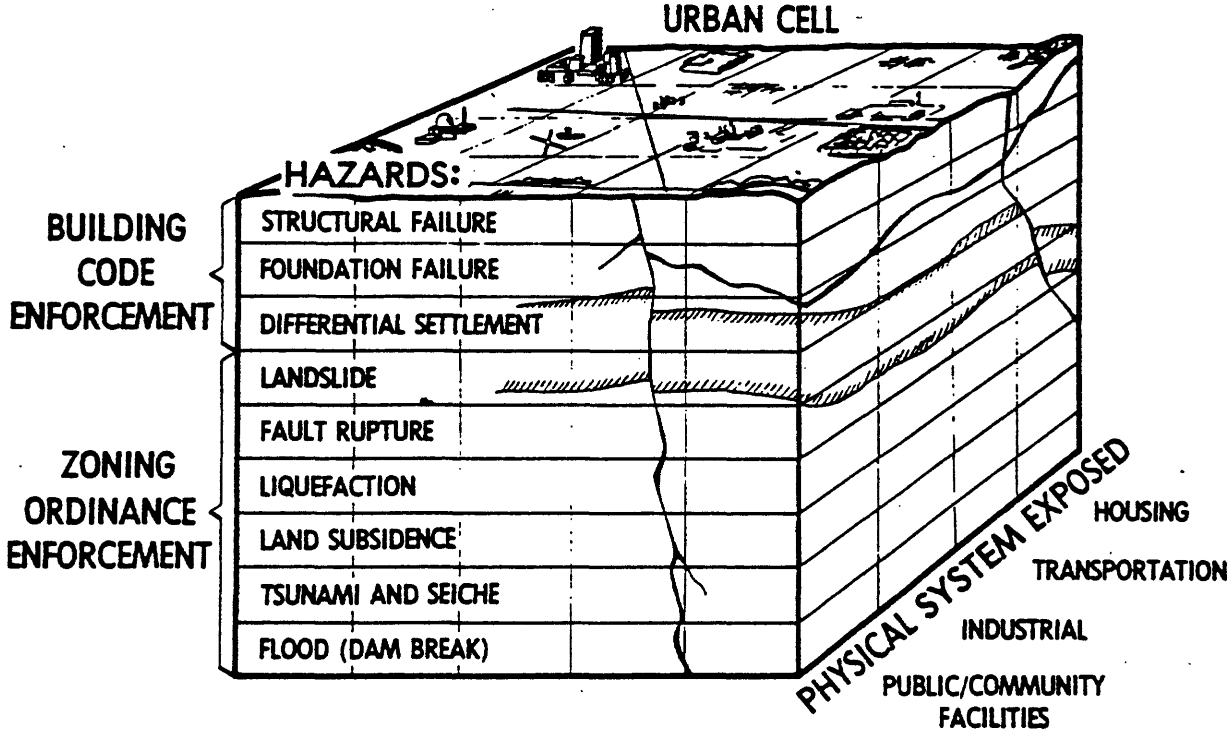

Figure 1.--Schematic illustration of a typical community having federally funded, assisted, and regulated construction exposed to the seismic hazards of ground shaking, surface fault rupture, tectonic deformation, and earthquake-induced ground failure. For Federal construction sites, the seismic hazards need to be evaluated in a standard manner, seeking answers to the following technical questions: 1) Where have seismic hazards occurred in the past and where are they occurring now?, 2) Why are they occurring?, 3) How often do they occur?, 4) What are their spatial and temporal physical effects?, and 5) What are the options for earthquake-resistant design to withstand these effects? The seismic design parameters that are appropriate for each structure or facility are determined from consideration of the type of structure or facility, its functional lifetime and uses, and its exposure and potential vulnerability from each of the various seismic hazards. The level of acceptable risk for each structure or facility is determined as a part of the overall process of evaluating seismic hazards and assessing the risk.

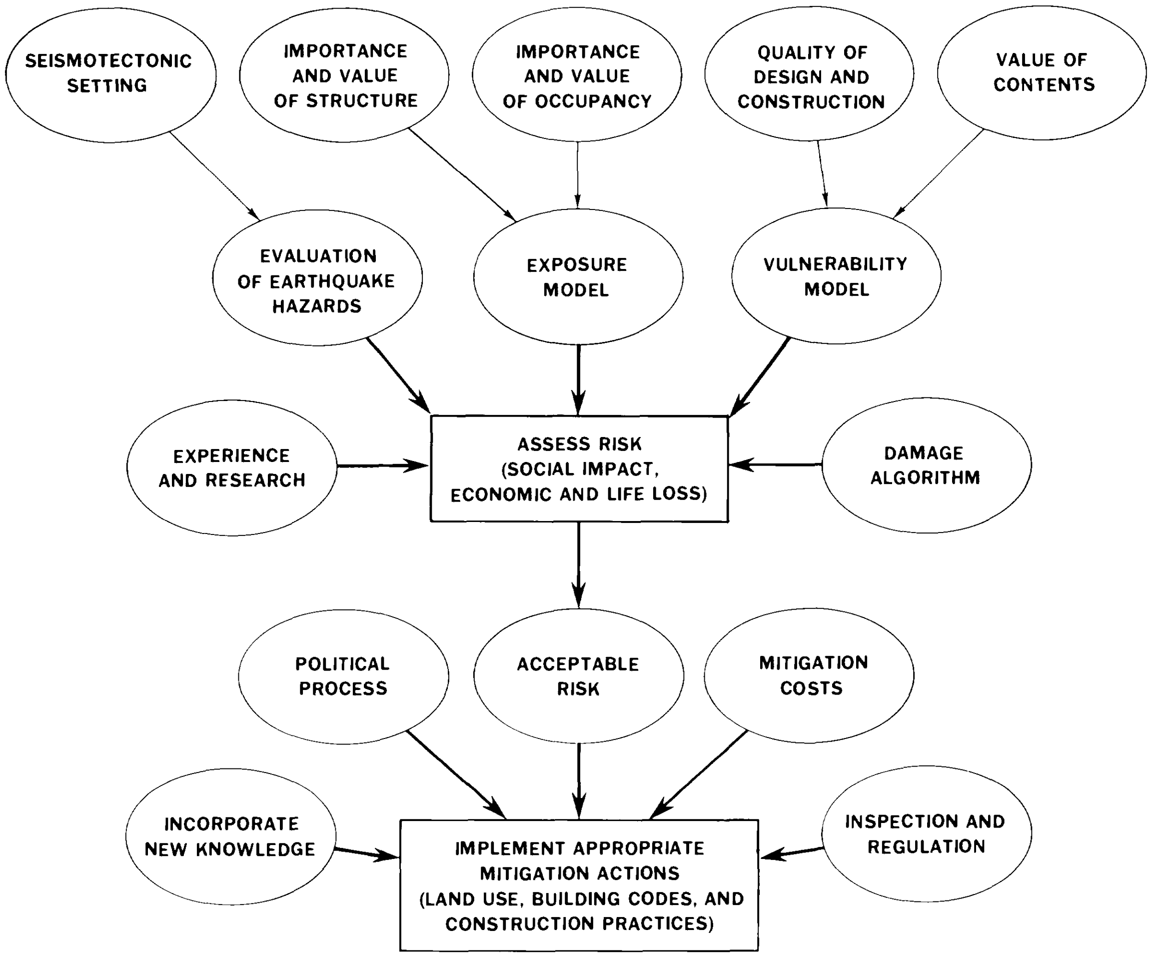

Figure 2.--Flow diagram showing the types of evaluations that are involved in earthquake-resistant design (after Petak and Atkisson, 1982).

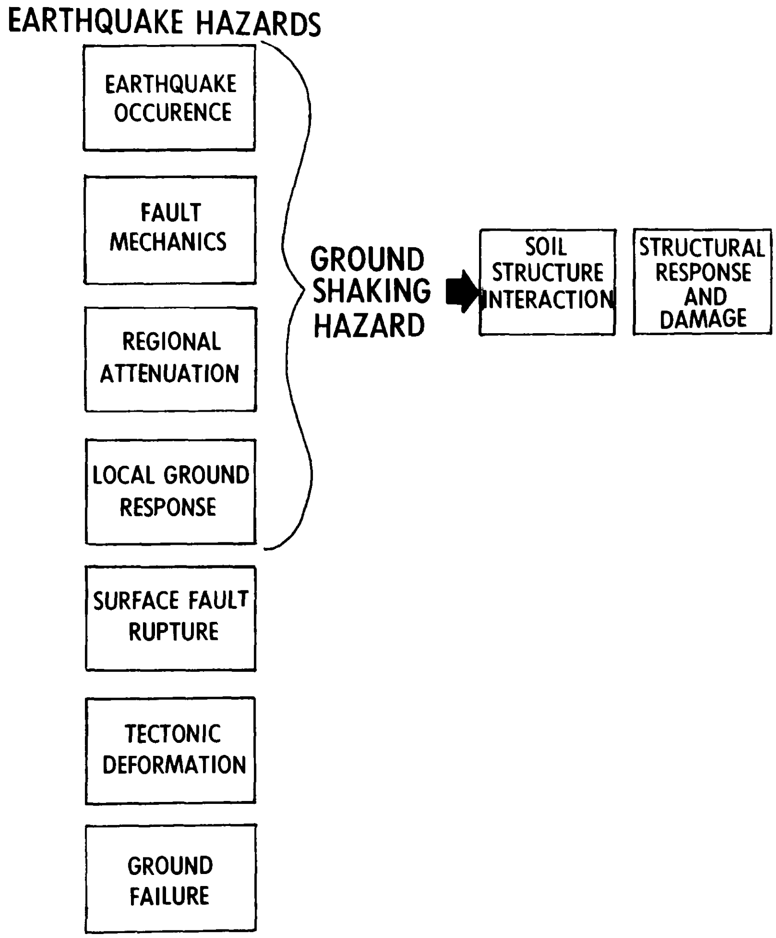

Figure 3.--Schematic illustration of the generic steps involved in evaluating the seismic hazards of ground shaking, surface fault rupture, and earthquake-induced ground failure.

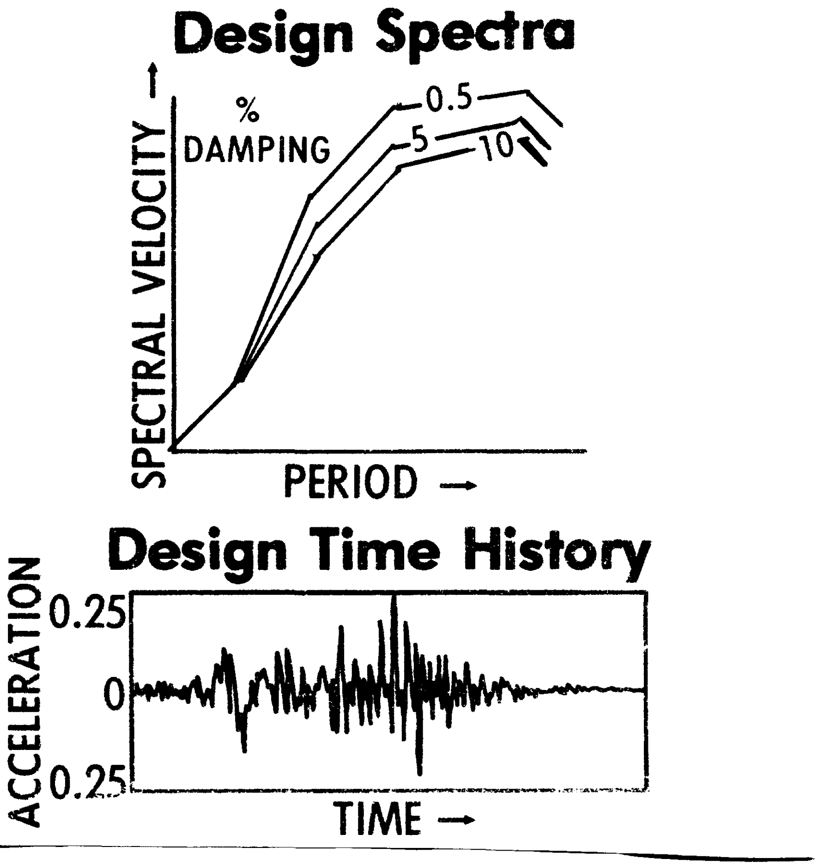

Figure 4.--Schematic illustration of the design time history and elastic design response spectra. Seismic-design parameters such as these are used to define the ground motion input in the design of a nuclear power plant and other important structures.

1) The kinds of technical questions that must be addressed when evaluating seismic hazards in order to determine WHERE? WHY? HOW BIG? HOW OFTEN? WHAT ARE THE PHYSICAL EFFECTS? and WHAT ARE THE OPTIONS FOR DESIGNING TO WITHSTAND THESE EFFECTS?

2) The technical issues that need resolution in the evaluation of seismic hazards. These issues cause controversy and affect decisions about the seismic-design parameters.

3) The steps that can be taken to ensure an adequate margin of safety (conservatism) in the earthquake-resistant design of important structures and facilities, and

4) The requirements, for data, the sources of data, and the basic literature references.

Because the evaluation of seismic hazards is a complex technical subject, this report is designed to enable readers to have a broad understanding of the technical concepts. The reader who wishes additional details is encouraged to refer to the pertinent references. A glossary of terms is included in the report to facilitate standard usage of the technical terms.

This report will be combined with the three prior reports published and distributed by Subcommittee 3 for trial use and comment by Federal agencies involved in Federally funded, assisted, and regulated construction. The reports are: 1) **Evaluation of earthquake-induced ground failure** (Ferritto, 1982), 2) **Evaluation of potential surface faulting and other tectonic**

deformation (Bonilla, 1982), and 3) **Considerations in selecting earthquake ground motions for the engineering design of large dams** (Krinitzsky and Marcusson, 1983). Other reports are also being prepared by Subcommittee 3 to facilitate the evaluation of seismic hazards.

In this report, the term seismic hazards describes physical phenomena accompanying an earthquake, such as ground shaking, surface fault rupture, tectonic deformation, earthquake-induced ground failure (liquefaction and landslides), seiches, and tsunamis. The term seismic risk refers to the expected loss (economic losses, loss of function, loss of confidence, fatalities, and injuries) from a seismic hazard. Each seismic hazard is described below:

1) Ground motion or ground shaking - Ground shaking refers to the amplitude, frequency, and duration of the vibration of the ground produced by seismic waves arriving at a site, independent of the structure. The frequency range of interest in earthquake-resistant design is 0.1-20 Hertz. Ground shaking will cause damage to structures and facilities unless they are designed and constructed to have a lateral-force-resisting system that will withstand the vibrations that coincide with the natural frequencies of the structure. Structures and facilities are generally more susceptible to damage from the forces and deformations caused by horizontal ground shaking than from vertical ground shaking. Ground shaking can also trigger ground failure.

   Peak ground acceleration, response spectra, and duration are the parameters used most frequently in earthquake-resistant design to characterize ground motion. 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 are typically 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 problems with use of instrumental peak ground acceleration are: 1) 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 2) elastic response spectra anchored to the instrumental peak ground acceleration tend to overestimate the actual damage to a structure because the effect of the duration of strong ground motion and the number of cycles of inelastic response is not incorporated. The maximum Modified Mercalli Intensity (MMI) is used when instrumental data are not available. Under certain conditions, the structure can modify the ground motion through the phenomenon of soil-structure interaction.

Evaluation of the ground-shaking hazard is complex and requires consideration of the earthquake occurrence and the physical effects of the source, propagation path, and local site geology. Deterministic and probabalistic methods are used in the evaluation of the ground-shaking hazard and the determination of the appropriate seismic-design parameters.

2) Surface faulting - Surface faulting is the offset or tearing of the ground surface by differential movement across a fault during an earthquake. Not all earthquakes cause surface faulting which is typically limited to a

linear zone. In the Eastern United States, no historic earthquakes, except possibly the 1811-1812 New Madrid earthquakes, have caused surface faulting; whereas, surface faulting has occurred at many locations in the Western United States from earthquakes generally having magnitudes of 5.5 and greater (Bonilla, 1982).

3) Tectonic deformation - Tectonic deformation includes: 1) tilting, uplift, and downwarping; 2) fracturing, cracking, and fissuring; 3) compaction and subsidence; and 4) 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 an earthquake having magnitudes greater than 8.0 (i.e., earthquakes such as the 1964 Prince William Sound, Alaska, earthquake).

4) Liquefaction - Liquefaction is a physical process that generally always takes place in a localized area during moderate to great earthquakes and leads to ground failure. Liquefaction has the potential of occurring when seismic shear waves, usually 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. When this occurs, 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 solid. Although uncommon, liquefaction can occur at distances of 50-100 miles from the epicenter of an earthquake and at levels of ground shaking as low as MM IV-VI.

5) Landslides - Landslides refer to downward and outward movement on slopes of rock, soil, artificial fill, and combinations of these materials. Landslides can be triggered by fairly low levels of ground motion during an earthquake if the slope is unstable.

6) Tsunami - A tsunami is a long-period water wave caused primarily by the sudden vertical movement of a large area of the seafloor during an undersea earthquake. Tsunamis travel at high speeds across oceans and may cause damage locally at coastal locations, as well as at very distant locations, by flooding, impact of waves, floating debris, and erosion of the foundations around structures. Tsunamis have impacted Hawaii many times in the historical past as well as locations in Alaska, along the West Coast, and in Puerto Rico and the Virgin Islands. Although tsunamis have not been a threat in historical times on the East Coast, they cannot be ruled out completely.

7) Seiche - A seiche is a term used to describe the oscillations of liquid excited by ground motion generated in an earthquake. The liquid can be in lakes or in storage tanks and other containers. Seiches can cause structural damage, as well as flooding, in low-lying areas.

1.2 THE FEDERAL GOVERNMENT'S CONCERN FOR SEISMIC SAFETY

The Federal Government is concerned about seismic safety because it has many structures and facilities throughout the Nation that are exposed, in varying degrees, to the seismic hazards of ground shaking, earthquake-induced ground failure, surface faulting, tectonic deformation, seiches, and tsunamis. The potential for loss to some of these structures and facilities is very great if they are adequately designed to withstand the forces of vibration and deformation generated by an earthquake. Thirty-five Federal agencies are directly or indirectly concerned with construction, ranging from: 1) direct construction of facilities for Federal use, 2) regulatory functions such as insuring mortgages, granting funds for construction, and approving construction plans, and 3) leasing of facilities. Of the approximately 450,000 Federal buildings in use today, approximately 400,000 are owned by the Government and 50,000 are leased. The General Services Administration (GSA) and the Department of Defense (DOD) administer the majority of these buildings with GSA controlling the nearly 10,000 buildings housing Federal agencies. A number of other agencies, including the Veterans Administration (VA), the Army Corps of Engineers (COE), the Bureau of Reclamation (BUREC), the National Park Service (NPS), and the Department of Transportation (DOT) have direct construction programs. The Department of Housing and Urban Development (HUD), Department of Health and Welfare (DHW), and Department of Education (DE) have major grant programs for constructing housing and medical facilities. Mortgage insurance programs for housing are administered by the Federal Housing Administration in HUD; the Farmers Home Administration (FHA) of the Department of Agriculture administers a direct loan program for the improvement or repair of rural homes and related facilities. The U.S. Nuclear Regulatory Commission (NRC) regulates construction and operation of nuclear power plants and certain other facilities.

The Federal agency having responsibility for construction also has responsibility for evaluating the seismic hazards and assessing the risk for new construction sites as well as existing structures and facilities.

Although most Federal agencies have procedures for evaluating seismic hazards and criteria for selecting seismic-design parameters for its structures and facilities, the practice varies widely both within individual agencies and between agencies.

1.3 TYPES OF FEDERAL STRUCTURES AND FACILITIES

A list of Federal structures and facilities requiring an evaluation of seismic hazards is given below to provide a perspective on the problem of earthquake-resistant design. The Federal responsibility encompasses:

1) Buildings - Ordinary buildings, which have a useful life of about 50 years, comprise most of the Federal inventory. In the private sector, the option exists to design buildings according to the seismic-design provisions of the Uniform Building Code or some other building code (e.g. BOCA). Many types of Federal buildings are not designed according to the seismic provisions of the current Uniform Building Code, but rather according to the provisions of another code. For example, GSA uses their "Design Guidelines," published in 1978, in the evaluation of seismic hazards and earthquake-resistant design of their buildings. National Bureau of Standards published "Analysis of Tentative Seismic Design Provisions for Buildings," in 1979 as a guide to standard practice; these provisions are undergoing trial designs to ascertain costs of earthquake-resistant design.

2) Hospitals - Hospitals, because of their importance, receive special consideration. The VA uses their "Earthquake Resistant Design

Requirements for VA Hospital Facilities," updated after the 1971 San Fernando earthquake and published in 1973, in the evaluation of seismic hazards for earthquake-resistant design of their hospitals. The Department of Defense also has developed special procedures for their hospitals. A hospital has a useful life of about 50 years, but it must remain functional during an earthquake.

3) Nuclear waste storage facilities - These facilities, which can have a useful life of thousands of years, are presently not licensed. Procedures for evaluating seismic hazards and the earthquake-resistant design of nuclear waste storage facilities are being developed by the Department of Energy (DOE).

4) Liquified natural gas storage facilities - Procedures for evaluating seismic hazards and the earthquake-resistant design of liquified natural gas storage facilities are currently lacking, but are being developed by DOE.

5) Dams and hydraulic structures - These important structures have a useful life of 50-100 years. COE and BUREC currently utilize a procedure for evaluating seismic hazards at a construction site which involves three levels of investigations: appraisal, feasibility, and advance planning. Evaluation of seismic hazards and assessment of the risk become more rigorous as siting studies progress through each phase prior to actual construction. The report by Krinitzsky and Marcusson (1983) describes some of the considerations based on use of intensity data that are

followed in selecting earthquake ground motions for use in engineering design of large dams.

6) Nuclear power plants and associated structures, systems, and components - Nuclear power plants, which have a useful life of about 40 years, receive special consideration because of safety issues. The procedures now used for siting nuclear power plants are described in Appendix A to 10 CFR part 100, "Seismic and geologic siting criteria for nuclear power plants." These criteria are used in evaluating systems and components. Detailed guidance is indicated in the Standard Review Plan published by NRC.

7) Military facilities - Many military facilities (for example, communication systems, emergency power generation stations, computer centers, fire stations) are designed to remain operational following a major earthquake. "The Tri-Services Manual on Seismic Design for Buildings," published in 1982, is used as a guide for evaluating seismic hazards and setting design criteria for some military facilities; others, depending on their use, are designed according to more stringent criteria.

8) Lifeline systems - Lifeline systems, the responsibility of Subcommittee 2 of ICSSC, will not be considered in detail in this report. Lifelines include: 1) **energy** - electricity, gas, liquid fuel, and steam; 2) **water** - potable, flood, sewage and solid waste, and fire water; 3) **transportation** - highway, railway, airport, harbor, and transit; and 4) **communication** - telephone and telegraph, radio and television, mail, and press. Because lifeline systems tend to be long and linear, knowledge of the spatial variation of earthquake hazards is important. Specific procedures for the

evaluation of seismic hazards for lifelines are presently lacking, both in the Federal Government and the private sector. The American Society of Civil Engineers initiated a major effort following the 1971 San Fernando earthquake to upgrade the state-of-knowledge in lifeline earthquake engineering. Lifeline earthquake engineering is an emerging field which has the goal of preserving the essential functions of lifelines, both during and after an earthquake.

2 THE EARTHQUAKE THREAT

The Federal Government must consider the possibility of loss (economic loss, loss of confidence, loss of function, and loss of life) to new as well as to existing buildings and facilities which are exposed along with their occupants and contents to the several thousand earthquakes (Figure 5) that occur each year in the United States. Although most of the earthquakes that occur each year are small and do not cause economic loss, they represent a threat in terms of potential loss of confidence and loss of function. Some earthquakes such as the 1971 San Fernando, California, earthquake have caused great loss. Since 1900, earthquakes in the United States have caused at least 1,380 deaths and more than $5 billion in property damage (1979 dollars). The greatest cumulative economic loss, which averages about $680 million per year, comes from moderate (magnitudes of 6 - 7) and large (magnitudes of 7 - 8) earthquakes because they occur much more frequently than great (magnitudes of 8 and above) earthquakes. For example, a moderate earthquake occurs in California, on the average, about once every 3 years; whereas, a great earthquake happens only about once every 100-150 years. A great earthquake in the East, such as the 1811-1812 New Madrid, Missouri, earthquakes, occurs, on the average, about once every 600 - 1,000 years; whereas, a moderate earthquake occurs about once every 50-100 years. Although earthquakes happen most frequently in Alaska, damaging earthquakes are more frequent in California because of the population and building density. Earthquakes, historically, happen relatively infrequently in the Central and Eastern United States. Some of the recent earthquakes causing damage include: 1979 Imperial Valley, California; 1983 Coalinga, California; 1983 Borah Peak, Idaho; and 1983 Hawaii. Damaging earthquakes are infrequent in the Eastern United States, but they have occurred in widely different places, including: the St. Lawrence River region on many occasions from 1650 to 1928; the vicinity of Boston in 1755; the central Mississippi Valley in 1811-1812 and in 1895; and near Charleston, South Carolina, in 1886 (Figure 5).

In 1983, 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 (Figure 6), Alaska, Hawaii, Puerto Rico and the Virgin Islands.

2.1 NORTHEAST REGION

The record of earthquakes in the United States (and the Northeast) is believed to have started with the Rhode Island earthquake of 1568. Including the St. Lawrence River Valley in Canada, 16 important earthquakes have occurred in the region since 1568 (Table 1). The distribution of earthquakes with respect to the maximum MMI in the Northeastern United States, excluding Canada and offshore epicenters, is as follows:

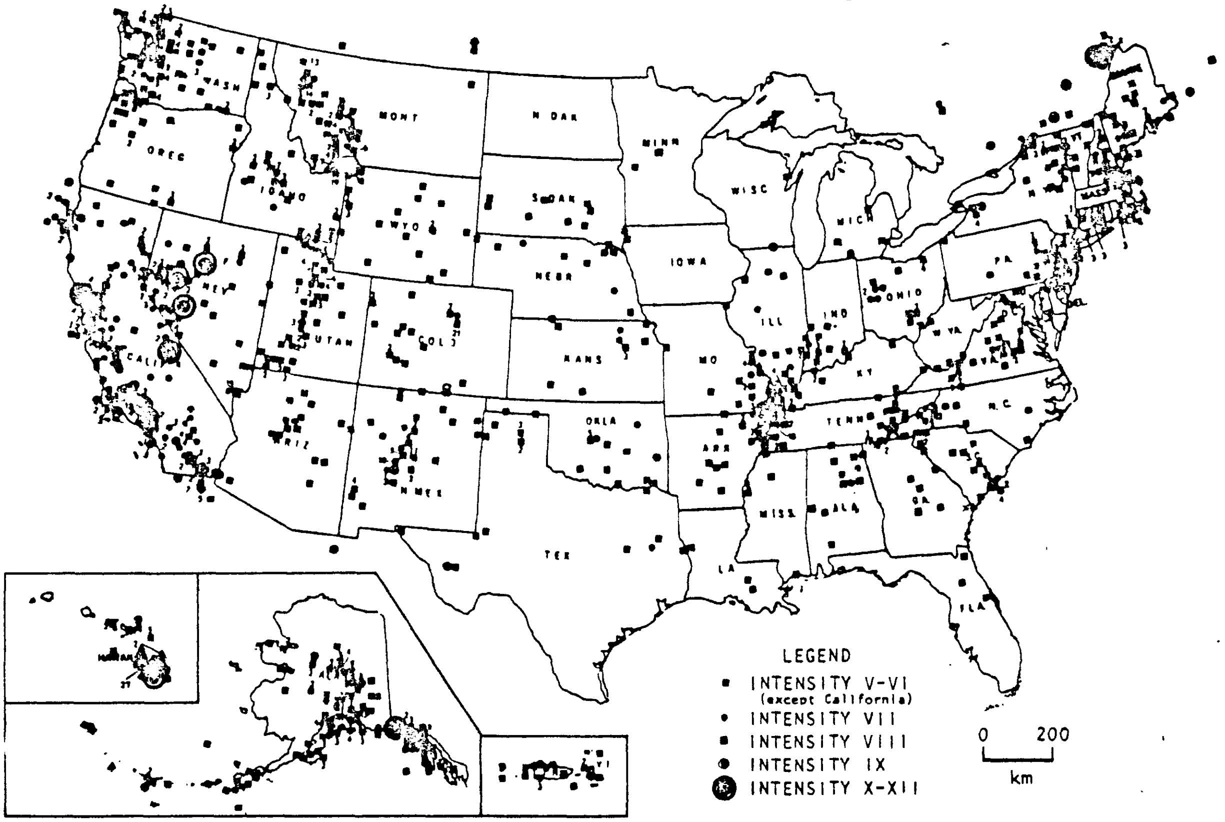

Figure 5.--Location of damaging historic earthquakes through 1976 in the United States, Puerto Rico and the Virgin Islands (Algermissen, 1983). Earthquakes having maximum Modified Mercalli intensities of V or greater are shown; intensity V is the degree of the Modified Mercalli intensity scale at which very minor damage such as cracking of plaster will occur. In general, earthquakes tend to recur where they happened in the past and occur most frequently in Alaska. In the conterminous United States, earthquakes occur most frequently in California (but less frequently than in Alaska) and relatively infrequently in the Central, Southeastern, and Northeastern United States. Earthquakes cause social impacts, economic losses, loss of function, fatalities and injuries from ground shaking, surface faulting, tectonic deformation, earthquake-induced ground failures, seiches, and tsunamis (for some coastal locations). The present avarage annual loss is about 680 million dollars. The loss increases, in general, as the magnitude of the earthquake increases and as the distance from the energy source decreases.

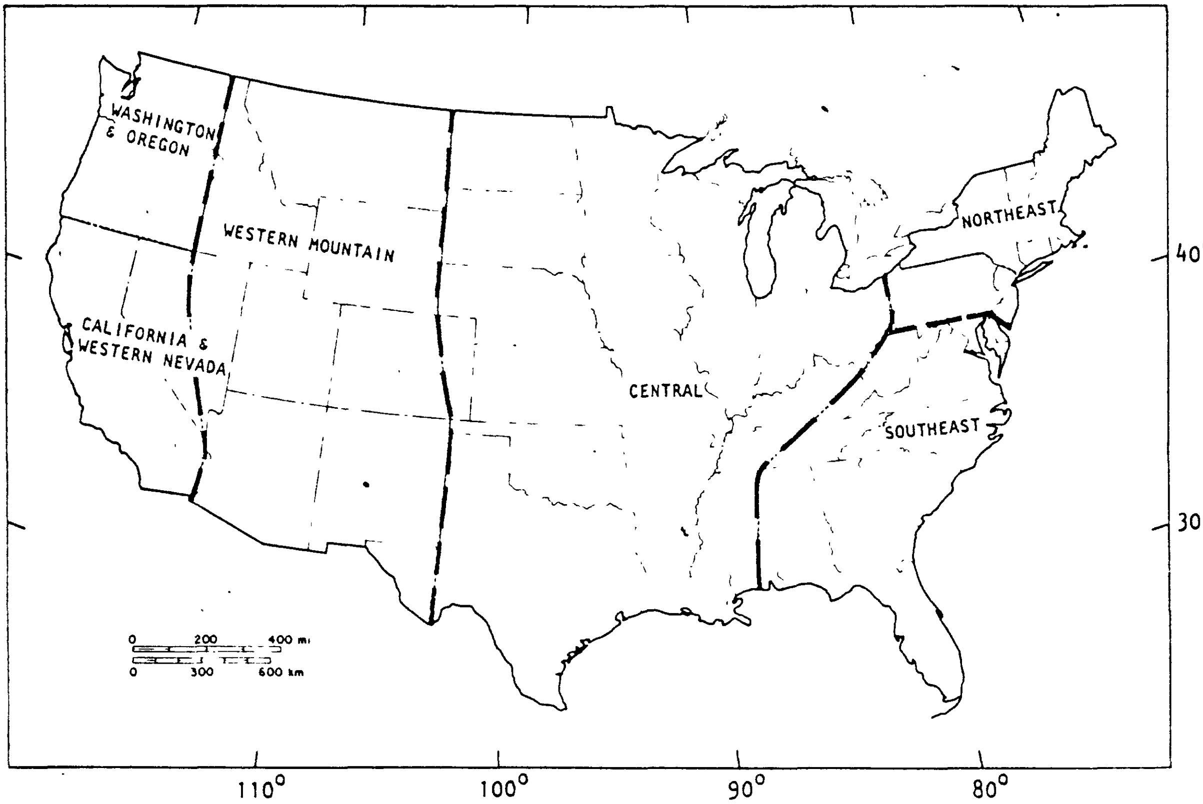

Figure 6.--Map showing designation of various regions of the United States for discussion of historic seismicity (From Algermissen, 1983).

MMI	Number
V	120
VI	37
VII	10
VIII	3

TABLE 1

IMPORTANT EARTHQUAKES FOR EASTERN CANADA AND NEW ENGLAND (FROM ALGERMISSEN, 1983)

Date	Location	Maximum MMI (I_0)	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, MA	VIII	7.0
Sep 16, 1732	Near Montreal	VIII	
Nov 18, 1755	Near Cape Ann, MA	VIII	
May 16, 1791	East Haddam, CT	VIII	
Oct 5, 1817	Woburn, MA	VII-VIII	
Oct 17, 1860	Charlevoix Zone	VIII-IX	6.0
Oct 20, 1870	Charlevoix Zone	IX	6.5
Mar 1, 1925	Charlevoix Zone	IX	7.0
Aug 12, 1929	Attica, NY	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, NY-Cornwall, Ontario	VIII	6.0
Jan 9, 1982	North Central New Brunswick	V	5.7(m_b)

2.2 SOUTHEAST REGION

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

MMI	Number
V	133
VI	70
VII	10
VIII	2
IX	0
X	1

TABLE 2
IMPORTANT EARTHQUAKES OF THE SOUTHEAST REGION
(FROM ALGERMISSEN, 1983)

Date	Location	Maximum MMI (I_0)	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	

2.3 CENTRAL REGION

The seismicity of the central region is dominated by the three great earthquakes that occurred in 1811-1812 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). Some 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).

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

TABLE 3
OTHER 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, MO	XI	8.6
Jan 23, 1812	New Madrid, MO	X-XI	8.4
Feb 7, 1812	New Madrid, MO	XI-XII	8.7
Jun 9, 1838	Southern IL	VIII	5.7
Jan 5, 1843	Near Memphis, TN	VIII	6.0
Apr 24, 1867	Near Manhattan, KS	VII	5.3
Oct 22, 1882	West Texas	VII-VIII	5.5
Oct 31, 1895	Near Charleston, MO	VIII-IX	6.2
Jan 8, 1906	Near Manhattan, KS	VII-VIII	5.5

Mar 9, 1937	Near Anna, OH	VIII	5.3
Nov 9, 1968	Southern IL	VII	5.5
Jul 27, 1980	Near Sharpsburg, KY	VII	5.1

2.4 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 in 1959 Yellowstone Park-Hebgen Lake earthquake which had a magnitude (M_S) now believed to be in excess of 7.3. The strongest earthquake in 24 years occurred at Borah Peak in Idaho in October 1983; it had a magnitude (M_S) of 7.3. The distribution of historic earthquakes in the western mountain region is as follows:

MMI	Number
V	474
VI	149
VII	26
VIII	22
IX	0
X	1

TABLE 4

OTHER 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, AZ	VIII?	
Nov 10, 1884	Utah-Idaho border	VIII	
Nov 14, 1901	About 50 km east of Milford, UT	VIII	
Nov 17, 1902	Pine Valley, UT	VIII	
Jul 16, 1906	Socorro, NM	VIII	
Sept 24, 1910	Northeast AZ	VIII	
Aug 18, 1912	Near Williams, AZ	VIII	
Sept 29, 1921	Elsinore, UT	VIII	
Sept 30, 1921	Elsinore, UT	VIII	
Jun 28, 1925	Near Helena, MT	VIII	6.7
Mar 12, 1934	Hansel Valley, UT	VIII	6.6
Mar 12, 1934	Hansel Valley, UT	VIII	6.0
Oct 19, 1935	Near Helena, MT	VIII	6.2
Oct 31, 1935 (Aftershock)	Near Helena, MT	VIII	6.0
Nov 23, 1947	Southwest MT	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, ID	VIII	6.1
Jun 30, 1975	Yellowstone National Park	VIII	6.4
Oct 28, 1983	Lost River Mtns., ID	VII est.	7.3

2.5 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 generalization can be made: 1) the earthquakes are nearly all shallow, usually less than 15 km in depth, 2) the recurrence rate for a large (M_S greater than 7.8) earthquake on the San Andreas fault system is of the order of 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) almost all of the major earthquakes have produced surface faulting. Excluding offshore earthquakes, the distribution in California and western Nevada is given below:

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

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, CA	IX	
Apr 15, 1898	Mendocino County, CA	VIII-IX	
Dec 25, 1899	San Jacinto, CA	IX	
Apr 18, 1906	San Francisco, CA	XI	8.3
Oct 3, 1915	Pleasant Valley, NV	X	7.7
Apr 21, 1918	Riverside County, CA	IX	6.8
Mar 10, 1922	Cholame Valley, CA	IX	6.5
Jan 22, 1923	Off Cape Mendocino, CA	(IX)	7.3
Jun 29, 1925	Santa Barbara Channel	VIII-IX	6.5
Nov 4, 1927	West of Point Arguello, CA	IX-X	7.3
Dec 21, 1932	Cedar Mountain, NV	X	7.3
Mar 11, 1933	Long Beach, CA	IX	6.3
May 19, 1940	Southeast of El Centro, CA	X	7.1
Jul 21, 1952	Kern County, CA	XI	7.7
Jul 6, 1954	East of Fallon, NV	IX	6.6
Aug 24, 1954	East of Fallon, NV	IX	6.8
Dec 16, 1954	Dixie Valley, NV (2 shocks)	X	7.3
Feb 9, 1971	San Fernando, CA	XI	6.4
Oct 15, 1979	Imperial Valley, CA	IX	6.6
May 2, 1983	Coalinga, CA	VIII	6.5

2.6 WASHINGTON AND OREGON REGION

This region is charcterized by a low to moderate level of seismicity despite the active volcanism of the Cascade range. With the exception of plate interaction between the North American and Pacific tectonic plates, there is no clear relationship 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 km. Currently, there is speculation 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 Washingtona and Oregon region is given below:

MMI	Number
V	150
VI	57
VII	8
VIII	3
IX	1

TABLE 6

IMPORTANT EARTHQUAKES OF WASHINGTON AND OREGON (FROM ALGERMISSEN, 1983)

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Dec 14, 1872	Near Lake Chelan, WA (Probably shallow depth of focus)	IX	(7.0)
Oct 12, 1877	Cascade Mountains, OR	VIII	
Mar 7, 1893	Umatilla, OR	VII	
Mar 17, 1904	About 60 km NW of Seattle	VII	
Jan 11, 1909	North of Seattle, near Washington/British Columbia	VII	
Dec 6, 1918	Vancouver Island, B.C.	(VIII)	7.0
Jan 24, 1920	Straits of Georgia	(VII)	
Jul 16, 1936	Northern Oregon, near Freewater	VII	(5.7)
Nov 13, 1939	NW of Olympia (Depth of focus about 40 km)	VII	(5.8)
Apr 29, 1945	About 50 km SE of Seattle	VII	
Feb 15, 1946	About 35 km NNE of Tacoma (Depth of focus 40-60 km)	VII	6.3
Jun 23, 1946	Vancouver Island	(VIII)	7.2
Apr 13, 1949	Between Olympia and Tacoma (Depth of focus about 70 km)	VIII	7.1
Apr 29, 1965	Between Tacoma and Seattle (Depth of focus about 59 km)	VIII	6.5

2.7 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 southeast Alaska were 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 has recently been assigned a moment magnitude of 9.2, also probabaly was the largest historical earthquake. 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:

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

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

2.8 HAWAIIAN ISLANDS REGION

The seismicity in the Hawaiian Islands is related to the well-known volcanic activity and is primarily associated 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 distance earthquakes have impacted the islands, some having wave heights of as much as 55 feet. The distribution of earthquakes in terms of maximum MMI is given below:

MMI	Number
V	56
VI	9
VII	9
VIII	3
IX	1
X	1

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 northeast coast of Hawaii	VIII	6.3
Nov 29, 1975	Near northeast coast of Hawaii	VIII	7.2
Nov 16, 1983	Near Mauna Loa, Hawaii		6.6

2.9 PUERTO RICO AND VIRGIN ISLANDS REGION

The seismicity in Puerto Rico and 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 cm/year. Earthquakes in this region are known to have caused damage as early as 1524-1528. 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 Virgin Islands region.

MMI	Number
V	24
V-VI	4
I	5
VI-VII	1
VII	6
VIII	2
VIII-IX	1

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, VI	(VII)	
Apr 16, 1844	Probably north of PR	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, PR	VII	
Sep 27, 1906	North of PR	VI-VII	
Apr 24, 1916	Possibly Mona Passage	(VII)	
Oct 11, 1918	Mona Passage	VIII-IX also tsunami	7.5

3 EVALUATION OF SEISMIC HAZARDS

3.1 METHODOLOGY

To evaluate the seismic hazards at a new or existing Federal construction site, a multidisciplinary methodology incorporating geology, seismology, and engineering is required. Deterministic and/or probabilistic methodologies are typically used. 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 site. The values of magnitudes used in the evaluation are typically the maximum magnitudes judged capable of occurring on the identified seismic sources. When the probabilistic approach 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 construction site. The evaluation is made for all discrete source zones in the region containing the construction site. These evaluations use the geologic, seismological, and geotechnical data for the region and the specific site to determine the relative severity of ground shaking, ground failure, surface faulting, and their frequency of occurrence. The evaluation of the seismic hazards provides a sound scientific basis for selecting the seismic-design parameters that are appropriate in terms of the type of structure or facility, its uses and functional lifetime, and its exposure to the various seismic hazards.

3.2 CURRENT PROCEDURES

The Federal Government does not have a standard procedure for evaluating seismic hazards for all Federal construction. Some of the procedures being used now by various Federal agencies are listed below:

1) The Uniform Building Code (1970, 1973, 1976, 1979, and 1982 editions).

2) Appendix A to 10 CFR part 100, "Seismic and geologic siting criteria for nuclear power plants," (U.S. Nuclear Regulatory Commission, 1983).

3) The "Tri-Services Manual on seismic design for buildings," (Departments of the Army, the Navy, and the Air Force, 1973, 1982).

4) The Veterans Administration's Handbook on "Earthquake-resistant Design of VA Hospital Facilities," published in 1973.

5) The "Standard Review Plan" of U.S. Nuclear Regulatory Commission, 1981.

6) The Department of Housing and Urban Development's report on "Methodology for Seismic Design and Construction of Single-family Dwellings," published in 1976.

7) The Federal Highway Administration's report, "Determination of Seismically Induced Soil Liquefaction Potential at Proposed Bridge Sites," published in 1977.

8) The General Services Administration's report on "Design Guidelines for Earthquake Resistance of Buildings," published in 1978.

9) The Applied Technology Council's report on "Tentative Provisions for the Development of Seismic Regulations for Buildings," published by National Bureau of Standards in 1978.

10) The National Bureau of Standards' report on "The Analysis of the Tentative Seismic Design Provisions for Buildings," published in 1979.

11) ICSSC's report "Draft Seismic Standard for Federal Buildings" (Harris and Leyendecker, 1981).

12) ICSSC's report, "Evaluation of Potential Surface Faulting and other Tectonic Deformation" (Bonilla, 1982).

13) ICSSC's report, "Evaluation of Earthquake-induced Ground Failure" (Ferritto, 1982).

14) ICSSC's report, "Considerations in Selecting Earthquake Motions for the Engineering Design of Large Dams" (Krinitzsky and Marcusson, 1983).

In addition, standards have been created by professional groups such as the American Nuclear Society (ANS) to assist in the evaluation of seismic hazards and to provide criteria for earthquake-resistant design. Examples of some of the standards published by ANS for siting of nuclear power plants include:

a) "Guidelines for Evaluating Site-related Geotechnical Parameters for Nuclear Facilities," ANS 2.11,

b) "Guidelines for Determining Tsunami Criteria for Power Reactor Sites," ANS 2.4,

c) "Guidelines for Determining Design Basis Flooding at Power Reactor Sites," ANS 2.8,

d) "Guidelines for Combining Natural and External Manmade Hazards at Power Reactor Sites," ANS 2.12,

e) "Guidelines for Assessing Capability for Surface Faulting at Nuclear Power Reactor Sites," ANS 2.7/N180,

4 RECOMMENDED PROCEDURE FOR EVALUATING SEISMIC HAZARDS AT FEDERAL CONSTRUCTION SITES

4.1 TECHNICAL CRITERIA

The Federal Government needs a standard procedure for evaluating seismic hazards. Such a procedure must meet certain criteria, including:

1) Flexibility - The procedure must be flexible enough to permit the full range of technical options, allowing each agency to utilize proven techniques and methodologies as well as to incorporate new knowledge gained from postearthquake investigations and current research.

2) State-of-the-art - The procedure must be comprehensive enough to represent the state-of-the-art, yet simple enough to ensure that each agency is able to apply it uniformly and consistently.

3) Reasonableness - The procedure must permit the agency to select reasonable seismic-design parameters and to establish an earthquake-resistant design that is consistent with the level of acceptable risk based on the type and importance of the structure or facility, its uses and functional lifetime, and the frequency of occurrence of the seismic hazards at the construction site.

4.2 ESSENTIAL ELEMENTS OF THE PROCEDURE

The Federal agency having responsibility for the seismic safety of the construction also has responsibility for establishing the level of acceptable risk (see Figure 7 and section 4.3) for their structures or facilities. The acceptable risk is determined on the basis of the structure's exposure to seismic hazards and the consequences of its failure or loss of function. Specification of the acceptable risk is based on technical evaluations which may be based on either deterministic or probabilistic methodologies.

The essential elements of the procedure recommended for evaluating seismic hazards are summarized below. Readers can refer to the sample publications cited below for technical guidance as well as to those cited in section 9. Data requirements are discussed in section 7.

4.2.1 GROUND-SHAKING HAZARD (HAYS, 1980; ALGERMISSEN ET AL, 1982, KRINITZSKY AND MARCUSSON, 1983)

The essential requirements are to:

1) Determine the earthquake potential of the region containing the construction site, integrating the record of historical seismicity with the geologic information.

2) Determine the relative severity of ground shaking throughout the region that each earthquake source in the region is physically capable of producing. This step requires:

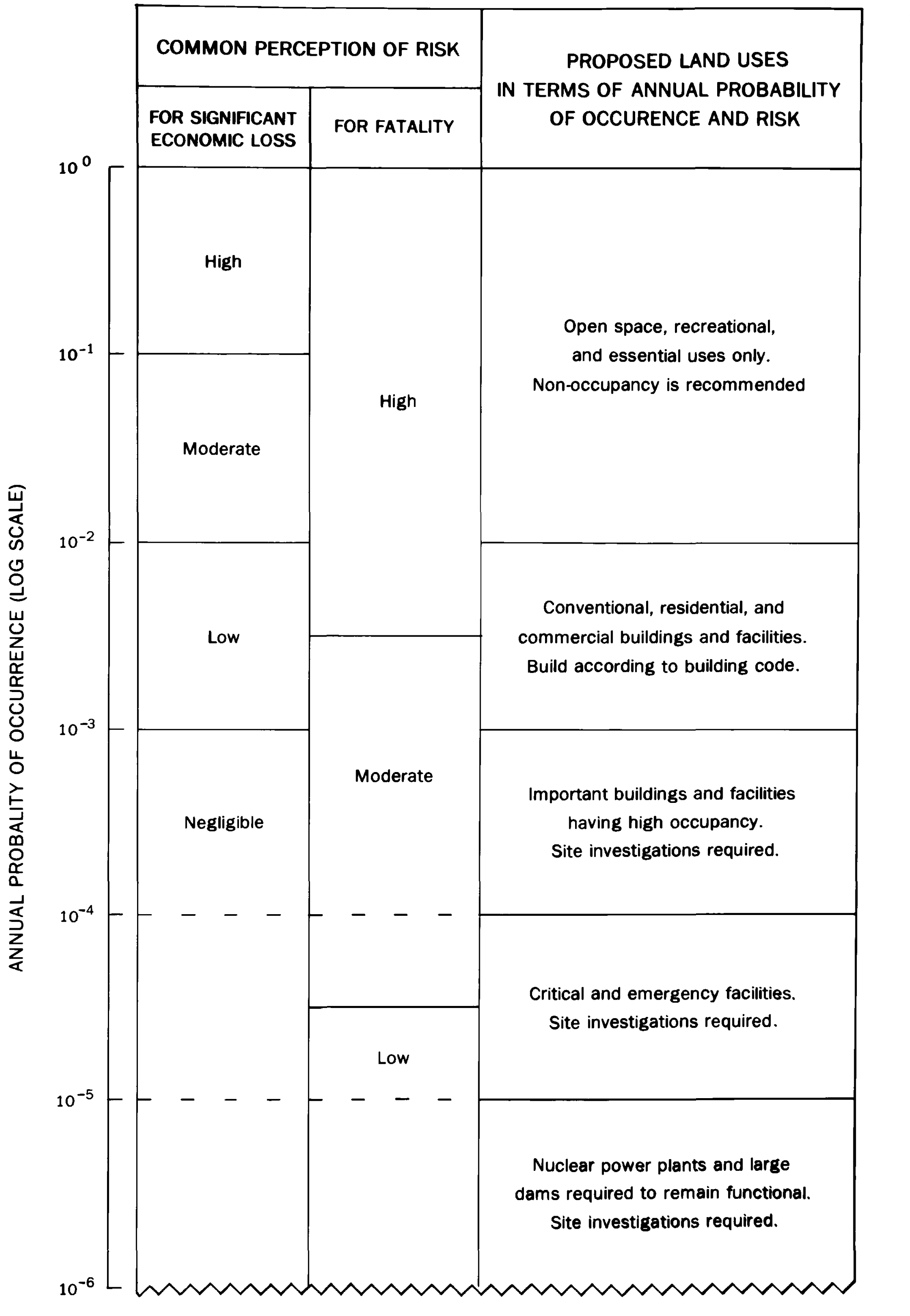

Figure 7.--Criteria to guide decisions about acceptable risk and earthquake-resistant design in terms of the annual probability of occurrence.

a) Determination of the seismic-wave attenuation relation that is appropriate for the region, and

b) Determination of the response of the soil and rock column underlying the site.

3) Determine the seismic-design parameters that are appropriate for use in creating the lateral force-resisting system and the earthquake-resistant design of the specific structure or facility.

4.2.2 SURFACE FAULTING AND TECTONIC DEFORMATION HAZARDS (BONILLA, 1982)

The essential requirement is to determine the potential for surface fault rupture and regional tectonic deformation at the site.

4.2.3 EARTHQUAKE-INDUCED GROUND FAILURE HAZARD (FERRITTO, 1982)

The essential requirement is to determine the potential for earthquake-induced ground failure at the site.

4.2.4 TSUNAMI AND SEICH HAZARD (HAYS, 1982; SUBCOMMITTEE 3, IN PRESS)

The essential requirement is to determine the potential for tsunamis and seiches generated by regional, local, and distant earthquake sources.

4.3 ASSESSMENT OF RISK

An acceptance of some level of risk (expected loss) is implicit in the siting, design, and construction of every Federal structure and facility (see Figure 7). The level of acceptable risk shall be established by the Federal agency on the basis of the type of structure or facility, its uses and functional lifetime, its exposure to various seismic hazards, and the consequences of its failure or loss of function. For perspective, an annual probability of 0.01 approximately represents the frequency of a great earthquake on the San Andreas fault zone in California; whereas 0.001 is approximately the frequency of a great earthquake in the Eastern United States. An annual probability of 0.01 is the average disease mortality; 0.0001 is the risk of death from automobile accidents; and 0.000001 is commonly perceived as an "act of God," (e.g., getting hit by lightning). The "100-year flood" is typically used as a criterion of an acceptable level of risk for many types of land development. Exposure of capital to this level of risk represents a self-insurance cost of 1 percent. The "500-year return period ground acceleration" is typically used as a criterion for the seismic design provisions of building codes. Federal agencies having responsibility for construction utilize such criteria in conjunction with probabilistic ground-shaking hazard curves to establish policy for determining the acceptable risk to their structures. (Adapted from Mader et al, 1980). The level of acceptable risk determines the range of technical options available for earthquake-resistant design and influences decisions about the seismic-design parameters. Selection of the appropriate seismic-design parameters is based on an integration of geologic, seismological, geotechnical, and engineering information gained from an assessment that addresses technical questions such as the following:

1) Do active fault systems exist in the region containing the construction site? How close are these fault systems to the site? What is the seismic cycle of each fault system? Can the point in the cycle be specified?

2) Have significant earthquakes occurred in the region? What were their physical characteristics? Were any of these earthquakes the upper-bound earthquake?

3) Are accelerograms and response spectra available from past earthquakes, that occurred either in the region containing the construction site or in other geographic regions having similar geologic and tectonic characteristics representative of the potential maximum ground-shaking hazard in the region.

4) Have the hazards of ground shaking, surface fault rupture, tectonic deformation, ground failure, seiches, and tsunami waves occurred previously in the region? When? Where are these hazards occurring now? On the basis of geologic, geophysical, and engineering data, where are these hazards expected to occur in the future?

5) In the region containing the construction site, what is the frequency of occurrence of ground shaking? surface faulting? tectonic deformation? earthquake-induced ground failure? tsunami wave run up?

6) What are the physical causes and physical characteristics of each type of seismic hazard?

7) What is the relative severity of each type of seismic hazard and how have their physical effects varied spatially within the region?

8) What average annual loss is expected from each type of seismic hazard?

9) What is the maximum sudden-loss potential from each type of seismic hazard?

10) How many and what size (magnitude) earthquakes are expected to occur on fault systems in the vicinity of the site during various exposure times (for example, 10, 25, 50, 100, 250, 500, 1,000, 10,000 years)? How do these exposure times correlate with the functional lifetime and uses of the structure or facility?

11) What is the probability of occurrence of is a specific level of seismic hazard at the site during the functional lifetime of the structure or facility (for example, a level of peak ground acceleration, the occurrence of surface faulting along a specific fault, or the occurrence of liquefaction in a certain area)?

12) In terms of the functional lifetime and uses of the structured facility and the probability of occurrence of a specific seismic hazard at a construction site, what is the acceptable level of risk for the structure or facility?

13) Is static analysis of the structure adequate or is dynamic analysis needed?

5 TECHNICAL ISSUES

Many technical issues will arise in the evaluation of seismic hazards for a specific Federal construction site. Each Federal agency is responsible for trying to resolve these issues by acquiring the appropriate data or performing relevant analyses to limit the range of possible hypotheses and models. However, most of the technical issues cannot yet be resolved completely. For these reasons, the Federal agency is responsible for introducing a reasonable and adequate margin of safety (see section 6). The questions listed below define some of the technical issues that are commonly debated when evaluating the ground-shaking hazard.

5.1 ISSUES CONCERNING SEISMICITY

The following questions give a perspective on some of the principal issues concerning seismicity:

1) Can catalogs of instrumentally recorded and felt earthquakes (usually representing a regional scale and a short-time interval) be used to give a reliable estimate of the frequency of occurrence of major earthquakes on a reliable local scale?

2) Can the seismic cycle of individual fault systems be determined accurately and, if so, can the position in the cycle be identified?

3) Can the location of the largest earthquake that is physically possible on an individual fault system or in a seismotectonic province be specified accurately? Can the recurrence of this event be specified? Can the frequency of occurrence of smaller earthquakes (e.g., the earthquake that occurs roughly once every decade) be specified?

4) Can seismic gaps (i.e., locations having a noticable lack of activity of large earthquakes surrounded by locations that have experienced activity) be identified and their earthquake potential evaluated accurately?

5) Does the geologic evidence for the occurrence of major tectonic episodes in the geologic past and the evidence provided by current and historic patterns of seismicity in a geographic region agree? If not, can these two sets of data be reconciled?

5.2 ISSUES CONCERNING THE NATURE OF THE EARTHQUAKE SOURCE

The following questions give a perspective on issues concerning earthquake sources:

1) Can seismic source zones be defined accurately on the basis of historic seismicity; on the basis of geology and tectonics; on the basis of historical seismicity generalized by geologic and tectonic data? Which

approach is most accurate for use in deterministic studies? In probabilistic studies?

2) Can the magnitude of the largest earthquake expected to occur in a given period of time on a particular fault system or in a seismic source zone be estimated accurately? Has the region containing the construction site experienced its maximum or upper-bound earthquake in historic time?

3) Should the physical effects of important earthquake source parameters such as stress drop and seismic moment be quantified and incorporated in the seismic-design parameters even though these parameters have not been used in design in the past? If used, how should they be represented?

5.3 ISSUES CONCERNING GROUND MOTION

The following questions give a perspective on issues concerning ground motion:

1) Can the complex details of the earthquake fault rupture (e.g., rupture dimensions, fault type, fault offset, and fault-slip velocity) be modeled accurately enough to give good estimates of the amplitude and frequency characteristics of ground motion both close to the fault and far from the fault?

2) Do peak ground-motion parameters (e.g., peak acceleration) in the Western United States saturate at large magnitudes? In the Eastern United States?

3) Are the data bases adequate for defining bedrock attenuation laws? Soil attenuation laws?

5.4 ISSUES CONCERNING LOCAL GROUND RESPONSE

The following questions give a perspective on the issues concerning the response of soil and rock to ground motion.

1) For specific soil types, can behavior during severe earthquakes be scaled from behavior during small earthquakes?

2) Can the 2- and 3-dimensional variation of selected physical properties of the soil and rock column (e.g., thickness, lithology, geometry, water content, shear-wave velocity, and density) be modeled accurately? Under what physical conditions do one or more of these physical properties control the spatial variation, the duration, and the amplitude and spectral characteristics of ground response in a geographic region?

3) Does the uncertainty associated with the response of a soil and rock column to ground motion vary with magnitude?

4) Can the subsurface variation of ground motion be modeled accurately?

6 CONSERVATISM IN EARTHQUAKE-RESISTANT DESIGN OF CRITICAL FACILITIES

6.1 JUSTIFICATION FOR A MARGIN OF SAFETY

When one or more technical issues affecting the choice of seismic-design parameters cannot be resolved, the parameters must be selected conservatively to provide a reasonable margin of safety. Procedures used to define the seismic-design parameters (e.g., effective peak ground acceleration, response spectra, and time histories) for critical facilities (e.g., a nuclear power plant) are currently based primarily on empirical data and empirical analysis techniques. These procedures are designed with an adequate margin of safety to compensate for uncertainty in estimated values of the physical parameters that control the amplitude, spectral, and time-duration characteristics of ground motion (see Table 10). Experience (for example, see Hays, 1980; McCann, 1983) has shown that some uncertainty is always associated with the definition of the seismic-design parameters for a site. For example, if an earthquake with the same magnitude as the 1971 San Fernando earthquake recurred 10 times at the same epicenter in the San Fernando Valley and horizontal accelerograms were recorded at each of the sites recording the 1971 earthquake, the set of time histories and spectra for each recording site would have values that are distributed about a central value because of changes in the source parameters (e.g., stress drop, seismic moment, fault rupture dynamics). If 10 new recording sites having the same epicentral distance as Pacoima Dam also recorded each hypothesized recurrence of the San Fernando earthquake, the set of time histories and spectra at these sites would also have values that differ from a central value as well as from the data obtained at Pacoima Dam in the 1971 earthquake. In this case, the variability would primarily be caused by changes in the transmission path and the seismic radiation pattern close to the fault. In either case, an irreducible level of variation always exists in the parameters describing the earthquake ground motion. Because the limited data sample of ground motion records now available does not permit a precise determination of the central values of ground motion and their variance, some conservatism is needed to ensure an adequate margin of safety in seismic design. Even if the central value were known precisely, some conservatism would still be needed because the irreducible variance can be quite large.

6.2 WAYS TO INTRODUCE CONSERVATISM

The steps described below are typically taken, either individually or collectively, to introduce a reasonable level of conservatism in the seismic-design parameters. Care must be taken in each step of the process because, depending on the physics of the wave propagation, a given step may not always introduce conservatism.

TECHNICAL QUESTIONS	STEPS TO INTRODUCE CONSERVATISM
Seismicity and source parameters	
-- What is the largest earthquake that could occur in the site vicinity and how frequently will it occur?	1. Postulating for design a low-probability event having an energy release (magnitude) or MMI equal to or greater than that of any earthquake that has occurred in the short (100-300 years) record of historical seismicity typical of most regions in the United States.
-- Where will the design earthquake occur?	2. Placing the epicenter of the postulated design earthquake at the closest distance from the site that is physically meaningful

(i.e., on a specific fault or tectonic structure or on the closest boundary of a tectonic province.)

-- What are the amplitude and spectral characteristics of the seismic input at sites close to the earthquake source?

3. Using a smooth, broadband, 84th percentile design response spectrum whose shape is independent of the distance from the fault.

4. Using peak ground acceleration (zero period acceleration) to scale the amplitude level of the smooth design response spectrum, independent of the frequency-dependent effects of earthquake source parameters such as magnitude, seismic moment, and stress drop as well as fault rupture length (which controls duration of shaking).

Transmission path parameters

-- How does the seismic energy decay as distance from the fault increases?

5a. Applying no attenuation if the epicenter of the postulated design earthquake is located near the site; thus, the maximum site acceleration or site intensity is considered to be identical with the epicentral intensity.

5b. Attenuating the epicentral intensity to the site by using the appropriate regional attenuation curve, or if a choice is involved, that curve which gives the largest value of intensity at the site, then converting this value of intensity to peak acceleration by using the empirical relation which gives the largest value of acceleration.

5c. Converting epicentral intensity to peak acceleration, choosing the largest value and attenuating it to the site by using the appropriate regional attenuation curve, or if a choice is involved, that curve which gives the largest value of peak acceleration at the site.

Local site parameters

-- Will the soil and rock column underlying the site modify (amplify) the input ground motion?	6. Using a 84th percentile, smooth, broadband, site-independent design response spectrum whose shape and amplitude level are based on statistical analysis of earthquake data recorded at a variety of soil sites in the Western United States.
	7. Increasing the level of the smooth, 84th percentile, site-independent design response spectrum over a discrete range of periods centered about the natural period of the local soil column to account for possible amplification of ground motion in that period band.

Two additional steps can be introduced through the design time history to increase the conservatism of the seismic-design parameters. They are:

8. Requiring the design acceleration time history to produce a response spectrum for various levels of critical damping that envelopes the corresponding smooth design spectrum. A maximum of five points on the spectrum generated from the time history may fall below the smooth design spectrum by as much as 10 percent.

9. Requiring the design spectra for each of the two horizontal components to be identical, even though the amplitude and characteristics of the wave coda of the horizontal design time histories may differ.

Ultimately, the degree of conservatism in the choice of the seismic-design parameters is integrally bound up with the conservatism inherent in the design approaches (e.g., allowance for ductility, use of building code, et cetera).

6.3 PEAK GROUND ACCELERATION AND CONSERVATIVE SEISMIC-DESIGN PARAMETERS

The most controversial part of defining the seismic-design parameters is associated with the question of how intense the peak design ground acceleration should be, especially for nuclear power plant sites in the Eastern United States. In terms of the present state-of-knowledge, it is not only very difficult to specify the time, location, and size of the largest earthquake that will occur during the functional lifetime of a nuclear power plant, but it is also difficult to determine the value of peak ground acceleration that it will produce because peak ground acceleration and magnitude are not well correlated. Consequently, in present day licensing of nuclear power plants, other parameters are being used in addition to peak ground acceleration. The zero period anchor of the design response spectrum is typically defined through application of empirical procedures that maximize the energy release or epicentral intensity and minimize the epicentral distance of the design earthquake. When compared with the corresponding parameters of ground motion for the largest historic earthquake in the region, application of some or all of the empirical steps listed above can produce a value of peak ground acceleration (and a response spectrum) for design that significantly exceeds the level of peak acceleration (and the response spectrum values) that the site has actually experienced in past earthquakes. For example, in both the Eastern and Western United States, increasing the epicentral intensity of the design earthquake by one unit above that produced by the largest historical event (step 1) will increase the peak ground acceleration by a factor of 2. In the Western United States where the far-field seismic waves decay with distance approximately as R^{-2}, decreasing the epicentral distance by 30 percent (step 2) will also increase the peak ground acceleration by a factor of 2; the corresponding increase in peak acceleration is not as great in the Eastern United States because the seismic waves decay more slowly as distance from the fault increases.

When the peak ground acceleration used for design is a factor of 2 to 8 greater than that observed at the site during historic earthquakes, the return period of the design ground motion may be much greater than the recurrence time of the largest ground motion observed at the site. Consequently, the design earthquake can be an event having a very low probability of occurrence and a long recurrence time, compared with the functional lifetime of a nuclear power plant and the recurrence time of maximum events derived from the record of historic seismicity and the geologic data. Unless careful technical judgment is used in the introduction of conservatism, the design earthquake may be either physically impossible or the level of conservatism may be unreasonable.

7 DATA REQUIREMENTS AND SOURCES OF DATA

7.1 DATA NEEDS

The best available data are needed when evaluating the seismic hazards at a Federal construction site. The types of data needed include: (1) data on the character of the hazard (for example, its frequency, expected magnitude, and duration), (2) data on the nature of the risk (for example, property and population at risk; lifeline, social, and economic systems likely to be disrupted), (3) data from postearthquake investigations, and (4) data on community preparedness to face the hazards (for example, land use regulations, insurance, building codes, and emergency preparedness plans). The report, "Inventory of Natural Hazards Data Resources in the Federal Government" published in 1979 by the National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS), contains a list of the diverse sources of data available for all natural hazards. Data on earthquake hazards are primarily available from USGS and NOAA. USGS and State geological surveys often have data on the regional geologic framework, but they may not have site-specific data needed to resolve questions requiring a different scale than that of the regional framework data.

The National Science Foundation (NSF) is the source of data on earthquake engineering research. NSF does not collect data, but it supports activities such as the development and maintenance of an earthquake-engineering library with over 12,000 items and the annual publication of "Abstract Journal in Earthquake Engineering."

7.2 USE OF GEOLOGIC, GEOPHYSICAL, AND ENGINEERING DATA FOR EVALUATING SEISMIC HAZARDS

An important factor in the evaluation of the seismic hazards of ground shaking, ground failure, surface faulting, tectonic deformation, seiches, and tsunamis is a skillful use of existing geologic, geophysical, and engineering data. These data are used to determine:

1) Where have the hazards occurred in the past and where are they occurring now?

2) Why are they occurring?

3) How often do they occur? and

4) How big are the earthquakes and how severe are their physical effects?

To answer these questions, the following evaluations are made:

1) Evaluation of seismicity- The historical and present record of seismicity provides an answer to the four questions. The primary constraint in the analysis is the length and completeness of the historical record. The only data available for most earthquakes prior to 1900 are historical accounts that are given in terms of MMI. The intensities were derived from: a) observations of human and animal reaction to ground shaking, b) the effects of shaking on structures, trees, and bushes, and c) geologic effects such as landsliding and liquefaction. Instrumental data from seismograph stations in the United States were not available until after 1887.

2) Evaluation of earthquake potential- Geologic mapping, age dating, and trenching of the Quaternay deposits can extend the limited historical record of a few hundred years based on seismicity catalogs to as much as 1,000,000 years. These data, combined with geophysical data obtained from seismic reflection, gravity, and magnetic surveys may help to establish recurrence intervals (based on fault slip) for major or regional seismotectonic features or zones that may have a potential for a damaging earthquake even though little or no historic seismicity is known to be associated with them.

3) Evaluation of the nature of the physical characteristicsof the earthquake source, seismic wave propagation path, and local site conditions- Intensity data, in spite of the subjective nature of the intensity scales, can provide useful information about source, path, and site effects associated with an earthquake. The problem with intensity data is that they can not be easily correlated with more quantitative measures of strong ground motion such as peak ground acceleration, peak ground velocity, peak ground displacement, spectral response, and duration. Although instrumental data (available since 1887) and strong ground motion data (available since 1933) provide a better quantitative measure of earthquake effects, these data are often incomplete and limited, especially in the Eastern United States.

4) Evaluation of the Potential for ground failure and surface faulting- Aerial photography, geologic mapping, and soil borings provide the best data for evaluating the potential for ground failure and surface faulting.

5) Evaluation of the potential for seiches and tsunamis- The historical record provides information about prior occurrences of seiches and tsunamis and can be combined with aerial photogaphy, topographic maps, and surface and subsurface maps of coastal areas to evaluate the potential for loss.

7.2.1 THE "IDEAL" DATA BASE FOR EVALUATION OF THE GROUND-SHAKING HAZARD

The "ideal" data base (a goal of hazards evaluations) does not yet exist. It would contain complete information about the site and the region surrounding it, including the statistical distribution for the empirical relations used to estimate the severity of physical effects. For example, the basic data needed to define the ground-shaking hazard at a site should include:

1) Earthquake potential parameters

- A complete record of all historic earthquakes;
- Identification of seismic source zones;
- Spatial and temporal definition of current seismicity;
- Determination of earthquake recurrence rates; and
- Determination of the seismic cycle of specific faults.

2) Source parameters

- Information about the source parameters (for example, epicenter, focal depth, epicentral intensity, fault type, fault length, fault width, fault rupture characteristics, magnitude, seismic moment, and stress drop) of each historic earthquake;

- Maps showing seismotectonic provinces and all active faults, noting those that have had displacements within the Quaternary (last 2 million years) and Holocene (last 10,000 years);

- Information about the earthquake generating potential of each seismotectonic province; and

- Correlation of historic earthquakes with tectonic models to estimate the maximum magnitude of the earthquake likely to be associated with each specific tectonic feature.

3) <u>Seismic-wave attenuation relations</u>

- Isoseismal maps of significant historic earthquakes that have affected the site;

- Ensembles of strong-ground motion records adequate for calibrating regional seismic-wave transmission characteristics for a wide range of earthquake source mechanisms; and

- Ensembles of Fourier, power spectral density, and response spectra adequate for calibrating the frequency-dependent characteristics of the near-field and regional seismic-wave attenuation relations for a wide range of earthquake source mechanisms.

4) Local ground response

- Ensembles of strong-ground motion records and spectra at surface and subsurface locations for a wide range of unconsolidated materials overlying bedrock and a wide range of dynamic shear-strain levels; and

- Information about the static and dynamic properties of a wide range of near-surface materials, including: seismic shear-wave velocity, bulk density, and water saturation by total weight.

Similar requirements for "ideal" data bases can be given for the ground failure and surface faulting hazards. At the present time, the geologic, geophysical, and engineering data bases may be inadequate for precise specification of the design-earthquake ground motion for some sites. In these cases, the responsible Federal agency shall introduce conservatism in the seismic design parameters that will give an adequate margin of safety in terms of the uncertainty in the data. The level of conservatism must be balanced against the level of acceptable risk.

7.3 GROUND-SHAKING HAZARD MAPS AS DESIGN AIDS

The maps shown in Figures 8-13 describe the bedrock ground-shaking hazard in the conterminous United States in terms of peak horizontal bedrock ground acceleration and velocity, taking into account the differences in seismicity in the Eastern and Western United States and the geologic characteristics of specific seismic source zones. These maps are from Algermissen et al, (1982). In Figure 9, the ground-shaking hazard is depicted in terms of contoured values of the peak horizontal ground acceleration 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, (i.e., buildings having a useful life of about 50 years) whose design is typically governed by building codes. Maps for longer exposure times, such as 250 years (Figure 10), may be useful when siting critical structures such as hospitals, which have about the same useful life, but which are required to remain functional after an earthquake. Consideration of even longer exposure times may be required when siting large dams, nuclear power plants, and radioactive waste repositories because a higher level of nonexceedance (i.e., greater than 90 percent) of a given level of ground motion is required, even though the useful life may be as short as 40 years (the case of a nuclear power plant) or as long as several thousand years (the case of radioactive waste repositories). The values of peak bedrock acceleration and velocity can be used to estimate the response spectra using procedures described in Hays (1980).

Figure 14 shows the probabilistic ground shaking hazard map for Alaska. This map is similar to that shown in Figure 9; i.e., a 50-year exposure time and a 90 percent probability of nonexceedance.

Figure 15 shows the seismic zones for Alaska, Hawaii, Puerto Rico, and the Virgin Islands in the 1985 edition of the Uniform Building code.

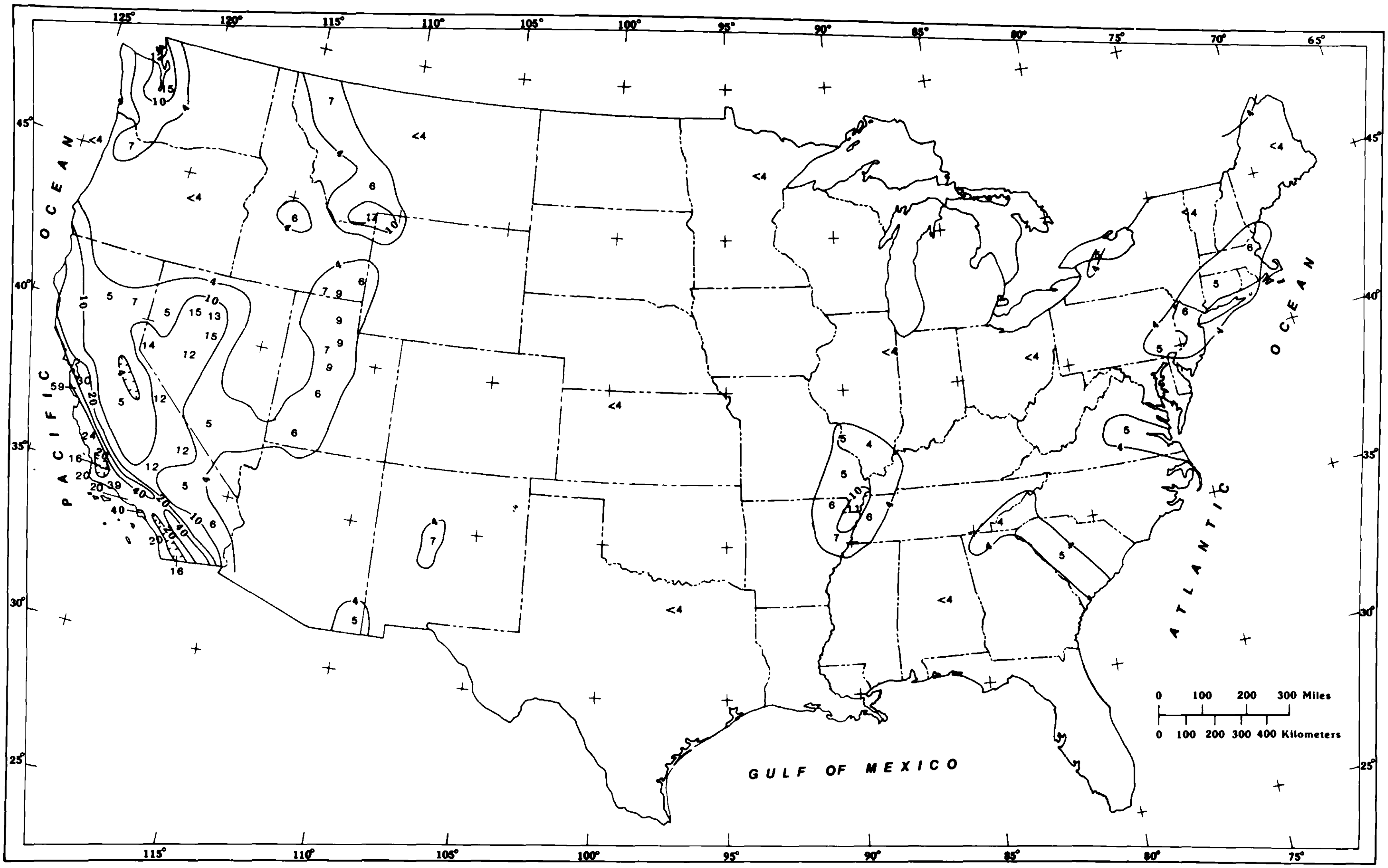

Figure 8.--Map showing maximum levels of peak horizontal ground acceleration expected in the United States in an exposure time of 10 years at sites underlain by bedrock (Algermissen et al, 1982). The corresponding return period is approximately 500 years (actually 95 years). The values of peak bedrock acceleration have a 90 percent probability that they will not be exceeded in a 10-year period. Soil effects must be considered separately.

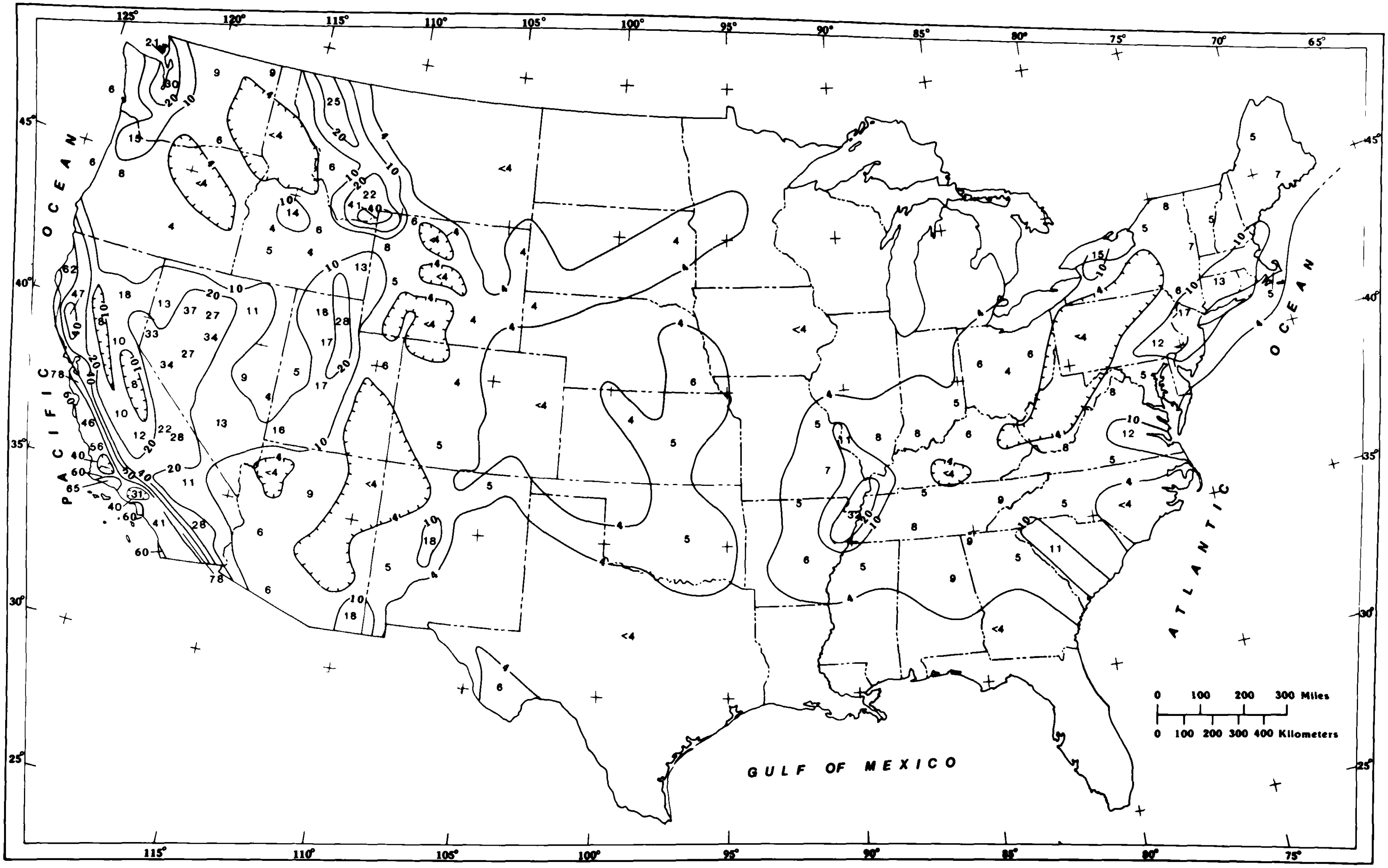

Figure 9.--Map showing maximum levels of peak horizontal ground acceleration expected in the United States in an exposure time of 50 years at sites underlain by bedrock (Algermissen et al; 1982). The corresponding return period is approximately 500 years (actually 474 years). The values of peak bedrock acceleration have a 90 percent probability that they will not be exceeded in a 50-year period. Soil effects must be considered separately.

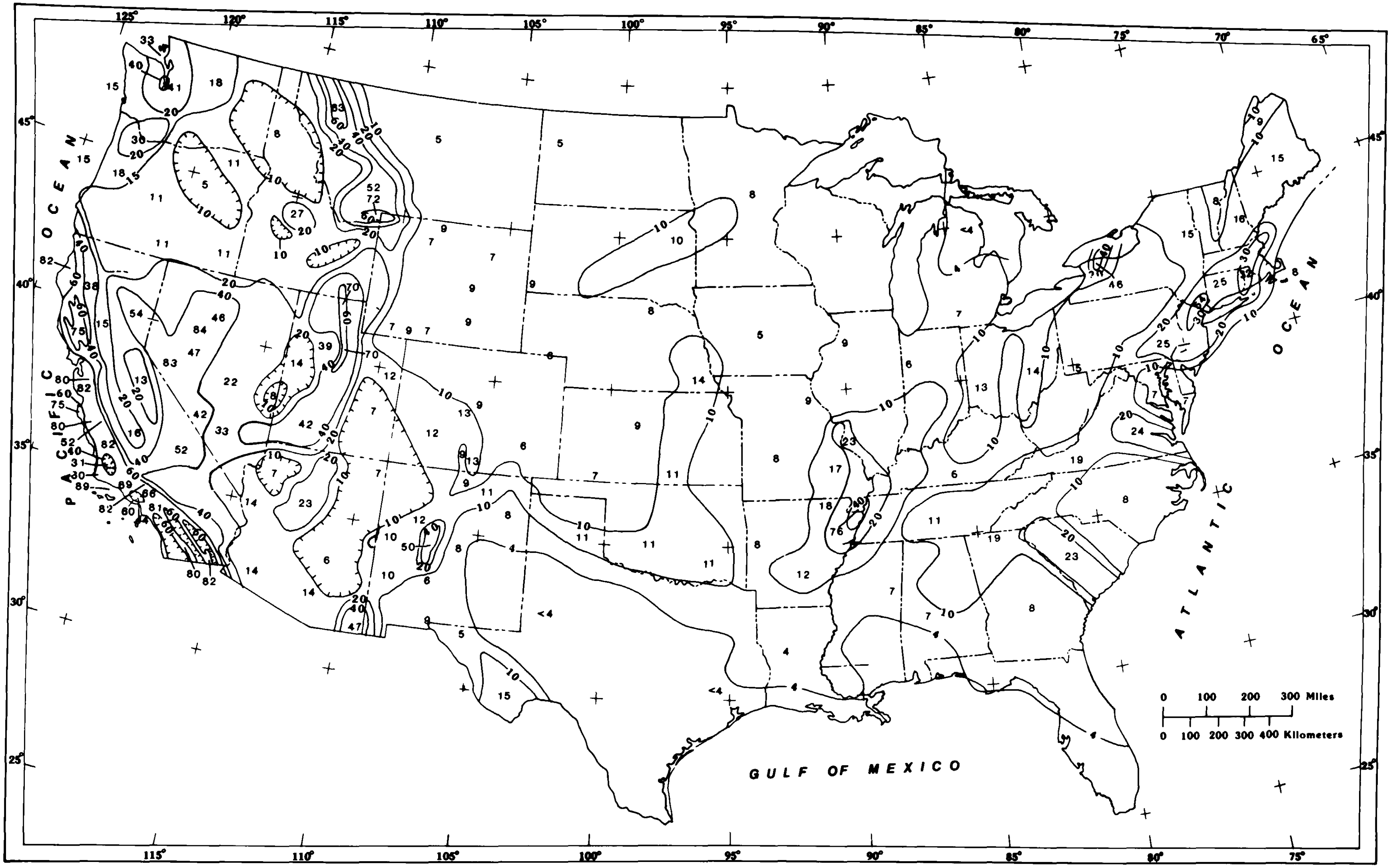

Figure 10.--Map showing maximum levels of peak horizontal ground acceleration expected in the United States in an exposure time of 250 years at sites underlain by bedrock (Algermissen et al, 1982). The corresponding return period is approximately 2,500 years (actually 2,372 years). The values of peak bedrock acceleration have a 90 percent probability that they will not be exceeded in a 250-year period. Soil effects must be considerately separately.

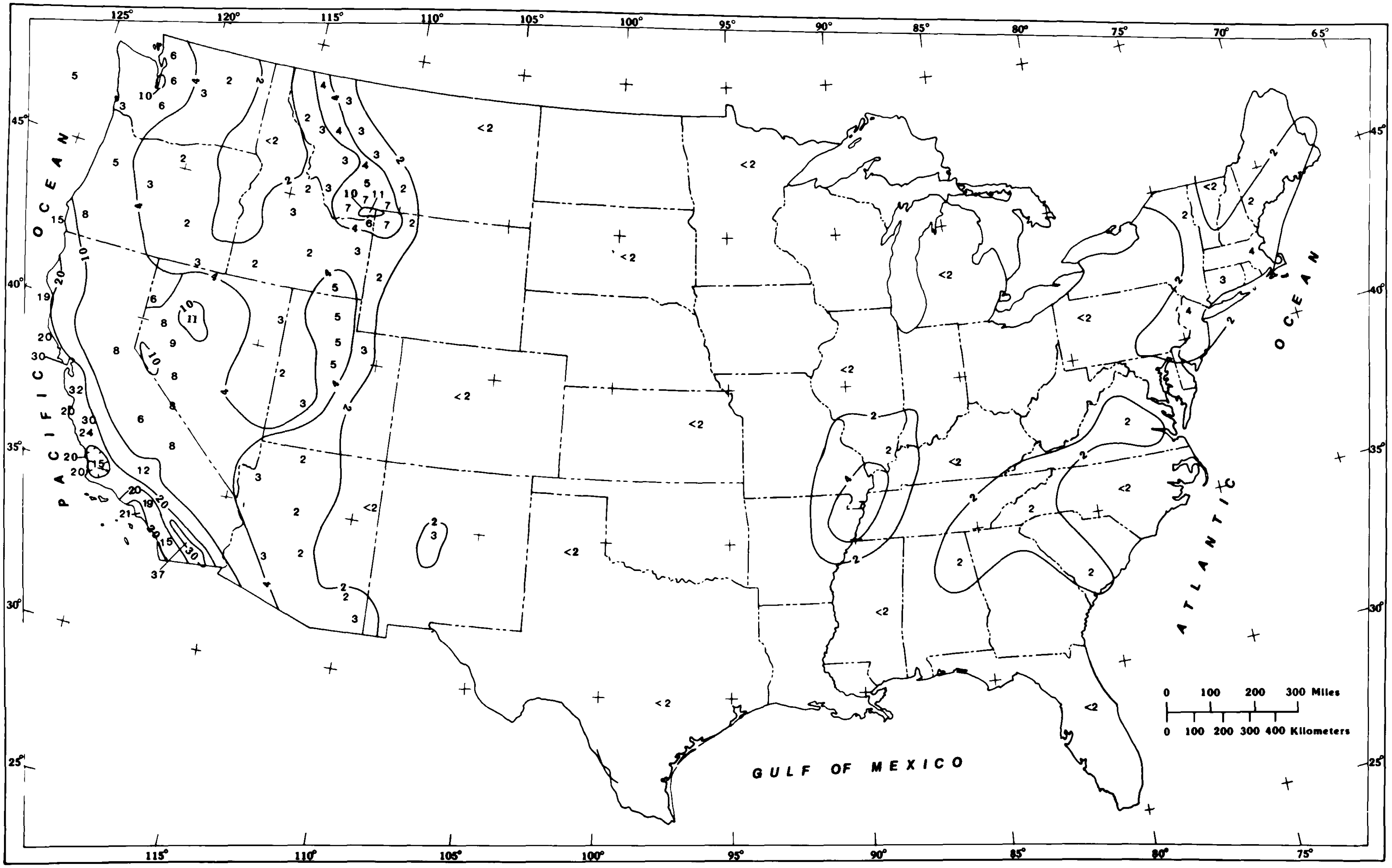

Figure 11.--Map showing maximum levels of peak horizontal ground velocity expected in the United States in an exposure time of 10 years at sites underlain by bedrock (Algermissen et al, 1982). The corresponding return period is approximately 500 years (actually 95 years). The values of peak bedrock velocity have a 90 percent probability that they will not be exceeded in a 10-year period. Soil effects must be considered separately.

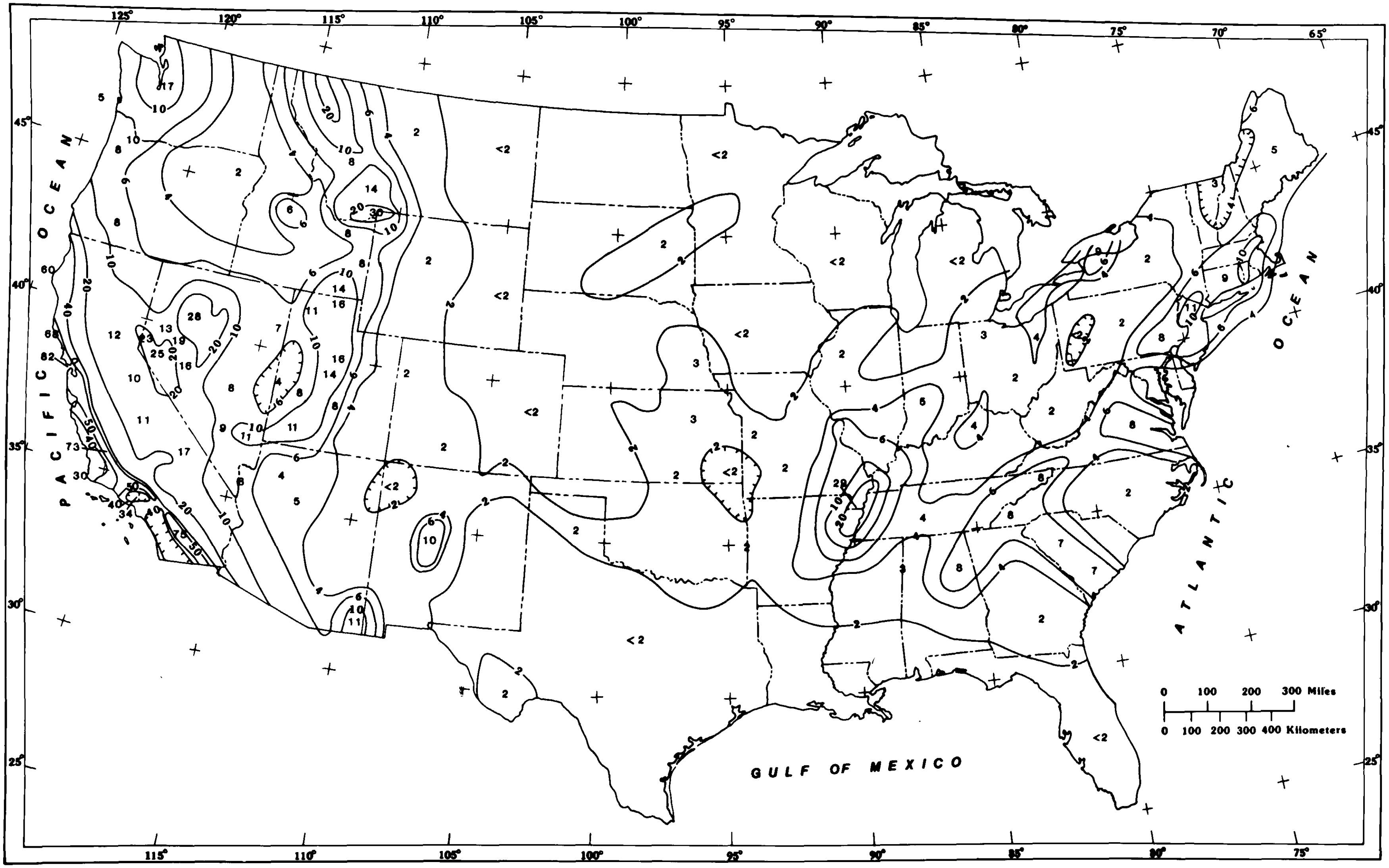

Figure 12.--Map showing maximum levels of peak horizontal ground velocity expected in the United States in an exposure time of 50 years at sites underlain by bedrock (Algermissen et al, 1982). The corresponding return period is approximately 500 years (actually 474 years). The values of peak bedrock velocity have a 90 percent probability that they will not be exceeded in a 50-year period. Soil effects must be considered separately.

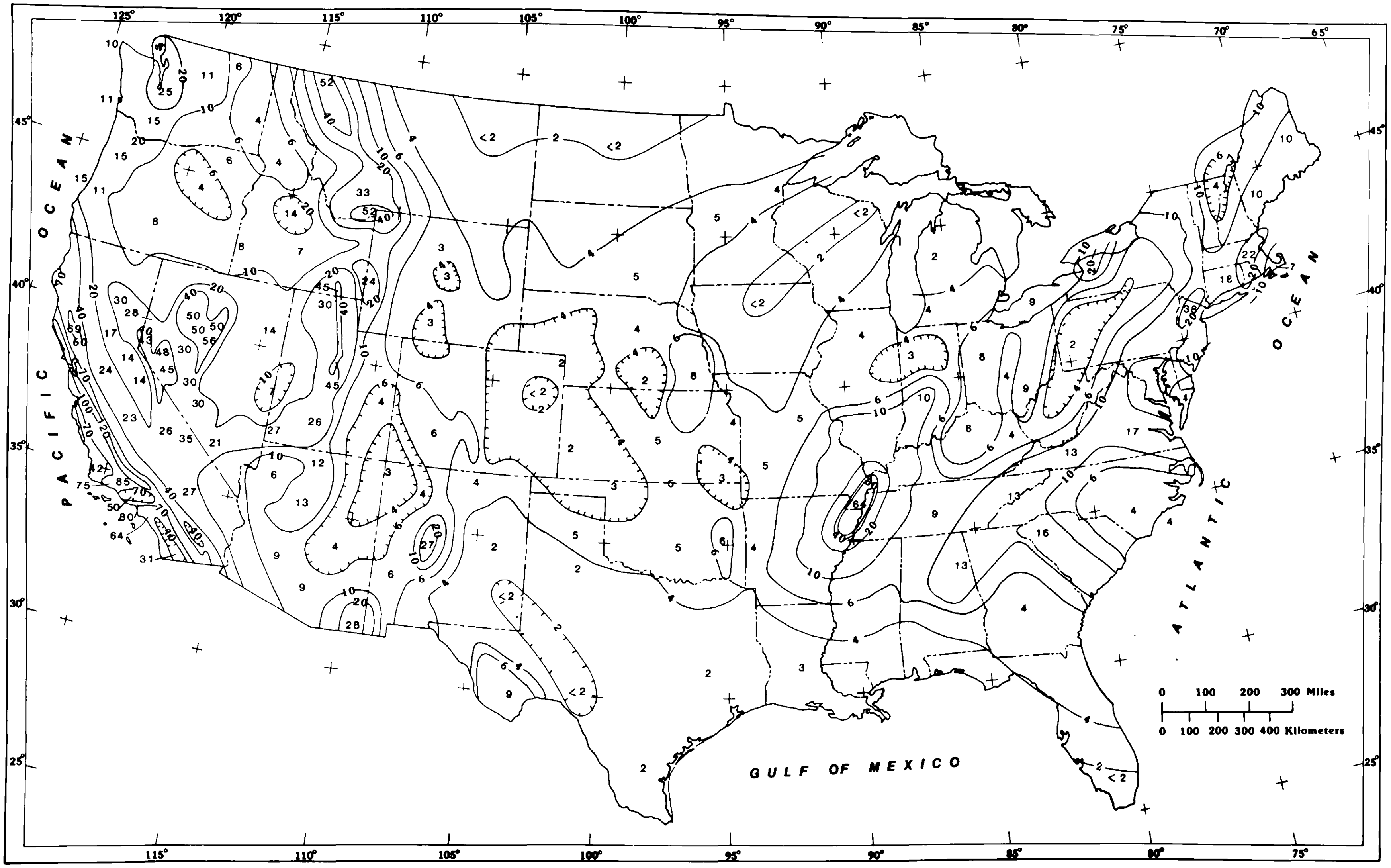

Figure 13.--Map showing maximum levels of peak horizontal ground velocity expected in the United States in an exposure time of 250 years at sites underlain by bedrock (Algermissen et al, 1982). The corresponding return period is approximately 2,500 years (actually 2,372 years). The values of peak bedrock velocity have a 90 percent probability that they will not be exceeded in a 250-year period. Soil effects must be considered separately.

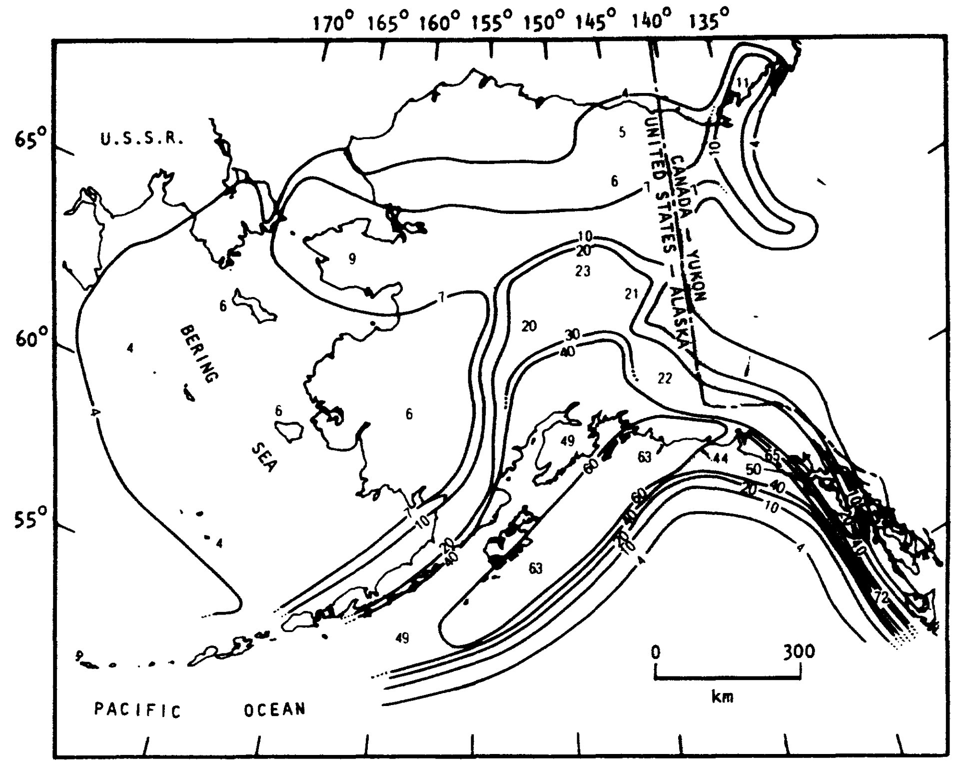

Figure 14.--Map showing maximum levels of peak horizontal ground acceleration expected in Alaska in an exposure time of 50 years at sites underlain by bedrock (Algermissen et al, 1982). The corresponding return period is approximately 500 years (actually 474 years). The values of peak bedrock acceleration have a 90 percent probability that they will not be exceeded in a 50-year period. Soil effects must be considered separately.

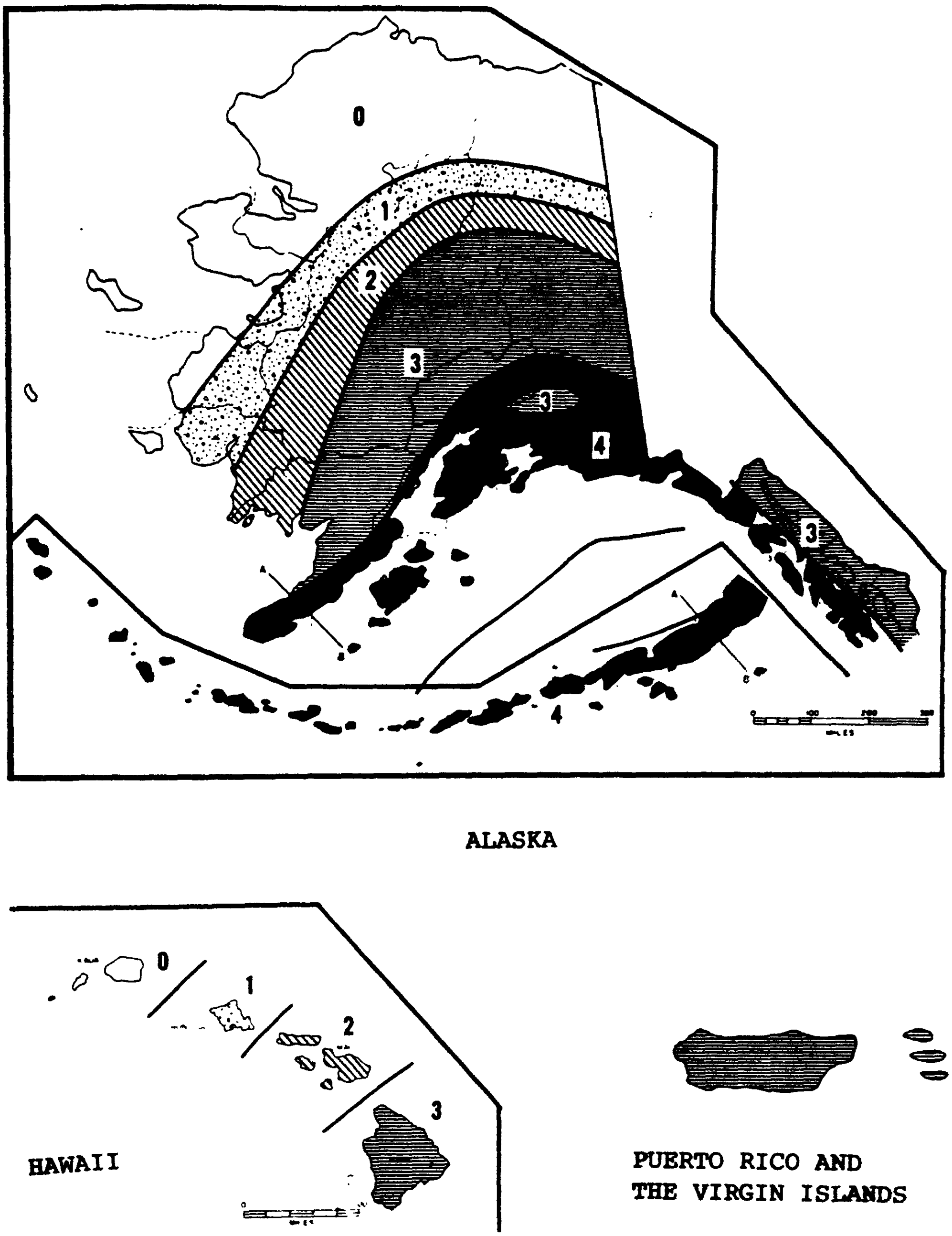

Figure 15.--Map showing seismic zones for Alaska, Hawaii, Puerto Rico, and the Virgin Islands (from Uniform Building Code).

Figure 16 shows examples of probabilistic bedrock ground-shaking hazard curves derived from the maps for various urban areas as a function of exposure time. These curves can also be presented in terms of return period. The correlation shown in Figure 17 provides insight into the differences.

These curves can also be presented in terms of return period. The relative values between locations are very stable although absolute values may be somewhat uncertain.

7.4 UNCERTAINTY

The question of uncertainty in the basic data is a fundamental problem that must be faced in the evaluation of seismic hazards (Hays, 1980; McCann, 1983). Although basic knowledge now exists about the physical parameters that control ground motion, knowledge of the statistical distribution of the parametric relations is limited (see Table 10). Additional geologic, geophysical, and engineering data are needed to reduce the level of uncertainty and to approach the irreducible level of uncertainty. Some of the empirical relations currently used to estimate the characteristics of ground shaking have large uncertainty.

7.5 LITERATURE

The literature contains numerous maps and reports which can be used as "design aids" when evaluating seismic hazards and determining the appropriate seismic-design parameters for a Federal construction site. A number of Federal

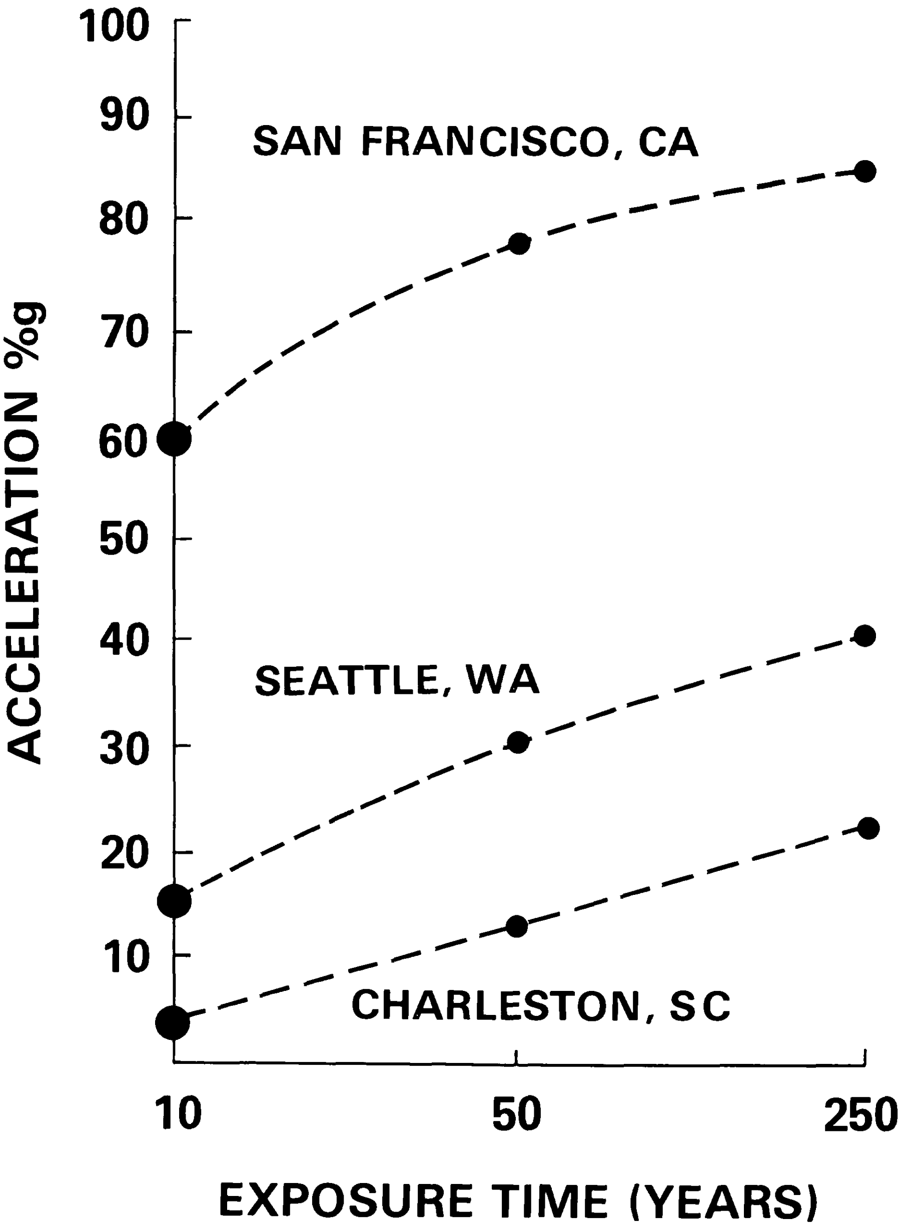

Figure 16.--Example of probabilistic ground-shaking hazard curves for sites underlain by bedrock in the United States. This type of representation of the ground-shaking hazard can be used in establishing the level of acceptable risk. These curves are based on data from Algermissen et al (1982) and having 90 percent probability of not being exceeded. Building codes typically are based on the 500-year return period acceleration (i.e., an annual probability of exceedance of 0.002). As an approximation, a 500-year return period correlates roughly with a 50-year exposure time (useful life of the structure). Although controversy exists about the actual value of peak acceleration at a location, the relative values between sites are stable.

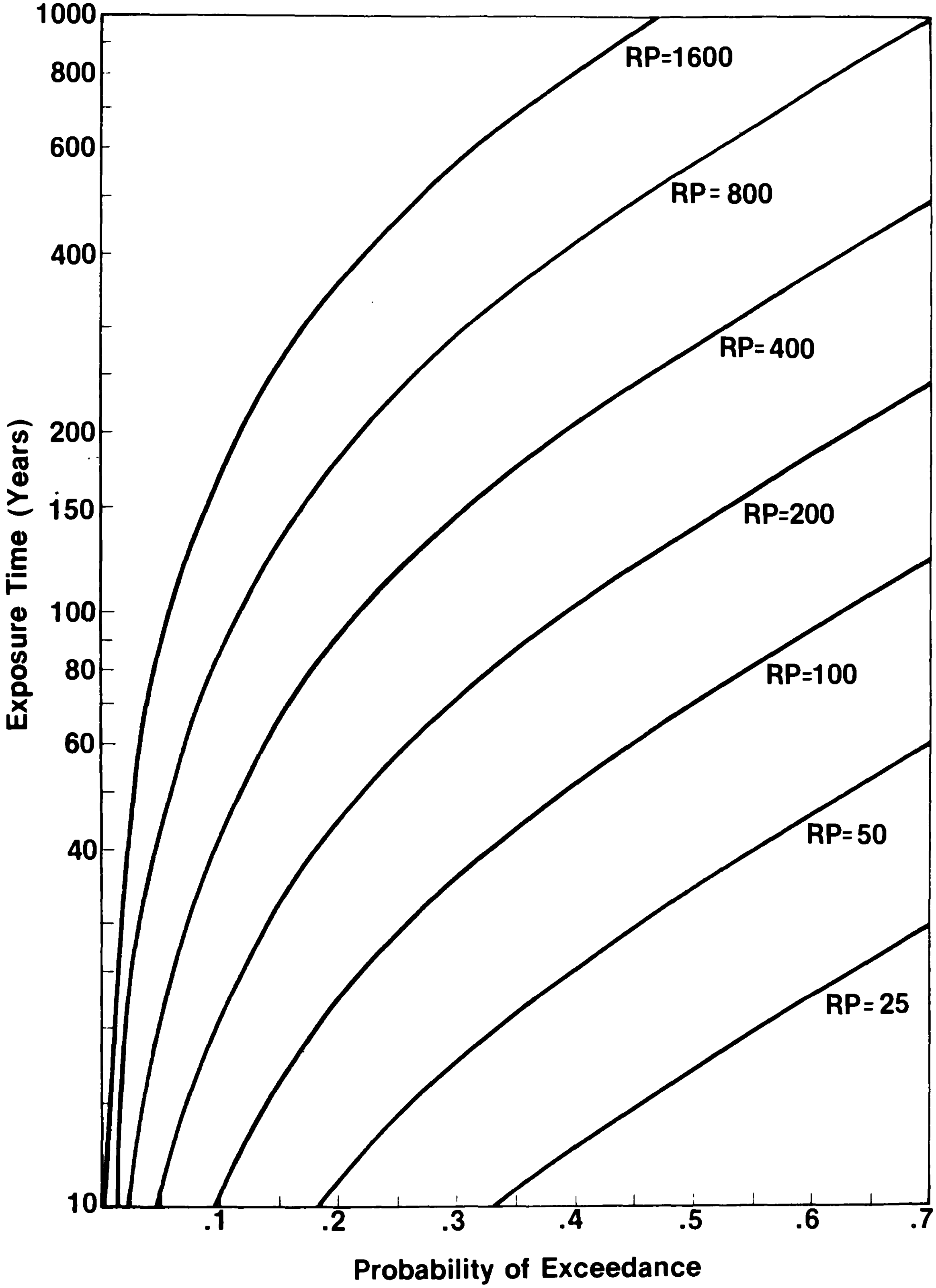

Figure 17.--Graph showing the relation between return period (RP), exposure time, and probability of exceedance.

THE UNCERTAINTY IN PHYSICAL PARAMETERS THAT AFFECT GROUND MOTION

PHYSICAL PARAMETER	EFFECT ON GROUND MOTION	UNCERTAINTY AND FUNCTIONAL DEPENDENCE
SEISMICITY PARAMETERS		
SEISMIC SOURCE ZONE	ZONE SHAPE AFFECTS GROUND MOTION LEVEL	NOT KNOWN. FUNCTION OF SEISMICITY RECORD, GEOLOGIC AND TECTONIC HISTORY
RECURRENCE RATE (b)	AFFECTS UPPER BOUND EARTHQUAKE	$\bar{b} = 0.45$ IN EASTERN U.S. WHERE $\text{Log } N = a - bI$; $\sigma = f(N)$
UPPER BOUND EARTHQUAKE	ESTABLISHES GROUND MOTION DESIGN LEVELS	NOT KNOWN. FUNCTION OF COMPLETNESS AND LENGTH OF SEISMICITY RECORD AND GEOLOGIC DATA ON FAULT RUPTURE.
SOURCE PARAMETERS		
EPICENTER	ESTABLISHES LOCATION OF DESIGN EARTHQUAKE	BEST LOCATION ACCURACY IS 1 KM; WORST IS 50 KM. FUNCTION OF REGIONAL VELOCITY MODEL AND INSTRUMENT LOCATIONS.
FOCAL DEPTH	AFFECTS PARTITION OF BODY/SURFACE WAVE ENERGY	BEST LOCATION ACCURACY IS 2 KM; WORST IS 50 KM. FUNCTION OF REGIONAL VELOCITY MODEL AND INSTRUMENT LOCATIONS.
MAGNITUDE (m_b, M_L, M_S)	AFFECTS LOW FREQUENCIES; GROUND MOTION SCALING	BEST ACCURACY IS 0.1 UNIT; WORST IS >1 UNIT. FUNCTION OF INSTRUMENTS AND SITE CALIBRATION.
SEISMIC MOMENT (M_0)	AFFECTS LOW FREQUENCIES, ESPECIALLY FOR GREAT EARTHQUAKES	$\text{Log } M_0 \sim 3/2\, M_S$ until $M_0 \geq 10^{28}$dyne-cm. $M_0 = 21.9 + 3 \log L$ WITH $1\sigma \cong 2.$ FUNCTION OF INSTRUMENT DYNAMIC RANGE.
STRESS DROP ($\Delta\sigma$) AND EFFECTIVE STRESS	AFFECTS HIGH FREQUENCIES; PEAK ACCELERATION	$\Delta\sigma$ HAS A LOG-NORMAL DISTRIBUTION. EARTHQUAKES EXHIBIT A CONSTANT AVERAGE STRESS DROP OF ABOUT 10 BARS WITH $2\sigma \cong 10$. FUNCTION OF MOMENT DETERMINATION.
FAULT LENGTH (L)	AFFECTS MAGNITUDE AND MOMENT	M_L=1.235+1.243 Log L; σ=0.93
EPICENTRAL INTENSITY (I_0)	AFFECTS SITE ACCELERATION (a_H AND a_V)	$\text{Log } a_H = 0.24\, I_{MM} + 0.26$; $1\sigma = 2.19$ } $\text{Log } a_V = 0.28\, I_{MM} - 0.40$; $1\sigma = 2.53$ } WORLDWIDE DATA
PATH PARAMETERS		
RATE OF ATTENUATION OF SEISMIC ENERGY WITH DISTANCE	ESTABLISHES PEAK GROUND MOTION VALUES AT SITE AND FREQUENCY DEPENDENT SIGNATURE	NOT WELL DEFINED BECAUSE OF LIMITATIONS ON DATA SAMPLE. 1σ FOR PEAK ACCELERATION vs DISTANCE RELATION IS 2.01 FOR WORLDWIDE DATA; 1.62 FOR THE SAN FERNANDO EARTHQUAKE. 1σ FOR PEAK VELOCITY vs DISTANCE IS 1.5 FOR MODERATE U.S. EARTHQUAKES. 1σ FOR FREQUENCY-DEPENDENT ATTENUATION OF SPECTRAL VELOCITY RANGES FROM 1.61 TO 2.22 FOR A GENERAL AREA AND 1.58 TO 1.78 FOR A CALIBRATED'' AREA, ON THE BASIS OF NUCLEAR EXPLOSION DATA. THE STATISTICAL DISTRIBUTION FOR MM INTENSITY ATTENUATION IS NOT KNOWN.
LOCAL GROUND RESPONSE		
SOIL/ROCK ACOUSTIC IMPEDANCE ($\rho\beta$) CONTRAST	AFFECTS AMPLITUDE LEVEL OF GROUND MOTION	NOT WELL DEFINED. PHYSICAL PROPERTIES DEPEND ON GEOPHYSICAL AND LABORATORY MEASUREMENTS. GROUND MOTION DATA SAMPLE FOR EACH ROCK AND SOIL CLASSIFICATION IS SMALL.
SOIL THICKNESS AND GEOMETRY	AFFECTS DOMINANT FREQUENCY; DURATION; PSEUDO-ELLEPTICITY; DAMPING RATIO	NOT WELL DEFINED. DEPENDS ON GEOPHYSICAL, GEOLOGIC, BOREHOLE AND GROUND MOTION DATA.
STRAIN LEVEL	DETERMINES IF GROUND RESPONSE IS LINEAR OR NON-LINEAR	NOT WELL DEFINED BECAUSE OF LIMITATIONS OF THE GROUND MOTION DATA SAMPLE, ESPECIALLY CLOSE-IN.
MEAN GROUND RESPONSE	DETERMINES RELATIVE RESPONSE BETWEEN TWO SITES	REPEATABLE WITH $1\sigma = 1.30$ FOR NUCLEAR EXPLOSIONS AND 1.50 FOR EARTHQUAKE AFTERSHOCKS.

agencies (for example, U.S. Geological Survey, Nuclear Regulatory Commission, The U.S. Army Corps of Engineers Waterway Experiment Station, National Oceanic and Atmospheric Administration, Department of Energy) have produced maps and reports through their research programs. The following references identify pertinent information that Federal agencies can use in the evaluation of seismic hazards for earthquake-resistant design of their structures.

	MAP OR REPORT	REFERENCE
1)	Map of seismic source zones in the U.S.	Algermissen (1969); Algermissen and Perkins (1976); Algermissen and others (1982)
2)	Probabilistic map of peak ground acceleration in U.S. (exposure time of 50 years; approximate return period of 500 years;incorporated in the model code of the Applied Technology Council)	Algermissen and Perkins (1976); Applied Technology Council (1978)
3)	Probabilistic maps of peak ground acceleration and peak ground velocity in U.S. (Exposure times of 10, 50, and 250 years; approximate return periods of 100, 500, and 2,500 years).	Algermissen and others (1982)
4)	Map showing young faults in U.S.	Howard and others (1977)
5)	Maps and catalogs of earthquake epicenters for the U.S.	Stover (1977) Coffman and others (1982)
6)	Improved earthquake locations	Dewey (1979)
7)	Seismotectonic maps	Hadley and Devine (1975); Heyl and McKeown (1978)
8)	Studies of recurrence intervals of faulting on specific faults	Bucknam and Anderson (1979)
9)	Analysis of earthquake hazards, San Francisco Bay region	Borcherdt (1975); Blair and Spangle (1980)

10	Estimation of seismic risk	Rinehart anand others (1976); Algermissen and others (1978 a, b); Algermissen and Steinbrugge (1984)
11)	Postearthquake investigations	USGS and NOAA (1971); Espinosa (1976); Rankin (1977); McKeown and Pakiser (1982); and Gohn (1983)
12)	Estimating earthquake ground motion	Hays and others (1975); Krinitzsky and Chang (1975); Herrmann (1977); Boore and others (1978); Vanmarcke (1979); Hays (1980 a); Kennedy and others (1984)
13)	Seismic hazards analysis	Yegian (1979); Hays (1981); Bernreuter (1982)
14)	Damping capacity of soil during dynamic loading; effect of soil and rock on ground motion	Rohani (1972); Hays (1984)
15)	Design earthquakes for the Central United States	Nuttli (1973); Nuttli and Herrmann (1978)
16)	Fault assessment in earthquake engineering	Krinitzsky (1974); Slemmons (1977 a, b); Boatwright (1982)
17)	Plate tectonics and earthquake assessment	Walper (1976)
18)	Stong motion earthquake records	Chang and Krinitzsky (1977); Chang (1978)
19)	Seismographic networks	Bolt and others (1978)
20)	Attenuation of high-frequency seismic waves in the Central Mississippi Valley	Nuttli and Dwyer (1978)
20)	Wave propagation	Bolt (1983)
21)	Soil structure interaction	Johnston (1981)
22)	Surface faulting	Russ (1979); Bonilla (1982)
23)	Liquefaction	Seed (1970); Youd and Hoose (1978); and Ferritto (1982)
24)	Earthquake preparedness	Hays (1981); Gori and Hays (1982); Hays and Gori (1983 a, b, c)
25)	Seismic safety guides for managers of a physical plant	Eagling (1983)

26) Tentative seismic design provisions National Bureau of Standards (1979)

Because earthquake engineering is a dynamic field, the state-of-the-art changes rapidly. Therefore, the basic literature will evolve continually with time.

8 EARTHQUAKE-RESISTANT DESIGN

8.1 TECHNICAL CONSIDERATIONS

No part of the United States is free from the potential losses caused by an earthquake; therefore, a careful evaluation of seismic hazards is needed to guide the selection of seismic-design parameters used in earthquake-resistant design. These parameters are utilized in the earthquake-resistant design for new Federal construction and in the assessment of risk for existing construction. Although the density of Federal construction varies throughout the Nation, every community (such as shown schematically in Figure 1,) has existing Federal structures and facilities that are exposed to the potential seismic hazards of ground shaking, surface faulting, tectonic deformation, earthquake-induced ground failure, and in some cases, tsunamis. In addition, new Federal structures and facilities are being planned and constructed and existing ones are being leased. Continuous research and analyses are underway to evaluate the seismic hazards and to assess the risk for a variety of structures ranging from ordinary buildings (whose seismic-design parameters are typically governed by some type of a building code) to a nuclear power plant (whose seismic-design parameters must satisfy stringent criteria contained in Appendix A to 10 CFR part 100 (U.S. Nuclear Regulatory Commission, 1983)). In the case of ordinary buildings, the aim of the building code is to provide a minimum standard that will enable the buildings to: 1) resist minor earthquakes without damage, 2) resist moderate earthquakes without structural damage, but with some nonstructural damage, and 3) to resist major earthquakes with structural and nonstructural damage, but without collapse in order to prevent loss of life. In the case of a nuclear power plant, earthquake-resistant design is more complex because the aim is to withstand the effects of earthquakes without loss of capability to perform safety functions.

Earthquake-resistant design of a structure or facility requires close cooperation between the architect and the engineer and is based on the application of knowledge about: 1) the regional seismic hazards, 2) the response of the structure or facility to each of these hazards, 3) the performance of structural elements under earthquake-induced forces and deformation, and 4) the desired safety factor, or the acceptable risk. With this knowledge, the proper size and shape of the structural members can be determined and the appropriate lateral force-resisting system can be prescribed in a way that will lead to satisfactory performance of the structure in an earthquake.

Aside from critical facilities, in regions of the United States where earthquakes occur infrequently (e.g., the Eastern United States), the philosophy of structural design often is primarily to resist the force of gravity, secondarily to resist the horizontal force of the wind, and thirdly to resist earthquake ground shaking. In regions where earthquakes occur frequently (e.g., California), the structural design also primarily seeks to resist the vibratory forces generated by earthquake ground shaking, a more complicated design problem. When a building is subjected to earthquake ground shaking, its base tends to move with the ground, and it must resist the stresses and deformations that occur throughout the structure. If the building is very stiff (e.g., a low-rise building, a nuclear power plant) the entire structure moves with the ground, and the dynamic forces induced in the building are nearly equal to those associated with the ground acceleration. If the building is flexible, differential motions of the supports and floors can induce large dynamic deformations, but the dynamic forces are much less. To survive earthquake ground shaking, a rigid building must be strong enough to resist the induced forces; if the building is flexible, it must be able to accommodate the deformations without collapsing. Experience in past earthquakes has shown that earthquake ground shaking always will find every weakness in the lateral-force-resisting system of a structure or facility.

The earthquake resistance of a building is achieved by the proper selection, designing, detailing, and construction of the lateral force-resisting system. Such a building has: 1) a configuration that is simple in plan and elevation; 2) the same relative degree of stiffness throughout the elements of the structural system resisting the lateral forces; 3) all structural elements securely tied together as a unit. In general, an earthquake-resistant building has a lateral force-resisting system that is designed to be:

1) **continuous** - transfers all forces from their point of application to their point of resistance.

2) **ductile** - materials remain stable when deformed beyond yield limits.

3) **complete** - no missing links, inadequate joints or anchorages, or brittle elements.

Design of structures and facilities to resist earthquake ground shaking presents a different set of problems from those encountered in the design of structures to resist operational loads such as those caused by wind. Normal operational loads occur more frequently than earthquake loads during the lifetime of a structure; therefore technical experience accumulates fairly rapidly and can be integrated fairly quickly into building codes and standard practice. In contrast, the occurrence of strong earthquake ground shaking at a given site is a rare event, even in the earthquake-prone areas of the Nation. Consequently, many structures and facilities complete their useful lifetimes (e.g., 30-50 years) without being subjected to the intense ground shaking and other geologic phenomena that occur in the epicentral region of a major earthquake. The low frequency of occurrence of severe ground shaking at a given site influences policies and decisions with regard to earthquake-resistant design in several ways: 1) in some locations, it fosters an attitude that the seismic hazards of ground shaking, surface faulting, tectonic deformation, and earthquake-induced ground failure can be safely ignored, 2) motivation for programs to obtain data and experience is often lacking, and 3) building codes and standard practice lag about 10 years behind the accumulation of knowledge. As an example, the program to measure strong ground motion in the United States was started in 1933. After a half century, a relatively small sample of accelerograms has been acquired, mostly from California earthquakes. The strong ground-motion data base outside of California is much smaller.

8.2 LESSONS LEARNED FROM PAST EARTHQUAKES

Recent earthquakes, combined with research, have greatly increased knowledge about building damage and failure. On the basis of these data, the main reasons (not in order of priority) for building damage can be generalized as follows:

1) Underestimation of the effect on the structure of the interrelation between amplitude, frequency composition, and duration of ground shaking.

2) Underestimation (or no estimates at all) of the geotechnical properties of the foundation materials with respect to their potential for liquefaction, differential settlement, and landslides. (For example, liquefaction and lateral spreading were a major source of damage in the 1906 San Francisco and 1964 Prince William Sound earthquakes.)

3) Choosing lateral force-resisting systems that are not seismically resistant. (For example, unreinforced masonry, eccentric shear walls, brittle concrete columns, hollow columns for utilization of conduits, poor materials, et cetera.)

4) Lack of adequate connections and detailing. (For example, brittle concrete welds, short reinforcing anchorage, missing hoops and stirrups, lack of reinforcing steel ties from walls to floors and roofs, et cetera.)

5) Omissions in engineering analysis. (For example, neglect of torsion effects, overturning effects, static equilibrium of all forces acting on a structure, et cetera.)

6) Poor quality of construction. (For example, improper placement of reinforcing, cutting of holes or openings in structural members, careless welding or bending of reinforcing steel, poorly prepared construction joints in concrete, low quality concrete, et cetera.)

7) Use of poor materials. (For example, brittle steel, poor concrete, poor masonry mortar and placement, et cetera.)

9 REFERENCES

Algermissen, S.T., 1983, An introduction to the seismicity of the United States, Earthquake Engineering Research Institute monograph, Berkeley, California, 148 p.

Algermissen, S. T., 1969, Seismic risk studies in the United States, World Conference on Earthquake Engineering, 4th, Santiago, Chile, proceedings, v. 1, 14 p.

Algermissen, S. T., and Perkins, D. M., 1976, A probabilistic estimate of maximum acceleration in rock in the contiguous United States, U.S. Geological Survey Open-File Report 76-416, 45 p.

Algermissen, S. T., McGrath, M. B., and Hanson, S. L., 1976a, Development of a technique for the rapid estimation of earthquake losses, U.S. Geological Survey Open-File Report 78-440, 98 p.

Algermissen, S. T., Steinbrugge, K. V., and Lagorio, H. L., 1978, Estimation of earthquake losses to buildings (except single family dwellings), U.S. Geological Survey Open-File Report 78-441, 161 p.

Algermissen, S. T., Perkins, D. M., Thenhaus, P. C., Hanson, S. L., and Bender, B. L., 1982, Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States, U.S. Geological Survey Open-file Report 82-1033, 99 p.

Algermissen, S. T., and Steinbrugge, K. V., 1984, Seismic hazard and risk assessment: some case studies, Proceedings of the first meeting of the international working group on natural disasters and insurance, Association Interationale pour l'etude de l'economie de l'assurance, v. 9, no. 30, p 8-26.

American Nuclear Society, 1977, Guidelines for combining natural and external manmade hazards at power reactor sites, ANSI N-635/ANS 2.12 (draft), 101 p.

American Nuclear Society, 1977, Guidelines for evaluating site-related geotechnical parameters, ANSI N-174/ANS 2.11, draft), 59 p.

American Nuclear Society, 1978, Guidelines for assessing capability of surface faulting at nuclear power reactor sites, ANSI N-180/ANS 2.4, 30 p.

American Nuclear Society, 1979, Guidelines for determining tsunami criteria for power reactor sites, ANSI N-515/ANS 2.4, (draft), 57 p.

American Nuclear Society, 1979, Guidelines for determining design basis flooding at power reactor sites, ANSI N-170/ANS 2.8 (draft), 153 p.

Applied Technology Council, 1978, Tentative provisions for the development of seismic regulations for buildings, ATC-3-06, 514 p. (Available from National Bureau of Standards, Special Publications 510, Washington, D.C.)

Boatwright, John, (editor), 1982, The dynamic characteristic of faulting inferred from recordings of strong ground motion, Proceedings of Conference XVI, U.S. Geological Surver Open-file Report 82-591, 2 vols., 976 p.

Bollinger, G. A., 1977, Reinterpretation of the intensity data for the 1886 Charleston, South Carolina, earthquake, in Rankin, D. W., (editor) Studies related to the Charleston, South Carolina, earthquake of 1886--a preliminary report, U.S. Geological Survey Professional Paper 1028, p. 17-32.

Bolt, B. A., Okubo, P., and Uhrhammer, R. A., 1978, Optimum station distribution and determination of hypocenters for small seismographic networks, U.S. Army Waterways Experiment Station, Miscellaneous Paper S-78-9, 43 p.

Bolt, B. A., 1983, The contribution of directivity focusing to earthquake intensities, U.S. Army Waterways Experiment Station, Miscellaneous Paper S-73-1, report 20, 93 p.

Bonilla, M. G., 1982, Evaluation of potential surface faulting and other tectonic deformation, U.S. Geological Survey Open-file Report 82-732, 88 p.

Boore, D. M., Joyner, W. B., Oliver, A. A., and Page, R. A., 1978, Estimation of ground-motion parameters, U.S. Geological Survey circular 795, 43 p.

Borcherdt, R. D., ed., 1975, Studies for seismic zonation of the San Francisco Bay region, U.S. Geological Survey Professional Paper 941-A, 102 p.

Bucknam, R. C., and Anderson, R. E., 1979, Estimation of fault-scarp ages from a scarp-height-slope-angle relationship, Geology, v. 7, p. 11-14.

Chang, F. K., 1978, State-of-the-art for assessing earthquake hazards in the United States, catalogue of strong motion earthquake records, Western United States, 1933-1971, U.S. Army Waterways Experiment Station, Report 9, Miscellaneous Paper S-73-1, 53 p.

Chang, F. K., and Krinitzsky, E. L., 1977, State-of-the-art for assessing earthquake hazards in the United States, duration, spectral content, and predominant period of strong motion earthquake records from Western United States, U.S. Army Waterways Experiment Station, Report 8, Miscellaneous Paper S-73-1, 82 p.

Coffman, J. L., Von Hake, C. A., and Stover, C. W., (editors), 1982, Earthquake history of the United States, U.S. Department of Commerce, NOAA, and U.S. Department of Interior, Geological Survey, Pub., 41-1, Rev. Ed.

Departments of the Army, the Navy, and the Air Force, 1973, Seismic Design for buildings, TM5-809-10 NAV FAC P-355, AFM 88-3, 50 p. (NOTE: This reference was updated in 1982.) (Available from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.)

Department of Housing and Urban Development, 1976, A methodology for seismic design and construction of single-family dwellings, HUD-PDR-248-1, 649 p. (Available from Dept. of Housing and Urban Development, Washington, D. C.)

Dewey, J. W., 1979, A consumer's guide to instrumental methods for determination of hypocenters; in Hatheway, A. W., and McClure, C. R., Jr., eds.: Geology in the siting of nuclear power plants; Geological Society of America Reviews in Engineering Geology, v. 4, p. 175-200.

Eagling, D. G., (editor), 1983, Seismic safety guide, Lawrence Berkeley Laboratory, University of California, LBL-9143, UC-11, 138 p.

Espinosa, A. F., ed., 1976, The Guatemalan earthquake of February 4, 1976, a preliminary report, U.S. Geological Survey Professional Paper 1002, 90 p.

Federal Highway Administration, 1977, Determination of seismically induced soil liquefaction potential at proposed bridge sites, theoretical considerations and planning guide for evaluation of liquefaction, Report No. FHWA-RD-77-127 and 128, 426 p.

Ferritto, J. M., 1982, Evaluation of Earthquake-induced Ground Failure, U.S. Geological Survey Open-file Report 82-880, 109 p.

General Services Administration, 1978, Design guidelines, earthquake resistance of buildings, v. 1, 56 p. (Available from GSA Business Service Center, Denver, CO)

Gori, P. L., and Hays, W. W., (editors), 1983, Continuing actions to reduce losses from earthquakes in the Mississippi Valley area, Proceedings of conference XVIII, U.S. Geological Survey Open-file Report 83-157, 159 p.

Hadley, J. B., and Devine, J. F., 1974, Seismotectonic map of the Eastern United States, U.S. Geological Survey Miscellaneous Field Studies Map MF-620.

Harris, J. R., and Leyendecker, E. V., 1981, Draft seismic standard for federal buildings, National Bureau of Standards, NBSIR 81-2195, 87 p.

Hays, W. W., 1980, Procedures for estimating earthquake ground motions, U.S. Geological Survey Professional Paper 1118, 77 p.

Hays, W. W., (editor), 1981, Evaluation of regional seismic hazards and risk, Proceeding of conference XIII, U.S. Geological Survey Open-file Report 81-437, 231 p.

Hays, W. W., (editor), 1982, Facing geologic and hydrologic hazards - earth science considerations, U.S. Geological Survey Professional Paper 1040-B.

Hays, W. W., (editor), 1982, Preparing for and responding to a damaging earthquake in the Eastern United States, Proceedings of conference XV, U.S. Geological Survey Open-file Report 82-220, 197 p.

Hays, W. W., (editor), 1983, Site-specific effects of soil and rock on ground motion and the implications for earthquake resistant design, Proceedings of conference XXII, U.S. Geological Survey Open-file Report 83-845, 501p.

Hays, W. W., Algermissen, S. T., Espinosa, A. F., Perkins, D. M., and Rinehart, W. A., 1975, Guidelines for developing design earthquake response spectra, U.S. Army Construction Engineering Research Laboratory Technical Report M-1114, 369 p. (Available from National Technical Information Service, ADAO 12278)

Hays, W. W., and Gori, P. L., (editors), 1983 a, The 1886 Charleston South Carolina earthquake and its implications for today, Proceedings of conference XX, U.S. Geological Survey Open-file Report 83-843, 502 p.

Hays, W. W., and Gori, P. L., (editors), 1983 b, Continuing actions to reduce potential losses form future earthquakes in the Northeastern United States, Proceedings of conference XXI, U.S. Geological Survey Open-file Report 83-844, 173 p.

Hays, W. W., and Gori, P. L., (editors), 1983 c, Continuing actions to reduce potential losses from future earthquakes in Arkansas and nearby states, Proceedings of conference XXIII, U.S. Geological Survey Open-file Report 83-846, 234 p.

Herrmann, R. B., 1977, Earthquake generated SH waves in the near field and near-regional field, U.S. Army Waterways Experiment Station, Miscellaneous Paper S-77-12, 51 p.

Heyl, A. V., and McKeown, F. A., 1978, Preliminary seismotectonic map of Central Mississippi Valley and environs, U.S. Geological Survey Miscellaneous Field Studies Map MF-1011, 1:500,000.

Hopper, M., Algermissen, S. T., and Dobrovolny, E. E., 1983, Estimation of earthquake effects associated with a great earthquake in the New Madrid seismic zone, _in_ Hays, W. W., and Gori, P. L., (editors), 1983 c, Continuing actions to reduce potential losses from future earthquakes in Arkansas and nearby states, Proceedings of conference XXIII, U.S. Geological Survey Open-file Report 83-846, pp. 31-112.

Howard, K. A., Aaron, J. M., Brabb, E. E., Brock, M. R., Gower, H. D., Hunt, S. J., Milton, D. J., Muehlberger, W. R., Nakata, J. K., Plafker, G., Prowell, D. C., Wallace, R. E., and Witkind, I. J., 1977, Preliminary map of young faults in the United States as a guide to possible fault activity, U.S. Geological Survey Miscellaneous Field Studies Map MF-916, 1:5,000,000 and 1:7,500,000.

Johnson, J. J., 1981, Soil structure interaction: the status of current analysis methods and research, U.S. Nuclear Regulatory Commission, NUREG/CR-1780, UCRL-53011, 375 p.

Kennedy, R. P., Short, S. A., Merz, K. L., Torkarz, F. J., Idriss, I. M., Power, M. S., and Sadigh, K., 1984 Engineering characterization of ground motion, Nuclear Regulatory Commission, NUREG-CR-3805, 275 p.

Krinitzsky, E. L., 1975, State-of-the-art for assessing earthquake hazards in the United States, earthquake intensity and the selection of ground motion for earthquake design, U.S. Army Waterways Experiment Station, Report 4, Miscellaneous Paper S-73-1, 58 p.

Krinitzsky, E. L., 1974, State-of-the-art for assessing earthquake hazards in the United States, fault assessment in earthquake engineering, U.S. Army Waterways Experiment Station, Report 2, Miscellaneous Paper S-73-1, 82 p.

Krinitzsky, E. L., and Chang, F. K., 1977, State-of-the-art for assessing earthquake hazards in the United States, specifying peak motions for design earthquakes, U.S. Army Waterways Experiment Station, Report 7, Miscellaneous Paper S-73-1, 34 p.

Krinitzsky, E. L. and Marcusson, W. F., 1983, Considerations in selecting earthquake motions for the engineering design of large dams, U.S. Geological Survey Open-file Report 83-636, 57 p.

McCann, M. W., 1983, Uncertainity in ground motion predictions, in Hays, W. W., (editor), Site-specific effects of soil and rock on ground motion and the implications for earthquake-resistant design, Proceedings of Conferences XXII, U.S. Geological Survey Open-file report 83-845, p 331-353.

McKeown, F. A., and Pakiser, L. C., 1982, Investigations of the New Madrid, Missouri, earthquake region, U.S. Geological Survey Professional Paper 1236, 201 p.

National Bureau of Standards, 1979, Analysis of tentative seismic design provisions for buildings, National Bureau of Standards Technical Note 1100, 594 p.

National Oceanic and Atmospheric Administration and U.S. Geological Survey, 1979, Inventory of natural hazards data resources in the Federal Government, National Geophysical and Solar Terrestrial Data Center, 122 p.

Nuttli, O. W., 1973, State-of-the-art for assessing earthquake hazards in the United States, design earthquakes for the Central United States, U.S. Army Waterways Experiment Station, Report 1, Miscellaneous Paper S-73-1, 48 p.

Nuttli, O. W., and Dwyer, J. J., 1978, State-of-the-art for assessing earthquake hazards in the United States, attenuation of high-frequency seismic waves in the Central Mississippi Valley, U.S. Army Waterways Experiment Station, Report 10, Miscellaneous Paper S-73-1, 75 p.

Nuttli, O. W., and Hermann, R. B., 1978, State-of-the-art for assessing earthquake hazards in the United States, credible earthquakes for the Central United States, U.S. Army Waterways Experiment Station, Report 12, Miscellaneous Paper S-73-1, 100 p.

Petak, W. J., and Atkisson, A. A., 1982, Natural hazard risk assessment and public policy, Springer Verlag publishing Co., New York, 489 p.

Rankin, D. W., 1977, Studies related to the Charleston, South Carolina, earthquake of 1886, a preliminary report, U.S. Geological Survey Professional Paper 1028, 204 p.

Rinehart, W. A., Algermissen, S. T., and Gibbons, M., 1976, Estimation of earthquake losses to single-family dwellings, U.S. Geological Survey Open-File Report 6-156, 185 p.

Rohani, B., 1972, Damping capacity of soil during dynamic loading, review of mathematical models, U.S. Army Waterways Experiment Station, Report 1, Miscellaneous Paper S-72-11, 44 p.

Russ, D. P., 1979, Late Holocene faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee, Geological Society of American Bulletin, pt. 1, v. 90, no. 11, p. 1013-1018.

Seed, H. B., 1970, Soil problems and soil behavior, in Weigel, R. L., (editor), Earthquake engineering, Englewood Cliffs, N.J., Prentice-Hall, Inc. p. 227-252.

Slemmons, D. B., 1977, State-of-the-art for assessing earthquake hazards in the United States, faults and earthquake magnitude, U.S. Army Waterways Experiment Station, Report 6, Miscellaneous Paper S-73-1, 166 p.

Slemmons, D. B., and McKinney, R., 1977, Definition of active fault, U.S. Army Waterways Experiment Station, Miscellaneous Paper S-77-8, 22 p.

Stover, C. W., 1977, Seismicity map of the conterminous United States and adjacent areas, U.S. Geological Survey Miscellaneous Field Studies Map MF-812, 1:500,000.

Uniform Building Code, 1970, International conference of building officials, Whittier, Calif., (updated every three years) 704 p.

United States Nuclear Regulatory Commission, 1983, Seismic and Geologic Siting Criteria for Nuclear Power Plants, 10 CFR Part 100, Appendix A.

United States Geological Survey and National Oceanic and Atmospheric Administration, 1971, The San Fernando, California earthquake of February 9, 1971, U. S. Geological Survey Professional Paper 733, 254 p.

United States Nuclear Regulatory Commission, 1981, Standard Review Plan, NUREG 0800.

Vanmarcke, E. H., 1979, State-of-the-art for assessing earthquake hazards in the United States, representation of earthquake ground motion: scaled accelerograms and equivalent response spectra, U.S. Army Waterways Experiment Station, Report 14, Miscellaneous Paper S-73-1, 83 p.

Veterans Administration, 1973, Earthquake resistant design requirements for VA hospital facilities, Handbook H-08-8, 36 p. (Available from Veterans Admin., Washington, D. C.)

Walper, J. L., 1976, State-of-the-art for assessing earthquake hazards in the United States, plate tectonics and earthquake assessment, U.S. Army Waterways Experiment Station, Report 5, Miscellaneous Paper S-73-1, 106 p.

Yegian, M. K., 1979, State-of-the-art for assessing earthquake hazards in the United States, probabilistic seismic hazard analysis, U.S. Army Waterways Experiment Station, Report 13, Miscellaneous Paper S-73-1, 133 p.

Youd, T. L., and Hoose, S. N., 1978, Historic ground failures in northern California, triggered by earthquakes, U.S. Geological Survey Professional Paper 993, 177 p.

10 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.

Exceedance 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 over a very long period of time, 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 geographic 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.

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