5 Strong Ground Motion

5.1 Introduction

This chapter introduces concepts and procedures that allow geotechnical earthquake engineers to describe, characterize, and simulate strong ground motion. Given that earthquake motions are complex, it becomes difficult to express the information in a precise manner. However, for engineering purposes, it is not necessary to exactly reproduce each time history to adequately describe it. As such, a variety of techniques have been proposed by various researchers and practicing engineers that allow computation or prediction of parameters that can adequately describe a motion of interest.

Because it is impossible to exactly predict strong ground motion time histories, geotechnical earthquake engineers must be able to adequately describe each time history of interest. For the purposes of this research, the three characteristics of earthquake motion of primary interest are: 1) amplitude, 2) frequency content, and 3) duration.

5.2 Characterization

Useful parameters for characterization of strong ground motion will describe the motion in a concise, quantitative manner. Many different parameters that describe amplitude, frequency content, and duration have been proposed by various researchers. While some of these parameters describe only one characteristic, some parameters "reflect" two or three characteristics. Because of the large number of different ground motion parameters that have been proposed, this discussion will be limited to those used during the course of this research.

5.2.1 Amplitude

Amplitude has historically been the most commonly used measure to describe a strong ground motion time history. Ground motion records typically consist of recorded acceleration time histories. The resulting velocity and displacement time histories are then determined by integration as shown in Figure 5.1. The process of integration provides a smoothing effect resulting in differing predominant frequencies; velocity shows less high-frequency motion than acceleration and the displacements are primarily dominated by low frequency motion.

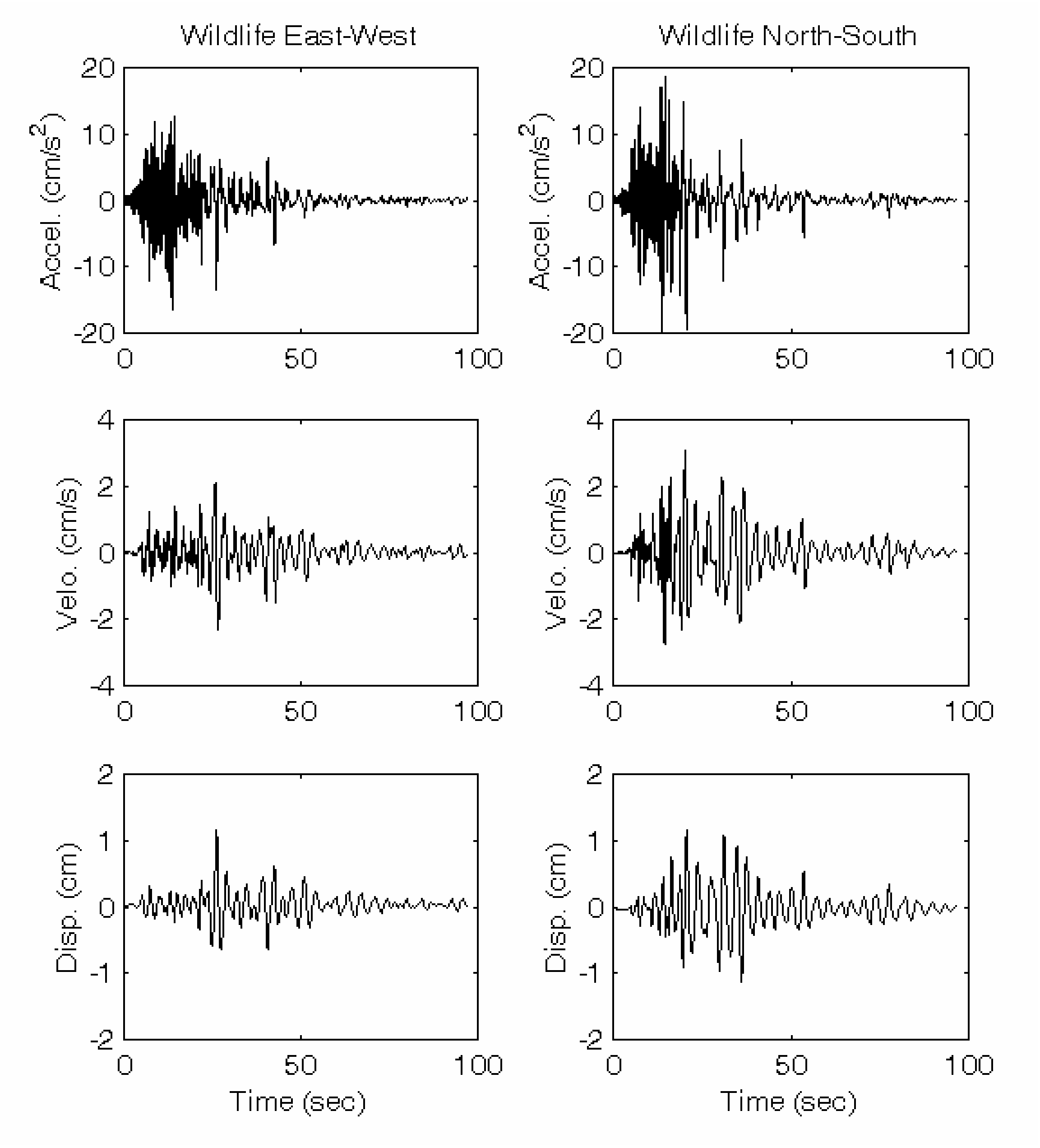

Figure 5.1 Acceleration, velocity, and displacement time histories for the East-West and North-South components of the Wildlife site soil strong ground motion records.

5.2.1.1 Peak Acceleration

Although acceleration, velocity, and displacements are easily displayed parameters, acceleration is most commonly used. Peak horizontal acceleration (PHA) is particularly used to characterize the amplitude of a ground motion. PHA is defined as the largest absolute value of horizontal acceleration obtained from the accelerogram of a particular component of motion. The maximum resultant PHA can be obtained by taking the vector sum of two orthogonal components.

Ground motions with a high PHA are typically more damaging to structures than a motion with a low PHA. However, a higher PHA ground motion that lasts for only a few seconds may cause little damage compared to a motion with a lower PHA that lasts for several tens of seconds. Furthermore, many earthquakes with high peak accelerations have produced little damage to structures because the peak accelerations occurred at high frequencies and with short durations. In the end, amplitude by itself does not provide a complete description of the ground motion. Additional information, specifically frequency content and duration, are required to form a complete description of the ground motion.

5.2.2 Frequency Content

The dynamic response of structures, whether they are buildings, bridges, slopes, etc., is very sensitive to the frequencies at which they are loaded. The frequency content of a ground motion describes how the amplitude of the motion is distributed across a range of frequencies. Therefore, several measures of frequency content are used to further characterize a ground motion.

5.2.2.1 Fourier Spectra

Spectral analysis seeks to describe the frequency content of a signal, the ground motion in this case, based on a finite set of data. The basis of spectral analysis is to represent the signal as the sum of a series of simple harmonic terms of different frequency, amplitude, and phase. In analyzing ground motions, this can be accomplished by using a Fourier series of the form

$$x(t) = c_0 + \sum_{n=1}^{\infty} c_n \sin(\omega_n t + \phi_n) \tag{5.1}$$

where c_n and ϕ_n are the amplitude and phase angle, respectively, of the n^{th} harmonic component of the Fourier series, and ω_n is the circular frequency with time. The Fourier series provides a complete description of the ground motion record since the inverse Fourier transform can be used to recover the original ground motion record. The Fourier amplitude spectrum is a plot of the Fourier amplitude, c_n, versus frequency, ω_n, and the Fourier phase spectrum is a plot of the Fourier phase angle, ϕ_n, versus frequency, ω_n; both of these are shown in Figure 5.2. The amplitude spectrum shows how the acceleration amplitude of the motion is distributed with frequency. The amplitude spectrum in Figure 5.2 shows that acceleration is distributed over a broad range and implies that the motion contains a variety of frequencies that produces a more irregular time history. This is indeed the case as shown in the acceleration time history in Figure 5.1. Although initially uninteresting, the phase spectra describes position of various ground motion components with respect to time. The phase spectra will later become very useful in simulating acceleration time histories for use in this research.

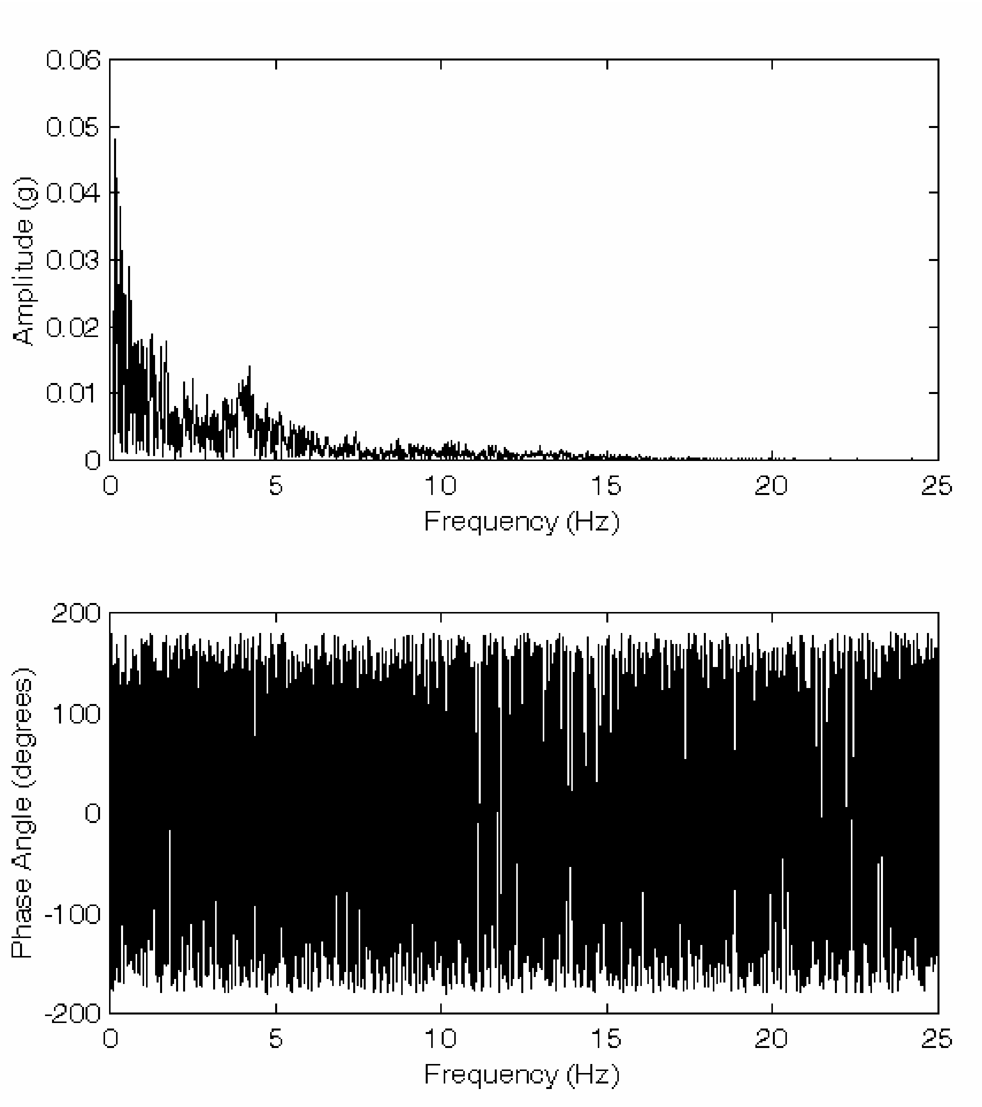

Figure 5.2 Fourier acceleration amplitude spectrum (a) and Fourier acceleration phase spectrum (b) for the east-west component of the Wildlife site strong ground motion.

5.2.2.2 Response Spectrum

The response spectrum describes the maximum response of a single degree of freedom (SDOF) system to a unique input motion as a function of the natural period and damping ratio of the SDOF system. The response is typically expressed in terms of acceleration, velocity, and displacement. The maximum values of these parameters depend on the natural period and damping ratio of the SDOF system. The maximum value of acceleration, velocity, and displacement are referred to as the spectral values of each. The response of a SDOF system subjected to a particular input motion for varying natural periods is shown in Figure 5.3. The response of the system is obtained by plotting the spectral values of acceleration against the period of vibration of the SDOF system as shown in Figure 5.4 for the Wildlife data.

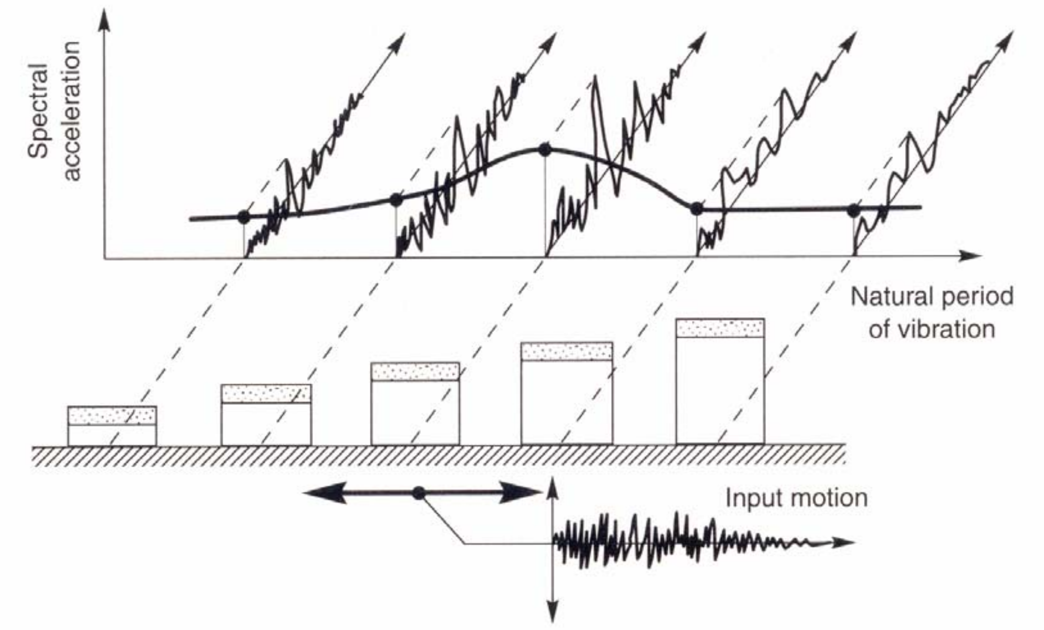

Figure 5.3 Response spectrum. Spectral accelerations are the maximum acceleration amplitudes of SDOF systems of varying natural periods in response to the same input motion. (Kramer, 1996)

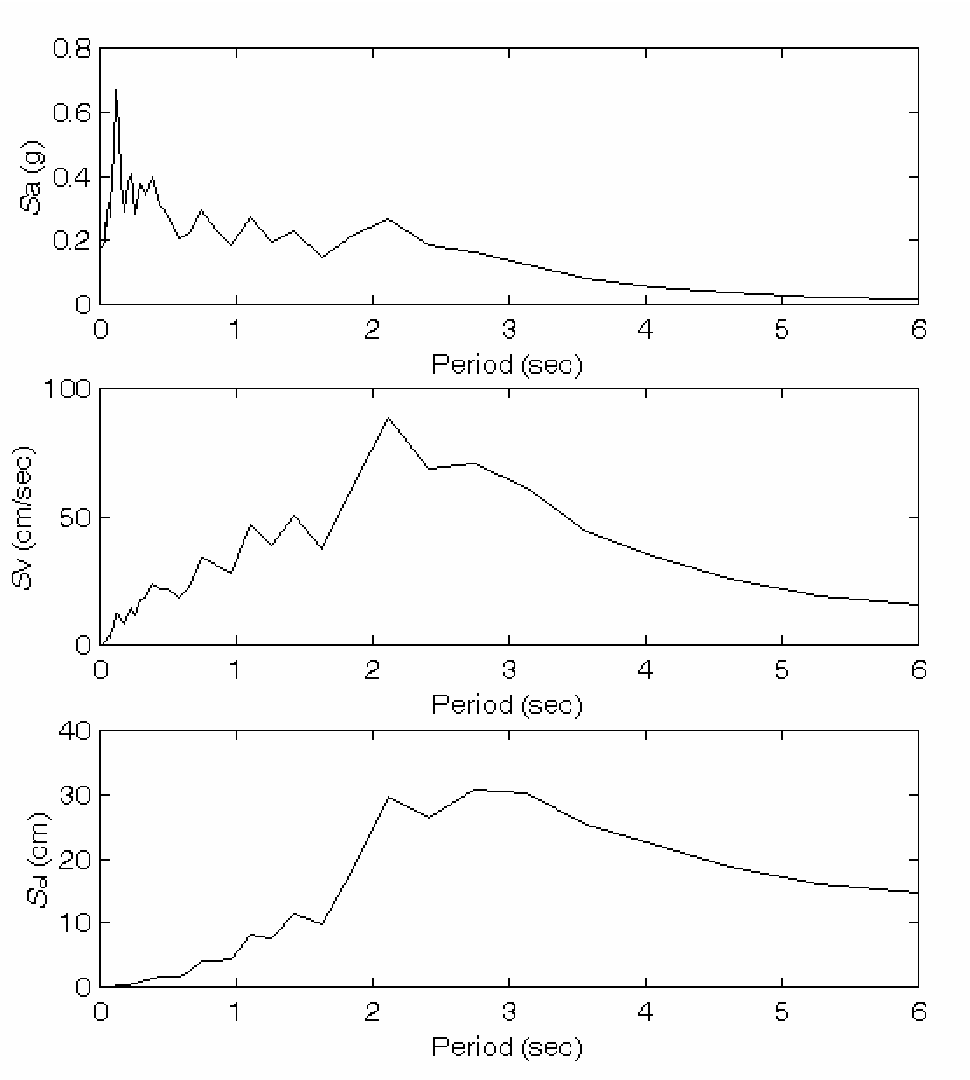

Figure 5.4 Response spectra using 5% damping for the Wildlife East-West component of strong ground shaking, where S_u, S_v, and S_d are the spectral displacements, velocities, and accelerations, respectively.

As seen in Figure 5.4, the shapes of the response spectra show that the peak spectral acceleration, velocity, and displacement values occur at different periods. Response spectra characterize strong motion indirectly since the motions are filtered by the response of the SDOF system. However, the frequency content, as well as amplitude, is clearly indicated by the response spectrum.

5.2.3 Duration

The duration of strong ground motion is related to the time that accumulated strain energy is released along a fault rupture (Kramer, 1996). Therefore, it is reasonable to expect that duration will increase with an increase in earthquake magnitude. An accelerogram contains all acceleration values from the time the earthquake begins until the acceleration values return to a baseline background level. However, only the strong-motion portion of the accelerogram is of interest for assessing the effects resulting from liquefaction.

Historically used as one of the most common measures of duration, bracketed duration is defined as the time between the first and last exceedances of a threshold acceleration (Bolt, 1969). The threshold is usually taken as 0.05g.

Duration based on normalized Arias intensity is becoming more commonly used because useful empirical relations exist to estimate this strong ground motion parameter. Arias intensity is discussed in more detail in the next section. Normalized Arias intensity is defined as

$$I(t) = \frac{\int_0^t [a(t)]^2 \, dt}{\int_0^\infty [a(t)]^2 \, dt} \tag{5.2}$$

where $a(t)$ is the acceleration time history and $I(t)$ ranges from 0 to 1 (Silva et al., 1996). The duration is defined as the time interval between which $I(t)$ reaches two values. That is, given $I(t)$, an inverse relation for $t(I)$ that defines the duration, $D_{I_2-I_1}$, is given by

$$D_{I_2-I_1} = t(I_2) - t(I_1) \tag{5.3}$$

For example, if $I_2 = 0.75$ and $I_1 = 0.05$, then $D_{I_2-I_1}$ is the duration of the 5 – 75% normalized Arias duration. The concept of normalized Arias duration is based on the Trifunac duration (Trifunac and Brady, 1975) that defined duration as the time interval between which 5% and 95% of the energy in a ground motion had occurred. Trifunac duration can also be computed from normalized Arias intensity, $I(t)$, that determines the duration in a range in energy corresponding to $I_2 = 0.95$ and $I_1 = 0.05$.

5.3 Arias Intensity

The aforementioned parameters were focused on only one of the characteristic aspects of strong ground motion: amplitude, frequency content, and duration. Other combined parameters that reflect more than one aspect of strong ground motion are also useful. One such parameter used in this research is Arias intensity. Arias intensity is a parameter that includes the characteristics of amplitude and frequency content. Arias intensity, I_a, is defined as

$$I_a = \frac{\pi}{2g}\int_0^{\infty}\left[a(t)\right]^2 dt \qquad (5.4)$$

and has units of velocity. Because Arias intensity is defined over the entire duration rather than the duration of strong shaking, it is independent of the method used to define the duration of strong shaking.

5.4 Estimation of Ground Motion Parameters

The level of shaking of strong ground motion is most often described in terms of the aforementioned parameters. Therefore, methods for estimating these parameters, called predictive relations, are required in the characterization of strong ground motion at a site of interest. These relations are important in the seismic hazard analyses used in this research.

The development of predictive relations express the ground motion parameter of interest as function of known quantities. These quantities can include magnitude and distance, as well as other parameters, for example,

$$Y = f(M, R, P_i) \qquad (5.5)$$

where Y is the ground motions parameter of interest, M is the magnitude of the earthquake, R is a measure of site to source distance, and P_i are other parameters that are known (Kramer, 1996). Predictive relations are based on regression analyses of recorded strong motions databases. The functional form of the relation is typically selected to reflect the mechanisms of the ground motion processes.

This research is based extensively on two database sets that were comprised of data resulting from a subduction zone earthquake, and data from a crustal event earthquake produced from strike-slip faulting. This data will be presented in the next chapter. Therefore, the predictive relations given in this section are limited to these types of earthquake mechanisms.

5.4.1 Estimation of Parameters Resulting from Subduction Zone Earthquakes

The work by Youngs et al. (1997) presents the attenuation relations for peak ground acceleration and response spectral acceleration for subduction zone interface and intraslab earthquakes of moment magnitude 5 and greater, and for distances of 10 to 500 km. For the purposes of this discussion, interface earthquakes are subduction zone earthquakes that typically result from the relative movement between a subducting plate and a stationary plate; in this case, between the subducting oceanic crust and a continental plate. An intraslab earthquake is associated with stress and physical changes in the subducting plate as it is pulled deeper under the continental plate.

As previously stated, the relations were developed by regression analyses. Youngs et al. (1997) found that the rate of attenuation of peak motions from subduction zone earthquakes was lower than that for shallow crustal earthquakes in active tectonic regions. The peak motions increase with earthquake depth, and intraslab earthquakes produce peak motions that are about 50% larger than interface earthquakes. The regression analyses are categorized as soil or rock sites. Therefore, the predictive equations are also presented for either soil or rock sites. The predictive attenuation equations for horizontal spectral acceleration on rock sites with 5% damping are as follows

$$\begin{aligned}\ln(y) = 0.2418 + 1.414M + C_1 + C_2\left(10 - M\right)^3 + \\ C_3 \ln\left(r_{rup} + 1.7818e^{0.554M}\right) + 0.00607H + 0.3846Z_T\end{aligned} \tag{5.6}$$

$$\sigma_{\ln(y)} = C_4 + C_5 M \tag{5.7}$$

where y is the spectral acceleration in g, M is the moment magnitude, r_{rup} is closest distance from the site to the rupture source in km, H is the focal depth in km, Z_{T} is the source type (0 for interface and 1 for intraslab events), $\sigma_{\ln(y)}$ is the standard deviation and C_{i} are regression coefficients presented in Table 5.1. The site to course distance is defined as the closest distance from the site to the rupture surface.

Table 5.1 Regression coefficients for Youngs et al. (1997)
attenuation relation at rock sites.

Period (s)	C_1	C_2	C_3	C_4	C_5
PHA	0	0	-2.552	1.45	-0.1
0.075	1.275	0	-2.707	1.45	-0.1
0.1	1.188	-0.0011	-2.655	1.45	-0.1
0.2	0.722	-0.0027	-2.528	1.45	-0.1
0.3	0.246	-0.0036	-2.454	1.45	-0.1
0.4	-0.115	-0.0043	-2.401	1.45	-0.1
0.5	-0.4	-0.0048	-2.36	1.45	-0.1
0.75	-1.149	-0.0057	-2.286	1.45	-0.1
1	-1.736	-0.0064	-2.234	1.45	-0.1
1.5	-2.64	-0.0073	-2.16	1.5	-0.1
2	-3.328	-0.008	-2.107	1.55	-0.1
3	-4.511	-0.0089	-2.033	1.65	-0.1

The predictive attenuation equations for horizontal spectral acceleration on soil sites with 5 percent damping are as follows

$$\begin{aligned}\ln(y) = -0.6687 + 1.438M + C_1 + C_2\left(10 - M\right)^3 + \\ C_3 \ln\left(r_{rup} + 1.097e^{0.617M}\right) + 0.00648H + 0.3643Z_T\end{aligned} \tag{5.8}$$

$$\sigma_{\ln(y)} = C_4 + C_5 M \tag{5.9}$$

The regression coefficients for soil sites are presented in Table 5.2.

Table 5.2 Regression coefficients for Youngs et al. (1997) attenuation relation at soil sites.

Period (s)	C_1	C_2	C_3	C_4	C_5
PHA	0	0	-2.329	1.45	-0.1
0.075	2.4	-0.0019	-2.697	1.45	-0.1
0.1	2.516	-0.0019	-2.697	1.45	-0.1
0.2	1.549	-0.0019	-2.464	1.45	-0.1
0.3	0.793	-0.002	-2.327	1.45	-0.1
0.4	0.144	-0.002	-2.23	1.45	-0.1
0.5	-0.438	-0.0035	-2.14	1.45	-0.1
0.75	-1.704	-0.0048	-1.952	1.45	-0.1
1	-2.87	-0.0066	-1.785	1.45	-0.1
1.5	-5.101	-0.0114	-1.47	1.5	-0.1
2	-6.433	-0.0164	-1.29	1.55	-0.1
3	-6.672	-0.0221	-1.347	1.65	-0.1

5.4.2 Estimation of Parameters Resulting from Crustal Event Earthquakes

The work of Boore et al. (1997) presented attenuation relations for estimating horizontal response spectra and peak horizontal acceleration for shallow earthquakes in western North America. The predictive equations give the ground motion parameter in terms of moment magnitude, distance, and site conditions for strike-slip, reverse-slip, or unspecified faulting mechanisms. For their predictive equations, site conditions were represented by the shear wave velocity at the site of interest averaged over the upper 30 m of the soil profile. Recommended values of average shear wave velocity were also given for typical rock and soil sites and for site categories used in the National Earthquake Hazard Reduction Program's (NEHRP) recommended seismic code provisions. The predictive equations are used for earthquakes ranging from $M = 5.5$ to 7.5 and for site to source distances of no greater than 80 km. The predictive attenuation equations for horizontal spectral acceleration with 5 percent damping is as follows

$$\ln(y) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5\ln(r) + b_V\ln(\frac{V_S}{V_A}) \tag{5.10}$$

$$r = \sqrt{r_{jb}^2 + h^2} \tag{5.11}$$

$$b_1 = \begin{cases} b_{1SS} & \textit{for strike} - \textit{slip earthquakes}; \\ b_{1RS} & \textit{for reverse} - \textit{slip earthquakes}; \\ b_{1ALL} & \textit{if mechanism not specified}. \end{cases} \tag{5.12}$$

where V_S is the average shear wave velocity in the upper 30 m of the site subsurface profile, and r_{jb} is the closest horizontal distance (km) to the vertical projection of the rupture. The coefficients determined by regression are h, a fictitious depth, and b_i and V_A given in Table 5.3. When NEHRP class sites are under consideration, the recommended values for the average shear wave velocity over the upper 30 m of the site subsurface profile are given in Table 5.4.

Table 5.3 Regression coefficients for Boore et al. (1997) attenuation relation.

Period (s)	b_{1SS}	b_{1RS}	b_{1ALL}	b_2	b_3	b_5	b_V	h	V_a	$\sigma_{\ln(Y)}$
PHA	-0.313	-0.117	-0.242	0.527	0	-0.778	-0.371	5.57	1396	0.52
0.1	1.006	1.087	1.059	0.753	-0.226	-0.934	-0.212	6.27	1112	0.479
0.12	1.109	1.215	1.174	0.721	-0.233	-0.939	-0.215	6.91	1452	0.485
0.15	1.128	1.264	1.204	0.702	-0.228	-0.937	-0.238	7.23	1820	0.492
0.17	1.09	1.242	1.173	0.702	-0.221	-0.933	-0.258	7.21	1977	0.497
0.2	0.999	1.17	1.089	0.711	-0.207	-0.924	-0.292	7.02	2118	0.502
0.24	0.847	1.033	0.941	0.732	-0.189	-0.912	-0.338	6.62	2178	0.511
0.3	0.598	0.803	0.7	0.769	-0.161	-0.893	-0.401	5.94	2133	0.522
0.4	0.212	0.423	0.311	0.831	-0.12	-0.867	-0.487	4.91	1954	0.538
0.5	-0.122	0.087	-0.025	0.884	-0.09	-0.846	-0.553	4.13	1782	0.556
0.75	-0.737	-0.562	-0.661	0.979	-0.046	-0.813	-0.653	3.07	1507	0.587
1	-1.133	-1.009	-1.08	1.036	-0.032	-0.798	-0.698	2.9	1406	0.613
1.5	-1.552	-1.538	-1.55	1.085	-0.044	-0.796	-0.704	3.92	1479	0.649
2	-1.699	-1.801	-1.743	1.085	-0.085	-0.812	-0.655	5.85	1795	0.672

Table 5.4 Recommended values of average shear wave velocity for use in Equation (5.10). (Boore et al., 1997)

Site Class	Shear Wave Velocity (m/sec)
NEHRP Site Class B	1070
NEHRP Site Class C	520
NEHRP Site Class D	250
Average Rock	620
Average Soil	310

5.4.3 Estimation of Parameters Resulting from Earthquakes in Central and Eastern North America

The work of Toro et al. (1997) presented attenuation relations for estimating horizontal response spectra and peak horizontal acceleration for shallow earthquakes in Central and Eastern North America. The predictive equations give the ground motion parameter in terms of moment magnitude and the closest horizontal distance to the earthquake rupture. The predictive equations are used for earthquakes ranging from 5 to 8 and for site to source distances of no greater than 100 km. The predictive attenuation equations for PHA is as follows

$$\ln Y = C_1 + C_2\left(M - 6\right) - C_4 \ln R_M - \left(C_5 - C_4\right)\max\left[\ln\left(\frac{R_M}{100}\right), 0\right] - C_6 R_M \tag{5.13}$$

where Y is PHA, $C_1 = 2.20$, $C_2 = 0.81$, M is moment magnitude, $C_4 = 1.27$, $R_M = \sqrt{R_{jb}^2 + C_7^2}$, R_{jb} = closest horizontal distance to the earthquake rupture, $C_5 = 1.16$, and $C_6 = 0.0021$ for Mid-continent sites using moment magnitude.

5.4.4 Estimation of Arias Duration

The work of Silva et al. (1996) used a two-step approach to develop the empirical model for horizontal, normalized Arias duration. In the first step, the model was developed describing the magnitude, distance, and site dependence effects for the 5-75% normalized Arias duration ($D_{0.05\text{-}0.75}$). In the second step, the model was developed to describe the ratio of the duration at other normalized Arias duration intensity levels (e.g. 5-95%) relative to the 5-75% duration. They combined these two models to provide a description of the magnitude, distance, and site dependence effects of the duration for a range of normalized Arias durations.

Their resulting duration model for normalized Arias duration, $D_{0.05\text{-}\mathrm{I}}$, is given by

$$\ln(D_{0.05-I}) = \ln\left[\frac{\left(\frac{\Delta\sigma(M)}{10^{1.5M+16.05}}\right)^{-1/3}}{4.9x10^{6}\beta} + Sc_1 + c_2(r - r_c)\right] + \ln\left(\frac{D_{0.05-I}}{D_{0.05-0.75}}\right) \tag{5.14}$$

for $r \geq r_c$,

$$\ln(D_{0.05-I}) = \ln\left[\frac{\left(\frac{\Delta\sigma(M)}{10^{1.5M+16.05}}\right)^{-1/3}}{4.9x10^{6}\beta} + Sc_1\right] + \ln\left(\frac{D_{0.05-I}}{D_{0.05-0.75}}\right) \tag{5.15}$$

for $r < r_c$, and

$$\Delta\sigma(M) = e^{\{b_1 + b_2(M-6)\}} \tag{5.16}$$

$$\ln\left(\frac{D_{0.05-I}}{D_{0.05-0.75}}\right) = a_1 + a_2\ln\left(\frac{I-0.5}{1-I}\right) + a_3\left\{\ln\left(\frac{I-0.5}{1-I}\right)\right\}^2 \tag{5.17}$$

where $\Delta\sigma(M)$ is the stress drop as a function of magnitude, S is a site dependence variable (1 for soil sites and 0 for rock sites), r is the site to source distance in km, r_c is a threshold distance of 10 km, I is the percentage of desired normalized Arias duration, and a_i, b_i, c_i, and β are regression coefficients given in Table 5.5. The standard error is given as

$$\begin{aligned}\sigma_{\ln(D)} = &-43.52I^7 + 180.82I^6 - 309.48I^5 + 282.69I^4 - \\ &149.53I^3 + 46.25I^2 - 8.08I + 1.31\end{aligned} \tag{5.18}$$

Table 5.5 Regression coefficients for Silva et al. (1996) attenuation relation.

Coefficient	Value
a_1	-0.532
a_2	0.552
a_3	-0.0262
b_1	5.204
b_2	0.851
c_1	0.805
c_2	0.063
β	3.2

5.5 Ground Motion Simulation

The ground motion parameters discussed previously do not alone describe the effects of ground shaking, particularly for the nonlinear analyses that are used for this research. Actual time histories are needed as input to nonlinear analyses. Because actual time history recordings were not available at the study sites where this research is focused, artificial time histories had to be developed. The main consideration when generating synthetic time histories is to ensue that they reasonably match the target parameters that are estimated from the previous section. Another important consideration is make sure that the synthetic time histories are realistic in both the time and frequency domains. The most commonly used methods of creating synthetic time histories are accomplished in the time domain and in the frequency domain. Given that the response spectrum is usually sufficient for the seismic design evaluation of most structures of interest, both methods use a spectrum matching process to generate realistic acceleration time histories whereby the resulting response spectra closely matches a smooth design response spectrum. The duration of the synthetic time history is obtained by using a specified time step.

The spectrum matching procedure begins with an initial acceleration time history whose characteristics reasonably represent the ground motions expected for the site. The characteristic used to represent the ground motion for the site is usually the smoothed, design response spectrum. The criteria for selecting the initial ground motion include similar tectonic environment, earthquake magnitude, type of faulting, site-to-source distance, similar site geology, response spectrum, and duration. The initial time-history will have individual spectral local maxima and minima that deviate from the smoothed design spectrum. The objective of the matching procedure is to reduce these deviations in the period range of interest while preserving the nonstationary characteristics of the initial time history to the extent possible. The nonstationary characteristics in this context are defined as the changes of amplitude with time (the build-up and decay of the motion). Convergence with the design spectrum is achieved when the spectral values of the modified time history are within a specified tolerance from the design values at the periods of interest being matched.

5.5.1 Frequency Domain Approach

The frequency domain approach adjusts the Fourier amplitudes of a seed motion while the Fourier phases are held constant. The approach by Silva and Lee (1987) utilizes random vibration theory (RVT) applied to a Brune source spectrum to characterized strong ground motion.

This method has been implemented in a computer program called RASCAL (Silva and Lee, 1987) and has been utilized for this research. The model uses a Brune spectrum to model root mean square (RMS) acceleration as function of magnitude and distance for stiff rock sites. To model the values of the spectra, RVT is used to relate the RMS predictions to the spectra (Silva and Lee, 1987). Because an observed phase spectrum is used, the nonstationary, randomness, and change in frequency with time are incorporated in a natural way.

The approach used for this research to generate synthetic time histories included the following:

1) The initial time-history recordings were selected from nearby recordings during the actual event of interest or by selecting candidate time histories form various strong ground motion databases that matched the criteria outlined previously. These time histories served as the seed motions where the Fourier phase spectrum would be used as discussed previously.

2) A site design response spectrum was generated using the empirical methods outlined in sections 5.4.1 and 5.4.2 based on magnitude, site-to-source distance and other site parameters.

3) The program RASCAL was used to generate the synthetic time histories based on the seed motion and design response spectrum.

4) The expected durations at the sites of interest were established using the empirical procedures outlined in section 5.4.3. Based on the length of the generated time history, the time step of the seed motion was adjusted until the desired duration was obtained.

5) The resulting synthetic time histories were then base line corrected to obtain a final time history to use in various analyses. These time histories conformed to the expected design response spectrum and expected duration for the earthquake events and sites of interest.

5.5.2 Time Domain Approach

The spectral matching approach in the time domain is accomplished by adding or subtracting finite-duration wavelets to and from an initial time history. One representative wavelet is used as the impulse response time-history of the single degree of freedom oscillator reversed in time (USACE, 2000). This approach typically provides for a closer response spectra fit over the frequency domain approach. This is because the wavelet abruptly ceases after the peak response time and thus limits the temporal extent of the modification made to the time history. However, the time domain approach is more difficult to implement because the methodology is usually tailored to the type of problem. Various methodologies in the time domain allow for generating spatially incoherent time histories in both phase and amplitude variations (Hao et al., 1989), whereas some methods generate incoherence in only the phase variations and treat amplitude variation separately (Abrahamson, 1992). Lilhanand and Tseng (1988) provide a methodology for generating time histories that are compatible with multiple damping design spectra. This research did not utilize the time domain approach.

5.6 Summary

The three characteristics of earthquake motion that are of primary interest are: 1) amplitude, 2) frequency content, and 3) duration of the ground motion of interest. Peak horizontal acceleration is the most commonly used parameter to characterize the amplitude of a ground motion. Spectral analysis seeks to describe the frequency content of a signal, the ground motion in this case, based on a finite set of data. Other combined parameters that reflect more than one aspect of strong ground motion are also useful, such as Arias intensity.

Methods for estimating these parameters, called predictive relations, are used in the characterization of strong ground motion. Predictive relations are based on regression analyses of recorded strong motions databases. The work by Youngs et al. (1997) presents the attenuation relations for peak ground acceleration and response spectral acceleration for subduction zone interface and intraslab earthquakes. The work of Boore et al. (1997) presents the attenuation relations for estimating horizontal response spectra and peak horizontal acceleration for shallow earthquakes in western North America. Silva et al. (1996) used a two-step approach to develop the empirical model for horizontal, normalized Arias duration.

For non-linear problems, actual time histories are needed as input to the analyses. Because actual time history recordings are not typically available at the study sites where this research is focused, artificial time histories were developed. The most commonly used methods of creating synthetic time histories are accomplished in the time domain and in the frequency domain. This method used in this research is accomplished in the frequency domain using a computer program called RASCAL.