Technical Manual for Strata

Albert R. Kottke
Department of Civil, Architectural, and Environmental Engineering
University of Texas, Austin

Ellen M. Rathje
Department of Civil, Architectural, and Environmental Engineering
University of Texas, Austin

PEER Report 2008/xx
Pacific Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley
October 2008

ABSTRACT

The computer program Strata performs equivalent linear site response analysis in the frequency domain using time domain input motions or random vibration theory (RVT) methods, and allows for randomization of the site properties. The following document explains the technical details of the program, as well as provides a user's guide to the program.

Strata is distributed under the GNU General Public License which can be found here:http://www.gnu.org/licenses/.

ACKNOWLEDGEMENTS

This project was sponsored by the Pacific Earthquake Engineering Research Center's Program of Applied Earthquake Engineering Research of Lifelines Systems supported by the California Energy Commission, California Department of Transportation, and the Pacific Gas and Electric Company.

This work made use of the Earthquake Engineering Research Centers Shared Facilities supported by the National Science Foundation, under award number EEC-9701568 through the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation.

Additional support was provided by the Nuclear Regulatory Commission.

TABLE OF CONTENTS

Abstract ... iii
Acknowledgements ... v
Table of Contents ... vii
List of Figures ... ix
List of Tables ... xiii

LIST OF FIGURES

LIST OF TABLES

1 Introduction

The computer program Strata performs equivalent linear site response analysis in the frequency domain using time domain input motions or random vibration theory (RVT) methods, and allows for randomization of the site properties. Strata was developed with financial support provided by the Lifelines Program of the Pacific Earthquake Engineering Research (PEER) Center under grant SA5405-15811 and funding from the Nuclear Regulatory Commission. Strata is distributed under the GNU General Public License which can be found here: http://www.gnu.org/licenses/.

The following document provides explanation of the technical details of the program. Chapter 2 provides an introduction to equivalent-linear elastic wave propagation using both time series and random vibration theory methods. Using the time series method, a single motion is propagated through the site to compute the strain compatible ground motion at the surface of the site or at any depth in the soil column. Using random vibration theory, the expected maximum response is computed from a mean Fourier amplitude spectrum (amplitude only) and duration. Chapter 3 introduces random variables and the models that Strata uses to govern the variability of the site properties (nonlinear properties, layering thickness, shear-wave velocity, and depth to bedrock). Chapter 4 discusses in the interaction with Strata along with several tutorials that introduce the features found in Strata.

2 Site Response Analysis

Strata computes the dynamic site response of a one-dimensional soil column using linear wave propagation with strain dependent dynamic soil properties. This is commonly referred to as the equivalent linear analysis method, which was first used in the computer program SHAKE (Schnabel et al. 1972; Idriss & Sun 1992). Similar to SHAKE, Strata only computes the response for vertically propagating, horizontally polarized shear waves propagated through a site with horizontal layers.

The following chapter introduces strain dependent soil properties, linear-elastic wave propagation through a layered medium, and the equivalent linear approach to site response analysis.

2.1 Equivalent Linear Site Response Analysis

2.1.1 Linear Elastic Wave Propagation

For linear elastic, one-dimensional wave propagation, the soil is assumed to behave as a Kelvin-Voigt solid, in which the dynamic response is described using a purely elastic spring and a purely viscous dashpot (Kramer, 1996). The solution to the one-dimensional wave equation for a single wave frequency (ω) provides displacement (u) as a function of depth (z) and time (t) (Kramer, 1996):

$$u(z,t) = A\exp[i(\omega t + k^* z)] + B\exp[i(\omega t - k^* z)] \tag{2.1}$$

In equation (1.1), A and B represent the amplitudes of the upward (-z) and downward (+z) waves, respectively (Figure 2.1). The complex wave number (k^*) in equation (2.1) is related to the shear modulus (G), damping ratio (D), and mass density (ρ) of the soil using:

$$k^* = \frac{\omega}{v_s^*} \tag{2.2}$$

$$v_s^* = \sqrt{\frac{G^*}{\rho}} \tag{2.3}$$

$$G^* = G\left(1 - 2D^2 + i2D\sqrt{1 - D^2}\right) \cong G(1 + i2D) \tag{2.4}$$

G^* and v_s^* are called the complex shear modulus and complex shear-wave velocity, respectively. If the damping ratio (D) is small (<10-20%), then the approximation of the complex shear modulus in equation (2.4) is appropriate. Strata uses the complete definition of the complex shear-modulus, not the approximation, in the calculations.

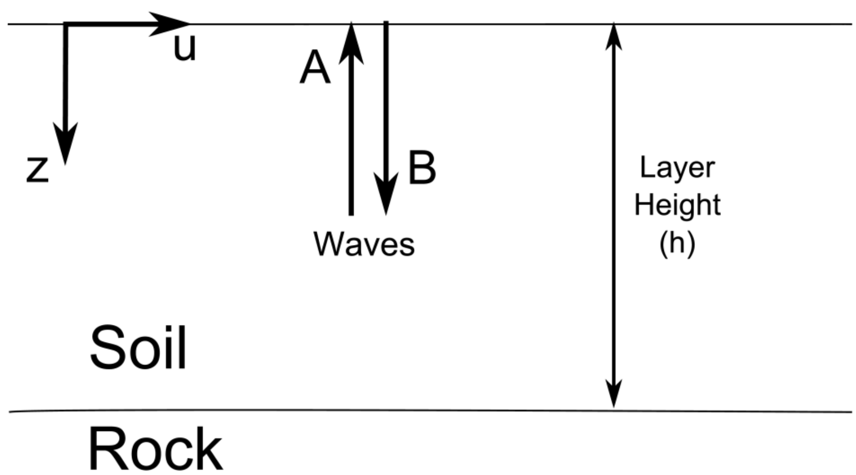


Figure 2.1: The notation used in the wave equation.

Equation (2.1) applies only to a single layer with uniform soil properties and the wave amplitudes (A and B) can be computed from the layer boundary conditions. For a layered system, shown in Figure 2.1, the wave amplitudes are calculated using recursive formulas developed by maintaining compatibility of displacement and shear stress at the layer boundaries. Using these assumptions, the following recursive formulas are developed (Kramer, 1996):

$$\begin{aligned} A_{m+1} &= \frac{1}{2}A_m(1+\alpha_m^*)\exp\left(\frac{ik_m^*h_m}{2}\right)+\frac{1}{2}B_m(1-\alpha_m^*)\exp\left(-\frac{ik_m^*h_m}{2}\right) \\ B_{m+1} &= \frac{1}{2}A_m(1-\alpha_m^*)\exp\left(\frac{ik_m^*h_m}{2}\right)+\frac{1}{2}B_m(1+\alpha_m^*)\exp\left(-\frac{ik_m^*h_m}{2}\right) \end{aligned} \tag{2.5}$$

where m is the layer number, h_m is the layer height and α_m* is the complex impedance ratio. The complex impedance ratio is defined as:

$$\alpha_m^* = \frac{k_m^* G_m^*}{k_{m+1}^* G_{m+1}^*} = \frac{\rho_m v_{s,m}^*}{\rho_{m+1} v_{s,m+1}^*} \tag{2.6}$$

At the surface of the soil column (m=1), the shear stress must equal zero and the amplitudes of the upward and downward waves must be equal (A_1=B_1).

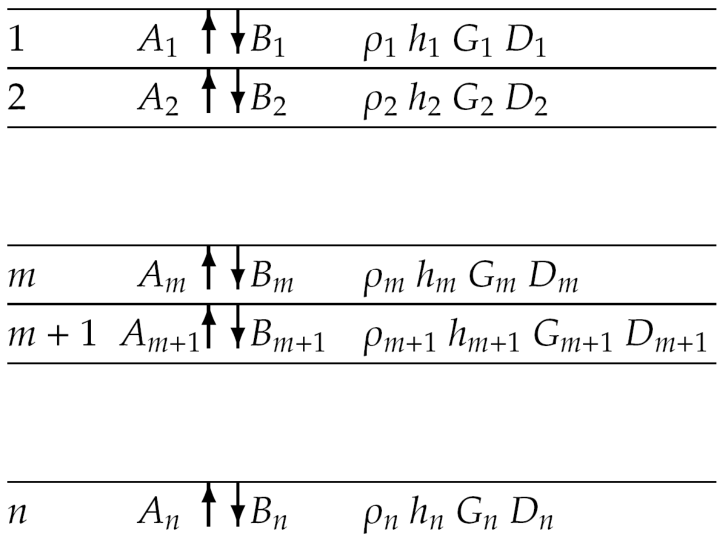


Figure 2.2: Nomenclature for the theoretical wave propagation.

The wave amplitudes (*A* and *B*) within the soil profile are calculated at each frequency (assuming known stiffness and damping within each layer) and used to computed the response at the surface of a site. This calculation is performed by setting A_1=B_1=1.0 at the surface and recursively calculating the wave amplitudes (A_{m+1},B_{m+1}) in successive layers until the input (base) layer is reached. The transfer function between the motion in the layer of interest (*m*) and in the rock layer (*n*) at the base of the deposit is defined as:

$$TF_{(m,n)}(\omega) = \frac{u_m(\omega)}{u_n(\omega)} = \frac{A_m + B_m}{A_n + B_n} \tag{2.7}$$

where ω is the frequency of the harmonic wave. The transfer function is the ratio of the amplitude of harmonic motion--either displacement, velocity, or acceleration--between two layers of interest and varies with frequency. The transfer function (surface motion / within motion) for the site with the properties presented in Table 2.1 is shown in Figure 2.3. The locations of the peaks in the transfer function are controlled by the modes of vibration of the soil deposit. The peak at the lowest frequency represents the fundamental (i.e. first) mode of vibration and results in the largest amplification. The peaks at higher frequencies are the higher vibrational modes of the site.

For the example site (Table 2.1), the first mode natural frequency is 1.75 Hz (site period = 0.57 s). In the transfer function (Figure 2.3), the peak with the largest amplification occurs at this frequency. The amplitudes of the peaks are controlled by the damping ratio of the soil. As the damping of the system increases, the amplitudes of the peaks decrease which results in less amplification.

Table 2.1: The site properties of an example site.

Property	Rock	Soil
Mass Density (ρ)	2.24 g/cm³	1.93 g/cm³
Height (h)	Inf	50 m
Shear-wave Velocity (v_s)	1500 m/s	350 m/s
Damping ratio (D)	1%	7%

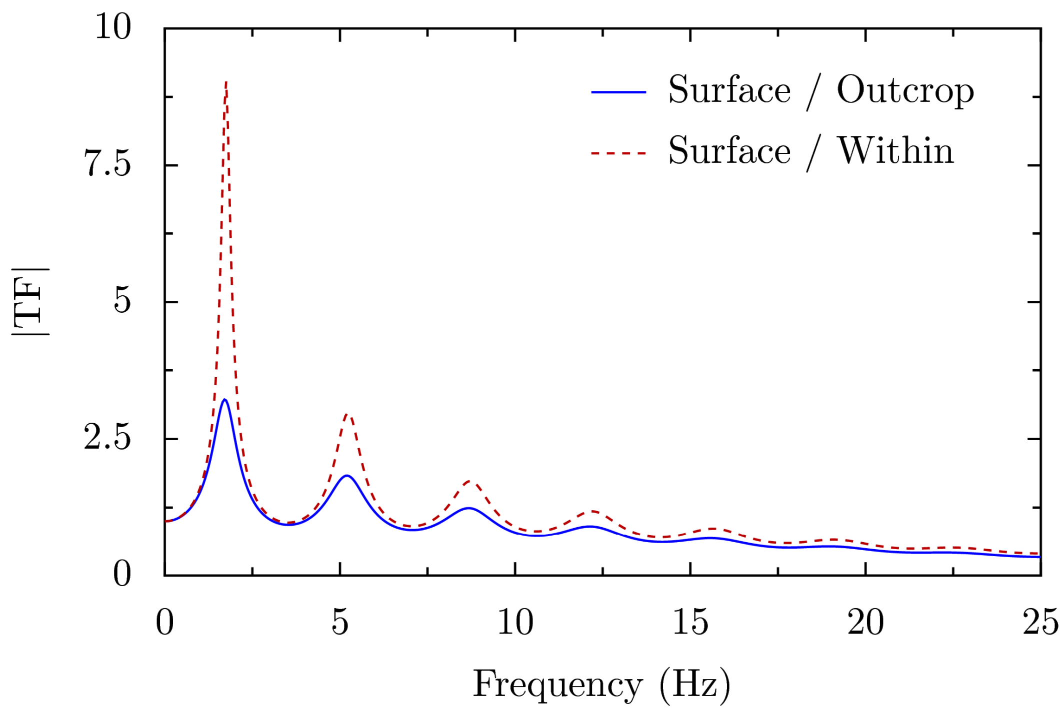


Figure 2.3: The input to surface transfer functions site in Table 2.1 considering different types of input.

The response at the layer of interest is computed by multiplying the Fourier amplitude spectrum of the input rock motion by the transfer function:

$$Y_m(\omega) = TF_{m,n}(\omega) Y_n(\omega) \tag{2.8}$$

where Y_n is the input Fourier amplitude spectrum at layer n and Y_m is the Fourier amplitude spectrum at the top of the layer of interest. The Fourier amplitude spectrum of the input motion can be defined using a variety of methods and is discussed further in Sections 2.2.1 and 2.2.2.

One issue that must be considered is that the input Fourier spectrum typically represents a motion recorded on rock at a free surface (i.e., the ground surface), where the upgoing and downgoing wave amplitudes are equal ($A_1 = B_1$), rather than on rock at the base of a soil deposit, where the wave amplitudes are not equal (Figure 2.4). The change in boundary conditions ($A_n = B_n$ for a free surface,

$A_n \neq B_n$ at the base of a soil deposit) must be taken into account. The motions at any free surface are referred to as outcrop motions and their amplitudes are described by twice the amplitude of the upward wave ($2A$). A transfer function can be defined that converts an outcrop motion into a within motion, and this transfer function can be combined with the transfer function in Equation (2.7) to create a transfer function that can be applied to recorded outcrop motions on rock (Equation 2.9).

$$TF_{m,n}(\omega) = \underbrace{\frac{A_n + B_n}{2A_n}}_{\substack{outcrop \\ to\ within}} \cdot \underbrace{\frac{A_m + B_m}{A_n + B_n}}_{\substack{within \\ to\ layer_n}} \tag{2.9}$$

Motions recorded at depth (e.g. recorded in a borehole) are referred to as within motions and for these motions the transfer function given in equation (2.7) can be used. Figure 2.3 shows the transfer function (surface motion / outcrop motion) for the site profile presented in Table 2.1 using equation (2.9) where the input motion is specified as outcrop. In comparison with the surface / within transfer function, the surface / outcrop transfer function displays less amplification for all modes.

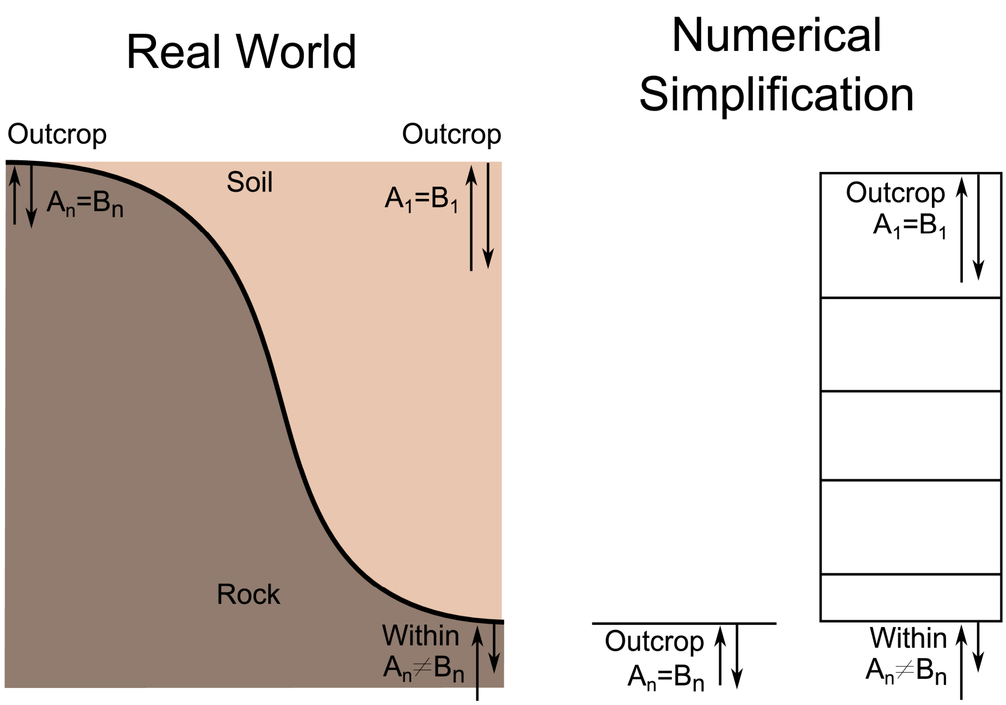


Figure 2.4: The input to surface transfer functions site in Table 2.1 considering different types of input.

2.1.2 **Equivalent-Linear Analysis**

The previous section assumed that the soil was linear-elastic. However, soil is nonlinear, such that the dynamic properties of soil (shear modulus, *G*, and damping ratio, *D*) vary with shear strain, and thus the intensity of shaking. In equivalent-linear site response analysis, the nonlinear response of the soil is approximated by modifying the linear elastic properties of the soil based on the induced strain level.

Because the induced strains depend on the soil properties, the strain compatible shear modulus and damping ratio values are iteratively calculated based on the computed strain.

A transfer function is used to compute the shear strain in the layer based on the outcropping input motion. In the calculation of the strain transfer function, the shear strain is computed at the middle of the layer ($z=h_m/2$) and used to select the strain compatible soil properties. Unlike the previous transfer functions that merely amplified the Fourier amplitude spectrum, the strain transfer function amplifies the motion and converts acceleration into strain. The strain transfer function based on an outcropping input motion is defined by:

$$TF_{m,n}^{strain}(\omega) = \frac{\gamma\left(\omega, z = \frac{h_m}{2}\right)}{\ddot{u}_{n,outcrop}(\omega)} = \frac{i\,k_m^*\left(A_m \exp\left(\frac{ik_m^* h_m}{2}\right) - B_m \exp\left(-\frac{ik_m^* h_m}{2}\right)\right)}{-\omega^2(2A_n)} \tag{2.10}$$

The strain Fourier amplitude spectrum within a layer is calculated by applying the strain transfer function to the Fourier amplitude spectrum of the input motion. The maximum strain within the layer is derived from this Fourier amplitude spectrum -- either through conversion to the time domain or through RVT methods, further discussed in Section 2.2. However, it is not appropriate to use the maximum strain within the layer to compute the strain-compatible soil properties, because the maximum strain only occurs for an instant in time. Instead, an effective strain (γ_{eff}) is calculated from the maximum strain. Typically, the effective strain is 65% of the maximum strain. An example of a strain time-series and the effective strain is shown in Figure 2.5.

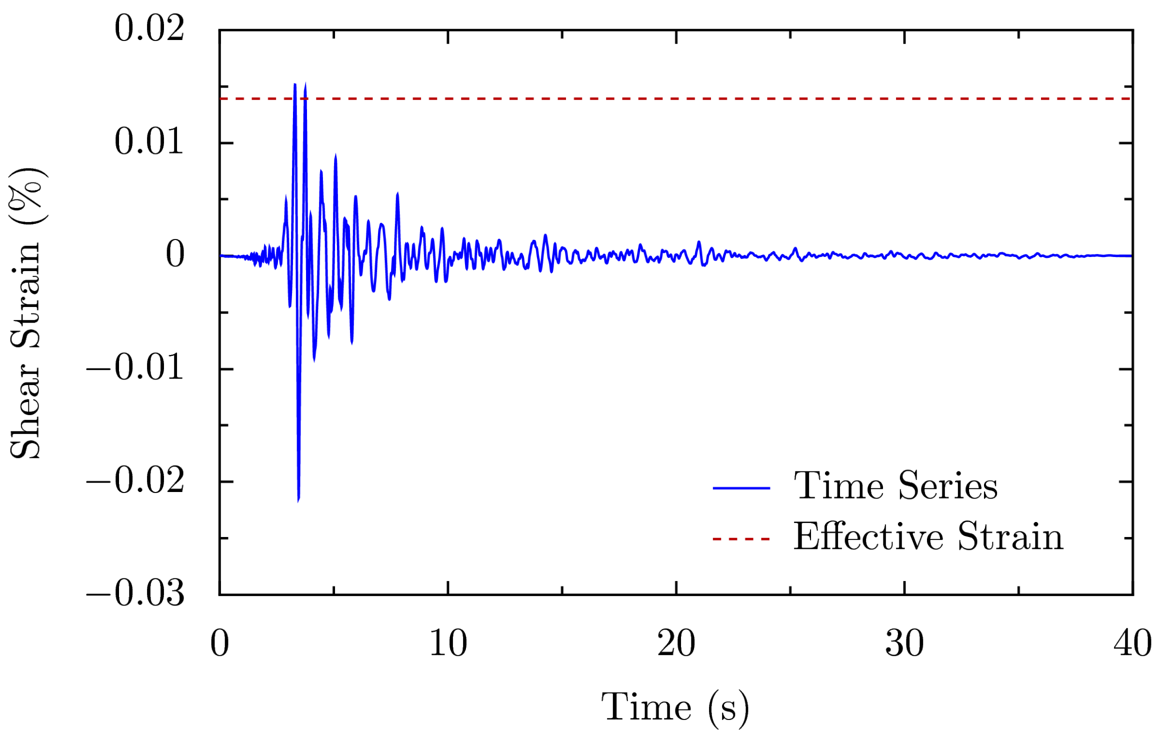


Figure 2.5: An example of the strain-time history and effective strain (γ_{eff}).

Equivalent-linear site response analysis requires that the strain dependent nonlinear properties (i.e. G and D) be defined. The initial (small strain) shear modulus (G_{max}) is calculated by:

$$G_{max} = \rho v_s^2 \tag{2.11}$$

where ρ is the mass density of the site, and v_s is the measured shear-wave velocity. Characterizing the nonlinear behavior of G and D is achieved through modulus reduction and damping curves that describe the variation of G/G_{max} and D with shear strain (discussed in the next section). Using the initial dynamic properties of the soil, equivalent-linear site response analysis involves the following steps:

1. The wave amplitudes (A and B) are computed for each of the layers.
2. The strain transfer function is calculated for each of the layers.
3. The maximum strain within each layer is computed by applying the strain transfer function to the input Fourier amplitude spectrum and finding the maximum response (see Section 2.2).
4. The effective strain (γ_{eff}) is calculated from the maximum strain within each layer.
5. The strain compatible shear modulus and damping ratio are recalculated based on the new estimate of the effective strain within each layer.
6. The new nonlinear properties (G and D) are compared to the previous iteration and an error is calculated. If the error for all layers is below a defined threshold the calculation stops.

After the iterative portion of the program finishes, the dynamic response of the soil deposit is computed using the strain-compatible properties.

2.1.3 **Dynamic Soil Properties**

In a dynamic system, the properties that govern the response are the mass, stiffness, and damping. In soil under seismic shear loading, the mass of the system is characterized by the mass density (ρ) and the layer height (*h*), the stiffness is characterized by the shear modulus (*G*), and the damping is characterized by the viscous damping ratio (*D*). The dynamic behavior of soil is challenging to model because it is nonlinear, such that both the stiffness and damping of the system change with shear strain. Section 2.1.2 introduced equivalent-linear site response analysis in which the nonlinear response of the soil was simplified into a linear system that used strain-compatible dynamic properties (*G* and *D*). The analysis requires that the strain dependence of the nonlinear properties within a layer be fully characterized.

Defining the mass density of the system is a straight forward process because the density of soil falls within a limited range for soil and a good estimate of the mass density can be made based on soil type. Characterization of the stiffness and damping properties of soil is more complicated, the most rigorous approach requiring testing in both the field and laboratory.

The shear modulus and material damping of the soil are characterized using the small strain shear modulus (G_{max}), modulus reduction curves that relate G/ G_{max} to shear strain, and damping ratio curves that relate *D* to shear strain. The small strain shear modulus is best characterized by in situ measurement of the shear-wave velocity as a function of depth. An example shear-wave velocity profile is shown in Figure 2.6. The profile tends to be separated into discrete layers with a generally increasing shear-wave velocity with increasing depth. Examples of modulus reduction and damping curves for soil are shown in Figure 2.7. These curves show a decrease in the soil stiffness and an increase in the damping ratio with an increase in shear strain.

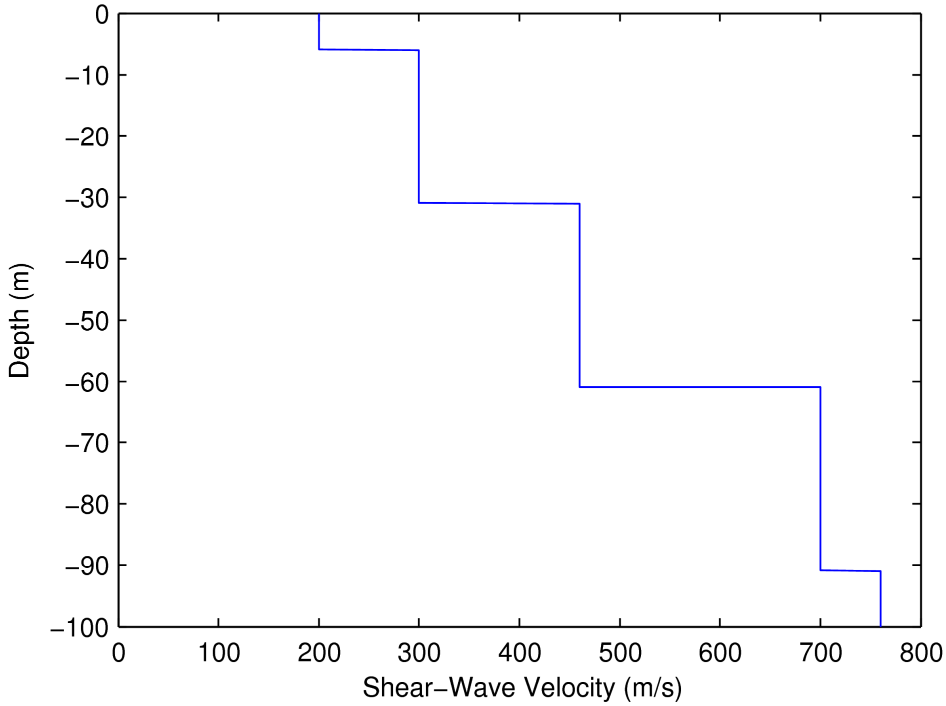


Figure 2.6: An example shear-wave velocity profile.

Modulus reduction and damping curves may be obtained from laboratory measurements on soil samples or derived from empirical models based on soil type and other variables. One of the most comprehensive empirical models was developed by Darendeli (2001) and is included with Strata. The model expands on the hyperbolic model presented by Hardin and Drnevich (1972) and accounts for the effects of confining pressure (σ_0'), plasticity index (PI), overconsolidation ratio (OCR), frequency (f), and number of cycles of loading (N) on the modulus reduction and damping curves.

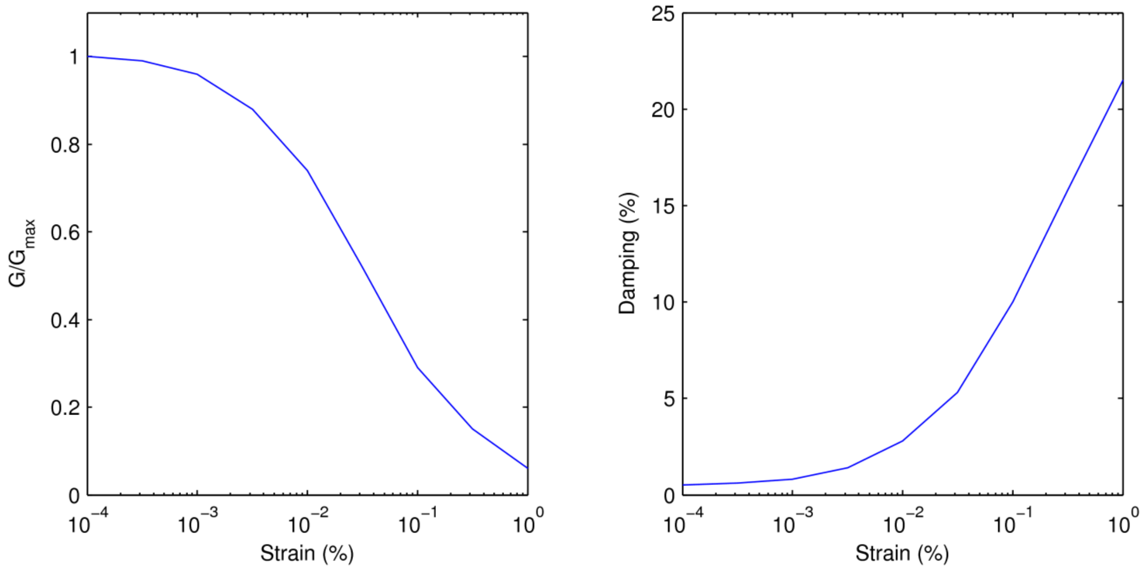


Figure 2.7: Examples of shear modulus reduction and material damping curves for soil.

In the Darendeli (2001) model, the shear modulus reduction curve is a hyperbola defined by:

$$\frac{G}{G_{max}} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_r}\right)^a} \tag{2.12}$$

where a is 0.9190, γ is the shear strain and γ_{ref} is the reference shear strain. The reference shear strain (not in percent) is computed from:

$$\gamma_r = \left(\frac{\sigma_0'}{p_a}\right)^{0.3483} (0.0352 + 0.0010\ PI\ OCR^{0.3246}) \tag{2.13}$$

where σ_0' is the mean effective stress and p_a is the atmospheric pressure in the same units as σ_0'. In the model, the damping ratio is calculated from the minimum damping ratio at small strains (D_{min}) and from the damping ratio associated with hysteretic Masing behavior (D_{Masing}). The minimum damping is calculated from:

$$D_{min}(\%) = (\sigma_0')^{-0.2889}(0.8005 + 0.0129\ PI\ OCR^{-0.1069})(1 + 0.2919 \ln f) \tag{2.14}$$

where f is the excitation frequency (Hz). The computation of the Masing damping requires the calculation of the area within the stress-strain curve predicted by the shear modulus reduction curve. The integration can be approximated by:

$$D_{\mathrm{Masing}}(\%) = c_1 D_{\mathrm{Masing},a=1} + c_2 D_{\mathrm{Masing},a=1}^2 + c_3 D_{\mathrm{Masing},a=1}^3 \tag{2.15}$$

where:

$$D_{\text{Masing},a=1}(\%) = \frac{100}{\pi}\left\{4\left[\frac{\gamma - \gamma_r \ln\left(\frac{\gamma+\gamma_r}{\gamma_r}\right)}{\frac{\gamma^2}{\gamma+\gamma_r}}\right] - 2\right\} \tag{2.16}$$

$$\begin{aligned} c_1 &= -1.1143a^2 + 1.8618a + 0.2533 \\ c_2 &= 0.0805a^2 - 0.0710a - 0.0095 \\ c_3 &= -0.0005a^2 + 0.0002a + 0.0003 \end{aligned} \tag{2.17}$$

The minimum damping ratio in equation (2.14) and the Masing damping in equation (2.16) are combined to compute the total damping ratio (D) using:

$$D = b\left(\frac{G}{G_{max}}\right)^{0.1} D_{Masing} + D_{min} \tag{2.18}$$

where b is defined as:

$$b = 0.6329 - 0.0057 \ln N \tag{2.19}$$

where N is the number of cycles of loading. In most site response applications, the number of cycles (N) and the excitation frequency (f) in the model are defined as 10 and 1, respectively. Figure 2.8 shows the predicted nonlinear curves for a sand (PI=0, OCR=1) at an effective confining pressure of 1 atm.

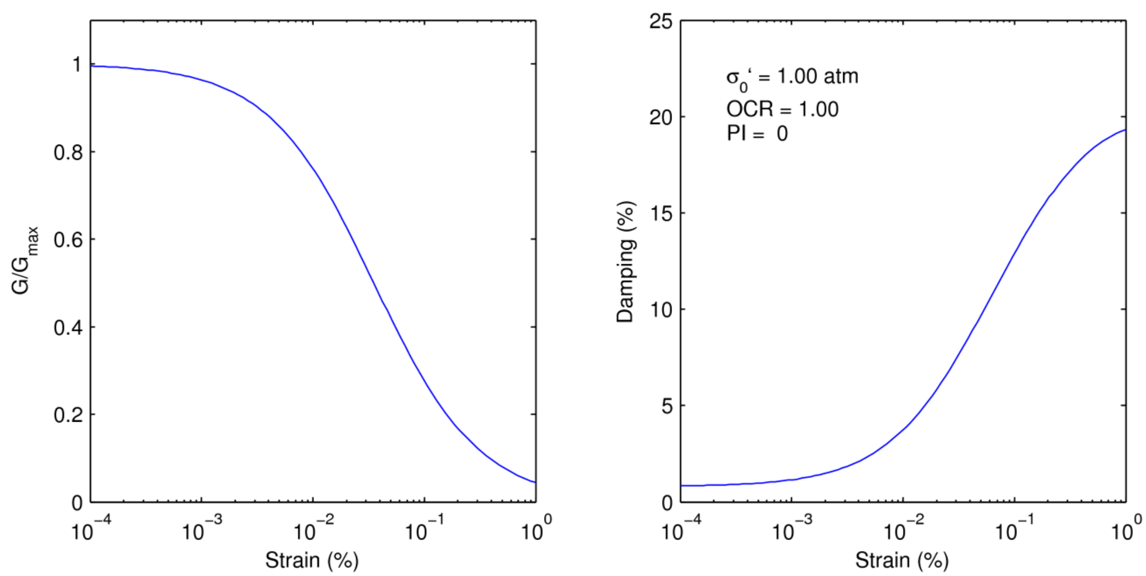


Figure 2.8: The nonlinear soil properties predicted by the Darendeli (2001) model.

A Bayesian approach was used in the Darendeli (2001) model to calculate the model coefficients. One of the unique aspects of this model is that the scatter of the data about the mean estimate is quantified. In the Darendeli (2001) model, the variability about the mean value is assumed to be normally distributed. The normal distribution is described using a mean and standard deviation. The mean values are calculated from equations (2.12) and (2.18). The standard deviation is a function of the amplitude of the nonlinear property (i.e. G/G_{max} and D). The standard deviation of the normalized shear modulus (σ_{NG}) is computed by:

$$\sigma_{NG} = \exp(-4.23) + \sqrt{\frac{0.25}{\exp(3.62)} - \frac{\left(\frac{G}{G_{\max}} - 0.5\right)^2}{\exp(3.62)}} \tag{2.20}$$

$$= 0.015 + 0.16 \cdot \sqrt{0.25 - (G/G_{max} - 0.5)^2}$$

This model results in small σ_{NG} when G/G_{max} is close to 1 or 0 and relatively large σ_{NG} when G/G_{max} is equal to 0.5. The standard deviation of the damping ratio (σ_D) is computed by:

$$\begin{aligned} \sigma_D &= \exp(-5.0) + \exp(-0.25)\sqrt{D(\%)} \\ &= 0.0067 + 0.78 \cdot \sqrt{D(\%)} \end{aligned} \tag{2.21}$$

In the damping ratio model, σ_D increases with increasing damping ratio. Using these definitions for the standard deviation, the $\pm\sigma$ modulus reduction and damping curve for sand at a confining pressure of 1 atm are shown in Figure 2.9.

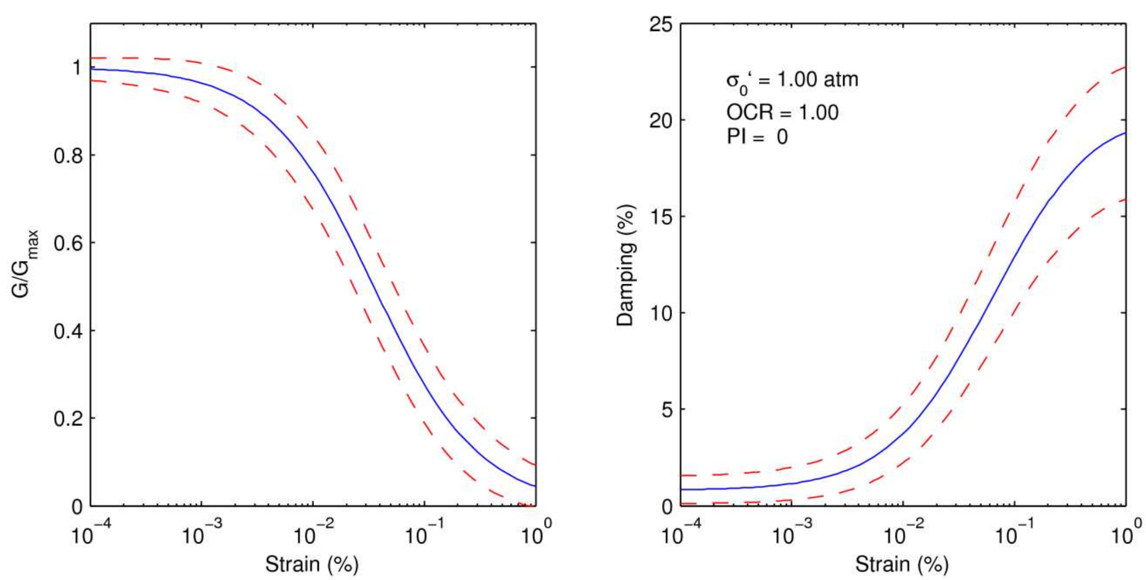


Figure 2.9: The mean and mean $\pm\sigma$ nonlinear soil properties predicted by Darendeli (2001).

2.2 Site Response Methods

The previous section introduced transfer functions which transform the input Fourier amplitude spectrum (FAS) into a FAS of strain or acceleration, and transfer functions can also be derived to compute the response of a single-degree-of-freedom oscillator. In both the time domain and random vibration theory methods, the same transfer functions are applied to the input FAS. The difference in the methods is in how this FAS in the frequency domain is converted into time domain information.

2.2.1 Time Series Method

In the time series method, an input acceleration-time history is provided and the input FAS is computed from that time series using the fast Fourier transform (FFT) to compute the discrete Fourier transformation on the provided time series. The computed FAS is complex valued, and can be converted into amplitude and phase information. Strata uses the free and open-source FFTW library (http://www.fftw.org). The inverse discrete Fourier transform is used to compute a time series for a given FAS. The details of the FFT process are not discussed here, but can be found on the FFTW webpage.

In Strata, the time series is padded with zeros to obtain a number of points that is a power of two. If a time series contains a power of two values, then it is padded with zeros until the next power of two.

After the FAS of the motion has been computed it is possible to perform site response analysis with the motion. The following is a summary of the steps to compute the surface acceleration time-series for the site described in Table 2.1 (after Kramer 1996):

1. Read the acceleration-time series file (Figure 2.10a).
2. Compute the input FAS with the Fast Fourier transformation (FFT) (Figure 2.10b, only amplitude is shown).
3. Compute the transfer function for the site properties (Figure 2.10c, only amplitude is shown).
4. Compute the surface FAS by applying the transfer function to the input FAS (Figure 2.10d, only amplitude is shown).
5. Compute the surface acceleration-time series through the inverse FFT of the surface FAS (Figure 2.10e).

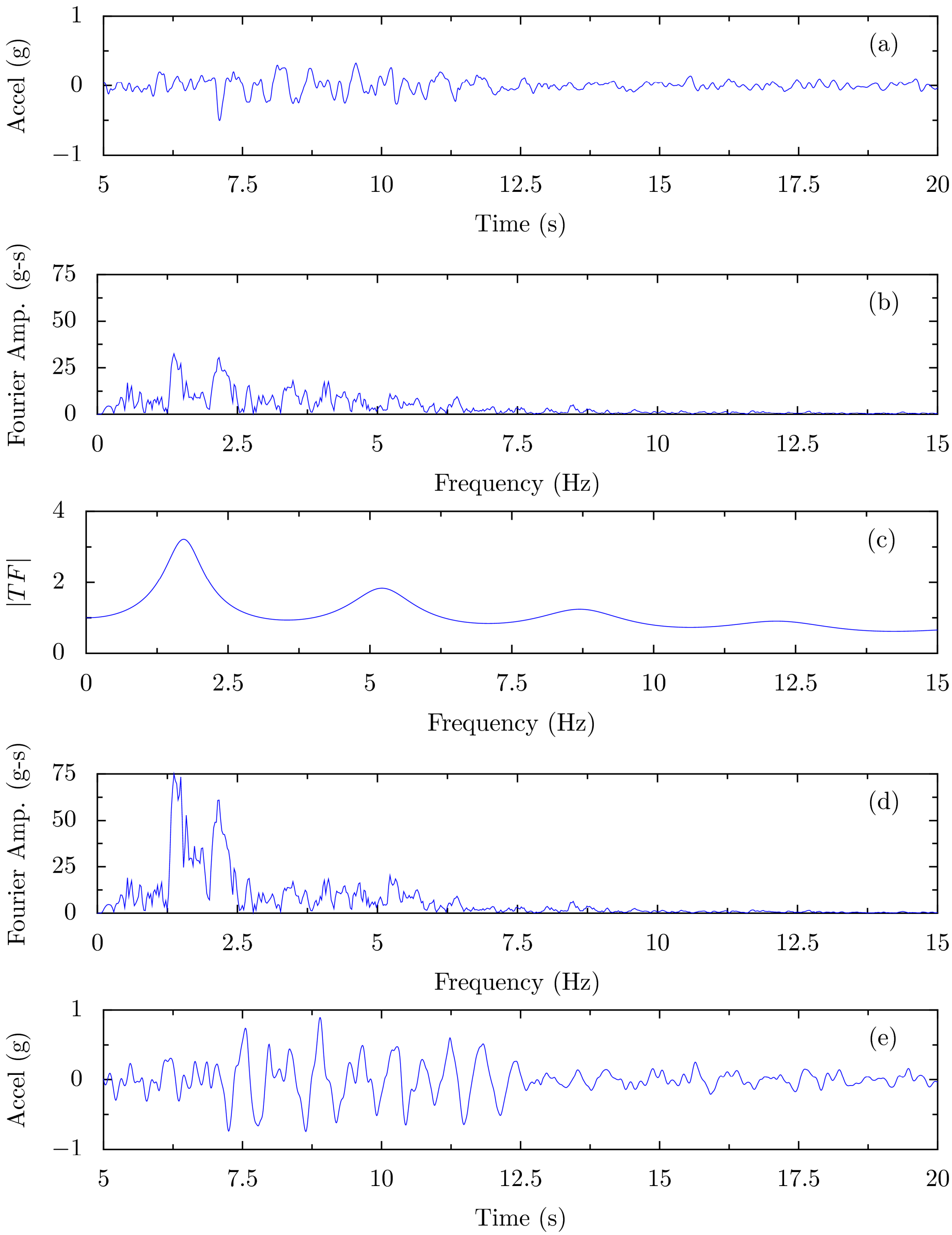


Figure 2.10: Time domain method sequence: (a) input acceleration-time series, (b) input Fourier amplitude spectrum, (c) transfer function from input to surface, (d) surface Fourier amplitude spectrum, and (e) surface acceleration-time series (after Kramer 1996).

2.2.2 **Random Vibration Theory Method**

The random vibration theory (RVT) approach to site response analysis was first proposed in the engineering seismology literature (e.g. Schneider et al. (1991)) and has been applied to site response analysis (Silva et al. 1997, Rathje and Ozbey 2006, Rathje and Kottke 2008). RVT does not utilize time domain input motions, but rather initiates all computations with the input FAS (amplitude only, no phase information). Because RVT does not have the accompanying phase angles to the Fourier amplitudes, a time history of motion cannot be computed. Instead, extreme value statistics are used to compute peak time domain parameters of motion (e.g. peak ground acceleration, spectral acceleration) from the Fourier amplitude information. Due to RVT's stochastic nature one analysis can provide a median estimate of the site response with a single analysis and without the need for time domain input motions.

2.2.2.1 RVT Basics

Random vibration theory can be separated into two parts: (1) conversion between time and frequency domain using Parseval's theorem, and (2) estimation of the peak factor using extreme value statistics. Consider a time varying signal $x(t)$ with its associated Fourier amplitude spectrum, $X(f)$. The root-mean-squared value of the signal (x_{rms}) is a measure of its average value over a given time period, T_{rms}, and is computed from the integral of the times series over that time period:

$$x_{rms} = \sqrt{\frac{1}{T_{rms}} \int_0^{T_{rms}} [x(t)]^2 dt} \tag{2.22}$$

Parseval's theorem relates the integral of the time series to the integral of its Fourier Transform, such that equation (2.22) can be written in term of the FAS of the signal:

$$x_{rms} = \sqrt{\frac{2}{T_{rms}} \int_0^{\infty} |X(f)|^2 df} = \sqrt{\frac{m_0}{T_{rms}}} \tag{2.23}$$

where m_0 is defined as the zero-th moment of the FAS. The N-th moment of the FAS is defined as:

$$m_n = 2 \int_0^{\infty} (2\pi f)^n |X(f)|^2 df \tag{2.24}$$

The peak factor (*PF*) represents the ratio of the maximum value of the signal (x_{max}) to its *rms* value (x_{rms}), such that if x_{rms} and the *PF* are known, then x_{max} can be computed using:

$$x_{max} = PF \cdot x_{rms} \tag{2.25}$$

Cartwright and Longuet-Higgins (1956) studied the statistics of ocean wave amplitudes, and considered the probability distribution of the maxima of a signal to develop expressions for the *PF* in terms of the characteristics of the signal. Cartwright and Longuet-Higgins (1956) derived an integral expression for the expected values of the peak factor in terms of the number of extrema (N_e) and the bandwidth (ξ) of the time series (Boore 2003):

$$E[PF] = \sqrt{2}\int_0^\infty 1 - \left[1 - \xi e^{-z^2}\right]^{N_e} dz \tag{2.26}$$

where the bandwidth is defined as:

$$\xi = \sqrt{\frac{m_2^2}{m_0 m_4}} \tag{2.27}$$

and the number of extrema is defined as:

$$N_e = \frac{T_{gm}}{\pi}\sqrt{\frac{m_4}{m_2}} \tag{2.28}$$

Boore (2003) illustrated the need to modify the duration used in the *rms* calculation when considering requires modification for spectral acceleration to account for the enhanced duration due to the oscillator response. Generally, adding the oscillator duration to the ground motion duration will suffice, except in cases where the ground motion duration is short (Boore & Joyner, 1984). Boore and Joyner (1984) recommend the following expressions to define T_{rms}:

$$T_{rms} = T_{gm} + T_0\left(\frac{\gamma^n}{\gamma^n + \alpha}\right) \tag{2.29}$$

$$\gamma = \frac{T_{gm}}{T_n} \tag{2.30}$$

$$T_0 = \frac{T_n}{2\pi\beta} \tag{2.31}$$

where T_0 is the oscillator duration, T_n is the oscillator natural period, and β is the damping ratio of the oscillator. Based on numerical simulations, Boore and Joyner (1984) proposed n=3 and α=1/3 for the coefficients in equation (2.29).

2.2.2.2 Defining the Input Motion

The input motion in an RVT analysis is defined by a Fourier amplitude spectrum (FAS) and ground motion duration (Tgm). The FAS can be directly computed using seismological source theory (e.g (Brune, 1970, 1971)), or it can be back-calculated from an acceleration response spectrum (see Section 2.2.2.24). When the FAS is directly provided, the frequencies provided with the Fourier amplitude spectrum represent the frequency range used by the program so it is critical that enough points be provided.

Calculation of the duration for use in RVT analysis can be done using seismological theory or empirical models. Boore (2003) recommends the following description of ground motion duration (T_{gm}) for the Western United States using seismological theory:

$$T_{gm} = \underbrace{\frac{1}{f_0}}_{\substack{\text{Source} \\ \text{duration, } T_s}} + \underbrace{0.05R}_{\substack{\text{Path} \\ \text{duration, } T_p}} \tag{2.32}$$

where *R* is the distance in km, and the corner frequency (f_0) in hertz is given by:

$$f_0 = 4.9 \cdot 10^6 \beta_s \left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}} \tag{2.33}$$

where $\Delta\sigma$ is the stress drop in bar, β_s is the shear-wave velocity in units of km/s, and M_0 is the seismic moment in units of dyne-cm (Brune, 1970). The seismic moment (M_0) is related to the moment magnitude (M_w) by:

$$M_0 = 10^{\frac{3}{2}(M_w + 10.7)} \tag{2.34}$$

For the Eastern United States, Campbell (1997) proposes that the path duration effect be distance dependent:

$$T_p = \begin{cases} 0, R \leq 10km \\ 0.16R, 10km < R \leq 70km \\ -0.03R, 70\ km < R \leq 130km \\ 0.04R, R > 130km \end{cases} \tag{2.35}$$

Empirical ground motion duration models such as Abrahamson and Silva (1996) can also be used to estimate the duration of the scenario event (T_{gm}). When such a model is applied, it is recommended that T_{gm} be taken as time between the build up from 5% to 75% of the normalized arias intensity ($D_{5\text{-}75}$).

2.2.2.3 Source Theory Model

Strata provides functionality for the calculation of a single-corner frequency ω^2 point source model originally proposed by Brune (1970) and more recently discussed in Boore (2003). The default values for the Western United States and the Central and Eastern United States are taken from Campbell (1997).

2.2.2.4 *Calculation of a FAS from an Acceleration Response Spectrum*

The input rock FAS ($Y(f)$) can be derived from an acceleration response spectrum using an inverse technique. The inversion technique follows the basic methodology proposed by Gasparini and Vanmarcke (1976) and further described by Rathje et al. (2005). The inversion technique makes use of the properties of the single-degree-of-freedom (SDOF) transfer function used to compute the response spectral values. The square of the Fourier amplitude at the SDOF oscillator natural frequency f_n ($|Y(f_n)|^2$) can be written in terms of the spectral acceleration at f_n (S_{a,f_n}), the peak factor (*PF*), the *rms* duration of the motion (T_{rms}), the square of the Fourier amplitudes ($|Y(f)|^2$) at frequencies less than the natural frequency, and the integral of the SDOF transfer function ($\left|H_{f_n}(f)\right|^2$):

$$|Y(f_n)|^2 \cong \frac{1}{\int_0^\infty \left|H_{f_n}(f)\right|^2 df - f_n}\left(\frac{T_{\mathrm{rms}}}{2}\frac{S_{a,f_n}^2}{PF^2} - \int_0^{f_n} |Y(f)|^2 df\right) \tag{2.36}$$

Within equation (2.36), the integral of the transfer function is constant for a given natural frequency and damping ratio (β), allowing the equation to be simplified to (Gasparini & Vanmarcke, 1976):

$$|Y(f_n)|^2 \cong \frac{1}{f_n\left(\frac{\pi}{4\beta} - 1\right)}\left(\frac{T_{\mathrm{rms}}}{2}\frac{S_{a,f_n}^2}{PF^2} - \int_0^{f_n} |Y(f)|^2 df\right) \tag{2.37}$$

The peak factors in equation (2.37) depend on the moments of the FAS, which is currently undefined. So the peak factors for all natural frequencies are initially assumed to be 2.5.

Equation (2.37) is applied first to the spectral acceleration of the lowest frequency (longest period) provided by the user. At this frequency, the FAS integral term in equation (2.37) can be assumed to be equal to zero. The equation is then applied at successively higher frequencies using the previously computed values of $|Y(f_n)|$ to assess the integral.

To improve the agreement between the RVT-derived response spectrum ($S_a^{\mathrm{RVT}}(f)$) and the target response spectrum ($S_a^{\mathrm{Target}}(f)$), the RVT-derived FAS is corrected by multiplying it by the ratio of the two response spectra. This iterative process corrects the FAS from iteration *i* ($|Y_i(f)|$) using:

$$\left|Y_{(i+1)}(f)\right| = \frac{S_a^{\mathrm{RVT}}(f)}{S_a^{\mathrm{Target}}(f)} \cdot |Y_i(f)| \tag{2.38}$$

Additionally, the newly defined FAS is used to compute appropriate peak factors for each frequency. The full procedure used to generate a corrected FAS is:

1. Initial FAS is computed using the Gasparini and Vanmarcke (1976) technique (Equation 2.37).
2. The acceleration response spectrum associated with this FAS is computed using RVT.
3. The FAS is corrected using equation (2.38).
4. The peak factors are updated.

5. Using the corrected FAS and new peak factors, a new acceleration response spectrum is calculated.

This process is repeated until one of three conditions is met:

1. maximum of 30 iterations,
2. a root-mean-square-error of 0.005 is achieved between the RVT response spectrum and the target response spectrum, or
3. change in the root-mean-square-error is less than 0.001.

This ratio correction works very well in producing a FAS that agrees with the target response spectrum, but the resulting FAS may have an inappropriate shape at some frequencies, as discussed below.

To demonstrate the inversion process, consider a scenario event of magnitude 7 at a distance of 20 km. The target response spectrum is computed using the Abrahamson and Silva (1997) attenuation model (Figure 2.11). An initial estimate of the FAS is computed using the Gasparini and Vanmarcke (1976) method and then the ratio correction algorithm is applied. This methodology (called “Ratio Corrected”) results in good agreement with the target response spectrum (Figure 2.11), with less than 5% relative error as shown in Figure 2.12. However, the associated FAS slopes up at low and high frequencies (Figure 2.13). The sloping up at low frequencies can be mitigated by extending the frequency domain because the spectral acceleration at a given frequency is affected by a range of frequencies in the FAS.

The frequency domain extension involves expanding frequencies to half of the minimum frequency and twice the maximum frequency specified in the target response spectrum. For example, if the target response spectrum is provided from 0.2 to 100 Hz (5 to 0.01 seconds), then the frequencies of the FAS are defined at points equally spaced in log space from 0.1 to 200 Hz. The resulting response spectrum essentially displays the same agreement with the target response spectrum (curve labeled ``Ratio and Extrapolated'' in Figures 2.11 and 2.12), but the FAS shows no sloping up at low frequencies and less sloping up at high frequencies (Figure 2.13).

While the results in Figures 2.11-2.13 would appear to be adequate, it was observed that the sloping up at high frequencies was affecting the RVT calculation. The peak factor depends on the 4th moment of the FAS (Equations 2.27, 2.28), which is more sensitive to higher frequencies. Additionally, seismological theory indicates that the slope of the FAS at high frequencies should be increasingly negative due to a path-independent loss of the high-frequency motion (Boore 2003). To deal with these issues, the slope of the FAS at high frequencies is forced down (curve labeled “Ratio, Extrap., & Slope Forced” in Figure 2.13). The corrected portion of the FAS is computed through linear extrapolation in log-log space from where the slope deviates from its steepest value by more than 5%. This solution results in a slight under prediction (~3%) of the peak ground acceleration (Figure 2.11 and Figure 2.12).

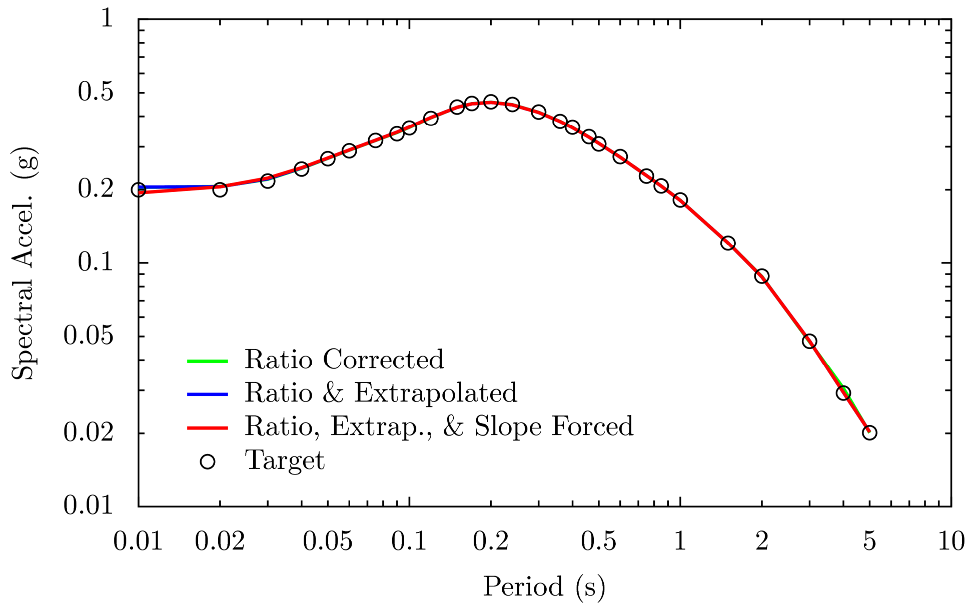


Figure 2.11: The comparison between the target response spectrum and the response spectrum computed with RVT.

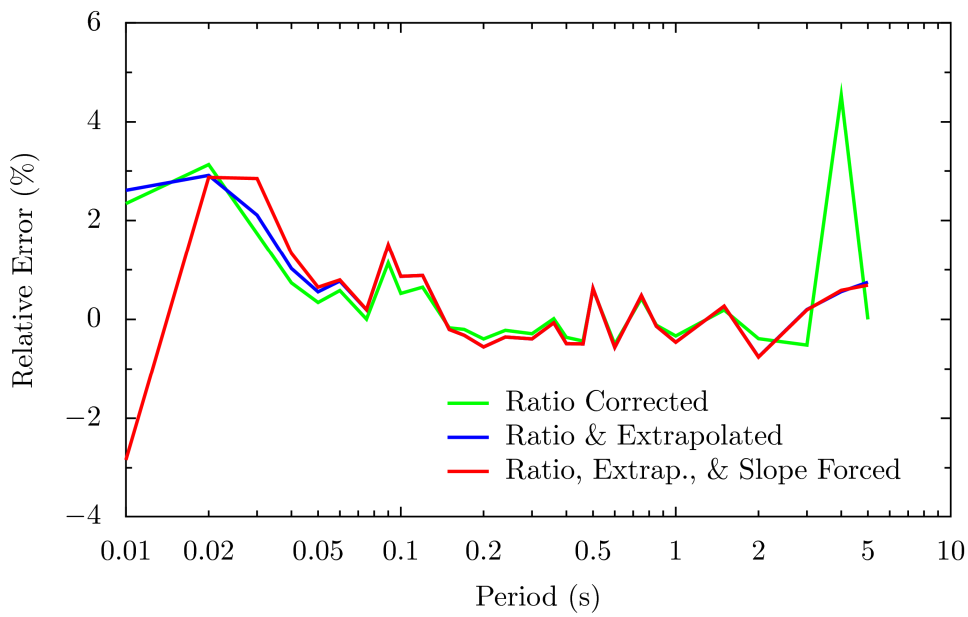


Figure 2.12: The relative error between the computed response spectra and the target response spectrum.

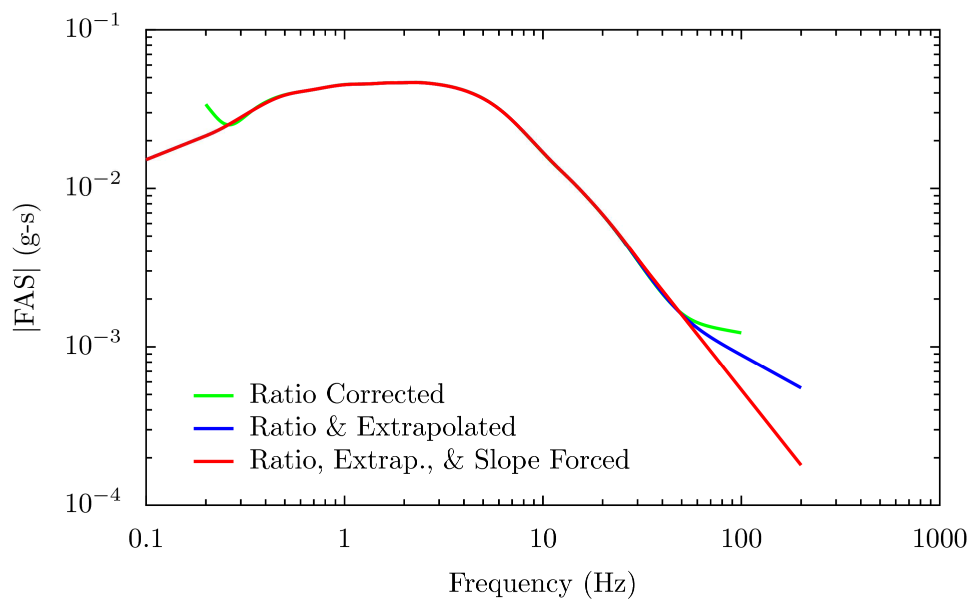


Figure 2.13: The FAS computing through the inversion process.

2.2.2.5 Example of the RVT Procedure

The following is an example of random vibration theory applied to site response analysis to estimate the peak acceleration at the top of the site described in Table 2.1: The earthquake scenario is a magnitude 7 event at a distance of 20 km, as described in the previous section.

1. Empirical relationships are used to specify the input rock response spectrum (Figure 2.11) and ground motion duration ($T_{gm} = D_{5-75} = 8.2$ s).
2. Using the inversion technique, the FAS corresponding to the target response spectrum is computed (Figure 2.14a). In this example, the peak acceleration of the input motion is computed with RVT to allow for a comparison in the peak response between the surface and the input. The RVT calculation results are shown in Table 2.2.

Table 2.2: The values of the RVT calculation for the input motion.

Parameter	**Value**	**Equation**
Moments of FAS (m_0, m_2, m_4)	0.0280, 93.84, 1.738x10^7	2.28
Bandwidth	0.1346	2.31
Number of extrema (N_e)	1123	2.32
Peak factor (PF)	3.325	2.30
Root-mean-square acceleration (a_{rms})	0.0584 g	2.27
Expected peak acceleration from RVT (a_{max})	0.1942g	2.29
Target peak acceleration (*PGA)*	0.20 g	---

3. Compute the transfer function for the site properties (Figure 2.14b).
4. Compute the surface FAS by applying the absolute value of the transfer function to the input FAS (Figure 2.14c). Using the surface FAS, the expected peak acceleration can be computed using RVT, as presented in Table 2.3. The calculation shows that the site response increases the peak ground acceleration by approximately 38%.

Table 2.3: The values of the RVT calculation for the surface motion.

Parameter	**Value**	**Equation**
Moments of FAS (m_0, m_2, and m_4)	0.0635, 39.6356, and 1.6306x10^7	2.28
Bandwidth	0.3895	2.31
Number of extrema (N_e)	167.414	2.32
Peak factor (PF)	3.0588	2.30
Root-mean-square acceleration (a_{rms})	0.0880 g	2.27
Expected maximum accleration (a_{max})	0.2692 g	2.29

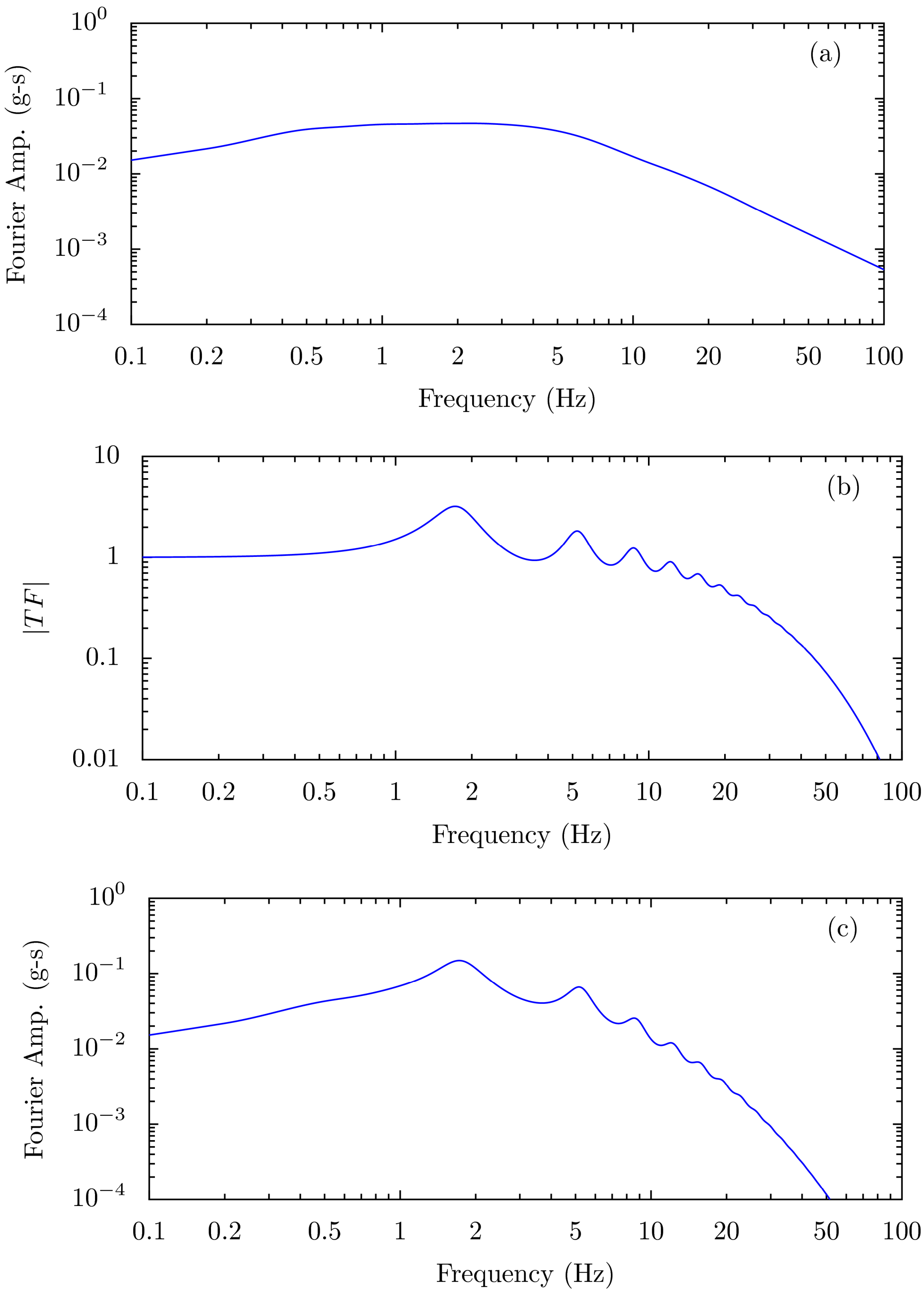


Figure 2.14: RVT method sequence: (a) input Fourier amplitude spectrum, (b) transfer function from input to surface, and (c) surface Fourier amplitude spectrum.

3 Variation of Site Properties

3.1 Introduction

A soil profile consists of discrete layers that vary in thickness based on the properties of the soil. The layers are typically discretized based on the soil type, recorded from borehole samples or inferred from a shear-wave velocity profile. In seismic site response analysis, each layer is characterized by a thickness, mass density, shear-wave velocity, and nonlinear properties (G/G_{max}, and D). One of the challenges in defining values for these properties is the natural variability across a site and the uncertainty in their measurement. Because the dynamic response of a site is dependent on the soil properties, any variation in the soil properties will change both the expected surface motion and its standard deviation.

In a simple system, the variability of the components can be analytically combined to quantify the variability of the complete system, thus allowing for the expected value and variability of the system response to be computed. In seismic site response analysis, the nonlinear response of the system does not allow an exact analytic quantification of the variability of the site response. Instead, an estimate of the expected surface response and its standard deviation due to variations in the soil properties can be made through Monte Carlo simulations. Monte Carlo simulations estimate the response of a system by generating parameters of the system based on defined statistical distributions and computing the response for each set of input parameters. The following chapter introduces Monte Carlo simulations as applied to site response analysis and presents the models that describe the variability of the layering, shear-wave velocity, and nonlinear properties (G/G_{max} and D).

3.2 Random Variables

The goal of a Monte Carlo simulation is to estimate the statistical properties of the response of a complex system. To achieve this goal, each of the properties of the system is selected from defined statistical distributions and the response of the system is computed. The response is computed for many realizations and the calculated response from each realization is then used to estimate statistical properties of the system's response. While Monte Carlo simulations can be used on a wide variety of problems, a major disadvantage is that a large number of simulations is required to achieve stable results.

Monte Carlo simulations require that each of the components in the system has a complete statistical description. The description can be in the form of a variety of statistical distributions (i.e. uniform, triangular, normal, log-normal, exponential, etc.), however the normal and log-normal distributions typically are used because they can be easily described using a mean (μ) and standard deviation (σ). For normally distributed variables, a random value (*x*) can be generated by:

$$x = \mu_x + \sigma_x \varepsilon \tag{3.1}$$

where μ_x is the mean value, σ_x is the standard deviation, and ε is a random variable with zero mean and unit standard deviation. Random values of ε are generated and used to define the random values of x.

To generate multiple random variables that are independent, Equation 3.1 can be used for each variable with different, random values of ε generated for each variable. In the case of correlated random variables, a more complicated procedure is required for the generation of values. The correlation between variables is quantified through the correlation coefficient (ρ). The correlation coefficient can range from -1 to 1. Uncorrelated variables have ρ=0 (Figure 3.2a). Positive correlation between variables indicates that the two variables have a greater tendency to both differ from their respective mean values in the same direction (Figure 3.1b). As ρ approaches 1.0, this correlation becomes stronger. Negative correlation indicates that variables have a greater tendency to differ in the opposite direction (Figure 3.2c).

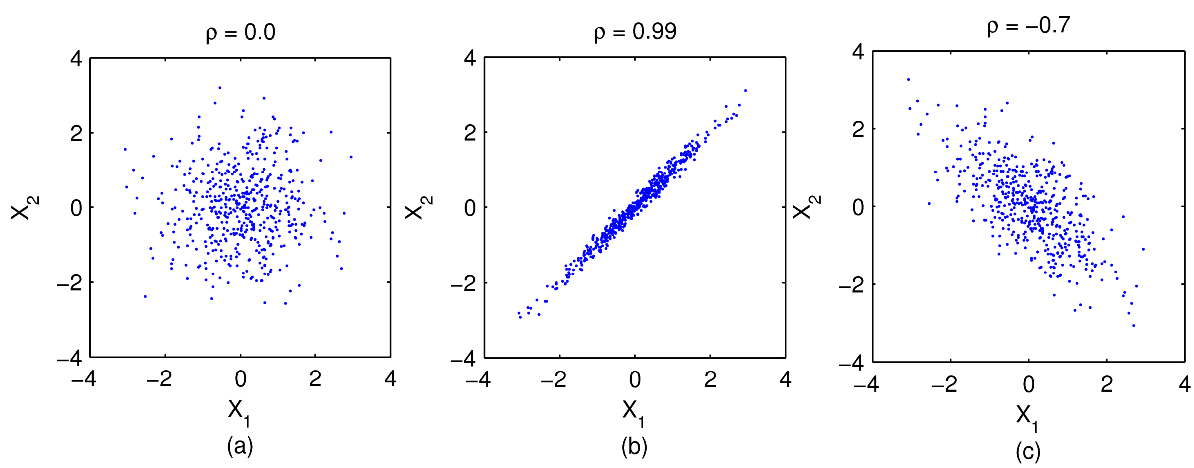


Figure 3.1: Two variables with a correlation coefficient of: (a) 0.0, (b), 0.99, and (c) -0.7.

As discussed previously, independent random variables from a normal distribution are generated by applying equation (3.1) independently to each random variable. By combining the multiple applications of equation (3.1) into a system of equations, the generation of two independent variables is achieved by multiplying a vector of random variables ($\vec{\varepsilon}$) by a matrix ($[\sigma]$) and adding a constant ($\vec{\mu}$), defined as:

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} \sigma_{X_1} & 0 \\ 0 & \sigma_{X_2} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \mu_1 \\ \mu_2 \end{Bmatrix} \tag{3.2}$$

where ε_1 and ε_2 are random variables randomly selected from a standard normal distribution ($\mu = 0$ and $\sigma = 1$), σ_{X_1} and σ_{X_2} are the standard deviations of x_1 and x_2, respectively, and μ_1 and μ_2 are the mean values of X_1 and X_2, respectively. Because the random variables x_1 and x_2 are independent ($\rho_{X_1,X_2} = 0$), the off-diagonal values in the matrix ($[\sigma]$) are zero.

Using the same framework, a linear system of equations is used to generate a pair of correlated random variables. However, the off diagonal values in the matrix are no longer be zero because of the correlation between X_1 and X_2. Instead, a pair of correlated random variables ($\vec{x}$) is generated by (Kao, 1997):

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} \sigma_{X_1} & 0 \\ \rho_{X_1,X_2}\sigma_{X_2} & \sigma_{X_2}\sqrt{1-\rho_{X_1,X_2}^2} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \mu_1 \\ \mu_2 \end{Bmatrix} \tag{3.3}$$

Here, the first random variable (x_1) is calculated based on the value of ε_1 alone, while the second random variable (x_2) is a function of both ε_1 and ε_2. Note that ε_1 and ε_2 still represent random and independent variables generated from the standard normal distribution.

3.3 Statistical Models for Soil Properties

For the properties of the soil to be randomized and incorporated into Monte Carlo simulations, the statistical distribution and properties of the soil need to be characterized. In this research, two separate models are used. The first model, developed by Toro (1995), describes the statistical distribution and correlation between layering and shear-wave velocity. The second model by Darendeli (2001) was previously introduced in Section 2.1.3 and is used to describe the statistical distribution of the nonlinear properties (G/G_{max} and *D*).

3.3.1 Layering and Velocity Model

In Strata, the randomization of the layering and the shear-wave velocity is done through the use of the models proposed by Toro (1995). The Toro (1995) models provide a framework for generating layering and then to vary the shear-wave velocity of these layers. The model for shear wave velocity variation improves upon previous work by quantifying the correlation between the velocities in adjacent layers. In previous models, one of two assumptions were made that simplified the problem: the velocities at all depths are perfectly correlated and can be randomized by applying a constant random factor to all velocities (McGuire et al. 1989; Toro et al. 1992), or the velocities within each of the layers are independent of each other, and therefore can be randomized by applying an independent random factor to each layer (Costantino el al. 1991). While these two assumptions simplify the problem, they represent two extreme conditions. The Toro (1995) model makes neither of these assumptions; instead the model incorporates correlation between layers.

3.3.1.1 Layering Model

The layering is modeled as a Poisson process, which is a stochastic process with events occurring at a given rate (λ). For a homogeneous Poisson process this rate is constant, while for a non-homogeneous Poisson process the rate varies. Generally, a Poisson process models the occurrence of events over time, but for the layering problem the event is a layer interface and its rate is defined in terms of length (i.e., number of layer interfaces per meter).

In the Toro (1995) model, the layering thickness is modeled as a non-homogeneous Poisson process where the rate changes with depth ($\lambda(d)$, where *d* is depth from the ground surface). Before considering the non-homogeneous Poisson process, first consider the simpler homogeneous Poisson process with a constant rate. For a Poisson process with a constant occurrence rate (λ), the distance between layer boundaries, also called the layer thickness (*h*), has an exponential distribution with rate λ. The probability density function of an exponential distribution is defined as (Ang & Tang, 1975):

$$f(h;\lambda) = \begin{cases} \lambda \exp(-\lambda h), h \geq 0 \\ 0, h < 0 \end{cases} \tag{3.4}$$

The cumulative density function for the exponential distribution is given by:

$$F(h;\lambda) = \begin{cases} 1 - \exp(-\lambda h), h \geq 0 \\ 0, h < 0 \end{cases} \tag{3.5}$$

A random layer thickness with an exponential distribution is generated by solving equation (3.5) with respect to thickness (*h*):

$$h = \frac{\ln[1 - F(h)]}{-\lambda}, \text{for } 0 < F(h) \leq 1 \tag{3.6}$$

By randomly generating probabilities (*F*(*h*)) with a uniform distribution between 0 and 1 and computing the associated thicknesses with equation (3.6), a layering profile was simulated for 10 layers with $\lambda = 1$ (Figure 3.2). An exponential distribution with $\lambda = 1$ will be referred to as a unit exponential distribution.

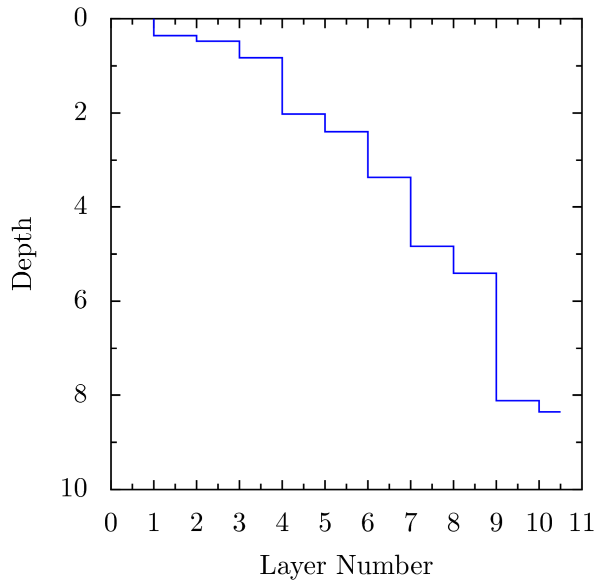


Figure 3.2: A 10 layer profile modeled by a homogeneous Poisson process with λ = 1.

Another way to think about generating exponential variables with a specific rate is to first generate a series of random variables with a unit exponential distribution and then convert them to a specific rate by dividing by the rate (see equation (3.6)). This process is shown graphically in FIGURE 3.3: TRANSFORMING FROMA CONSTANT RATE OF λ = 1 TO A CONSTANT RATE OF λ = 0.2.Figure 3.3 and the associated layering is shown in Figure 3.4. In this example, the thicknesses (and depth) for λ = 1.0 (unit rate) are transformed to thicknesses (and depth) for λ = 0.2 (transformed rate). Here, each thickness is increased by a factor of 5.0 (1/ λ). A similar technique is used to transform random variables generated with a unit exponential distribution into a non-homogenous Poisson process.

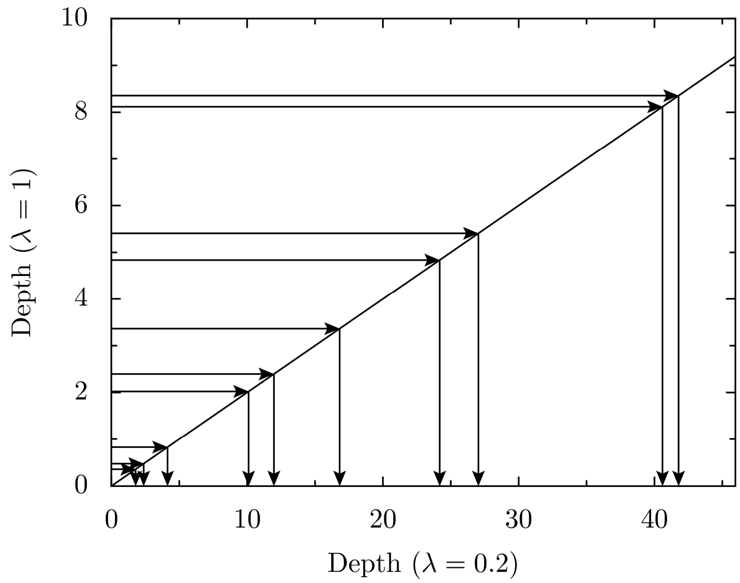


Figure 3.3: Transforming froma constant rate of λ = 1 to a constant rate of λ = 0.2.

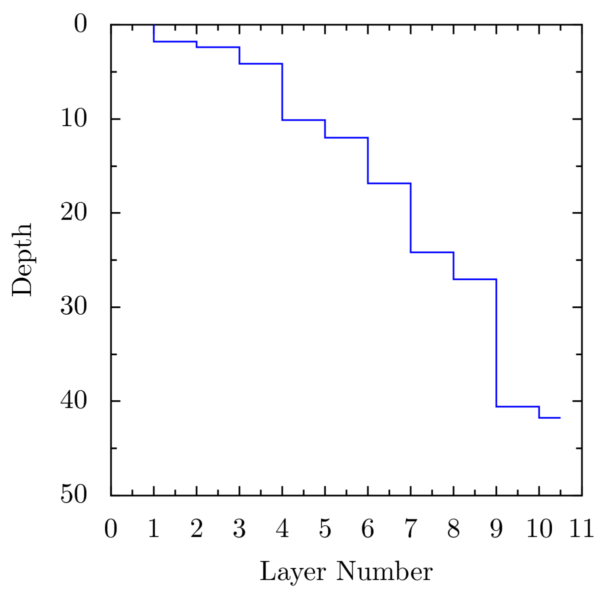


Figure 3.4: A 10 layer profile modeled by a homogeneous Poisson process with λ = 0.2.

For a non-homogeneous Poisson process with rate $\lambda(d)$ the cumulative rate ($\Lambda(d)$) is defined as (Kao, 1997):

$$\Lambda(d) = \int_0^d \lambda(s)ds \tag{3.7}$$

$\Lambda(d)$ represents the expected number of layers up to a depth ***d***. To understand the cumulative rate, consider a homogeneous Poisson process with a constant rate λ (i.e., $\lambda(s) = \lambda$). In this case, equation (3.7) simplifies to $\Lambda(d) = \lambda d$. For $\lambda = 1.0$ (unit rate), $\Lambda(d) = d$, such that the expected number of layers is simply equal to the depth. For $\lambda = 0.2$ (transformed rate), $\Lambda(d) = 0.2 \cdot d$, such that the expected number of layers is one-fifth the value of the unit rate because the layers are five times as thick. This warping of the unit rate into a constant rate of 0.2 is represented by the straight line shown in Figure 3.3.

Transforming between the y-axis and x-axis in Figure 3.3 requires the inverse of the cumulative rate function. For the homogenous case, $\Lambda^{-1}(u) = u/\lambda$, where u is the depth from an exponential distribution with $\lambda = 1.0$. For the non-homogenous case, the inverse cumulative rate function is used to convert from a depth profile for $\lambda = 1.0$ (generated by a series of unit exponential random variables, u) to depth profile with a depth dependent rate. Before $\Lambda^{-1}(u)$ can be defined for the non-homogenous process, $\Lambda(d)$ and $\lambda(d)$ must be defined.

Toro (1995) proposed the following generic depth dependent rate model:

$$\lambda(d) = a \cdot (d + b)^c \tag{3.8}$$

The coefficients *a*, *b*, and *c* were estimated by Toro (1995) using the method of maximum likelihood applied to the layering measured at 557 sites, mostly from California. The resulting values of *a*, *b*, and *c* are 1.98, 10.86, and -0.89, respectively. The occurrence rate ($\lambda(d)$) quickly decreases as the depth increases (Figure 3.5a). This decrease in the occurrence rate increases the expected thickness of deeper layers. The expected layer thickness (*h*) is equal to the inverse of the occurrence rate ($h = 1/\lambda(d)$) and is shown in Figure 3.5b. The expected thickness ranges from 4.2 m at the surface to 59 m at a depth of 200 m.

Using equations (3.7) and (3.8), the cumulative rate for the Toro (1995) modeled is defined as:

$$\Lambda(d) = \int_0^d a \cdot (s + b)^c ds = a \cdot \left[\frac{(d + b)^{c+1}}{c + 1} - \frac{b^{c+1}}{c + 1}\right] \tag{3.9}$$

The inverse cumulative rate function is then defined as:

$$\Lambda^{-1}(\mathrm{u}) = \left(\frac{\mathrm{cu}}{\mathrm{a}} + \frac{\mathrm{u}}{\mathrm{a}} + \mathrm{b}^{\mathrm{c}+1}\right)^{\frac{1}{\mathrm{c}+1}} - \mathrm{b} \tag{3.10}$$

Using this equation a homogeneous Poisson process with $\lambda = 1.0$ (Figure 3.2) can be warped into a non-homogeneous Poisson process as shown in Figure 3.6. The resulting depth profile is shown in Figure 3.7.

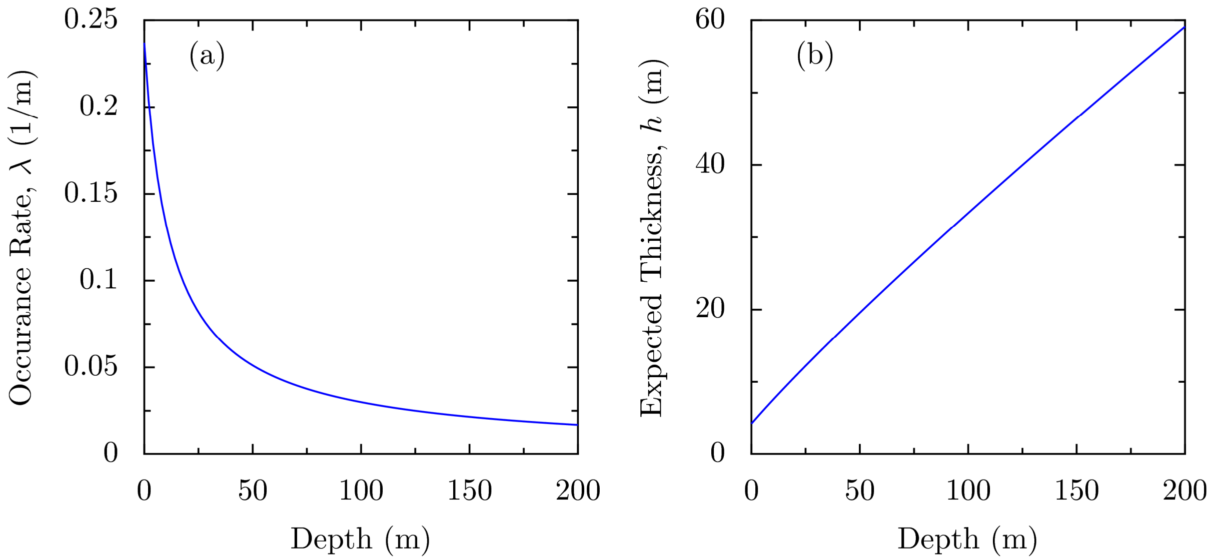


Figure 3.5: Toro (1995) layering model. (a) The occurrence rate (λ) as a function of depth (*d*), and (b) the expected layer thickness (*h*) as a function of depth.

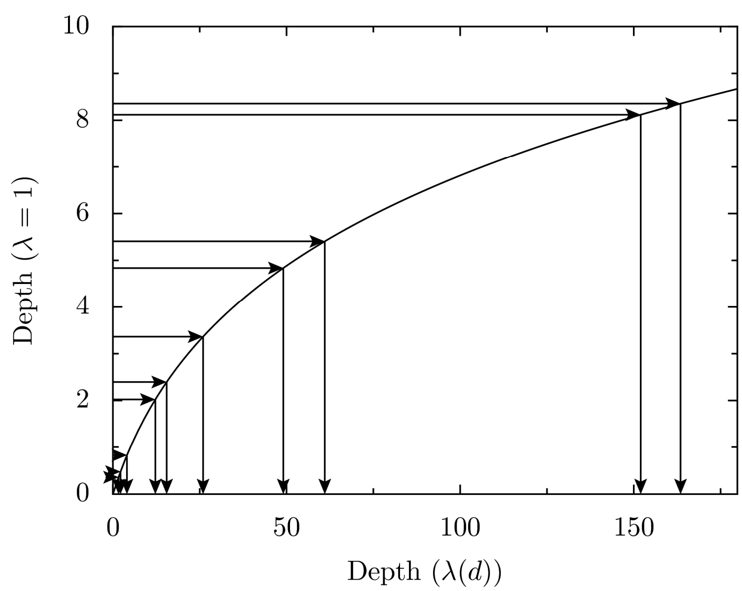


Figure 3.6: Transformation between a homogeneous Poisson process with rate 1 to the Toro (1995) non-homogeneous Poisson process.

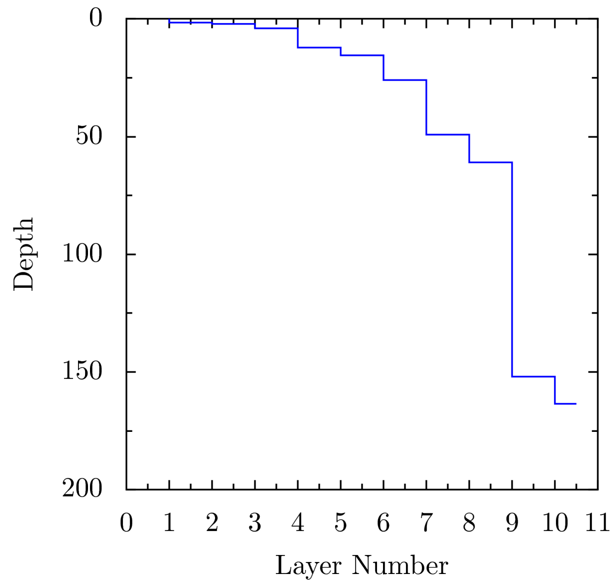


Figure 3.7: A layering simulated with the non-homogeneous Poisson process defined by Toro (1995).

3.3.1.2 Velocity Model

After the layering of the profile has been established, the shear-wave velocity profile can be generated by assigning velocities to each layer. In the Toro (1995) model, the shear-wave velocity at mid-depth of the layer is described by a log-normal distribution. The standard normal variable (*Z*) of the ith layer is calculated by:

$$Z_i = \frac{\ln V_i - \ln[V_{\text{median}}(d_i)]}{\sigma_{\ln V_s}} \tag{3.11}$$

where V_i is the shear-wave velocity in the ith layer, $V_{\text{median}}(d_i)$ is the median shear-wave velocity at mid-depth of the layer and $\sigma_{\ln V_s}$ is the standard deviation of the natural logarithm of the shear-wave velocity. Equation (3.11) is then solved for the shear-wave velocity of the ith layer (V_i):

$$V_i = \exp\{\sigma_{ln\,V_s} \cdot Z_i + ln[V_{median}(d_i)]\} \tag{3.12}$$

Equation (3.12) allows for the calculation of the velocity within a layer for a given median velocity at the mid-depth of the layer, standard deviation, and standard normal variable. In the model proposed by Toro (1995), values for median velocity versus depth ($V_{median}(d_i)$) and standard deviation ($\sigma_{ln\,V_s}$) are provided based on site class. However, in the implementation of the Toro (1995) model in Strata the median shear-wave velocity is defined by the user. Additionally, Strata includes the ability to truncate the velocity probability density function by specifying minimum and maximum values. The standard normal variable of the ith layer (Z_i) is correlated with the layer above it, and this inter-layer correlation is also dependent on the site class. The standard normal variable (Z_i) of the shear-wave velocity in the top layer (*i*=1) is independent of all other layers and is defined as:

$$Z_1 = \varepsilon_1 \tag{3.13}$$

where ε_1 is an independent normal random variable with zero mean and a unit standard deviation. The standard normal variables of the other layers in the profile are calculated by a recursive formula, defined as:

$$Z_i = \rho Z_{i-1} + \varepsilon_i \sqrt{1-\rho^2} \tag{3.14}$$

where Z_{i-1} is the standard normal variable of the previous layer, ε_i is a new normal random variable with zero mean and unit standard deviation, and ρ is the inter-layer correlation.

Correlation is a measure of the strength and direction of a relationship between two random variables. The inter-layer correlation between the shear-wave velocities proposed by Toro (1995) is a function of both the depth of the layer (*d*) and the thickness of the layer (*h*):

$$\rho(t,h) = [1-\rho_d(d)]\rho_h(h) + \rho_d(d) \tag{3.15}$$

where ρ_h is the thickness dependent correlation and ρ_d is the depth dependent correlation. The thickness dependent correlation is defined as:

$$\rho_{h(h)} = \rho_0 \exp\left(\frac{-h}{\Delta}\right) \tag{3.16}$$

where ρ_0 is the initial correlation and Δ is a model fitting parameter. As the thickness of the layer increases, the thickness-dependent correlation decreases. The depth dependent correlation (ρ_d) is defined as a function of depth (*d*):

$$\rho_d(d) = \begin{cases} \rho_{200}\left[\frac{(d+d_0)}{200+d_0}\right]^b, d \leq 200 \\ \rho_{200}, d > 200 \end{cases} \tag{3.17}$$

where ρ_{200} is the correlation coefficient at 200 m and d_0 is an initial depth parameter.

As the depth of the layer increases, the depth-dependent correlation increases. The final layer in a site response model is assumed to be infinitely thick, therefore the correlation between the last soil layer and the infinite half-space is only dependent on ρ_d. Toro (1995) evaluated each of the parameters in the correlation models (ρ_0, ρ_{200}, Δ, d_0, b) for different generic site classes.

A site class is used to categorize a site based on the shear-wave velocity profile and/or local geology. In the Toro (1995) model, the statistical properties of the soil profile (the median velocity, standard deviation, and layer correlation) are provided for two different classifications schemes, the Geomatrix and V_{s30} classifications. The Geomatrix site classification classifies sites based on a general description of the geotechnical subsurface conditions, distinguishing generally between rock, shallow soil, deep soil, and soft soil (Table 3.1). In contrast, the V_{s30} site classification is based on the time-weighted average shear-wave velocity of the top 30 meters (V_{s30}) (Table 3.2), and requires site specific measurements of shear-wave velocity.

Toro (1995) computed the statistical properties of the profiles for both the Geomatrix and V_{s30} classifications using a maximum-likelihood procedure. The procedure used a total of 557 profiles, with 541 profiles for the V_{s30}USGS classification and only 164 profiles for the Geomatrix classification. The correlation parameters (ρ_0, ρ_{200}, Δ, d_0, b) are presented in Table 3.3 and the median shear-wave velocities in are presented in Table 3.4.

Table 3.1: The categories of the geotechnical subsurface conditions (third letter) in the Geomatrix site classification Toro (1995).

Designation	Description
A	Rock Instrument is found on rock material (V_s > 600 m/s) or a very thin veneer (less than 5 m) of soil overlying rock material.
B	Shallow (Stiff) Soil Instrument is founded in/on a soil profile up to 20 m thick overlying rock material, typically a narrow canyon, near a valley edge, or on a hillside.
C	Deep Narrow Soil Instrument is found in/on a soil profile at least 20 m thick overlying rock material in a narrow canyon or valley no more than several kilometers wide.
D	Deep Broad Soil Instrument is found in/on a soil profile at least 20 m thick overlaying rock material in a broad canyon or valley.
E	Soft Deep Soil Instrument is found in/on a deep soil profile that exhibits low average shear-wave velocity (V_s < 150 m/s).

Table 3.2: Site categories based on V_{s30} (Toro (1995)).

Average Shear-wave Velocity
V_{s30} greater than 750 m/s
V_{s30} =360 to 750 m/s
V_{s30} =180 to 360 m/s
V_{s30} less than 180 m/s

Table 3.3: Coefficients for the Toro (1995) model,.

	GeoMatrix		V_{s30} (m/s)			
Property	**A &B**	**C&D**	**>750**	**360 to 750**	**180 to 360**	**< 180**
$\sigma_{ln\,V_s}$	0.46	0.38	0.36	0.27	0.31	0.37
ρ_0	0.96	0.99	0.95	0.97	0.99	0.00
ρ_{200}	0.96	1.00	0.42	1.00	0.98	0.50
Δ	13.1	8.0	3.4	3.8	3.9	5.0
d_0	0.0	0.0	0.0	0.0	0.0	0.0
b	0.095	0.160	0.063	0.293	0.344	0.744
Profiles	45	109	35	169	226	27

Table 3.4: Median shear-wave velocity (m/s) based on the generic site classification.

	GeoMatrix		V_{s30} (m/s)			
Depth (m)	**A &B**	**C&D**	**>750**	**360 to 750**	**180 to 360**	**< 180**
0	192	144	314	159	145	176
1	209	159	346	200	163	165
2	230	178	384	241	179	154
3	253	193	430	275	191	142
4	278	204	485	308	200	129
5	303	211	550	337	208	117
6	329	217	624	361	215	109
7.2	357	228	703	382	226	106
8.64	395	240	789	404	237	109
10.37	443	253	880	433	250	117
12.44	502	270	973	467	269	130
14.93	575	291	1070	501	291	148
17.92	657	319	1160	535	314	170
21.5	748	357	1260	567	336	192
25.8	825	402	1330	605	372	210
30.96	886	444	1380	654	391	229
37.15	942	474	1420	687	401	246
44.58	998	495	1460	711	408	266
53.2	1060	516	1500	732	413	289
64.2		541		749	433	318
77.04		566		772	459	353
92.44		593		802	486	392
110.93				847	513	435
133.12				900	550	
159.74					604	
191.69					676	
230.03					756	

Ten generated shear-wave velocity profiles were created for a deep, stiff alluvium site using the two previously discussed methods. In the first method, a generic site profile is generated by using the layering model coefficients and median shear-wave velocity for a V_{s30} = 180 to 360 m/s site class, shown in Figure 3.8(a). This approach essentially models the site as a generic stiff soil site. The second method uses the layer correlation for the V_{s30} = 180 to 360 m/s site class, but the layering and the median shear-wave velocity profile are defined from field measurements, shown in Figure 3.8(b). The site specific layering tends to be much thicker than the generic layering as a result of the field measurements indicating thick layers with the same shear wave velocity. In general both of the methods show an increase in the shear-wave velocity with depth. However, the site-specific shear-wave velocity values are significantly larger than the generic shear-wave velocity values. At the surface, the generic site has a median shear-wave velocity of 150 m/s compared to the site specific shear-wave velocity of 200 m/s. At a depth of 90 m, the difference is even greater, with the generic site having a median shear-wave velocity of 470 m/s compared to the site specific median shear-wave velocity of 690 m/s. The difference in shear-wave velocity is a result of the difference between the site specific information and the generic shear-wave velocity profile.

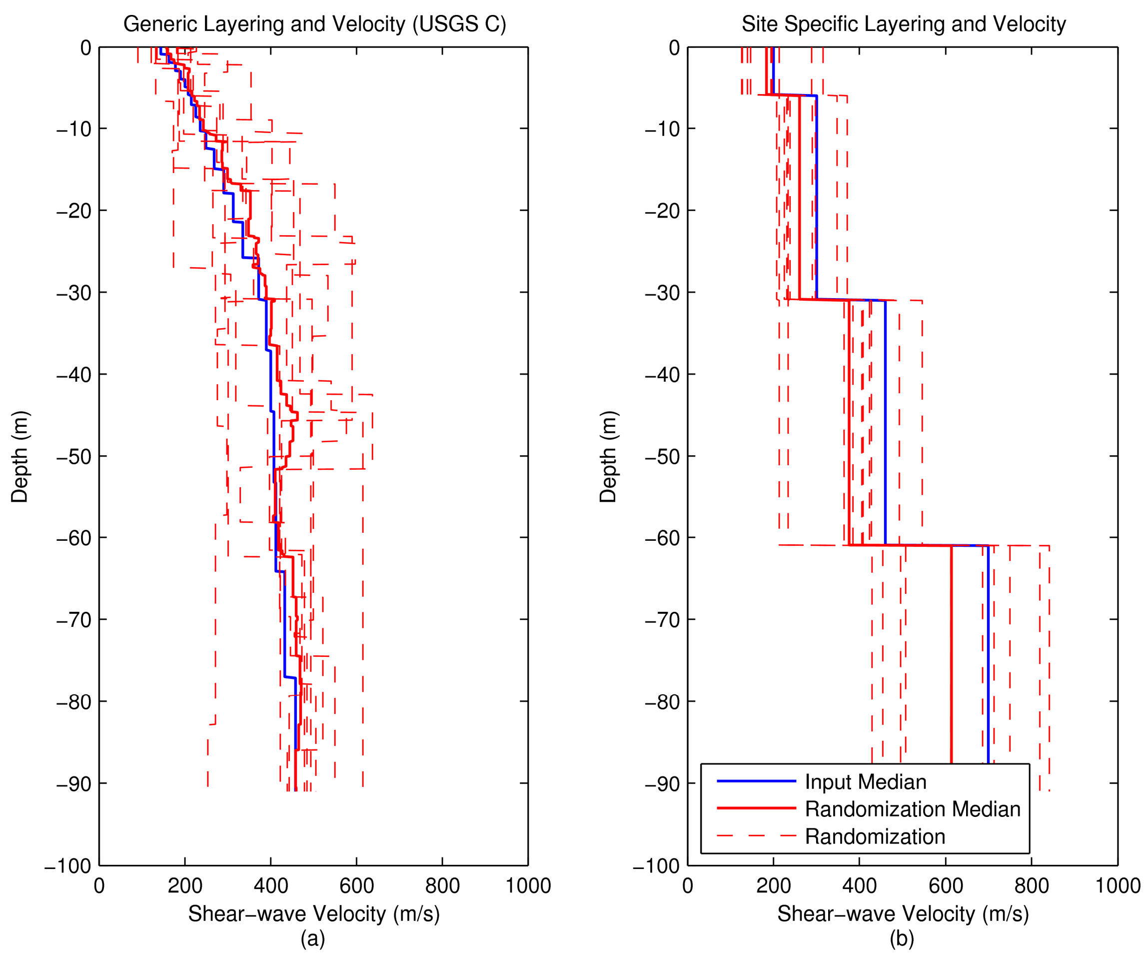


Figure 3.8: Ten generated shear-wave velocity (v_s) profiles for a USGS C site class. (a) Using generic layering and median v_s, (b) using user defined layering and median v_s.

3.3.2 **Depth to Bedrock Model**

The depth to bedrock can be modeled using either a uniform, normal, or log-normally distributed random variable. When using the normal or log-normal distribution, the median depth is based by the soil profile. The variation in the depth to bedrock is accommodated by varying the height of the soil layers. If the depth to bedrock is increased, then the thickness of the deepest soil layer is increased. Conversely, if the depth to bedrock is decreased then the thickness of this deepest soil layer is decreased. If the depth to bedrock is less than the depth to the top of a soil layer, then the soil layer is removed from the profile.

3.3.3 **Non-Linear Soil Properties Model**

The Darendeli (2001) empirical model for nonlinear soil properties (G/G_{max} and *D*) was previously discussed in Section 2.1.3. The Darendeli (2001) empirical model assumes the variation of the properties follows a normal distribution. The standard deviation of G/G_{max} and *D* varies with the magnitude of the property and is calculated with equations (2.20) and (2.21), respectively. Because the variation of the properties is modeled with a normal distribution that is continuous from $-\infty$ to ∞, the generated values of G/G_{max} or *D* may fall below zero. The most likely location for the negative values occurs when the mean value is small, which occurs at large strains for G/G_{max} and at low strains for *D*. Negative values for either G/G_{max} or *D* are not physically possible, therefore the normal distributions need to be truncated. To correct for this problem, minimum values for G/G_{max} and *D* are specified. The default values in Strata are G/G_{max} = 0.05 and D = 0.1%. Strata also includes the ability to specify maximum values of G/G_{max} and *D.*

G/G_{max} and *D* curves are not independent of each other. Consider a soil that behaves more linearly, that is to say the G/G_{max} is higher than the mean G/G_{max}. During a loading cycle, the area inside the hysteresis loop would be smaller which is indicative of less damping within the system. Therefore, as the linearity of the system increases, the damping decreases. To capture this effect, the soil properties are assumed to have a negative correlation with the default value set at -0.5 (i.e. ρ=-0.5).

To generate correlated G/G_{max} and D curves from baseline (mean) curves, the following expressions are used for each shear strain value in the curves:

$$G/G_{max}(\gamma) = [G/G_{max}(\gamma)]_{mean} + \varepsilon_1 \cdot \sigma_{NG} \tag{3.18}$$

$$D(\gamma) = [D(\gamma)]_{mean} + \rho \cdot \sigma_D \cdot \varepsilon_1 + \sigma_D \cdot \sqrt{1-\rho^2} \cdot \varepsilon_2 \tag{3.19}$$

where ε_1 and ε_2 are uncorrelated random variables with zero mean and unit standard deviation, $[G/G_{max}(\gamma)]_{mean}$ and $[D(\gamma)]_{mean}$ are the baseline values evaluated at strain level γ, σ_{NG} and σ_D are the standard deviations computed from (2.20) and (2.21) at the baseline values of $[G/G_{max}(\gamma)]_{mean}$ and $[D(\gamma)]_{mean}$, respectively, and ρ is the correlation coefficient between G/G_{max} and D. Equations (3.18) and (3.19) must be applied at different strain levels, but the same values of ε_1 and ε_2 are used at each strain level (i.e., perfect correlation between strain levels).

Using a correlation coefficient of -0.5, the nonlinear properties of sand (PI=0, OCR=0) at a confining pressure of 1 atm were generated 10 times, shown in Figure 3.9. Three of the realizations result in large shear modulus reduction curve relative to the mean. Because of the negative correlation, the relative high shear modulus reduction corresponds to a relative low damping ratio.

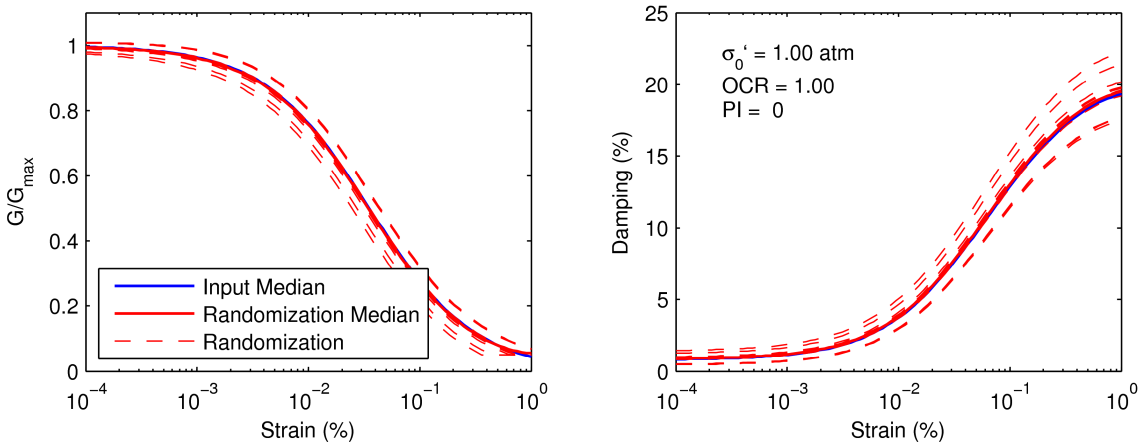


Figure 3.9: Generated nonlinear properties assuming perfect negative correlation.

4 Using Strata

Strata is introduced through two examples that demonstrate the organization and most of the features found in Strata. Before these two examples are discussed, some particular differences between Strata and other site response programs are introduced.

With the exception of acceleration time-series, all of the input to Strata is entered via the keyboard, or through copying and pasting from spreadsheets. The input file is not saved in the typical text format, instead a binary format is used that is only readable by Strata. Furthermore, when the calculation is complete no output text files are produced. Instead, the output can be directly view with Strata and saved, once again to a binary format. There is the option for the data to be exported to text files that can then be opened with a variety of applications, including Excel.

4.1 Strata Particulars

4.1.1 Auto-Discretization of Layers

One of the biggest differences between Strata and other site response analysis programs is the fact that the sublayers used in the calculation portion of the analysis are not defined by the user. Instead, the user defines a velocity layer that is then subdivided into sublayers by Strata. This fundamental difference exists because Strata allows for the layering and shear-wave velocity to vary (see Section 3.3.1.1) and therefore the required thickness of the sublayers changes.

The maximum thickness ($h_{\max,i}$) of the sublayers of i^{th} velocity layer is taken as a fraction of the minimum wavelength to be captured by the analysis:

$$h_{\max,i} = \lambda_{\text{frac}}\lambda_{\min} = \lambda_{\text{frac}}\frac{v_{s,i}}{f_{\max}} \tag{4.1}$$

where λ_{frac} is the wavelength fraction which typically varies between $\frac{1}{10}$ and $\frac{1}{5}$ (anything greater than $\frac{1}{3}$ is not recommended), $f_{\max}$ is the maximum frequency of engineering interest which is typically around 20 Hz, and $v_{s,i}$ is the shear-wave velocity of the i^{th} layer. The actual thickness of the sublayers is less than the maximum thickness such that the velocity layer height divided by the sub-layer thickness is a whole number. These parameters are defined on the General Settings Tab. To prevent the layers from being auto-discretized the wavelength fraction can be increased and the thickness of the velocity layers defined in the Soil Profile Tab can be selected to represent the actual layer thickness used in the analysis. This approach is the same as used in most site response programs.

In other site response programs, the location of the input motion or the location of requested output (e.g., acceleration-time history) is generally referenced by a sublayer index. However, because the sublayers are computed in Strata (and may change for each realization), the location is defined in terms of the depth within the soil profile or at the top of the bedrock. When the location is specified as Bedrock then the actual depth of the location may change if the depth of the bedrock changes. The location is specified with a drop down list shown in Figure 4.1, where the user can specify the depth as Bedrock (Figure 4.1a) or a fixed depth (Figure 4.1c).

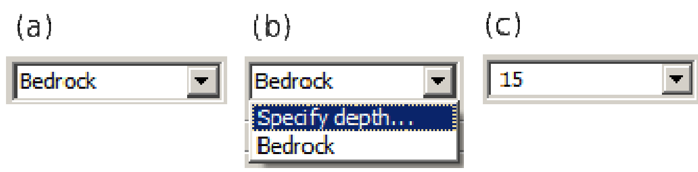
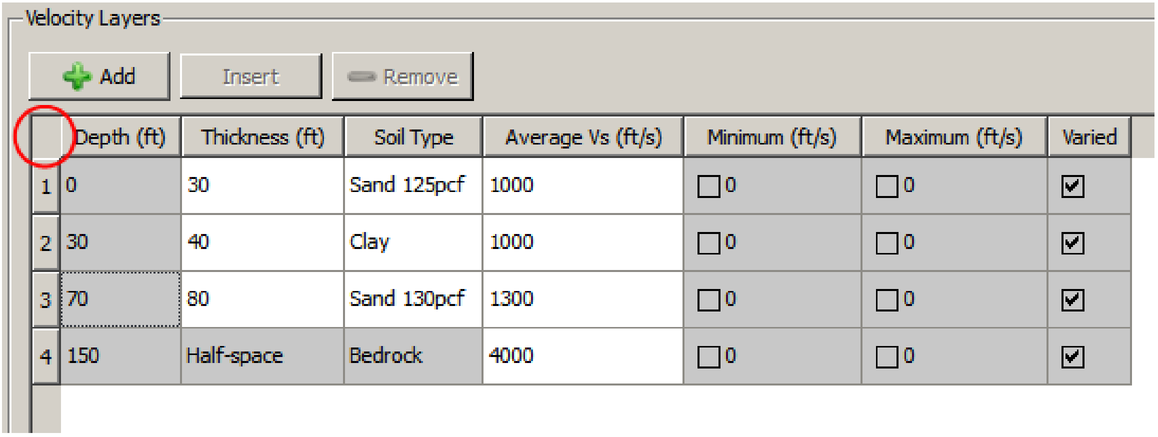


Figure 4.1: Location selection: (a) top of bedrock, (b) switching to a fixed depth, and (c) fixed depth specified as 15.

4.1.2 Interaction with Tables

Table cells are selected with one click. After a cell is selected, the cell can be edited by typing. A cell's edit mode can be directly entered by double clicking on the cell. In some cases, double clicking on a cell will produce a widget to aid specifying input to the cell.

All tables used in Strata are dynamic, that is the number of rows can be changed. Rows are added to the bottom of the list with the Add button. The Insert and Remove buttons are disabled until a complete row has been selected, which is most easily achieved by clicking on the number next to the row of interest. Multiple continuous rows can be selected by pressing the shift key while selecting the rows. After rows have been selected: Add will add the same number of rows to the end of the table, Insert will insert the same number of rows above the currently selected rows, and Remove will remove the selected rows. All rows in the table can be selected by click on the button in the upper right portion of the table as shown in Figure 4.2. Some tables have cells that cannot be edited and have a light gray background (Figure 4.2).



	Depth (ft)	Thickness (ft)	Soil Type	Average Vs (ft/s)	Minimum (ft/s)	Maximum (ft/s)	Varied
1	0	30	Sand 125pcf	1000	☐ 0	☐ 0	☑
2	30	40	Clay	1000	☐ 0	☐ 0	☑
3	70	80	Sand 130pcf	1300	☐ 0	☐ 0	☑
4	150	Half-space	Bedrock	4000	☐ 0	☐ 0	☑

Figure 4.2: By clicking on the button circled in red all rows in the table are selected.

Data can copied from spreadsheets and pasted into tables by first clicking on the table and:

1. Pressing Ctrl+v, or
2. Selecting Paste from the Edit menu in Strata, or
3. Right clicking on the table and selecting paste.

The table will automatically increase the numbers of rows to accommodate the size of the pasted data.

4.1.3 Non-Linear Curves

The nonlinear shear-modulus reduction and damping curves can be specified through three different methods in Strata: (1) fixed models that are present by default and cannot be removed, (2) user defined curves that can be used across projects, and (3) temporary models that only exist for the project.

Fixed Non-Linear Models

The following shear-modulus reduction models are included by default:

- Darendeli (2001)
- EPRI (1993)
  - Plasticity Based -- 10, 30, 50, and 70
  - Depth Based – 0-20, 20-50, 50-120, 120-250, 250-500, and 500-1000 ft.
- GEI (1993) – 0-50, 50-100, 100-250, 250-500, and >500 ft.
- GeoMatrix (Coppersmith, 1991) – 0-50, 50-150, and >150 ft.
- Idriss (1990) – clay and sand.
- Imperial Valley Soils (Turner and Stokoe, 1983) – 0-300 and >300 ft.
- Iwasaki (1976) – 0.25 and 1.0 atm.
- Peninsular Range (Silva et al., 1997) – 0-50 and 50-500 ft.

- Seed and Idriss (1970) – sand lower, mean, and upper.
- Vucetic and Dobry (1991) – Plasticity indices of 0, 15, 30, 50, 100, and 200.

User Defined Models

Non-linear curve models can be defined for use across multiple projects by adding models to the library. The nonlinear property manager is opened by selecting Add/Remove Non-Linear Property Curves from the Tools menu. Using the dialog (Figure 4.3), a new model can be defined by following these steps:

1. Click the Add button to add a new curve to the normalized shear-modulus reduction or damping models list.
2. Rename the model from ``Untitled`` to something meaningful.
3. Add the data points to the curve.

Models defined in this manner will be added to the nonLinearCurves.strd file found in the Strata installation folder.

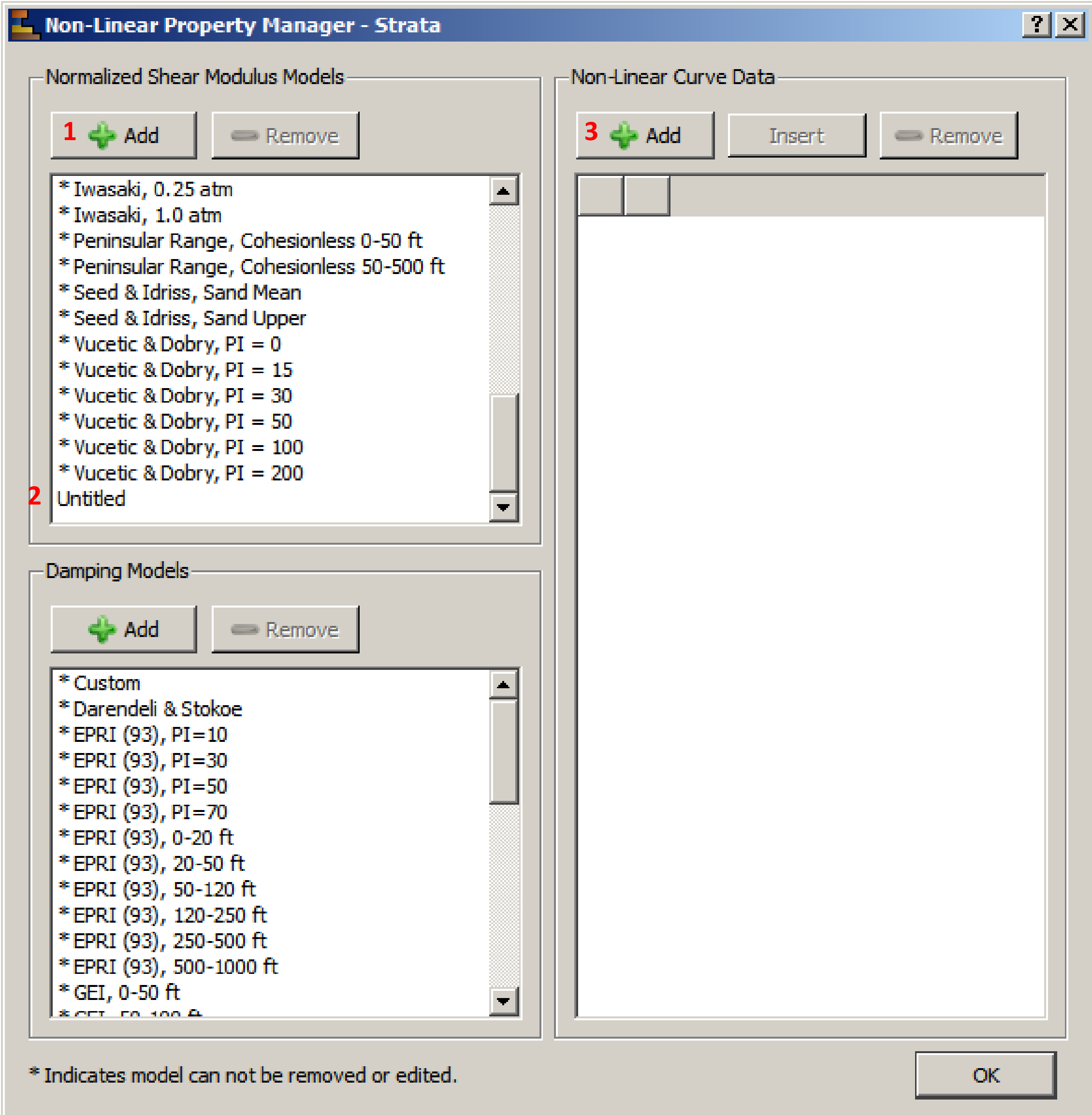


Figure 4.3: The nonlinear curve manager.

Temporary Models

If you want to define a curve without adding it to the library of models, simply select Custom from the drop-down list in the Soil Types Table. Changing to the Custom model does not clear the previous model's data which allows for a model to be modified.

4.1.4 **Recorded Motion Dialog**

The Recorded Motion Dialog is used to load a recorded motion into Strata and appears when the Add button is clicked in the Record Motion(s) table within the Motion(s) tab. The dialog, shown in Figure 4.4 allows the user to load a variety of motions in most formats using the following steps:

1. Click on the File button and select the acceleration time series text file. If the file is from the NGA database, then the remainder of the form will be automatically completed as shown in Figure 4.4. Regardless of the file format, the file is read and loaded into the preview area.
2. The remaining fields need to be filled to reflect the information in the file. Information is required for all fields except for the Description field. Fields can be completed by either typing values in, or selecting from the file preview and dragging the selected text into the field. The Start line and Stop line control which lines in the file contain the data. A zero value for the Stop line will result in the data being read until the end of the file. The file preview can be colored by clicking on the Refresh button.

   The colors have the following meanings:

   - Green -- text found prior to the acceleration-time series data (these lines are ignored).
   - Blue -- acceleration-time series data.
   - Red -- text after the time series data (these lines are ignored).

   An example of the colored data is shown in Figure 4.5.

3. The scale factor can be selected at this time or after the motion has been loaded. If the input acceleration-time history is not in units of g (g=acceleration of gravity), then the scale factor should be used to make this unit conversion. After the motion has been loaded, the scale factor can also be adjusted by assigning a peak-ground acceleration.
4. After the form has been completed, the time-series can be viewed by clicking on the Plot button.
5. Click OK to finish loading the file.

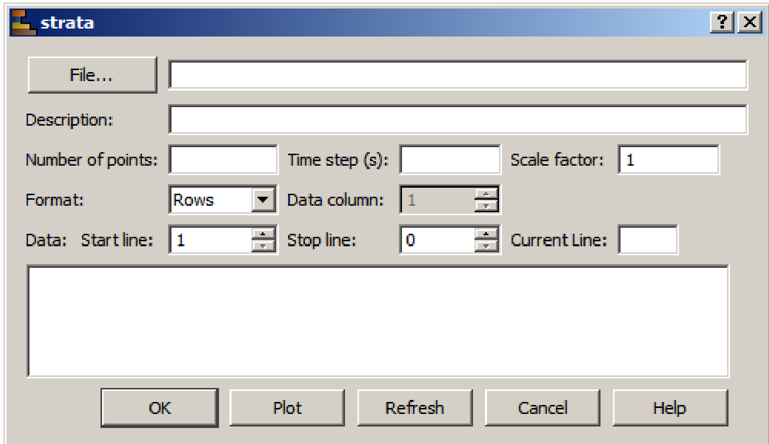


Figure 4.4: An initial view of the Recorded Motion Dialog.

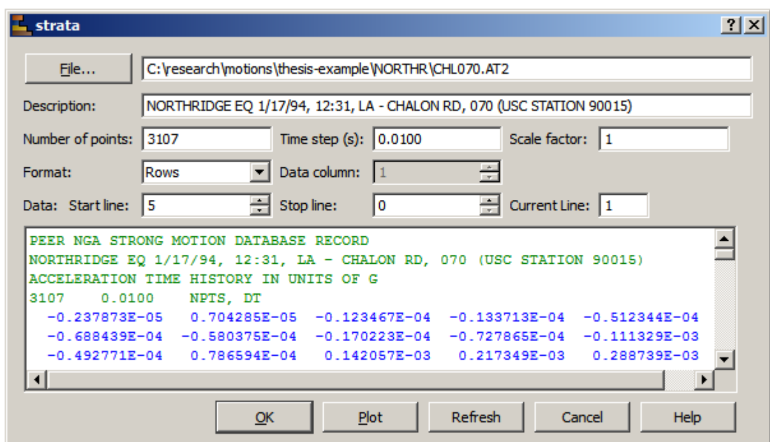


Figure 4.5: An example a completed Recorded Motion Dialog.

4.1.5 **Results Page**

Prior to the calculation of the site response, the Results tab is disabled. After the site response calculation has been completed, the Results tab will be enabled and selected. The remaining tabs are placed in a read-only (or "locked") mode where the fields can be reviewed but not edited. Therefore, the input parameters used to generate the output are strictly linked for later reference by the user.

Strata can be unlocked by clicking on the open lock icon in the upper left portion of the screen, by selecting Unlock from the Tools menu, or by pressing F2. By unlocking Strata, all of the results are deleted. If you wish to save the results and make changes to the input and re-run the analysis. First, save the results using either the Save or Save As… command from the File Menu. Next create a copy of the file by selecting Save As… from the File Menu and use a new name appropriate for the new input parameters. Finally, unlock the newly created file.

Strata does not output any data files automatically, instead the results are saved to the project file in a binary format. To work with the data outside of Strata, the data can be exported by selecting Export... from the File menu. The exported data file is in a comma-separated values (CSV) format that can be easily opened with Excel or another spreadsheet program. All data (even disabled results) are included in the files.

A screenshot of the Results tab is shown in Figure 4.6. Each result represents a site realization subjected to an input motion. The output of interest is selected from a drop-down box containing a list of all requested output. Individual values from this list are selected by either clicking on the corresponding row in the Data Selection table, or by clicking on the result in the plot. In both cases, the result is colored green if the result is enabled, or red if the result is disabled. A result can be enabled or disabled by clicking on the checkbox next to the site realization that produced the result. After the status of a result has been changed, the Recompute Statistics button will become enabled indicating that the median and standard deviation (shown on the plot in solid and dash blue lines, respectively) need to be updated. Click this button to recompute the statistics.

At the bottom of the table there are two buttons that allow all motions or sites related to the currently selected result to be enabled or disabled. In the example (Figure 4.6), the motion CHICHI06\TCU076-E.AT2 has been disabled. Whenever the status of a result is changed (e.g. from disabled to enabled) the Recompute Statistics button will become enabled allowing the user to update the median and standard deviation. The current plot can be printed by selecting Print… or Print to PDF… from the File menu. The current plot can also be copied by right clicking on the plot and selecting Copy.

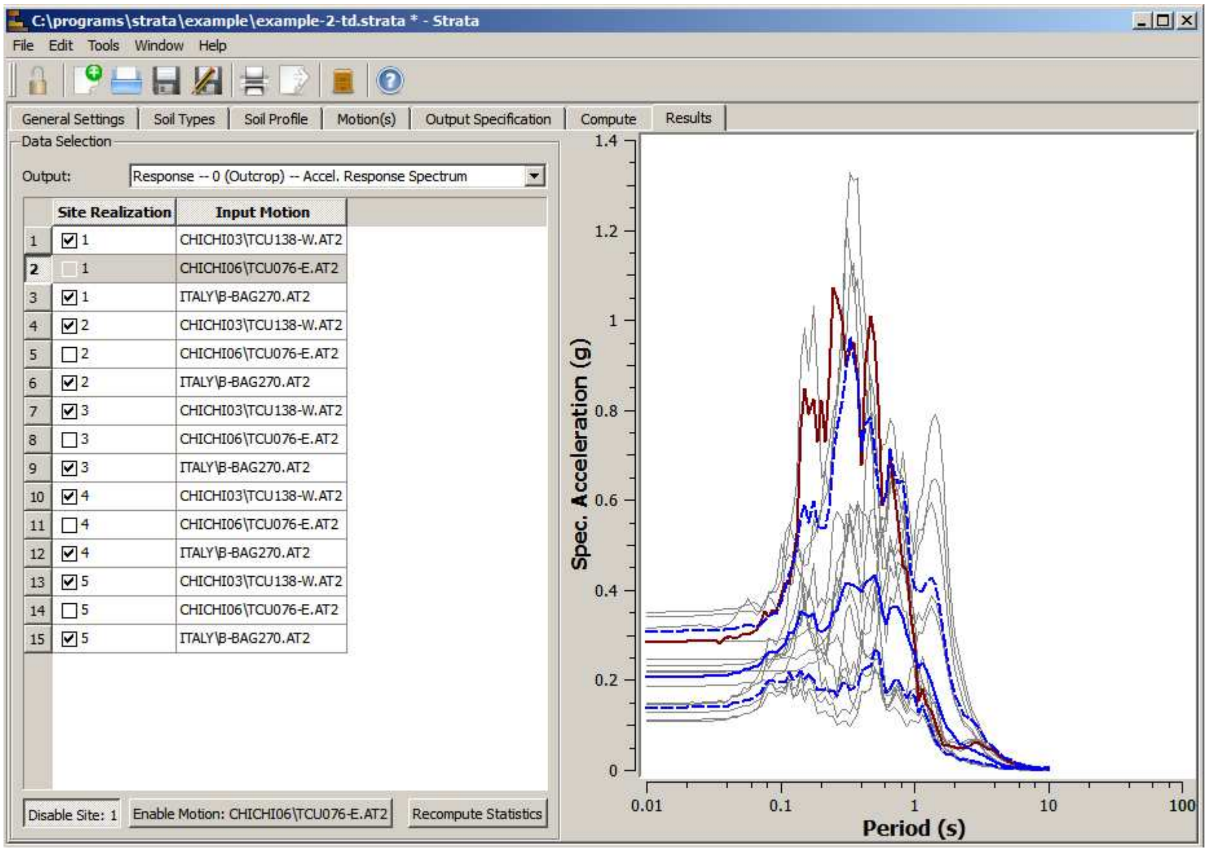


Figure 4.6: Using the Output view to examine the results of a calculation.

4.2 Glossary of Fields

The following section contains screenshots of the program and describes each of the fields. Assume that information is required for each field, unless stated otherwise.

4.2.1 General Settings Page

Project Group Box

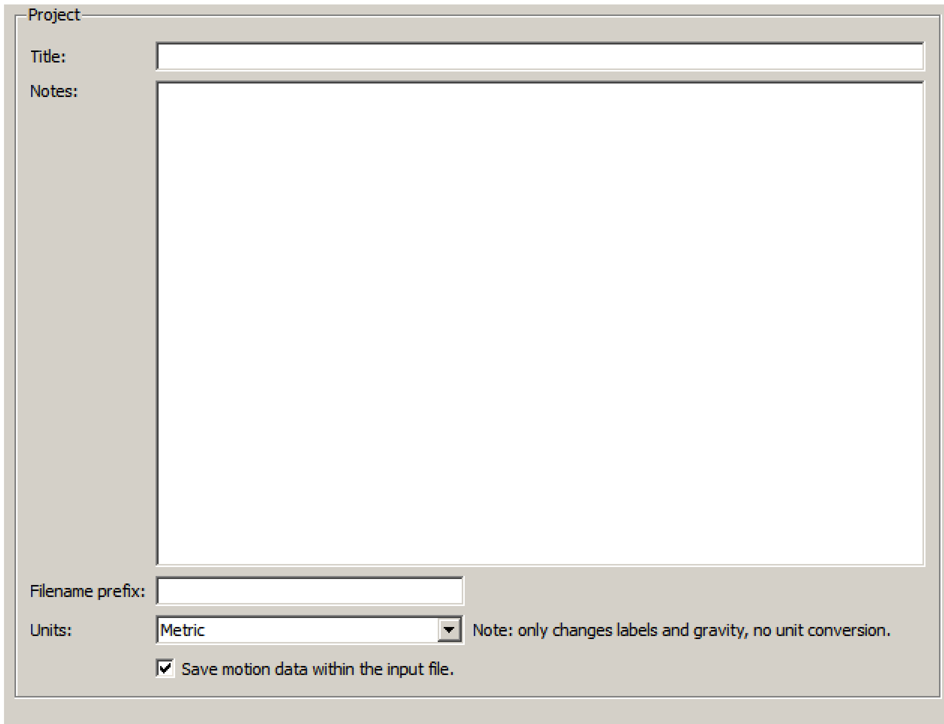


Figure 4.7: Screenshot of the Project group box.

- Title – name of the project (optional). The title is included in the first row of the exported data and therefore can be extremely useful in identifying the output
- Notes – a place to store information about the input (optional); only used to preserve your sanity.
- Filename prefix – placed at the beginning of the name of all exported files (optional). The prefix offers a means to distinguish a group of analyses.
- Units – defines gravity in the analysis. Changing the units does not perform any conversion; it is recommended that the units be defined before any site information is provided.
- Save motion data checkbox – allows time series to be saved within the input file (optional). If checked then the time series information is stored within the input file allowing one file to be transferred between computers. However, larger input files will be generated.

Type of Analysis Group Box

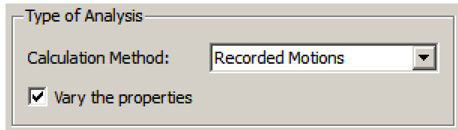


Figure 4.8: Screenshot of the Type of Analysis group box.

- Calculation Method – either Recorded Motions for a time series analysis, or Random Vibration Theory for RVT analysis.
- Vary the properties checkbox – Controls if site properties will be varied in the calculation.

Site Property Variation Group Box

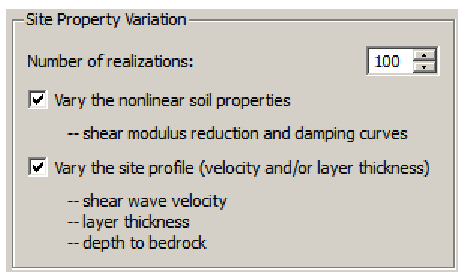


Figure 4.9: Screenshot of the "Site Property Variation" group box.

This group box is only enabled if the Vary the Properties check box in the Type of Analysis group box is enabled.

- Number of realizations – number of sites to be generated. A site consists of nonlinear curves, shear-wave velocity profile, layering thickness, and depth to bedrock – the variation of each of these properties is controlled elsewhere. Each of the input motions is propagated through a generated site.
- Vary the nonlinear soil properties – controls if the shear modulus reduction and damping curves are varied.
- Vary the site profile – controls if the velocity, layer thickness, and/or depth to bedrock are varied.

Equivalent Linear Parameters Group Box

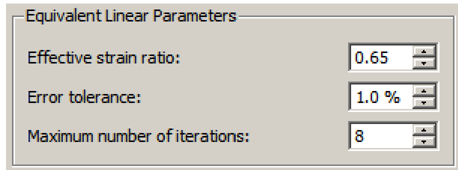


Figure 4.10: Screenshot of the Equivalent Linear Parameters group box.

- Effective strain ratio – the ratio between the effective shear strain (used for the strain compatible nonlinear properties) and the maximum shear strain computed in the layer.
- Error tolerance – the maximum error in the nonlinear properties between iterations.
- Maximum number of iterations – if the error tolerance is not achieved in this number of iterations, the calculation ends.

Layer Discretization Group Box

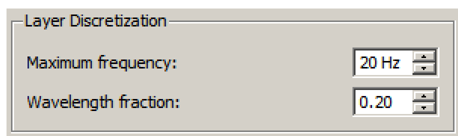


Figure 4.11: Screenshot of the Layer Discretization group box.

- Maximum frequency – maximum frequency of engineering interest
- Wavelength fraction -- thickness of the layer relative to the wavelength at the maximum frequency of engineering interest.

4.2.2 Soil Types Page

Soil Types Group Box

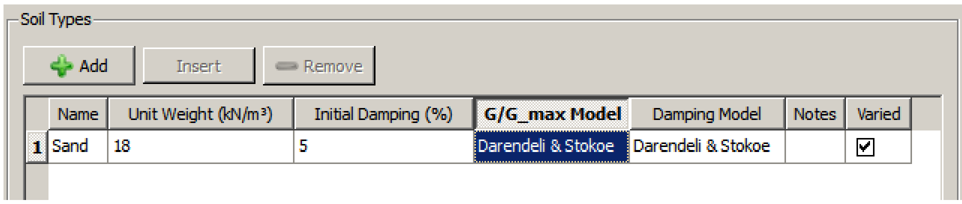


Figure 4.12: Screenshot of the Soil Types group box.

- Name – used for indentifying soil layer in the program and output.
- Unit weight – total unit weight of the soil.
- Initial damping – this damping is used during the initial iteration.
- G/G_max Model – model that describes the variation of normalized shear modulus with shear strain.
- Damping Model – model that describes the variation of the damping ratio with shear strain.
- Notes – for your sanity only (optional).
- Varied – check box to identify if the nonlinear curves of the soil type will be varied. Only visible if variation of the nonlinear curves is enabled.

Bedrock Layer Group Box

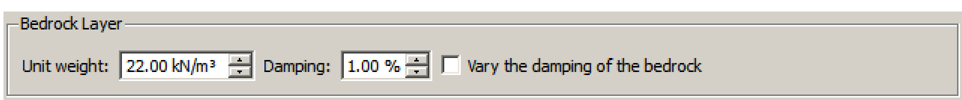


Figure 4.13: Screenshot of the Bedrock Layer group box.

- Unit weight – total unit weight of the infinite half space.
- Initial damping – damping of the infinite half space.
- Vary the damping of the bedrock - check box to identify if the damping in the bedrock is to be varied

Nonlinear Curve Variation Parameters Group Box

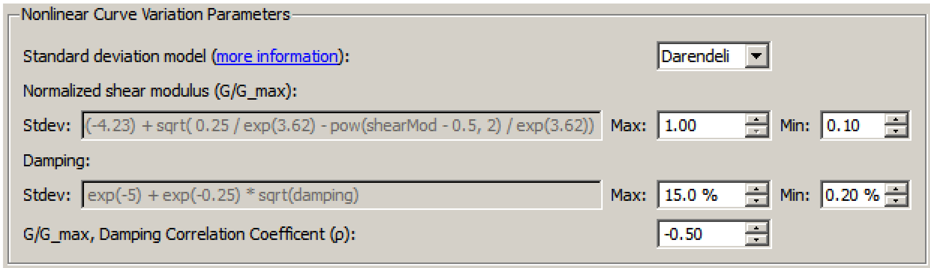


Figure 4.14: Screenshot of the Nonlinear Curve Variation Parameters group box.

- Standard Deviation Model – model to describe the variability of the nonlinear parameters.
- Normalized shear modulus
    - o Stdev – formula to describe the standard deviation. Enabled if standard deviation model is set to custom.
    - o Max – maximum value of the normalized shear modulus reduction.
    - o Min -- minimum value of the normalized shear modulus reduction.
- Damping
    - o Stdev – formula for the standard deviation. Enabled if standard deviation model is set to custom.
    - o Max – maximum value of the damping ratio.
    - o Min -- minimum value of the damping ratio.
- G/G_max, Damping Correlation Coefficient (ρ) – correlation coefficient between the varied nonlinear curves.

Darendeli and Stokoe Model Parameters Group Box

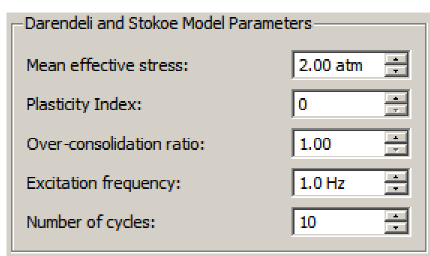
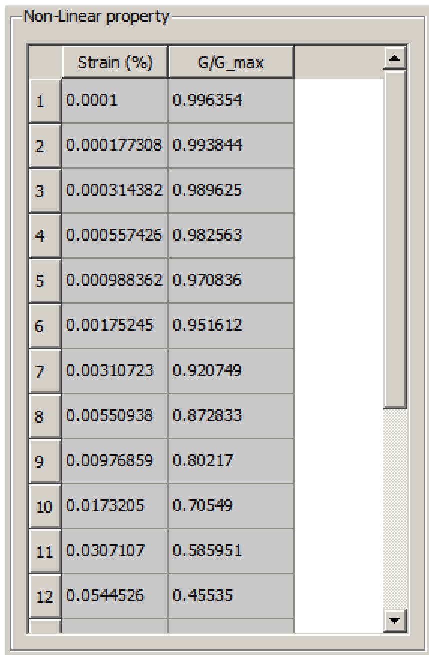


Figure 4.15: Screenshot of the Darendeli and Stokoe Model Parameters group box.

This group box is only enabled when a soil type that uses the Darendeli and Stokoe (2001) model for either of the nonlinear soil properties is selected.

- Mean effective stress – mean effective stress of the soil in units of atmospheres.
- Plasticity index – plasticity index of the soil.
- Overconsolidation ratio – overconsolidation ratio of the soil.
- Excitation frequency – frequency of excitation.
- Number of cycles – number of loading cycles.

Nonlinear Property Group Box



Non-Linear property

	Strain (%)	G/G_max
1	0.0001	0.996354
2	0.000177308	0.993844
3	0.000314382	0.989625
4	0.000557426	0.982563
5	0.000988362	0.970836
6	0.00175245	0.951612
7	0.00310723	0.920749
8	0.00550938	0.872833
9	0.00976859	0.80217
10	0.0173205	0.70549
11	0.0307107	0.585951
12	0.0544526	0.45535

Figure 4.16: Screenshot of the Nonlinear Property group box.

For fixed models, this table will provide a read only view of the data points used in the models. The values of the models can be edited by switching the model to custom. The second column in the table changes depending on what type of model is selected in the Soil Type table.

- Strain (%) – shear strain in percent.
- G/G_max – normalized shear modulus.
- Damping (%) – damping ratio in percent.

4.2.3 **Soil Profile Page**

Velocity Layers Group Box

	Depth (m)	Thickness (m)	Soil Type	Vs (m/s)	Stdev.	Minimum (m/s)	Maximum (m/s)	Varied
1	0	20	Sand	700	0	☐ 0	☐ 0	☑
2	20	Half-space	Bedrock	760	0	☐ 0	☐ 0	☑

Figure 4.17: Screenshot of the Velocity Layers group box.

- Depth – depth of the top of the velocity layer – computed by Strata.
- Thickness – thickness of velocity layer.
- Soil Type – Soil Type associated with the velocity layer. This associates the velocity layer to a specific unit weight and nonlinear properties for the analysis.
- Vs –shear-wave velocity of the layer.
- Minimum – minimum shear-wave velocity. Minimum value of shear wave velocity allowed during Monte Carlo simulation
- Maximum – maximum shear-wave velocity. Maximum value of shear wave velocity allowed during Monte Carlo simulation
- Varied – check box to identify if the shear-wave velocity of the layer is to be varied.

Variation of the Site Profile Group Box

The Variation of the Site Profile group is hidden unless the Vary the Site Profile checkbox is checked on the General Settings page. For each of the functionalities (shear-wave velocity variation, layer thickness variation, and depth to bedrock variation), there is a check box that controls if the functionality should be activated. A group box for model parameters appears for each functionality when the functionality is enabled.

Shear-wave velocity variation Group Box

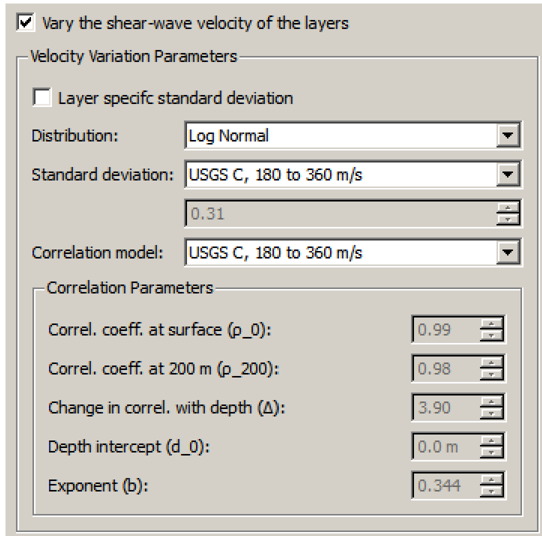


Figure 4.18: Screenshot of the Velocity Variation Parameters group box.

- Layer specific standard deviation checkbox – Checkbox to identify if the standard deviation for each velocity layer will be defined in the Velocity Layers table.
- Distribution – statistical distribution of the shear-wave velocity.
- Standard deviation – the site class for a generic standard deviation. If set to custom, a specific value of standard deviation for the site can be defined.
- Correlation model – the site class for the correlation model. If set to custom, specific correlation parameters must be defined in the Correlation Parameters group box.
- Correlation Parameters -- for information on these parameters see Section 3.3.1.2.
    - Correl. coeff. at surface – correlation coefficient at the surface (ρ_0).
    - Correl. Coeff. at 200 m – correlation coefficient at a depth of 200 m (ρ_{200}).
    - Change in correl. with depth – change in correlation coefficient with depth (Δ).
    - Depth intercept – depth intercept (d_0).
    - Exponent – exponent in the depth correlation term (b).

Layer thickness variation Group Box

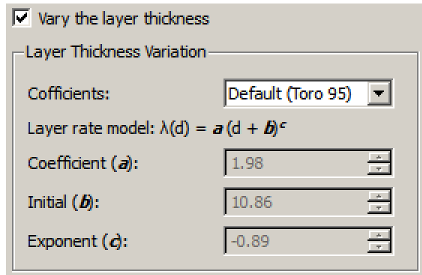


Figure 4.19: Screenshot of the Layer Thickness Variation group box.

For more information on the parameters in this group box see Section 3.3.1.1.

- Coefficients – the parameters for the model used to vary layer thickness. If set to custom then the model parameters *a*, *b*, and *c* are defined by the user.

Bedrock depth variation

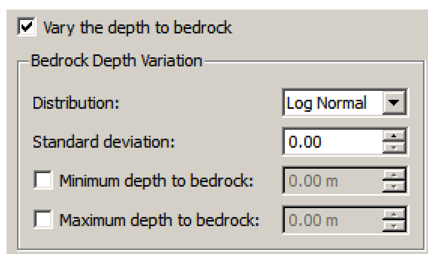


Figure 4.20: Screenshot of the Bedrock Depth Variation group box.

- Distribution – the statistical distribution of the bedrock depth, either uniform, normal, or log normal.
- Standard deviation – standard deviation of the log normal or normal distribution. For a log normal distribution this value is defined in log space.
- Minimum depth to bedrock – check box to identify if the distribution is to be truncated at a minimum depth, and associated minimum depth.
- Maximum depth to bedrock – check box to identify if the distribution is to be truncated at a maximum depth, and associated maximum depth.

4.2.4 **Motion(s) Page**

The Motion Page is used to define the input motion(s) and where the input motion(s) is (are) input into the soil profile. Depending on the type of analysis, the motion(s) are defined in different ways.

Motion Input Location Group Box

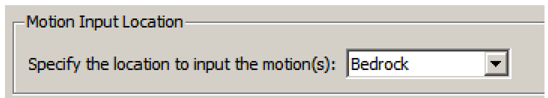
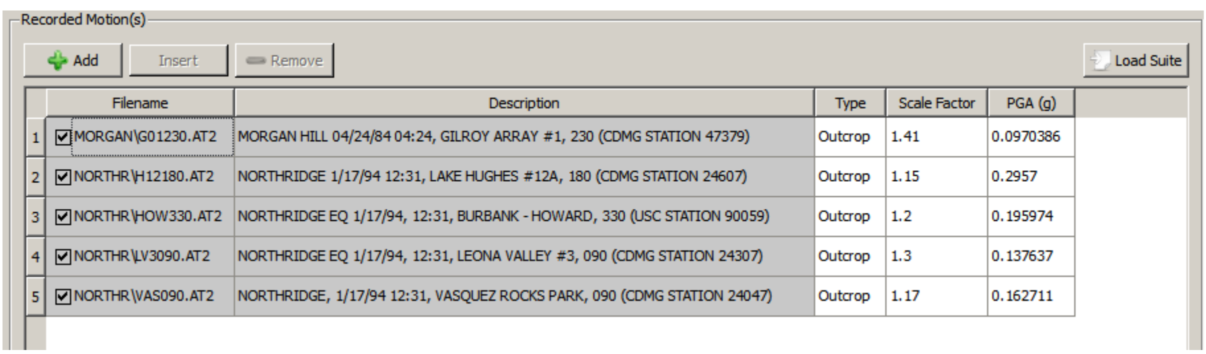


Figure 4.21: Screenshot of the Motion Input Location group box.

- Specify the location to input the motion(s) – The input location specifies where the input motion should be specified. The adjacent box can be used to specify a specific depth or the bedrock (see Section 4.2). If the input location is defined as bedrock then location will be at the top of the bedrock regardless of the randomized depth of the bedrock.

Recorded Motion(s)



	Filename	Description	Type	Scale Factor	PGA (g)
1	MORGAN\G01230.AT2	MORGAN HILL 04/24/84 04:24, GILROY ARRAY #1, 230 (CDMG STATION 47379)	Outcrop	1.41	0.0970386
2	NORTHR\H12180.AT2	NORTHRIDGE 1/17/94 12:31, LAKE HUGHES #12A, 180 (CDMG STATION 24607)	Outcrop	1.15	0.2957
3	NORTHR\HOW330.AT2	NORTHRIDGE EQ 1/17/94, 12:31, BURBANK - HOWARD, 330 (USC STATION 90059)	Outcrop	1.2	0.195974
4	NORTHR\LV3090.AT2	NORTHRIDGE EQ 1/17/94, 12:31, LEONA VALLEY #3, 090 (CDMG STATION 24307)	Outcrop	1.3	0.137637
5	NORTHR\VAS090.AT2	NORTHRIDGE, 1/17/94 12:31, VASQUEZ ROCKS PARK, 090 (CDMG STATION 24047)	Outcrop	1.17	0.162711

Figure 4.22: Screenshot of the Motion Input Location group box.

A recorded motion is added to the table by clicking on the Add button, and filling out the information in the dialog (see Section 4.1.4 for more information). The following information is presented in the Recorded Motion(s) table:

- Filename – contains the directory and filename of the motion.
- Description – description of the time series (optional).
- Type – type of boundary conditions of the motion; either Outcrop or Within.

- Scale Factor – scale factor to convert the motion into units of gravity (if required, see Section 4.1.4) at the desired amplitude. Changing the scale factor changes the listed peak ground acceleration (PGA) value.
- PGA – the PGA of the record in units of gravity can be specified. Changing this value changes the listed scale factor.

An entire suite of motions in the NGA (Next Generation Attenuation, http://peer.berkeley.edu/nga) format can be added by clicking on the Load Suite push button which opens a file selection dialog. The suite file is a simple text file with the extension '.csv'. Each line of the file contains the path name to the motion and the scale factor separated by a comma. The path name can be either absolute or relative to the path of the suite file. If examples were installed during the installation of Strata then an example suite file named 'suite-10-1.csv' can be found in the examples directory.

Random Vibration Theory

When the random vibration theory method is selected there are a variety of methods that can be used to specify the input motion. Regardless of the method there are some basic properties that must be defined.

Properties

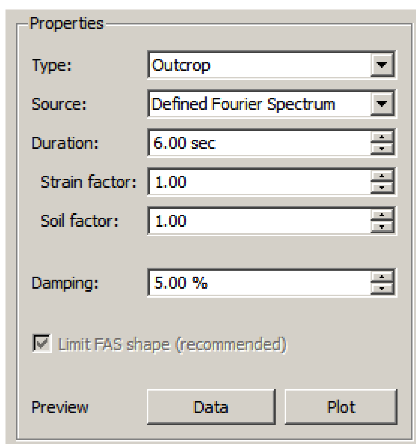


Figure 4.23: Screenshot of the Motion Input Location group box.

- Type – type of boundary conditions of the motion; either Outcrop or Within.
- Source – method used to characterize the motion. The following options are available:
    - Defined Fourier Spectrum
    - Defined Response Spectrum
    - Calculated Fourier Spectrum

- Duration – duration of the event (D_{5-75}) (disabled when the source is a calculated Fourier spectrum).
- Strain factor – the factor to apply to the duration used for the RVT calculation of the strain (recommended value 1.0).
- Soil factor – the factor to apply to the duration used for the RVT calculation of motion at the top of the soil column (recommended value 1.0).
- Damping – damping of the response spectrum. This damping is used for both the preview of the response spectrum and for the input response spectrum.
- Limit FAS shape checkbox – limits the shape of the FAS during the inversion (see Section ??) from response spectrum to Fourier spectrum (enabled only when the source is a defined response spectrum).
- Data push button – clicking on this push button shows a table of the Fourier amplitude spectrum and associated response spectrum for the motion.
- Plot push button – clicking on this push button shows a plot of the Fourier amplitude spectrum and associated response spectrum for the motion.

Fourier Amplitude Spectrum Group Box

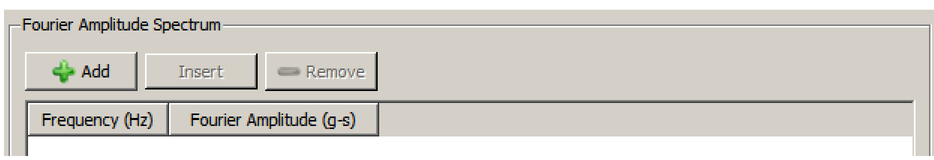


Figure 4.24: Screenshot of the Fourier Amplitude Spectrum group box.

The Fourier Amplitude Spectrum group box is used to specify an acceleration Fourier amplitude spectrum directly. The simplest method of entering data into this table is pasting from a spread sheet. The columns represent the following:

- Frequency – frequency in Hertz.
- Fourier Amplitude – Fourier amplitude at the frequency in units of gravity-seconds.

Acceleration Response Spectrum Group Box

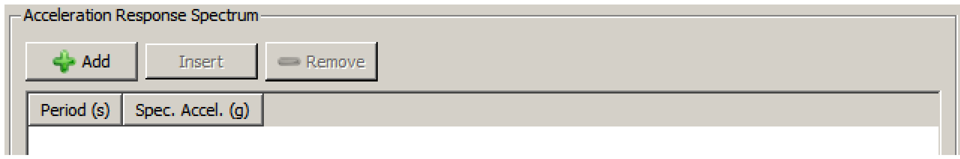


Figure 4.25: Screenshot of the Acceleration Response Spectrum group box.

The Acceleration Response Spectrum group box is used to specify an acceleration response spectrum that is used to compute a Fourier spectrum through inversion (see Section 2.2.2.4). The simplest method of entering data into this table is pasting from a spread sheet. The columns represent the following:

- Period (s) – period of the oscillator in units of seconds.
- Spec. Accel. (g) – spectral acceleration of the oscillator in units of gravity.

Point Source Model Group Box

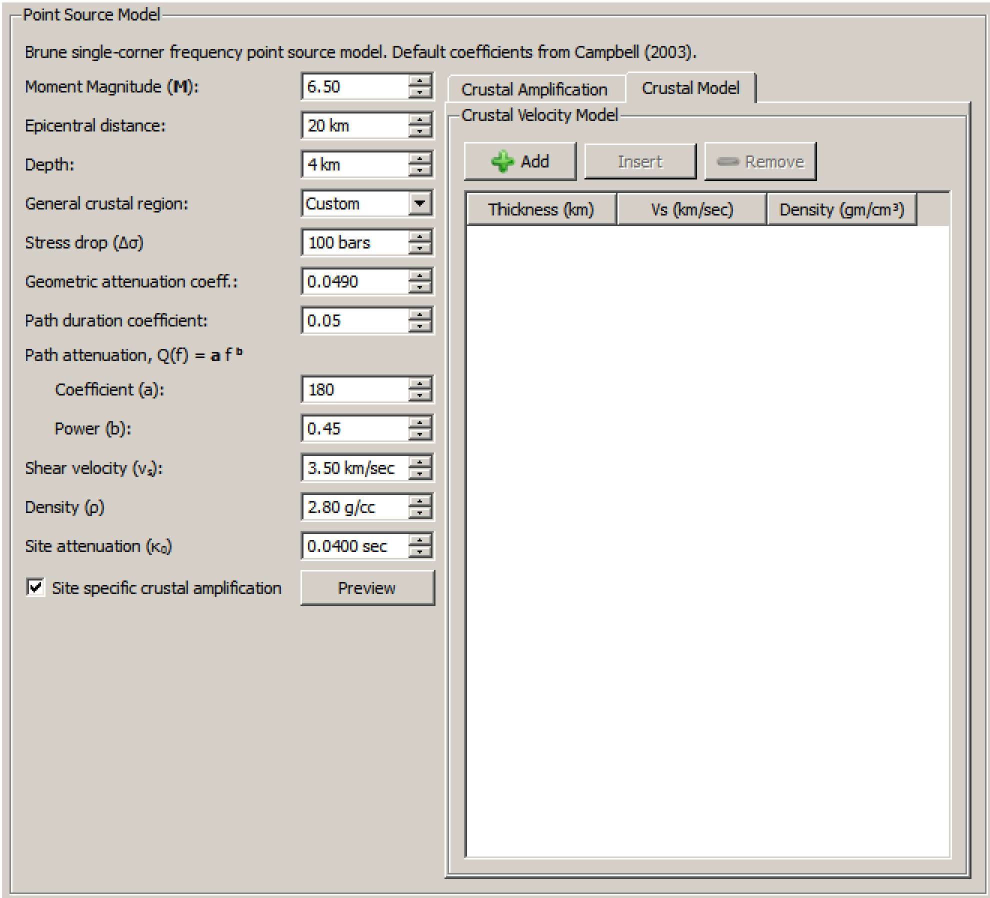


Figure 4.26: Screenshot of the Acceleration Response Spectrum group box.

- Moment Magnitude – moment magnitude of the event.
- Epicentral distance – distance to the epicenter in km.
- Depth – depth to the rupture in km.
- Location – crustal region associated with the source and crustal properties. Choose from Western US, Central and Eastern US, and Custom. The Western US and Central and Eastern US values are from Campbell (2003).
- Stress drop – stress drop of the rupture (required for Custom location).
- Geometric attenuation coeff. – geometric attenuation coefficient. For example, if the geometric attenuation relationship is 1/*R* and R=20, then this value would be 0.05.
- Path duration coefficient – factor used to define the portion of the duration that is dependent on the path distance (Tp). See section 2.2.2.2 for details.
- Path attenuation – frequency dependent path attenuation Q defined by a coefficient (a) and a power (b) using $Q = a f^b$
- Shear velocity – shear-wave velocity at the rupture in km/s.

- Density – density of the rock at the rupture in g/cm^3.
- Site attenuation – site attenuation κ_o.
- Site specific crustal amplification – allows for the crustal amplification to be computed for a site specific crustal velocity profile using the quarter-wavelength method (Boore 2003). Enabling this check box requires that the user then define the thickness, shear-wave velocity, and density of the crustal layers, as shown in Figure 4.27.

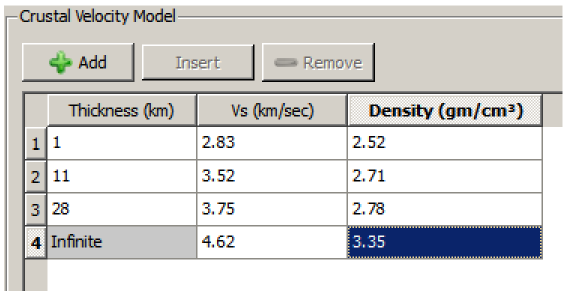


Figure 4.27: Screenshot of the Crustal Velocity Model group box.

4.2.5 **Output Specification Page**

Response Location Output Group Box

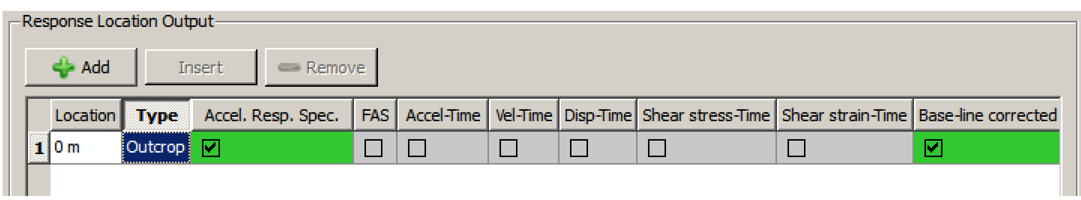


Figure 4.28: Screenshot of the Response Location Output group box.

Response location output is an acceleration response spectrum, FAS, or acceleration-time history that is associated with a specific point with the soil column.

- Location – depth of the response, either Bedrock or a specific depth.
- Type – boundary conditions of the response (Bedrock or Outcrop).
- FAS – Fourier amplitude spectrum of the input motion using the frequency spacing of the input motion.
- Accel-time – acceleration-time series in units of gravity.
- Vel-time – velocity-time series in units of cm/s or in/s.
- Disp-time – displacement-time series in units of cm or in.
- Shear stress-time – shear stress-time series for Within boundary conditions.

- Shear strain-time – shear strain-time series for Within boundary conditions.
- Base-line corrected – if this box is checked then the acceleration-, velocity-, and displacement-time series are baseline corrected using a polynomial.

Ratio Output

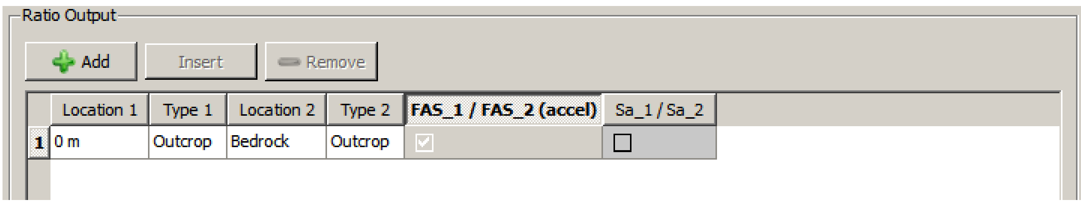


Figure 4.29: Screenshot of the Ratio Output group box.

Ratio output represents the ratio of responses at two locations within the soil column.

- Location 1 – depth of the response at location 1, either Bedrock or a specific depth.
- Type 1 – boundary conditions at location 1 (Within or Outcrop).
- Location 2 – depth of the response at location 2, either Bedrock or a specific depth.
- Type 2 – boundary conditions at location 2 (Within or Outcrop).
- FAS_1/FAS_2 – the ratio of the Fourier amplitude spectrum of the acceleration (i.e. transfer function) between locations 1 and 2.
- Sa_1/Sa_2 – the ratio of the response spectra at locations 1 and 2.

4.3 Examples

The following examples give a basic introduction to using Strata to perform equivalent linear site response analysis. Each of the examples and required acceleration-time series can be installed by including the examples option during installation. The examples files are found within the examples folder in the installation path (e.g. C:\Program Files\Strata\examples), or by the shortcut in the Strata start manual folder. The examples can be opened by either double clicking on the file, or by selecting them from the 'Open…' item from the File menu.

All examples use the deep alluvium Sylmar County Hospital Parking Lot (SCH) site located in Southern California for the site profile. The soil types and velocity layering of the site was proposed by Chang (1996). The soil properties are listed in Table 4.1 with a water table at a depth of 46 meters. The nonlinear properties for each of the layers were computed using the Darendeli (2001) empirical model with PI=0, OCR=1, and the confining pressures listed in Table 4.1. The corresponding velocity profile is shown in Figure 4.30 (Chang, 1996). The minimum and maximum values are those recommended in Chang (1996). The time-averaged shear-wave velocity over the top 30 meters was computed as 273 m/s.

Table 4.1: Soil profile at the Sylmar County Hospital Parking Lot site Chang (1996). The mean effective stress (σ'_m) is computed assuming a k_0 of 1/2 and a water table depth of 46 meters.

Depth Range (m)	Soil Type	V_s (m/s)	γ_{total} (kN/m³)	σ'_v (kPa)	σ'_m (atm)
0 to 6	Alluvium (Sand)	200 (150 to 230)	18	54	0.36
6 to 31	Alluvium (Sand)	300 (240 to 350)	18	222	2.2
31 to 61	Alluvium (Sand)	460 (370 to 550)	19	562	5.6
61 to 91	Alluvium and Older Alluvium (Sand)	700 (580 to 750)	22	776	7.7
91+	Bedrock	760	22		

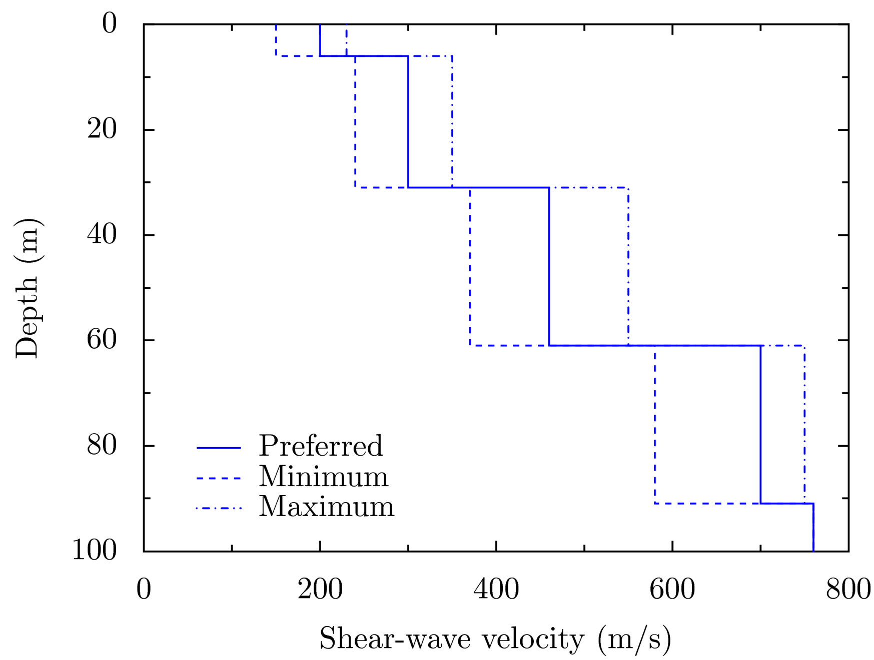


Figure 4.30: The shear-wave velocity profile of the Sylmar County Hospital Parking Lot site (CHANG, 1996).

4.3.1 Example 1: Basic time domain

In the first example, the site response is computed for the Sylmar County Hospital Parking Lot site using a single acceleration-time series. The input file for this example is named example-1-td.strata. In this example, the steps required to compute the acceleration response spectrum at the surface of the site are presented. The following steps assume that you are working from a new project.

4.3.1.1 *General Settings Page*

For the most part, the default values are acceptable on the General Settings page, but there are a few options that one should be sure to define properly. The following steps are taken to define the proper information:

1) A title should be created that accurately represents the project. For this example, this example uses, “Sylmar County Hospital Site -- Time domain.”
2) The default unit system in Strata is the metric system. The units specified on the General Settings Page must be in agreement with the units used throughout the input file.
3) The default calculation method is ‘Recorded Motions’ which is used for this example.

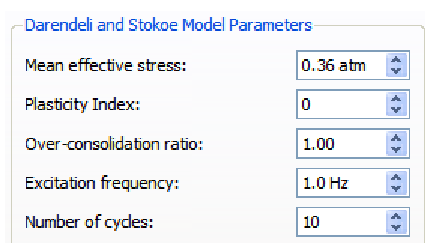
4.3.1.2 *Soil Types Page*

The information presented regarding the site information (Table 4.1 and Figure 4.30) is input into Strata in two different steps. First, the Soil Types Page is used to define the soil types found within the profile. These soil types are then spatially arranged in the Soil Profile Page. The following steps are required to define the Soil Types for the Sylmar County Hospital Site:

1) In the Soil Types Table, click the Add Button to create a new soil type and enter the information found in Table 4.1. The initial damping is the damping in the soil used for the first equivalent-linear iteration and 5% is appropriate for most cases. The nonlinear property model is selected from a drop down list. Select the Darendeli (2001) nonlinear model for both the shear modulus reduction and damping curves.

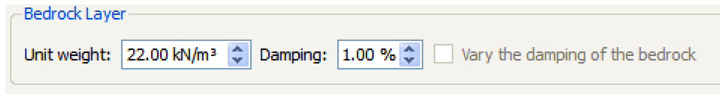
	Name	Unit Weight (kN/m³)	Initial Damping (%)	G/G_max Model	Damping Model	Notes
1	Alluvium (0.36 atm)	18	5	Darendeli & Stokoe	Darendeli & Stokoe	

2) Additional information regarding the soil type is required for the Darendeli (2001) nonlinear model and is found within the Darendli and Stokoe Model Parameters group box. The soil is an alluvium with a plasticity index of 0 and an over-consolidation ratio of 1, which are the default values for the PI and OCR. The excitation frequency and number of cycles will also be left at the default values (1 Hz and 10, respectively). The Darendeli (2001) model requires the mean effective stress for the soil, which is 0.36 atm for the center of the top alluvium layer.



3) Repeat steps (1) and (2) for the remaining three soil types.

4) The bedrock layer is defined by a unit weight of 22 kN/m^3 and damping of 1%.



4.3.1.3 Soil Profile Page

The Soil Profile Page is used to spatially arrange the soil types and define the shear-wave velocity associated with each layer. The following steps are used to input the soil profile information:

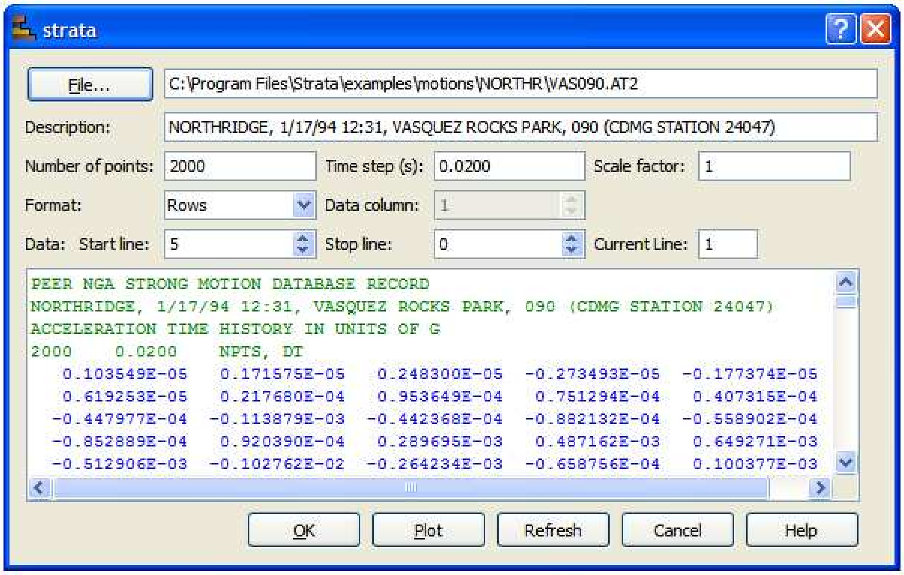
1) In the Velocity Layers Table, click on the Add button to create a new soil profile layer.
2) Define the thickness (6 m), soil type (Alluvium (0.36 atm)), and shear-wave velocity (200 m/s) of the layer.
3) Repeat steps (1) and (2) until all of the layers are defined.

	Depth (m)	Thickness (m)	Soil Type	Average Vs (m/s)
1	0	6	Alluvium (0.36 atm)	200
2	6	25	Alluvium (2.2 atm)	300
3	31	30	Alluvium (5.6 atm)	460
4	61	30	Alluvium (7.7 atm)	700
5	91	Half-space	Bedrock	760

4.3.1.4 Motion (s) Page

For this example, the site response analysis is being computed for one recorded motion. This motion is loaded using the following steps:

1) The motion will be input at the top of the bedrock, so the default location to input the motion is correct.
2) The motion is loaded by clicking on the Add button in the Recorded Motion(s) Table. This will open a dialog box that assists in loading the file (see Section 4.1.4). Click on the File button in the upper left portion of the dialog and select the VAS090.AT2 file from the NORTHR directory (depending on where you installed Strata this might be "C:\Program Files\Strata\example\motions\NORTHR"). Strata automatically parses the AT2 file and fills in the required information. For motions not in the AT2 format, all of the boxes would need to be filled in by hand.



3) Click on the OK button to complete the loading of the file.

4.3.1.5 Output Specification Page

In this example, the goal is compute the acceleration response spectrum at the surface of the site. The requested output will also include the shear strain profile, the acceleration response spectrum at the bedrock, and the spectral ratio between the surface and input rock motions.

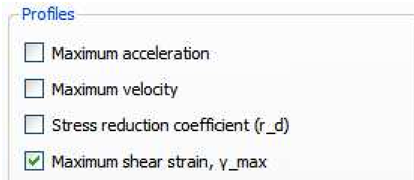
1) For the acceleration-response spectrum, click on the Add button in the Response Location Output Table. Assign the location of the layer to be at the surface (0 m) and select an outcrop boundary condition. Next, click on the check box in the Accel. Resp. Spec. column.
2) To obtain the input acceleration response spectrum at the bedrock level, click on the add button to generate another Response Location. For this row, use the drop down box in the location column to set the depth to be 'Bedrock' and select the 'Outcrop' boundary condition.

	Location	Type	Accel. Resp. Spec.	FAS	Accel-Time
1	0 m	Outcrop	☑	☐	☐
2	Bedrock	Outcrop	☑	☐	☐

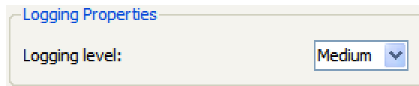
3) For the spectral ratio, click on the Add button in the Ratio Output Table. The default values for the locations are correct (Location 1 at 0 m, Location 2 at Bedrock), but the spectral ratio (Sa_1/Sa_2) column needs to be enabled.

	Location 1	Type 1	Location 2	Type 2	FAS_1 / FAS_2 (accel)	Sa_1 / Sa_2
1	0 m	Outcrop	Bedrock	Outcrop	☐	☑

4) The shear-strain profile is enabled by clicking on the check box in the Profiles Group Box.



5) Sett the logging level to Medium in the Logging Properties. This logging level will report the maximum error for each iteration.

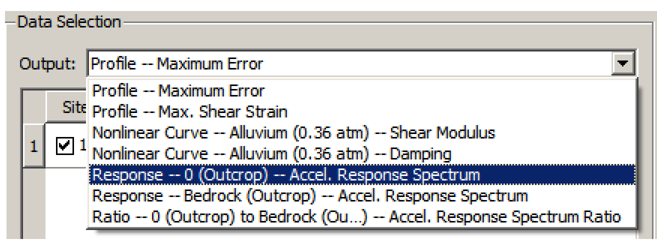


4.3.1.6 *Compute Page*

The calculation is started by clicking on the Compute Button. If you wish you stop the calculation at anytime press the Cancel Button. After the calculation is complete, the Results Page will be selected.

4.3.1.7 *Results Page*

The Results Page allows the user to immediately view the results in a plot. To change the plotted information, select the desired parameter from the Output dropdown list. The data can be exported to use in another program (like Excel) by selecting Export from the File menu.



4.3.2 **Example 2: Time Series with Multiple Input Motions**

In this example, the response at the surface of the site is computed for a suite of input motions. The site properties and output are defined using the same procedure as in Example 1. In this example, the site response is computed for a suite of 10 input motions, each with a different scale factor. This example can be directly loaded from the 'example-2-td.strata' file in the examples directory.

The suite of input motions is presented in Table 4.2. Two different methods may be used to enter these motions into Strata. The direct method is to add each motion individually using the procedure described in Section 4.1.4. If the suite is composed only of AT2 files from the NGA database it is possible to add them using a suite list file. This procedure can be convenient for suites that include a large number of motions. The suite list for the suite in Table 4.2 can be found in the examples directory and is named 'suite-10-1.csv'. To load the suite follow these steps:

1) Select the Motion(s) Page
2) Click on the Load Suite Button
3) Select the appropriate suite file.

After the suite is loaded, switch to the Compute Page and start the calculation.

Table 4.2: Suite of input motions used in Example 2

File	Scale Factor
CHICHI03\TCU138-W.AT2	1.17
NORTHR\H12180.AT2	1.15
CHICHI06\TCU076-E.AT2	1.19
LOMAP\GIL067.AT2	1
NORTHR\VAS090.AT2	1.17
NORTHR\LV3090.AT2	1.3
MORGAN\G01230.AT2	1.41
ITALY\B-CTR000.AT2	1.11
NORTHR\HOW330.AT2	1.2
ITALY\B-BAG270.AT2	1.48

After the calculation is completed the Results Page is selected. The plot shows the individual response spectra (light gray), as wellas the median (solid blue line) and plus and minus one standard deviation (dashed blue line) response spectra (Figure 4.31). The currently selected record is shown in a thick green line if the motion is enabled or in a thick red line if it is disabled. If the result is disabled then it is not included in the statistics. Individual responses can be selected by either clicking on them in the plot window, or selecting them from the table.

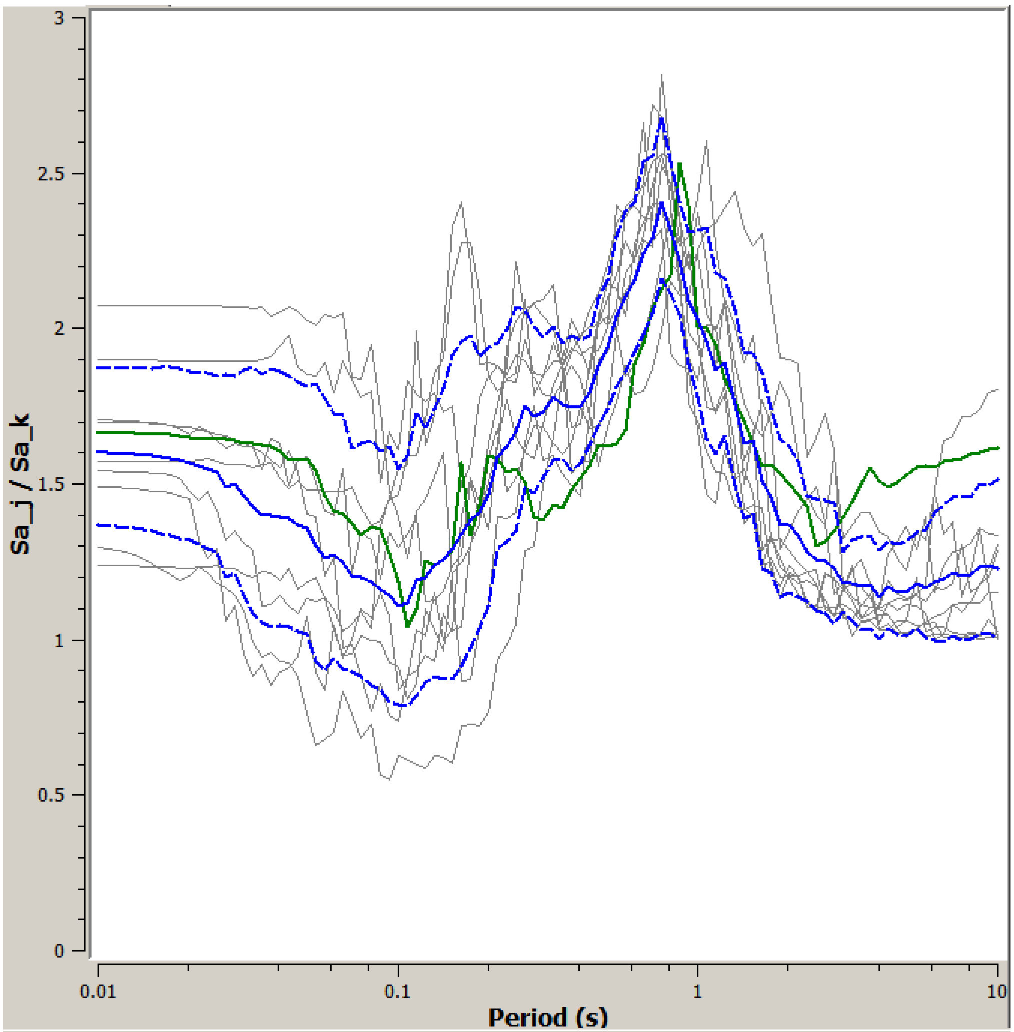


Figure 4.31: Example of a plot with multiple responses.

4.3.3 **Example 3: RVT and Site Variation**

This example uses the same site properties as in the previous examples, but the input motion is defined using a response spectrum and the site response calculation utilizes random vibration theory. Additionally, the shear-wave velocity of the site is varied. This example can be directly loaded from the 'example-3-rvt.strata' file in the examples directory. After the soil types and site profile are defined using the procedures presented in Section 4.3.1, the following changes need to be made:

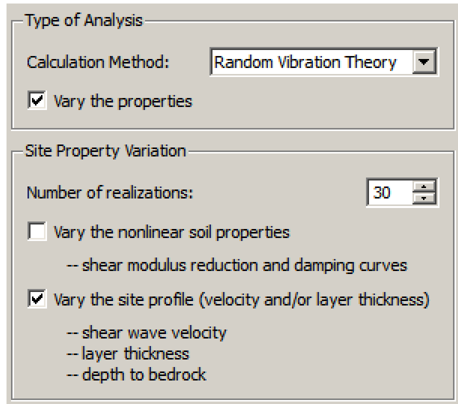
1) General Settings Page

a) Select Random Vibration Theory from the Calculation Method Combo Box.

b) Check the 'Vary the properties' check box to enable site property variation

c) Set the number of realizations to be 30.

d) Disable the variation of the nonlinear soil properties, and enable variation of the site profile.

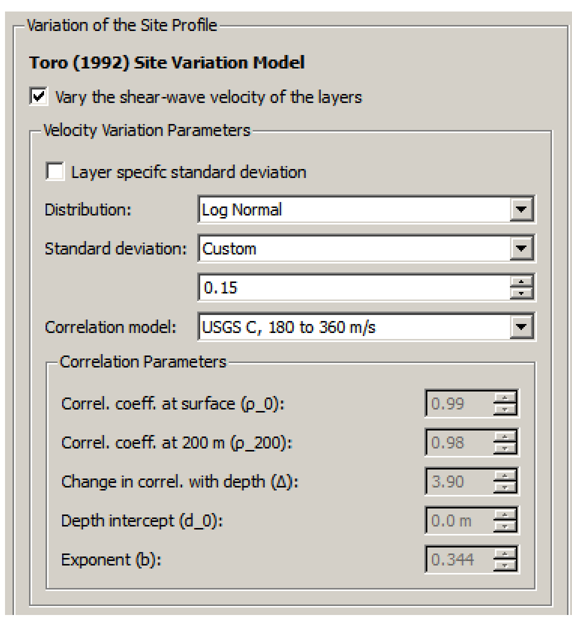


2) **Soil Profile Page** -- now shown in the Soil Profile Page are the widgets that control the site profile variation. This example uses a user specified standard deviation for the site, but uses the generic correlation model.

a) The standard deviation model for the site is defined as 'Custom' through the combo list labeled 'Standard Deviation'.

b) After 'Custom' has been selected, the standard deviation (in natural log units) of the site is set in the box below the 'Custom' selection. For this example the standard deviation is specified as 0.15.

c) The V_{s30} of site is used as a guide to select the 180 to 360 m/s correlation model.



3) Motion(s) Page

a) The response spectrum of the event is loaded into Strata by copying and pasting.

   i) Using a spreadsheet program, open the file name 'response-spectrum.csv' from the examples directory. If the .csv file is associated with Excel, this can be done by double clicking on the file. The damping for this response spectrum is 5%.

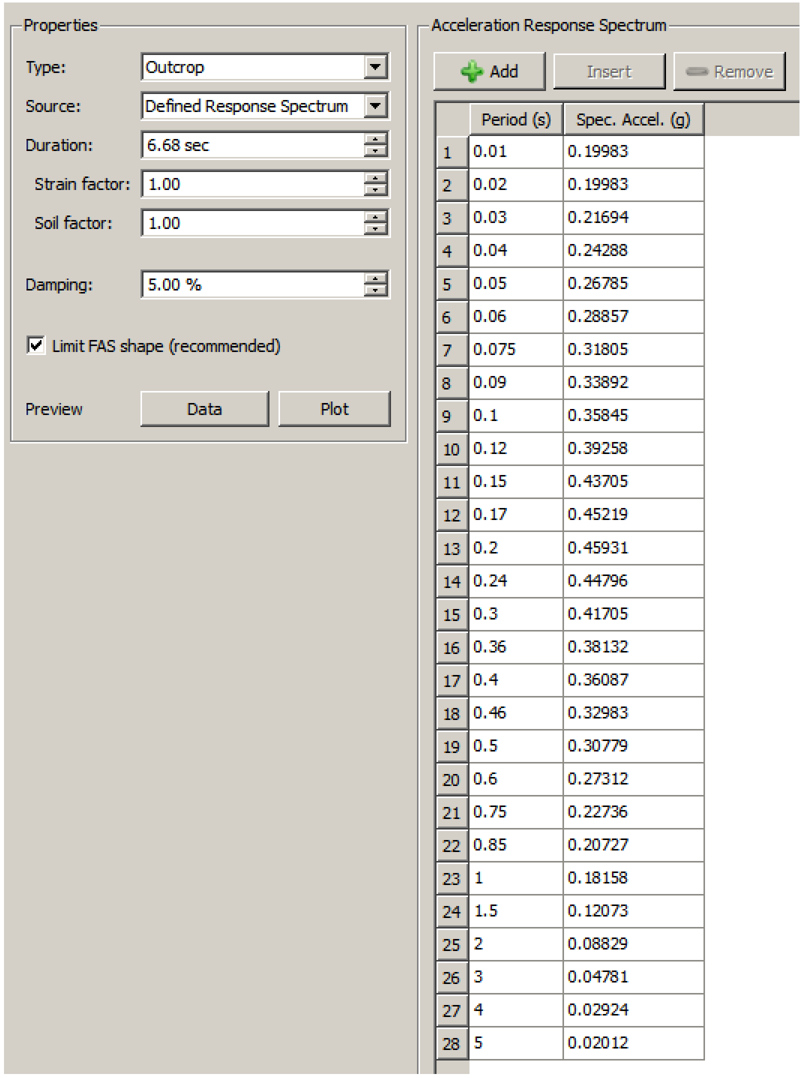
   ii) Select the columns of data from the spread sheet and select Copy from the Edit menu.

   iii) In Strata, select the source to be defined by a response spectrum.

   iv) Click on the Acceleration Response Spectrum Table and then select Paste from the Edit Menu.

b) Define the duration of the event to be 6.68 seconds.

c) The computed Fourier amplitude spectrum can be viewed by clicking on the Plot button.



	Period (s)	Spec. Accel. (g)
1	0.01	0.19983
2	0.02	0.19983
3	0.03	0.21694
4	0.04	0.24288
5	0.05	0.26785
6	0.06	0.28857
7	0.075	0.31805
8	0.09	0.33892
9	0.1	0.35845
10	0.12	0.39258
11	0.15	0.43705
12	0.17	0.45219
13	0.2	0.45931
14	0.24	0.44796
15	0.3	0.41705
16	0.36	0.38132
17	0.4	0.36087
18	0.46	0.32983
19	0.5	0.30779
20	0.6	0.27312
21	0.75	0.22736
22	0.85	0.20727
23	1	0.18158
24	1.5	0.12073
25	2	0.08829
26	3	0.04781
27	4	0.02924
28	5	0.02012

4) Compute Page

The necessary changes have been made to compute the response of the site using RVT with variation of the shear-wave velocity. To see the results, start the calculation on the Compute page.

5 References

Abrahamson, N. A., & Silva, W. J. (1996). *Empirical ground motion models.* Upton, New York: Brookhaven National Laboratory.

Abrahamson, N. A., & Silva, W. J. (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters* , 94-127.

Ang, A. H.-S., & Tang, W. H. (1975). *Probability Concepts in Engineering Planning and Design: Volume I--Basic Principles.* New York: John Wiley and Sons.

Ang, A. H.-S., & Tang, W. H. (1990). *Probability Concepts in Engineering Planning and Design: Volume II--Descision, Risk, and Reliability.* Ang and Tang.

Boore, D. M. (2003). Simulation of Ground Motion Using the Stochastic Method. *Pure and Applied Geophysics , 160* (3-4), 635-676.

Boore, D. M., & Joyner, W. B. (1984). A note on the use of random vibration theory to predict peak amplitudes of transient. *Bulletin of the Seismological Society of America , 74* (5), 2035-2039.

Brune, J. N. (1971). Correction. *Journal of Geophysics Research , 76*, 5002.

Brune, J. N. (1970). Tectonic stress and the spectra of seismic shear waves from earthquake. *Journal of Geophysics Research , 75* (26), 4997-5009.

Campbell, K. W. (1997). Empirical near-source attenuation relationships for horizontal and veritcal components of peak ground acceleraion, peak ground velocity, and pseudo-absolute accleration response spectra. *Seismological Research Letters* , 154-179.

Campbell, K. W. (2003). Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in the Eastern North America. *Bulletin of the Seismological Society of America , 93* (3), 1012-1033.

Cartwright, D. E., & Longuet-Higgins, M. S. (1956). The Statistical Distribution of the Maxima of a Random Function. *Proceedings of the Royal Soceity of London, Series A, Mathematical and Physical , 237* (1209), 212-232.

Chang, S. W.-Y. (1996). *Seismic response of deep stiff soil deposits.* Berkeley: University of California.

Coppersmith, K. (1991). *Ground Motion Following Selection of SRS Design Basis Earthquake and Associated Deterministic Approach.* San Francisco, CA: GeoMatrix Consultants.

Costantino, C. J., Heymsfield, E., & Gu, Y. T. (1991). *Site Specific Estimates of Surface Ground Motions for the K-Reactor Site, Savannah River Plant.* Upton, New York: Structural Analysis Division, Nuclear Energy Department, Brookhaven National Laboratory.

Darendeli, M. B. (2001). *Development of a new family of normalized modulus reduction and material damping curves.* Austin, Texas: The University of Texas.

EPRI. (1993). *Guidelines for Determining Design Ground Motions.* EPRI TR-102293.

Gasparini, D. A., & Vanmarcke, E. H. (1976). *Simulated earthquake motions compatible with prescribed response spectra.* Cambridge, Massachusetts: Massachusetts Institute of Technology.

Geotechnical Engineers Inc. (GEI). (1983). *Evaluation of Dynamic Soil Profiles for the F-Area Sand Filter Structures.* Boston, MA.

Hardin, B. O., & Drnevich, V. P. (1972). Shear modulus and damping in soils: design equations and curves. *Journal of soil mechanics and foundation engineering division, ASCE , 78*, 667-692.

Idriss, I. M., & Sun, J. I. (1992). *SHAKE91: a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits.* Davis, California: Center for Geotechnical Modelling, Department of Civil and Environmentall Engineering, University of California.

Iwasaki, T., Tatsuoka, F., & Takagi, Y. (1976). *Dynamic Shear Deformation Properties of Sand for Wide Strain Range.* Tokyo, Japan: Civil Engineering Institue, Ministry of Construction.

Kao, E. P. (1997). *An Introduction to Stochastic Processes.* Belmont, CA: Duxbury Press.

Kramer, S. L. (1996). *Geotechnical Earthquake Engineering.* Upper Saddle River, New Jersey: Prentice Hall.

McGuire, R. K., Toro, G. R., O'Hara, T. P., Jacobson, J. P., & Silva, W. J. (1989). *Probablistic seismic hazard evaluations at nuclear plant sites in the Central and Eastern United States: Resolution of the Charleston Earthquake Issue.* Palo Alto, California: Electric Power Research Institute.

Rathje, E. M., & Kottke, A. R. (2008). *Procedures for Random Vibration Theory Based Seismic Site Response Analyses.* Rockville, MD: Nuclear Regulatory Commission.

Rathje, E. M., Kottke, A. R., & Ozbey, C. M. (2005). Using inverse random vibration theory to develop input Fourier amplitude spectra for use. *16th International Conference on Soil Mechanics and Geotechnical Eningeering: TC4*, (pp. 160-166). Osaka, Japan.

Schnabel, P. B., Lysmer, J., & Seed, H. B. (1972). *SHAKE: A computer program for earthquake response analysis of horizontally-layered.* University of California, Berkeley, CA: Earthquake Engineering Research Center.

Schneider, J. F., Silva, W. J., Chiou, S., & J.C., S. (1991). Estimation of ground motion at close distances using the band-limited-white-noise model. *Fourth Interntional Conference on Seismic Zonation* (pp. 187-194). Stanford, CA: EERI.

Seed, H. B., & Idriss, I. M. (1970). *Moduli and Dynamic Factors for Dynamic Response Analyses.* University of California, Berkeley: Earthquake Engineering Research Center.

Silva, W. J., Abrahamson, N., Toro, G., & Costantino, C. (1997). *Description and validation of the stochastic ground motion model.* Upton, New York: Brookhaven National Laboratory.

Toro, G. R. (1995). *Probablistic models of site velocity profiles for generic and site-specific ground-motion amplification studies.* Upton, New york: Brookhaven National Laboratory.

Toro, G. R., Silva, W. J., McGuire, R. K., & Hermann, R. B. (1992). Probabilistic Seismic Hazard Mapping of the Mississippi Embayment. *Seismological Research Letters , 63* (3), 449-475.

Turner, E., & Stokoe II, K. H. (1982). *Static and Dynamic Properties of Clayey Soils Subjected to 1979 Imperial Valley Earthquake.* Menlo Park, CA: USGS Geological Engineering Branch.

Vucetic, M., & R, D. (1991). Effect of Soil Plasticity on Cyclic Response. *Journal of the Geoechnical Engineering Division, ASCE* , 89-107.