Chapter 3
Development of Site-Specific Response Spectra for Seismic Analysis of Concrete Hydraulic Structures

Section I
Introduction

3-1. Purpose and Scope

This chapter describes procedures for developing site-specific response spectra of ground motions throughout the United States for seismic analyses of hydraulic structures. Also covered, but in less detail, are approaches for developing acceleration time-histories of ground motions. Section I provides an overview of the general approaches to developing site-specific response spectra, a brief discussion of factors influencing earthquake ground motions, and a brief discussion of differences in ground motion characteristics in different regions of the United States. This is followed in Sections II and III by descriptions of procedures for developing site-specific response spectra using deterministic and probabilistic approaches, respectively.

3-2. General Approaches for Developing Site-Specific Response Spectra

The two general approaches for developing site-specific response spectra are the deterministic and probabilistic approaches.

a. Deterministic approach.

(1) General. In this approach, often termed a deterministic seismic hazard analysis, or DSHA, site ground motions are deterministically estimated for a specific, selected earthquake, that is, an earthquake of a certain size on a specific seismic source occurring at a certain distance from the site. The earthquake size may be characterized by magnitude or by epicentral intensity. In the WUS, the practice has been to use magnitude, whereas in the EUS, both magnitude and Modified Mercalli Intensity (MMI) have been used. However, in the EUS, magnitude is increasingly being used as the measure of earthquake size, and ground motions are correspondingly being estimated using correlations with magnitude. In this manual, ground motions are estimated using relationships with magnitude. For procedures for estimating ground motions as a function of intensity, reference should be made to the state-of-the-art publication by Krinitzsky and Chang (1987).

(2) Size and location of design earthquakes. In the deterministic approach, earthquake magnitude is typically selected to be the magnitude of the largest earthquake judged to be capable of occurring on the seismic source, i.e., MCE. The selected earthquake is usually assumed to occur on the portion of the seismic source that is closest to the site (an exception is the “random earthquake” analysis described in Section II and Appendix D). After the earthquake magnitude and distance are selected, the site ground motions are then estimated using ground motion attenuation relationships or other techniques. Procedures for deterministically estimating earthquake ground motions are described in Section II.

b. Probabilistic approach. In the probabilistic approach, often termed a probabilistic seismic hazard analysis, or PSHA, site ground motions are estimated for selected values of the probability of ground motion exceedance in a design time period or for selected values of annual frequency or return period for ground motion exceedance. As an example, ground motions could be estimated for a 10 percent probability of exceedance in 100 years or for a return period of 950 years. The probabilistic approach thus provides an expression of potential earthquake loading in terms analogous to those used for other environmental loads in civil engineering design such as wind and flood loading. A probabilistic ground motion assessment incorporates the frequency of occurrence of earthquakes of different magnitudes on the seismic sources, the uncertainty of the earthquake locations on the sources, and the ground motion attenuation including its uncertainty. Section III describes the procedures for probabilistically estimating earthquake ground motions.

3-3. Factors Affecting Earthquake Ground Motions

a. General. As stated in paragraph 1-8, It has been well-recognized that earthquake ground motions are affected by earthquake source conditions, source- to-site transmission path properties, and site conditions. The source conditions include the stress drop, source depth, size of the rupture area, slip distribution (amount and distribution of static displacement on the fault plane), rise time (time for the fault slip to complete at a given point on the fault plane), type of faulting, and rupture directivity. The transmission path properties include the crustal structure and the shear-wave velocity and damping characteristics of the crustal rock. The site conditions include the rock properties beneath the site to depths of up to about 2 km, the local soil conditions at the site to depths of up to several hundred feet, and the topography of the site. In developing relationships for estimating ground motions, the effects of source, path, and site have been commonly represented in a simplified manner by earthquake magnitude, source-to-site distance, and local subsurface conditions. The important influences of these factors on ground motion are summarized below.

b. Effects of earthquake magnitude and distance on ground motions.

(1) General. The effects of earthquake magnitude and distance on the amplitude of ground motions are well known; ground motion amplitudes tend to increase with increasing magnitude and decreasing distance. However, the effects of magnitude and source-to-site distance on relative frequency content (response spectral shape) and duration of ground motions are not as well known and therefore are briefly reviewed below.

(2) Effects of magnitude. The Guerrero, Mexico, accelerograph array data illustrate the large effect of magnitude on the relative frequency content and duration of earthquake ground motions. The Guerrero array has provided recordings of rock motions over a wide range of magnitudes. Figures 3-1 and 3-2 show the accelerograms and the corresponding response spectra for six recordings selected by Anderson and Quaas (1988) to be approximately equally spaced in magnitude from the smallest event of magnitude 3.1 to the largest of magnitude 8.1. Figure 3-1 illustrates the effect of magnitude on the duration of the strong shaking part of an accelerogram; with increasing magnitude, duration rapidly increases. All events have epicenters about 25 km from the station, and all stations are on hard rock (Anderson and Quaas 1988). Figure 3-2 illustrates that the larger magnitude events have somewhat larger spectral amplitudes at high frequencies and much larger spectral amplitudes at long periods. In other words, increasing magnitude results in greatly enriched relative frequency content (higher spectral shapes) at long periods. Figure 3-3 illustrates a generalization of the effect of magnitude on response spectral shape, in this case, from the empirically based attenuation relationships for rock developed by Sadigh et al. (1993).

(3) Effects of distance. Data from the Loma Prieta earthquake of October 17, 1989, provide an example of the effect of distance on response spectral shape. Figure 3-4 shows that the spectral shape of the recordings obtained on rock during this earthquake reduce in the high-frequency range and increase in the long-period range with increasing distance. A generalization of the effect of distance on spectral

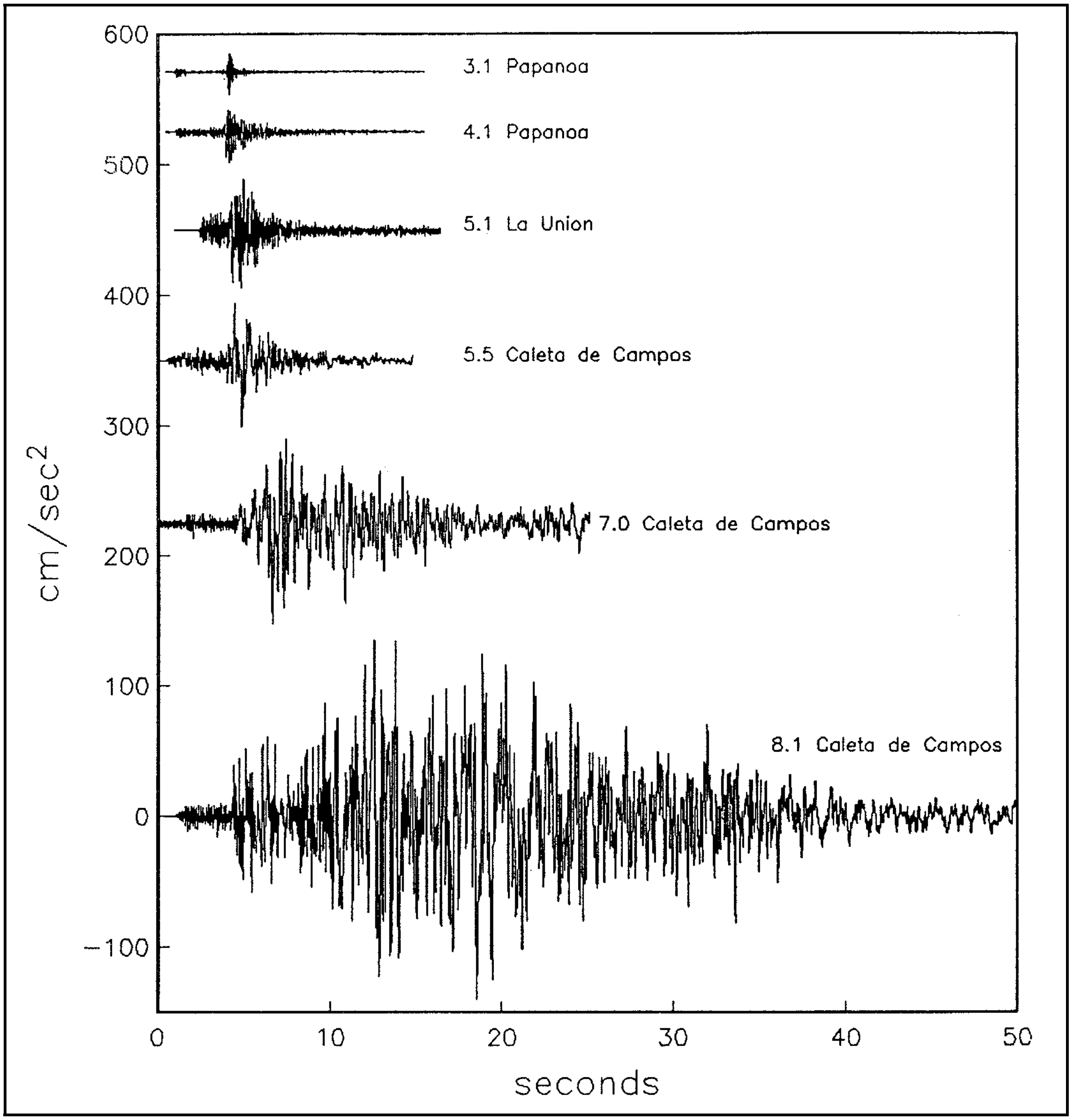


Figure 3-1. An example of accelerograms recorded in 1985 and 1986 on the Guerrero accelerograph array (Anderson and Quaas (1988), courtesy of Earthquake Engineering Research Institute, Oakland, CA)

shape, in this case from the theoretically based relationships for rock of Silva and Green (1989), is illustrated in Figure 3-5. In general, within source-to-site distances of about 50 km, the effect of distance on spectral shape is much smaller than the effect of magnitude. Similarly, although the relative duration of the strong shaking part of an accelerogram tends to increase with increasing distance (e.g., Dobry, Idriss, and Ng 1978), this effect appears to be relatively small within 50 km of an earthquake source.

(4) Special effects of near-source earthquakes. Near the earthquake source (within approximately 10 to 15 km of the source), earthquake ground motions often contain a high-energy pulse of medium-to-long-period ground motion (at periods in the range of approximately 0.5 to 5 sec) that occurs when fault

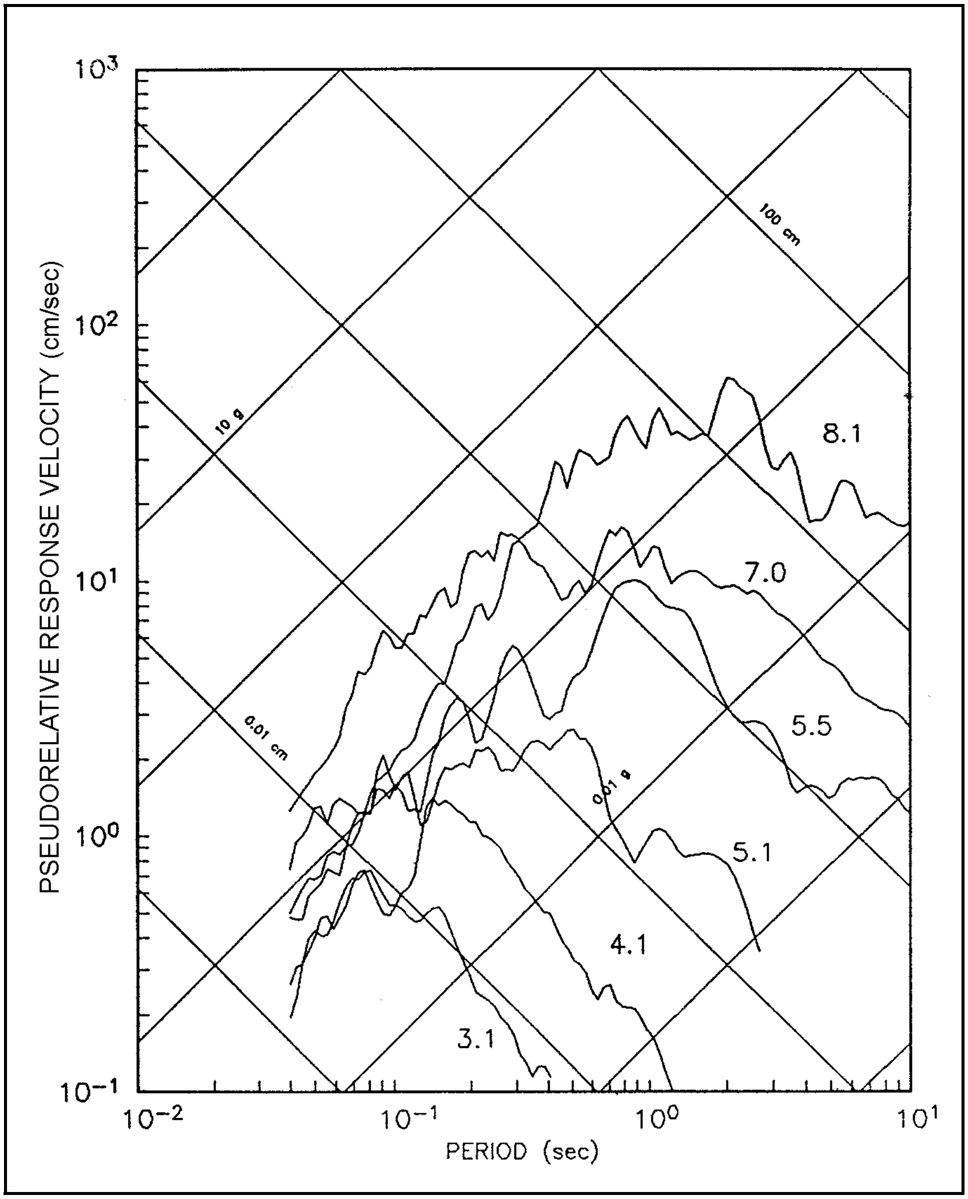


Figure 3-2. Response spectra (5 percent damped, pseudo-relative velocity) corresponding to the acceleration traces in Figure 3-1 (Anderson and Quaas (1988), courtesy of Earthquake Engineering Research Institute, Oakland, CA)

rupture propagates toward a site. It has also been found that these pulses exhibit a strong directionality, with the component of motion perpendicular (normal) to the strike of the fault being larger than the component parallel to the strike (see, for example, Sadigh et al. 1993; Somerville and Graves 1993; Somerville et al. 1997). These characteristics of near-source ground motions are illustrated by the Rinaldi recording obtained during the 1994 Northridge earthquake (Figure 3-6). These characteristics should be included in ground motion characterization for near-source earthquakes.

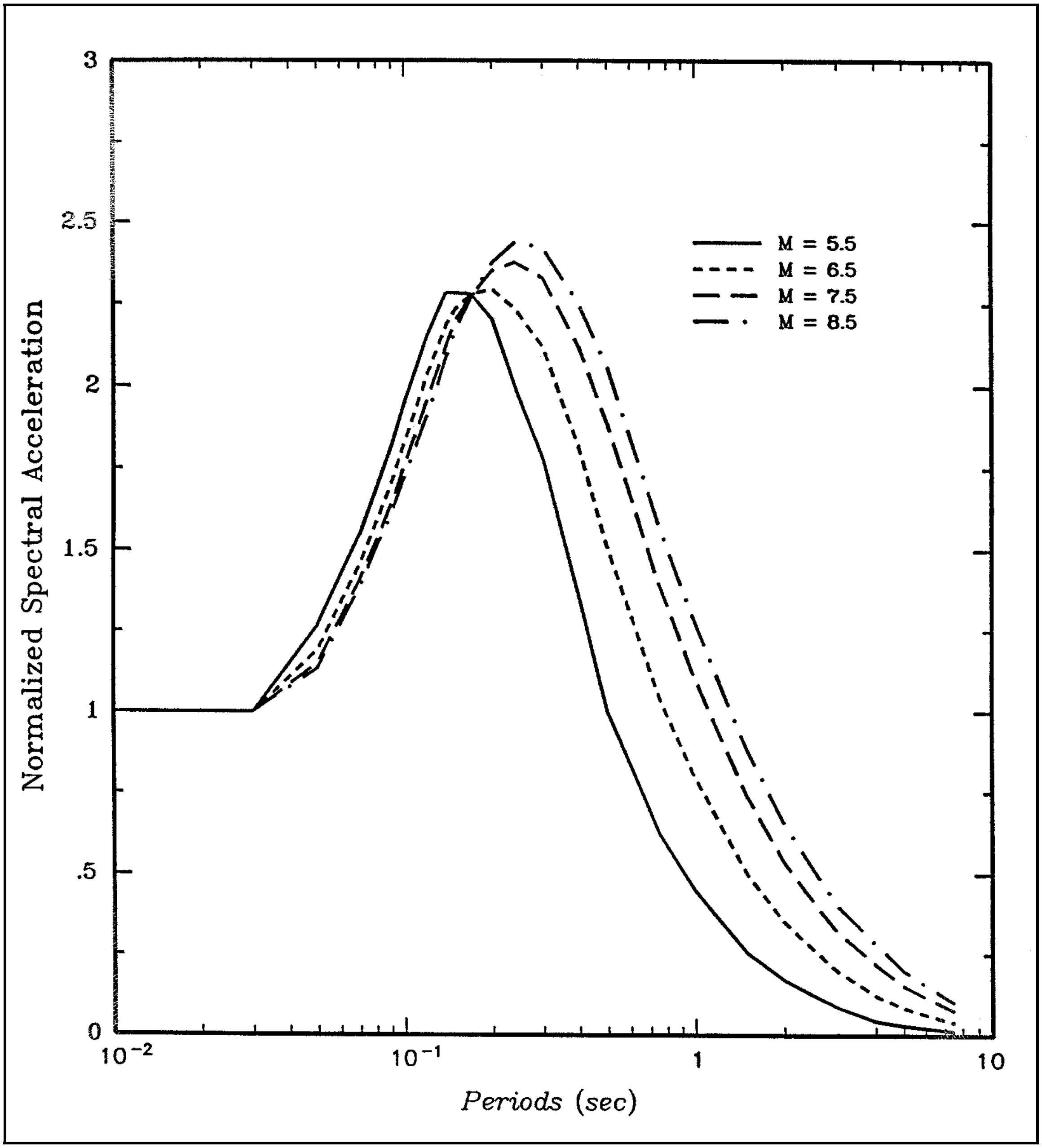


Figure 3-3. Effect of magnitude *M* on response spectral shape of rock motions based on attenuation relationships of Sadigh et al. (1993), 30-km distance from source to site, 5 percent damping

c. Effect of local subsurface conditions on ground motions.

(1) General. It is well established that local soil conditions have a major effect on the amplitude and response spectral characteristics of earthquake ground motions. It was demonstrated again by the dramatic differences in ground motions in different parts of Mexico City in the 1985 Mexico earthquake, and in different locations in the San Francisco Bay Area in the 1989 Loma Prieta earthquake.

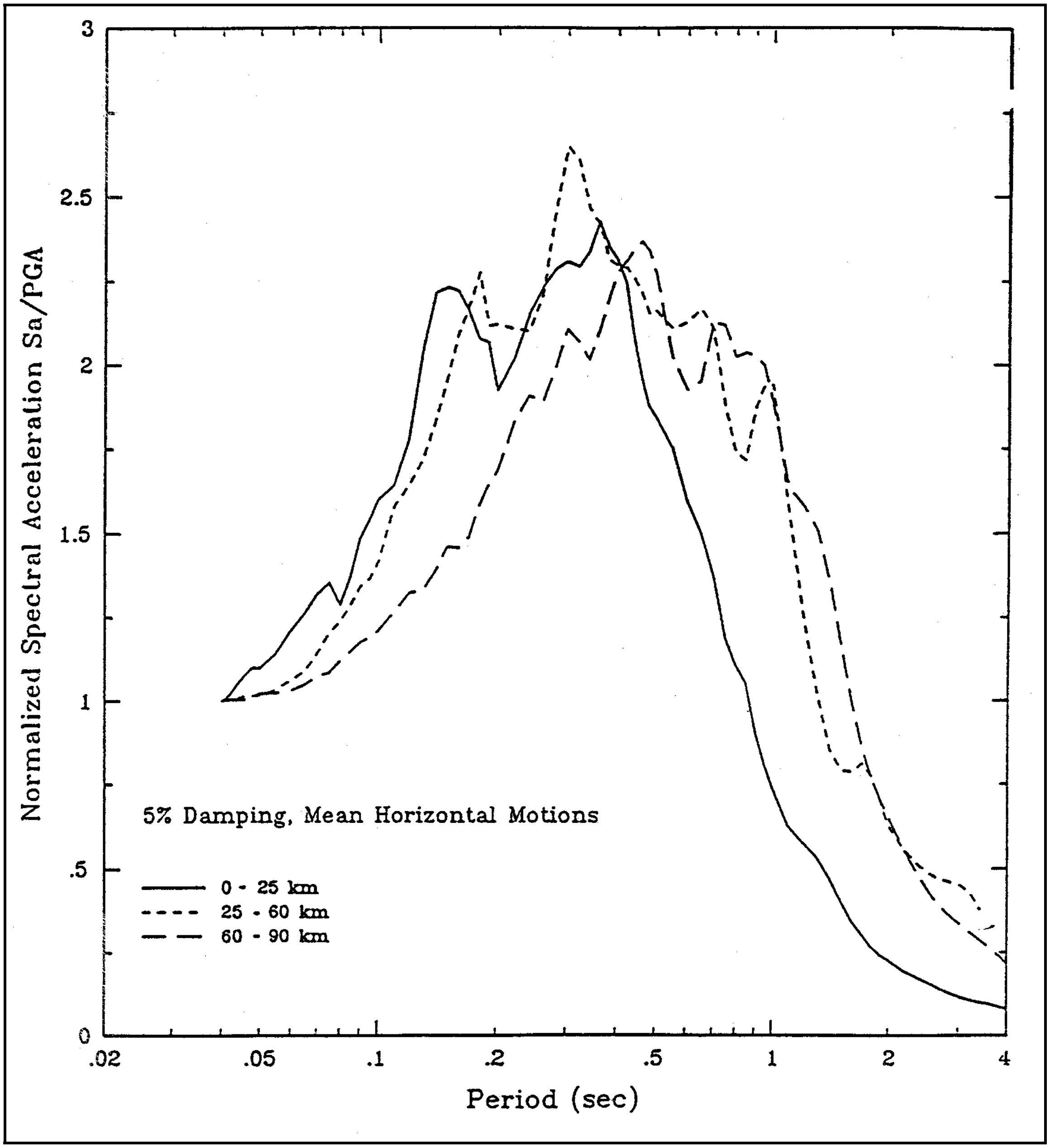


Figure 3-4. Variation of spectral shape with distance for rock recordings of the October 17, 1989, Loma Prieta earthquake

(2) Site amplification effects. Recordings obtained on different soil conditions and analytical studies indicate that soil amplification is dependent on the type and depth of soil. Figure 3-7 illustrates the amplification of response spectra of a soft soil site recording (Treasure Island site) relative to an adjacent rock site recording (Yerba Buena site) during the Loma Prieta earthquake. The effects illustrated in Figure 3-7 are qualitatively typical of those expected in soft soil for relatively low levels of ground motion (peak rock acceleration less than about 0.4 g). However, for higher levels of ground motion, higher soil damping due to nonlinear soil behavior tends to result in deamplification of high-frequency response spectra and peak ground accelerations a_{max} while longer period components continue to be amplified but

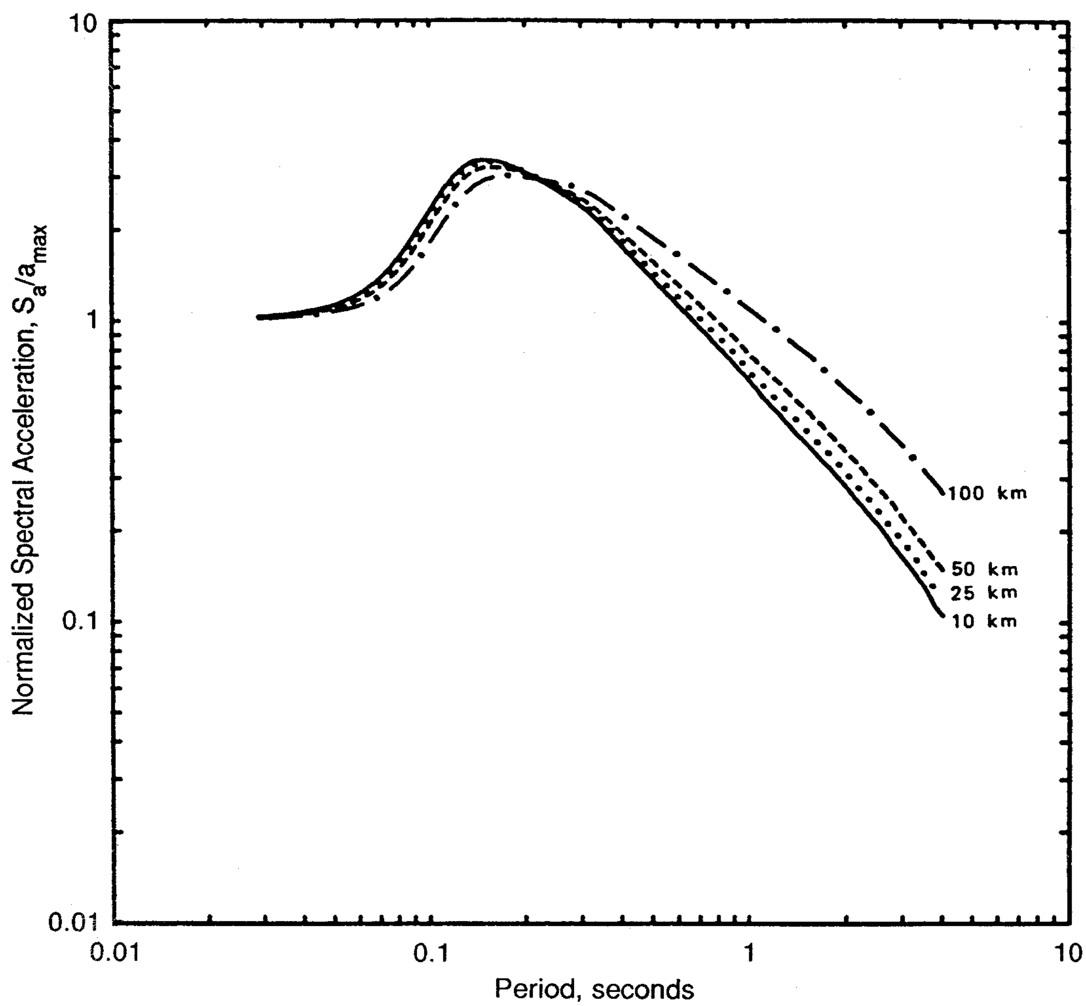


Figure 3-5. Effect of distance on response spectral shapes for a moment magnitude M_w 6.5 earthquake using western North American parameters (Silva and Green 1989, courtesy of Earthquake Engineering Research Institute, Oakland, CA)

by smaller amounts than for low levels of ground motion. Thus, site amplification effects are dependent on the level of ground motion as well as the soil characteristics. For peak ground acceleration, this dependence of amplification on ground motion level is illustrated by the relationship for soft soil developed by Idriss (1991a) shown in Figure 3-8. For response spectral values, the dependence of spectral amplifications on soil type and ground motion level are illustrated by the curves in Figure 3-9, which were the result of the National Center for Earthquake Engineering Research (NCEER)/Structural Engineers Association of California (SEAOC)/Building Seismic Safety Council (BSSC) workshop on site response held in 1992. The response spectral ratios shown in Figure 3-9 have been adopted into the NEHRP Provisions (BSSC 1994) and the Uniform Building Code (International Conference of Building Officials 1997).

(3) Effects on response spectral shape. The shape of the response spectrum is greatly influenced by the local subsurface conditions. This is illustrated in Figure 3-10 by the site-dependent spectral shapes developed by Seed, Ugas, and Lysmer (1976) for four different subsurface site classifications on the basis of statistical analysis of ground motion data. Although these spectral shapes could be updated

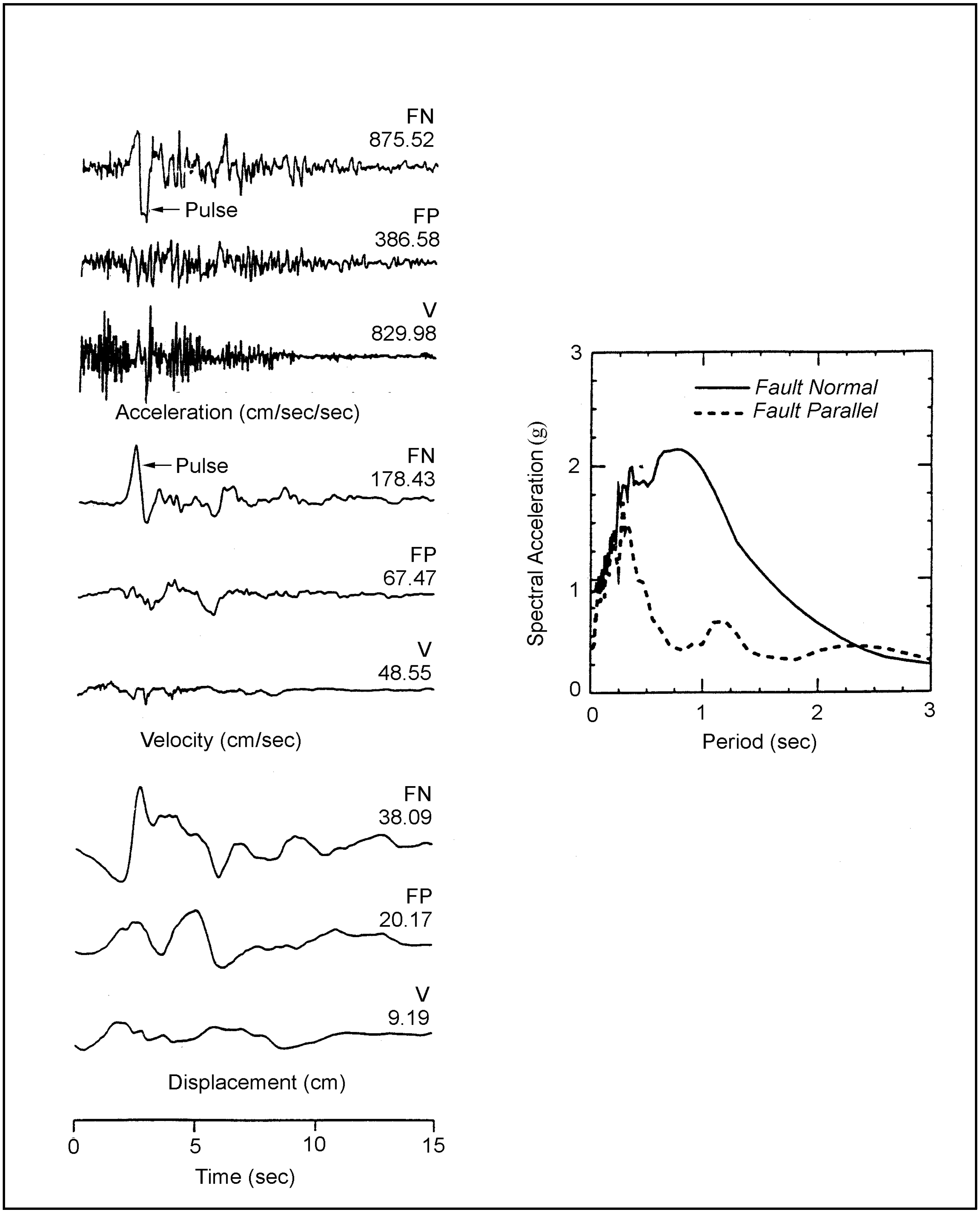


Figure 3-6. Time-histories and horizontal response spectra (5 percent damping) for the fault strike-normal (FN) and fault strike-parallel (FP) components of ground motion (V = vertical) for the Rinaldi recording obtained 7.5 km from the fault rupture during the 1994 Northridge, California, earthquake (Somerville (1997), courtesy of Multidisciplinary Center for Earthquake Engineering Research, State University of New York at Buffalo)

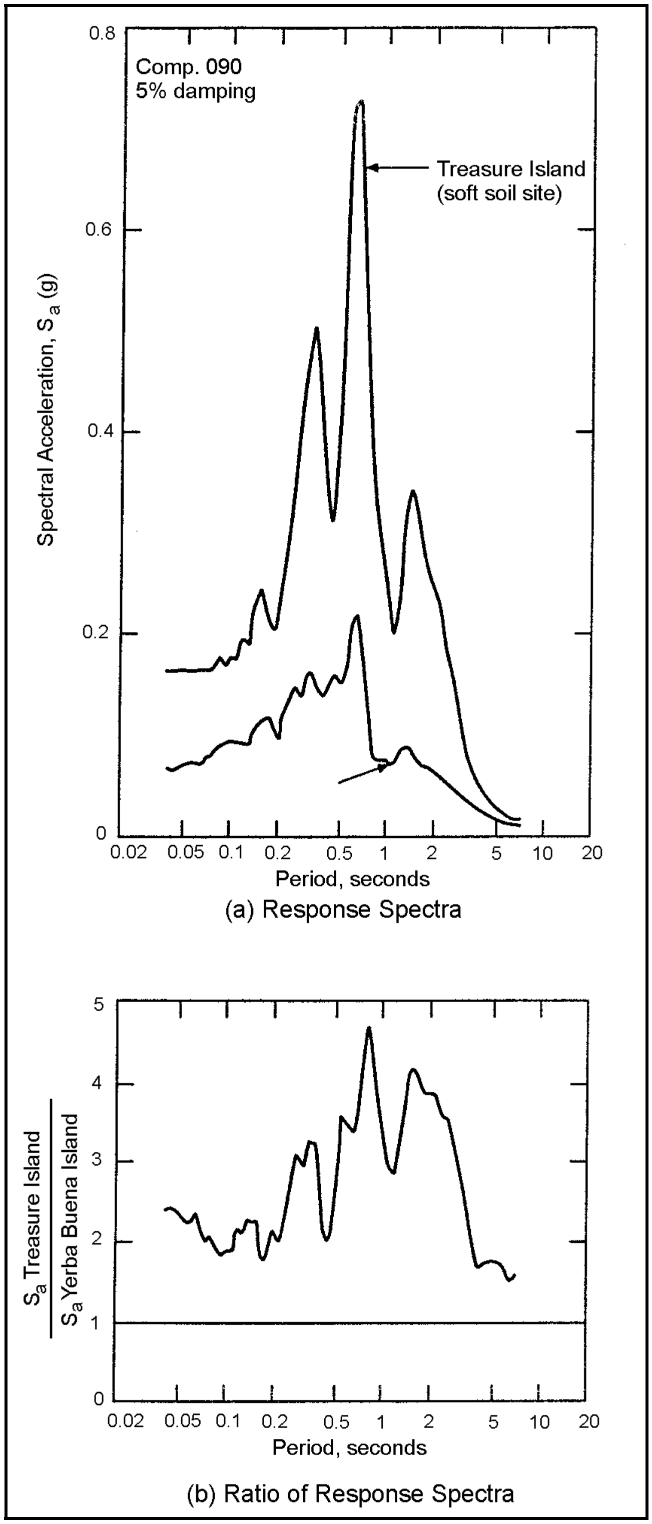


Figure 3-7. Response spectra and ratio of response spectra for ground motions recorded at a soft and nearby rock site during the 1989 Loma Prieta earthquake

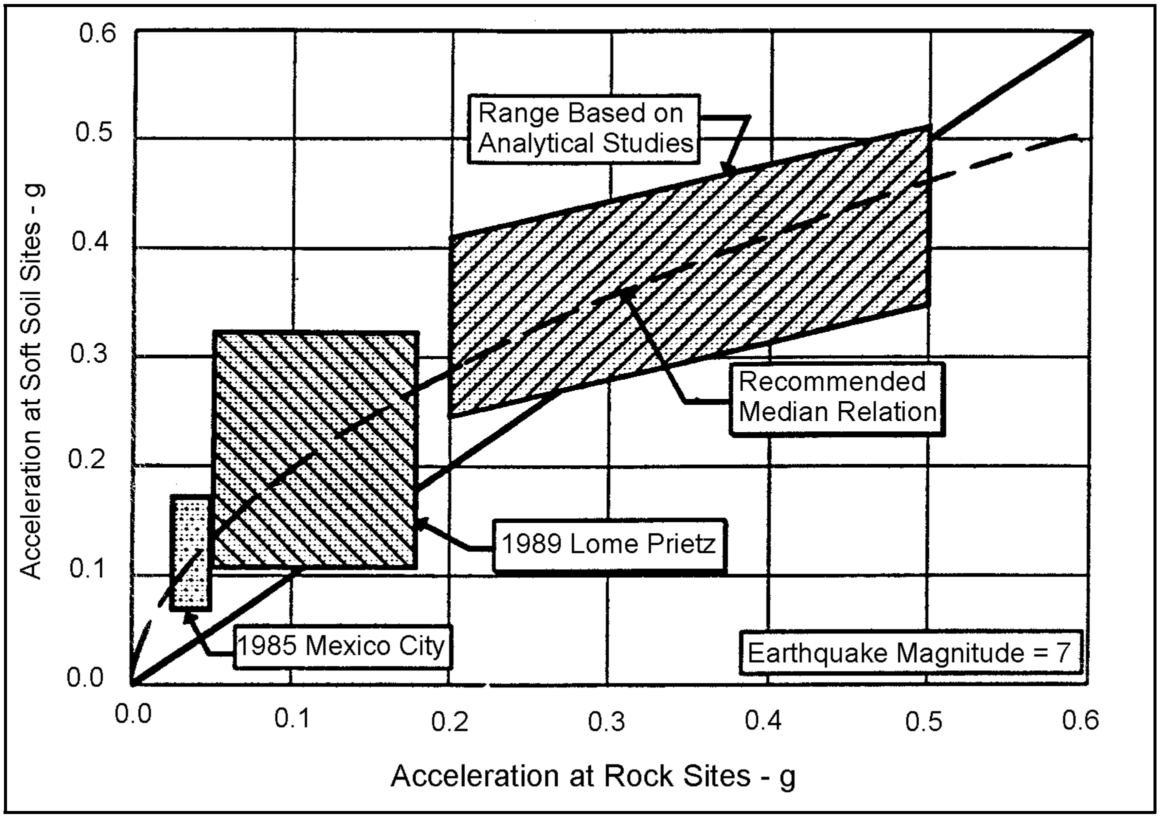
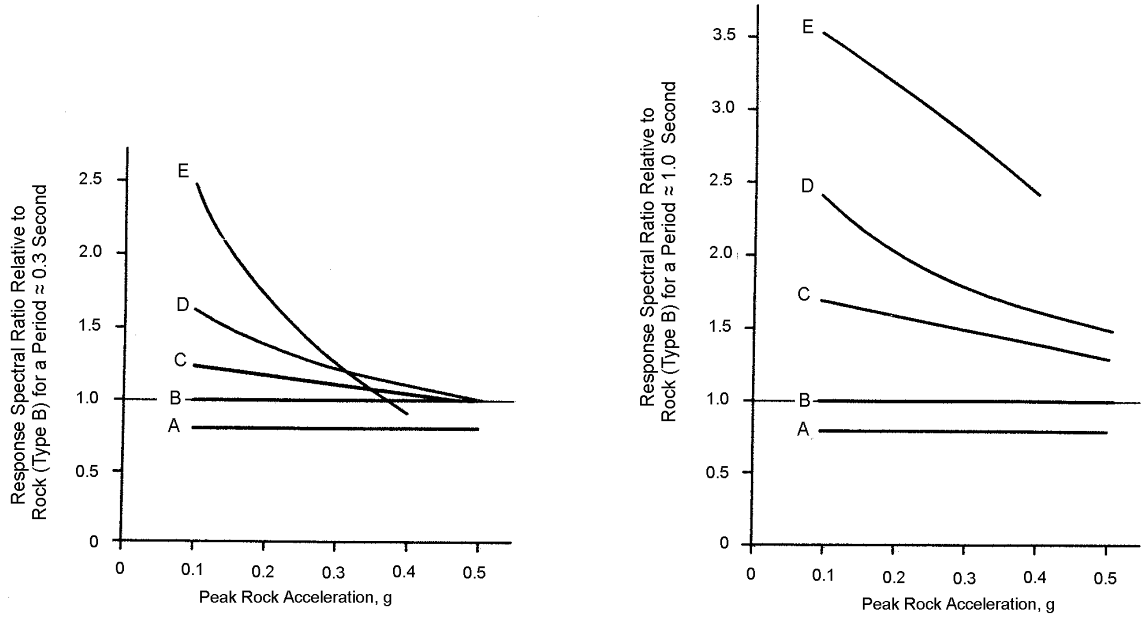


Figure 3-8. Variation of accelerations on soft soil sites versus rock sites (Idriss 1991a, courtesy of I. M. Idriss and Shamsher Prakesh, ed.)

using data from more recent earthquakes and specialized to different magnitudes, the spectral shapes developed by Seed, Ugas, and Lysmer (1976) have been widely used and have provided the basis for quantification of spectral shapes in building codes (Applied Technology Council 1978; Uniform Building Code (International Conference of Building Officials 1994).

3-4. Differences in Ground Motion Characteristics in Different Regions of the United States

a. Eastern versus western United States. Differences in strong ground motions between the WUS and EUS are due somewhat to earthquake source differences (somewhat higher stress drops in the EUS) but are currently believed to be due primarily to differences in travel path and site effects. In the stable intraplate region of the EUS, crustal rocks have higher shear wave velocities and lower damping than crustal rocks in the tectonically active interplate regions of the WUS. As a result, ground motions tend to attenuate more slowly with distance in the EUS than in the WUS. At the same time, the softer rocks within the upper 1 to 2 km of the crust in the WUS exhibit different site effects from those of the harder rocks of the EUS. Specifically, the WUS rocks, having higher damping and steeper velocity gradients with depth than EUS rocks, tend to damp out high-frequency components of motion while amplifying long-period components relative to EUS rocks. As a result of the interaction of these travel path and site effects, rock motions at relatively close source-to-site distances (within about 50 km) exhibit increased high-frequency motions (frequencies greater than about 5 to 10 Hz) but somewhat reduced long-period motions at EUS sites compared to WUS sites. Illustration of these differences in terms of response spectral shapes is shown by comparison of recorded ground motion data from California and Nahanni,



Site Classification	Description
A	Hard rock, shear wave velocity, $v_s >$ 1500 m/sec (5000 fps)
B	Rock, v_s 760 to 1500 m/sec (2500 to 5000 fps)
C	Very dense soil and soft rock, v_s 360 to 760 m/sec (1200 to 2500 fps)
D	Stiff soils, v_s 180 to 360 m/sec (600 to 1200 fps)
E	Soil profile with v_s <180 m/sec (600 ft/sec) or more than 3 m (10 ft) of soft clay with PI > 20, w ≥ 40%, and s_u <25 kPa (500 psf)

Note: v_s = weighted average shear wave velocity for the top 30 m (100 ft) of the soil profile

PI = plasticity index

w = water content

s_u = undrained shear strength

Figure 3-9. Response spectral ratios relative to rock for different site classifications and ground motion levels (BSSC 1994)

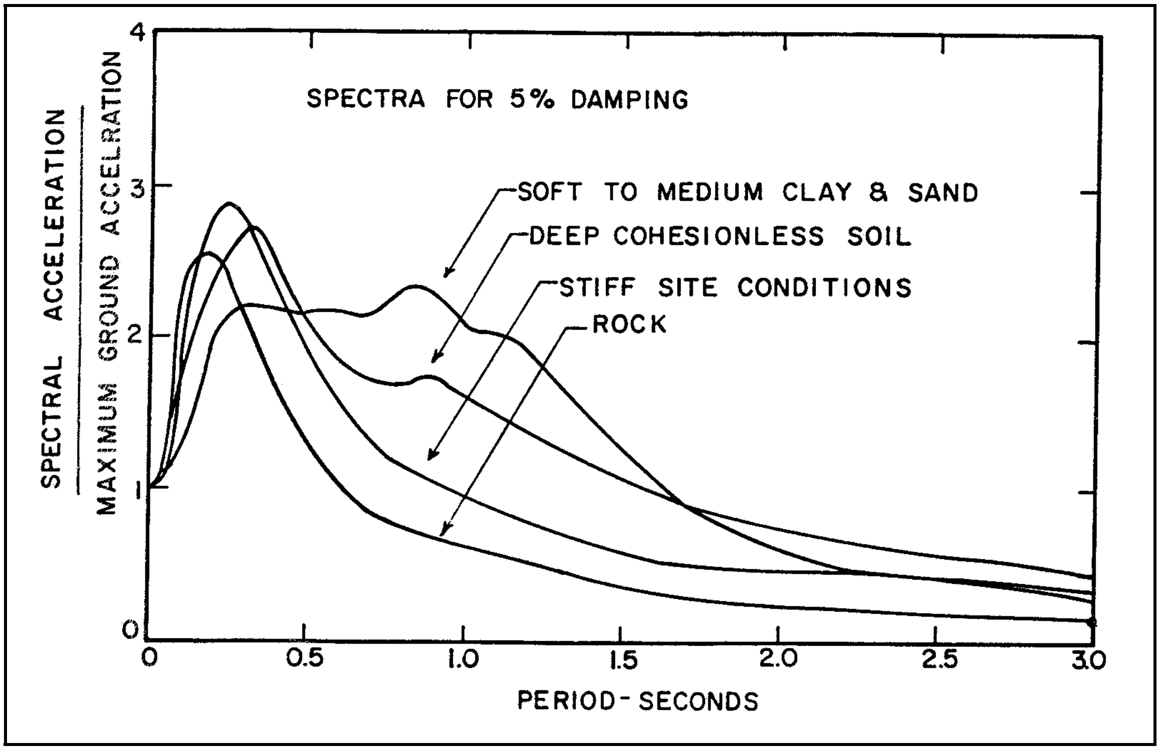


Figure 3-10. Average acceleration spectra for different site conditions (Seed, Ugas, and Lysmer 1976, courtesy of Seismological Society of America)

Canada, in Figure 3-11 (Nahanni is located in an EUS-like tectonic environment). In terms of absolute response spectra, these differences are illustrated in Figures 3-12 and 3-13, where response spectra for relatively close source-to-site distances have been calculated using the theoretical model of Silva and Green (1989). As distance increases, the effects of travel path attenuation begin to dominate over the local site effects, leading to higher ground motions in the EUS over a broader frequency range.

b. Subduction zone versus shallow crustal earthquakes. The collision of tectonic plates of the earth in subduction zones has caused numerous large and relatively deep earthquakes (e.g., in subduction zones in Japan; west coast of Central and South America; coastal northwest California, Oregon, and Washington; Alaska; Puerto Rico; and many other areas). Analyses of ground motion data from subduction zone earthquakes indicate that the main difference between ground motions from subduction zone earthquakes and ground motions from WUS shallow crustal earthquakes is a slower rate of attenuation for the subduction zone events. This is illustrated in Figure 3-14 in which attenuation of peak rock acceleration from shallow crustal WUS earthquakes is compared with that from subduction zone earthquakes as determined by Youngs et al. (1993a). Attenuation curves for two types of subduction zone earthquakes are shown in Figure 3-14—interface earthquakes occurring at the interface between the subducting tectonic plate and the overriding plate, and intraslab earthquakes occurring within the subducting plate. Analyses by Youngs, Day, and Stevens (1988) and Youngs et al. (1993a) also suggest that ground motions from subduction zone earthquakes have response spectral shapes that are lower in the long-period range than response spectral shapes for WUS shallow crustal earthquakes (Figure 3-15).

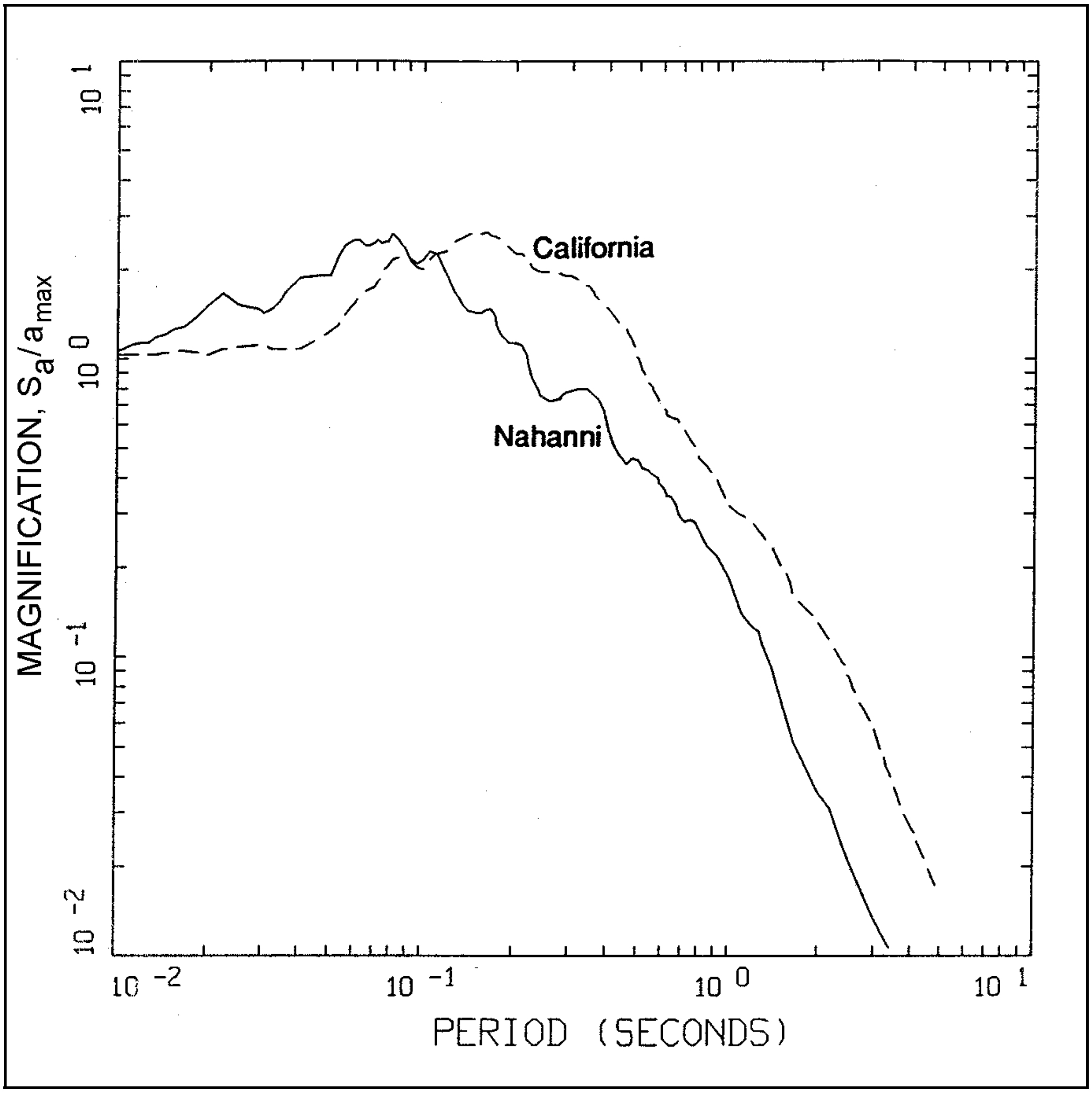


Figure 3-11. Comparison of average 5 percent damped response spectral shapes (S_a/a_{max}) computed from strong-motion data recorded at rock sites in Nahanni, Canada, and California for M_w 5.3 earthquakes (Darragh et al. 1989)

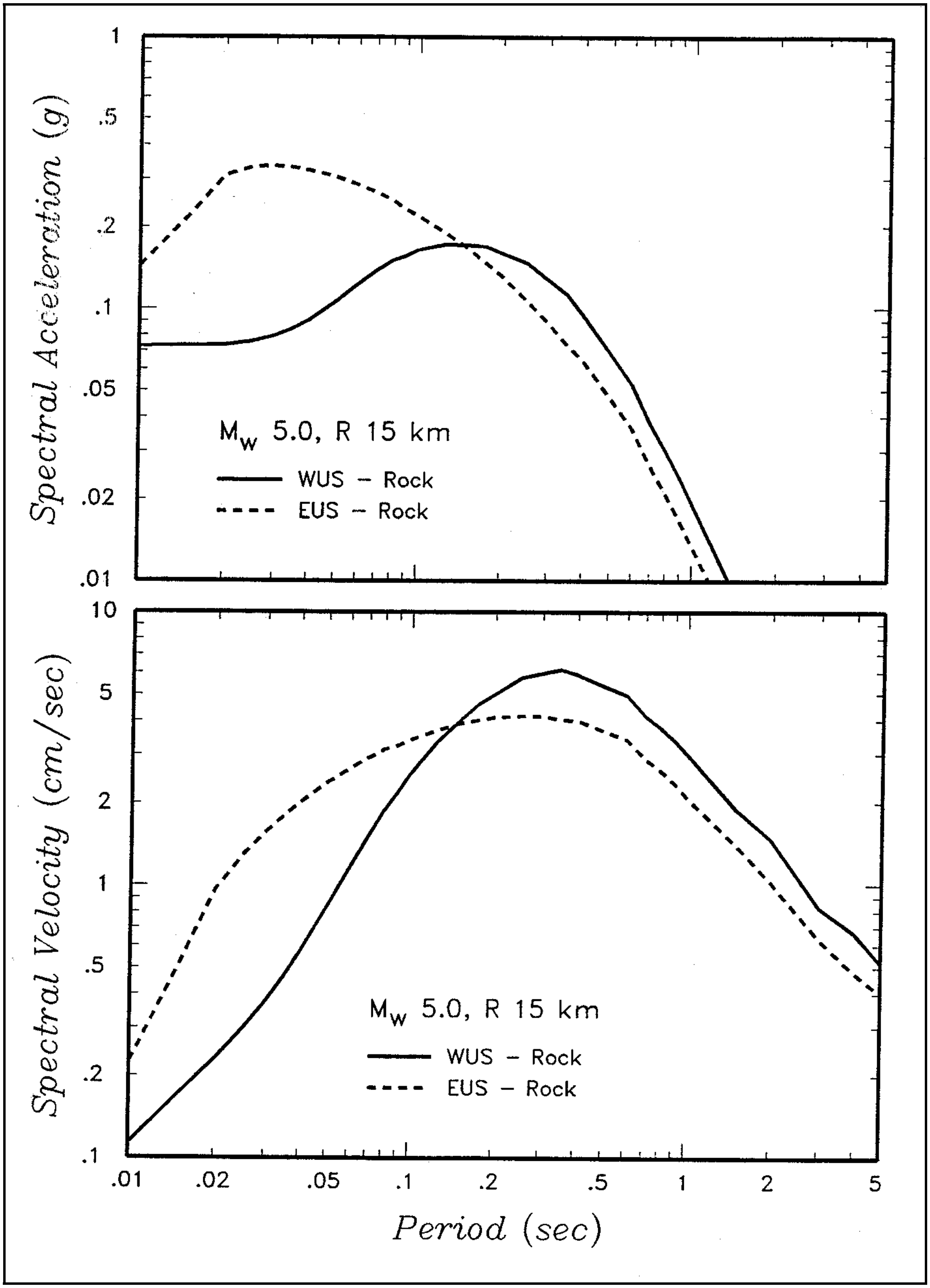


Figure 3-12. Comparison of response spectra for a magnitude 5 earthquake at 15 km using WUS and EUS attenuation relationships (calculated using Band-Limited-White-Noise/Random Vibration Theory (BLWN/RVT) model as formulated by Silva and Green 1989)

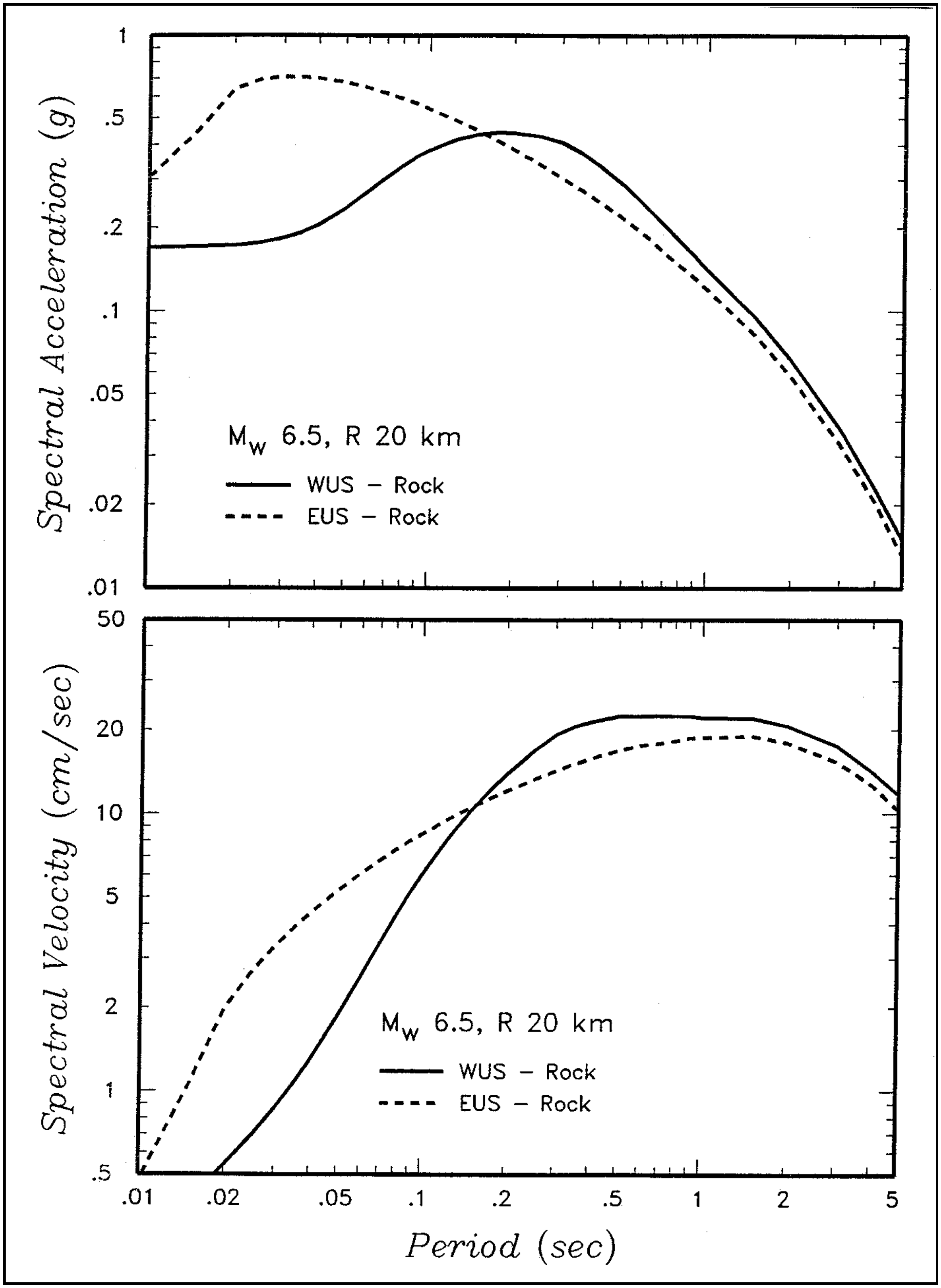


Figure 3-13. Comparison of response spectra for a magnitude 6.5 earthquake at 20 km using WUS and EUS attenuation relationships (calculated using BLWN/RVT model as formulated by Silva and Green 1989)

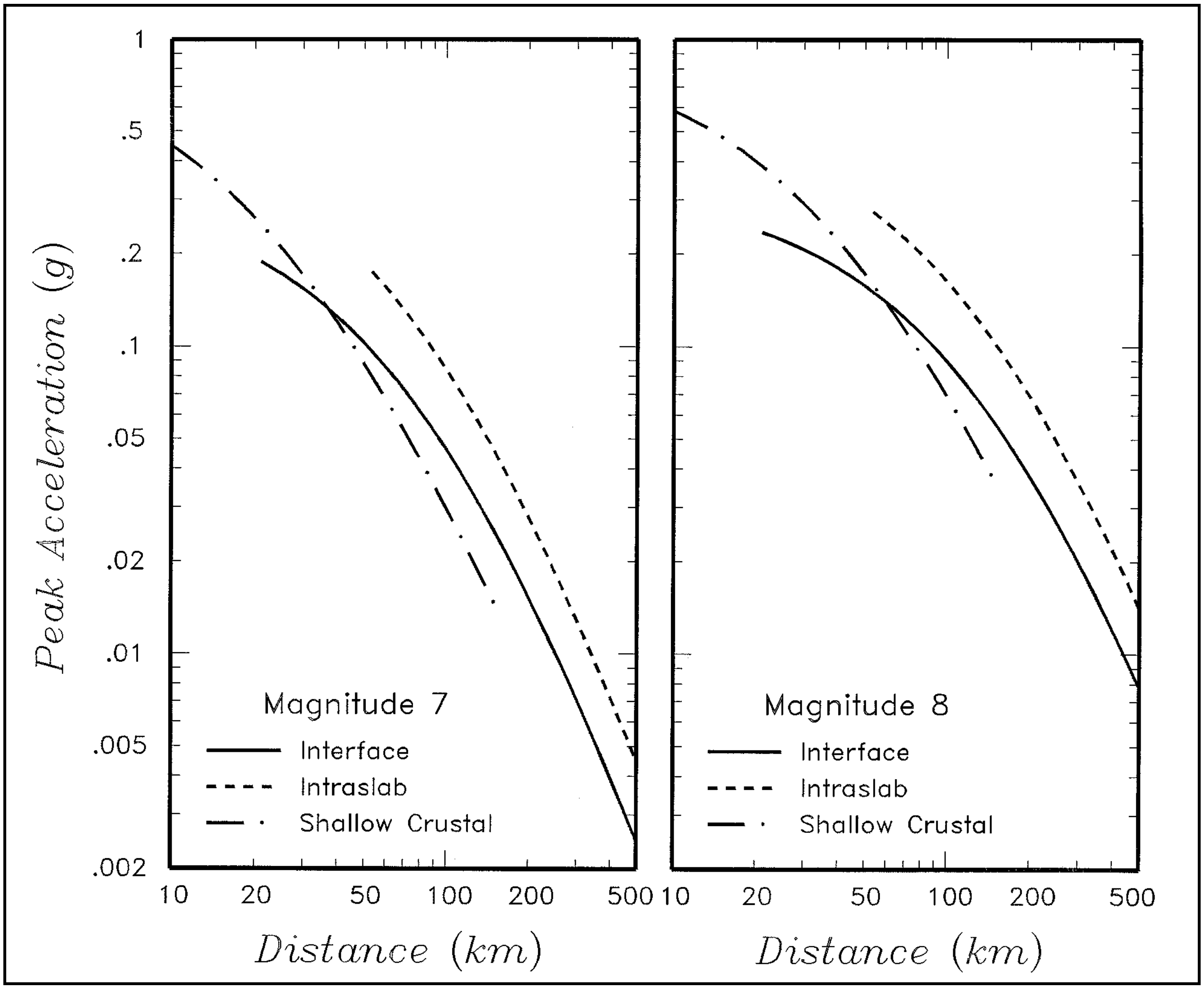


Figure 3-14. Comparison of median peak accelerations on rock from subduction zone earthquakes with peak accelerations from WUS shallow crustal earthquakes

Section II
Deterministic Procedures for Developing
Site-Specific Response Spectra

3-5. Summary of Alternative Procedures

Two basic approaches can be considered in developing design response spectra using a deterministic approach (deterministic seismic hazard analysis, or DSHA): Approach 1, anchoring response spectral shape to peak ground acceleration, and Approach 2, estimating the spectrum directly. These basic approaches are described below. This is followed in paragraphs 3-6 and 3-7 by an elaboration of the application of the two approaches to rock sites and soil sites, respectively.

a. Approach 1 - Anchoring response spectral shape to peak ground acceleration. Approach 1 is a three-part procedure in which peak ground acceleration is estimated, a response spectral shape is selected, and the shape is then multiplied by the peak ground acceleration to obtain the response spectrum, i.e.,

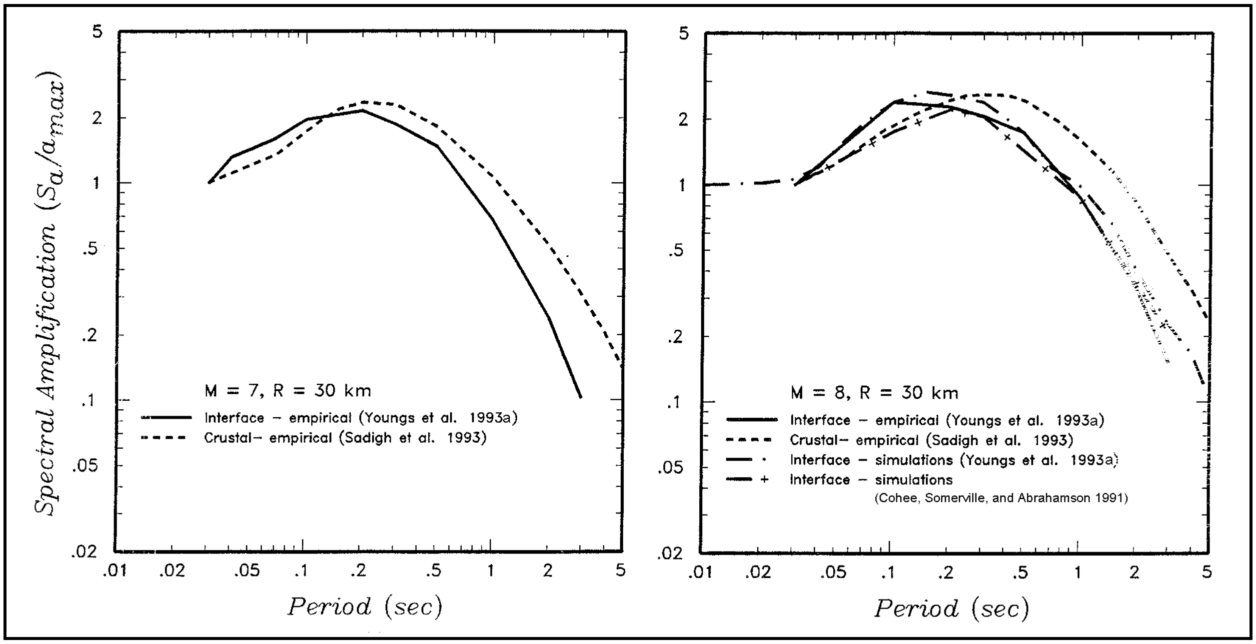


Figure 3-15. Comparison of spectral shapes using WUS and subduction zone attenuation relationships

(1) Step 1: Estimate peak ground acceleration (PGA).

(2) Step 2: Select response spectral shape, which is the curve of spectral amplification factors, (SA_T/PGA), where SA_T is spectral acceleration at period T.

(3) Step 3: Obtain response spectrum as the product of the peak ground acceleration and the spectral shape, SA_T = PGA × (SA_T/PGA). This approach is often referred to as "anchoring" the spectral shape to the peak ground acceleration. A variation on this approach is to estimate peak ground velocity (and, if desired, peak ground displacement) as well as peak ground acceleration and multiply these ground motion parameters by the appropriate spectral amplification factors (Newmark and Hall 1978, 1982); the Newmark and Hall procedure is summarized in Appendix B.

b. Approach 2 - estimating the spectrum directly. In Approach 2 the response spectrum ordinates are estimated directly as a single process. In general, there are three different approaches within Approach 2 for directly estimating response spectra: using response spectral attenuation relationships; performing statistical analysis of spectra from selected ground motion records; and theoretical (numerical) modeling. These approaches are briefly outlined below.

(1) Using response spectral attenuation relationships. Attenuation relationships have been developed by several investigators for response spectral values of ground motions (spectral acceleration or spectral pseudo-relative velocity) at selected periods of vibration by performing statistical regression analyses of ground motion data and by conducting theoretical analyses. Relationships have been developed for different site conditions and tectonic environments. Specific relationships are presented in paragraph 3-6 for rock sites and paragraph 3-7 for soil sites. These relationships can be used to make period-by-period estimates of response spectral values, given the design earthquake magnitude and distance. (The zero-period spectral value is obtained from the corresponding attenuation relationship for the peak ground acceleration, i.e., zero-period spectral acceleration (ZPA) = PGA.)

Typically, these relationships have been developed for 5 percent damping; and ratios between spectral values at different damping ratios (e.g., Newmark and Hall 1978, 1982; Appendix B) are used to obtain the corresponding spectra for other damping ratios.

(2) Performing statistical analysis of ground motion data. Spectral attenuation relationships discussed above are based on all the available applicable ground motion data, and they typically cover a wide range of earthquake magnitudes and distances. However, for a specific magnitude and distance, it may be possible to obtain an improved or a comparative estimate of the response spectrum by performing statistical analysis using a set of response spectra of ground motion records from earthquakes having magnitudes and distances that are close to the design magnitude and distance. The data set is typically a subset of the data used to develop attenuation relationships. The analysis may consist of direct, period-by-period statistical analysis of the data. However, it is also possible to "scale" or adjust each response spectral value of each record to values for the design magnitude and distance and then do statistical analysis of the scaled data set. The attenuation relationships for response spectral values (discussed in (1) above) are used to perform the scaling. This approach of scaling before performing statistical analyses is recommended unless the magnitudes and distances for the data set are closely bunched around the design magnitude and distance. Appendix C illustrates the approach of statistical analyses of a set of scaled response spectra. A particular type of statistical analysis that has been used for many nuclear power plant sites in the EUS and for other sites and locations as well is termed a "random earthquake" analysis. This analysis is performed to estimate the response spectrum at a site due to a randomly located ("floating") earthquake within the vicinity of the site, i.e., when its location cannot be assigned to a specific geologic structure at a specific distance from the site. After the design magnitude of the random earthquake is selected, a statistical analysis is made of response spectra of ground motion records from earthquakes having magnitudes close to the design magnitude, recorded on site conditions similar to those for the actual site, and recorded within a selected source-to-site distance, typically 25 km. A random earthquake analysis can also be performed using attenuation relationships. Appendix D illustrates a random earthquake analysis.

(3) Performing theoretical (numerical) ground motion modeling. The state of the art for theoretical (numerical) modeling of ground motions is being vigorously advanced and is being increasingly used for site-specific project applications. Various methods attempt to simulate the earthquake rupture, the propagation of seismic waves from earthquake source to site, and/or the effect of local site conditions. A number of methods have been developed. These methods warrant consideration as a supplementary means for ground motion estimation. They can be particularly useful for extrapolating to conditions that lie outside those represented by the database of strong motion recordings. The methods vary considerably in degree of complexity and sophistication. One relatively simple model that has been used increasingly to simulate earthquake rupture and source-to-site wave propagation is the Band Limited White Noise/Random Vibration Theory (BLWN/RVT) Model (Atkinson 1984; Atkinson and Boore 1995; Boore 1983, 1986; Boore and Atkinson 1987; Boore and Joyner 1991; Hanks and McGuire 1981; McGuire, Toro, and Silva 1988; Silva and Green 1989). This method has been applied particularly in the EUS because of the relative scarcity of ground motion data in the EUS, and attenuation relationships for the EUS have been developed using this model. A particular form of theoretical analysis applicable to soil sites is "site response analysis," or "ground response analysis" in which the objective is to assess the modifying influence of the local soil conditions on rock motions estimated for the site and, in this manner, estimate the motions at the ground surface of the soil site. Site response analyses are discussed in paragraph 3-7 in the context of their use in estimating response spectra for soil sites.

c. Relative advantages of Approach 1 and Approach 2. Approach 2, estimating the spectrum directly, should be used rather than Approach 1, anchoring spectral shape to peak ground acceleration, because, as was outlined in Section I, spectral shapes depend on more than just the site conditions (i.e., on tectonic environment, earthquake magnitude, and other factors), yet the readily available and widely used spectral shapes generally incorporate only the effect of the local site conditions. Currently available procedures, relationships, and data enable response spectra to be estimated as a single process in Approach 2. When spectra are estimated using Approach 2, it is often useful to make comparative estimates using Approach 1. In paragraph 3-6 procedures and relationships for Approaches 1 and 2 for developing response spectra for rock sites are discussed. A similar presentation is made in paragraph 3-7 for soil sites.

3-6. Developing Site-Specific Spectra for Rock Sites

a. Using Approach 1 - Anchoring rock response spectral shape to peak rock acceleration.

(1) Estimating peak rock acceleration. Recently developed attenuation relationships for estimating peak rock acceleration for shallow crustal earthquakes in the WUS, for the EUS, and for subduction zones are summarized in Table 3-1. The relationships for the WUS shallow crustal earthquakes are better constrained than those for the other tectonic environments because of the relative abundance of strong motion data for WUS shallow earthquakes. The peak acceleration attenuation relationships in Table 3-1 generally include the standard deviations of the estimates, from which 84th percentile values may be obtained.

Table 3-1
Summary of Recently Developed Attenuation Relationships for Peak Ground Acceleration

Tectonic Environment	Relationship	Site Condition
WUS shallow earthquakes	Idriss (1991b)[1]	Rock
	Idriss (1991a)[1]	Soft soil
	Sadigh et al. (1993)[1,2]	Rock
	Abrahamson and Silva (1997)[1,2]	Rock and deep firm soil
	Campbell (1997)[1,2]	Alluvium, soft rock, hard rock
	Boore, Joyner, and Fumal (1997)[1]	Four site classifications based on shear wave velocity
	Sadigh et al. (1997) [1]	Rock and deep firm soil
EUS	Boore and Joyner (1991)	Deep soil
	Frankel et al. (1996)	Hard rock
	Atkinson and Boore (1997)	Hard rock
	Toro, Abrahamson, and Schneider (1997)	Hard rock
Subduction zone	Crouse (1991)	Firm soil
	Molas and Yamazaki (1995)	Rock; hard soil; medium soil; soft soil
	Youngs et al. (1997)	Rock and deep soil
Subduction zone and shallow earthquakes (no distinction)	Fukushima and Tanaka (1990)	Rock; hard soil; medium soil; soft soil
	Krinitzsky, Chang, and Nuttli (1987)	Hard site and soft site

[1] Includes a factor for type of faulting.
[2] Including vertical ground motions.

(2) Estimating response spectral shape and the response spectrum. Available spectral shapes for rock site conditions are summarized in Table 3-2. Multiplying spectral shape times peak ground acceleration results in the absolute response spectrum. Using the Newmark and Hall (1978, 1982) approach (Appendix B), peak ground acceleration is multiplied by the acceleration amplification factor, peak ground velocity by the velocity amplification factor, and peak ground displacement by the displacement amplification factor. Newmark and Hall's recommended relationships between peak ground acceleration, peak ground velocity, and peak ground displacement for rock site conditions may be used to estimate peak ground velocity and peak ground displacement, given peak ground acceleration; or peak ground velocity and peak ground displacement may be independently estimated. Note that the relationships in Table 3-2 of Seed, Ugas, and Lysmer (1976), Mohraz (1976), Applied Technology Council (1978), and Newmark and Hall (1978, 1982), do not explicitly incorporate the important effects of magnitude on spectral shape. The relationships of Mohraz (1976) and Newmark and Hall (1978, 1982) can indirectly incorporate the effects of magnitude through its effect on peak ground velocity and peak ground displacement if these parameters are estimated independently from peak ground acceleration (Appendix B).

Table 3-2
Summary of Available Response Spectral Shapes of Ground Motions

Tectonic Environment	Relationship	Site Conditions
WUS shallow earthquakes	Seed, Ugas, and Lysmer (1976)	Rock; stiff soil; deep cohesionless soil; soft to medium clay and sand
	Mohraz (1976)	Rock; shallow alluvium; moderately deep alluvium; alluvium
	Applied Technology Council (1978)[1]	Rock or shallow stiff soil; deep stiff soil; soft soil
	Newmark and Hall (1978, 1982)	Rock; firm soil
	Sadigh et al. (1997)	Rock and deep firm soil
WUS shallow earthquakes; EUS	Silva and Green (1989)	Rock
Subduction zones	Youngs et al. (1997)	Rock and deep soil

[1] These spectral shapes are based primarily on Seed, Ugas, and Lysmer (1976). The Applied Technology Council (1978) spectral shapes are also the spectral shapes that appear in the 1994 Uniform Building Code (International Conference of Building Code Officials 1994) and the 1995 Recommended Lateral Force Requirements and Commentary ("Blue Book") of the Seismology Committee of the Structural Engineers Association of California (SEAOC 1996).

(3) Uncertainty in response spectral prediction. Response spectra obtained using the median or mean peak ground acceleration attenuation relationships and the median or mean spectral shapes summarized above result in median (50th percentile) or mean ground motion estimates, given a design earthquake magnitude and distance. Additional consideration must be given if a higher percentile ground motion is to be predicted, for example the 84th percentile (median plus standard deviation) ground motion. Spectra for the 84th percentile can be estimated by multiplying median or mean peak ground acceleration by 84th percentile spectral shapes. For example, Seed, Ugas and Lysmer (1976) present 84th percentile shapes as well as mean shapes. However, this procedure results in a lesser degree of conservatism in the very short period part of the spectrum because the anchor value of peak ground acceleration (equal to the zero-period spectral acceleration, ZPA) is at the median or mean level. In order to have a uniform degree of conservatism throughout the period range, the peak ground acceleration and the very short period part of the spectrum should be adjusted upward to the 84th percentile level. Alternatively, the entire median response spectrum may be scaled upward by a factor to the approximate 84th percentile level. When the entire spectrum is scaled, often the standard deviation in peak ground acceleration is used to obtain a scaling factor. This is an approximation, since the standard deviation has

been found to vary with period of vibration. (The period dependence can be directly accounted for when using Approach 2.) The 84th percentile amplification factors of the Newmark and Hall (1978, 1982) approach can be applied to median estimates of peak ground acceleration, velocity, and displacement to obtain 84th percentile spectral values (Appendix B, Table B-1). Again, a separate adjustment should be applied to raise the peak ground acceleration and very short period part of the spectrum to the 84th percentile level.

(4) Estimating vertical ground motion response spectra. Ratios of vertical to horizontal response spectral amplitudes can be used to estimate vertical response spectra, given an estimate of horizontal response spectra. Recent studies (e.g., Silva 1997) indicate that vertical-to-horizontal response spectral ratios are a function of period of vibration, earthquake source to site distance, earthquake magnitude, tectonic environment (WUS and EUS), and subsurface conditions (soil and rock). Figure 3-16 provides a guideline for ratios of vertical to horizontal spectral values on rock sites that is generally conservative for earthquake magnitudes equal to or less than about 6.5. However, if a facility is sensitive to short-period (less than 0.3 sec) vertical motions, and is located within 10 km of the earthquake source or the magnitude exceeds 6.5, further evaluation of vertical response spectra on rock is recommended because vertical response spectra can significantly exceed horizontal response spectra for these conditions.

b. Using Approach 2 - Estimating the rock response spectrum directly.

(1) General. The three approaches discussed in paragraph 3-5*b* can be used: using response spectral attenuation relationships, performing statistical analyses of ground motion response spectra, and theoretical (numerical) modeling. The following paragraphs refer to particular relationships or methods.

(2) Using response spectral attenuation relationships. Recently developed attenuation relationships that can be used to predict horizontal rock response spectral values for WUS shallow crustal earthquakes, for EUS earthquakes, and for subduction zone earthquakes are summarized in Table 3-3. The spectral acceleration attenuation relationships summarized in Table 3-3 generally include the standard deviations of the estimates, from which 84th percentile values may be obtained. As illustrated in Figures 3-12 and 3-13, EUS attenuation models characteristically estimate much higher spectral response in the short-period range (less than 0.1 to 0.2 sec) than estimated by relationships for the WUS. As discussed in paragraph 3-4*a* the higher short-period response is attributed to the hardness of the rock in the EUS. Such short-period (high-frequency) motions may or may not be significant to the response and performance of hydraulic structures. The assessment of the significance of such motions should be made by the principal design engineer in collaboration with the seismic structural analyst and the materials engineer.

(3) Using statistical analyses of response spectra. Abundant strong motion data are available to permit statistical analyses of data sets for many design earthquake scenarios for WUS shallow crustal earthquakes. As noted in paragraph 3-5*b*(2), statistical "random earthquake" analyses have been made at many EUS sites because, in general, discrete faults have not been identified in the EUS. Yet it was desired to model the possibility of an earthquake (usually of moderate magnitude, in the range of magnitude 5 to 6) occurring near the site. Many of these analyses have been carried out using WUS ground motion data because only a few records from moderate magnitude earthquakes are available in the EUS. Such analyses may be reasonable for estimating longer period rock motions but would apparently underestimate shorter period (less than 0.1 to 0.3 sec) ground motions at hard rock sites. In this case, an adjustment should be made for the short-period response spectral values, if these short-period motions are of significance to the structure under consideration. The adjustment can be made by comparing

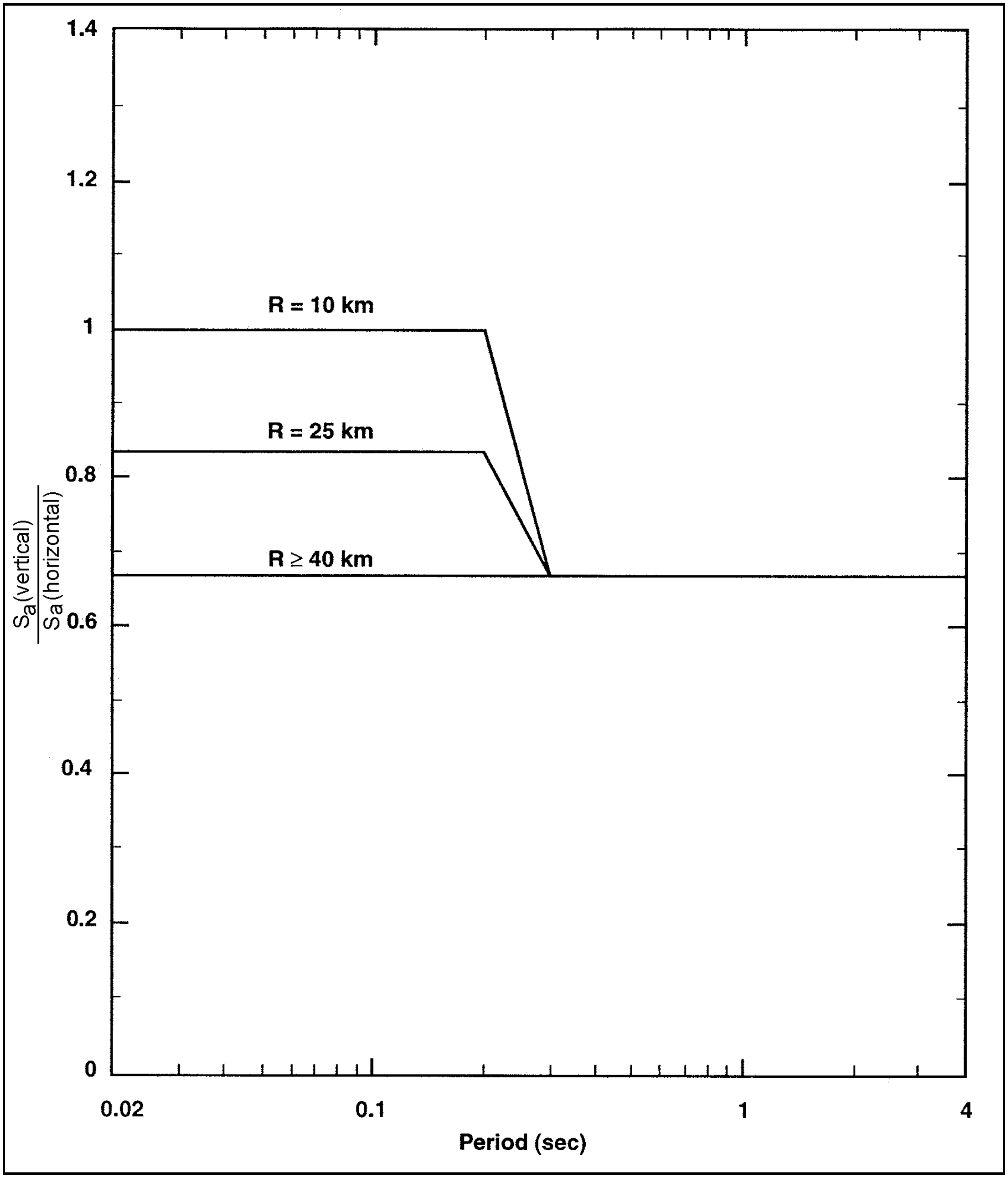


Figure 3-16. Simplified relationships between vertical and horizontal response spectra as a function of distance *R*

Table 3-3
Summary of Recently Developed Attenuation Relationships for Response Spectral Values of Ground Motions

Tectonic Environment	Relationship	Site Conditions
WUS shallow earthquakes	Idriss (1991b)[1]	Rock
	Sadigh et al. (1993)[1,2]	Rock
	Abrahamson and Silva (1997)[1,2]	Rock and deep firm soil
	Campbell (1997)[1,2]	Alluvium, soft rock, hard rock
	Boore, Joyner, and Fumal (1997)[1]	Four site classifications based on shear wave velocity
	Sadigh et al. (1997)[1]	Rock and deep firm soil
EUS	Boore and Joyner (1991)	Deep soil
	Frankel et al. (1996)	Hard rock
	Atkinson and Boore (1997)	Hard rock
	Toro, Abrahamson, and Schneider (1997)	Hard rock
Subduction zone	Crouse (1991)	Firm soil
	Youngs et al. (1997)	Rock and deep soil

[1] Includes a factor for type of faulting.
[2] Including vertical ground motions.

response spectrum amplitudes predicted by EUS and WUS attenuation relationships for rock (Table 3-3). As illustrated in Appendix D, a random earthquake analysis can also be carried out using attenuation relationships. Thus this analysis can be performed using the EUS spectral attenuation relationships that predict higher short-period motions at hard rock sites.

(4) Using theoretical (numerical) modeling techniques. The techniques discussed in paragraph 3-5*b*(3) can be used. These techniques attempt to simulate the earthquake rupture and the propagation of seismic waves from the earthquake source to the site.

(5) Estimating vertical ground motion response spectra. The available recently developed attenuation relationships for response spectral values of vertical rock motions are summarized in Table 3-3. These relationships can be used directly to estimate vertical rock response spectra. The vertical to horizontal spectral ratios discussed in paragraph 3-6*a*(4) and shown in Figure 3-16 can be used as a guide in estimating vertical response spectra, given an estimate of the horizontal spectra.

c. Developing acceleration time-histories of rock motions consistent with the design response spectrum.

(1) General. When acceleration time-histories of ground motions are required for the dynamic analysis of a structure, they should be developed to be consistent with the design response spectrum over the period range of significance for the structure, as well as have an appropriate strong motion duration for the particular design earthquake. Two general approaches to developing acceleration time-histories are selecting a suite of recorded motions and synthetically developing or modifying one or more motions.

These approaches are discussed below. For either approach, when near-source earthquake ground motions are modeled, it may be desirable that an acceleration time-history include a strong intermediate- to long-period pulse to model this particular characteristic of ground motion often observed in the near field (paragraph 3-3*b*(4) and Figure 3-6).

(2) Selecting recorded motions. Every earthquake produces a unique set of acceleration time-histories having characteristics that depend on the earthquake magnitude and other source characteristics, distance, attenuation and other travel path characteristics, and local site conditions. The response spectrum of any individual ground motion accelerogram has peaks and valleys that occur at different periods of vibration. Thus, the response spectrum of any single accelerogram is unlikely to match the developed smooth design response spectrum. Typically, when recorded motions are selected, it is necessary to choose a suite of time-histories (typically at least four) such that, in aggregate, valleys of individual spectra that fall below the design curve are covered by peaks of other spectra and (preferably) the exceedance of the design spectrum by individual spectral peaks is not excessive. For nonlinear analyses, it may be desirable to have additional time-histories because of the importance of pulse sequencing to nonlinear response (see also comments in (3) below). In the approach of selecting recorded motions, simple scaling of individual accelerograms by a constant factor is done to improve the spectral fit, but the wave form and the relative spectral content of the accelerograms are not modified. The advantage of selecting recorded motions is that each accelerogram is an actual recording, and thus the structure is analyzed for natural motions that are presumably most representative of what the structure could experience. The approach has the following disadvantages: multiple dynamic analyses are needed for the suite of accelerograms selected; although a suite of accelerograms is selected, there will typically be substantial exceedances of the smooth design spectrum by individual spectrum peaks; and although a reasonably good spectral fit may be achieved for one horizontal component, when the same simple scaling factors are applied to the other horizontal components and the vertical components for the records selected, the spectral fit is usually not as good for the other components.

(3) Synthetically developing or modifying motions. A number of techniques and computer programs have been developed either to completely synthesize an accelerogram or modify a recorded accelerogram so that the response spectrum of the resultant accelerogram closely fits or matches the design spectrum. It is preferred to use techniques that modify a recorded accelerogram rather than completely synthesize a motion since the recorded motion will have time-domain characteristics representative of actual ground motions. Two techniques that have been found to do a good job of spectrally modifying recorded motions are the frequency-domain RASCAL computer code developed for the Corps of Engineers by Silva and Lee (1987) and the time-domain technique developed by Lilhanand and Tseng (1988). These techniques preserve the basic time-domain character of the accelerogram yet provide an excellent match to a smooth spectrum. An example of the spectral matching technique is given in Figures 3-17 and 3-18. The RASCAL computer code was used in this case. Figure 3-17 illustrates the initial (recorded) acceleration, velocity, and displacement time-histories and the time-histories after the spectral matching process. Figure 3-18 illustrates the initial (recorded) acceleration response spectra, the smooth design response spectrum, and the response spectrum of the acceleration time-history after the spectral matching process. Figure 3-18 illustrates the very close spectral match that was achieved, while Figure 3-17 illustrates that the modified time-histories preserve the basic time-domain character of the original record. Synthetic techniques for developing time-histories have the following advantages: a good fit to the design spectrum can be achieved with a single accelerogram; the natural appearance and strong motion duration can be maintained in the accelerograms; and three component motions (two horizontal and one vertical) each providing a good spectral match can be developed, and these can be made statistically independent if desired; and the process is relatively efficient.

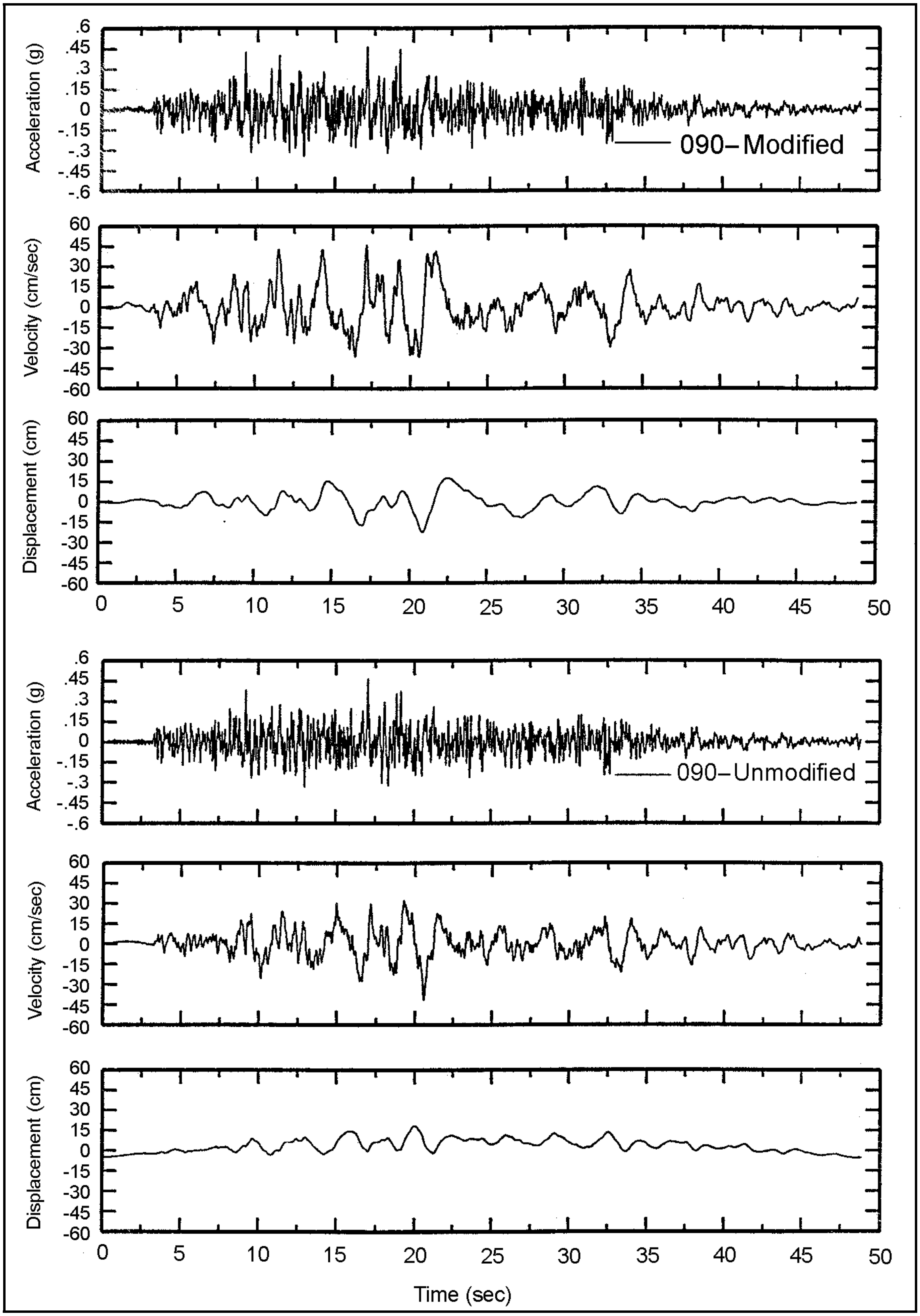


Figure 3-17. Example of original time-histories and time-histories after a spectral matching process

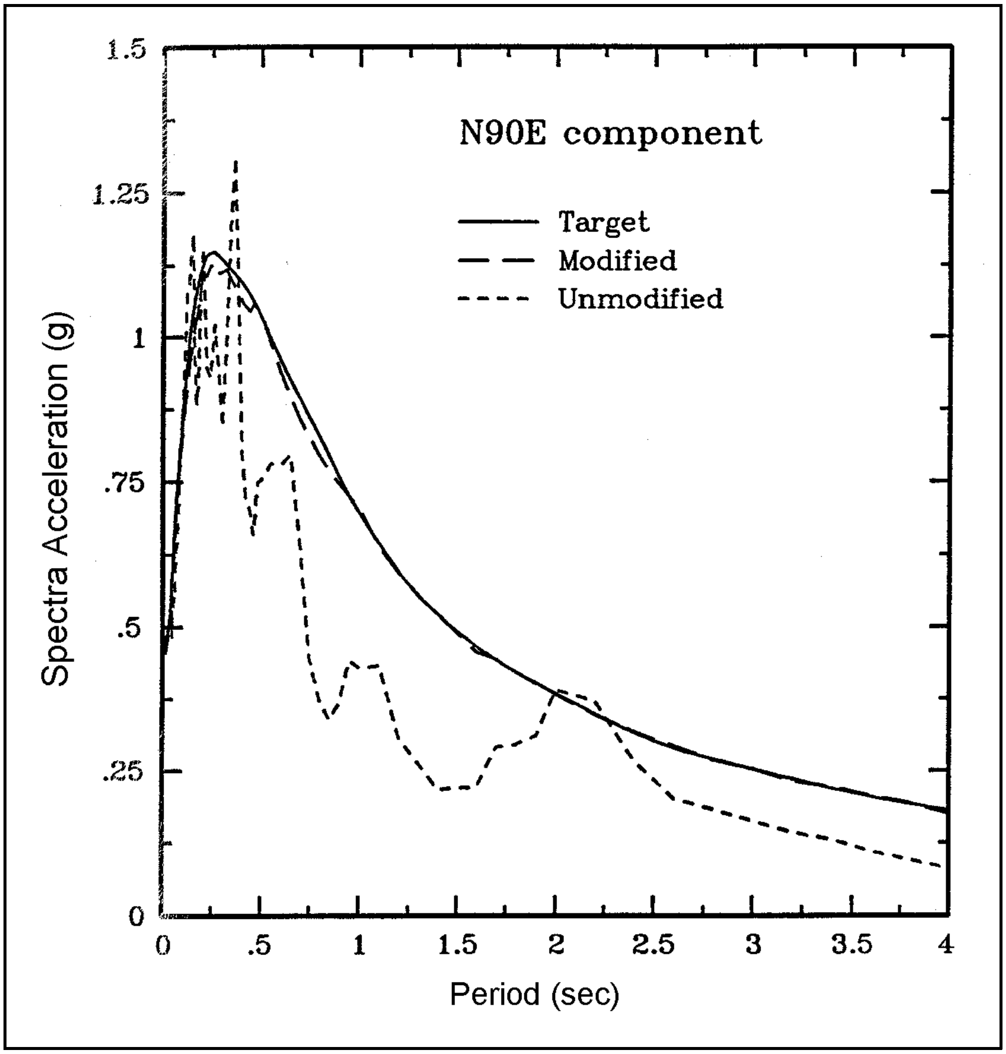


Figure 3-18. Example of response spectrum of time-history matched to a design response spectrum and spectrum of original time-history

The disadvantage is that the motions are not "real" motions, which would not exhibit smooth design spectra. Also "real" motions may contain less energy than synthetic spectrum-matched motions of similar amplitude. Although a good fit to a design spectrum can be attained with a single accelerogram, it may be desirable in some cases to fit the spectrum using more than one accelerogram. For nonlin ear analysis applications, it is particularly desirable to have multiple accelerograms because different accelerograms may have different pulse sequencing characteristics of importance to nonlinear response yet have essentially identically response spectra. Numerical ground motion modeling methods can also be used to produce synthetic accelerograms. Such motions have the character of recorded motions since the modeling procedures are intended to simulate the earthquake rupture and wave propagation process.

3-7. Developing Site-Specific Spectra for Soil Sites

As is the case for developing site-specific rock spectra, either the approach of anchoring spectral shapes to a peak ground acceleration (Approach 1) or the approach of directly estimating the spectra (Approach 2) can be used for soil sites. The implementation of these approaches is outlined below.

a. Approach 1 - Anchoring the response spectral shape to the peak ground acceleration.

(1) Estimating peak ground acceleration. Table 3-1 summarizes recently developed attenuation relationships for estimating peak ground acceleration. For WUS shallow crustal faulting earthquakes, several recent attenuation relationships are available to estimate top-of-soil peak ground accelerations for firm soil conditions, and Idriss (1991a) has developed a peak acceleration attenuation relationship for soft soil sites. Combining the BLWN/RVT method for rock motion estimation with a site response analysis for a deep soil column, Boore and Joyner (1991) developed a peak ground acceleration attenuation relationship for deep soil sites in the EUS. For subduction zone earthquakes, attenuation relationships have been developed for firm soil conditions and in some cases for soft soil conditions (Table 3-1). As is the case for rock attenuation relationships, the soil attenuation relationships are better constrained by data for WUS shallow crustal earthquakes than for EUS or subduction zone earthquakes.

(2) Estimating response spectral shape and the response spectrum. Spectral shapes that have been developed for soil sites for WUS shallow crustal earthquakes and for subduction zone earthquakes on the basis of statistical analyses of ground motion data are summarized in Table 3-2. Spectral shapes have not been developed for soil sites for EUS earthquakes. Using the Newmark and Hall (1978, 1982) approach (Appendix B), the effect of soil is accounted for by estimating values of peak ground velocity and peak ground displacement directly, or by using Newmark and Hall's relationships between peak ground acceleration, peak ground velocity, and peak ground displacement for firm soil to estimate peak ground velocity and peak ground displacement, given peak ground acceleration. Peak ground acceleration, velocity, and displacement then are multiplied by Newmark and Hall's amplification factors to obtain the absolute response spectrum.

(3) Uncertainty in response spectra predictions. The comments made in paragraph 3-6*a*(3) regarding estimating 84th percentile response spectra for rock also apply to response spectra for soil.

(4) Estimating vertical ground motion response spectra. Recent studies (e.g., Silva 1997) indicate that vertical-to-horizontal ratios of response spectra of ground motions are higher on soil than on rock for short periods of vibration. Figure 3-16 provides a guideline for ratios of vertical-to-horizontal spectral ratios on firm soil sites that is generally conservative. However, if a facility is sensitive to short-period (less than 0.3 sec) vertical motions, and is located within 25 km of the earthquake source or the magnitude exceeds 6.5, further evaluation of vertical response spectra on soil is recommended because vertical response spectra can significantly exceed horizontal response spectra for these conditions.

b. Using Approach 2 - Estimating the soil response spectrum directly.

(1) General. The three approaches discussed in paragraph 3-5*b* can be used for soil sites. These approaches are using response spectral attenuation relationships, performing statistical analysis of ground motion response spectra, and theoretical (numerical) modeling.

(2) Using response spectral attenuation relationships. Recently developed response spectral attenuation relationships for soil are summarized in Table 3-3. The spectral attenuation relationships in

Table 3-3 generally include the standard deviations of the estimates, from which 84th percentile values may be obtained.

(3) Using statistical analyses of response spectra. Abundant ground motion data for firm soil sites in the WUS are available to permit statistical analyses of data sets for many design earthquakes. Although such data are not available for EUS earthquakes, the WUS data can be used, recognizing that the analyses may underestimate short-period (less than 0.1 to 0.3 sec) response spectra. (Refer to discussion for rock sites in paragraph 3-6*b*(3).) The degree of underestimation should be less at soil sites than at rock sites because soils will tend to damp out the short-period motions.

(4) Using theoretical (numerical) modeling techniques. The techniques discussed in paragraph 3-5*b*(3) can be used to simulate the earthquake rupture and propagation of seismic waves from the earthquake source to the site. In addition, site response analyses may be carried out to estimate top-of-soil response spectra, given a response spectrum in rock. With this approach, rock motions, including response spectra, are first defined for the site (using procedures and relationships described in paragraph 3-6). The soil profile between the ground surface and the underlying rock is modeled. The rock motions are assigned to a hypothetical rock outcrop at the site rather than to the rock at depth beneath the soil column. This is because rock motion recordings are obtained at the ground surface rather than at depth, and unless the rock is rigid, the rock motion beneath the soil column will differ somewhat from the rock outcrop motion. Then, using nonlinear or equivalent linear soil response analytical methods, rock motions are propagated through the soils column and top-of-soil motions are estimated. The site response analysis process is schematically illustrated in Figure 3-19. This figure illustrates the commonly used one-dimensional site response analysis method applicable where the soil stratigraphy is relatively uniform and flat-lying and the ground surface topography is relatively level. Two-dimensional site response analysis methods are available for situations where these conditions are not sufficiently met. Just as in other types of theoretical modeling and numerical analyses, results of site response analyses are sensitive to the details of the analytical procedures, modeling of the process, and inputs to the analysis. Broad guidelines for conducting these analyses are listed below:

(a) More than one input rock acceleration time-history should be used, and the selected motions should be reasonably representative of the rock motions in terms of spectra and duration.

(b) Parametric analyses for variations in the dynamic soil properties should be made to examine the sensitivity of the response to uncertainties in the soil properties. This is particularly important when soil properties are based on generalized correlations rather than on a program of field shear wave velocity measurements.

(c) It is useful to compute ratios of response spectra of top-of-soil motion to input rock motion for each analysis that is carried out. The ratios are much less sensitive to the actual input motion than is the absolute top-of-soil motion. The spectral ratios can then be examined and smoothed and multiplied by the rock smooth spectrum to obtain a top-of-soil spectrum, which can be further smoothed.

An illustration of a site response analysis is presented in Appendix E. Articles by Seed and Sun (1989), Chang et al. (1990), and Ahmad, Gazetas, and Desai (1991) provide useful background information on site response analysis methodologies. Site response analyses are needed relatively more for soft soil sites than for firm soil sites because the site response effects are greater for soft soils and because ground motion data and empirically based ground motion relationships are relatively scarce for soft soil sites.

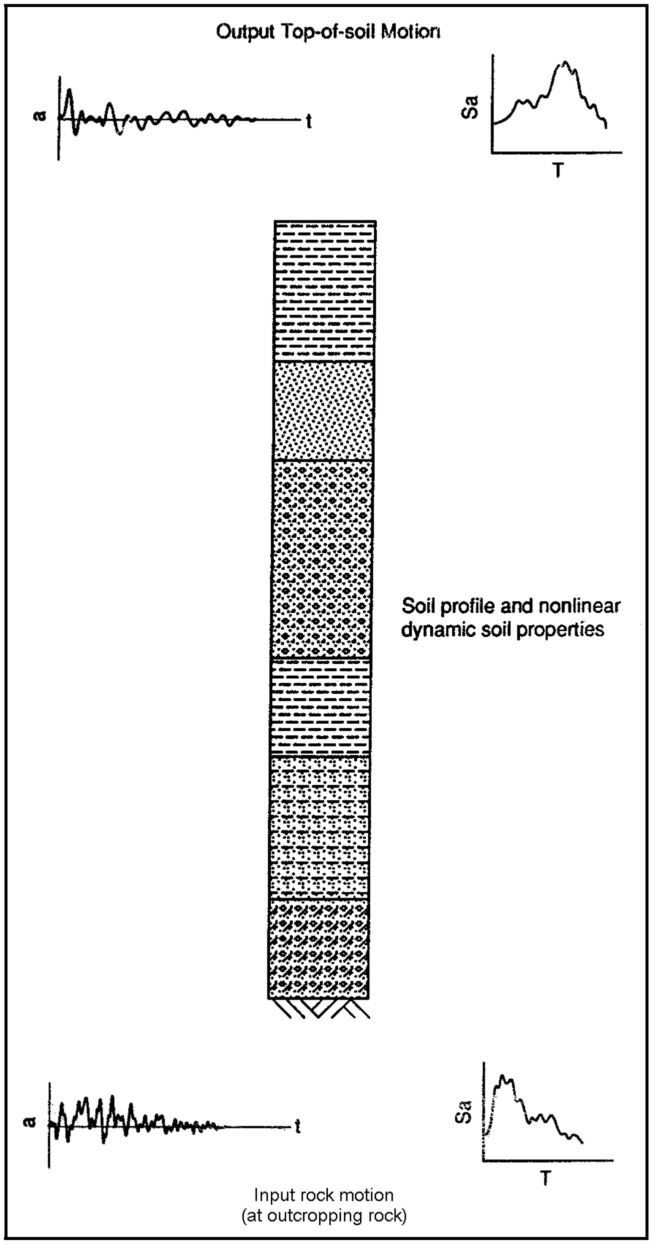


Figure 3-19. Schematic of one-dimensional site response analysis

(5) Estimating vertical ground motion response spectra. The available recently developed attenuation relationships for response spectral accelerations of vertical firm-soil site motions are summarized in Table 3-3. These relationships can be used directly to estimate vertical response spectra on firm soils sites. The vertical to horizontal response spectral ratios discussed in paragraph 3-7*a*(4) and shown in Figure 3-16 can be used as a guide in estimating vertical response spectra, given an estimate of horizontal response spectra.

c. Developing acceleration time-histories of soil motions consistent with design response spectrum. The two alternatives for developing acceleration time-histories for rock motions that were discussed in paragraph 3-6*c*, namely, selecting recorded motions and synthetically developing or modifying motions, can also be used to develop time-histories for top-of-soil motions. In the case where site response analyses are carried out to define top-of-soil motions, there is a third alternative, which is to obtain the time-histories directly from the site response analyses.

Section III
Probabilistic Approach for Developing Site-Specific Response Spectra

3-8. Overview of Probabilistic Seismic Hazard Analysis (PSHA) Methodology

a. General. PSHA takes the elements of a deterministic assessment of earthquake ground shaking hazard—identification of seismic sources; specification of limiting earthquake sizes; assessment of ground motions as a function of earthquake magnitude; source-to-site distance; and site conditions—and adds an assessment of the likelihood that ground shaking will occur during a specified time period. Figure 3-20 shows a typical result of PSHA, termed a hazard curve, that relates the level of ground shaking to the annual frequency of exceedance of that level. The ground motion parameter for the example in Figure 3-20 is peak ground acceleration. PSHA may be conducted for other ground motion parameters, such as peak ground velocity or response spectral values for specific periods of vibration and damping ratios. If a PSHA is carried out for response spectral values at a number of periods of vibration, then response spectra having selected probabilities of exceedance (i.e., "equal hazard" response spectra) may be constructed, as will be discussed later.

b. Elements of a PSHA. Evaluation of the frequency or probability of exceedance of ground motions at a site is a function of earthquake source definition (distance of the sources from the site, source geometries, and frequencies of occurrence (recurrence) of earthquakes of different magnitudes on each source), and ground motion attenuation (amplitudes of ground motion as a function of earthquake magnitude and distance). These basic inputs to a PSHA are then combined in a probabilistic model to obtain hazard curves and (if desired) equal-hazard response spectra as discussed above. The basic elements of a PSHA are illustrated in Figure 3-21 for peak ground acceleration and in Figure 3-22 for equal hazard response spectra.

c. Formulation of PSHA methodology.

(1) Formulation. The methodology used to conduct PSHA was initially developed by Cornell (1968). Current practice is described in several publications, such as National Research Council (1988) and Earthquake Engineering Research Institute Committee on Seismic Risk (1989). Using a Poisson probability model (paragraph 3-9*d*), the probability of exceedance $p_E(z)$ of a ground motion level z in an exposure time or design time period t at a site is related to the annual frequency of ground motion exceedance at the site, ν_z, by:

$$p_E(z) = 1 - e^{-(\nu_z \cdot t)} \tag{3-1}$$

A PSHA is carried out to obtain ν_z, and $p_E(z)$ can then be obtained using Equation 3-1. The return period (RP) for ground motion exceedance at a site is equal to the reciprocal of ν_z. The results of a PSHA are, in practice, expressed in terms of one or more of the parameters, $p_E(z)$, ν_z, and RP. Using Equation 3-1, the interrelationship between these fundamental parameters is illustrated in graphical form in Figure 3-23 and in tabular form in Table 3-4. Note that when ($\nu_z \cdot t$) is small (approximately $\leq$ 0.1), $p_E(z)$ is approximately equal to $\nu_z \cdot t$. For larger values of $\nu_z \cdot t$, $p_E(z)$ is less than ($\nu_z \cdot t$). The basic formulation for ν_z is:

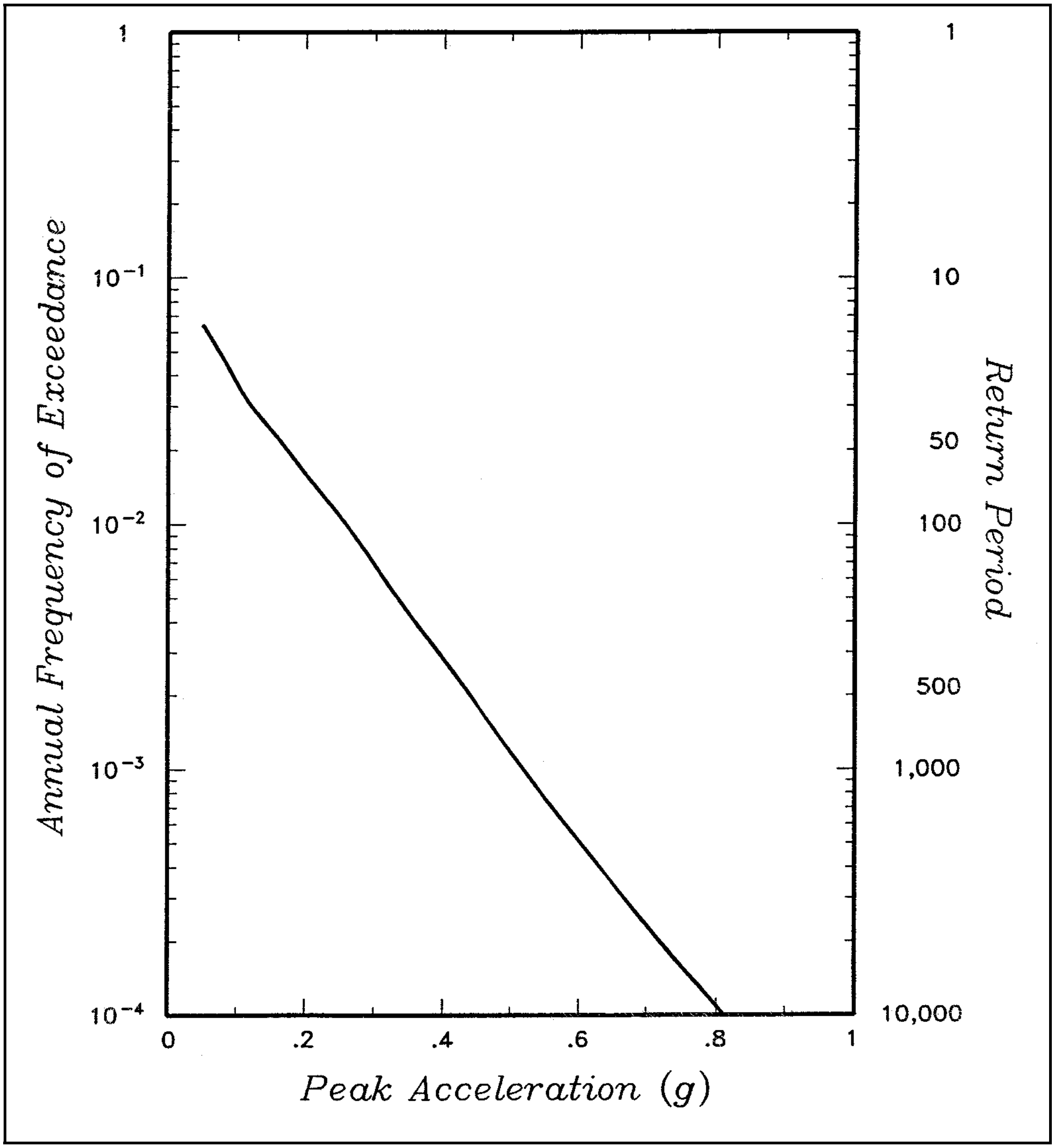


Figure 3-20. Example seismic hazard curve showing relationship between peak ground acceleration and probability (annual frequency) of exceedance

$$v_z = \sum_N \left[\sum_M \lambda\,(m_i) \bullet \sum_R P\,(R = r_j\,|m_i) \bullet P\,(Z > z\,|\,m_i\ r_j) \right]_n \qquad (3\text{-}2)$$

where

$\sum_N$ = summation over all (N) seismic sources

$\lambda(m_i)$ = the annual frequency of occurrence of earthquakes of magnitude m_i (above a certain minimum size of engineering significance) on seismic source n

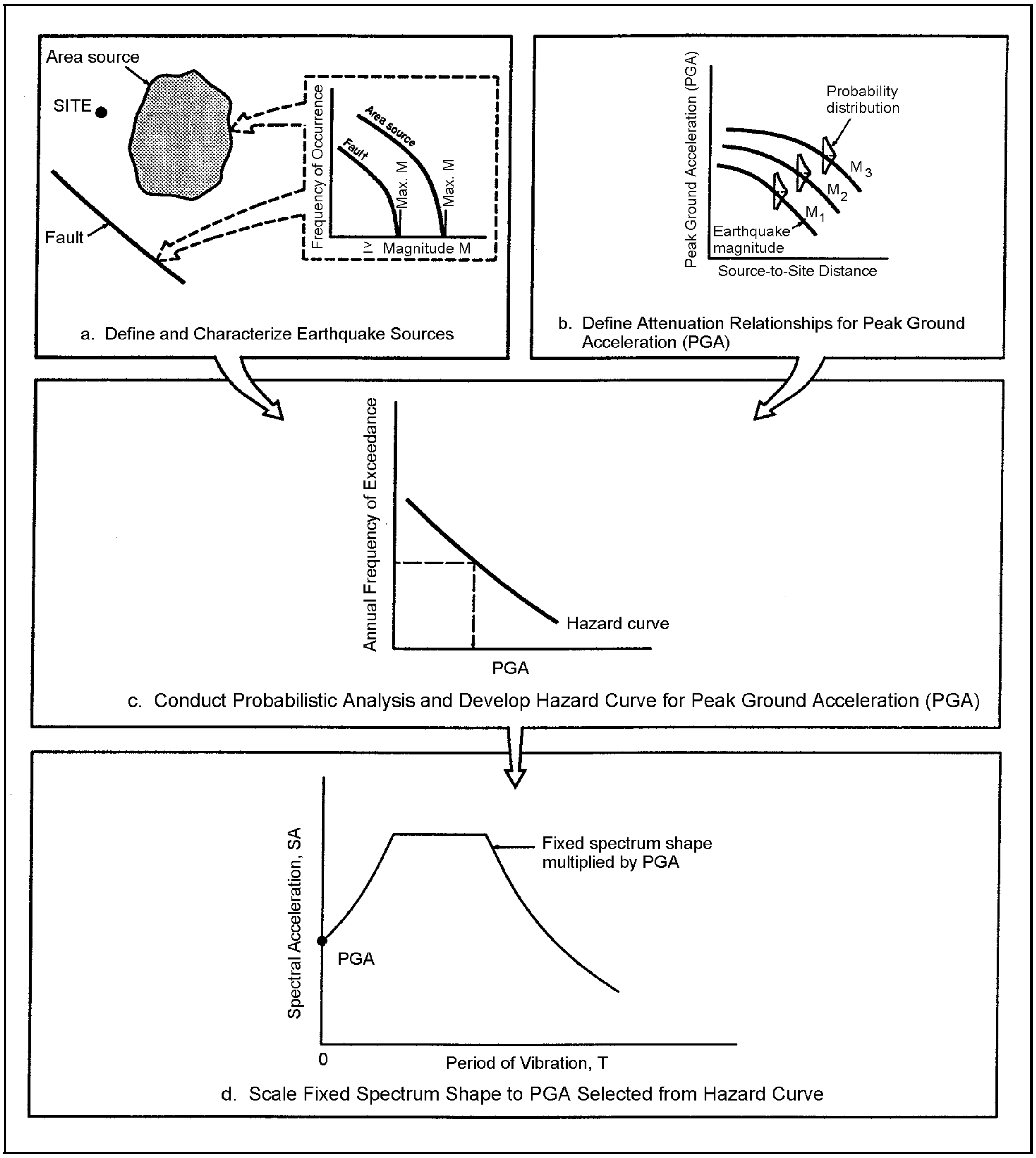


Figure 3-21. Development of response spectrum based on a fixed spectrum shape and a probabilistic seismic hazard analysis for peak ground acceleration

$P(R=r_j \mid m_i)$ = the probability of an earthquake of magnitude m_i on source n occurring at a certain distance r_j from the site

$P(Z>z \mid m_i, r_j)$ = the probability that ground motion level z will be exceeded, given an earthquake of magnitude m_i on source n at distance r_j from the site

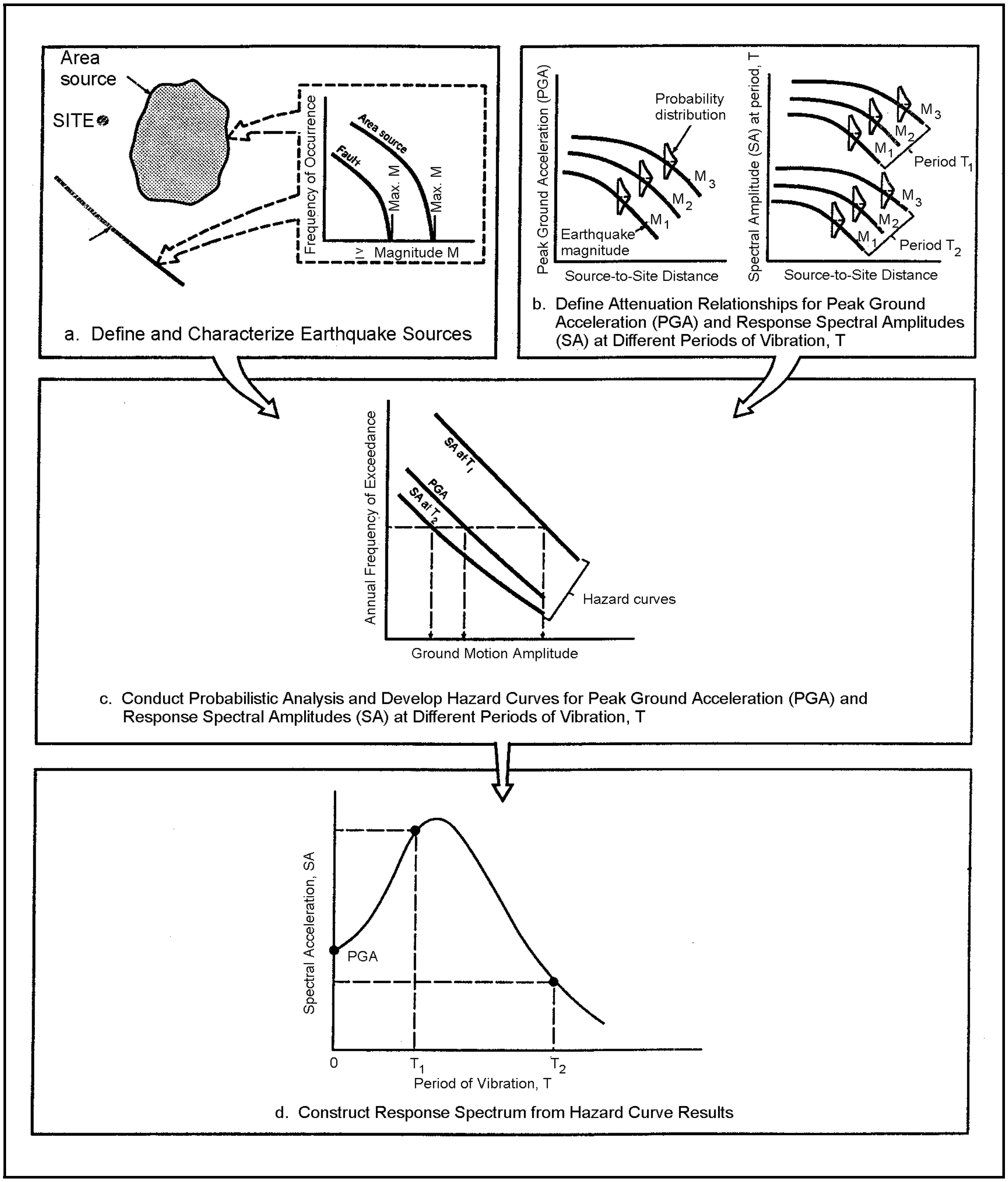


Figure 3-22. Development of equal-hazard response spectrum from probabilistic seismic hazard analysis for response spectral values

Thus, for a given source, the annual frequency or rate of exceeding a certain ground motion level at the site is obtained by summing over all magnitudes and source-to-site distances for that source. Then, the total rate of ground motion exceedance at the site ν_z is obtained by adding the rates for all the sources. The components of Equation 3-2 are discussed in (2), (3), and (4) below. A simplified example of a PSHA illustrating the calculation process using Equation 3-2 is presented in Appendix G (Example G-1).

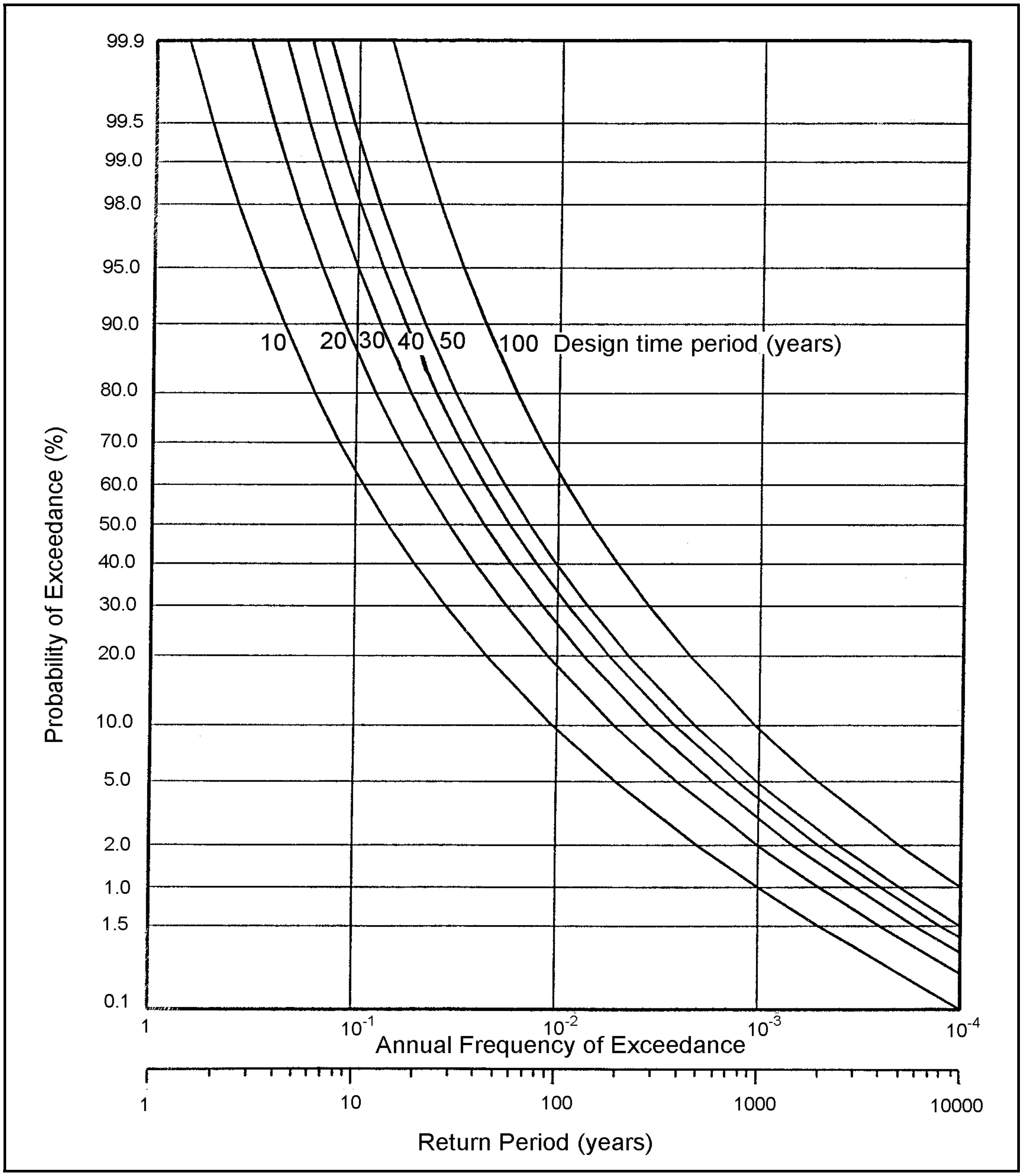


Figure 3-23. Relationship between annual frequency of exceedance/return period and probability of exceedance for different design time periods

(2) Rate of occurrence of earthquakes. The rate of occurrence of earthquakes $\lambda(m_i)$ is obtained based on earthquake recurrence assessments. Typical earthquake recurrence curves for earthquake sources are illustrated in the upper part of Figure 3-24. As shown, recurrence curves express the rate of occurrence of earthquakes equal to or greater than a certain magnitude. $\lambda(m_i)$ is obtained by discretizing the recurrence curves into narrow magnitude intervals as illustrated in the lower part of Figure 3-24. The two different types of magnitude distributions shown in Figure 3-24, exponential and characteristic, are discussed in paragraph 3-9(d).

Table 3-4
Relationship Between Return Period and Probability of Exceedance for Different Time Periods

	Return Period, Years, for Different Design Time Periods *t*					
Probability of Exceedance, %	***t* = 10 years**	***t* = 20 years**	***t* = 30 years**	***t* = 40 years**	***t* = 50 years**	***t* = 100 years**
1	995	1,990	2,985	3,980	4,975	9,950
2	495	990	1,485	1,980	2,475	4,950
5	195	390	585	780	975	1,950
10	95	190	285	380	475	950
20	45	90	135	180	225	450
30	28	56	84	112	140	280
40	20	39	59	78	98	195
50	14	29	43	58	72	145
60	11	22	33	44	55	110
70	8.3	17	25	33	42	83
80	6.2	12	19	25	31	62
90	4.3	8.7	13	17	22	43
95	3.3	6.7	10	13	17	33
99	2.2	4.3	6.5	8.7	11	22
99.5	1.9	3.8	5.7	7.5	9.4	19

(3) Distance probability distribution. The distance probability distribution, $P(R=r_j \mid m_i)$, depends on the geometry of earthquake sources and their distance from the site; an assumption is usually made that earthquakes occur with equal likelihood on different parts of a source. The function $P(R=r_j \mid m_i)$ also should incorporate the magnitude-dependence of earthquake rupture size; larger magnitude earthquakes have larger rupture areas, and thus have higher probability of releasing energy closer to a site than smaller magnitude earthquakes on the same source. An example of probability distributions for the closest distance to an earthquake source is shown in Figure 3-25. In this particular example, the source (fault) is characterized as a line source, and the probability distributions are based on the formulations presented by Der Kiureghian and Ang (1977). Figure 3-25a illustrates the probability distributions for a fault rupture length of 5 km; Figure 3-25b illustrates the probability distributions for a fault rupture length of 25 km. The longer rupture length corresponds to a larger magnitude. The figure shows the distributions for both the probability of the closest distance to the fault rupture R being less than a certain value $P(R<r_j \mid m_i)$, and the probability of earthquakes occurring at a certain distance ($P(R=r_j \mid m_i)$, which is obtained by discretizing the curves for $P(R<r_j \mid m_i)$. The higher probability for earthquakes to occur at closer distances for longer rupture lengths (larger magnitudes) can be noted by comparing Figure 3-25b with 3-25a. It can also be observed in Figure 3-25 that there is zero probability of earthquake occurrence either closer than the closest distance to the earthquake source (10 km in the example) or farther than the closest distance to the rupture placed at the farthest end of the fault (farther than a distance of approximately 61 km $[10^2 + (65 - 5)^2]^{1/2}$ for a 5-km rupture and a distance of approximately 41 km $[10^2 + (65 - 25)^2]^{1/2}$ in the case of the 25-km rupture length). The probability abruptly changes at a closest distance equal to the distance defined by placing the fault rupture at the nearest end of the fault (distance of approximately 32 km $[10^2 + (35 - 5)^2]^{1/2}$ for a 5-km rupture and a distance of approximately 14 km $[10^2 + (35 - 25)^2]^{1/2}$ for a 25-km rupture). Note that the distance to the earthquake rupture must be

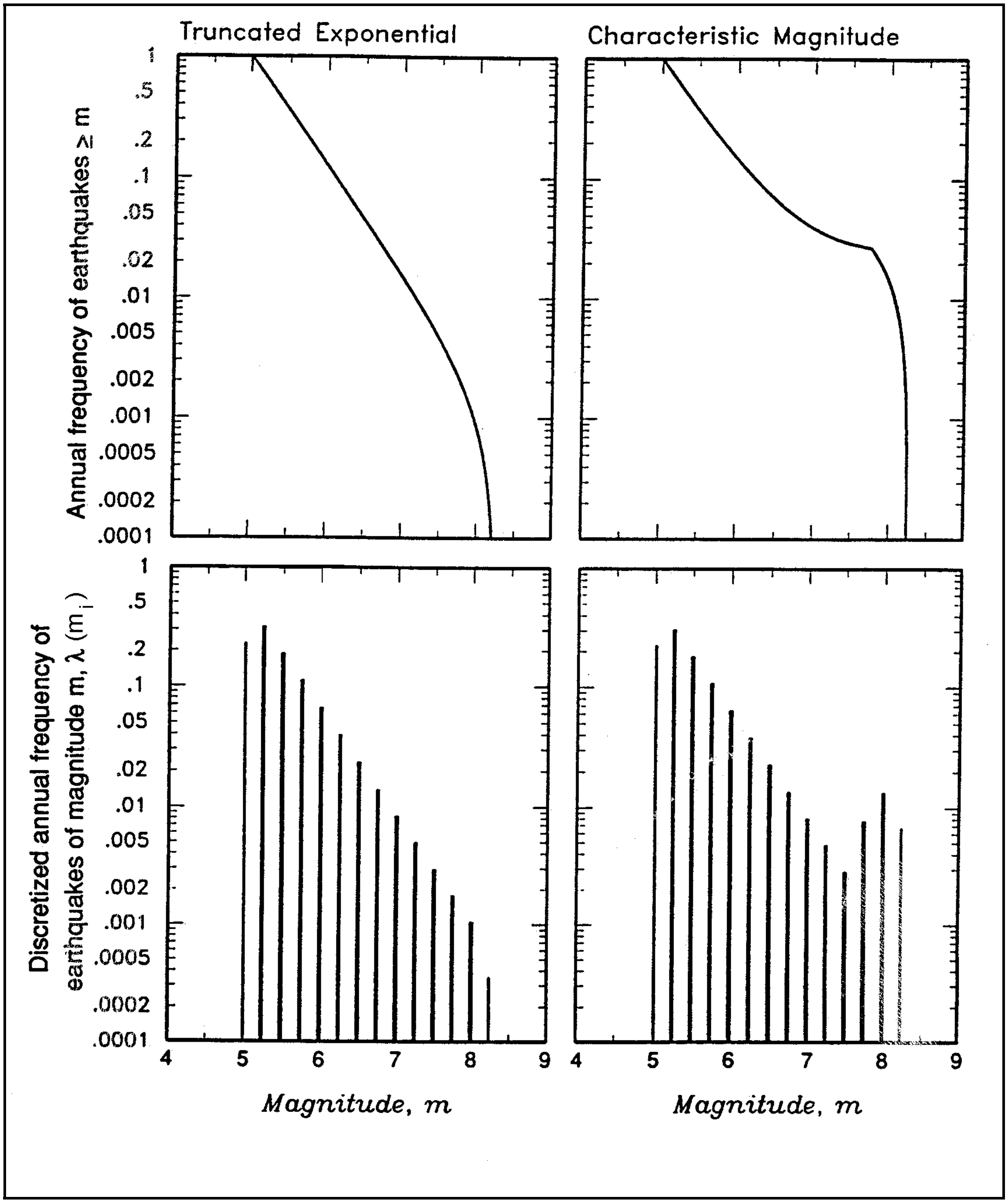


Figure 3-24. Typical earthquake recurrence curves and discretized occurrence rates

expressed in terms of the same definition of distance as used in the ground motion attenuation relationships. Typically, some form of closest distance to rupture definition is used for attenuation relationships (variations in this definition include closest distance to rupture, closest distance to rupture of the seismogenic zone, closest horizontal distance to surface projection of rupture, etc.).

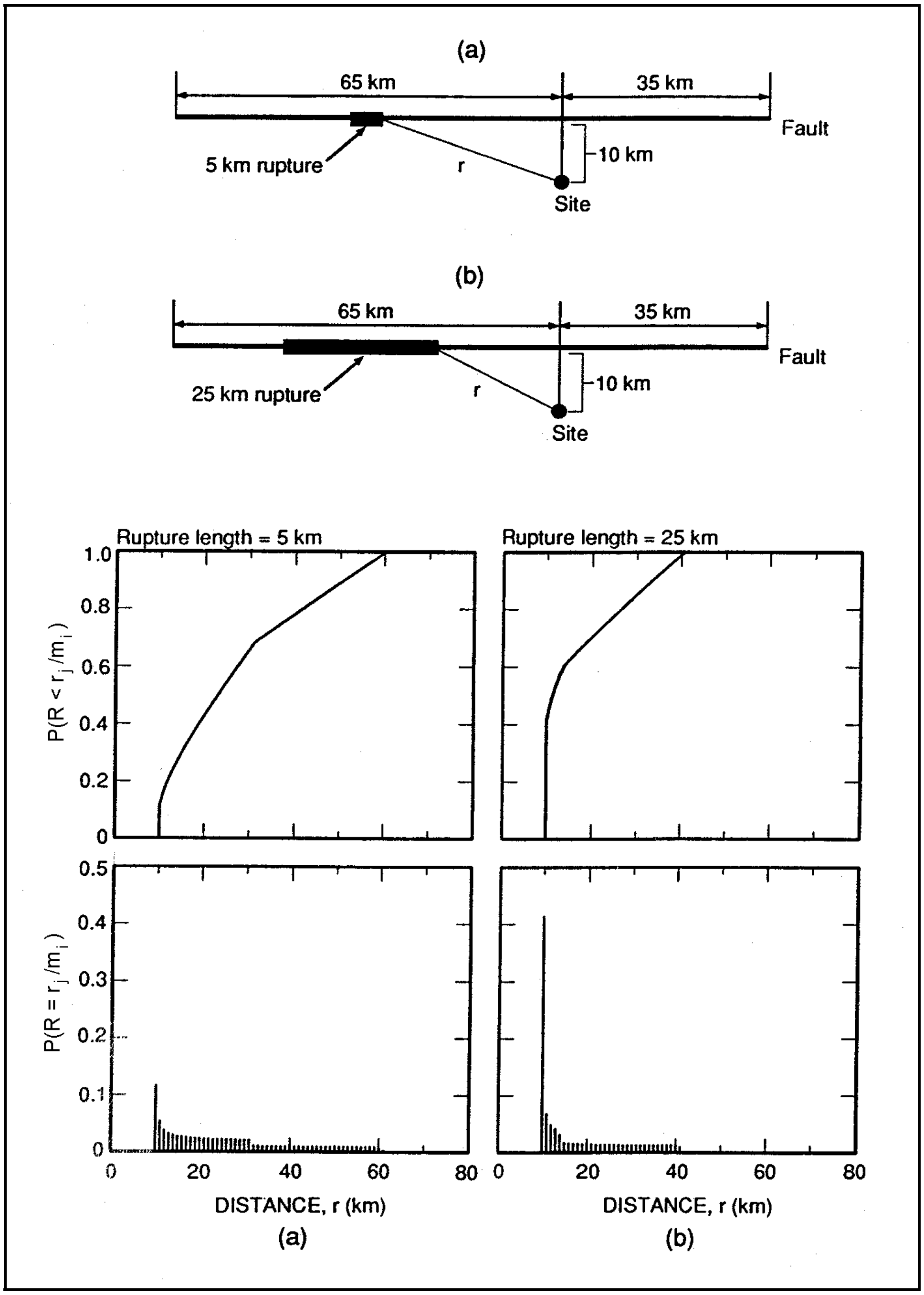


Figure 3-25. Illustration of distance probability distribution

(4) Conditional probability of ground motion exceedance. The conditional probability of exceeding a ground motion level for a certain earthquake magnitude and distance $P(Z>z|m,r)$ is determined from the ground motion attenuation relationships selected for the site. (Available relationships are discussed in Section II.) These relationships incorporate the uncertainty in ground motion estimation given m and r (see Figures 3-21 and 3-22). The function $P(Z>z|m,r)$ is usually evaluated assuming that ground motion values are log normally distributed about the median value; the calculation of this function is illustrated in Figure 3-26.

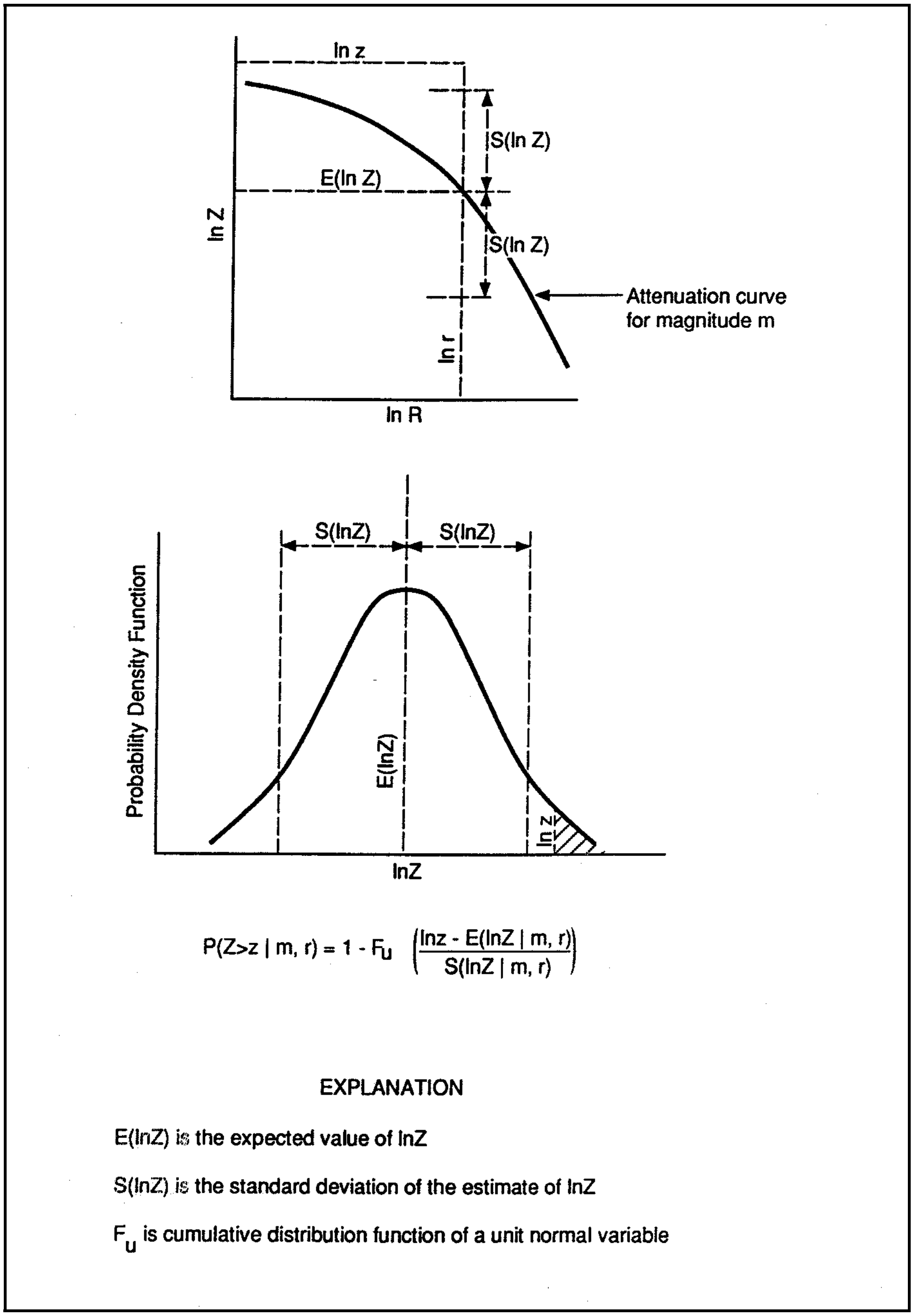


Figure 3-26. Ground motion estimation conditional probability function

3-9. Characterizing Seismic Sources for PSHA

Although the following discussion is oriented toward probabilistic approaches for characterizing seismic sources, much of the discussion is applicable to deterministic approaches as well.

a. Source identification.

(1) Seismic source. A seismic source represents a region of the earth's crust where the characteristics of earthquake activity are recognized to be different from those of the adjacent crust. Seismic sources are identified on the basis of geological, seismological, and geophysical data. An understanding of the regional tectonics, local Quaternary geologic history, and seismicity of an area leads to the identification of seismic sources. The development of tectonic models for crustal deformation and the assessment of the tectonic role of individual geologic structures are useful for both identifying potential sources and assessing their characteristics. Geologic studies can be used to assess the location, timing, and style of crustal deformation. The association of geologic structures with historic or instrumental seismicity may clarify their role within the present tectonic stress regime. Characteristics of seismicity, including epicenter locations, focal depths, and source mechanisms, also aid in identifying potential sources.

(2) Faults. Because earthquakes occur as a result of differential slip on faults, modeling of seismic sources as individual faults is the most physically realistic model for seismic hazard analysis. Under favorable conditions, individual faults can be identified and treated as distinct seismic sources. Active faults are usually identified on the basis of geomorphic expression and stratigraphic displacements but can also be identified by lineations of seismicity, by geophysical measurements, or by inference from detailed investigations of related geologic structures, such as active folding or crustal plate subduction. A fault model for individual sources allows the use of geologic data on fault behavior, as well as seismicity data, to characterize earthquake activity.

(3) Seismic source zones. In areas with low rates of crustal deformation away from plate margins, such as the EUS, seismic sources are often defined as seismic source zones. Seismic source zones are used to model the occurrence of seismicity in areas where specific faults cannot be identified and where the observed seismicity exhibits a diffuse pattern not clearly associated with individual faults. These conditions are typical of areas with lower rates of crustal deformation, such as regions away from plate margins (e.g., EUS). Seismic source zones can be defined based either on historical seismicity patterns or geology and tectonics. When defined based on historical seismicity patterns, a large region can be subdivided into small regular areas that are treated as individual source zones (Electric Power Research Institute (EPRI) 1987; U.S. Geological Survey (USGS) 1996). With this approach, it is assumed that the spatial variation in the occurrence rate of future earthquakes is similar to the historical pattern of seismicity. Due to the relatively short historical period and low rates of seismicity, the seismicity patterns are usually determined by small earthquakes. It is not clear whether this pattern reflects the likelihood of future earthquakes of engineering significance (generally taken to be earthquakes of magnitude approximately equal to or greater than 5). The alternative approach is to define areas thought to have homogeneous earthquake potential characteristics (in terms of rate of earthquake occurrence and maximum earthquake size) on the basis of the geology and tectonics of the region. For example, recent evidence from studies of global earthquakes in stable continental regions such as the EUS has shown that most larger earthquakes occur through reactivation of faults in geologically ancient rift zones (Johnston et al. 1994). Where available, paleoseismological data (e.g., spatial and temporal distribution of liquefaction features) should be used to identify source regions for large-magnitude earthquakes. Because of uncertainty regarding the most appropriate model for earthquake occurrence, both seismicity-based and geologically based seismic source zones should be included in a probabilistic analysis.

b. Source geometry.

(1) General. Description of the geometry of a seismic source is necessary to evaluate the distances from the site at which future earthquakes could occur. In addition, source geometry can place physical constraints on the maximum size earthquake that can occur on a source.

(2) Faults. Seismic sources defined as faults are modeled in a PSHA as segmented linear or planar features. Earthquake ruptures on fault sources are modeled as rupture lengths or rupture areas, with the size of rupture defined on the basis of empirical relationships between earthquake magnitude and rupture size (Wyss 1979; Wells and Coppersmith 1993).

(3) Seismic source zones. For seismic sources defined as geologic structures suspected to contain faults, the distribution of earthquakes can be modeled as rupture surfaces occurring on multiple fault planes distributed throughout the source volume if the general trend of such planes is known or can be inferred. Alternatively, earthquake locations can be modeled as random point sources within the source volume if the orientation of potential fault planes is unknown. The spatial distribution of seismicity within large areal sources can be modeled similarly.

c. Maximum earthquake magnitude.

(1) Faults. The limiting size earthquake that can occur on each seismic source is an important parameter, especially in evaluating seismic hazard at low probability levels. The maximum magnitude can most easily be estimated when the seismic source is defined on the basis of an identifiable fault. For faults, the maximum earthquake magnitude is related to fault geometry and fault behavior through an assessment of the maximum dimensions of a single rupture. Evaluation of fault segmentation can play a key role in identifying portions of a fault zone likely to represent the largest size of a single rupture (Schwartz and Coppersmith 1986; Schwartz 1988). The maximum magnitude is related to the maximum rupture size through empirical relationships (Slemmons 1982; Bonilla, Mark, and Lienkaemper 1984; Wells and Coppersmith 1994). Because these relationships are subject to uncertainty, the use of a number of magnitude estimation techniques can result in more reliable estimates of maximum magnitude than the application of a single relationship.

(2) Seismic source zones. The assessment of maximum magnitude is more difficult when seismic sources are defined on the basis of large-scale tectonic features or crustal blocks, as is typically done in the EUS. In such cases the maximum magnitude is often estimated to be the maximum historical earthquake magnitude plus an increment, or is estimated to be a magnitude having a specified return period. The chief weakness of these approaches is the generally short period of historical observations compared with the likely return period of a maximum event for an individual source. Another approach that attempts to extend the generally short observational period for individual sources is based in augmenting the assessment using data from analogous structures worldwide. This approach identifies analogous features for which the maximum magnitude is better defined or identifies the largest event that has occurred on such features. In the application of analogies, the seismicity of similar structures on a worldwide basis can be examined to supplement the limited local historical record. Recent efforts have been made to use a global earthquake database to identify the factors that control or limit the maximum size of earthquakes within stable continental regions like the EUS to develop a formal method for estimating maximum magnitude in such regions (Johnston et al. 1994)

d. Rate of earthquake occurrence and distribution in earthquake size.

(1) Estimating recurrence rates. Earthquake recurrence rates are estimated from historical seismicity, from geological data on rates of fault movement, and from paleoseismic data on the timing of large prehistoric events. For areal sources, historical seismicity is usually used to estimate earthquake recurrence rates. When recurrence for small, regular source zones (cells) is analyzed (*a*(3) above), procedures can be employed to smooth seismicity rates among adjoining cells (EPRI 1987; USGS 1996). In an analysis of the earthquake catalog of historical seismicity, it is important to translate the data into a common magnitude scale consistent with the magnitude scale used in the ground motion attenuation

relationships, and to account for completeness in earthquake reporting as a function of time and location. Straightforward statistical techniques can then be used to estimate earthquake recurrence parameters (Weichert 1980).

(2) Use of geologic data for faults. For sources defined as individual faults, the available historical seismicity is usually insufficient to characterize the earthquake recurrence. Geologic data on fault slip rates can be used to estimate the rate of seismic moment release, leading to the rate of earthquake recurrence. In addition, paleoseismic studies of the occurrence of large prehistoric events can be used to estimate recurrence of larger magnitude earthquakes on a fault. Predictions of recurrence rates for larger events from fault-specific geologic data have been shown to match well with observed historical rates on a regional basis (Youngs and Coppersmith 1985b; Youngs, Swan, and Power 1988; Youngs et al. 1987; Youngs et al. 1993b). The rate of earthquake occurrence may not be uniform along the strike or dip of an earthquake fault. Evaluation of fault segmentation can be used to characterize variations in recurrence along the length of a fault. The depth distribution of historical seismicity can be used to specify down-dip variations in recurrence.

(3) Recurrence models. The relative frequency of various size earthquakes has usually been specified by the truncated exponential recurrence model (Cornell and Van Marke 1969) based on Gutenberg and Richter's (1954) recurrence law. This model was developed on the basis of observations of global seismicity. It has been found to work well on a regional basis and for modeling seismicity for nonfault specific sources such as distributed seismicity zones and generalized tectonic structures. Recent advances in understanding of the earthquake generation process have indicated that earthquake recurrence on individual faults may not conform to the exponential model. Instead, individual faults or fault segments may tend to rupture in what have been termed “characteristic” magnitude events at or near the maximum magnitude (Schwartz and Coppersmith 1984). This has led to the development of fault-specific recurrence models such as the maximum moment model (Wesnousky et al. 1983) and the characteristic magnitude recurrence model (Youngs and Coppersmith 1985a, 1985b). Figure 3-27 illustrates a characteristic magnitude recurrence model. Figure 3-28 compares exponential and characteristic earthquake recurrence relationships. The figure illustrates the differences between the two recurrence models depending on how the earthquake recurrence rate is specified. Figure 3-28a shows recurrence curves if the total rate of seismic moment release is specified to be the same for each model; Figure 3-28b shows recurrence curves if the rate of large-magnitude earthquakes is specified to be the same for each model. Detailed studies of earthquake recurrence in the Wasatch fault region, Utah, and in the San Francisco Bay region have shown excellent matches between regional seismicity rates and recurrence modeling when combining the characteristic recurrence model for individual faults with the exponential model for distributed source areas (Youngs et al. 1987; Youngs, Swan, and Power 1988; Youngs et al. 1993b).

(4) Poisson versus real-time recurrence. Nearly all PSHA's assume that earthquake occurrence in time is a random and memoryless (Poisson) process. In the Poisson process, it is assumed that the probability of an event in a specified period is completely determined by the average frequency of occurrence of events, and the probability of occurrence of the next event is independent of when the last event occurred. While the observed seismicity data on a regional basis have been shown to be consistent with the Poisson model, the model does not conform to the physical process believed to result in earthquakes, one of a gradual, relatively uniform rate of strain accumulation followed by sudden release. Detailed paleoseismic studies of several faults as well as historical seismicity from very active subduction zones have indicated that the occurrence of the larger events on a source tends to be more cyclic in nature. These observations have led to the use of nonstationary or “real-time” recurrence models that predict the probability of events in the next period, rather than any period. Typically, a

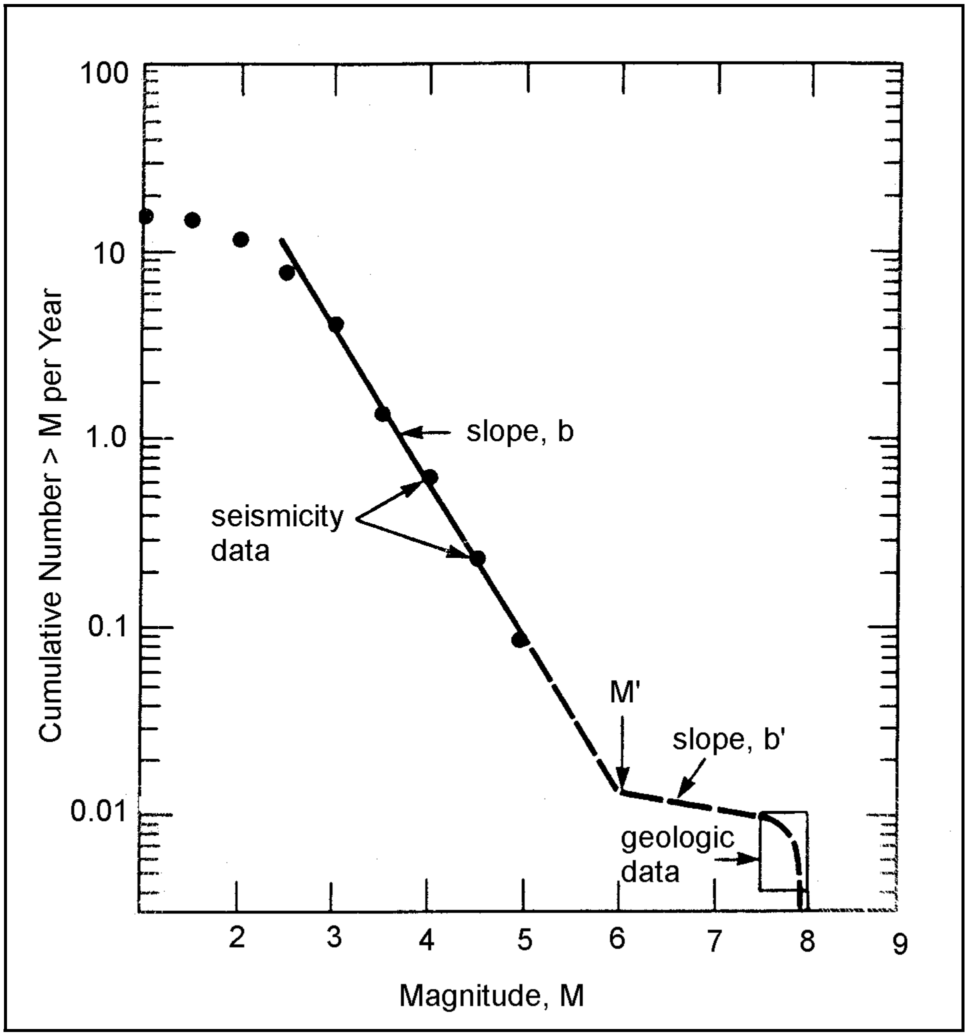


Figure 3-27. Diagrammatic characteristic earthquake recurrence relationship for an individual fault or fault segment. Above magnitude *M'* a low *b* value (*b'*) is required to reconcile the small-magnitude recurrence with geologic recurrence, which is represented by the box (Schwartz and Coppersmith 1984; National Research Council 1988)

simple "renewal model" is used to evaluate the likelihood of events within specified future periods. A recent example of the use of a renewal model was a study of the probabilities of large earthquakes on the San Andreas fault system in northern California for use in regional planning (Working Group on California Earthquake Probabilities 1990). Consideration may be given to such time-dependent models in the few cases where there is sufficient information to develop the required parameters.

3-10. Ground Motion Attenuation Characterization for PSHA

Specification of ground motions for PSHA is subject to all of the requirements discussed in Section II for deterministic ground motion assessments. The analysis requires ground motion attenuation relationships for the full range of magnitudes and distances considered. Recently developed attenuation relationships for peak ground acceleration and response spectral values of ground motion are listed in Tables 3-1 and 3-3, respectively. The uncertainties in the level of a ground motion parameter given a certain

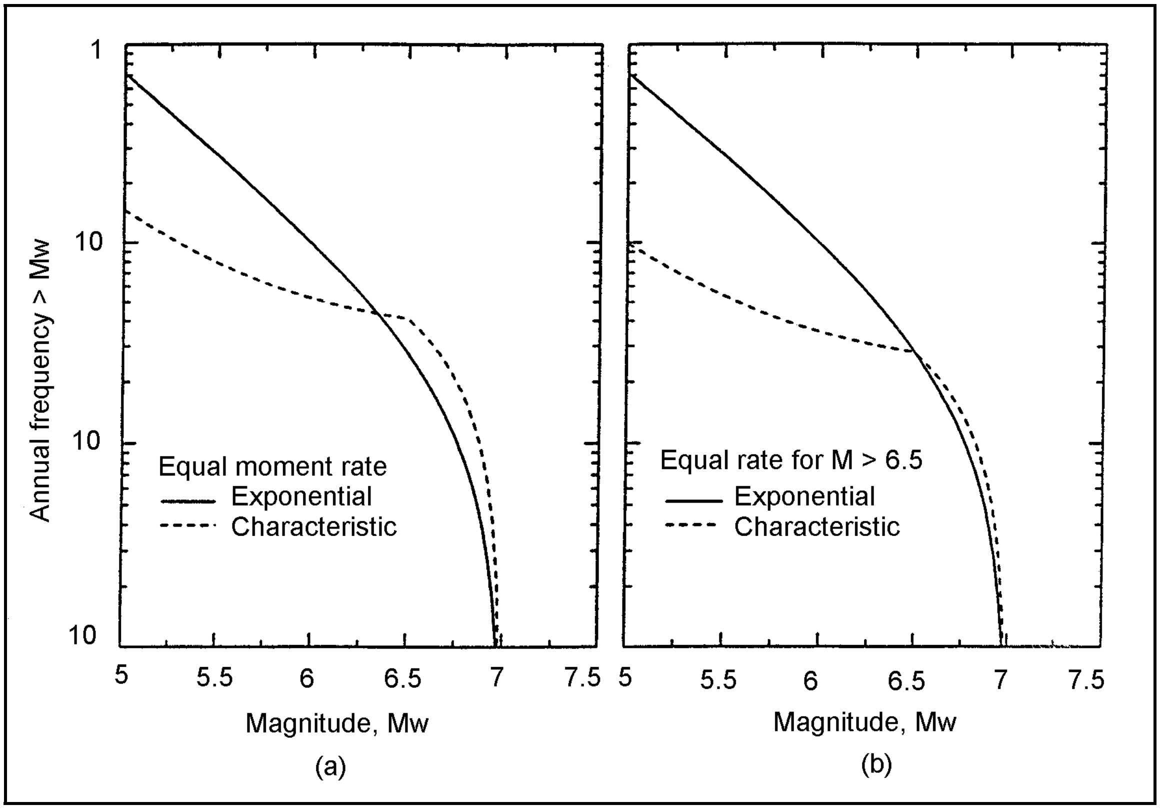


Figure 3-28. Comparison of truncated exponential and characteristic earthquake recurrence relationships

earthquake magnitude and distance (modeled by the probability distribution for the attenuation relationship (Figure 3-26)) are of considerable importance in influencing the results of a PSHA and should be included in the analysis.

3-11. Treatment of Scientific Uncertainty in PSHA

The basic probability formulations in Equations 3-1 and 3-2 incorporate the randomness of the physical process of earthquake generation and seismic wave propagation. Although these formulations incorporate the inherent uncertainty due to randomness, they do not incorporate additional sources of uncertainty that may be associated with the choice of particular models or model parameters. For example, there could be uncertainty about which ground motion attenuation relationship is most applicable to a site, whether an exponential or characteristic earthquake recurrence model is most applicable, the most appropriate model for seismic source zones, the geometry of earthquake sources, the values of maximum earthquake magnitude, or earthquake recurrence parameters. In a deterministic analysis, these uncertainties, which are termed scientific or epistemic uncertainties, are usually treated by applying conservatism in selecting design earthquakes and estimating ground motions. In PSHA, these uncertainties can be directly modeled within the analysis framework to provide an assessment of the uncertainty in the result. The technique of “logic trees” has been widely used to incorporate scientific uncertainty in a PSHA (Kulkarni, Youngs, and Coppersmith 1984; Youngs et al. 1985; Coppersmith and Youngs 1986; National Research Council 1988). Figure 3-29 shows an example of a logic tree used in a PSHA. Although only a few branches of the logic tree are shown, there may be many thousands of branches in the tree. Each path through the tree to an end branch (on the right side of Figure 3-29)

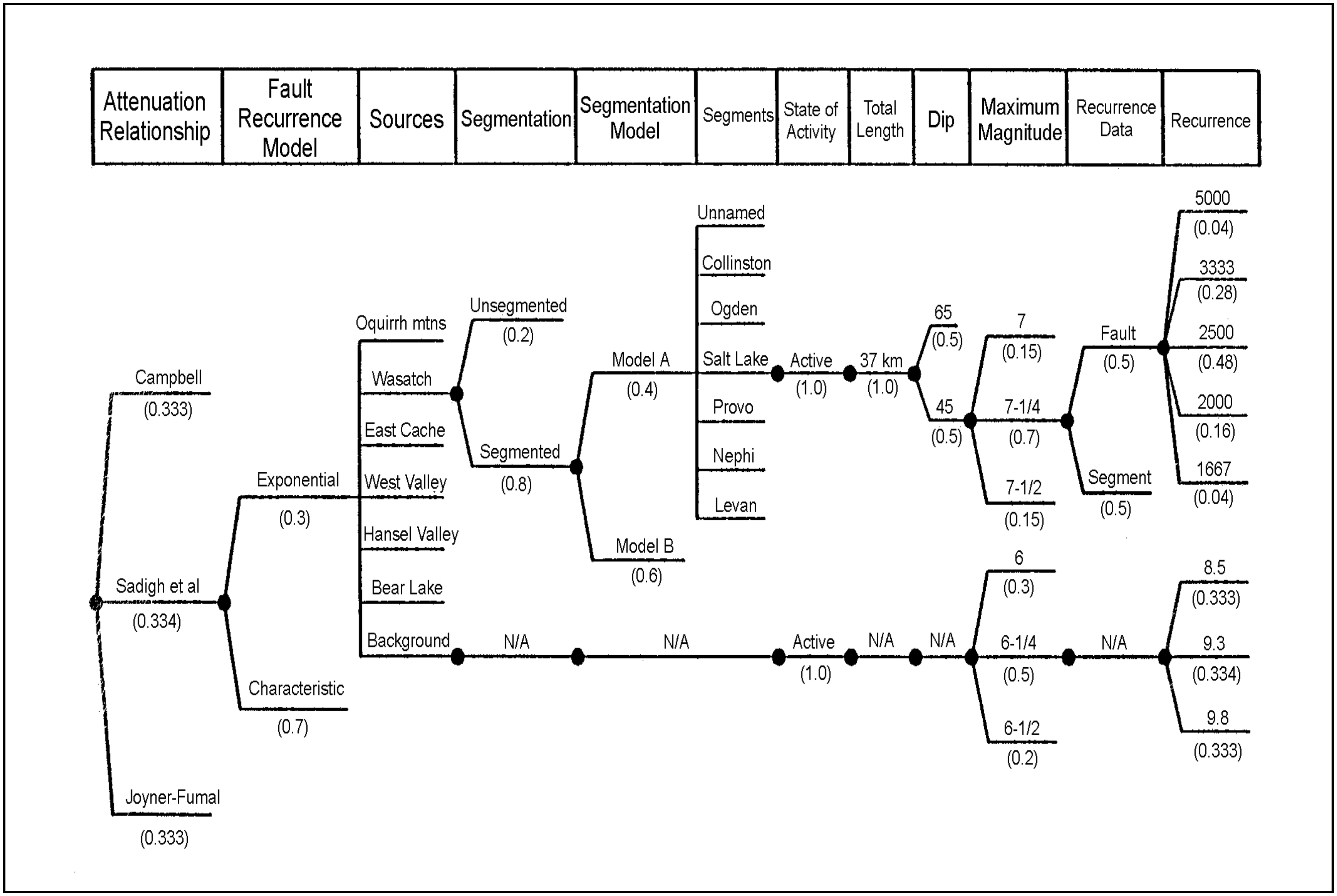


Figure 3-29. Example of logic tree for characterizing uncertainty in seismic hazard input (Youngs, Swan, and Power 1988, reprinted by permission of ASCE)

defines a set of parameters that are used to conduct a basic seismic hazard analysis for that path and end branch using Equation 3-2. Basic hazard analyses are carried out for each path. Each path also has an associated probability or weight that is determined by the product of the relative probabilities or weights assigned to the various models and parameters along the path. (The relative probabilities or weights of the alternative models and parameters are illustrated by the numbers in parentheses in Figure 3-29.) The relative probabilities or weights assigned to alternative models or parameter values are often assigned subjectively, on the basis of the preponderance of scientific evidence or judgment. The sensitivity of the PSHA to changes in the weights can be tested. For some parameters, such as earthquake recurrence based on observed seismicity, the relative weights assigned to different recurrence rates and b-values can be derived from statistical analysis of the seismicity data. The basic hazard analysis results for all the paths in the logic tree are combined using the associated weights to arrive at best estimates (mean or median values) for the frequencies of exceedance of ground motions as well as uncertainty bands for the estimates. Through the approach of incorporating scientific uncertainty, PSHA incorporates the alternative hypotheses and data interpretations that may significantly affect the computed results. The use of logic trees in PSHA, including the mathematical formulation, is discussed in more detail in Appendix F. A simplified example of a PSHA illustrating the calculation process using logic trees is presented in Appendix G (Example G-1).

3-12. Development of Site-Specific Response Spectra from PSHA

The approaches that can be followed in specifying site-specific spectra on the basis of a probabilistic seismic hazard analysis mirror those outlined in Section II for deterministic analyses and involve either anchoring a spectral shape to a peak acceleration level determined from a PSHA for peak acceleration (Figure 3-21) or estimating the entire spectrum on the basis of PSHA for response spectral values at a number of periods of vibration (i.e., developing an equal-hazard spectrum, Figure 3-22). For soil sites, the ground motions can be obtained either by conducting the PSHA using attenuation relationships for soil sites or by conducting the PSHA for rock site conditions and then using site response analyses to evaluate the effects of the site soil column on the ground motions.

a. Approach 1 - Anchoring spectral shape to peak ground acceleration determined from PSHA. In this approach a probabilistic seismic hazard analysis is conducted to establish the relationship between peak ground acceleration and frequency of exceedance. The design peak acceleration level is specified by selecting an appropriate frequency, return period, or probability level. For example, Figure 3-20 shows a typical result of a PSHA for peak ground acceleration. If the exceedance frequency is taken to be 0.001 (return period of 1,000 years), then the corresponding peak acceleration level would be approximately 0.5 g for the example in Figure 3-20. A site-specific spectrum could then be constructed by anchoring an appropriate spectral shape to this acceleration level. As discussed in Section II, it is desirable to select a spectral shape appropriate for the earthquake size and distance producing the hazard as well as the local subsurface conditions. Consideration of earthquake size and distance is less straightforward in a PSHA than in a deterministic analysis because the hazard is the result of the possible occurrences of many different earthquakes of varying sizes and distances from the site. Thus, the hazard analysis results must be examined to identify the major contributors to the hazard at the ground motion level of interest. As an example, Figure 3-30 shows the relative contribution of earthquakes of various magnitudes and distances from three different return periods. As indicated in the figure, the major contribution to seismic hazard shifts to larger magnitudes and closer distances as the return period increases. The example also indicates that a wide range of magnitudes can contribute to the hazard at a selected probability level. This suggests that more than one spectral shape may be appropriate in particular circumstances to address the different types of events that may affect the site.

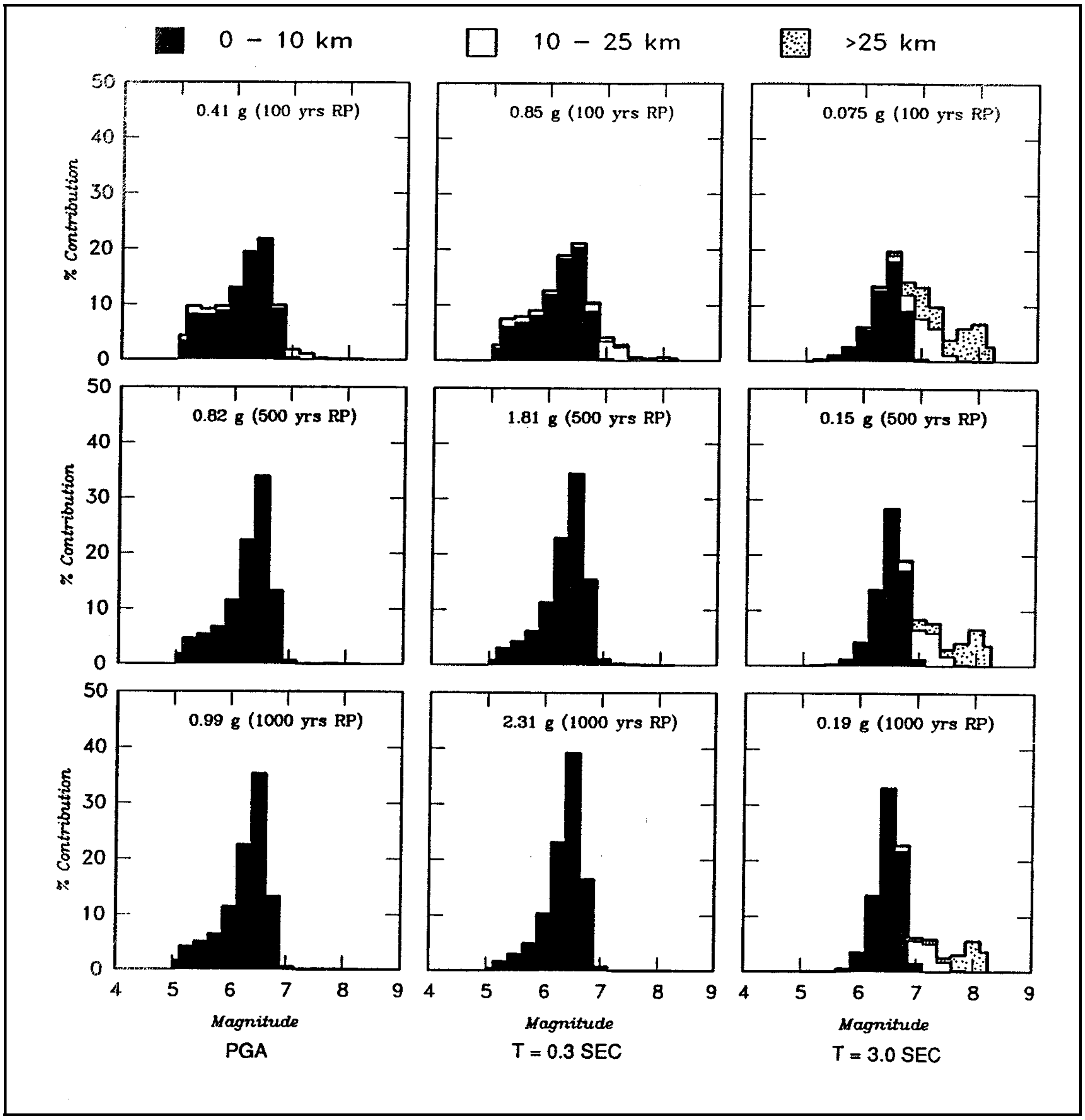


Figure 3-30. Example of contributions of events in various magnitude and distance intervals to mean hazard for peak acceleration and 5 percent damped spectral acceleration at periods of 0.3 and 3 sec

b. Approach 2 - Development of equal-hazard spectra. In this approach, PSHA's are conducted for response spectral values covering the range of vibrational periods of interest for the project. Figure 3-31a shows the results of PSHA's for peak ground acceleration and for 5 percent-damped spectral ordinates at seven selected periods of vibration for the example site used in Figure 3-20. When the appropriate exceedance frequency or return period to use for design is specified, spectral ordinates are read off each hazard curve and are plotted against frequency as shown in Figure 3-31b. (Note that peak ground acceleration is equal to zero-period response spectral acceleration, which, in this example, is equal to response spectral acceleration at 0.03-sec period.) A smooth spectral shape is then drawn through these points to construct the equal-hazard spectrum, a spectrum that has the same probability of exceedance at each frequency. As was the case for the peak ground acceleration hazard results, the

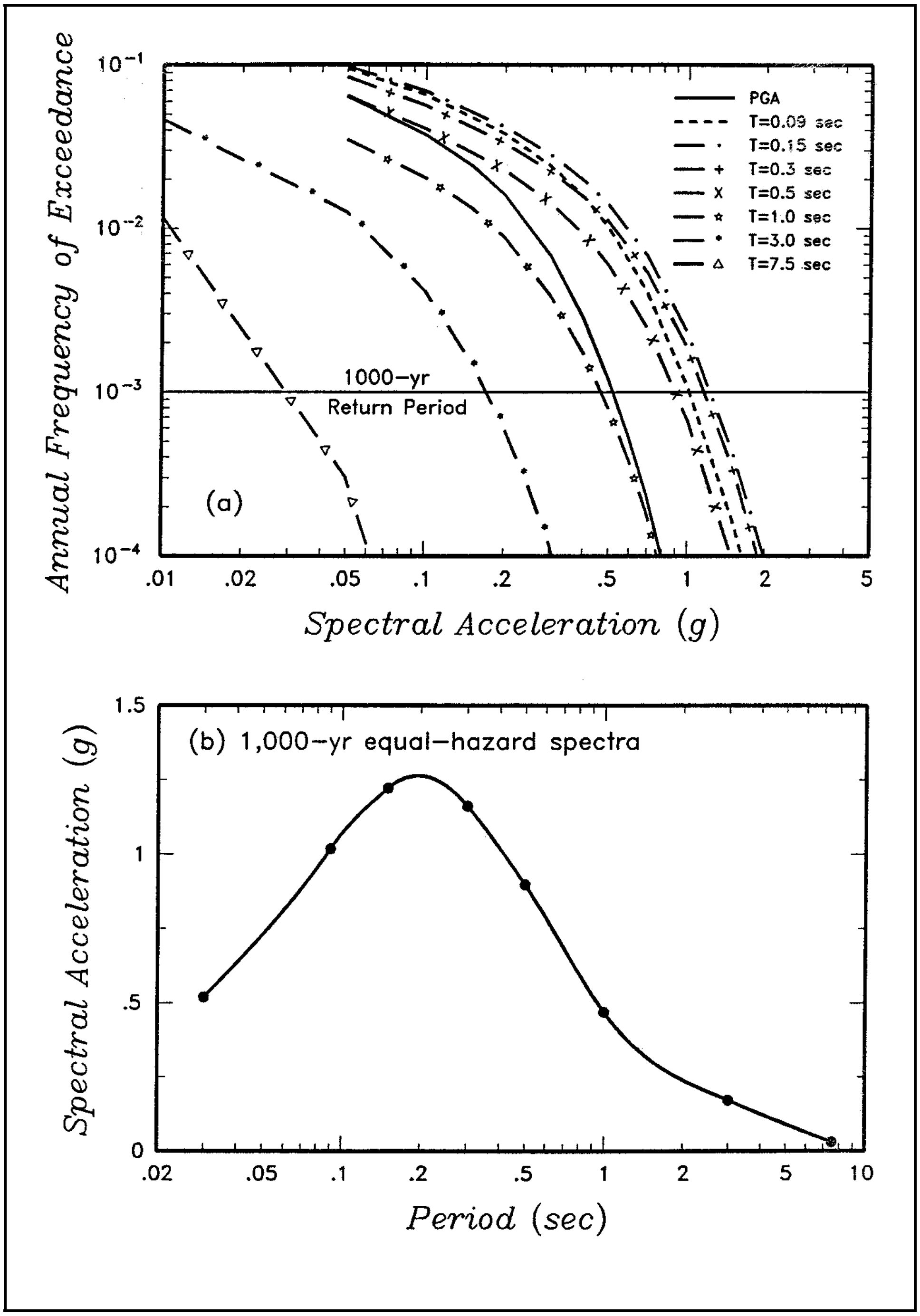


Figure 3-31. Construction of equal-hazard spectra. Top plot (a) shows hazard curves for a range of spectral periods. Bottom plot (b) shows equal hazard spectrum for a period of 1,000 years

equal-hazard spectrum is the result of many possible earthquakes of different sizes and locations. This is illustrated in Figure 3-30, which shows the relative contributions of different magnitude earthquakes to the hazard as a function of return period for spectral values at two periods of vibration as well as for peak ground acceleration. As can be seen, for the same probability of exceedance, the contributions shift to larger magnitudes as the spectral period of vibration increases. This is because the ground motion attenuation relationships are more strongly a function of magnitude at long periods than short periods of vibration.

c. Preferred approach. Approach 2 is recommended over Approach 1 because it is not straightforward to select appropriate spectral shapes in Approach 1. It will be feasible to develop an equal-hazard response spectra from a PSHA using Approach 2. Response spectral value attenuation relationships are available for both the EUS and WUS (Section II and Table 3-3) that are as reliable as those developed for peak ground acceleration. The computation of equal-hazard spectra using these spectral attenuation relationships directly accounts for the changes in contributions to the hazard from different magnitudes and source-to-site distances. The use of equal-hazard spectra also accounts for the change in spectral shape with change in return period or probability level, as is illustrated in Figure 3-32 showing an example of equal-hazard response spectral shapes for three probability levels. These are compared in the figure to a standard spectral shape for a similar site condition.

3-13. Development of Accelerograms

Appropriate accelerograms for use with probabilistically based response spectra can be developed using the same two methods described in Section II for deterministic analyses. The additional step required for probabilistically based response spectra is identification of the appropriate magnitude and distance range from which candidate accelerograms may be selected. This information is obtained by deaggregation of the composite hazard to identify the contributions of various magnitudes and distances, as illustrated in Figure 3-30. Suites of natural accelerograms representing the range of events with major contributions to the hazard may be selected and scaled to approximately correspond to the level of the equal-hazard spectrum. Alternatively, synthetically modified accelerograms can be generated to provide a close match to the equal-hazard spectrum (paragraph 3-6c).

3-14. Summary of Strengths and Limitations of DSHA and PSHA

a. DSHA.

(1) Strengths.

(a) The concept of the design maximum earthquake (MCE) is straightforward and readily understood by the engineer. The MCE represents an estimate of the maximum earthquake size on a source and is located a defined distance from the site.

(b) Provided an appropriate degree of conservatism is incorporated in defining the earthquake magnitude, source-to-site distance, and resulting site ground motions, design for the MCE should provide an appropriately high level of safety.

(2) Limitations.

(a) The frequency of earthquakes and resulting ground motions is not explicitly considered. As a result, a deterministic estimate for a maximum earthquake will have a lower probability of being exceeded in a low-seismicity environment than in a high-seismicity environment.

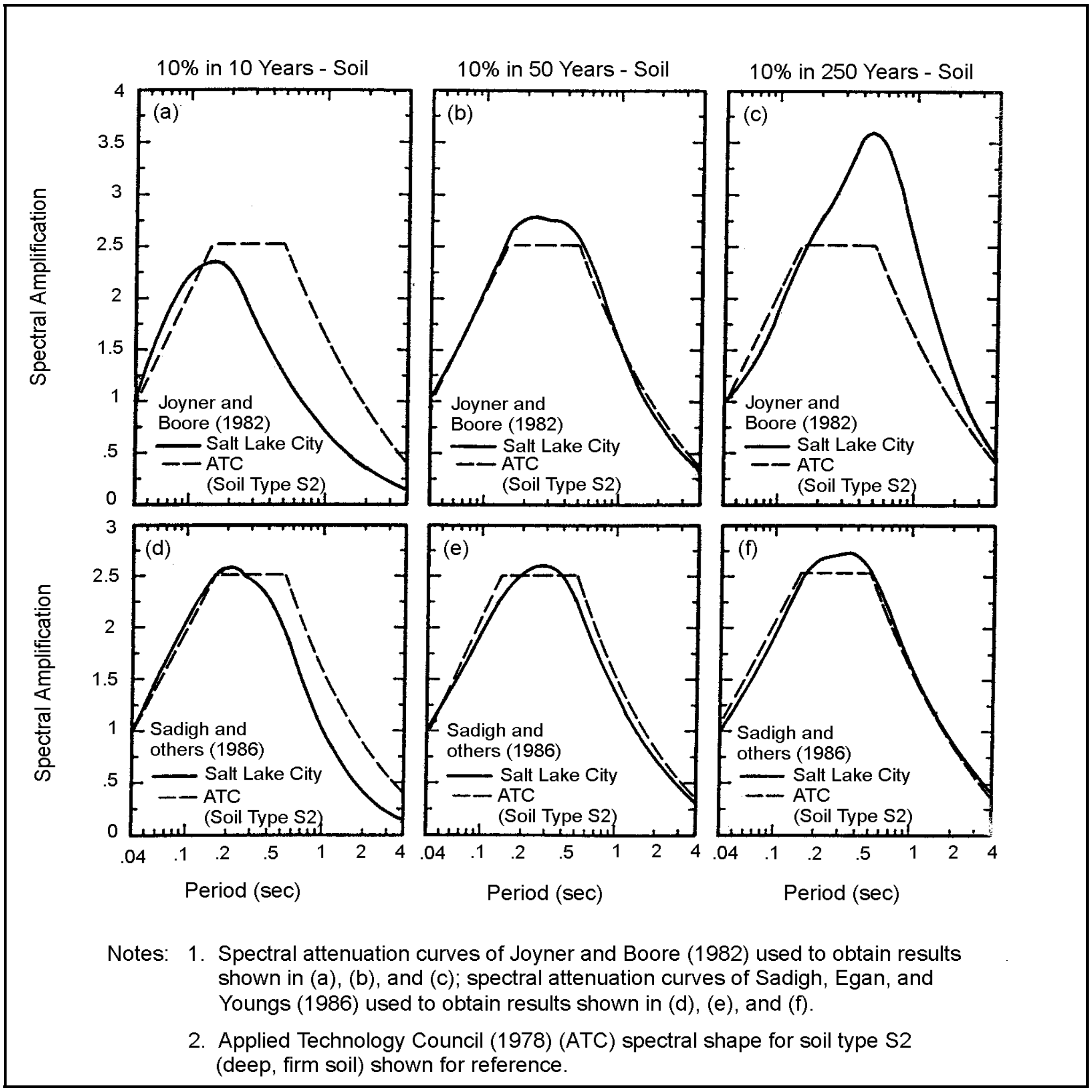


Figure-3-32. Response spectral shapes for different probability levels resulting from probabilistic hazard analysis for a deep soil site in Utah

(b) The uncertainties and scientific judgments that are present in a DSHA may not be explicitly recognized or quantified (e.g., uncertainties and judgments in assigning the MCE). As a result, the degree of uncertainty or conservatism in a deterministic estimate is not always known or apparent.

(c) For regions in which active faults have not been identified and sites are located within seismic source zones (e.g., EUS), there is not a standard approach or clear basis for selecting the distance to the design earthquake.

b. PSHA

(1) Strengths.

(a) A PSHA allows the designer to balance risk and cost for a project in a manner similar to that used for other environmental loadings such as flood or wind loadings. The reduction in risk by selecting a lower probability level (longer return period) and correspondingly higher seismic loading may be compared to the increased project cost involved with designing for the higher loading.

(b) The frequency of occurrence of earthquakes is explicitly incorporated in a PSHA. As such, regions of greater seismic activity (thus higher probabilities of earthquake occurrence) will have higher ground motion levels for given probabilities or return periods.

(c) The uncertainty or randomness in earthquake location is explicitly incorporated in a PSHA. Thus, the conservatism of assuming that the earthquake occurs at the closest location on the source to the site is not necessary in a PSHA. For sites located within low-seismicity seismic source zones in the EUS, it is usually very conservative to “float” the earthquake to the site or even within a small radius of the site.

(d) Uncertainties in the earthquake occurrence and ground motion estimation process are explicitly considered in a PSHA.

(2) Limitations.

(a) The fact that there are significant scientific uncertainties in earthquake source characterization and ground motion estimation means that there is not a unique result for the relationship between ground motion level and probability of exceedance. In fact, there is usually a significant range of possible ground motion levels for a given probability of exceedance. Usually, the mean estimate from a logic tree analysis is used as a basis for selecting project design criteria.

(b) Probability of exceedance versus ground motion relationships and equal hazard spectra from PSHA's involve contributions from multiple earthquake sources, magnitudes, and distances. As a result, the concept of a design earthquake is not as straightforward as in a DSHA. Furthermore, the evaluation of the duration of shaking and selection of acceleration time-histories based on probabilistic results are more difficult than for a deterministic analysis because of the multiple contributions. Therefore, it is important to deaggragate the results of a PSHA so that the primary contributors (earthquake sources, magnitude ranges, distance ranges) are known.

(c) While uncertainties are incorporated in the analysis (e.g., by the logic tree approach), nevertheless the weights assigned to alternative models and parameter values generally involve subjective judgment. The basis for these judgments should be fully documented.

c. Summary. Both deterministic and probabilistic ground motion analyses have their place in developing earthquake ground motions for seismic design. These two approaches should be used to complement each other as specified in ER 1110-2-1806. It is usually appropriate to carry out both types of analyses to aid the design engineer in developing the project seismic design criteria. Of paramount importance in either deterministic or probabilistic analyses is the expertise of the individuals conducting the analyses.

3-15. Examples of PSHA

Appendix G presents examples of PSHA. The first example is a simplified calculation that illustrates the basic calculational process and probability functions. The other examples represent actual applications in the WUS and EUS. These examples also illustrate how deterministic and probabilistic analyses can be used together in selecting project seismic design ground motions.