SeismoSoil Tutorial and Manual

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SeismoSoil is a site-specific response analysis software application, which performs 1-D linear elastic, equivalent linear, and nonlinear site response analyses.

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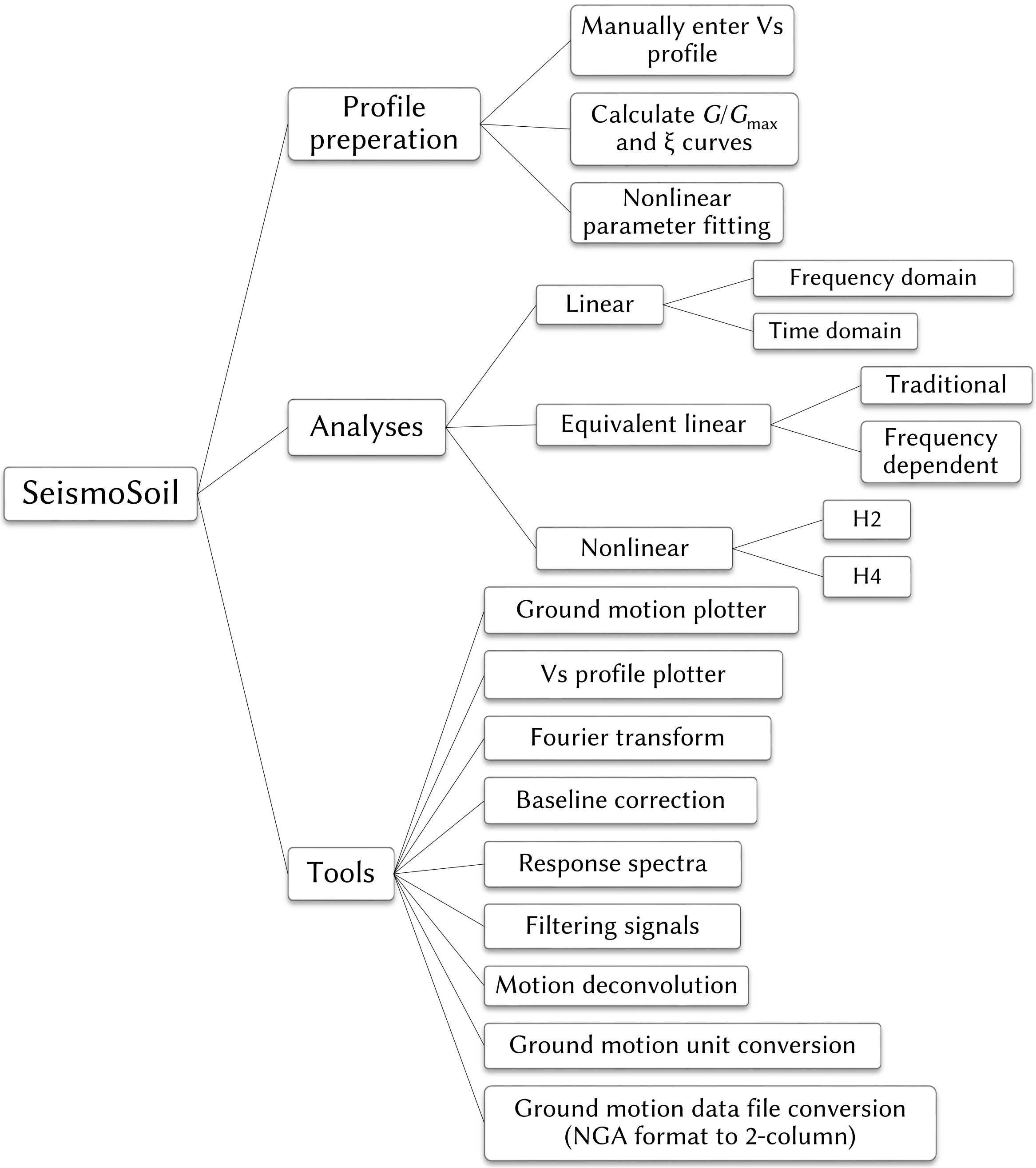
1 Introduction

SeismoSoil is a one-dimensional (1D) site response analysis simulation and visualization application.

1.1 Main features

- **Linear analysis**
  - Frequency domain analysis, which performs the most basic and simplest type of analysis, following the Haskell-Thompson formulation
  - Time domain analysis, useful when the "wrap-around" phenomenon of Fourier transform is pronounced and needs to be addressed
- **Equivalent linear analysis (frequency domain)**
  - Traditional method, which follows the original equivalent linear algorithm
  - Frequency dependent moduli and damping method
- **Nonlinear analysis (time domain)**
  - Uses the traditional Masing hysteretic rule (denoted as *H2*), or
  - Uses Muravskii hysteresis model (denoted as *H4*)
  - Provides built-in tools for doing *H2* and *H4* curve fitting
- **Auto-generation of modulus reduction and damping curves**
  - Generates G/G_{max} and damping curves directly from the soil property profile
  - Based on the formulae proposed by Darendeli
- **Various tools that aid the simulation of site response**
  - Baseline correction, digital signal filtering
  - Motion deconvolution, response spectra calculations, etc.
- **Fast and easy-to-use graphical user interface (GUI)**
  - The GUI is intuitive and self-explanatory
  - SeismoSoil is able to utilize parallel computing technique, using all the cores of the CPU, thus its speed is very fast, even for nonlinear analysis
  - All input and output data files are in plain text format, and can be pasted directly from/to Excel
  - Figures generated can be directly saved to the hard drive

1.2 Functionality structure



2 User Tutorial

2.1 Installation

SeismoSoil requires no installation itself, but some libraries may be required to be installed first.

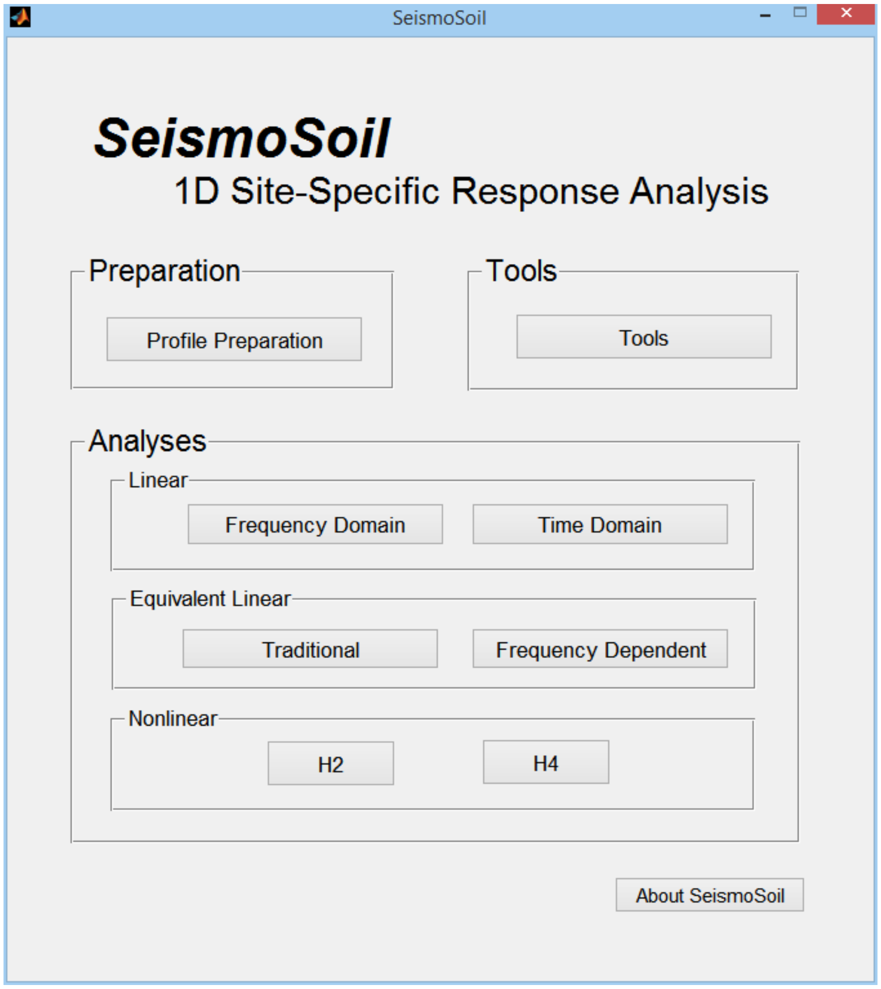
1. If the user has MATLAB R2014b (64-bit) installed on the computer, then SeismoSoil can be launched directly.

2. If the user does not have MATLAB installed, or the user has other versions of 64-bit MATLAB installed, then the installation of MCR (MATLAB Compiler Runtime) is required. MCR is readily provided by MathWorks for free[1]. The users only need to install MCR once, before launching SeismoSoil for the first time. Installing of MCR requires administrator privilege, however, running SeismoSoil does not.

The system requirement of SeismoSoil is: Windows (64-bit), with enough disk space (recommended 4 GB) for installing MCR and storing output files. There is no requirement for minimum CPU and memory, but SeismoSoil runs much faster on more advanced machines (especially with more cores). Mac and Linux versions are currently unavailable. Please contact the authors if you have needs for Mac or Linux versions.

Please keep the four auxiliary files, *TDLinear*, *FDEQ*, *NLH2* and *NLH4*, in the same directory as *SeismoSoil.exe*. The screenshot of the `main` panel of SeismoSoil, shown below, will appear after startup.

[1] http://www.mathworks.com/products/compiler/mcr (please choose "R2014a, 64-bit")


SeismoSoil
SeismoSoil
1D Site-Specific Response Analysis
Preparation
Profile Preparation
Tools
Tools
Analyses
Linear
Frequency Domain
Time Domain
Equivalent Linear
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About SeismoSoil

2.2 Input files preparation

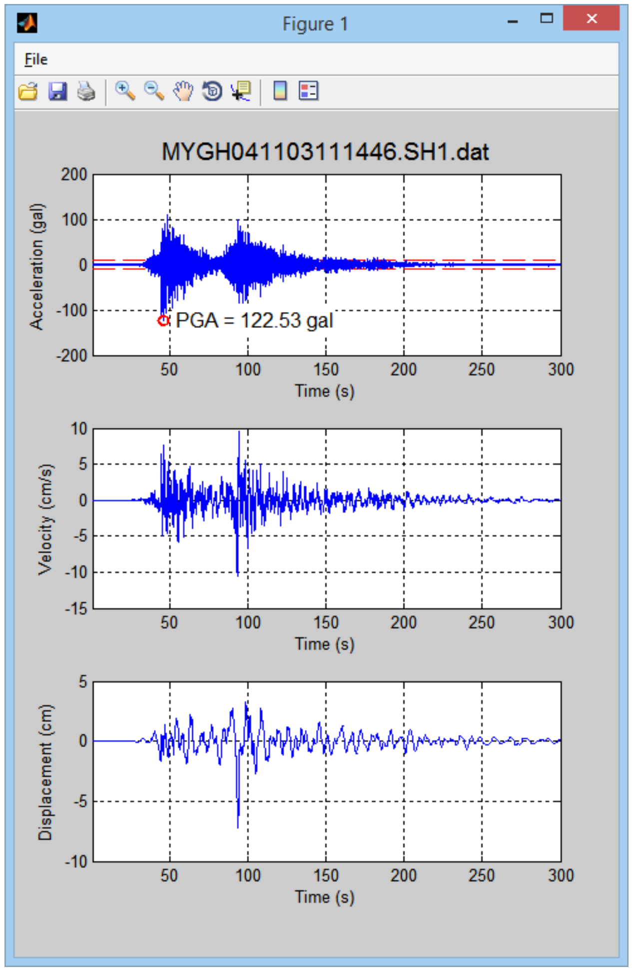
Input file examples are provided in the folder "Sample Input Files". Users can start trying SeismoSoil right away using these files, or can follow the following paragraphs in this section to learn to prepare new input files.

All input files are in plain text format (for example, .txt files). Acceptable delimiters include spaces, commas, and horizontal tabs. The output files generated by SeismoSoil will have horizontal tabs as delimiters.

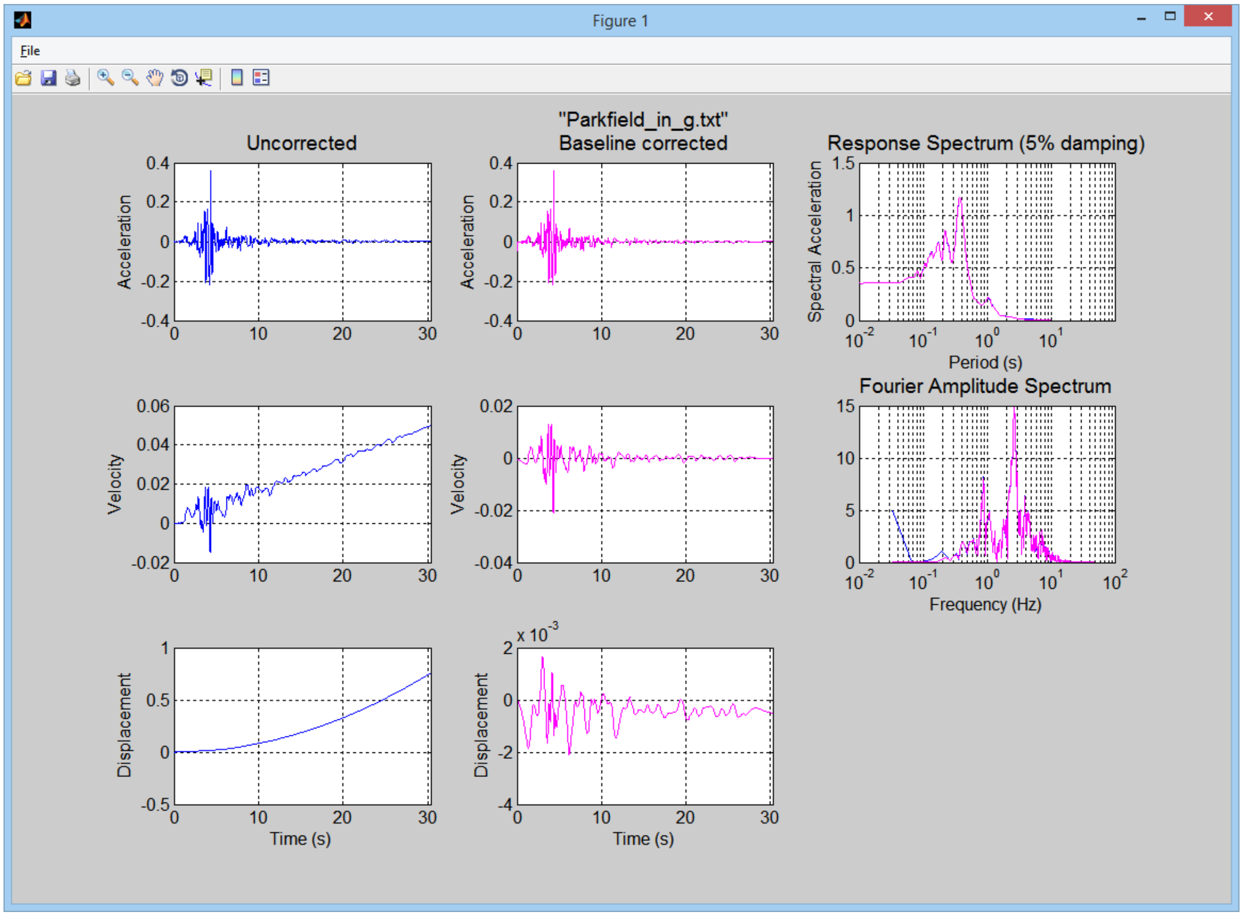
2.2.1 Ground motion

Ground motion data files that can be read by SeismoSoil should have two (and only two) columns—the left column is the time vector in units of seconds, and the right column is the acceleration, in units of $\mathrm{m/s^2}$, gal (= 1 $\mathrm{cm/s^2}$), or g (= 9.81 $\mathrm{m/s^2}$). Users can choose their corresponding unit in simulation graphical panels. There is a NGA to 2-column converter panel under main → tools, which converts the .AT2 format used by PEER/NGA database into the 2-column format.

Main → tools → ground motion plotter provides plots of acceleration time history, as well as velocity and displacement time histories, which are integrated from the acceleration. Arias intensity and RMS acceleration can also be calculated. An example output of the ground motion plotter is shown below.



Under `main` → `tools`, users can also find `signal filter` and `baseline correction`, which filter or baseline-correct the ground motion accelerations; in addition, they can plot the Fourier spectra with `Fourier transform` and elastic response spectra (with any damping ratio value) with `elastic response spectra`. An example of the baseline correction output is shown below.



2.2.2 Soil profile

The input file containing the soil property profile should be in the following five-column format:

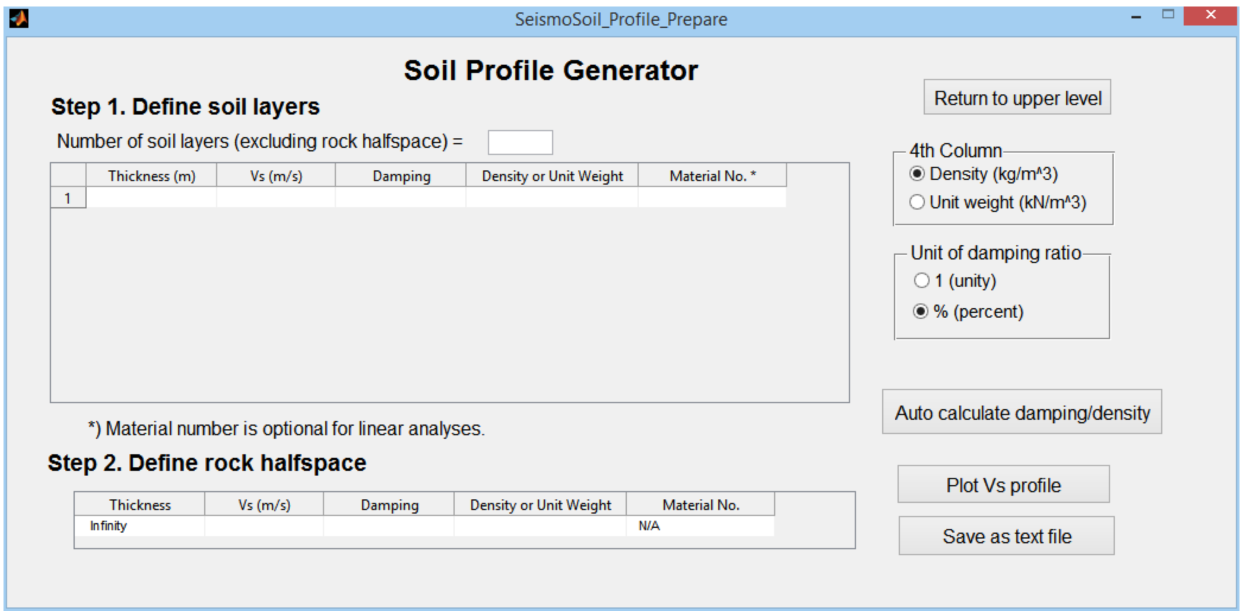
2.00	119.27	0.1000250	1600	1
4.00	366.50	0.0787403	1800	2
3.00	385.05	0.0866096	1800	1
7.00	638.00	0.0408380	1800	2
10.0	577.02	0.0437784	1800	3
11.0	787.65	0.0497050	1800	4
11.0	1533.40	0.0198613	2000	5
15.3	2046.90	0.0170759	2000	5
20.0	2803.90	0.0192725	2000	6
0.00	2795.40	0.0147539	2000	0

From left to right, the columns mean: soil layer thickness (m), shear wave velocity V_s (m/s), low-strain damping ratio, ξ, soil mass density, ρ, and "material number", respectively. The units of ξ can be either % or unity (i.e., 1), and the unit of ρ can be either $\mathrm{g/cm^3}$ or $\mathrm{kg/m^3}$. The users can specify the units of ξ and

ρ on the simulation panels, before the analysis starts. The last thickness value *should always be 0*, which indicates the last layer (i.e., the halfspace) has infinite depth.

The fifth column, the "material number", should be a series of positive integers, not necessary in a continuous and ascending order, with the exception of the last value, which *should always be 0*. The material number refers to the nonlinear dynamic soil parameters, namely the $G/G_{\max}$ and damping curves. For example, the layers with "material number"=5 correspond to the 5th set of $G/G_{\max}$ and damping curves in the "curve file", which will be explained in 2.2.3.

The soil profile can be manually entered through `main` → `profile preparation` → `manually enter Vs profile`. A screenshot of this panel is shown below. Alternatively, users can prepare the input files in external applications like Excel or Notepad, and save them as plain text files.



2.2.3 Nonlinear dynamic soil properties: $G/G_{\max}$ and ξ (damping ratio) curves

The two input files mentioned in 2.2.1 and 2.2.2 are the only files required for linear site response analysis. For the equivalent linear and nonlinear analyses options, dynamic soil properties $G/G_{\max}$ and ξ of soils are required. In SeismoSoil, these properties are specified in a single text file (the "curve file").

Below is the format of a "curve file". The headers are just for demonstration and should not be included in the actual "curve file".

Material #1				Material #2			
Strain (%)	G/G_{max}	Strain (%)	ξ (%)	Strain (%)	G/G_{max}	Strain (%)	ξ (%)
0.0001	0.99454	0.0001	1.8607	0.0001	0.9962	0.0001	1.3366
0.0003	0.98516	0.0003	1.9529	0.0003	0.98965	0.0003	1.3989
0.001	0.95644	0.001	2.2684	0.001	0.96935	0.001	1.6133
0.003	0.8889	0.003	3.1111	0.003	0.92014	0.003	2.1984
0.01	0.72573	0.01	5.5279	0.01	0.79212	0.01	3.9773
0.03	0.49086	0.03	9.8481	0.03	0.58131	0.03	7.554
0.1	0.24177	0.1	15.745	0.1	0.31469	0.1	13.333
0.3	0.10408	0.3	19.875	0.3	0.14333	0.3	18.114
1	0.037002	1	21.884	1	0.052432	1	20.997
3	0.013806	3	21.816	3	0.019763	3	21.489

Each group of four columns corresponds to the dynamic nonlinear soil properties of one material: $G/G_{\max}$ and ξ vs shear strain. The material number, k, on the fifth column of the input soil profile file corresponds to the k-th set of 4 columns in the "curve file".

In main → profile preparation → dynamic soil properties, the $G/G_{\max}$ curves and ξ curves can be automatically calculated using M. B. Darendeli's (2001)[2] formulae. The assumptions are:

- Total stress analysis (deep groundwater table)
- PI (plasticity index) = 20%
- OCR: 1.0 (normally consolidated)
- N (number of cycles): 10
- f = 1 Hz

Thus, the only variable that governs the nonlinear dynamic soil properties is the overburden pressure, which is internally calculated using mass density and depth information.

The ground motion, soil profile and nonlinear dynamic soil properties are the necessary input files for equivalent linear analyses. For nonlinear analyses, the users should also specify the constitutive model parameters, as will be discussed in 2.2.4.

2.2.4 Nonlinear constitutive soil model parameters

Apart from the ground motion, soil profile, dynamic curves, the nonlinear analysis in SeismoSoil requires additional information—the constitutive soil parameters. The *H2* nonlinear method requires one file, H2_n.txt, and the *H4* nonlinear method requires two files, H4_G.txt and H4_x.txt. These files have the same format, which looks like below (actual input files should not have the table headers):

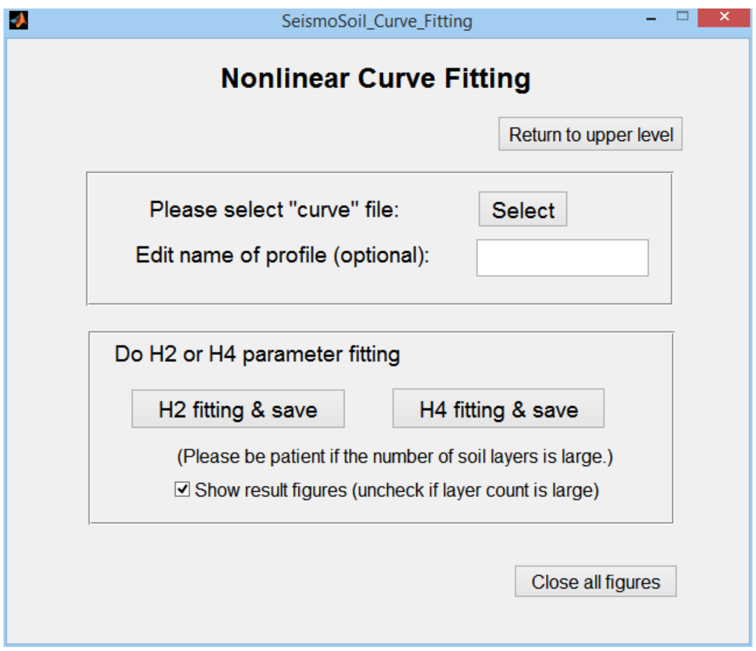
[2]Darendeli, M. B. (2001). "Development of a new family of normalized modulus reduction and material damping curves." Pages 220–272, *PhD thesis*, The University of Texas at Austin.

	Material #1	Material #2	Material #3
γ_{ref}	0.0007952	0.0005334	0.0008326
(always 0)	0	0	0
s	0.61011	0.62597	0.63383
β	1.4072	0.80149	0.91498

Each column of the file corresponds to a set of 4 columns in the "curve file", and in the same order as the "curve file". γ_{ref} is the reference strain, and s and β are the two parameters in the MKZ model. These three parameters are obtained by curve-fitting the two predefined hysteretic models (*H2* and *H4*).

Curve fitting can be done using the main → profile preparation → nonlinear curve fitting panel (shown in the figure below), which takes a "curve file" as the input, and generates a H2_n.txt file (using *H2* curve fitting) or H4_G.txt and H4_x.txt files (using *H4* curve fitting).

The details of the two hysteretic models and these curve-fitting parameters will be explained in Section 3, the technical manual.



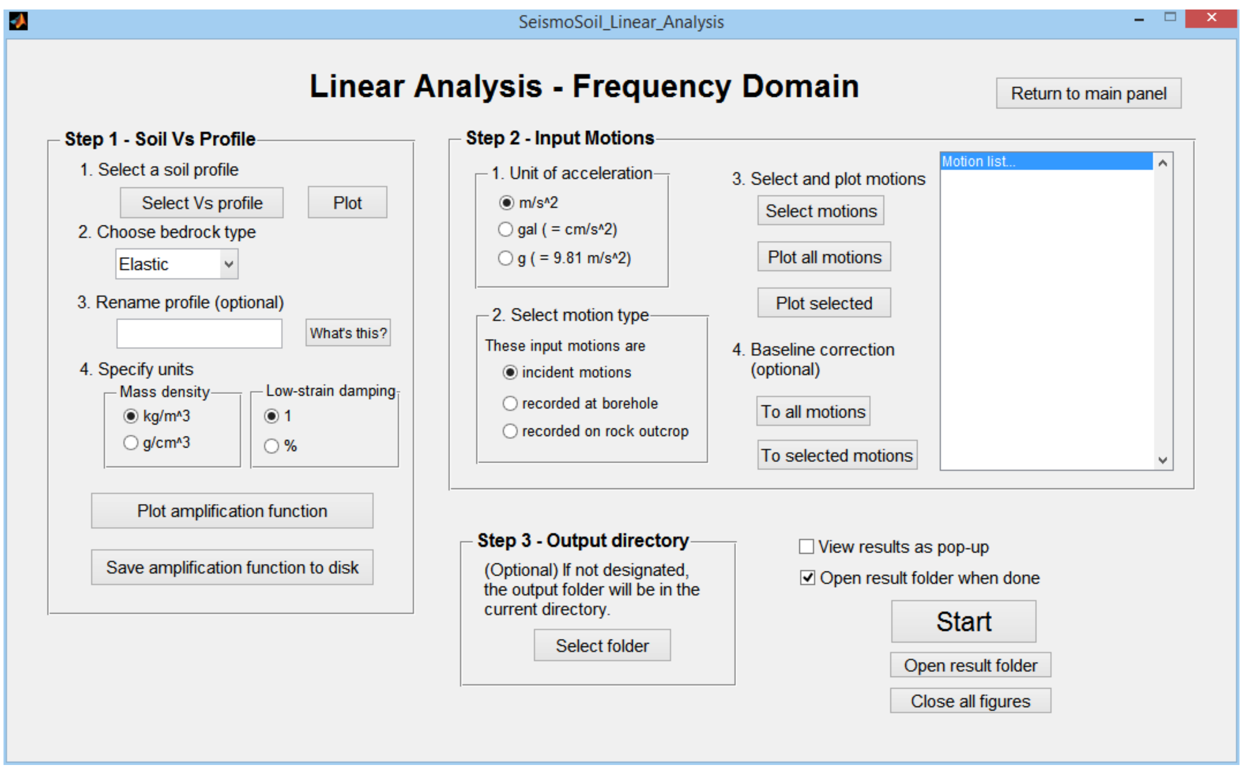
2.3 Run the simulation

The input files necessary for different kinds of simulations are summarized below.

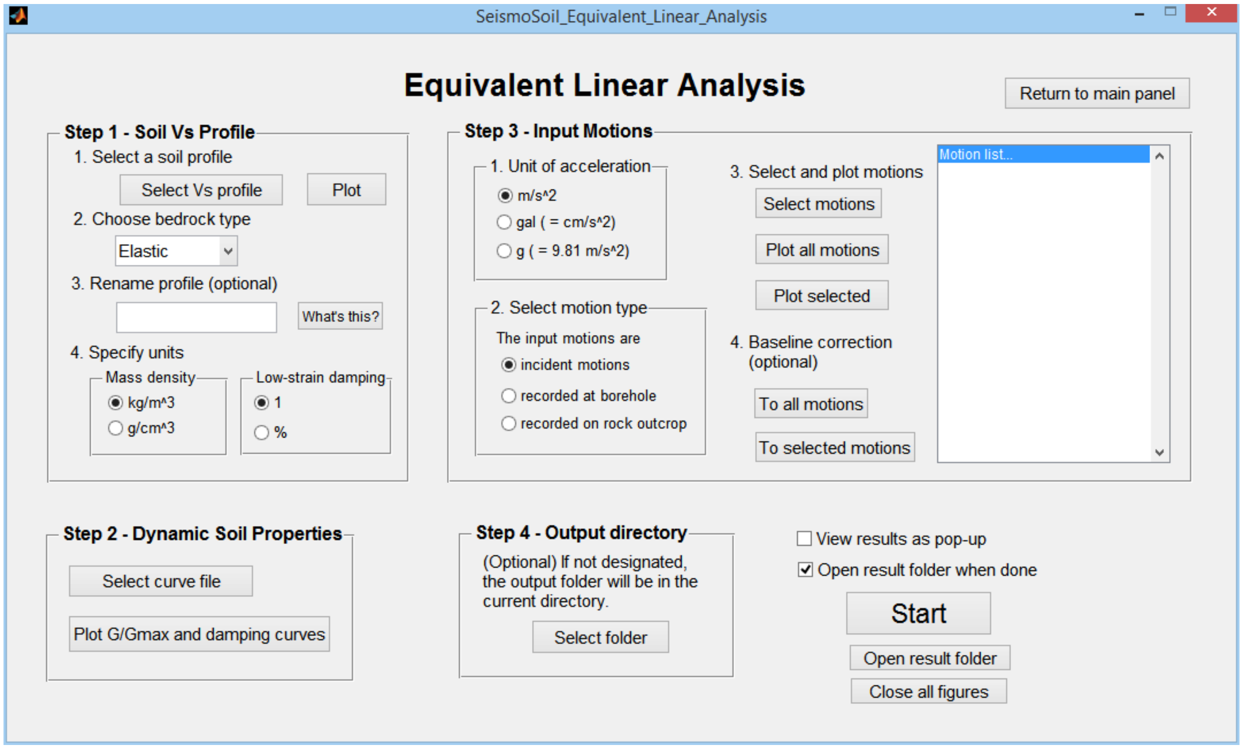
		profile	motion	curve	H2_n	H4_G	H4_x
Linear	frequency domain	✓	✓				
	time domain	✓	✓				
Equivalent linear	traditional	✓	✓	✓			
	frequency dependent	✓	✓	✓			
Nonlinear	H2	✓	✓	✓	✓		
	H4	✓	✓	✓		✓	✓

The user interface for linear analysis is shown below. The users can follow "step 1" to "step 3" on the panel and import the corresponding data. And then the users can click Start to start the calculation. Time-domain and frequency-domain linear methods both have the same user interface.

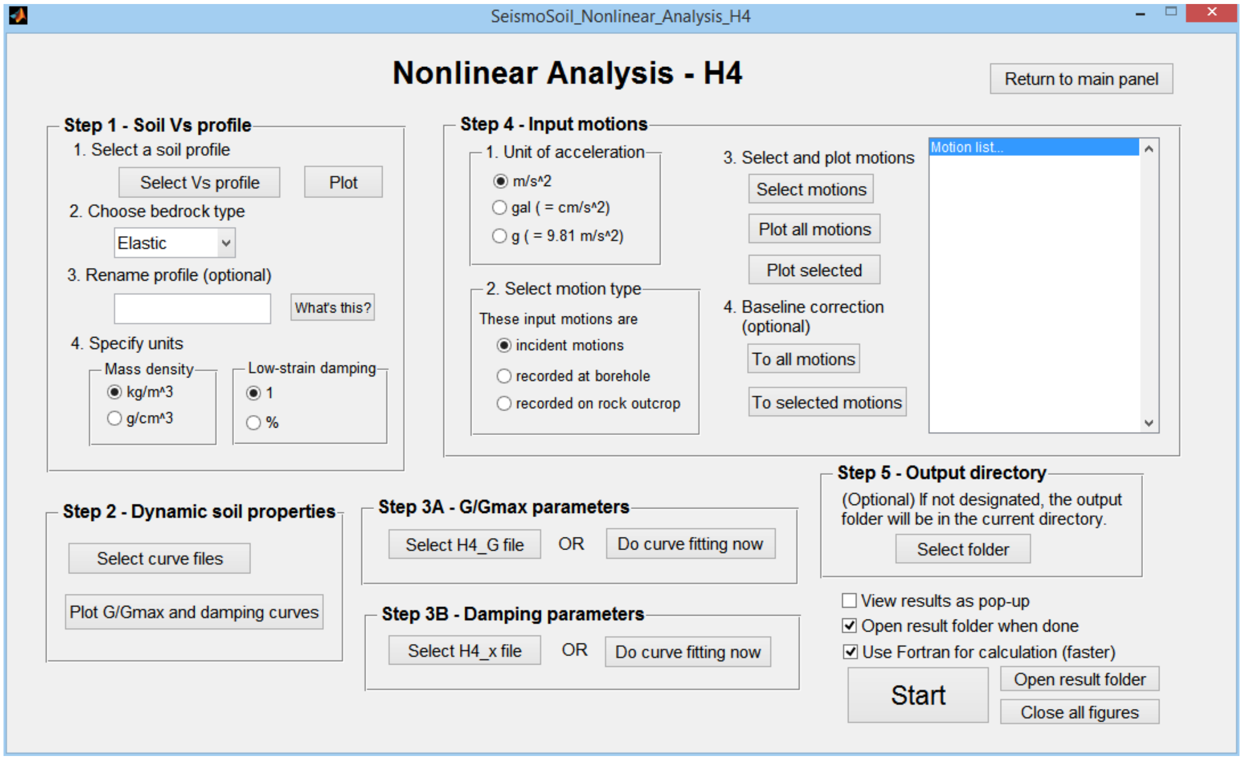
Please note that in Step 1.2 and Step 3.2, bedrock type and motion type should be chosen. Careful consideration is strongly recommended here, since different combinations of these two can lead to rather different results. Please refer to the notes in Section 2.3.1 on page 16 for a detailed explanation of how to make the choice.



The user interface for equivalent linear (traditional and frequency dependent) methods is shown below. Similarly to the linear analysis, the users can follow the procedures indicated on the panel and import the corresponding data.



The user interface for *H4* nonlinear analysis is shown below. The users should have no problem following the procedures indicated on the panel and import the corresponding data. The interface for *H2* nonlinear analysis differs slightly with *H4*, only in "step 3", where *H2* only requires one input file, namely, H2_n.txt.



2.3.1 Notes on bedrock type and input motion location

SeismoSoil has two options of bedrock in the numerical scheme: rigid and elastic. It also accepts three types of input motion: incident motion at the bedrock, total motion at the bedrock (or borehole recorded motion, or sometimes referred as the "within motion"), and total motion on rock outcrop—as shown in the figure below. So there are six combinations:

A) Borehole recorded motion, with:

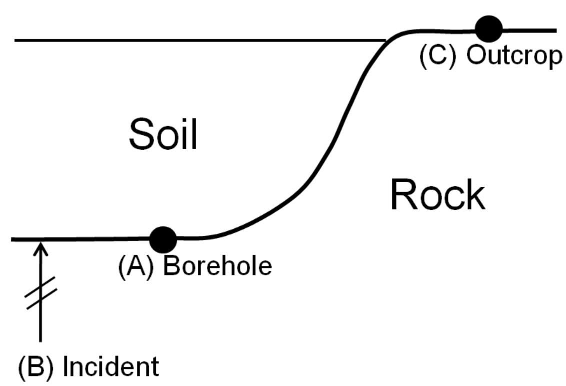
1. **Rigid bedrock** – suitable when the borehole motion is known and prescribed

2. **Elastic bedrock** – for this combination, the software generates a error message and does not do the simulation. Because elastic/viscoelastic bedrock means that the rock outcrop site has its own site response. The traditional approach of dividing the motion by 2 and using it as incident, or directly using the rock outcrop motion as total motion at the base of the profile are not correct and should be avoided if needed. The users are encouraged to remove this response by performing rock outcrop deconvolution to the incident motion, and then run the analysis with other appropriate motion-bedrock combinations.

B) Incident motion, with:

1. **Rigid bedrock** – in this case, the borehole motion, i.e., the total motion, is equal to the outcrop motion, and twice the incident motion

2. **Elastic bedrock** – in this case, the input motion is the borehole motion free of downgoing waves



C) Rock outcrop motion, with:

1. **Rigid bedrock** – this combination is identical to combination A1

2. **Elastic bedrock** – use with caution: the actual motion at the soil-rock interface is slightly different from the outcrop motion, so it is recommended that the users deconvolve the rock outcrop motion to incident motion, and use combination B2

The choice of different combinations affects how SeismoSoil calculates the site response, and thus the results of simulations. Figure 2 on page 20 shows three different types of linear amplification factors corresponding to different choices of bedrock-motion combinations.

2.4 Interpretation of output files

The output data files include the following (assuming the input motion name is M1):

- M1_accel_on_surface.txt - Acceleration time history on ground surface. Two columns: time array (on the left) and acceleration (on the right).
- M1_max_a_v_d.txt - Maximum acceleration, velocity, and displacement of each layer
- M1_max_gamma_tau.txt - Maximum strain and stress of each layer
- M1_nonlinear_TF_raw.txt - Nonlinear transfer function (absolute value, and unprocessed). Two columns: frequency array (on the left) and amplification factor (on the right)
- M1_nonlinear_TF_smoothed.txt - Nonlinear transfer function (absolute value, smoothed, using Konno-Ohmachi algorithm[3]). The format is the same as the raw transfer function.
- M1_re-discretized_profile.txt - Re-discretized soil profile used internally in the simulation, usually finer than the original[4]
- M1_time_history_accel.txt - Acceleration time history of every layer. Each column represents the time history of one layer. And the columns from left to right represent the soil layers from the surface to the bedrock. The time array is not included.
- M1_time_history_veloc.txt - Velocity time history of every layer. Format same as above.
- M1_time_history_displ.txt - Displacement time history of every layer. Format same as above.
- M1_time_history_strain.txt - Strain time history of every layer. Format same as above.
- M1_time_history_stress.txt - Stress time history of every layer. Format same as above.

There are also three .png figures corresponding to the data files.

The units of the output files: the units of results *are all in SI units* (sec, Hz, m, m/s, m/s/s, and Pa), and the unit of the output strains is 1 (not %).

[3]Please refer to Section 3.4.2 on page 23 for details of the Konno-Ohmachi smoothing algorithm
[4]Please refer to Section 3.4.3 on page 23 for details of layer re-discretization.

3 Technical Manual

3.1 Linear approach

In linear approach, the soil is assumed as a Kelvin-Voigt solid, whose dynamic behavior is is described using a purely elastic spring and a purely viscous dashpot[5], having two defining parameters, G (soil modulus) and ξ (soil damping ratio). Linear approach assumes G and ξ to remain unchanged in dynamic processes, which is not the case, especially when the ground motion intensity is strong.

3.1.1 Frequency domain linear approach

In frequency domain linear analysis, the amplification of ground motions by the soil layers are computed via transfer functions, using the following formula,

$$a_{\text{out}}(t) = \text{IFT}\left[H(\omega) \cdot \text{FT}\left[a_{\text{in}}(t)\right]\right] \tag{1}$$

where $a_{\text{in}}(t)$ and a_{out} are the input and output ground motions in time domain, FT[ ] and IFT[ ] represent Fourier transform and inverse Fourier transform, and $H(\omega)$ is the complex-valued transfer function in frequency domain, which can be solely determined by the soil property profile.

The following paragraphs show the derivation of $H(\omega)$ from the soil properties.

Let j denote the soil layer index, and A_j and B_j the upgoing and downgoing SH wave displacement amplitudes at the j-th layer. In this case, the following relationship holds for every j:

$$\left\{ \begin{array}{c} A_{j+1} \\ B_{j+1} \end{array} \right\} = \left[\begin{array}{cc} \frac{1}{2}(1+\alpha_j^*)\mathrm{e}^{ik_j^* h_j} & \frac{1}{2}(1-\alpha_j^*)\mathrm{e}^{-ik_j^* h_j} \\ \frac{1}{2}(1-\alpha_j^*)\mathrm{e}^{ik_j^* h_j} & \frac{1}{2}(1+\alpha_j^*)\mathrm{e}^{-ik_j^* h_j} \end{array} \right] \cdot \left\{ \begin{array}{c} A_j \\ B_j \end{array} \right\} \stackrel{\text{def}}{=\!=} \mathbf{D}_j \cdot \left\{ \begin{array}{c} A_j \\ B_j \end{array} \right\} \tag{2}$$

where $\alpha_j^* = \dfrac{\rho_j V_{s,j}^*}{\rho_{j+1} V_{s,j+1}^*}$ is the complex impedance ratio of two successive layers j and $(j+1)$; $V_{s,j}^* = V_{s,j} \cdot \sqrt{1 + 2i\xi_j}$ is the complex shear wave velocity of layer j; h_j is the thickness of layer j; and $k_j^* = \dfrac{\omega}{V_{s,j}^*} = \dfrac{k_j}{1 + i\xi_j}$ is the complex wave number of layer j, where ω is the angular frequency.

Hence

$$\left\{ \begin{array}{c} A_j \\ B_j \end{array} \right\} = \mathbf{D}_{j-1} \left\{ \begin{array}{c} A_{j-1} \\ B_{j-1} \end{array} \right\} = \mathbf{D}_{j-1}\mathbf{D}_{m-2} \left\{ \begin{array}{c} A_{j-2} \\ B_{j-2} \end{array} \right\} = \cdots = \mathbf{D}_{j-1}\mathbf{D}_{j-2}\cdots\mathbf{D}_1 \left\{ \begin{array}{c} A_1 \\ B_1 \end{array} \right\} \tag{3}$$

where $A_1 = B_1 = S/2$, and S is the total surface displacement amplitude.

Let $\mathbf{E}_{j-1} = \mathbf{D}_{j-1}\mathbf{D}_{j-2}\cdots\mathbf{D}_1$, thus Equation (3) becomes

$$\left\{ \begin{array}{c} A_j \\ B_j \end{array} \right\} = \mathbf{E}_{j-1} \left\{ \begin{array}{c} A_1 \\ B_1 \end{array} \right\} = \left[\begin{array}{cc} E_{j-1}^{\langle 11 \rangle} & E_{j-1}^{\langle 12 \rangle} \\ E_{j-1}^{\langle 21 \rangle} & E_{j-1}^{\langle 22 \rangle} \end{array} \right] \left\{ \begin{array}{c} S/2 \\ S/2 \end{array} \right\} \tag{4}$$

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

Equation (4) relates the displacement amplitudes at the top of the j-th layer to the layer on ground surface. Using this equation we can also relate the displacement amplitudes of any two layers, j and k,

$$\begin{Bmatrix} A_j \\ B_j \end{Bmatrix} = \mathbf{E}_{j-1} \cdot \mathbf{E}_{k-1}^{-1} \cdot \begin{Bmatrix} A_k \\ B_k \end{Bmatrix} \tag{5}$$

And if m is the total number of soil layers (excluding the underlying bedrock), the displacement amplitudes between the top of bedrock and the top of ground surface is

$$\begin{Bmatrix} A_m \\ B_m \end{Bmatrix} = \mathbf{E}_{m-1} \begin{Bmatrix} A_1 \\ B_1 \end{Bmatrix} = \begin{bmatrix} E_{m-1}^{\langle 11 \rangle} & E_{m-1}^{\langle 12 \rangle} \\ E_{m-1}^{\langle 21 \rangle} & E_{m-1}^{\langle 22 \rangle} \end{bmatrix} \begin{Bmatrix} S/2 \\ S/2 \end{Bmatrix} \tag{6}$$

Referring to Figure 1, three types of transfer functions can be written,

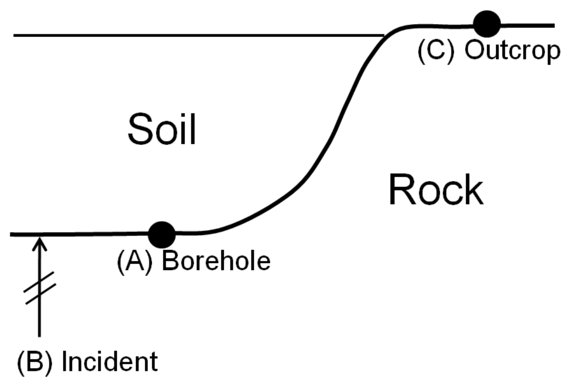


Figure 1: Three types of input motions

(A) The "surface to borehole" (surface motion to total borehole motion) transfer function:

$$H_{\mathrm{A}}(\omega) = \frac{\mathrm{Ampl}(u_1)}{\mathrm{Ampl}(u_{m-(\mathrm{total})})} = \frac{S/2 + S/2}{A_m + B_m} = \frac{2}{E_{m-1}^{\langle 11 \rangle} + E_{m-1}^{\langle 12 \rangle} + E_{m-1}^{\langle 21 \rangle} + E_{m-1}^{\langle 22 \rangle}} \tag{7}$$

(B) The "surface to incident" (surface motion to incident motion at borehole) transfer function is

$$H_{\mathrm{B}}(\omega) = \frac{S/2 + S/2}{A_m} = \frac{2}{E_{m-1}^{\langle 11 \rangle} + E_{m-1}^{\langle 12 \rangle}} \tag{8}$$

(C) The "surface to rock outcrop" (motion at soil surface to motion at rock outcrop site's surface) transfer function is

$$H_{\mathrm{C}}(\omega) = \frac{S/2 + S/2}{2A_m} = \frac{1}{E_{m-1}^{\langle 11 \rangle} + E_{m-1}^{\langle 12 \rangle}} \tag{9}$$

The three types of amplification functions of a same site, plotted together on the same graph, are shown in Figure 2.

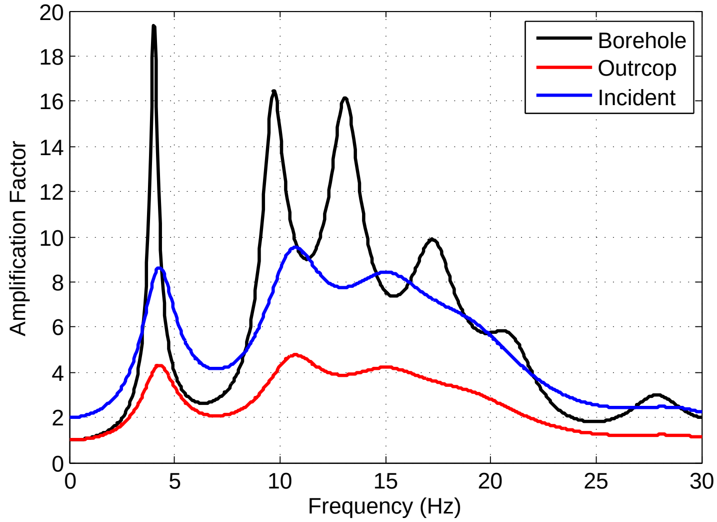


Figure 2: Three types of linear transfer functions

3.1.2 Time domain linear approach

The time domain linear approach solves the wave propagation functions directly in the time domain, using the finite difference scheme. The soil properties remain unchanged during the entire duration of shaking. In order to incorporate G and ξ information from the input into the time domain scheme, a numerical model aiming at approximating the frequency independent damping behavior of soil is used. The degree of approximation is satisfactory, however not perfect. Therefore there is a slight difference between the result of frequency domain linear approach and time domain linear approach.

The merit of time domain linear approach is that it prevents the "wrap-around" phenomenon that frequency-domain linear approach sometimes has. Because of the underlying assumption of Fourier transform, that the signal in time domain being transformed "starts from the beginning of time and lasts forever", the response that corresponds to the end of the input ground motion appears at the beginning part of the output ground motion, i.e., "wrapped-around". This phenomenon is especially pronounced when the input ground motion is synthetic and short, e.g., a Ricker wavelet.

For more details concerning how the temporal-spatial finite difference is carried out, please refer to Section 3.3 on page 22.

3.2 Equivalent linear approach

3.2.1 Traditional equivalent linear approach

The equivalent linear approach, first used in the computer program SHAKE (Schnabel et al., 1972; Idriss & Sun, 1992), is a modified linear approach which partly incorporates the nonlinear properties of soil. This approach accepts that modulus and damping of soil in a dynamic process are no longer the same as their initial values, which are G_{max} and $\xi_{\mathrm{small\ strain}}$. In order to determine the appropriate values for G and ξ, the equivalent linear approach calculates linear site response (in frequency domain) once, obtaining the strain time histories at the center of each soil layer. Then, an "effective" strain value is picked for each layer, which is subsequently used to obtain an updated G value and an updated ξ value from the modulus reduction and damping curves. Linear site response is carried out once more, obtaining updated strain time histories and effective strains, which are used to update G and ξ again. This process is repeated until convergence. The ground response after convergence is the result of the equivalent linear approach.

The detailed procedure of the equivalent linear approach in SeismoSoil is as follows.

1. Re-discretize the existing soil layers based on shear wave velocities of each layer (for details, see Section 3.4.3 on page 24)

2. Calculate linear transfer functions between each intermediate layer and the input point (can either be "borehole", or "incident", or "outcrop")

3. Use Equation (1) to calculate acceleration time histories on the top of each soil layer

4. Integrate acceleration time histories twice to get displacement time histories

5. Use the displacements between two neighboring layers to calculate the approximate strain time histories at the mid-point of each layer

6. Pick 65% of the maximum absolute strain as the "effective" strain (for every layer)

7. Pick updated G and ξ values according to the "effective" strains of each layer

8. Check if the relative differences between two successive G and ξ values fall below 7.5% (for every layer)

9. If true, end the iteration; of not, repeat steps 2–8

10. After 10 iterations, break out of the loop, regardless of convergence

The equivalent linear approach does not reflect the real-world soil behavior in that it assumes constant G and ξ values for each layer, during the entire duration of the dynamic response. In fact, modulus and damping of soil change instantaneously with the strain level that the soil has. Also, different frequency components in the input motion are associated with different strain levels, thus increasing damping values indiscriminatively causes the high frequency components in a ground motions, which are usually not as intense as the low frequency ones, to attenuate excessively. This is especially obvious for deep and soft sites.

An example of linear, equivalent linear and true amplification factors is shown in Figure 3. The true amplifications factor is calculated from actual surface and borehole seismographs. From the figure, we can see that how much equivalent linear approach overdamps the high frequency components, and how linear approach might overestimate ground response at some particular frequencies.

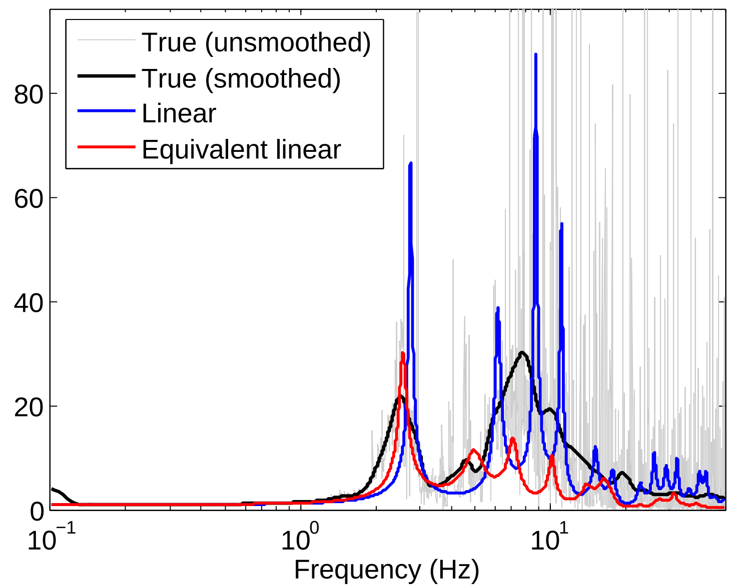


Figure 3: Comparison of amplifications factors

3.2.2 Equivalent linear approach with frequency dependent modulus and damping

(This section is not yet finished. For now, please refer to this paper: Assimaki and Kausel (2002) "An equivalent linear algorithm with frequency- and pressure-dependent moduli and damping for the seismic analysis of deep sites". Soil Dynamics and Earthquake Engineering. Vol. 22, 959–965.)

3.3 Nonlinear approach

(This section is not yet finished. For some first insights into our nonlinear algorithm, please refer to this paper: Assimaki, Li, Steidl, et al. (2008) "Quantifying Nonlinearity Susceptibility via Site-Response Modeling Uncertainty at Three Sites in the Los Angeles Basin". Bulletin of the Seismological Society of America, Vol.98, No.5, pp. 2364–2390.)

3.4 Miscellaneous technical details

3.4.1 Baseline correction

For various reasons, there are usually baseline offsets in the acceleration recordings, resulting in non-realistic shifts in the velocity and displacement time histories integrated from acceleration. To address this issue, we use high-pass filtering to remove the low frequency components in the acceleration recordings.

The procedures are as follows:

- Remove "pre-event" mean value, which is defined as the average acceleration of the "silent" part of the recording, where the acceleration should be zero
- Cut off the beginning and end of the motion using the first zero-crossings as bounds
- Pad zeros at both ends of the acceleration array
- Apply zero-phase high-pass filtering (default cut-off frequency: 0.2 Hz; users can use other values)
- Adjust the filtered time series so that it is aligned chronologically with the original time series

A demonstration of the result of baseline correction can be found on page 9.

3.4.2 Konno-Ohmachi smoothing of frequency spectra

Spectral ratios calculated from surface-borehole ground motion pairs of actual recordings, or from output-input accelerations of the time-domain nonlinear analysis, usually have lots of spikes due to "discrete spectral holes" in the Fourier spectrum at the denominator. A smoothing window applied to the spectral ratio is able to address this problem, making the spectral ratio more intuitive and understandable.

Some traditionally used of smoothing windows include uniform window and triangle window, which has the same span to the left and the right of the point to be smoothed. This type of window has the same "smoothing intensity" for all frequencies, which will be later referred to as the "linear-span smoothing"

However, since the spectral ratios are often plotted in log-frequency scales, and the spikes are usually more pronounced at higher frequencies (above 5−10 Hz), it is advantageous to use a class of smoothing windows that has the same left and right span in logarithmic scale. The Konno-Ohmachi smoothing window[6] is one of this kind. The function for Konno-Ohmachi smoothing window is

$$w(f, f_c) = \left(\frac{\sin\left(b \log_{10}(f/f_c)\right)}{b \log_{10}(f/f_c)} \right)^4 \tag{10}$$

[6] Konno, K. and T. Ohmachi. (1998) "Ground-Motion Characteristics Estimated from Spectral Ratio between Horizontal and Vertical Components of Microtremor". Bulletin of the Seismological Sociaty of Americ, Vol. 88, No. 1, pp. 228−241.

where f_c is the frequency at which the spectral ratio will be smoothed, f is the frequency variable, and b is the smoothing factor which adjusts the width of $w(f, f_c)$. The larger b is, the less "intense" the smoothing would be. In SeismoSoil, the default b value is 40.

Figure 4 shows a comparison of a raw (unsmoothed) spectral ratio, a linear-span smoothed, and two Konno-Ohmachi smoothed ($b = 20$ and 40). From the figure, we can see that the linear-span smoothing does not smooth the high-frequency (above 5 Hz) components enough, thus the two fundamental frequency modes cannot be clearly observed. On the other hand, Konno-Ohmachi smoothing does a better job in eliminating the spectral spikes at higher frequencies, which are mainly numerical artifacts.

However, the users should note that the choice of smoothing functions should serve the purpose of the smothing, Konno-Ohmachi smoothing is appropriate for spectral ratios, but might produce physically meaningless results for other applications.

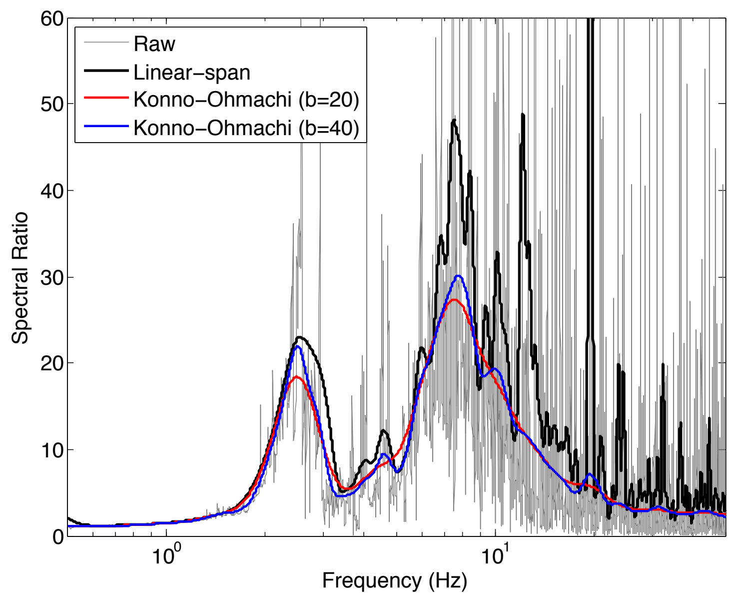


Figure 4: Comparison of different smoothing windows

3.4.3 Automatic re-discretization of soil layers

(Sorry, not yet finished.)

3.4.4 Deconvolution of rock-outcrop motions

(Sorry, not yet finished.)