Generation of Synthetic Ground Motion

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ABSTRACT

This report presents a method for generating synthetic ground motions. In this method, the characteristics of seismic source, path attenuation, and local soil condition are taken into account, when generating synthetic ground motions. Given a moment magnitude and an epicentral distance, we use a stochastic model to generate an acceleration time history at the rock outcrop. Then, we perform a nonlinear site response analysis to generate an acceleration time history at the ground surface. Variability of ground motion resulting from uncertainties in modeling of seismic source, path attenuation, and local site condition is not included in this report and is addressed in the paper by Hwang (2000).

The method has been applied to generate synthetic ground motions resulting from large New Madrid earthquakes. In this study, a deep soil profile overlaying the bedrock was established based on a boring log in the Memphis area. In addition, 12 pairs of moment magnitudes and epicentral distances were selected, and for each pair of moment magnitude and epicentral distance, two samples of ground motion at the rock outcrop and at the ground surface were simulated; thus, a total of 24 synthetic acceleration time histories were generated at the rock outcrop and at the ground surface. For different combinations of moment magnitude and epicentral distance, the synthetic ground motions have different amplitude and duration. It is noted that the seismic source is modeled as a point source; thus, the ground motions simulated in this study are appropriate for far-field condition. These ground motions may be used to perform seismic response analysis of buildings and bridges located on the top of a deep soil profile in the central United States.

ACKNOWLEDGMENTS

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INTRODUCTION

For seismic response analysis of buildings and bridges, earthquake acceleration time histories sometimes are required as inputs. In the central and eastern United States (CEUS), the recorded ground motions are sparse; thus, synthetic acceleration time histories are utilized. This report presents a method for generating synthetic ground motions. In this method, the characteristics of seismic source, path attenuation, and local soil condition are taken into account, when generating synthetic ground motions.

The generation of synthetic ground motions is illustrated in Figure 1-1. For a deep profile overlaying the bedrock, the profile is divided into rock layers and soil layers. Given a moment magnitude and an epicentral distance, we use a stochastic model (Hanks and McGuire, 1981; Boore, 1983; Hwang and Huo, 1994) to generate an acceleration time history at the outcrop of a rock site. Then, we perform a nonlinear site response analysis to generate an acceleration time history at the ground surface.

It is noted that the seismic source is modeled as a point source; thus, the ground motions simulated in this study are appropriate for far-field condition. Furthermore, uncertainties in modeling of seismic source, path attenuation, and local soil conditions are not considered in this study. The approach to include these uncertainties in the generation of synthetic ground motions is described in Hwang (2000).

The method has been applied to generate synthetic ground motions resulting from large New Madrid earthquakes. For a deep soil profile overlaying the bedrock and 12 pairs of moment magnitudes and epicentral distances, a total of 24 synthetic acceleration time histories were generated at the rock outcrop and at the ground surface. For different combinations of moment magnitude and epicentral distance, the synthetic ground motions have different amplitude and duration.

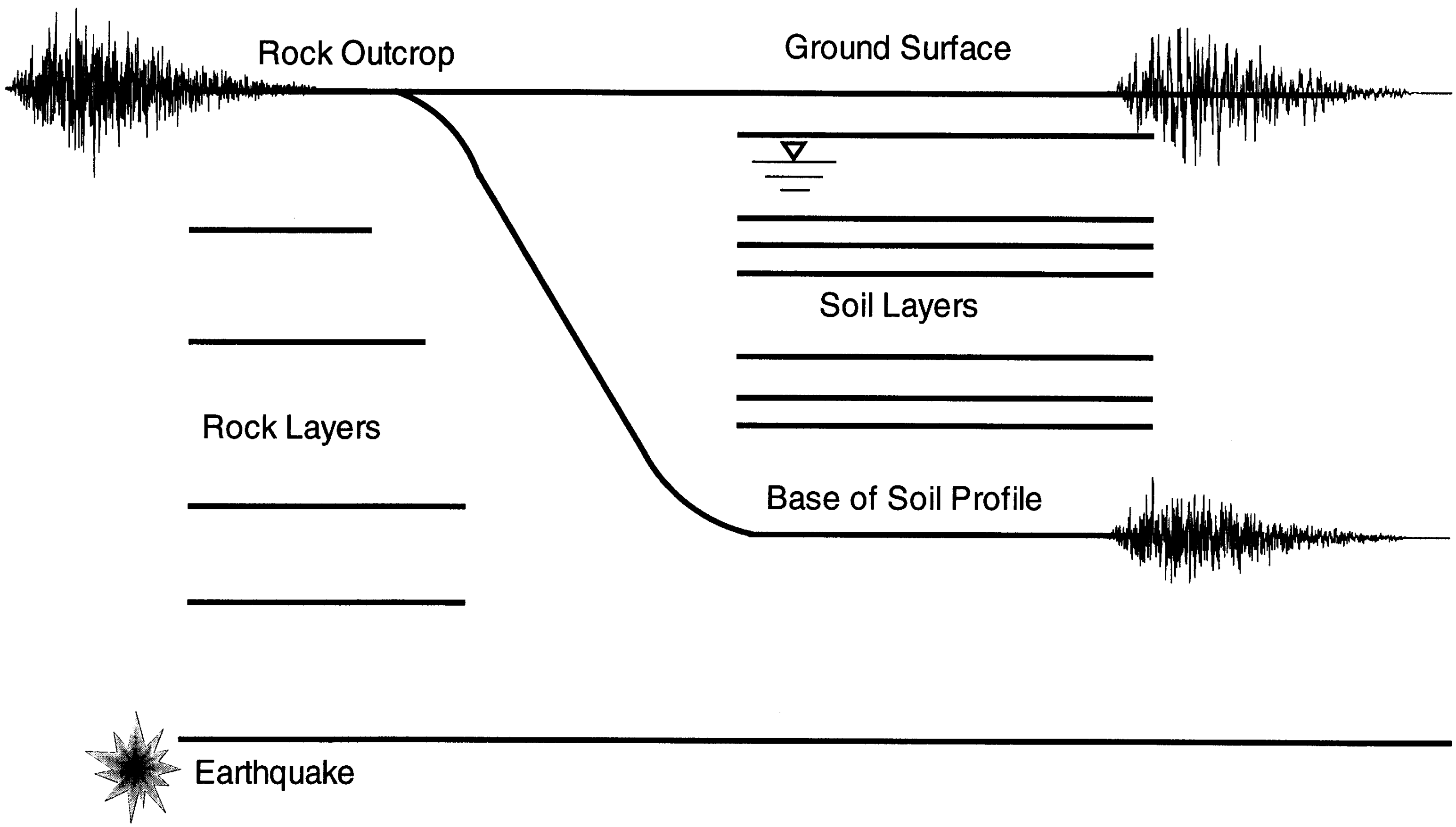

Figure 1-1. Illustration of Generating Synthetic Ground Motion

SECTION 2
GENERATION OF GROUND MOTION AT ROCK SITES

In this study, the computer program SMSIM developed by David Boore of the U.S. Geological Survey (USGS) (Boore, 1996) was used to generate synthetic ground motions at a rock site. The input parameter values are consistent with those used by Frankel et al. (1996) for producing the 1996 national seismic hazard maps.

2.1 Description of Rock Profiles

The Mississippi embayment is a broad southwest-plunging trough of unconsolidated sediments overlaying the Paleozoic rock (Stearns, 1957). The sediment layers, such as Jackson Formation, and Memphis Sand, can be established based on the geotechnical boring logs, water well logs and oil well logs. A preliminary profile of rock layers used in this study is shown in Figure 2-1 (Chiu et al., 1992; Dorman and Smalley, 1994). This profile will be refined once the reference Mississippi embayment is established. It is noted that the shear wave velocity of the top layer is set as 1 km/sec. The selection of this shear wave velocity is to ensure that the nonlinear soil effects do not need to be considered in the first step of generating of ground motions. According to the 1997 NEHRP Provisions (FEMA, 1998), the shear wave velocity of the NEHRP B site is between 0.75 km/sec and 1.5 km/sec. Thus, the selected rock site is classified as the NEHRP B site.

2.2 Fourier Acceleration Amplitude Spectrum

For an earthquake with a moment magnitude $\boldsymbol{M}$ at an epicentral distance R from the site, the Fourier acceleration amplitude spectrum is expressed as follows:

$$A(f) = C \cdot S(f) \cdot G(r) \cdot D(f) \cdot AF(f) \cdot P(f) \tag{2-1}$$

Where C is the scaling factor, $S(f)$ is the source spectral function, $G(r)$ is the geometric attenuation function, $D(f)$ is the diminution function, $AF(f)$ = amplification function of rock layers above the bedrock, and $P(f)$ is the high-cut filter.

The scaling factor C is expressed as (Boore, 1983)

$$C = \frac{< R_{\theta\phi} > FV}{4\pi\rho_0\beta_0^{\;3}} \tag{2-2}$$

where F is the factor for free surface effect (2 for free surface), V is the partition of a vector into horizontal components $\left(1/\sqrt{2}\right)$, ρ_0 is the crustal density (2.7 g/cm^3), β_0 is the shear wave velocity of continental crust at the seismic source region (3.5 km/sec), and $< R_{\theta\phi} >$ is the radiation coefficient averaged over a range of azimuths θ and take-off angles ϕ. For θ and ϕ averaged over the whole focal sphere, $< R_{\theta\phi} >$ is taken as 0.55 (Boore and Boatwright, 1984).

The source spectral function $S(f)$ used in this study is the source acceleration spectrum proposed by Brune (1970, 1971).

$$S(f) = (2\pi f)^2 \frac{M_0}{1+(f/f_c)^2} \tag{2-3}$$

where M_0 is the seismic moment and f_c is the corner frequency. For a given moment magnitude ***M***, the corresponding seismic moment can be determined (Hanks and Kanamori, 1979). The corner frequency f_c is related to the seismic moment M_0, shear wave velocity at the source region β_0 and stress parameter $\Delta\sigma$ as follows:

$$f_c = 4.9\times10^6\,\beta_0\left(\frac{\Delta\sigma}{M_0}\right)^{1/3} \tag{2-4}$$

In this study, the stress parameter is taken as 150 bars.

The geometric attenuation function *G(r)* is expressed as follows (Atkinson and Mereu, 1992):

$$G(r) = \begin{cases} \dfrac{1}{r} & 1 < r \leq 70 \ km \\ \dfrac{1}{70} & 70 < r \leq 130 \ km \\ \dfrac{1}{70}\sqrt{\dfrac{130}{r}} & r \geq 130 \ km \end{cases} \tag{2-5}$$

where *r* is the hypocentral distance, which can be calculated from the epicentral distance and the focal depth. The microearthquakes recorded in the New Madrid seismic zone (NMSZ) indicate that the focal depth ranges from 6 to 15 km. In this study, the focal depth *H* is taken as 10 km.

The diminution function *D(f)* represents the anelastic attenuation of seismic waves passing through the earth crust.

$$D(f) = exp\left[\frac{-\boldsymbol{p}\, f\, r}{Q(f)\boldsymbol{b}_0}\right] \tag{2-6}$$

where *Q(f)* is the frequency-dependent quality factor for the study region. The quality factor *Q(f)* is usually expressed as

$$Q(f) = Q_0 f^{\boldsymbol{h}} \tag{2-7}$$

In this study, the quality factor is taken as (EPRI, 1993):

$$Q(f) = 680 f^{0.36} \tag{2-8}$$

The amplification function *AF(f)* represents the amplification of ground-motion amplitude when seismic waves travel through the rock layers with decreasing shear wave velocity above the bedrock. The amplification function *AF(f)* is expressed as (Boore and Joyner, 1991)

$$AF(f) = \sqrt{\boldsymbol{r}_0 \boldsymbol{b}_0 / \boldsymbol{r}_e \boldsymbol{b}_e} \qquad (2\text{-}9)$$

where $\boldsymbol{r}_e$ and $\boldsymbol{b}_e$ are the frequency-dependent effective density and effective shear wave velocity of the rock layers from the surface to the depth of a quarter wavelength. Based on the rock layers shown in Figure 2-1, the amplification function used in this study is determined and shown in Table 2-1.

The high-cut filter *P(f)* represents a sharp decrease of acceleration spectra above a cut-off frequency f_m and the effect of the increase of damping of the rock layers near the ground surface as the seismic waves pass through the shallow soft rock layers beneath the site (Boore and Joyner, 1991).

$$P(f, f_m) = \left[1 + \left(\frac{f}{f_m}\right)^8\right]^{-1/2} exp(-\boldsymbol{k}\boldsymbol{p} f) \qquad (2\text{-}10)$$

where f_m is the high-cut frequency and is taken as 100 Hz in this study. $\boldsymbol{k}$ is the site dependent attenuation parameter and it can be determined as follows:

$$\boldsymbol{k} = \sum_{i=1}^{n} \frac{H_i}{\boldsymbol{b}_i Q_i} \qquad (2\text{-}11)$$

where H_i, Q_i, and $\boldsymbol{b}_i$ are the thickness, quality factor, and damping ratio of the i-th rock layer. In this study, $\boldsymbol{k}$ is determined as 0.0084 sec based on the properties of the rock layers shown in Figure 2-1.

2.3 Generation of Time Histories at the Outcrop of a Rock Site

To produce a synthetic ground motion, a time series of random band-limited white Gaussian noise is first generated and then multiplied by an exponential window. The normalized Fourier spectrum of the windowed time series is multiplied by the specified spectrum as expressed in Equation (2-1). The resulting spectrum is then transformed back to the time domain to yield a sample of synthetic earthquake ground motion. The corresponding response spectrum can also be established. By repeating this process, a sample having a response spectrum close to the response spectrum averaged from all the samples is chosen as the preferred synthetic ground motion.

The normalized exponential window is expressed as follows (Boore, 1996):

$$w(t) = at^b \exp(-ct) \qquad (2\text{-}12)$$

where a, b, and c are the parameters related to the duration and the peak of the window. The duration of the window, equivalent to the duration of ground motion T, is taken as twice the strong motion duration T_e. In this study, the strong motion duration is determined as follows:

$$T_e = 1/f_c + 0.05r \qquad (2\text{-}13)$$

where $1/f_c$ is the source duration, and r is the hypercentral distance. The exponential window used in this study is shown in Figure 2-2.

As an illustration, a sample of synthetic ground motion at the outcrop of a rock site (Figure 2-1) generated by an earthquake of ***M*** 7.0 located at 60 km from the site is shown in Figure 2-3. The corresponding response spectrum is shown in Figure 2-4. The seismic parameters used to generate this synthetic ground motion are summarized in Table 2-2. In this study, 12 pairs of moment magnitudes and epicentral distances were selected, and for each pair of moment magnitude and epicentral distance, two samples were produced. As shown in Table 2-3, a total of 24 synthetic acceleration time histories were generated in this study. For different combinations of moment magnitude and epicentral distance, the synthetic ground motions have different duration and amplitude. As an illustration, Figure 2-5 shows the acceleration time histories produced by three moment magnitudes, 6.5, 7.0, and 7.5, at an epicentral distance 60 km from the site. Furthermore, Figure 2-6 shows the acceleration time histories produced by the same moment magnitudes, 6.5, at two epicentral distances, 40 km and 100 km, from the site.

Depth (m)			Rock Outcrop
0			
	Rock	$\rho = 2.32$ g/cm^3	$V_S = 1.0$ km/s
91.50			
	Rock	$\rho = 2.32$ g/cm^3	$V_S = 1.0$ km/s
200			
	Rock	$\rho = 2.32$ g/cm^3	$V_S = 1.1$ km/s
500			
	Rock	$\rho = 2.38$ g/cm^3	$V_S = 1.4$ km/s
700			
	Rock	$\rho = 2.40$ g/cm^3	$V_S = 1.7$ km/s
900			
	Rock	$\rho = 2.50$ g/cm^3	$V_S = 2.0$ km/s
1000			
	Rock	$\rho = 2.70$ g/cm^3	$V_S = 3.5$ m/s
2500			
	Rock	$\rho = 2.70$ g/cm^3	$V_S = 3.2$ km/s
5000			
	Rock	$\rho = 2.70$ g/cm^3	$V_S =3.5$ km/s
10000			

Figure 2-1. A Profile of Rock Layers

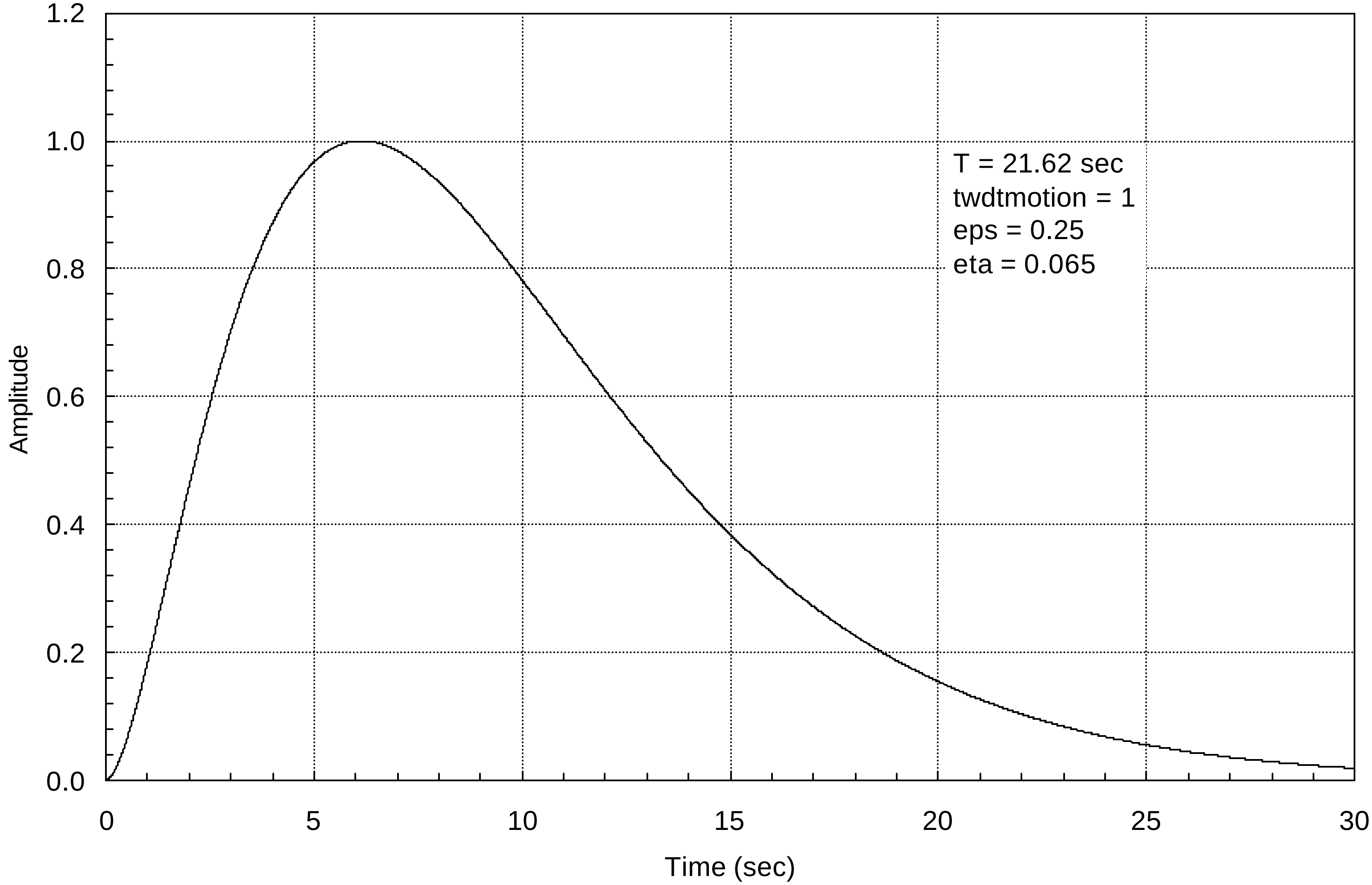

Figure 2-2. Exponential Window (M=7.0, R=60 km)

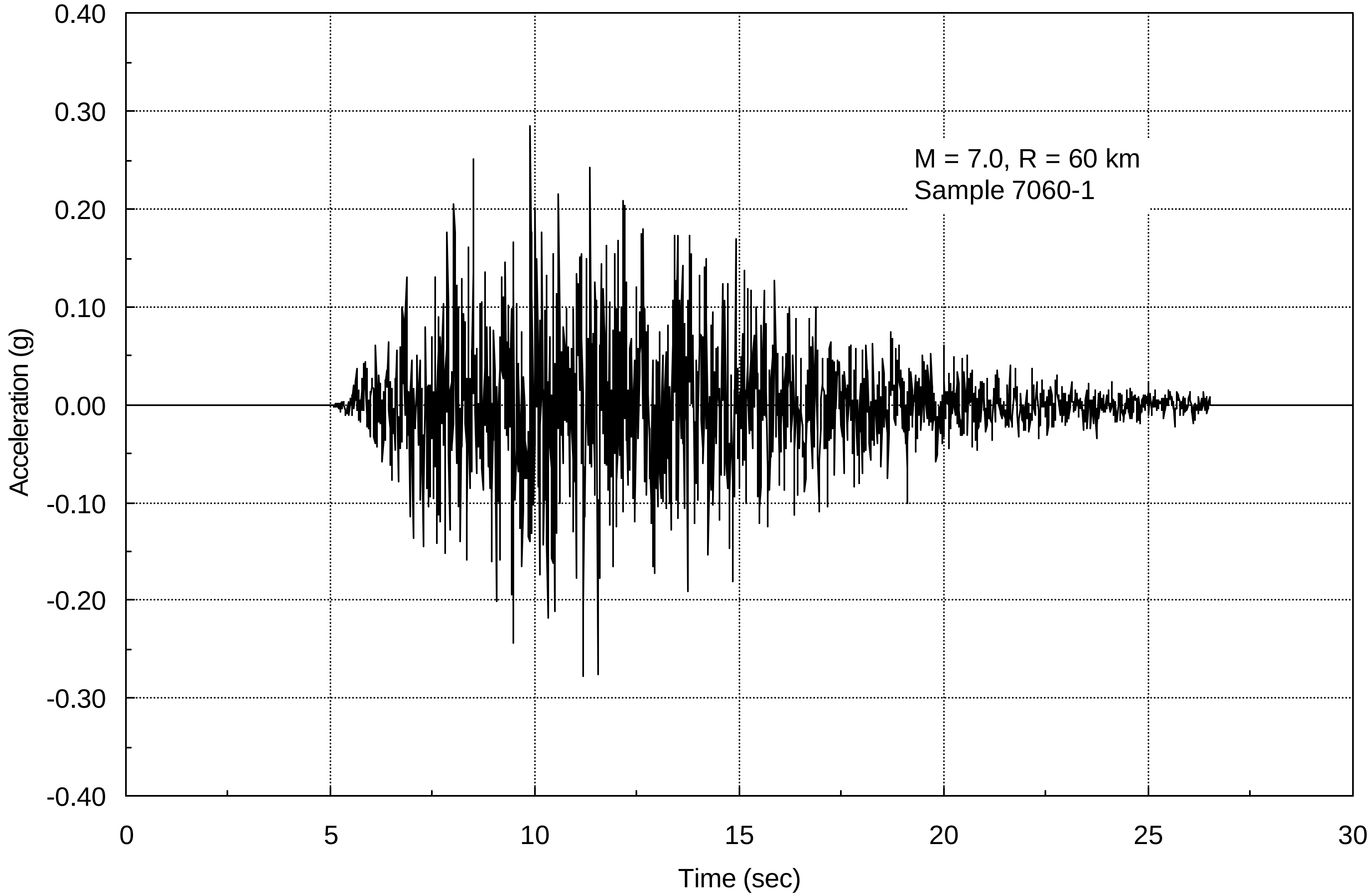

Figure 2-3. A Sample of Acceleration Time History at the Outcrop of a Rock Site

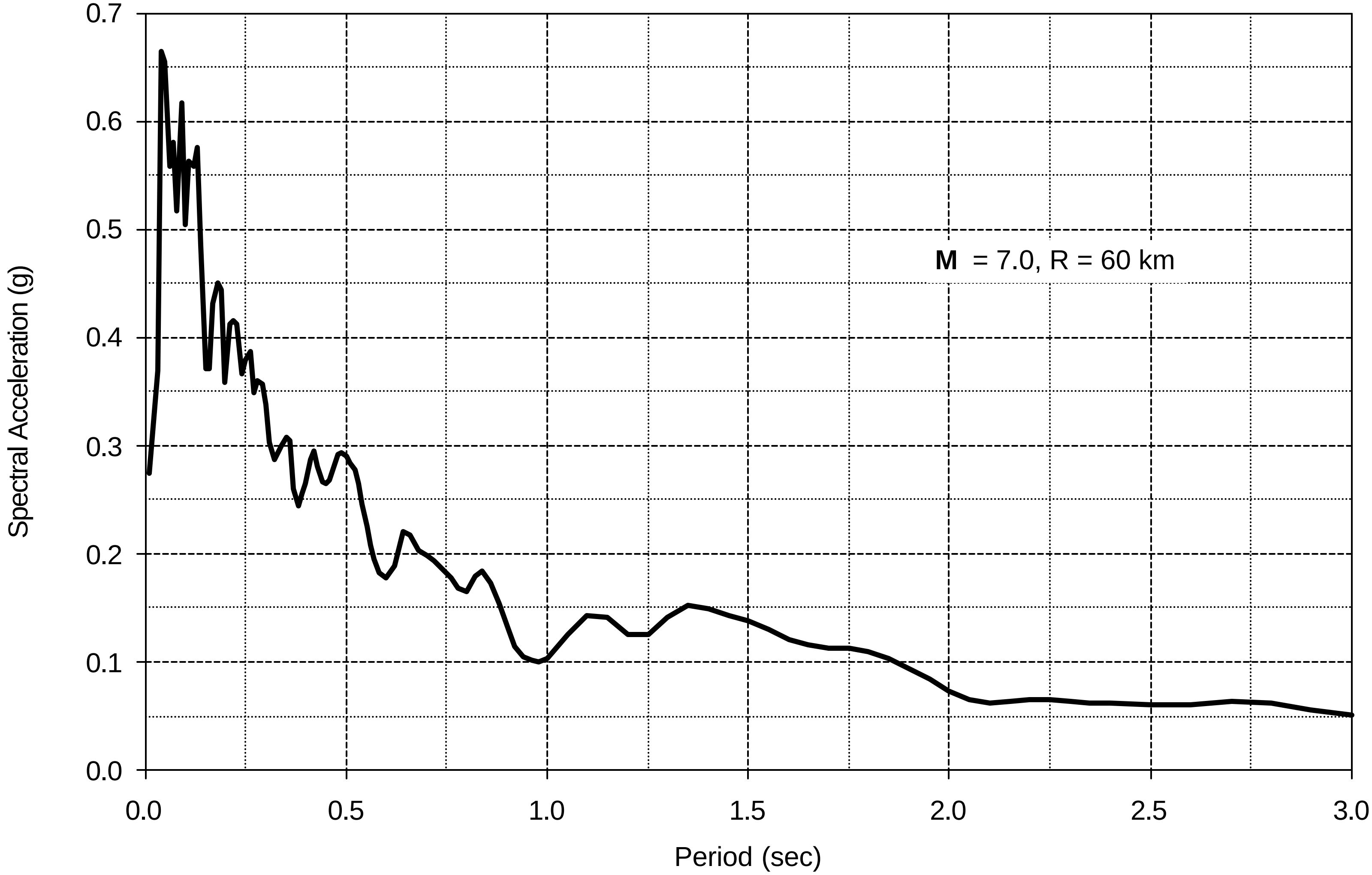

Figure 2-4. Acceleration Response Spectrum at the Outcrop of a Rock Site

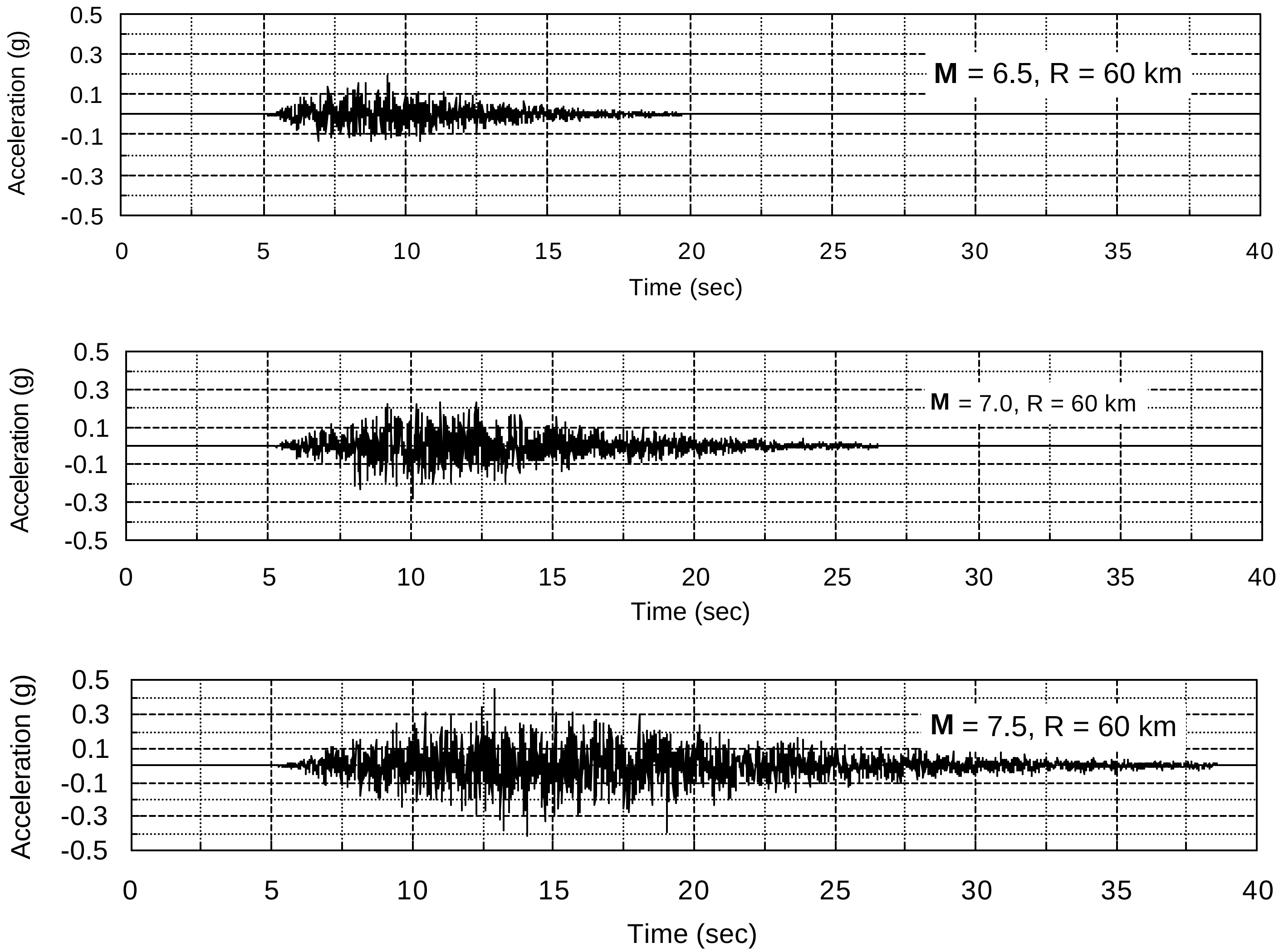

Figure 2-5. Comparison of Acceleration Time Histories at the Outcrop of a Rock Site for Different Moment Magnitudes and Same Epicentral Distance

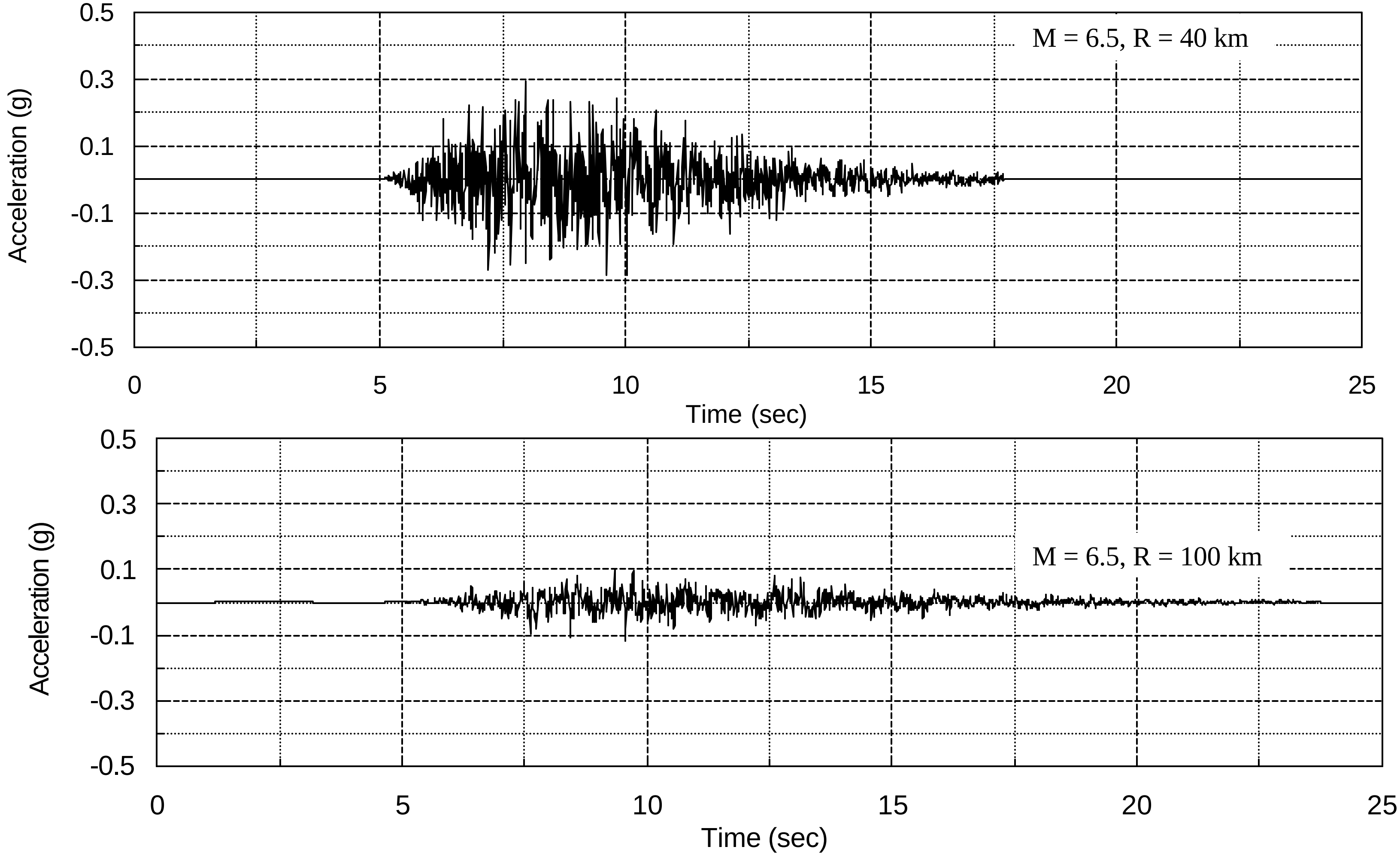

Figure 2-6. Comparison of Acceleration Time Histories at Outcrop of a Rock Site for Same Moment Magnitude and Different Epicentral Distances

Table 2-1. Amplification Function AF(f) for a Rock Site

Frequency (Hz)	Amplification Function AF(f)
0.01	1.00
0.13	1.19
0.21	1.34
0.32	1.76
0.34	1.81
0.41	1.89
0.53	1.97
1.25	2.02
2.73	2.02
5.85	2.02
8.20	2.02
13.66	2.02
15.76	2.02
18.63	2.03
24.11	2.02
68.31	2.06

Table 2-2. Summary of Seismic Parameters

Parameters	Value
Moment Magnitude, ***M***	7.0
Epicentral Distance, *R*	60 km
Site Condition (NEHRP)	B
Focal depth, *H*	10 km
Stress parameter, ***Ds***	150 bars
Radiation coefficient, $<R_{qf}>$	0.55
Quality factor, *Q(¦)*	$680\, f^{0.36}$
Kappa, ***k***	0.0084 sec
High-cut frequency, $¦_m$	100 Hz
Strong motion duration, T_e	$1/f_c + 0.05r$
Window shape	Exponential

Table 2-3. List of Earthquake Samples at a Rock Site

Moment Magnitude	Epicentral Distance (km)			
	40	60	80	100
6.5	6540-1 6540-2	6560-1 6560-2	6580-1 6580-2	65100-1 65100-2
7.0	7040-1 7040-2	7060-1 7060-2	7080-1 7080-2	70100-1 70100-2
7.5	7540-1 7540-2	7560-1 7560-2	7580-1 7580-2	75100-1 75100-2

SECTION 3

GENERATION OF GROUND MOTION AT SOIL SITES

The local soil conditions at a site have significant effects on the characteristics of earthquake ground motion. Earthquake motions at the base of a soil profile can be drastically modified in frequency content and amplitude as seismic waves transmit through the soil deposits. Furthermore, soils exhibit significantly nonlinear behavior under strong ground shaking. In this study, the nonlinear site response analysis is performed using SHAKE91 (Idriss and Sun, 1992). In the SHAKE91 program, the soil profile is considered as horizontal soil layers. For each soil layer, the required soil parameters include the thickness, unit weight, and shear wave velocity or low-strain shear modulus G_{max}. In addition, a shear modulus reduction curve and a damping ratio curve also need to be specified.

For sand layers, the shear modulus reduction curve and the damping ratio curve used in this study is shown in Figure 3-1. The shear modulus reduction curve is the one suggested by Hwang and Lee (1991), and the damping ratio curve is the one suggested by Idriss (1990). It is noted that the shear modulus reduction curve shown in this figure is expressed as a function of the shear strain ratio g/g_0, where g_0 is the reference strain, which can be computed using an empirical formula (Hwang and Lee, 1991). As shown in Figure 3-2, the shear modulus reduction curves vary as a function of the average effective confining pressure $\bar{s}$ of the sand layer. The curve gradually shifts to the right with increasing confining pressure. In general, the confining pressure increases with the depth of the soil profile. Thus, the shear modulus reduction curves are different for the sand layers at various depths. For clay layers, the shear modulus reduction curves and damping ratio curves used in this study are those suggested by Vucetic and Dobry (1991). These curves vary as functions of the plasticity index PI of a clay layer, but they are independent of the depth of the layer. Figure 3-3 shows the shear modulus reduction curves and damping ratio curves for clays with PI = 15 and Figure 3-4 shows the curves for clays with PI = 50.

A deep soil profile used in this study is shown in Figure 3-5. This soil profile was established based on a boring log in the Memphis area. It is noted that the base of the soil profile is a rock layer with the shear wave velocity of 1 km/sec, which is the same as the top layer of the rock profile shown in Figure 2-1. The shear wave velocity of soil layers shown in the figure can be determined from field measurements or estimated from empirical formula. Using the acceleration time history at the outcrop of a rock site as the input motion, a nonlinear soil response analysis is performed to generate the earthquake ground motion at the ground surface. As an illustration, using the input motion shown in Figure 2-3, the synthetic ground motion at the ground surface generated by an earthquake of ***M*** 7.0 located at 60 km from the site is shown in Figure 3-6. The response spectra for both ground motions are shown in Figure 3-7. The response spectra reveal that the frequency content of the ground motion has been significantly modified as seismic waves transmit through the soil deposits.

As shown in Table 3-1, 12 pairs of moment magnitudes and epicentral distances were selected, and for each pair of moment magnitude and epicentral distance, two samples were produced; thus, a total of 24 synthetic acceleration time histories were generated in this study. For the comparison, Figure 3-8 shows the acceleration time histories at the ground surface produced by three moment magnitudes, 6.5, 7.0, and 7.5, at an epicentral distance 60 km from the site. In addition, Figure 3-9 shows the acceleration time histories produced by the same moment magnitudes, 6.5, at two epicentral distances, 40 km and 100 km, from the site.

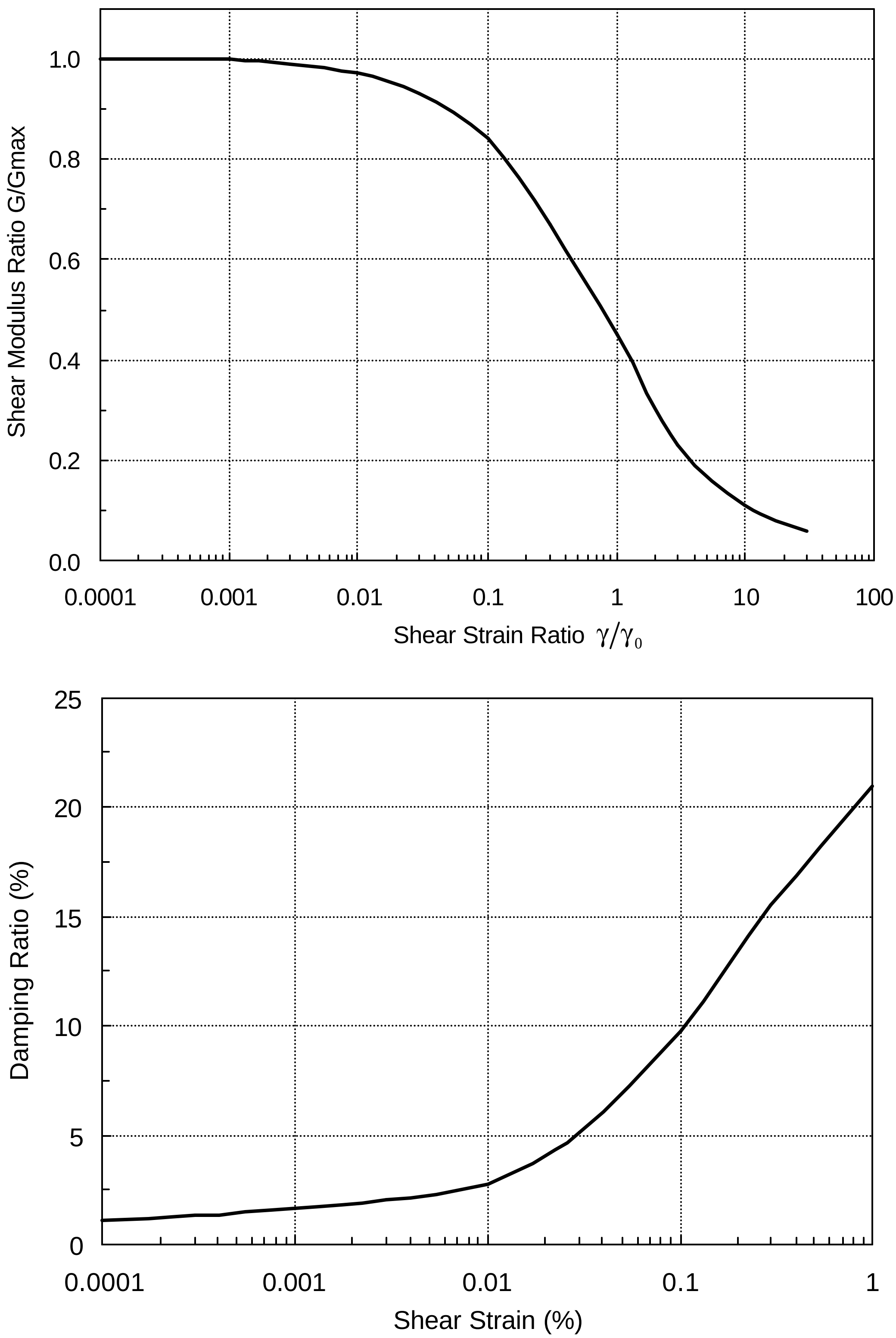

Figure 3-1 Shear Modulus Reduction and Damping Ratio Curves for Sands

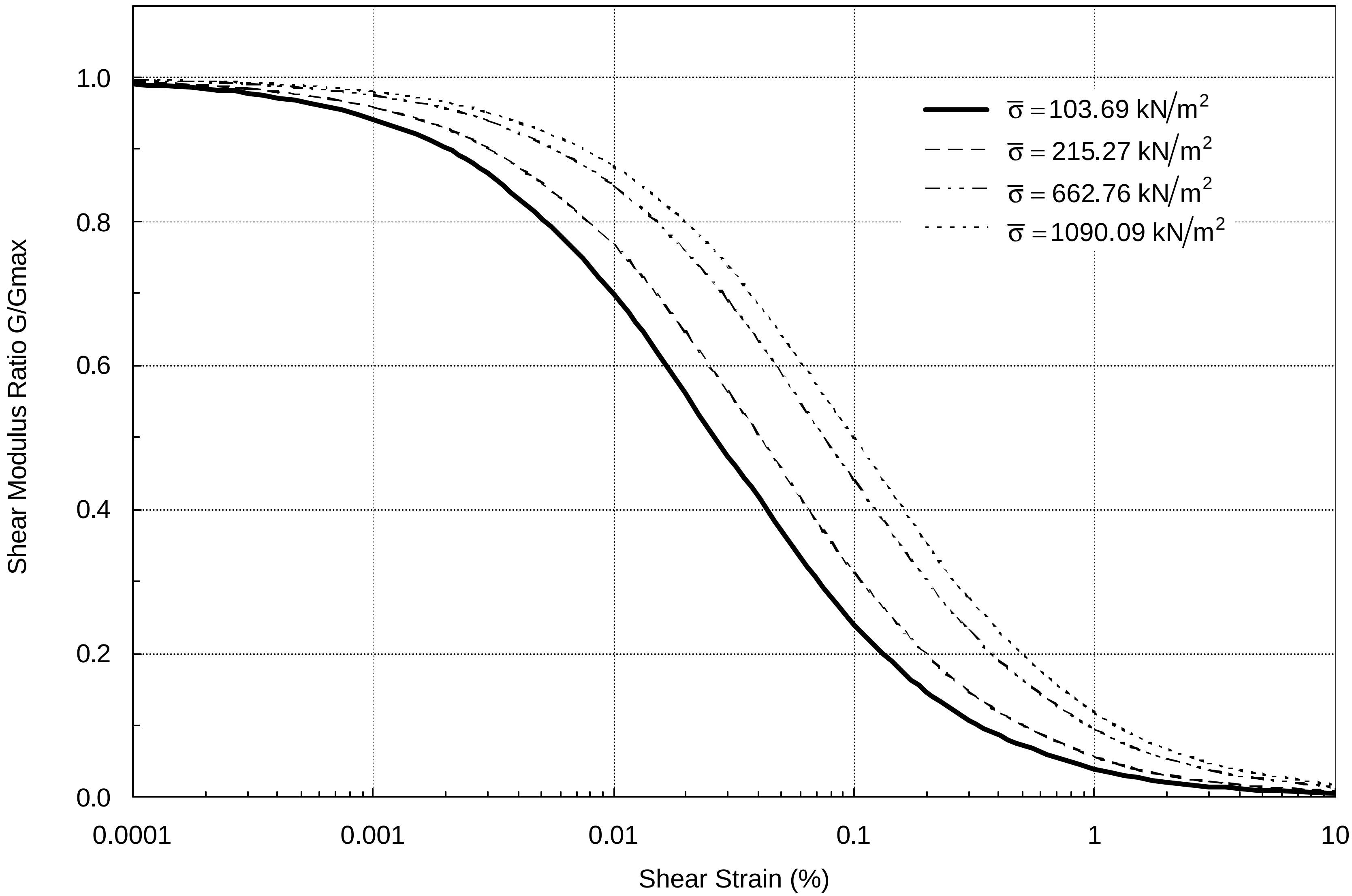

Figure 3-2. Influence of Confining Pressure on Shear Modulus Reduction Curves for Sands

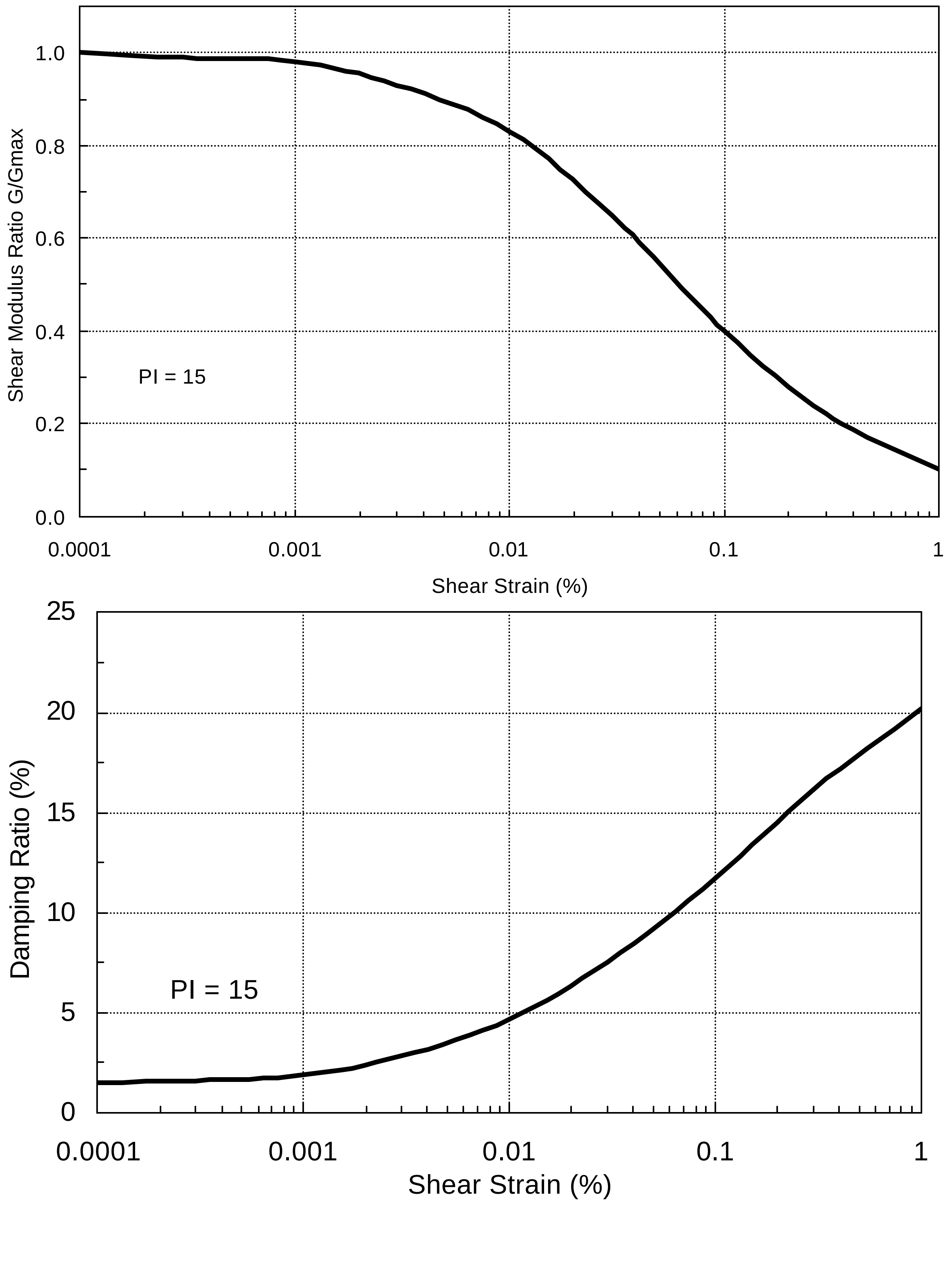

Figure 3-3. Modulus Reduction and Damping Ratio Curves for Clays with PI=15

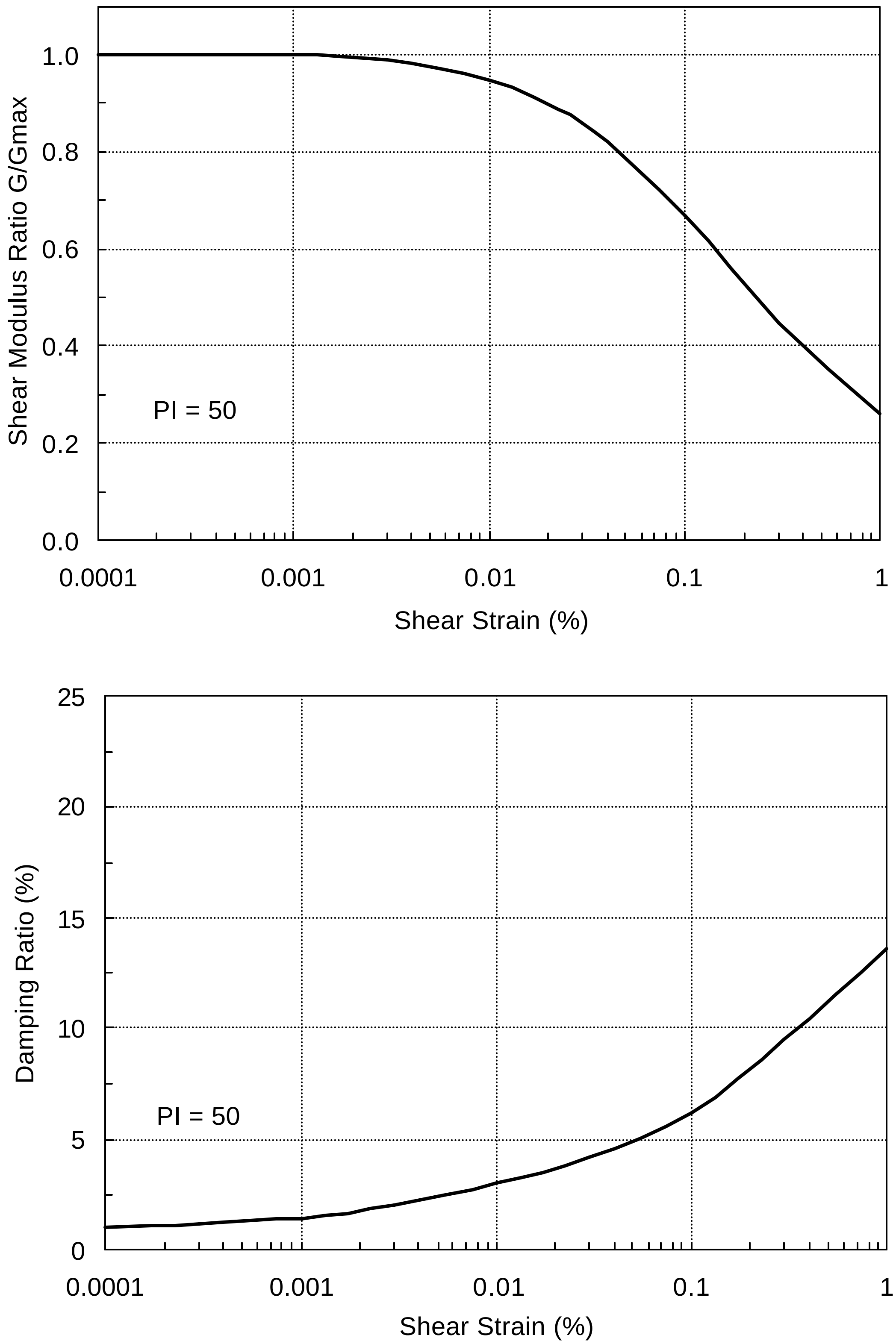

Figure 3-4. Shear Modulus Reduction and Damping Ratio Curves for Clays with PI=50

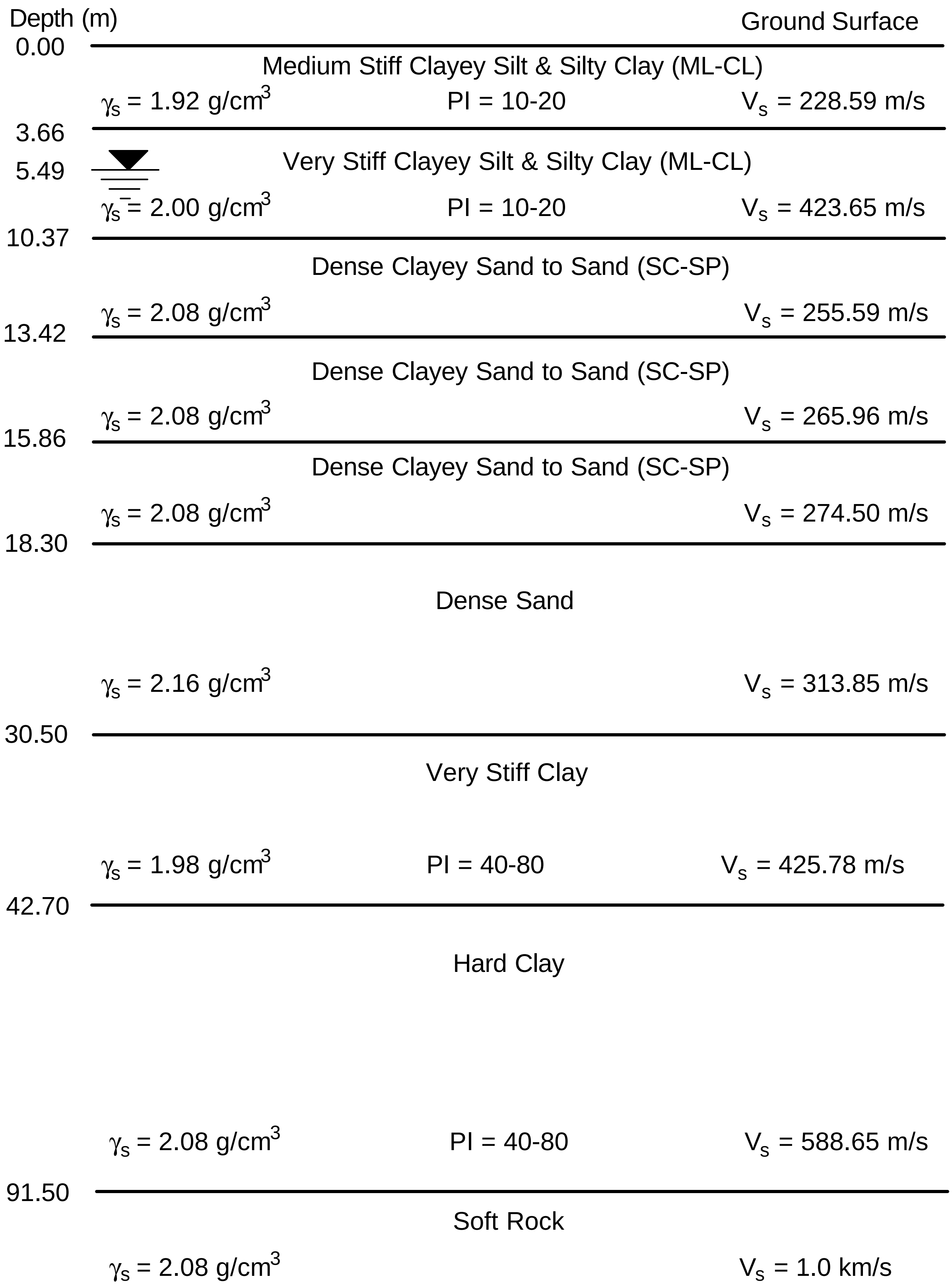

Figure 3-5. A Profile of Soil Layers

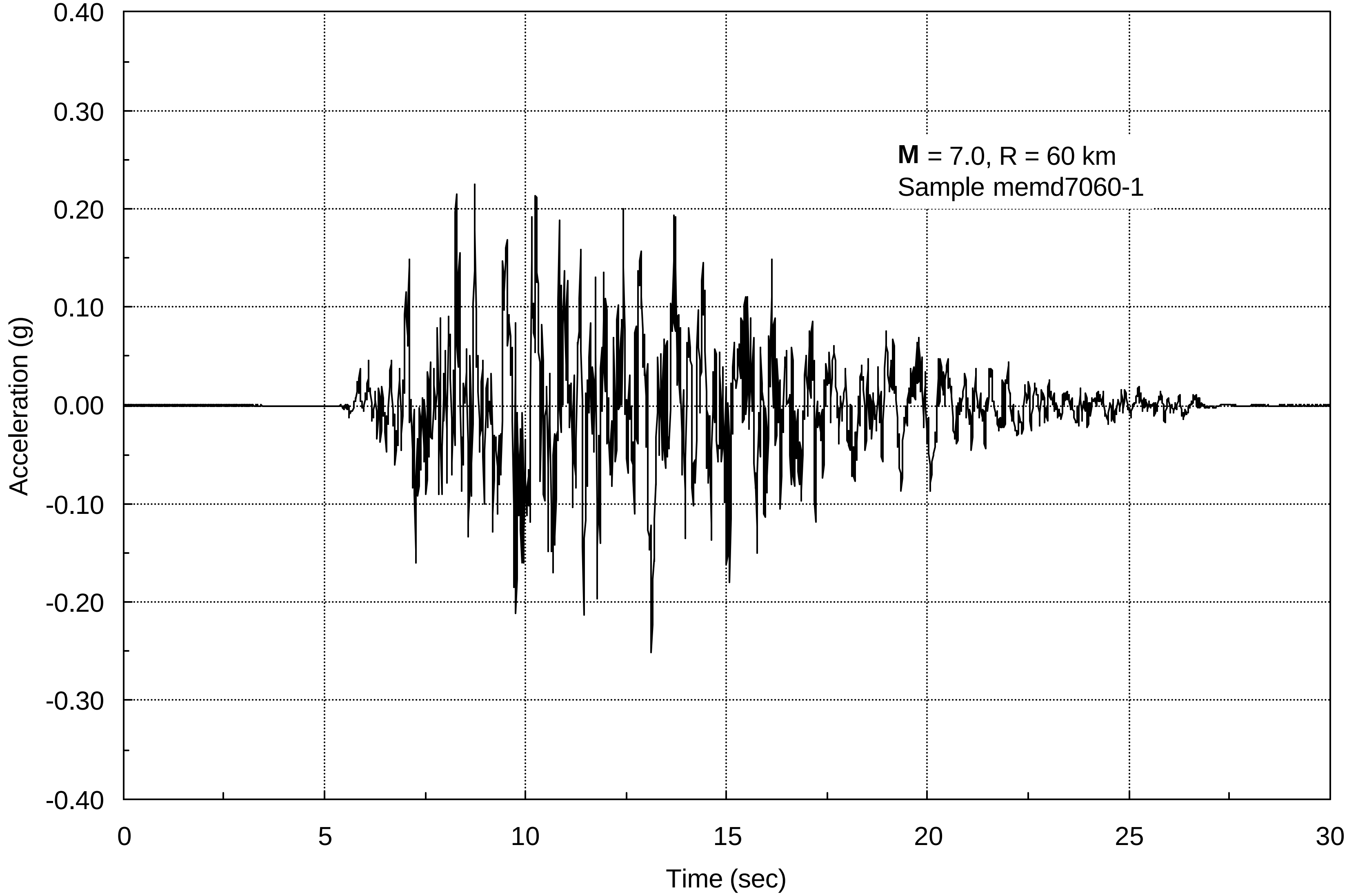

Figure 3-6. A Sample of Acceleration Time History at the Ground Surface

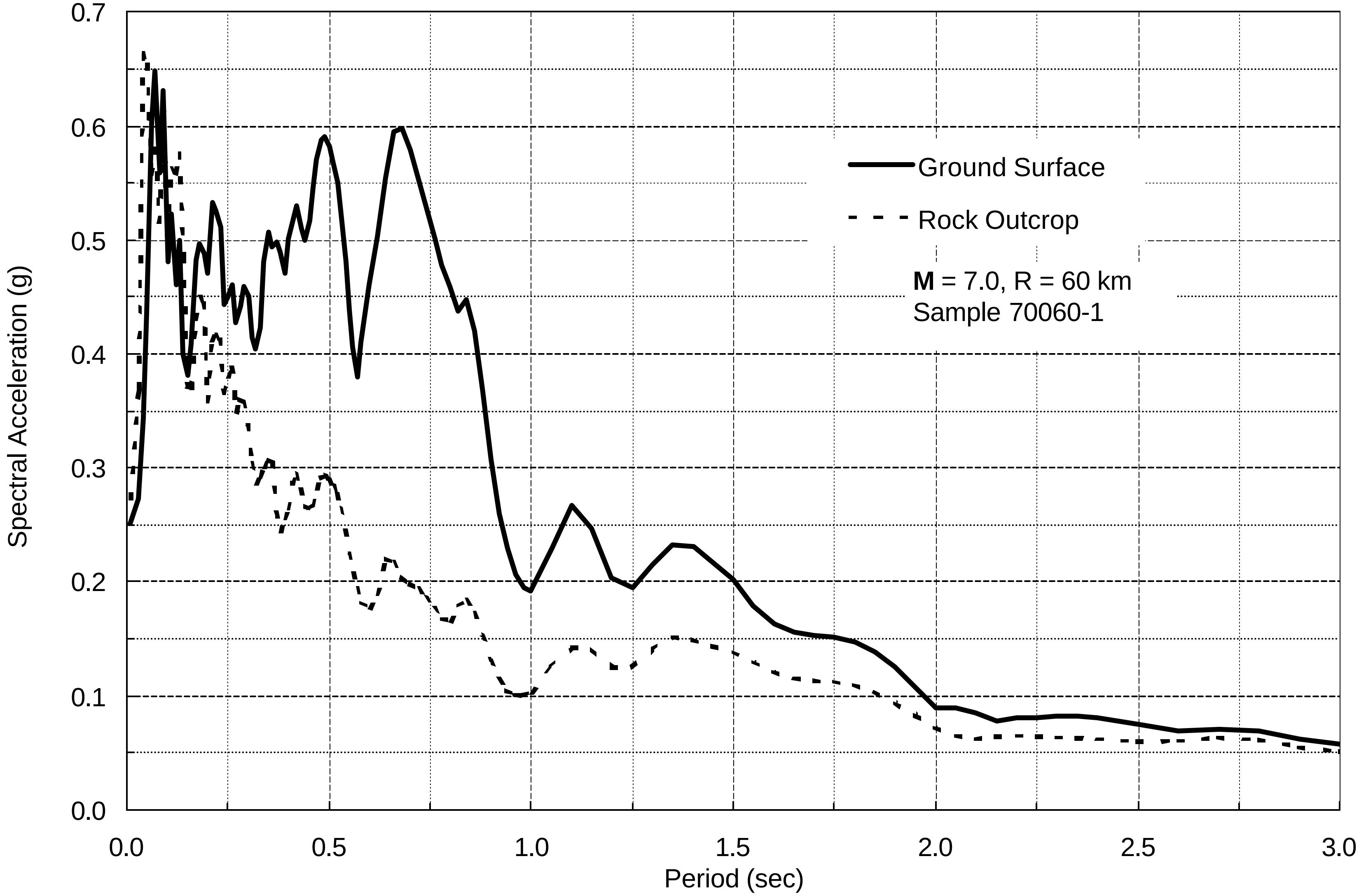

Figure 3-7. Acceleration Response Spectra at Ground Surface & Rock Outcrop

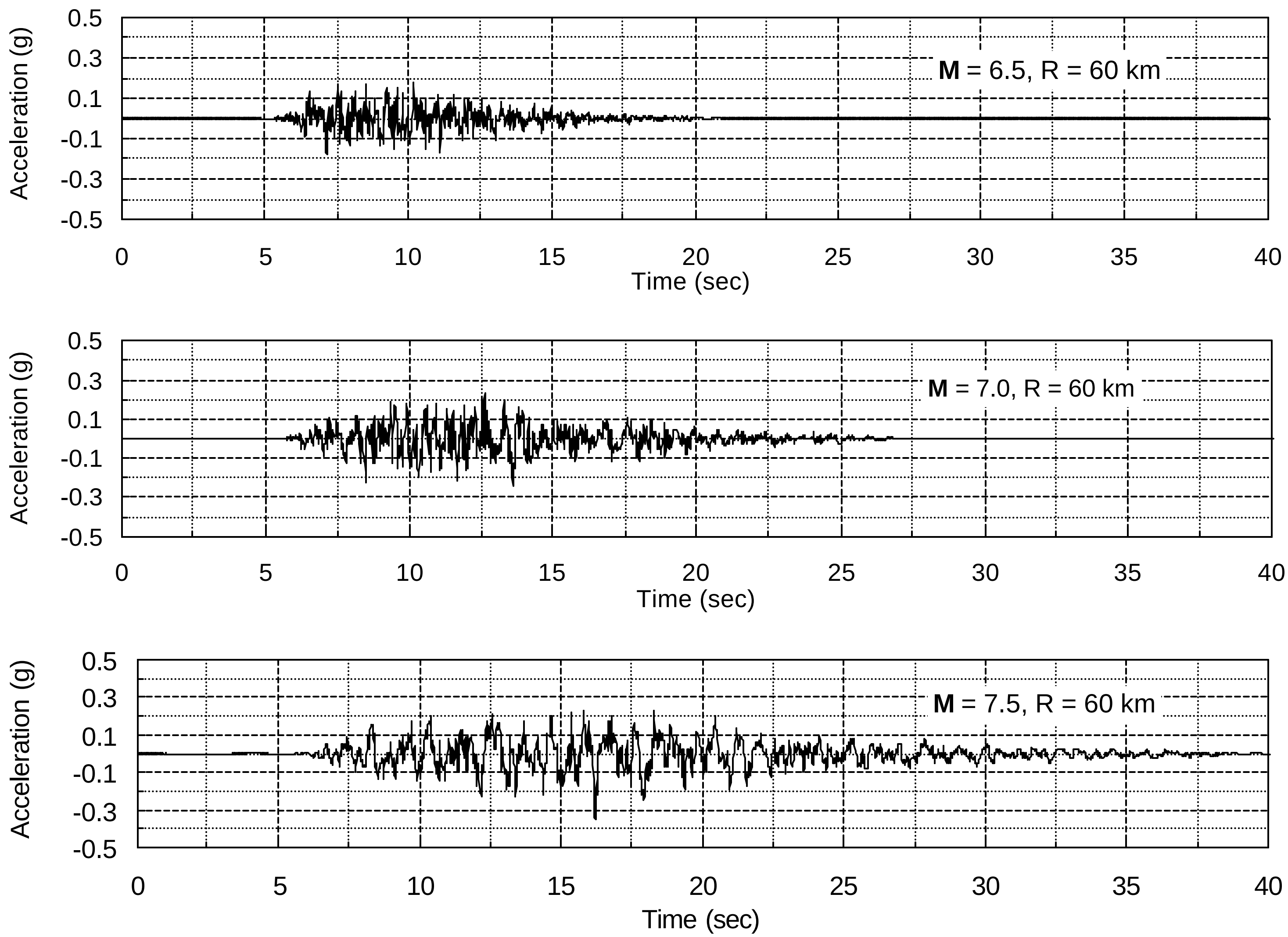

Figure 3-8. Comparison of Acceleration Time Histories at Ground Surface for Different Moment Magnitudes and Epicentral Distance

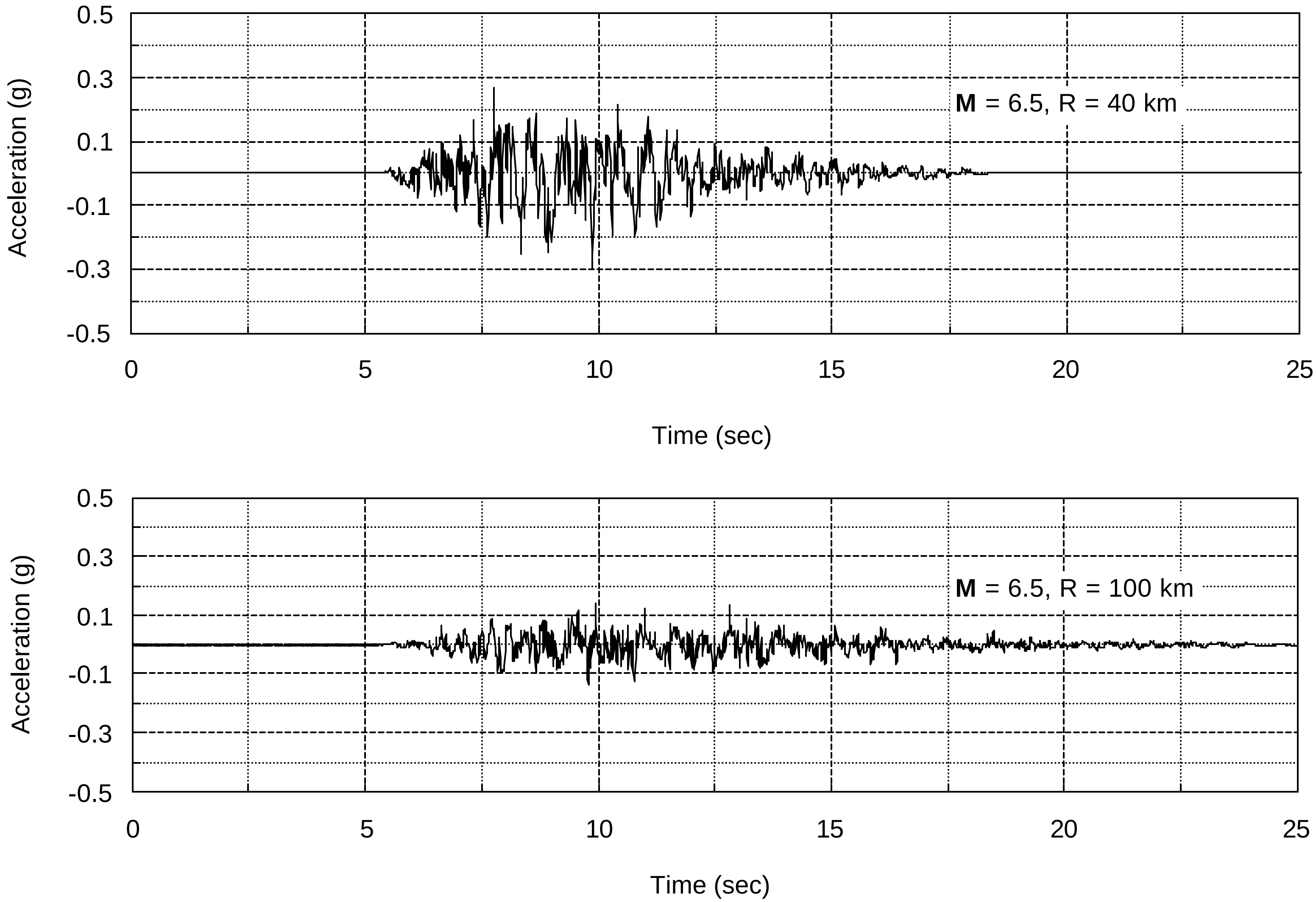

Figure 3-9. Comparison of Acceleration Time Histories at the Ground Surface for Same Moment Magnitude and Different Epicentral Distances

Table 3-1. List of Earthquake Samples at a Soil Site

Moment Magnitude	Epicentral Distance (km)			
	40	60	80	100
6.5	memd6540-1 memd6540-2	memd6560-1 memd6560-2	memd6580-1 memd6580-2	memd65100-1 memd65100-2
7.0	memd7040-1 memd7040-2	memd7060-1 memd7060-2	memd7080-1 memd7080-2	memd70100-1 memd70100-2
7.5	memd7540-1 memd7540-2	memd7560-1 memd7560-2	memd7580-1 memd7580-2	memd75100-1 memd75100-2

SECTION 4
CONCLUDING REMARKS

This report presents a method for generating synthetic ground motions. In this method, the characteristics of seismic source, path attenuation, and local soil condition have been taken into account, when generating synthetic ground motions. Given a moment magnitude and an epicentral distance, we use a stochastic model to generate an acceleration time history at the rock outcrop. Then, we perform a nonlinear site response analysis to generate an acceleration time history at the ground surface. It is noted that the seismic source is modeled as a point source; thus, the ground motions simulated in this study are appropriate for far-field condition. The methods proposed by other researchers, for example, Zeng et al. (1994) and Somerville et al. (2000), may be used to simulate near-field ground motions. Furthermore, uncertainties in modeling of seismic source, path attenuation, and local soil conditions are not considered in this study. The approach to include these uncertainties in the generation of synthetic ground motions is described in Hwang (2000).

The method utilized in this study has been applied to generate synthetic ground motions resulting from large New Madrid earthquakes. A total of 24 synthetic acceleration time histories were generated at the rock outcrop and at the ground surface. The synthetic ground motions have different amplitude and duration for different combinations of moment magnitude and epicentral distance. The ground motions produced in this study may be used to perform seismic response analysis of buildings and bridges located on the top of a deep soil profile in the central United States.

SECTION 5

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