

Nonlinear and Equivalent Linear Seismic Site Response of One-Dimensional Soil Columns

Version 6.1

www.illinois.edu/~deepsoil

New Soil Model: Specify strength with a Generalized Hyperbolic Formulation

June 22, 2016

USER MANUAL

Youssef M. A. Hashash

Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
hashash@illinois.edu

When referencing the DEEPSOIL program in a publication (such as journal or conference papers, or professional engineering reports) please use the following reference format:
Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Groholski, D.R., Phillips, C.A., and Park, D. (2016) "DEEPSOIL 6.1, User Manual".

© 2016 Youssef Hashash

TABLE OF CONTENTS

1 Program Background and Installation 7
1.1 About the Program 7
1.2 Historical Development 8
1.3 Program installation 11
2 Program Organization 12
2.1 Profiles Tab 14
2.2 Motions Tab 14
2.2.1 Baseline Correction 15
2.2.2 Response Spectra Calculation Methods 16
2.2.3 Fourier amplitude spectrum calculation and averaging 18
2.2.4 Arias Intensity 19
2.2.5 Significant Duration 20
2.2.6 Housner Intensity 20
2.2.7 Estimation of Kappa (κ) *(to be updated)* 20
2.2.8 Adding New Input Motions *(to be updated)* 21
2.3 Analysis Tab 22
3 Analysis Flow 23
3.1 Analysis Definition: Step 1 of 6 23
3.1.1 Equivalent Linear Analysis 25
3.1.2 Deconvolution via Frequency Domain Analysis 25
3.1.3 Non-Linear Analysis 26
3.2 Defining Soil Profile & Model Properties: Step 2a of 6 27
3.2.1 Creating/Modifying Soil Profiles 28
3.2.2 Maximum Frequency (for Time Domain Analysis only) (Step 2b) 28
3.2.3 Implied Strength Profile (Step 2b) 28
3.3 Define Rock Properties: Step 2c of 6 30
3.4 Output and Motion Selection: Step 3 of 6 31
3.5 Viscous Damping 33
3.5.1 Viscous Damping Formulation in Nonlinear Analysis (Time Domain) (Step 4) 33
3.5.2 Viscous Damping in Equivalent Linear Analysis (Frequency Domain) (Step 5) 37
3.6 Analysis Control Parameters: Step 5 of 6 37
3.6.1 Frequency domain analysis 38
3.6.2 Time domain analysis 39
3.7 Output: Step 6 of 6 40
3.7.1 Output data file 42
3.7.2 Summary Profiles 42
3.7.3 Displacement profile and animation 43
3.7.4 Convergence results (Equivalent Linear Analyses Only) 44
3.7.5 Input Summary 45
4 Soil Models 46
4.1 Backbone Curves 46
4.1.1 Hyperbolic / Pressure-Dependent Hyperbolic (MKZ) 46
4.1.2 Generalized Quadratic/Hyperbolic (GQ/H) Model with Shear Strength Control 47
4.2 Hysteretic (unload-reload behavior) behavior 48

4.2.1 Masing Rules 48
4.2.2 Non-Masing Unload-Reload Rules 48
4.3 Porewater Pressure Generation & Dissipation 50
4.3.1 Dobry/Matasovic Model for Sands 50
4.3.2 Matasovic and Vucetic Model for Clays 55
4.3.3 GMP (Green, Mitchel and Polito) Model for Cohesioneless Soil 58
4.3.4 Generalized Energy-based PWP Generation Model 59
4.3.5 Park and Ahn Model for Sands 60
4.3.6 Porewater pressure degradation parameters 62
4.3.7 Porewater pressure dissipation 63
5 Examples and Tutorials 64
5.1 Example 1: Undamped Linear Analysis with Resonance 64
5.1.1 Soil Profiles: 64
5.1.2 Input Motion: 64
5.1.3 Results: 64
5.2 Example 2: Undamped Linear Analysis with Elastic Bedrock 66
5.2.1 Soil Profiles: 66
5.2.2 Input Motion: 66
5.2.3 Results: 66
5.3 Example 3: Damped Linear Analysis with Elastic Bedrock 68
5.3.1 Soil Profiles: 68
5.3.2 Input Motion: 68
5.3.3 Results: 68
5.4 Example 4: Equivalent Linear Analysis with Discrete Points 70
5.4.1 Soil Profile: 70
5.4.2 Input Motion: 70
5.4.3 Results: 70
5.5 Example 5: Nonlinear Analyses, MKZ with Masing Rules 71
5.5.1 Soil Profile: 71
5.5.2 Input Motion: 71
5.5.3 Results: 71
5.6 Example 6: Nonlinear Analysis, MKZ with Non-Masing Behavior 72
5.6.1 Soil Profile: 72
5.6.2 Input Motion: 72
5.6.3 Results: 72
5.7 Tutorial 1: Single Element Test 73
5.7.1 Soil Profile: 73
5.7.2 Input Strain Path: 73
5.7.3 Results: 73
6 References 74
7 APPENDIX A: Included Ground Motions 78
8 APPENDIX B: Archived Examples 79
8.1 Example 1 Linear Frequency Domain Analysis / Undamped Elastic Layer, Rigid Rock 79
8.2 Example 2 Linear Frequency Domain Analysis / Undamped Elastic Layer, Elastic Rock 89
8.3 Example 3 Linear Frequency Domain Analysis / Damped Elastic layer, Elastic rock 93

8.4 Example 4 Equivalent Linear Frequency Domain Analysis / Single Layer, Elastic Rock96
8.5 Example 5 Equivalent Linear Frequency Domain Analysis / Multi-Layer, Elastic Rock 105
8.6 Example 6 Non-linear Analysis / Multi-Layer, Elastic Rock 110
8.7 Example 7 Non-linear Analysis / Multi-Layer, Elastic Rock, Pore Water Pressure Generation and Dissipation 120
8.8 Example 8 Non-linear Analysis / Multi-Layer, Elastic Rock, Pore Water Pressure Generation and Dissipation 125
8.9 Example 9 Equivalent Linear Frequency Domain Analysis / Multi-Layer, Elastic Rock, Bay Mud Profile 128
8.10 Example 10 Non-linear Analysis / Multi-Layer, Rigid Rock, Treasure Island Profile .. 128
8.11 Example 11 Non-linear Analysis / Multi-Layer, Elastic Rock, MRDF 128
9 APPENDIX C: Description of the GQ/H Model 129

LIST OF Tables

Table 1: Available Excess Pore Water Pressure Generation Models and Parameters 50
Table 2 Description of Dobry/Matasovic Model Parameters 51
Table 3: Material Parameters for Low Plasticity Silts and Sands for the Matasovic and Vucetic (1993) pore pressure generation model (From Carlton, 2014) 53
Table 4: Description of Matasovic and Vucetic Model Parameters 55
Table 5: Material parameters for the Matasovic and Vucetic (1995) clay pore pressure generation model (From Carlton, 2014) 57
Table 6: Description of GMP Model Parameters 58
Table 7: Description of Generalized Model Parameters 59
Table 8: Description of Park and Ahn Model Parameters 60

LIST OF FIGURES

Figure 1. DEEPSOIL Main Window and Key Tabs 12
Figure 2. DEEPSOIL Options Window. 13
Figure 3. Motion Viewer (Plots) 14
Figure 4. Motion Viewer (Tables) 15
Figure 5. Baseline Correction. 16
Figure 6. Kappa estimation tool. 21
Figure 7. Step 1/6: Choose type of analysis. 23
Figure 8. Step 2a/6: Input Soil Properties. 27
Figure 9. Profile Summary 29
Figure 10. Step 2b/6: Input Rock Properties. 30
Figure 11. Step 3/6: Input Motion and Output Layer(s) (Time History Plots Tab) 32
Figure 12. Step 3/6: Input Motion and Output Layer(s) (Spectral Plots Tab) 32
Figure 13. Step 3/6: Input Motion and Output Layer(s) (Tripartite Plots Tab) 33
Figure 14. Step 4/6: Small-Strain Damping Formulation. 34
Figure 15. Step 5/6: Analysis Options for Frequency Domain or Time Domain Analysis. 38
Figure 16. Step6/6: Analysis Results - Plot Output for Layer. 41
Figure 17. Summary Profiles 42
Figure 18. Column Displacement Animation 43
Figure 19. Convergence Check. 44
Figure 20. Input Summary 45
Figure 21: a) Carlton (2014), best fit correlating Vs (m/sec) to parameter F of Dobry pore water pressure model for sands. b) Carlton (2014), best fit correlating FC (%) to parameter s of Dobry pore water pressure model for sands. 52
Figure 22: Proposed correlation to estimate curve-fitting parameter F (Mei et al. 2015) 54
Figure 23: Comparison of the curves given by Matasovic (1993) and Vucetic (1992) (solid black lines) for t for different values of PI and OCR and the correlations presented (dotted red lines). (Carlton, 2014) 56

1 Program Background and Installation

1.1 About the Program

DEEPSOIL is a one-dimensional site response analysis program that can perform: a) 1-D nonlinear time domain analyses with and without pore water pressure generation, and b) 1-D equivalent linear frequency domain analyses including convolution and deconvolution.

DEEPSOIL was developed under the direction of Prof. Youssef M.A. Hashash in collaboration with several graduate and undergraduate students including Duhee Park, Chi-Chin Tsai, Camilo Phillips, David R. Groholski, Daniel Turner, Michael Musgrove, Byungmin Kim and Joseph Harmon at the University of Illinois at Urbana-Champaign.

When referencing the DEEPSOIL program in a publication (such as journal or conference papers, or professional engineering reports) please use the following reference format:

Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Groholski, D.R., Phillips, C.A., and Park, D. (2016) "DEEPSOIL 6.1, User Manual".

The program is provided as-is and the user assumes full responsibility for all results. The use of the DEEPSOIL program requires knowledge in the theory and procedures for seismic site response analysis and geotechnical earthquake engineering. It is suggested that the user reviews relevant literature and seek appropriate expertise in developing input of the analysis and interpretation of the results.

Initial development of DEEPSOIL was based on research supported in part through Earthquake Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9701785; the Mid-America Earthquake Center. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors gratefully acknowledge this support.

By using this program, the user(s) agree to indemnify and defend Youssef Hashash and the University of Illinois against all claims arising from use of the software and analysis results by the user(s) including all third party claims related to such use.

Please see the program license for additional information.

DEEPSOIL implements the Armadillo C++ linear algebra library (Sanderson, 2010; Sanderson, 2016). Armadillo is open-source software released under the Mozilla Public License 2.0. A copy of this license is available at https://www.mozilla.org/MPL/2.0/. You may obtain a copy of the Armadillo source code at http://arma.sourceforge.net/download.html.

1.2 Historical Development

DEEPSOIL has been under development at UIUC since 1998. The driving motivation of the development of DEEPSOIL was and continues to be making site response analysis readily accessible to students, researchers and engineers worldwide and to support research activities at UIUC.

In DEEPSOIL we maintain that it is always necessary to perform equivalent linear (EL) in conjunction with nonlinear (NL) site response analyses. Therefore, DEEPSOIL, since its inception, has incorporated both analysis capabilities. Version 6 of DEEPSOIL gives the user the option to automatically obtain EL analysis results whenever an NL analysis is selected without the need to separately develop an EL profile.

As with any development, DEEPSOIL has benefited from many prior contributions by other researchers as well as current and former students at UIUC. For the interested reader, a detailed description of many of the theoretical developments and the background literature can be found in the following publications:

Hashash, Youssef M. A., and Duhee Park (2001) "Non-linear one-dimensional seismic ground motion propagation in the Mississippi embayment," Engineering Geology, Vol. 62, No. 1-3, pp 185-206.

Hashash, Y. M. A., and D. Park (2002) "Viscous damping formulation and high frequency motion propagation in nonlinear site response analysis," Soil Dynamics and Earthquake Engineering, Vol. 22, No. 7, pp. 611-624.

Hashash, Y. M.A., Chi-Chin Tsai, C. Phillips, and D. Park (2008) "Soil column depth dependent seismic site coefficients and hazard maps for the Upper Mississippi Embayment," Bull. Seism. Soc. Am., Vol. in press.

Hashash, Y.M.A., Phillips, C. and Groholski, D. (2010). "Recent advances in non-linear site response analysis", Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Paper no. OSP 4.

Park, D. (2003) "Estimation of non-linear seismic site effects for deep deposits of the Mississippi Embayment," Ph.D. Thesis. Department of Civil and Environmental Engineering. Urbana: University of Illinois, p 311 p.

Park, D., and Y. M. A. Hashash (2004) "Soil damping formulation in nonlinear time domain site response analysis," Journal of Earthquake Engineering, Vol. 8, No. 2, pp 249-274.

Park, D., and Y.M.A. Hashash (2005) "Estimation of seismic factors in the Mississippi Embayment: I. Estimation of dynamic properties," Soil Dynamics and Earthquake Engineering, Vol. 25, pp. 133-144.

Park, D., and Y.M.A. Hashash (2005) "Estimation of seismic factors in the Mississippi Embayment: II. Probabilistic seismic hazard with nonlinear site effects," Soil Dynamics and Earthquake Engineering, Vol. 25, pp. 145-156.

Tsai, Chi-Chin (2007) "Seismic Site Response and Interpretation of Dynamic Soil Behavior from Downhole Array Measurements," Ph.D. Thesis. Department of Civil and Environmental Engineering. Urbana: University of Illinois at Urbana-Champaign.

Tsai, Chi-Chin, and Y. M. A. Hashash (2008) "A novel framework integrating downhole array data and site response analysis to extract dynamic soil behavior," Soil Dynamics and Earthquake Engineering, Vol. Volume 28, No. Issue 3, pp 181-197.

Tsai, Chi-Chin, and Youssef M.A. Hashash (2009) "Learning of dynamic soil behavior from downhole arrays," Journal of geotechnical and geoenvironmental engineering, Vol. in press.

Phillips, Camilo, and Youssef M. A. Hashash (2008) "A new simplified constitutive model to simultaneously match modulus reduction and damping soil curves for nonlinear site response analysis," Geotechnical Earthquake Engineering & Soil Dynamics IV (GEESD IV). Sacramento, California.

Phillips, C. and Hashash, Y. (2009) "Damping formulation for non-linear 1D site response analyses" Soil Dynamics and Earthquake Engineering, Vol. 29, No. 7, pp 1143-1158.

The executable version of DEEPSOIL was originally (circa 1998-1999) developed as a MATLAB program and (circa 1999) later redeveloped as a C based executable to improve computational efficiency. A visual user interface was added soon afterwards. Since then, numerous developments have been added. Listed below are some important milestones:

- DEEPSOIL v1.0: First version of DEEPSOIL with both an equivalent linear analysis capability and a new pressure dependent hyperbolic model in nonlinear analysis:

  - The equivalent linear capability was based on the pioneering work of Idriss and Seed (1968), and Seed and Idriss (1970) as employed in the widely used program SHAKE (Schnabel, et al., 1972) and its more current version SHAKE91 (Idriss and Sun, 1992).

  - The new pressure dependent hyperbolic model introduced by Park and Hashash (2001) is employed in nonlinear analysis. This model extended the hyperbolic model introduced by Matasovic (1992) and employed in the nonlinear site response code D-MOD, which was in turn a modification of the Konder and Zelasko (1963) hyperbolic model. The hyperbolic model had been employed with Masing criteria earlier in the program DESRA by Lee and Finn (1975, 1978). The hyperbolic model was originally proposed by Duncan and Chang (1970), with numerous modifications in other works such as Hardin and Drnevich (1972) and Finn et al. (1977).

- DEEPSOIL v2.0-2.6:
  - Full and extended Rayleigh damping is introduced in DEEPSOIL (Hashash and Park, 2002; Park and Hashash, 2004) with a user interface. This was in part based on Clough and Penzien (1993) and the findings of Hudson et al. (1994) as implemented in the program QUAD4-M.

  - Additional developments and modifications are made in DEEPSOIL benefited greatly from the PEER lifeline project "Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures (PEER 2G02)".

- DEEPSOIL v3.0-3.7: Additional enhancements are made to the user interface as well as inclusion of pore water pressure generation/dissipation capability.

  - Current pore water pressure models employed include the same model introduced by Matasovic (1992), Matasovic and Vucetic (1993, 1995) and employed in the program D_MOD.

- The current dissipation model used in DEEPSOIL is derived from FDM considerations.

- DEEPSOIL v3.5: A new soil constitutive model is introduced to allow for significantly enhanced matching of both the target modulus reduction and damping curves (Phillips and Hashash, 2008).

  - A new functionality in the user interface is implemented that allows the user to automatically generate hyperbolic model parameters using a variety of methods (Phillips and Hashash, 2008).

  - DEEPSOIL v3.7: A new pore water pressure generation model for sands is added – the GMP Model (Green et al., 2000), in addition to various improvements in the user interface, as well as the capability to export output data to a Microsoft Excel file.

- DEEPSOIL v4.0: Complete rewrite of DEEPSOIL user interface.

  - DEEPSOIL was made multi-core aware, leading to much faster completion of batch-mode analyses.

  - An update manager was added to notify the user when updated versions of DEEPSOIL were available.

  - Added a motion processor and a PEER motion converter

- DEEPSOIL v5.0: Updates of DEEPSOIL user interface and computational engine.

  - Introduced a new dynamic properties window with significant usability enhancements.

  - First version of DEEPSOIL to natively support 64-bit Windows, enabling faster analyses and the ability to use very long motions.

- DEEPSOIL v6.0: Complete rewrite of DEEPSOIL computational engine and user interface from the ground up resulting in significantly faster software. Numerous new capabilities are introduced. A new analysis workflow is introduced.

- DEEPSOIL v6.1: The GQ/H nonlinear model is added to DEEPSOIL allowing the user to specify soil strength in a Generalized Hyperbolic Model.

1.3 Program installation

Installing DEEPSOIL Using Setup

System Setup
DEEPSOIL uses “.” as the symbol for the decimal. For most users outside the USA please change "," to "." for the decimal mark in your system when using DEEPSOIL.

Hardware Requirements
2 GHz or faster processor*
2 GB or more available RAM
250 MB available on hard drive for installation

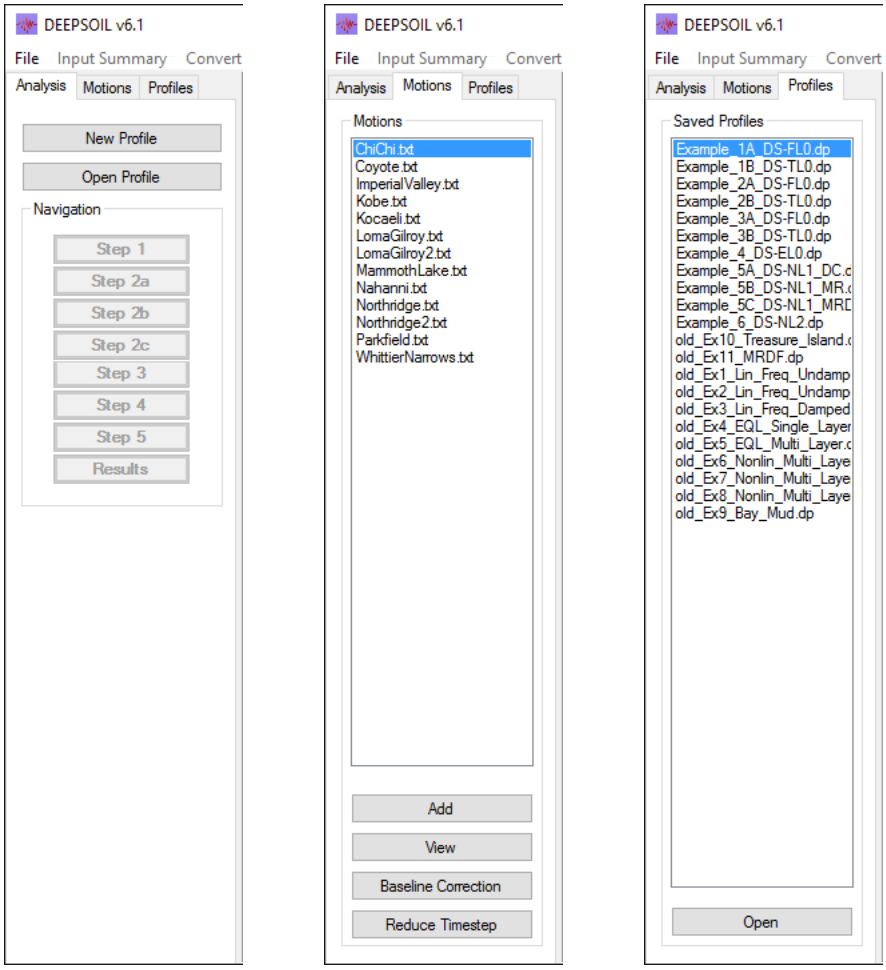
*Parallel analyses require a multi-core processor

Software Requirements
Windows 7 or later
Microsoft .NET Framework 4.5.2 or later
Administrator privileges are required for installation

Installation
Run “DEEPSOIL Installer.exe”
The DEEPSOIL installer will automatically detect if your system supports 64-bit installations and install the appropriate libraries

2 Program Organization

The DEEPSOIL graphical user interface is composed of several steps to guide the user throughout the site response analysis process as illustrated in the Navigation box shown in Figure 1 presented to the user upon starting DEEPSOIL.



(a) Analysis Tab; (b) Motions Tab; (c) Profiles Tab

Figure 1. DEEPSOIL Main Window and Key Tabs

At the top left, the user has the option of choosing the "Analysis," "Motions," or "Profiles" tab. These tabs are discussed in the following section.

Figure 2 shows the Options window. This window can be accessed by clicking on the "Options" menu. The window allows the user to set the default working directory, the directory containing input motions for use in analyses, the default directory in which to save profiles, the default units, the analysis priority, and enable or disable multi-core support.

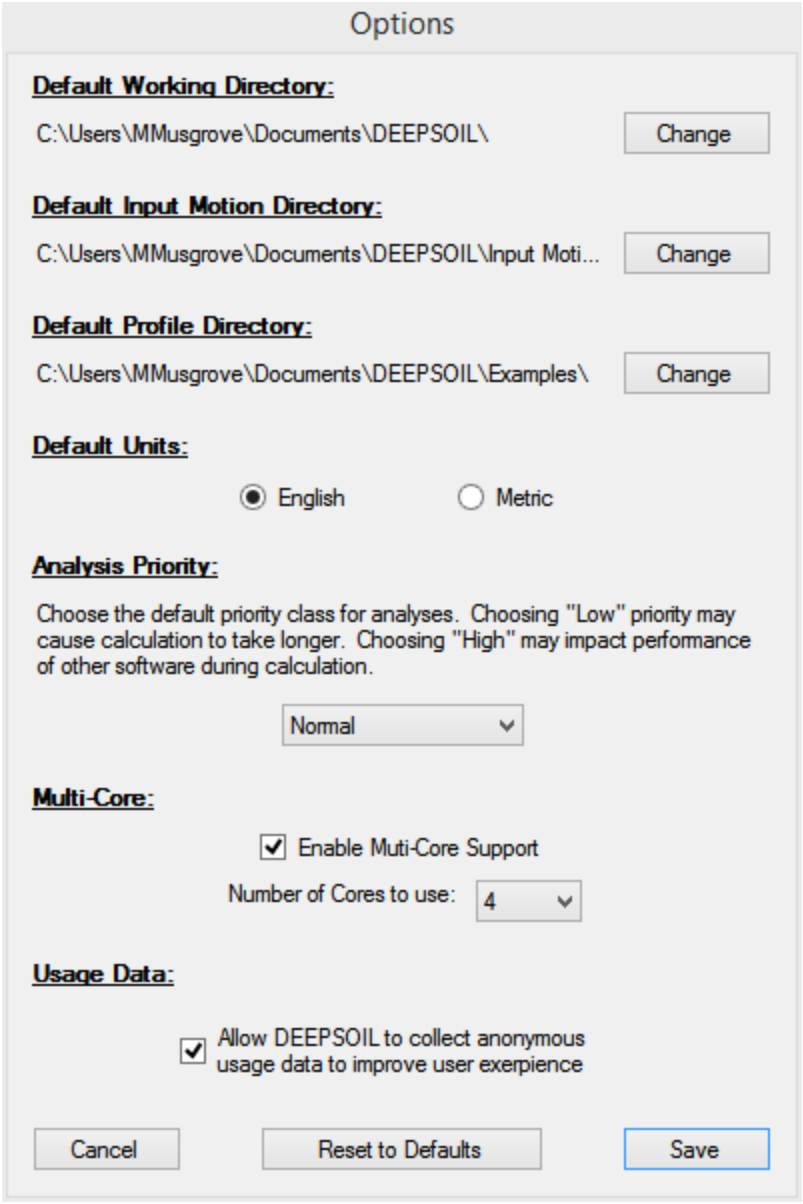


Figure 2. DEEPSOIL Options Window.

2.1 Profiles Tab

Saved profiles are shown in this tab. The user can directly select a profile and start a new analysis or modify a saved analysis file.

2.2 Motions Tab

DEEPSOIL contains a motion tab which can be used to view/process input motions. To view/process a motion, simply select it from the list and press the **View** button. A new window will open (Figure 3) and DEEPSOIL will generate acceleration, velocity, and displacement and Arias intensity time histories, as well as the response spectrum and Fourier amplitude spectrum for the selected motion. The relative size of the plots can be adjusted by clicking on the gray vertical line and dragging to the left or right. Double-clicking on the response spectrum and Fourier amplitude spectrum plots will cause the axes to alternate between linear and log scales on the axes (each plot supports 3 different views). The calculated data is also provided for the user in data tables which can be accessed by selecting the "Time History Data" or "Spectral Data" tabs at the top of the window (Figure 4).

This window also provides the user the option to linearly scale the selected input motion. The user is provided two options for scaling: scale the original motion by a specified factor (scale by) or scale the original motion to a specified maximum acceleration (scale to). The desired method can be selected using the drop-down list in the upper right corner of the window. Press the **Apply** button to scale the motion and recalculate the other data. After scaling, the user can save the new motion by pressing the **Save As** button.

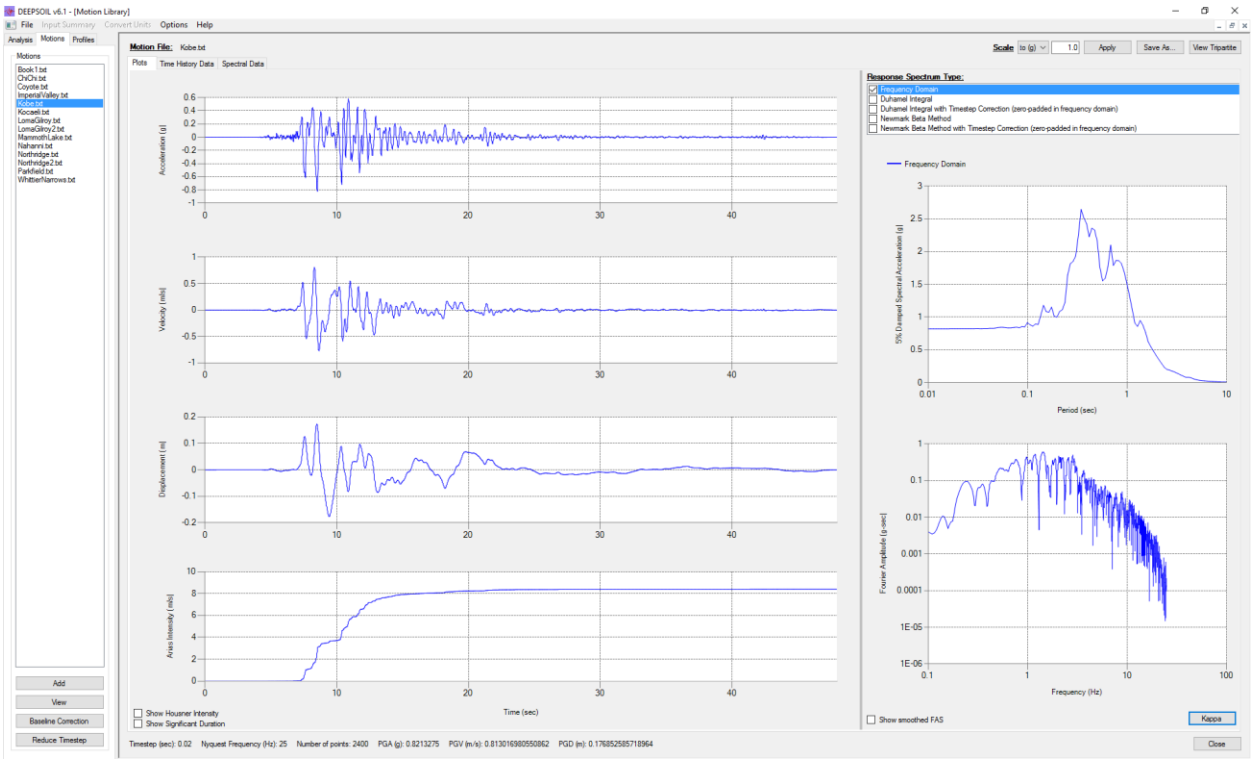
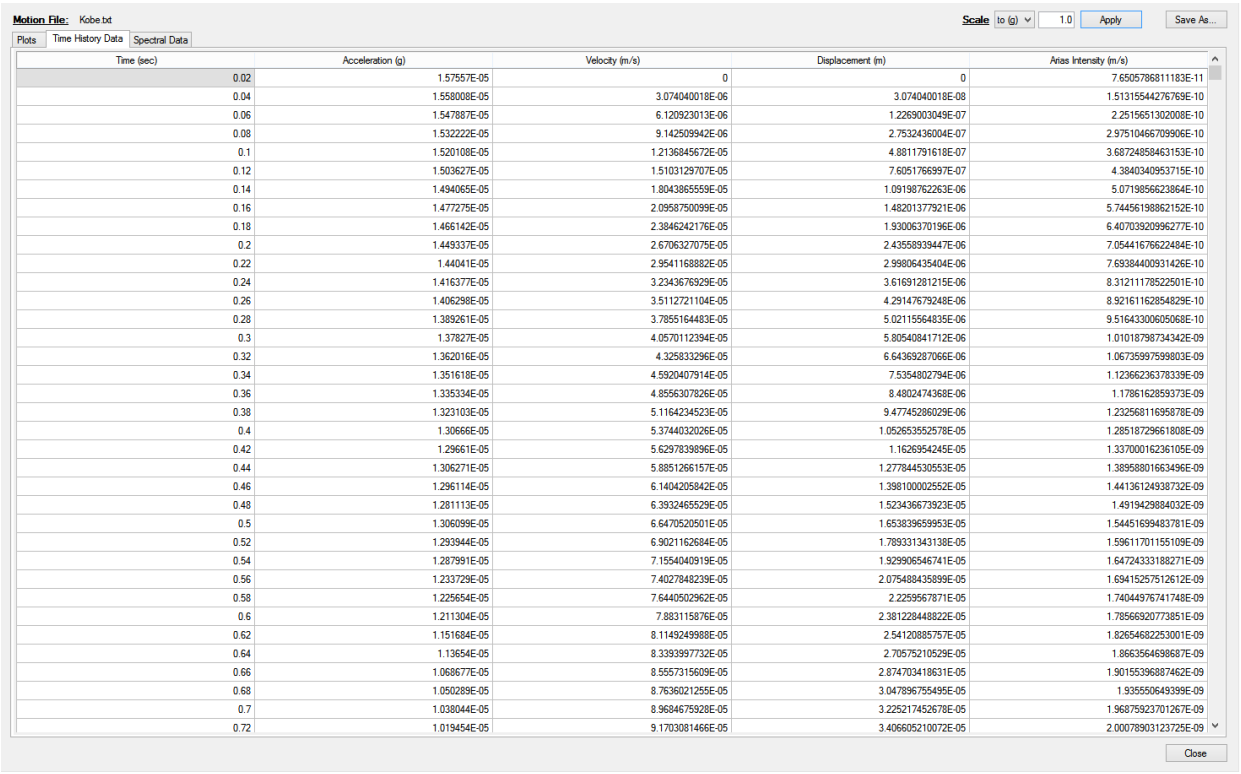


Figure 3. Motion Viewer (Plots)



Time (sec)	Acceleration (g)	Velocity (m/s)	Displacement (m)	Arias Intensity (m/s)
0.02	1.57557E-05	0	0	7.6505786811183E-11
0.04	1.558008E-05	3.074040018E-06	3.074040018E-08	1.513155442767 69E-10
0.06	1.547887E-05	6.120923013E-06	1.2269003049E-07	2.2515651302008E-10
0.08	1.532222E-05	9.142509942E-06	2.7532436004E-07	2.9751046670 9906E-10
0.1	1.520108E-05	1.2136845672E-05	4.8811791618E-07	3.6872485846 3153E-10
0.12	1.503627E-05	1.5103129707E-05	7.6051766997E-07	4.384034095 3715E-10
0.14	1.494065E-05	1.8043865559E-05	1.0919876226 3E-06	5.0719856623864E-10
0.16	1.477275E-05	2.0958750099E-05	1.48201377921E-06	5.7445619886 2152E-10
0.18	1.466142E-05	2.3846242176E-05	1.9300637019 6E-06	6.4070392099 6277E-10
0.2	1.449337E-05	2.6706327075E-05	2.4355893944 7E-06	7.0544167662 4484E-10
0.22	1.44041E-05	2.9541168882E-05	2.9980643540 4E-06	7.6938440093 1426E-10
0.24	1.416377E-05	3.2343676929E-05	3.6169128121 5E-06	8.3121117852 2501E-10
0.26	1.406298E-05	3.5112721104E-05	4.2914767924 8E-06	8.9216116285 4829E-10
0.28	1.389261E-05	3.7855164483E-05	5.0211556483 5E-06	9.5164330060 5068E-10
0.3	1.37827E-05	4.0570112394E-05	5.8054084171 2E-06	1.0101879873 4342E-09
0.32	1.362016E-05	4.325833296E-05	6.6436928706 6E-06	1.0673599759 9803E-09
0.34	1.351618E-05	4.5920407914E-05	7.5354802794 E-06	1.1236623637 8339E-09
0.36	1.335334E-05	4.8556307826E-05	8.4802474368 E-06	1.1786162859 373E-09
0.38	1.323103E-05	5.1164234523E-05	9.4774528602 9E-06	1.2325681169 5878E-09
0.4	1.30666E-05	5.3744032026E-05	1.0526535527 8E-05	1.2851729661 808E-09
0.42	1.29661E-05	5.6297839896E-05	1.1626954245 E-05	1.3370001623 6105E-09
0.44	1.306271E-05	5.8851266157E-05	1.2778445305 53E-05	1.3895880166 3496E-09
0.46	1.296114E-05	6.1404205842E-05	1.3981000025 52E-05	1.4413612493 8732E-09
0.48	1.281113E-05	6.3932465529E-05	1.5234366739 23E-05	1.491942988 4032E-09
0.5	1.306099E-05	6.6470520501E-05	1.6538396599 53E-05	1.5445169948 3781E-09
0.52	1.293944E-05	6.9021162684E-05	1.7893313431 38E-05	1.5961170115 5109E-09
0.54	1.287991E-05	7.1554040919E-05	1.9299065467 41E-05	1.6472433318 8271E-09
0.56	1.233729E-05	7.4027848239E-05	2.0754884358 99E-05	1.6941525751 2612E-09
0.58	1.225654E-05	7.6440502962E-05	2.2259567871 E-05	1.7404497674 1748E-09
0.6	1.211304E-05	7.883115876E-05	2.3812284488 22E-05	1.7856692077 3851E-09
0.62	1.151684E-05	8.1149249988E-05	2.5412088575 7E-05	1.8265468225 3001E-09
0.64	1.13654E-05	8.3393997732E-05	2.7057521052 9E-05	1.8663564698 687E-09
0.66	1.068677E-05	8.5557315609E-05	2.8747034186 31E-05	1.9015539688 74 62E-09
0.68	1.050289E-05	8.7636021255E-05	3.0478967554 95E-05	1.935550649 399E-09
0.7	1.038044E-05	8.9684675928E-05	3.2252174526 78E-05	1.9687592370 1267E-09
0.72	1.019454E-05	9.1703081466E-05	3.4066052100 72E-05	2.0007890312 3725E-09

Figure 4. Motion Viewer (Tables)

2.2.1 Baseline Correction

As with the motion viewer, the baseline correction can be used by selecting a motion in the list and pressing the appropriate button.

DEEPSOIL can perform baseline correction for any input motion (Figure 5). By selecting an input motion and pressing the **Baseline Correction** button, a new window appears which shows the acceleration, velocity, and displacement time-histories corresponding to the motion. Motions which exhibit non-zero displacement time-histories for the latter part of the motion should be corrected. The corrected time-histories are also calculated and presented to the user. The response spectra and Fourier amplitude spectra for the original motion and baseline-corrected motion are also provided for the user. The spectra should be carefully examined by the user to ensure the baseline correction process did not greatly alter the input motion. The baseline-corrected motion can then be stored as a file defined by the user. The relative size of the plots can be adjusted by clicking on the gray vertical line and dragging it to the left or right. Dragging to the left causes the response spectra and Fourier amplitude spectra plots to increase in size, while dragging to the right causes the time-histories plots to increase in size.

The baseline correction routine in DEEPSOIL is adapted from the baseline correction routine included in the USGS motion processing program BAP (USGS Open File Report 92-296A). The baseline correction is accomplished using the following steps:

1. Truncate both ends of the motion using the first and last zero-crossings as bounds.

2. Pad the motion with zeros at both ends.
3. Process the motion with a second order, recursive, high-pass (0.1 Hz cutoff frequency) Butterworth filter with convolution in both directions in the time domain.
4. Truncate the new motion using the last zero-crossing as bound.

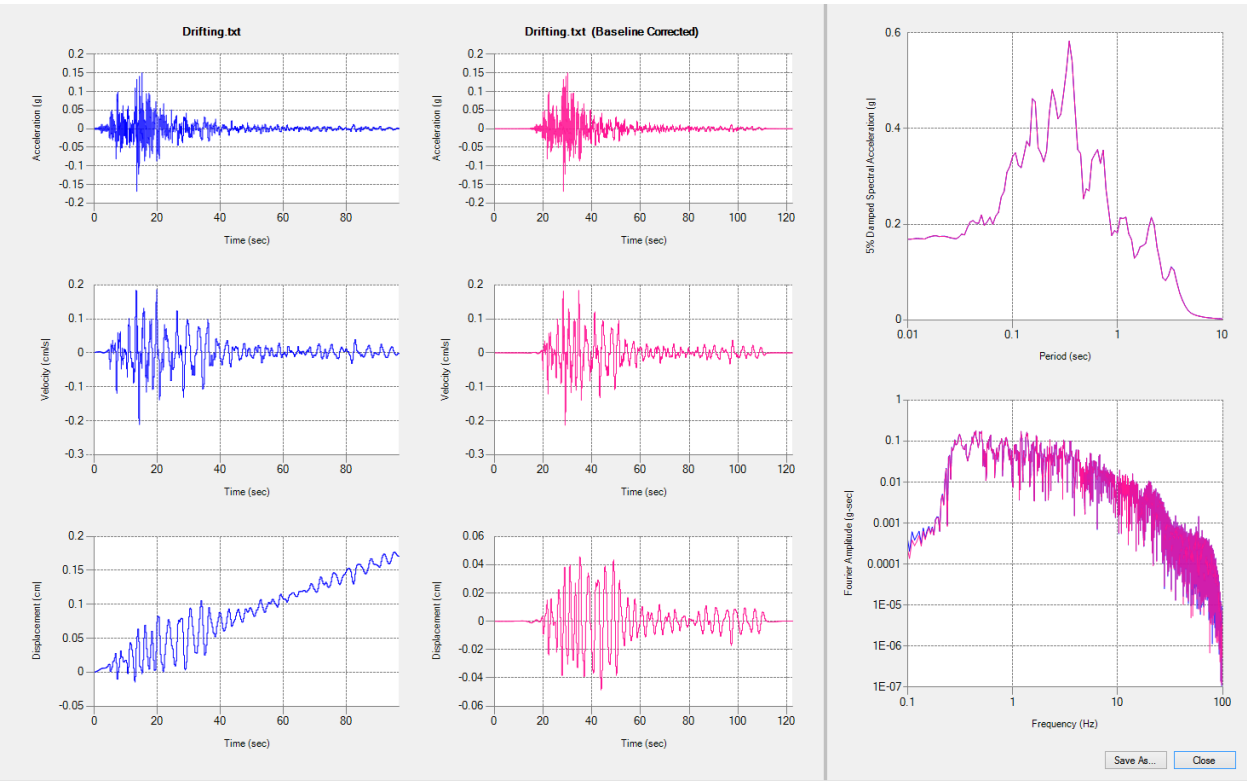


Figure 5. Baseline Correction.

2.2.2 Response Spectra Calculation Methods

The frequency-domain solution, the Newmark β method and Duhamel integral solutions are the three most common methods employed to estimate the response of Single Degree of Freedom (SDOF) systems and therefore to calculate the response spectra. A brief description is presented for each method to calculate the response of SDOF systems and to solve the dynamic equilibrium equation defined as (Chopra, 1995; Newmark, 1959):

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g$$

where m, c and k are the mass, the viscous damping and the system stiffness of SDOF system respectively. $\ddot{u}$, $\dot{u}$ and u are the nodal relative accelerations, relative velocities and relative displacements respectively and $\ddot{u}_g$ is the exciting acceleration at the base of SDOF.

Frequency-domain solution

In the frequency-domain solution, the Fourier Amplitude Spectra (FAS) input motion is modified

by a transfer function defined as:

$$H(f) = \frac{-f_n^2}{(f^2 - f_n^2) - 2i\xi f f_n}$$

where f_n is the natural frequency of the oscillator calculated as $f_n = \frac{1}{2\pi}\sqrt{k/m}$ and ξ is the damping ratio calculated as $\xi = \frac{c}{2\sqrt{km}}$. Use of the frequency-domain solution requires FFTs (Fast Fourier Transforms) to move between the frequency-domain, where the oscillator transfer function is applied, and the time-domain, where the peak oscillator response is estimated. Over the frequency range of the ground motion, the frequency-domain solution is exact.

Duhamel integral solution

The second method to compute the response of linear SDOF systems interpolates –commonly assuming linear interpolation– the excitation function $(-m\ddot{u}_g)$ and solves the equation of motion as the addition of the exact solution for three different parts: (a) free-vibration due to initial displacement and velocity conditions, (b) a response step force $(-m\ddot{u}_{g_i})$ with zero initial conditions and (c) response of the ramp force $\left[-m\left(\ddot{u}_{g_{i+1}} - \ddot{u}_{g_i}\right)/\Delta t\right]$. The solution in terms of velocities and displacements is presented in the following equations:

$$\dot{u}_{i+1} = A'u_i + B'\dot{u}_i + C'(-m\ddot{u}_{g_i}) + D'(-m\ddot{u}_{g_{i+1}})$$

$$u_{i+1} = Au_i + B\dot{u}_i + C\left(-m\ddot{u}_{g_i}\right) + D\left(-m\ddot{u}_{g_{i+1}}\right)$$

where:

$$A = e^{-\xi\omega_n\Delta t}\left(\frac{\xi}{\sqrt{1-\xi^2}}sin(\omega_D\Delta t) + cos(\omega_D\Delta t)\right)$$

$$B = e^{-\xi\omega_n\Delta t}\left(\frac{1}{\omega_D}sin(\omega_D\Delta t)\right)$$

$$C = \frac{1}{k}\left\{\frac{2\xi}{\omega_n\Delta t} + e^{-\xi\omega_n\Delta t}\left[\left(\frac{1-2\xi^2}{\omega_D\Delta t} - \frac{\xi}{\sqrt{1-\xi^2}}\right)sin(\omega_D\Delta t) - \left(1 + \frac{2\xi}{\omega_n\Delta t}\right)cos(\omega_D\Delta t)\right]\right\}$$

$$D = \frac{1}{k}\left[1 - \frac{2\xi}{\omega_n\Delta t} + e^{-\xi\omega_n\Delta t}\left(\frac{2\xi^2-1}{\omega_D\Delta t}sin(\omega_D\Delta t) + \frac{2\xi}{\omega_n\Delta t}cos(\omega_D\Delta t)\right)\right]$$

$$A' = -e^{-\xi\omega_n\Delta t}\left(\frac{\omega_n}{\sqrt{1-\xi^2}}sin(\omega_D\Delta t)\right)$$

$$B' = -e^{-\xi\omega_n\Delta t}\left(cos(\omega_D\Delta t) - \frac{\xi}{\sqrt{1-\xi^2}}sin(\omega_D\Delta t)\right)$$

$$C' = \frac{1}{k}\left\{-\frac{1}{\Delta t} + e^{-\xi\omega_n\Delta t}\left[\left(\frac{\omega_n}{\sqrt{1-\xi^2}} + \frac{\xi}{\Delta t\sqrt{1-\xi^2}}\right)sin(\omega_D\Delta t) + \frac{1}{\Delta t}cos(\omega_D\Delta t)\right]\right\}$$

$$D' = \frac{1}{k\Delta t}\left[1 - e^{-\xi\omega_n\Delta t}\left(\frac{\xi}{\sqrt{1-\xi^2}}sin(\omega_D\Delta t) + cos(\omega_D\Delta t)\right)\right]$$

Newmark β time integration method in time-domain SDOF analysis

The third method is the Newmark β method. The Newmark β method calculates the nodal relative velocity $\dot{u}_{i+1}$and u_{i+1} displacements at a time i+1 by the using the following equations:

$$\dot{u}_{i+1} = \dot{u}_i + [(1-\gamma)\Delta t]\ddot{u}_i + (\gamma\Delta t)\ddot{u}_{i+1}$$

$$u_{i+1} = u_i + (\Delta t)\dot{u}_i + [(0.5-\beta)(\Delta t)^2]\,\ddot{u}_i + [\beta(\Delta t)^2]\ddot{u}_{i+1}$$

The parameters β and γ define the assumption of the acceleration variation over a time step (Δt) and determine the stability and accuracy of the integration of the method. A unique characteristic of the assumption of average acceleration (β = 0.5 and γ = 0.25) is that the integration is unconditionally stable for any Δt with no numerical damping. For this reason, the Newmark β method with average acceleration is commonly used to model the dynamic response of single and multiple degree of freedom systems.

The Newmark β method has inherent numerical errors associated with time step of the input motion (Chopra, 1995; Mugan and Hulbe, 2001). These errors generate inaccuracy in the solution resulting in miss-prediction of the high-frequency response. To determine if a motion's time step is too large to be used directly, the response spectrum calculated with the Newmark β method can be compared with the response spectra calculated by other means and with and without a time step correction in the motion viewer/processor (see section 2.2).

2.2.3 Fourier amplitude spectrum calculation and averaging

One of the most important factors to consider when evaluating ground motions is frequency content. The most common measure of frequency content is the Fourier amplitude spectrum, which indicates how the amplitude of the ground motion is distributed across different frequencies. Calculation of the spectrum requires a transformation of the ground motion from the time domain to the frequency domain. This transformation is called a Fourier transform. In DEEPSOIL, the transformation is completed using a Fast Fourier Transform (FFT). The resulting Fourier spectrum is then used to calculate the Fourier amplitude spectrum using the following equations:

$$f_i = \frac{i}{\text{time step} * n}$$

$$|F|_i = \frac{\sqrt{(\text{real}(C_i))^2 + (\text{imag}(C_i))^2}}{\text{time step}}$$

where f_i is the *i*-th frequency, *n* is the number of points in the FFT, $|F|_i$ is the Fourier amplitude at the *i*-th frequency, and C_i is the *i*-th amplitude and phase (in complex number representation) of the FFT. The maximum frequency that can be contained in the motion is dictated by the motion's time step. This maximum frequency is called the Nyquest frequency and is calculated using the following equation:

$$f_{\text{Nyquest}} = \frac{1}{2 * \text{time step}}$$

DEEPSOIL can also smooth the calculated Fourier amplitude spectrum to make interpretation easier by providing a clearer view of the overall frequency content. DEEPSOIL uses a triangle smoother in log space (also called a log-triangle smoother). The smoothing routine in DEEPSOIL uses a sliding triangular smoothing window in log-space and is adapted from a routine developed by David Boore. The weights assigned to each point are based on the log distance from the point of interest. We currently have our maximum smoothing width set to 0.2. At each frequency of the spectrum the weights of the smoothing window are calculated as follows:

for frequencies below the current frequency:

$$W_i = \frac{\log_{10}(i \,/\, \text{lower bound index})}{\log_{10}(\text{current index} \,/\, \text{lower bound index})}$$

for the current frequency:

$$W_i = 1$$

for frequencies above the current frequency:

$$W_i = 1 - \frac{\log_{10}(i \,/\, \text{current index})}{\log_{10}(\text{upper bound index} \,/\, \text{current index})}$$

where the upper and lower bound indices are determined using the desired window width and index of the current frequency.

2.2.4 Arias Intensity

The Arias intensity provides a measure of the intensity of the motion as a function of acceleration. It is plotted as a function of time and is calculated using the following equation:

$$I_a(t) = \frac{\pi}{2g}\int_0^t [a(t)]^2 dt$$

where g is the acceleration due to gravity and $a(t)$ is the acceleration time history.

2.2.5 Significant Duration

The significant duration is defined as the timespan (in seconds) between the occurrence of 5% and 95% of the total Arias Intensity (section 2.2.4). The significant duration, and its location in the motion time histories, can be shown by checking the box at the lower left of the motion viewer.

2.2.6 Housner Intensity

The Housner intensity (also referred to as spectral intensity) provides a measure of the intensity of the motion as a function of spectral velocity. It is plotted as a function of time. The Duhamel integral method is used in calculation of the acceleration response spectra for computational efficiency, and converted to velocity spectra by multiplying the spectra by the corresponding angular frequency. The Housner intensity is often reported as a single value, however, DEEPSOIL is able to provide the Housner intensity as a time-history by calculating the response spectrum at each point of an acceleration record. The Housner intensity is calculated using the following equation:

$$I_h(t) = \sum_0^t \int_{T=0.1}^{2.5} S_v(T,\xi)$$

where *T* is the period and ξ is the damping ratio. In DEEPSOIL, the Housner intensity is calculated assuming a damping ratio of 5%.

2.2.7 Estimation of Kappa (κ) *(to be updated)*

DEEPSOIL includes a tool to aid in the estimation of the high-frequency attenuation parameter κ. This tool is accessed by pressing the **Kappa** button below the Fourier amplitude spectrum on the motion processor window. To estimate κ, the user defines two bounding frequencies. DEEPSOIL will then average the Fourier amplitude spectrum (as described in section 2.2.3) and then perform a linear regression over the range of frequencies chosen by the user. The plot is then updated to reflect the chosen range of frequencies and the resulting κ and amplitude intercept.

The user can also plot a fixed κ value. The resulting line can be moved vertically by specifying an amplitude intercept.

Once a line of constant κ is plotted (either by estimation or user-specification), it can be interactively positioned vertically using the scroll-wheel on the mouse. The user can also show/hide the averaged Fourier amplitude spectrum and plot legend by right-clicking on the plot.

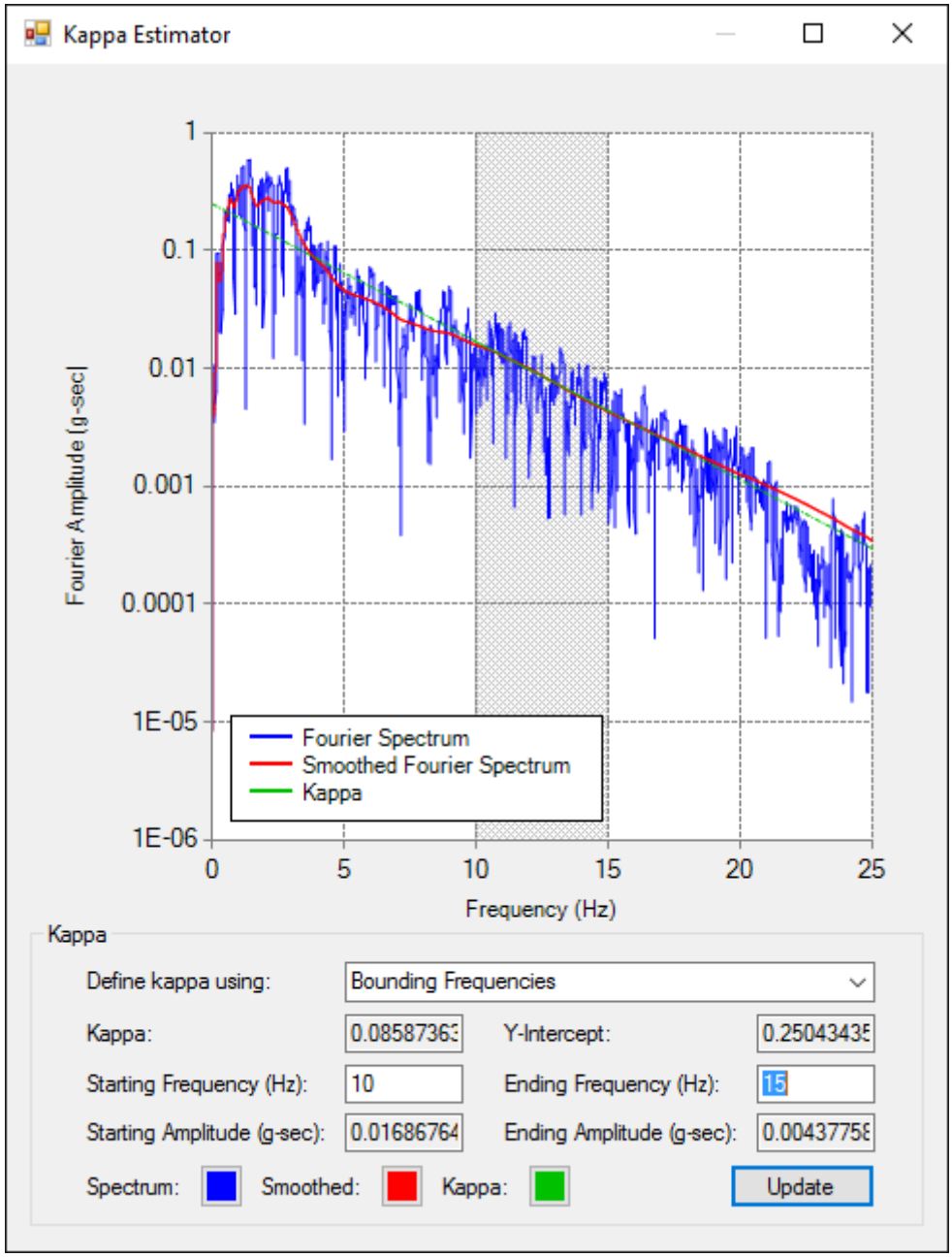


Figure 6. Kappa estimation tool.

2.2.8 Adding New Input Motions *(to be updated)*

Motions may be added to DEEPSOIL by using the built-in Add Motion window. To access this tool, click on the **Motions** tab of the main DEEPSOIL window and press the **Add** button. Alternatively, click on the **File** menu and select **New** and then **Motion**. This tool is designed to convert motions from the PEER ".AT2" format to the DEEPSOIL format. This process is fully automated. DEEPSOIL will read through the PEER file and determine the number of data points and the time step. Additional options are provided for reading non-PEER motions and should be set as needed. If DEEPSOIL cannot complete the conversion, a message box is used to notify the

user of the failure. Upon successful conversion, the user is notified by a message box and the motion is added to the Motion Library.

Motions can also be added manually. This is done using a text editor capable of producing .TXT files. To add an input motion, enter the necessary data in the format described below and save as a .TXT file in the "Input Motion" directory. The default input motion directory is: C:\Users\[User Name]\Documents\DEEPSOIL\Input Motions\. If the user has specified a different directory, the input motion file should be placed in the user-specified directory. If this method is used, DEEPSOIL must be closed and reopened before the input motion is available for analyses.

Units of the ground motion should be seconds and g's.

The format should be as follows:

1st row: Number of data points & time step (separated by 1 space)
2nd and subsequent rows: time & acceleration (separated by 1 space)

2.3 Analysis Tab

The analysis tab options are discussed in detail in the next section.

3 Analysis Flow

3.1 Analysis Definition: Step 1 of 6

The first step in the analysis requires the selection of analysis type. Figure 7 illustrates the form for Step 1. The user may also specify a workspace or "working directory" to use during this session.

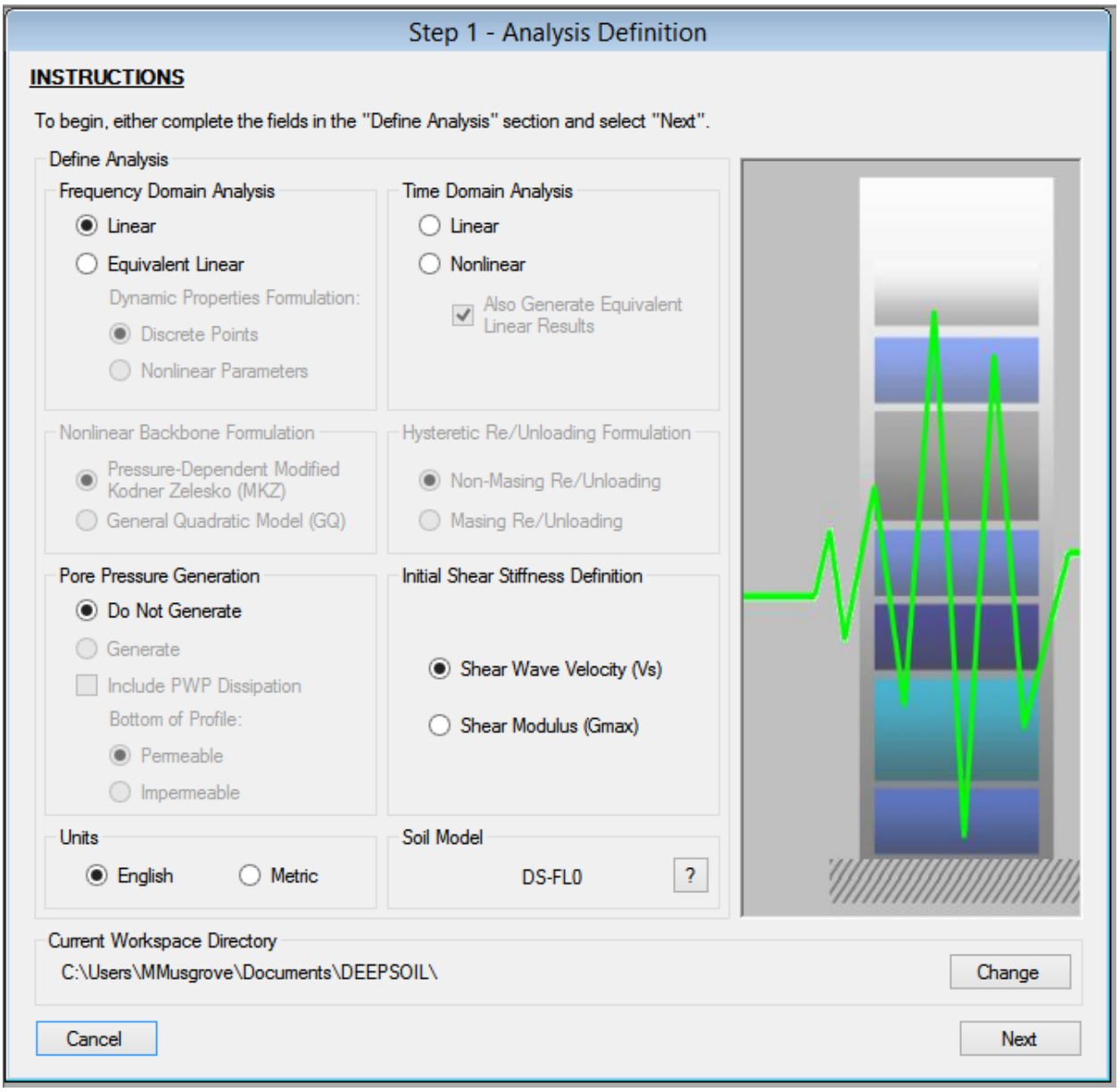


Figure 7. Step 1/6: Choose type of analysis.

Before creating a new profile, or opening an existing profile, it is recommended to verify the "Current Workspace Directory" at the bottom of the page. The DEEPSOIL "Working" directory is chosen by default as the default working directory specified using the Options window (Figure

2). If a different directory is preferred, press the "Change" button to bring up a folder browser and select the preferred directory.

To create a new analysis, the user must specify the type of analysis before proceeding to the next stage of analysis. The user must specify:

1. The analysis method:
    - Frequency Domain
        - Linear
        - Equivalent Linear
    - Time Domain
        - Linear
        - Nonlinear

2. The type of input for shear properties:
    - Shear Modulus
    - Shear Wave Velocity

3. The units to be used in analysis:
    - English
    - Metric

4. The pore water pressure control:
    - No pore water pressure generation
    - Pore water pressure generation without dissipation (nonlinear only)
    - Pore water pressure generation and dissipation (nonlinear only)

5. The method to define the soil curve:
    - For Equivalent Linear
        - Discrete Points
        - Any model supported for nonlinear analyses
    - For Nonlinear
        - MRDF Pressure-Dependent Hyperbolic Model
        - Pressure-Dependent Hyperbolic Model
        - MRDF General Quadratic/Hyperbolic Model
        - General Quadratic/Hyperbolic Model

6. The porewater pressure boundary condition at the bottom of the soil profile (for analysis with PWP generation and dissipation)
    - Permeable
    - Impermeable

The pore water pressure generation and dissipation options are only available for nonlinear (time domain) analyses. Note that (2) and (3) can also be changed in the next stage.

After selecting they type of analysis, the Soil Model description will be updated. These identifiers are included in the analysis results file and can be used to quickly convey the type of analysis that was performed. The soil model identifiers are:

Model	Description
DS-FL0	Frequency Domain Linear
DS-EL0	Frequency Domain Equivalent Linear - Discrete Points
DS-EL1	Frequency Domain Equivalent Linear - MKZ with Masing Rules
DS-EL2	Frequency Domain Equivalent Linear - MKZ with Non-Masing Behavior
DS-EL3	Frequency Domain Equivalent Linear - GQ/H with Masing Rules
DS-EL4	Frequency Domain Equivalent Linear - GQ/H with Non-Masing Behavior
DS-TL0	Time Domain Linear
DS-NL1	Time Domain Nonlinear - MKZ with Masing Rules
DS-NL2	Time Domain Nonlinear - MKZ with Non-Masing Behavior
DS-NL3	Time Domain Nonlinear - GQ/H with Masing Rules
DS-NL4	Time Domain Nonlinear - GQ/H with Non-Masing Behavior
-PWP0	Porewater pressure generation without dissipation
-PWP1	Porewater pressure generation and dissipation - permeable halfspace
-PWP2	Porewater pressure generation and dissipation - impermeable halfspace

3.1.1 Equivalent Linear Analysis

The equivalent linear model employs an iterative procedure in the selection of the shear modulus and damping ratio soil properties as pioneered in program SHAKE. These properties can be defined by discrete points or by defining the soil parameters that define the backbone curve of one of the nonlinear models.

The option of defining the soil curves using discrete points is only applicable for the Equivalent Linear analysis. For this option, the G/G_{max} and damping ratio (%) are defined as functions of shear strain (%).

3.1.2 Deconvolution via Frequency Domain Analysis

This approach is the same as the frequency-domain linear equivalent linear analysis approaches except that the input motion can be applied at the ground surface or anywhere else in the soil column. The corresponding rock motion is then computed and provided to the user.

Deconvolution requires definition of a soil profile. The following properties need to be defined for each layer:

- Thickness
- Shear Wave Velocity (V_s) or Initial Shear Modulus (G_{max})
- Damping Ratio (%)

- Unit Weight

To perform the deconvolution,

1. Open or create a frequency domain profile.
2. Enter the requested information into the table on Step 2a, as shown in Figure 14.
3. Additional layers may be added using the **Add Layer** button. Unwanted layers may similarly be removed using the **Remove Layer** button.
4. Click **Next** to advance through Steps 2b to Step 2c.
5. On Step 2c, check the box labeled **Deconvolution** near the bottom of the window.
6. Specify the point of application of the ground motion by selecting the appropriate layer in the drop-down list.
7. Use the circular buttons to select the type of ground motions for generated as output.
8. Click **Next** to advance to Step 3 and select the locations for output and the motion(s) to be deconvolved.
9. Click **Next** to advance to Step 5 and set the frequency-domain parameters.
10. Click **Analyze**.

The output from a deconvolution analysis is a set of DEEPSOIL-formatted motions. Regardless of the output selection, there will be a file named "Deconvolved - [motion name].txt" that is the motion at the top of rock (bottom of profile). Additional files will be produced for each layer output requested and will be named "Deconvolved - [motion name] - layer [#].txt". These file can be used directly in DEEPSOIL.

Note: Deconvolution cannot be performed in the time domain analysis. Finding the motion at the bottom of the soil profile given the motion at the ground surface is an inverse problem in nonlinear analysis that is complex to solve and is not amenable to a simple deconvolution computation.

3.1.3 Non-Linear Analysis

Non-linear analysis solve the equations of motions in time domain using the Newmark β method.

Several soil models are available for user to select from. The analysis can be with or without porewater pressure generation.

The user has the option of obtaining the site response results using the equivalent linear method automatically whenever nonlinear site response analysis is conducted. It is highly recommended that EL results be always examined whenever a NL analysis is conducted.

3.2 Defining Soil Profile & Model Properties: Step 2a of 6

This stage is divided into three partitions. The first partition to be considered requires the user to define the soil profile and specify the soil properties of each layer (Figure 8). The type of input required depends on the analysis parameters selected in Step 1.

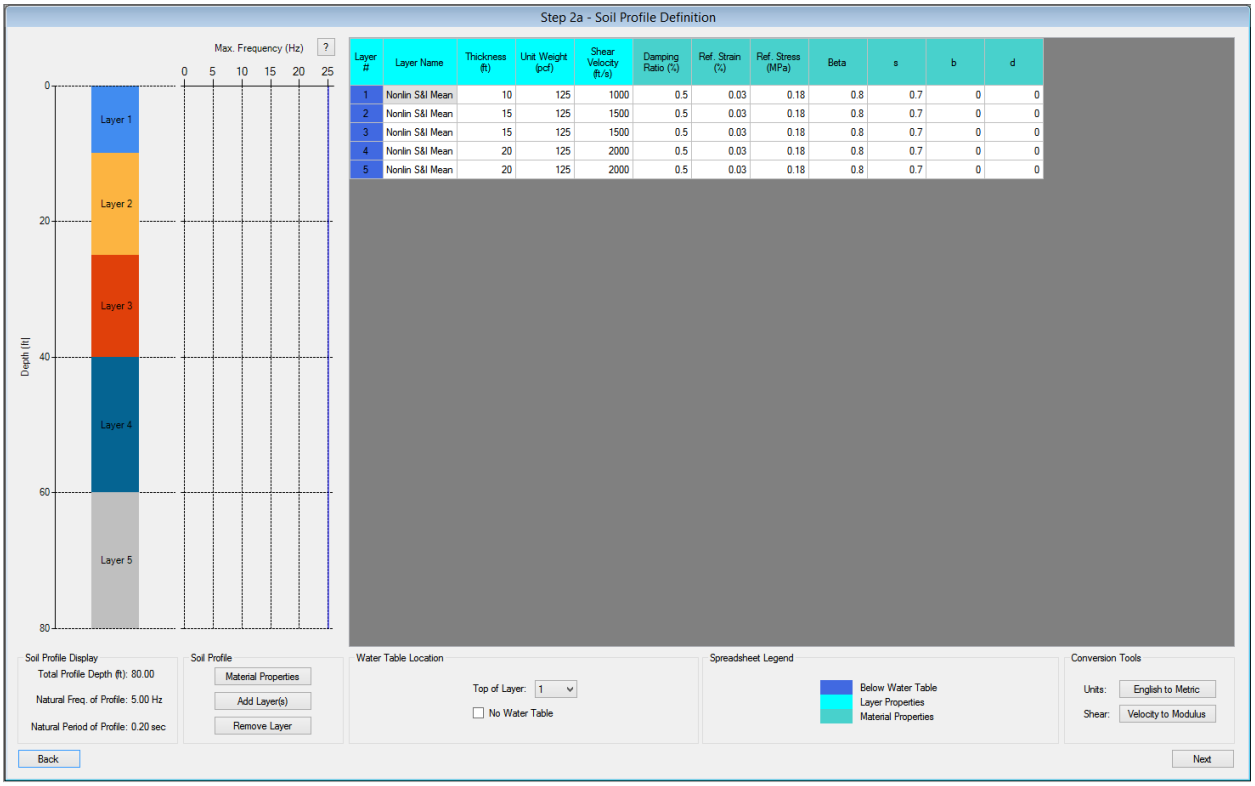


Figure 8. Step 2a/6: Input Soil Properties.

The entire form is broken up into three sections. The section located at the left is a visual display of the soil profile. The section at the right is the table where the values for required input parameters must be entered. The section at the bottom contains information about the soil column, options for adding/removing layers, water table settings, and conversion functions.

The user must specify the typical soil properties of each layer based on the type of analysis that was selected (Linear, Nonlinear, etc). The input parameters for each soil model are discussed in Chapter 4.

If the user selects to generate porewater pressure during the analysis (nonlinear analyses only), additional parameters must be specified, including the model to be used and their respective parameters. Each model and the required inputs are discussed in Section 4.3.

3.2.1 Creating/Modifying Soil Profiles

a. *Material Properties / Defining Material Properties:* Details will be provided in the next section.

b. *Convert Units:* Convert all units from English to Metric or vice versa.

c. *Convert Shear:* Convert shear modulus to shear wave velocity or vice versa. All layers require a unit weight to perform this conversion.

d. *Water Table:* Choose the depth of the water table by clicking the drop-down menu. The layers appear in ascending order, so click the layer that the water table will be above. The graphical soil column display responds to this by changing the background color of every layer beneath the water table to blue. The location of the water table is only of influence when introducing the pressure dependent soil parameters or performing an effective stress analysis. The location of the water table does not influence the frequency domain solution.

3.2.2 Maximum Frequency (for Time Domain Analysis only) (Step 2b)

Upon completing the definition of the soil and model properties, the user is shown a plot of the maximum frequency versus depth for each layer (Figure 9). A plot of maximum frequencies (Hz) versus depths of all layers are displayed. The maximum frequency is the highest frequency that the layer can propagate and is calculated as: $f_{max} = V_s/4H$, where V_s is the shear wave velocity of the layer, and H is the thickness of the layer. To increase the maximum frequency, the thickness of the layer should be decreased. This check is performed solely for time domain analyses. It is recommended that the layers have the same maximum frequency throughout the soil profile, though this is not required. For all layers, the maximum frequency should generally be a minimum of 30 Hz.

3.2.3 Implied Strength Profile (Step 2b)

Upon completing the definition of the soil and model properties, the user is shown a plot of the implied strength of the soil profile. The window provides three plots for the user to view: implied shear strength versus depth, normalized implied shear strength (shear strength divided by effective vertical stress) versus depth, and implied friction angle versus depth (Figure 9). The shear strength and friction angle are also provided in the table to the right for closer inspection.

The implied shear strength is calculated from the modulus reduction curves entered as part of step 2a. At each point on the curve, the shear stress is calculated using the following equation:

$$\tau = \rho V_s^2 \frac{G}{G_0}\gamma$$

- τ is the shear stress at the given point
- V_s is the shear wave velocity in the given layer
- ρ is the mass density of the soil

- G is the shear modulus at the given point
- G_0 is the shear modulus at 0% shear strain
- γ is the shear strain at the given point

The maximum value of shear stress for the given layer is then plotted at the depth corresponding to that layer. Using this maximum value, the implied friction angle is then calculated using the following equation:

$$\phi = tan^{-1}\left(\frac{\tau_{max}}{\sigma_v^{'}}\right)$$

- ϕ is the friction angle
- τ_{max} is the maximum shear stress as calculated above
- $\sigma_v^{'}$ is the effective vertical stress at the mid-depth of the layer

The user is encouraged to carefully check the provided plots. If the implied strength or friction angle of particular layer is deemed unreasonable, the user should consider modifying the modulus reduction curve for the layer to provide a more realistic implied strength or friction angle.

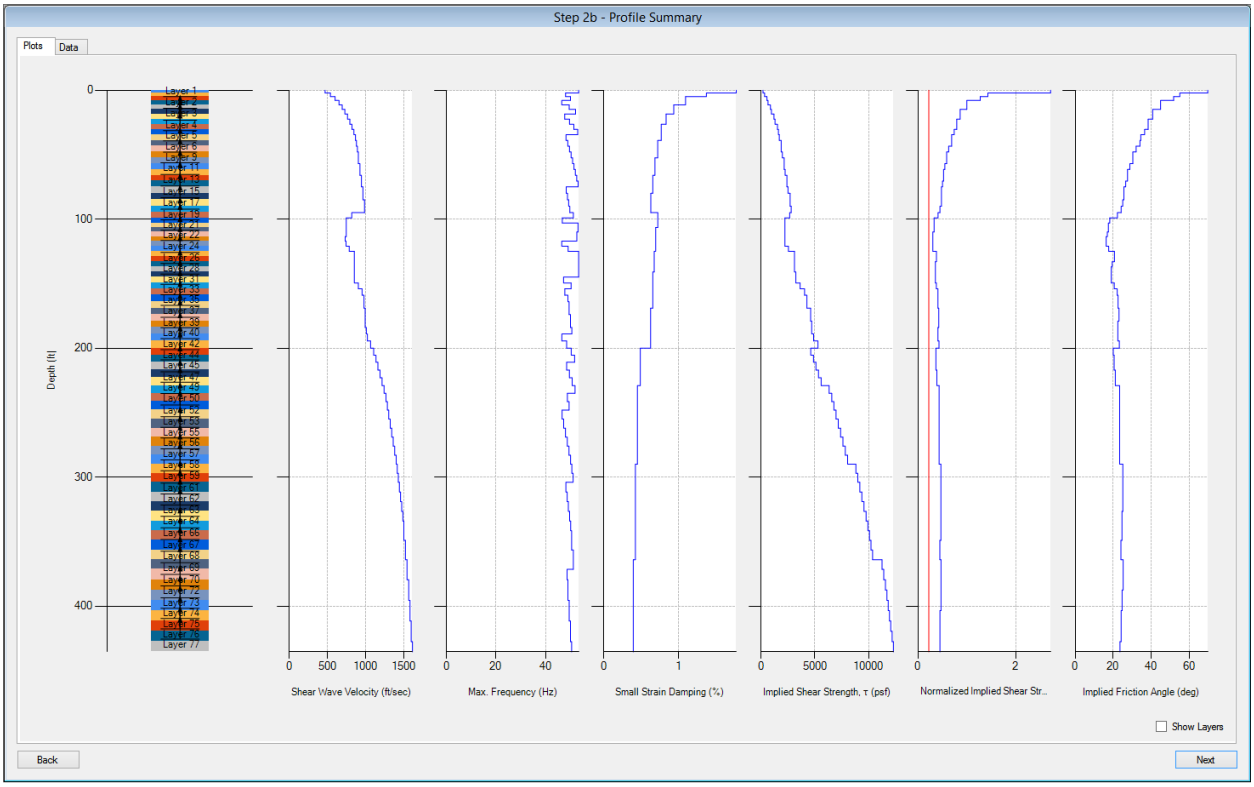


Figure 9. Profile Summary

3.3 Define Rock Properties: Step 2c of 6

After defining the soil and model properties, the user must now define the rock / half-space properties of the bottom of the profile (Figure 10).

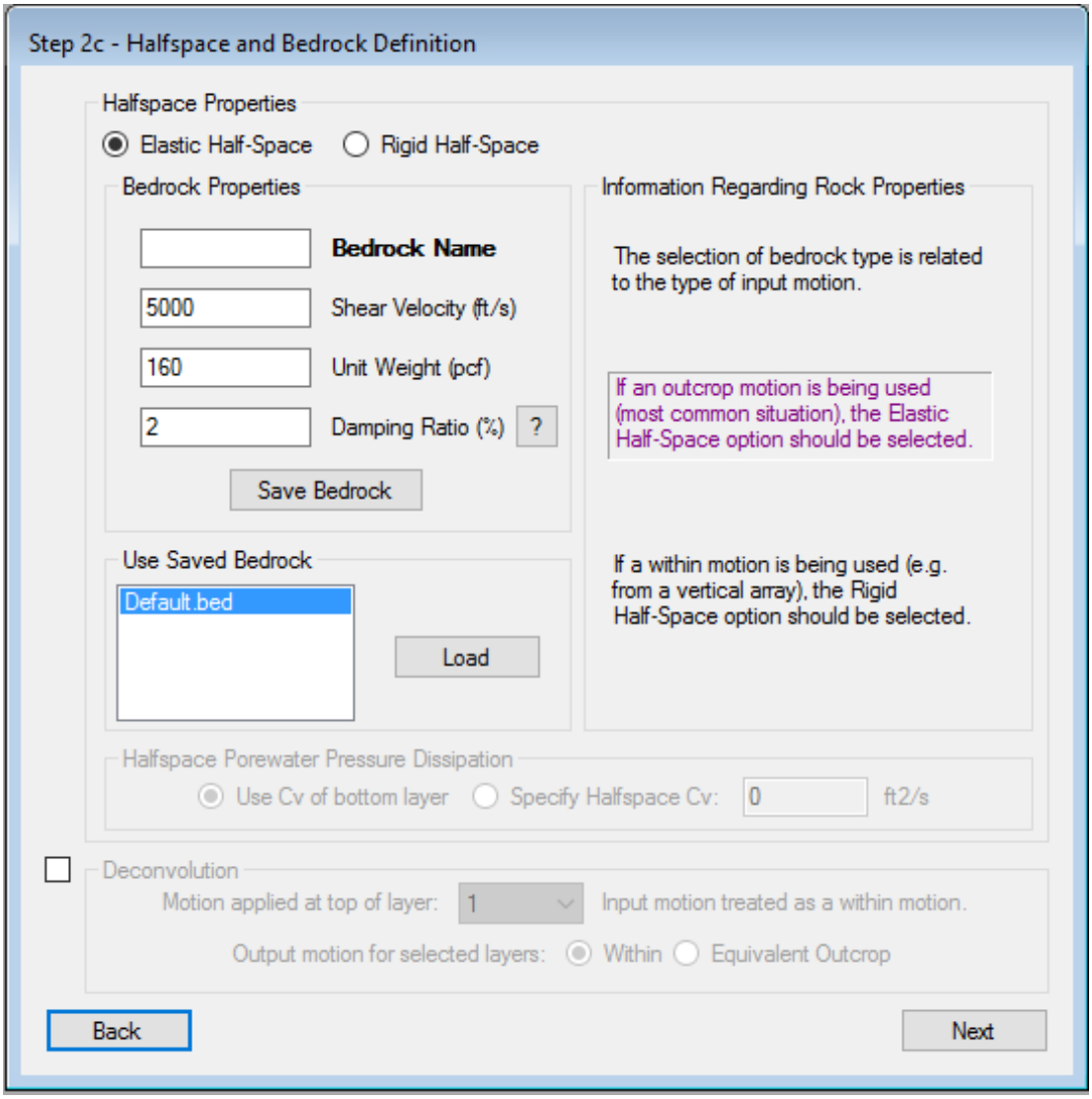


Figure 10. Step 2b/6: Input Rock Properties.

The user has the option of selecting either a **Rigid Half-Space** or an **Elastic Half-Space**. An informational display makes the user aware that a rigid half-space should be chosen if a within motion will be used, and an elastic half-space should be selected if an outcrop motion is being used. If a rigid half-space is being used, no input parameters are required. If an elastic half-space is being used, the user must supply the shear wave velocity (or modulus), unit weight, and damping ratio of the half-space. In general, the shear wave velocity of the bedrock should be greater than that of the overlying soil profile. It should be noted that the bedrock damping ratio has no effect in time domain analyses and only a negligible effect in frequency domain analyses regardless of the value specified by the user.

Bedrock properties may be saved by giving the bedrock a name and pressing the **Save Bedrock** button. The new bedrock will appear in the list of saved bedrocks below. To use a saved bedrock, select the file from the list box and press the **Load** button.

If the analysis includes porewater pressure generation and dissipation with a permeable half-space, the user is also given the option to specify the coefficient of consolidation for the half-space. If no value is specified, DEEPSOIL will use the coefficient of consolidation of the last layer for the half-space as well.

If the user is conducting a frequency domain analysis, deconvolution can be performed rather than a forward analysis. Deconvolution is discussed in section 3.1.2.

3.4 Output and Motion Selection: Step 3 of 6

The motion and output selection stage allows the user to select layers for time-history output and specify the input motion(s) to be used in the analysis.

The layers at which output data is needed may be selected by checking the appropriate checkbox in the first column of the window. All layers can be selected or deselected using the **Select All** button located at the bottom of the layer list. Note that requesting time-history output for additional layers will increase the time required for analyses to complete. Maximum PGA, stress, strain and pore pressure (if applicable) profiles will be generated regardless of the layer output selection. Therefore, it is recommended that the user only request time-history output for layers of interest.

The input motion(s) must be selected from the current input motion library (to which the user may add additional motions, see section 2.2.8). The motions may be selected by checking the appropriate checkbox in the second column of the window. All motions can be selected or deselected by using the **Select All** button at the bottom of the motion list. Once a motion is selected, DEEPSOIL will calculate and plot the acceleration, velocity, displacement, and Arias intensity time histories (Figure 11) and the response and Fourier amplitude spectrum (Figure 12). If multiple motions are selected, a single motion can be highlighted in the plots by clicking on it in the motion list or clinking in its column in the table below the plots. The table also allow for control of which motions are displayed in the plots. Buttons are available at the bottom of the window to change the colors of the plots.

The user should also enter the damping ratio for the calculated response spectra. The response spectra are calculated using the frequency domain method (see section 2.2.2) and the default damping ratio is 5%. This value may be adjusted at the user's discretion.

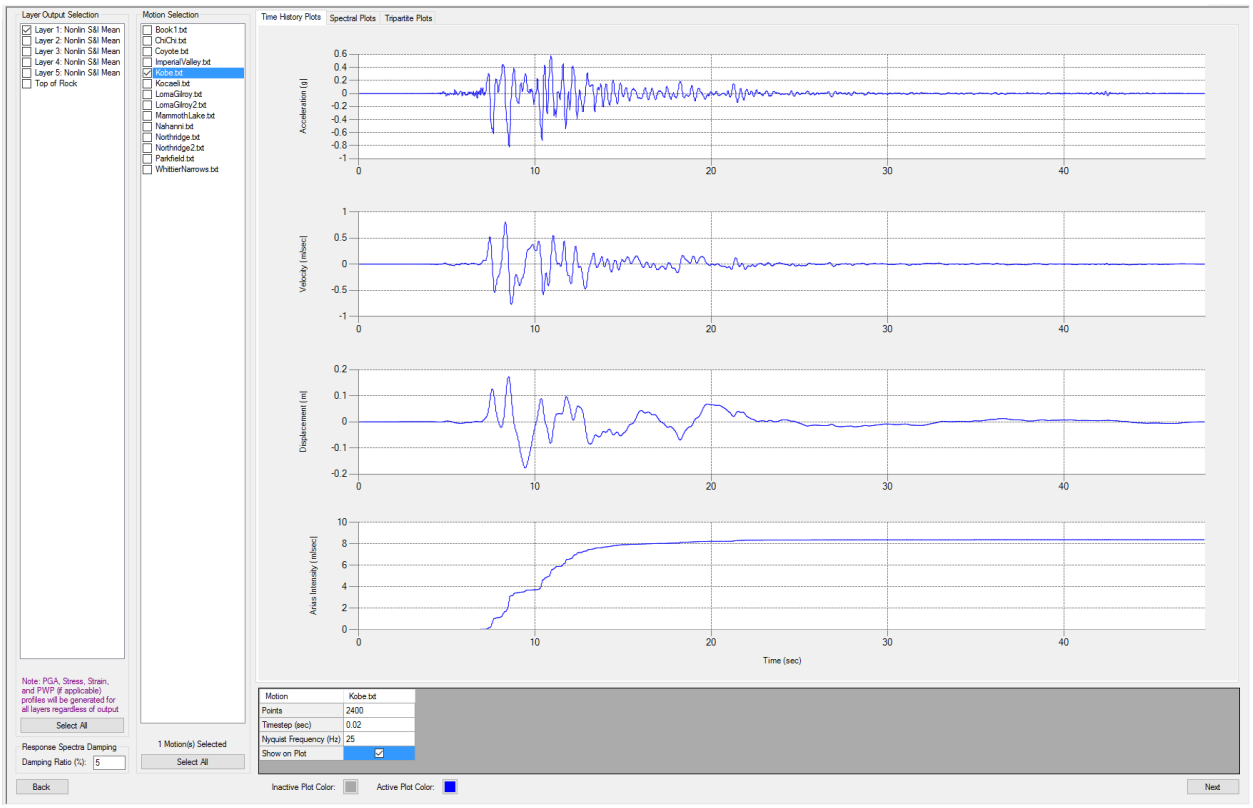


Figure 11. Step 3/6: Input Motion and Output Layer(s) (Time History Plots Tab)

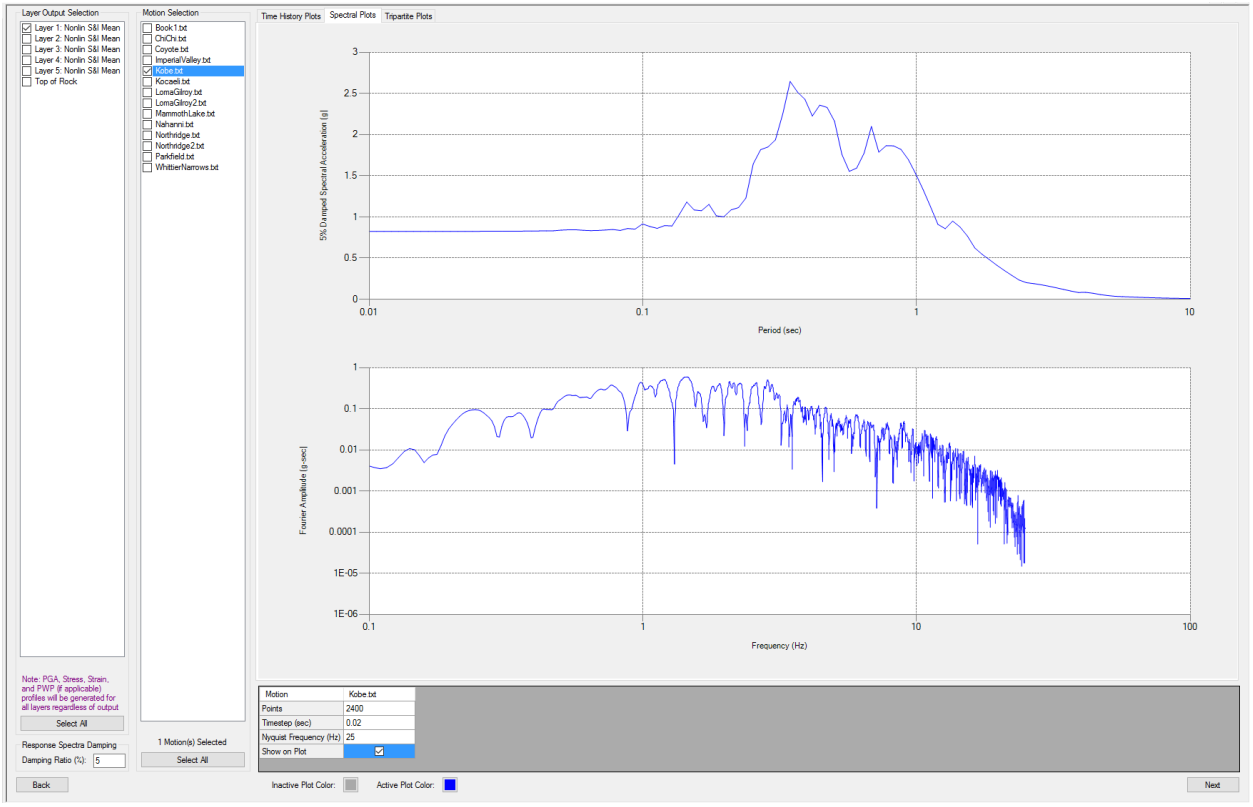


Figure 12. Step 3/6: Input Motion and Output Layer(s) (Spectral Plots Tab)

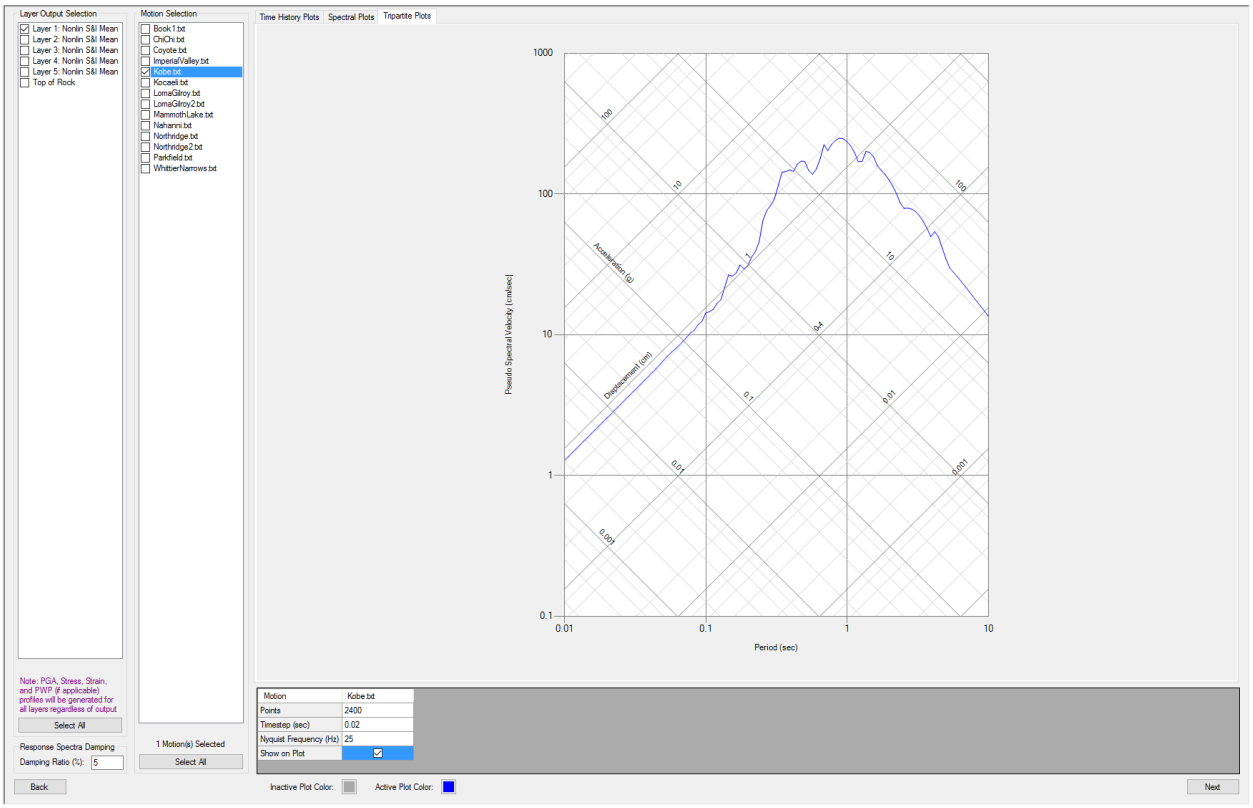


Figure 13. Step 3/6: Input Motion and Output Layer(s) (Tripartite Plots Tab)

3.5 Viscous Damping

3.5.1 Viscous Damping Formulation in Nonlinear Analysis (Time Domain) (Step 4)

This stage will only appear for time domain analyses. This step allows the user to set the viscous damping formulation and select the optimum modes/frequencies for the analysis (Figure 14). This window is unique to DEEPSOIL. This window will help control the introduction of numerical damping through frequency dependent nature of the viscous damping formulation. Note that when multiple input motions are selected for an analysis, the viscous damping formulation and selected modes/frequencies are the same for all selected input motions.

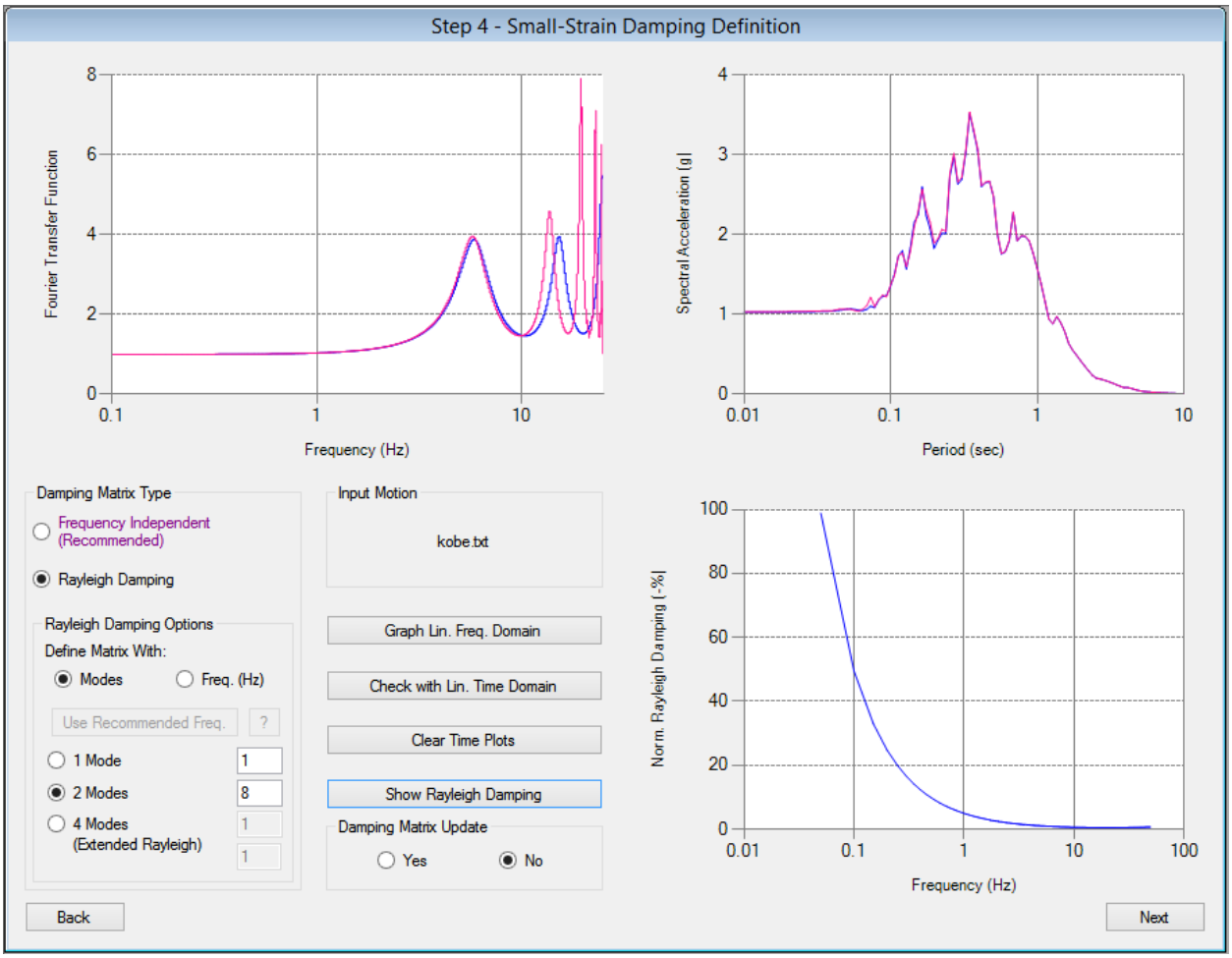


Figure 14**. Step 4/6: Small-Strain Damping Formulation.**

The following options must be specified:

- Damping Matrix Type
  - Frequency Independent (recommended)
  - Rayleigh Damping
    - 1 mode/freq.
    - 2 modes/freq. (Rayleigh)
    - 4 modes/freq. (Extended Rayleigh)
- Damping Matrix Update
    - Yes
    - No

The remaining options are at the discretion of the user:

- Graph Lin. Freq. Domain – Graphs the linear frequency domain for specified options above
- Check with Lin. Time Domain – Graphs corresponding linear time domain
- Clear Time Plots – Clears the time domain graphs
- Show Rayleigh Damping – Graphs the Rayleigh damping, not available for frequency independent formulation

For more details on this stage, please refer to Example 6 in the tutorial.

When ready to proceed, click **Next.**

Viscous damping formulation is used to model small strain damping. The viscous damping formulation results in frequency dependent damping and can introduce significant artificial damping. It is therefore important to select an appropriate viscous damping formulation and corresponding coefficients to reduce the numerical damping (Hashash and Park, 2002; Park and Hashash, 2004). There are three types of Rayleigh damping formulations in DEEPSOIL, as listed below. *It is, however, recommended that the* ***frequency independent*** *damping formulation be selected for most analyses*.

3.5.1.1 Frequency Independent Damping Formulation

This procedure solves for the eigenvalues and eigenvectors of the damping matrix and requires no specification of modes or frequencies. This formulation removes many of the limitations of Rayleigh Damping and does not greatly increase the required analysis time in most situations. A complete explanation of the damping formulation is presented in Phillips and Hashash, 2009.

3.5.1.2 Rayleigh Damping formulation types

- Simplified Rayleigh Damping formulation (1 mode/frequency)
  Uses one mode/frequency to define viscous damping.

- Full Rayleigh Damping formulation (2 modes/frequencies)
  Uses two modes/frequencies to define viscous damping.

- Extended Rayleigh Damping formulation (4 modes)
  Uses four modes/frequencies to define viscous damping.

A complete explanation of the extended Rayleigh damping formulation is presented in Park and Hashash, 2004.

Modes/frequencies selection

There are two options available for selecting modes. The first option is choosing the natural modes (e.g. 1st and 2nd modes). The second option is choosing the frequencies for Rayleigh damping directly. The resulting Rayleigh damping curve can be displayed by pressing **Show Rayleigh Damping** and the curve will be displayed at the right bottom window. Note again that the viscous damping is frequency dependent. The goal in time domain analysis is to make the viscous damping as constant as possible at significant frequencies.

Verification of the selected modes/frequencies

The time domain solution uses the frequency dependent Rayleigh damping formulation, whereas actual viscous damping of soils is known to be fairly frequency independent. The frequency domain solution uses frequency independent viscous damping. The appropriateness of the chosen modes/frequencies should be therefore verified with the linear frequency domain solution.

Press **Graph Lin. Freq. Domain**. The results of the linear frequency domain solution (Frequency ratio vs. Freq. and Response spectrum plots) will be displayed as blue curves. The goal is to choose the appropriate modes/frequencies that compare well with the linear frequency domain solution.

Enter the desired modes/frequencies as input. Then press the **Check with Lin. Time Domain** button. The results (in the same window as frequency domain solution) will be displayed as pink curves. Choose the modes/frequencies that agree well with the linear frequency domain solution. This is an iterative procedure and optimum modes/frequencies should be chosen by trial and error.

Damping Matrix Update

This option is only applicable for nonlinear solutions. During the excitation, soil stiffness and the frequencies corresponding to the natural modes of the profile change at each time step. The natural modes selected are recalculated at each time step to incorporate the change in stiffness and the damping matrix is recalculated.

This feature is enabled by clicking the **Yes** button in the **Damping Matrix Update** selection window. Note that *using this feature may significantly increase the time required to complete an analysis*.

3.5.2 Viscous Damping in Equivalent Linear Analysis (Frequency Domain) (Step 5)

DEEPSOIL allows a choice among three types of complex shear modulus formulae in performing frequency domain analysis:

- Frequency Independent Complex Shear Modulus (Kramer, 1996)
  The frequency independent shear modulus results in frequency independent damping, and is thus recommended to be used in the analysis. This is the same modulus used in SHAKE91.

$$G^* = G(1 + i2\xi)$$

- Frequency Dependent Complex Shear modulus (Udaka, 1975)
  The frequency dependent shear modulus results in frequency dependent damping, and should thus be used with caution.

$$G^* = G\left(1 - 2\xi^2 + i2\sqrt{1 - \xi^2}\right)$$

- Simplified Complex Shear modulus (Kramer, 1996)
  This is a simplified form of frequency independent shear modulus defined as:

$$G^* = G(1 - \xi^2 + i2\xi)$$

3.6 Analysis Control Parameters: Step 5 of 6

In this stage of analysis, the user may specify options to be used for either the frequency domain or time domain analysis (Figure 15).

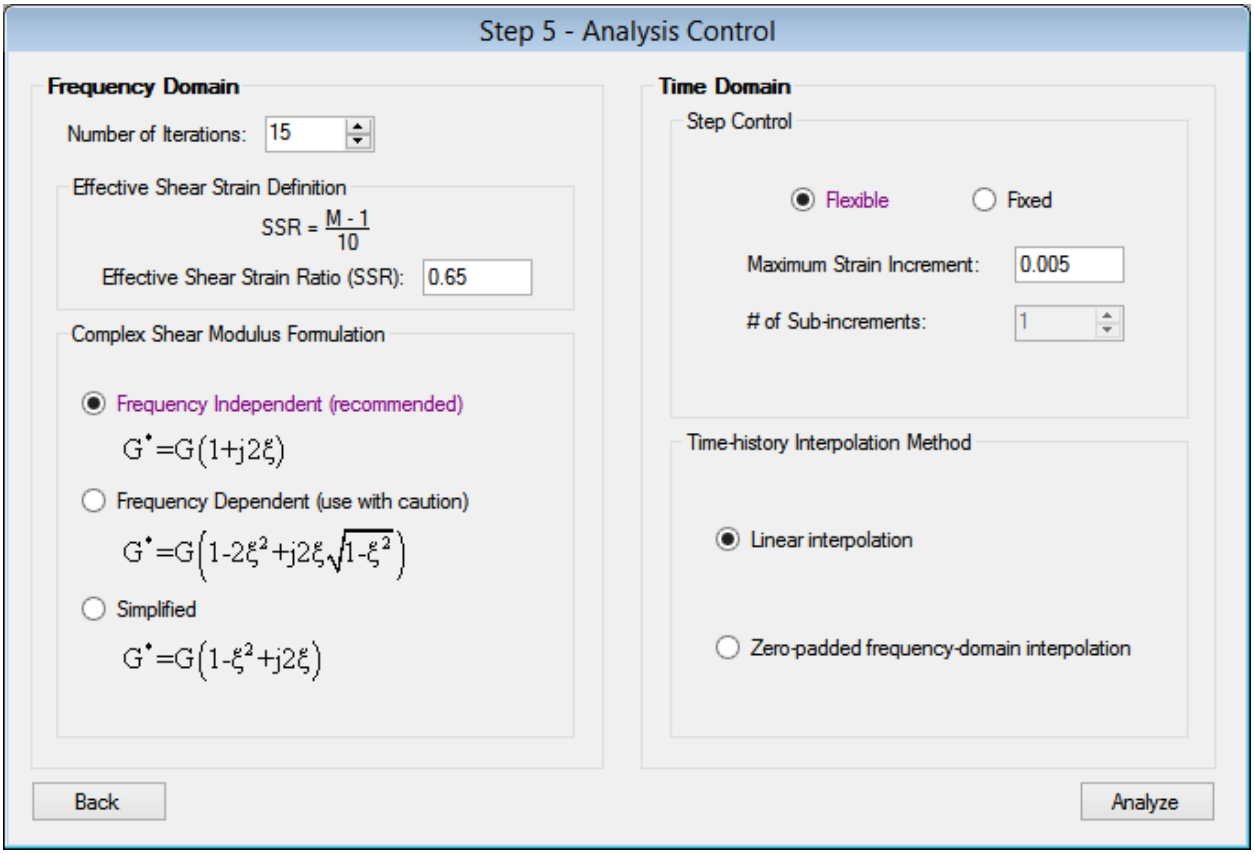


Figure 15. Step 5/6: Analysis Options for Frequency Domain or Time Domain Analysis.

3.6.1 Frequency domain analysis

The options in a frequency domain analysis are:

- Number of Iterations
- Effective Shear Strain Ratio
- Complex Shear Modulus
    - Frequency Independent
    - Frequency Dependent
    - Simplified

3.6.1.1 Number of Iterations

Determines the number of iterations in performing an equivalent linear analysis. Check whether the solution has converged and the selected iteration number is sufficient by clicking **Check Convergence** during Step 6/6 after running the analysis.

3.6.1.2 Effective Shear Strain Ratio

When performing an equivalent linear analysis, the effective strain needs to be defined. An effective shear strain, calculated as a percentage of the maximum strain, is used to obtain new estimates of shear modulus and damping ratio. The default and recommended value is 0.65 (65%). The following equation relates this value to earthquake magnitude.

$$SSR = \frac{M - 1}{10}$$

3.6.1.3 Complex Shear Modulus

Please see section 3.5.2 for a full description of the available options.

3.6.2 Time domain analysis

For a time domain analysis, the options are:

- Step Control
  - Flexible
  - Fixed
- Maximum Strain Increment
- Number of Sub-Increments

The accuracy of the time domain solution depends on the time step selected. There are two options in choosing the time step (Hashash and Park, 2001).

3.6.2.1 Flexible Step

A time increment is subdivided only if computed strains in the soil exceed a specified *maximum strain increment*.

The procedure is the same as that for the Fixed Step above, except the **Flexible** option is chosen. Type the desired **Maximum Strain Increment** into the text box. The default and recommended value is 0.005 (%).

3.6.2.2 Fixed Step

Each time-step is divided into N equal *sub-increments* throughout the time series.
To choose this option:

- Click the option button labeled **Fixed**
- DEEPSOIL responds by disabling the text box labeled **Maximum Strain Increment** and enabling **Number of sub-increments**
- Type the desired integer value of sub-increments into the text box

3.6.2.3 Time-history Interpolation Method

This option is only available when the flexible step is selected. When subdividing a time step, accelerations must be computed at intermediate points. DEEPSOIL implements two subdivision strategies: 1) linear time-domain interpolation and 2) zero-padded frequency-domain interpolation.

Linear (time-domain) interpolation is the classical approach in which the change in acceleration is simply divided into equal increments. This method has been shown to fundamentally alter the motion by adding energy to the signal at frequencies above the Nyquest frequency of the original signal. This can potentially add high frequency noise to the output signal.

Zero-padded frequency-domain interpolation is often referred to as "perfect interpolation" because it allows for increased resolution (reduced time step) without adding energy above the Nyquist frequency of the original signal. This means that the intermediate points are added to the signal in a manner that is consistent with the actual behavior of the propagating wave. However, they are not reported in the output and hence can cause a distortion in the output motion. Results from this method should always be compared to the linear interpolation results.

3.7 Output: Step 6 of 6

Upon completion of analysis, the following output for each selected layer will be directly exported to a text file "Results - *motion*.txt" in the working directory specified in step 1.

For "Total Stress Analysis"

- Acceleration (g) vs Time (sec)
- Strain (%) vs Time (sec)
- Stress (shear/effective vertical) vs Time (sec)
- Response Spectra: PSA (g) vs Period (sec)
- Fourier Amplitude (g-sec) vs Frequency (Hz)
- Fourier Amplitude Ratio (surface/input) vs Frequency (Hz)
- PGA Profile: Max PGA vs Depth
- Strain Profile: Max Strain vs Depth

For "Effective Stress Analysis"

- All from "Total Stress Analysis"
- Pore Water Pressure (pwp/effective vertical) vs Time (sec)
- PWP Profile: Max PWP Ratio vs Depth

If multiple motions were selected for analysis, the output can be found in the user's working directory in a folder named "Batch Output". Within this folder, there will be a folder corresponding to each collection of batch analyses (ie. Batch0, Batch1, …etc). These folders will contain the results from each motion.

If a single motion was selected for analysis, the results can be found in the user's working directory.

After analysis is complete, the user may immediately view the following output visually (Figure 16) by selecting the appropriate tab for the selected layer:

- Acceleration (g) vs Time (sec)
- Velocity (ft/sec or m/sec) vs Time (sec)
- Relative Displacement (ft or m) vs Time (sec)
- Arias Intensity (ft/sec or m/sec) vs Time (sec)
- Strain (%) vs Time (sec)
- Stress (shear/effective vertical) vs Time (sec)
- Stress (shear/effective vertical) vs Strain (%)
- Excess Porewater Pressure (excess/effective vertical) vs Time (sec) (if applicable)
- Fourier Amplitude (g-sec) vs Frequency (Hz)
- Fourier Amplitude Ratio (surface/input) vs Frequency (Hz)
- Response Spectra: PSA (g) vs Period (sec)

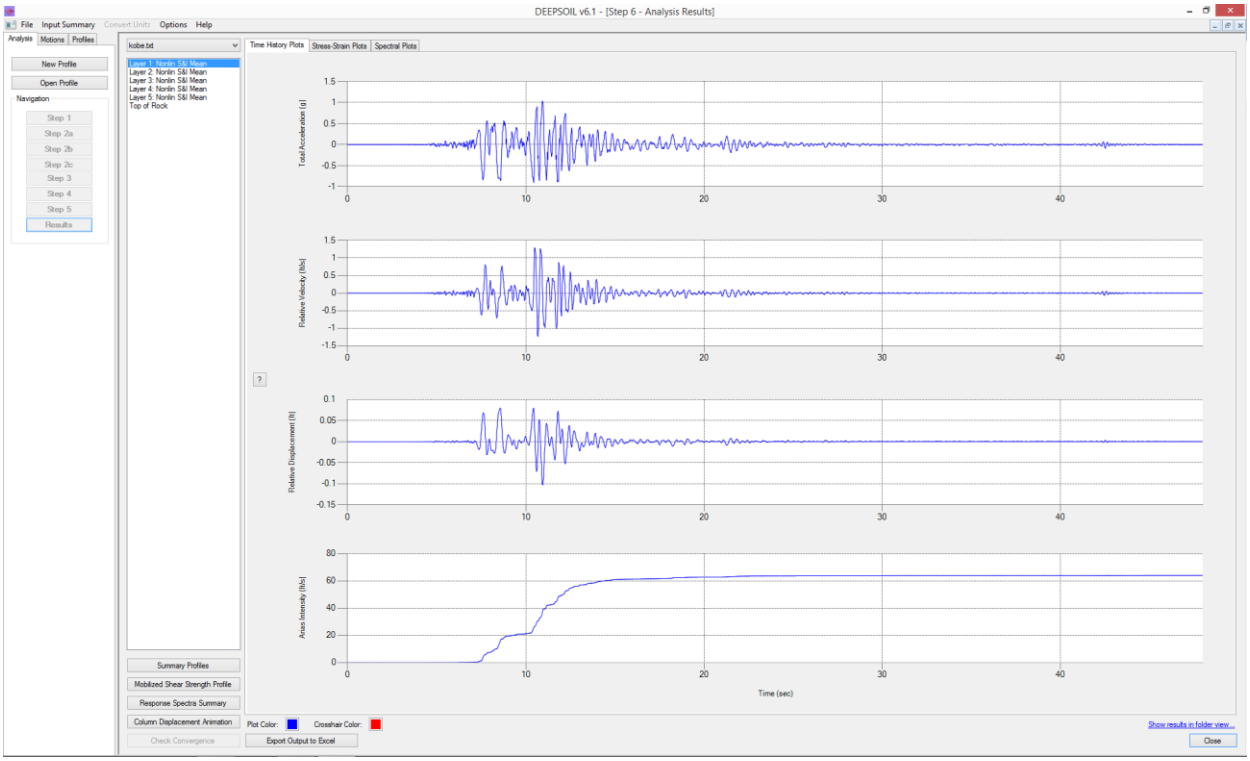


Figure 16. Step6/6: Analysis Results - Plot Output for Layer.

3.7.1 Output data file

Output data for each layer analyzed is automatically exported to "Results – *motion*.txt" in the user's working directory.

DEEPSOIL also provides the option to export the analysis results to a Microsoft Excel file. This is done by clicking the **Export to Excel** button on the results form. Note that **this feature requires Microsoft Excel be installed on the system**.

3.7.2 Summary Profiles

To view the PGA profile click the command button labeled **Summary Profiles** in the lower left-hand side of the window.

The Summary Profiles Window shows the PGA, maximum strain, and maximum shear stress ratio for each layer. If an analysis with porewater pressure generation was conducted, this window will also show the maximum excess porewater pressure ratio (excess/effective vertical) for each layer. Note that the PGA is calculated at the top of each layer, while all other values are calculated at the midpoint of each layer. To view the layers in the plots, check **Show Layers**. To change the color of the plotted layer lines, click the color box and select a new color. When you are finished, press **Back** to return to the output plots.

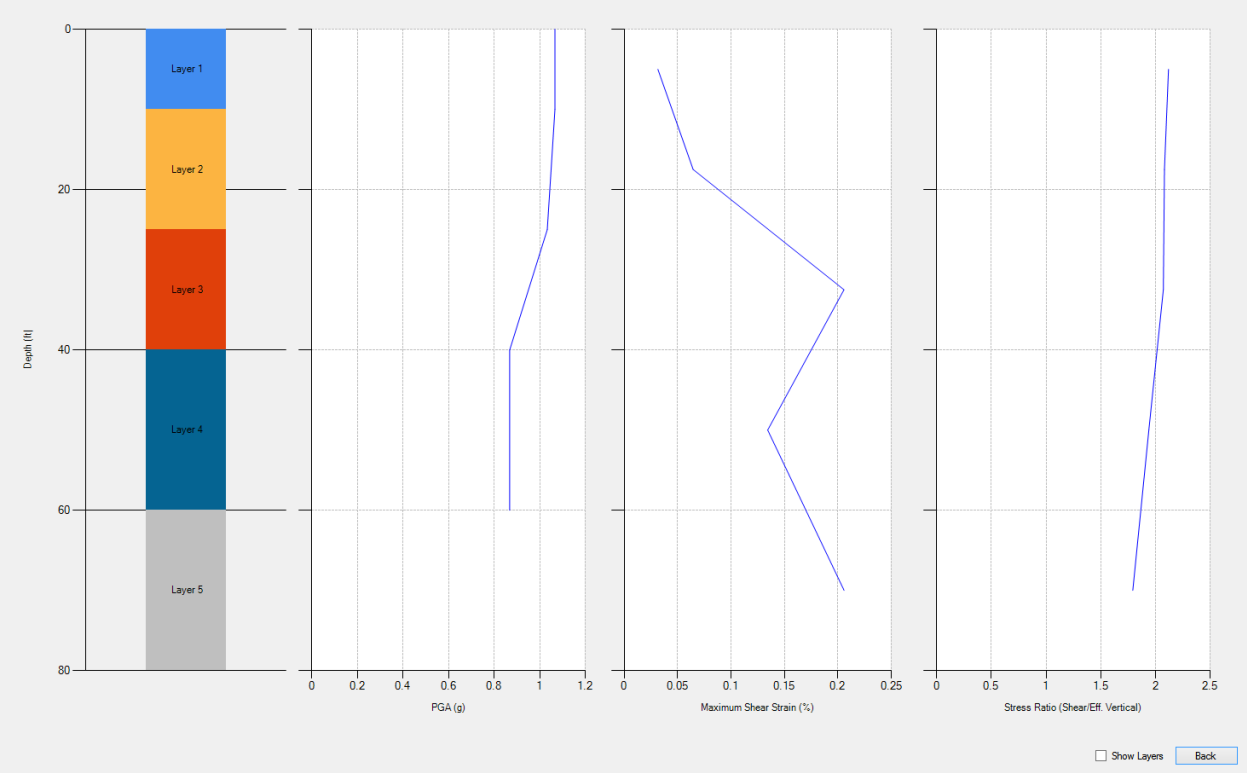


Figure 17. Summary Profiles

3.7.3 Displacement profile and animation

To view the displacement profile and animation click the command button labeled **Column Displacement Animation** in the lower left-hand side of the window.

The Column Displacement Animation Window allows the user to adjust the speed of the animation as well as to stop the animation and show the displacement at a given time. These options can be adjusted using the scroll bars below the plot. Click **Start** to start the animation or click **Back** to return to the output plots.

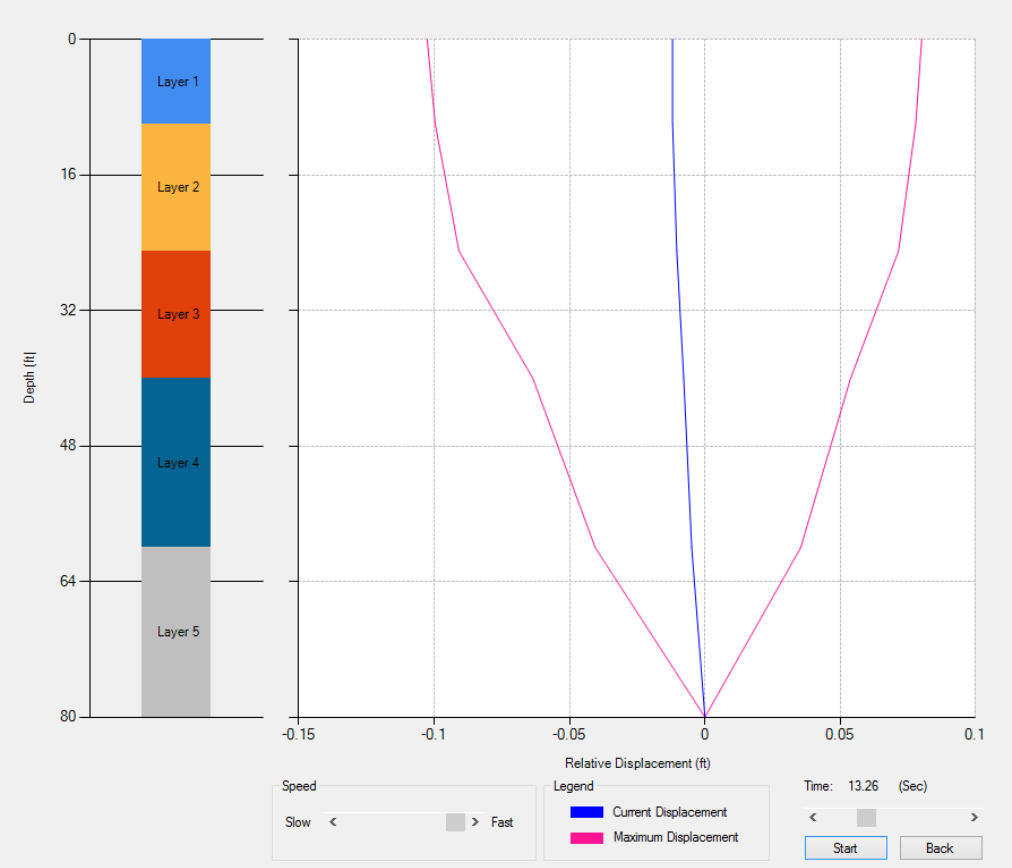


Figure 18. Column Displacement Animation

3.7.4 Convergence results (Equivalent Linear Analyses Only)

To view the convergence of the solution, click the command button labeled **Check Convergence** in the lower left-hand side of the window.

This option enables checking whether the solution has converged in an equivalent linear analysis. Plots of maximum strain profiles for each iteration are displayed (Figure 19). To view the layers in the plots, check **Show Layers**. To change the color of the plotted layer lines, click the color box and select a new color. When you are finished, press **Back** to return to the output plots.

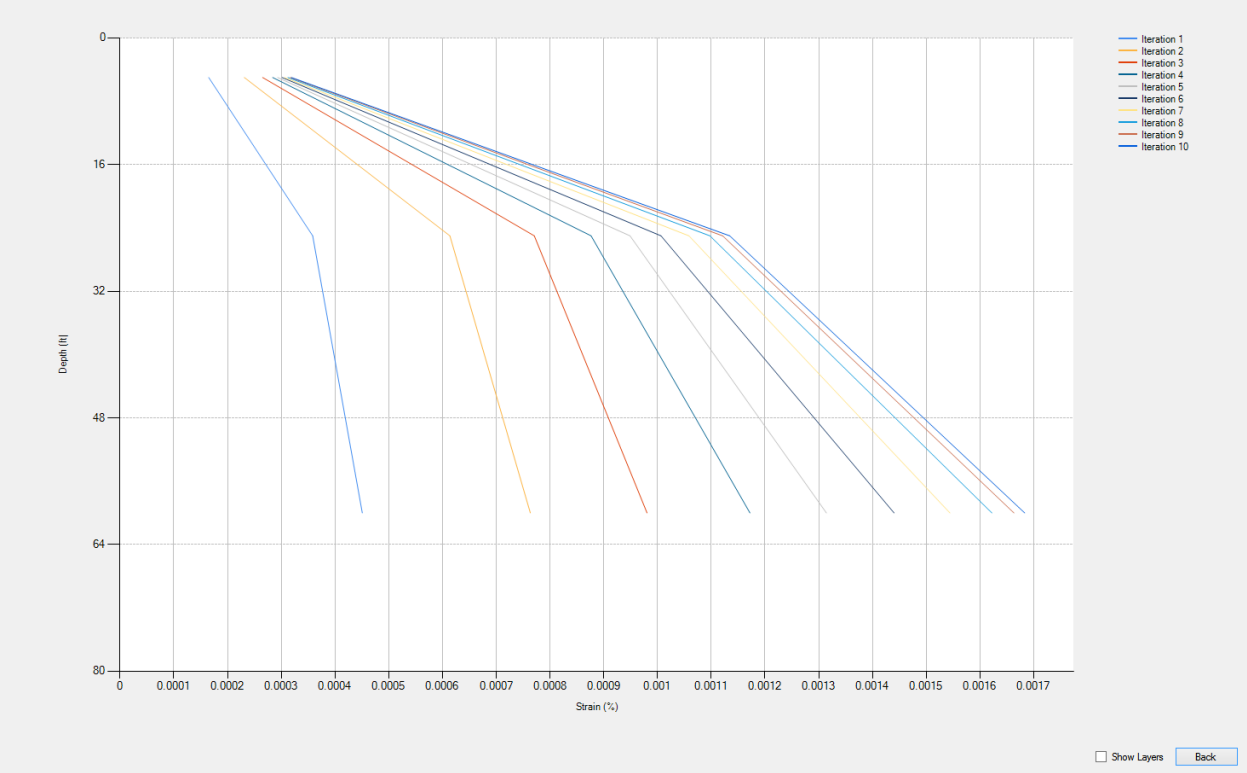


Figure 19. Convergence Check.

3.7.5 Input Summary

To review the input parameters, click the **View** menu and select **Input Summary**. The input summary window (Figure 20) may be viewed any time after completing step 1. Note: tabs will only appear after the corresponding parameters have been input. Use the **Save** button to create a text file of the input parameters.

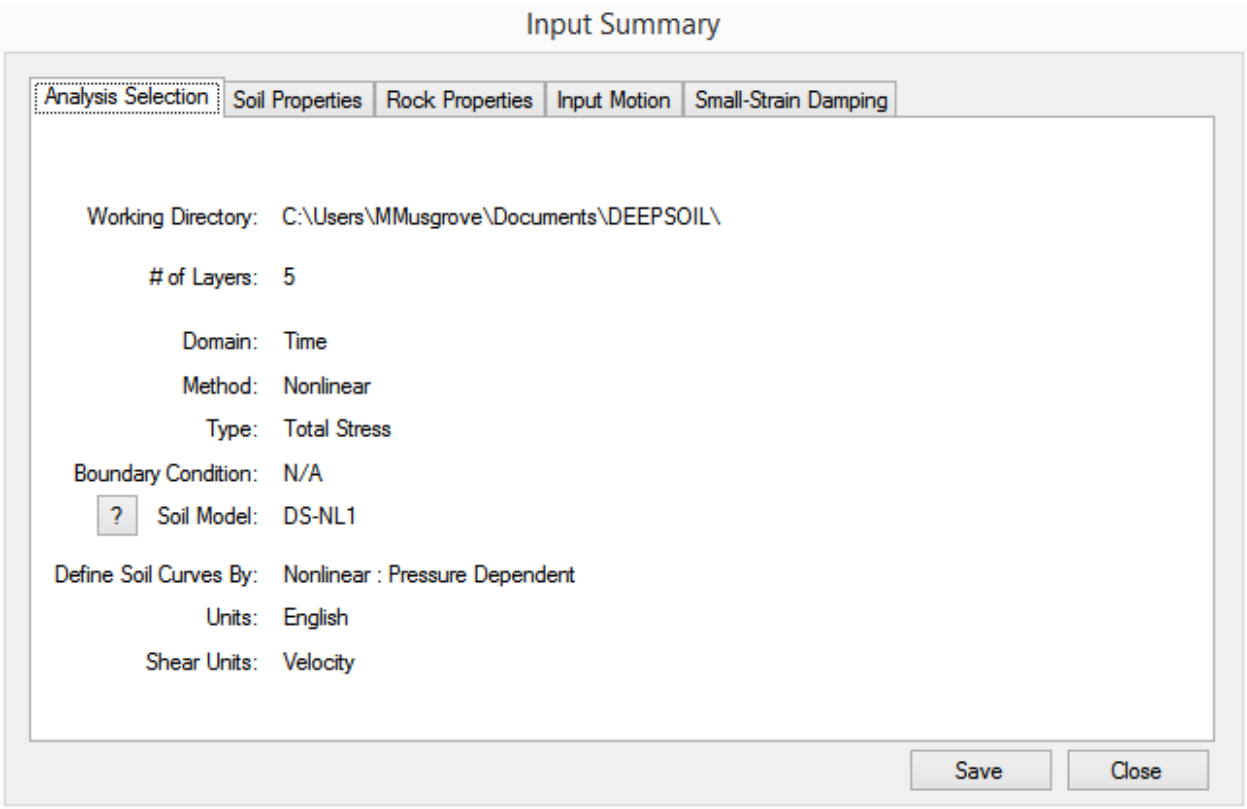


Figure 20. Input Summary

4 Soil Models

A variety of models are available for DEEPSOIL analyses. These models include: a) Equivalent Linear, b) Hyperbolic (MR, MRD, DC), c) a Non-Masing Hyperbolic model (MRDF), and d) Porewater Pressure Generation and Dissipation.

4.1 Backbone Curves

4.1.1 Hyperbolic / Pressure-Dependent Hyperbolic (MKZ)

DEEPSOIL incorporates the pressure-dependent hyperbolic model. The modified hyperbolic model, developed by (Matasovic, 1993), is based on the *hyperbolic model* by (Konder and Zelasko, 1963), but adds two additional parameters Beta (β) and **s** that adjust the shape of the backbone curve:

$$\tau = \frac{G_0 \gamma}{1 + \beta \left(\frac{\gamma}{\gamma_r}\right)^s}$$

where G_0 = initial shear modulus, τ = shear strength, γ = shear strain. *Beta*, *s*, and γ_r are model parameters. There is no coupling between the confining pressure and shear stress.

DEEPSOIL extends the model to allow coupling by making γ_r confining pressure dependent as follows (Hashash and Park, 2001):

$$\gamma_r = Reference\ Strain \left(\frac{\sigma_v'}{Reference\ Stress}\right)^b$$

where σ_v' is the effective vertical stress. Ref. stress is the vertical effective stress at which γ_r = Ref. stress. This model is termed as the "pressure-dependent hyperbolic model."

The pressure-dependent modified hyperbolic model is almost linear at small strains and results in zero hysteretic damping at small strains. Small strain damping has to be added separately to simulate actual soil behavior which exhibits damping even at very small strains (Hashash and Park, 2001). The small strain damping is defined as

$$\xi = Small\ Strain\ Damping\ Ratio \left(\frac{1}{\sigma_v'}\right)^d$$

d can be set to zero in case a pressure independent small strain damping is desired.

In summary, the parameters to be defined in addition to the layer properties are:

- *Reference Strain*

- *Stress-strain curve parameter, Beta* (β)
- *Stress-strain curve parameter, s*
- *Pressure dependent (reference strain) parameter, b*
- *Reference Stress*
- *Pressure dependent (damping curve) parameter, d*

4.1.2 Generalized Quadratic/Hyperbolic (GQ/H) Model with Shear Strength Control

This section will be updated in future revisions of the manual. Please see Appendix C for a description of the GQ/H model.

4.2 Hysteretic (unload-reload behavior) behavior

4.2.1 Masing Rules

When the user wishes to fit a soil curve (i.e. determine the model parameters which most closely match the defined curves), the following options are available:

MR: Procedure to find the parameters that provide the best fit for the modulus reduction curve with potentially significant mismatch of the damping curve.

MRD: Procedure to find the parameters that provide the best fit for both the modulus reduction and damping curve

DC: Procedure to find the parameters that provide the best fit for the damping curve with potentially significant mismatch of the backbone curve.

4.2.2 Non-Masing Unload-Reload Rules

The non-Masing model included in DEEPSOIL is the MRDF Pressure-Dependent Hyperbolic (Phillips and Hashash, 2009) model. This model is implemented as a reduction factor which effectively alters the Masing rules. By introducing the reduction factor, the modulus reduction and damping curves can be fit simultaneously. The damping behavior is modified as:

$$\xi_{MasingHysteretic} = F(\gamma_{max}) * \xi_{Masing}$$

where $F(\gamma_m)$ is the reduction factor calculated as a function of $\gamma_{m,}$, the maximum shear strain experienced by the soil at any given time, and ξ_{Masing} is the hysteretic damping calculated using the Masing rules based on the modulus reduction curve. Two formulations for $F(\gamma_m)$ are implemented in DEEPSOIL and are discussed in the following sections.

4.2.2.1 MRDF-UIUC

The MRDF Pressure-Dependent Hyperbolic (Phillips and Hashash, 2009) model available in DEEPSOIL allows the user to introduce a reduction factor into the hyperbolic model. The reduction factor has the form:

$$F(\gamma_m) = P_1 - P_2(1 - G(\gamma_m)/G_0)^{P_3}$$

where γ_m is the maximum shear strain experienced at any given time, $G(\gamma_m)$ is the shear modulus at γ_m, and P_1, P_2, and P_3 are fitting parameters.

By setting P_1= 1 and P_2= 0, the reduction factor is equal to 1 (regardless of the value of P_3), and the model is reduced to the Extended Masing criteria.

4.2.2.2 MRDF-Darendeli

The MRDF Pressure-Dependent Hyperbolic (Phillips and Hashash, 2009) model can also be used with alternative formulations for the reduction factor. One alternative is the formulation proposed by Darendeli, 2001. This formulation is an empirically-based modified hyperbolic model to predict the nonlinear dynamic responses of different soil types. The developed model is implemented as a reduction factor with the form:

$$F(\gamma_m) = P_1(G(\gamma_m)/G_0)^{P_2}$$

where γ_m is the maximum shear strain experienced at any given time, $G(\gamma_m)$ is the shear modulus at γ_m, and P_1 and P_2 are fitting parameters.

By setting P_1= 1 and P_2= 0, the reduction factor is equal to 1, and the model is reduced to the Extended Masing criteria.

4.2.2.3 Non-Masing Unload-Reload Formulation

The hyperbolic / pressure-dependent hyperbolic unload-reload equation is modified with the reduction factor, $F(\gamma_m)$, as follows:

$$\tau = F(\gamma_m)\left[2\frac{G_0((\gamma-\gamma_{rev})/2)}{1+\beta\left(\frac{(\gamma-\gamma_{rev})}{2\gamma_r}\right)^s} - \frac{G_0(\gamma-\gamma_{rev})}{1+\beta\left(\frac{\gamma_m}{\gamma_r}\right)^s}\right] + \frac{G_0(\gamma-\gamma_{rev})}{1+\beta(\gamma_m-\gamma_r)^s} + \tau_{rev}$$

4.3 Porewater Pressure Generation & Dissipation

The following table summarizes the available excess pore water pressure generation models and required parameters.

Table 1: Available Excess Pore Water Pressure Generation Models and Parameters

PWP Model	Soil Type	Abbrev.	Model No:	Input 1	Input 2	Input 3	Input 4	Input 5	Input 6	Input 7
Dobry & Matasovic	Sand	S-M/D	1	f	p	F	s	γ_{tvp}	v	-
Matasovic & Vucetic	Clay	C-M	2	s	r	A	B	C	D	γ_{tvp}
GMP	Cohesioneless	GMP	3	α	D_r (%)	FC(%)	-	-	v	-
Park & Ahn	Sand	P/A	4	α	β	$D_{ru=1.0}$	CSR_t	-	v	-
Generalized	Any	G	5	α	β	-	-	-	v	-

Each model is described in the following sections. The user is referred to the original sources for additional details.

4.3.1 Dobry/Matasovic Model for Sands

The Matasovic (1992) pore water pressure generation parameters must be determined by a curve-fitting procedure of cyclic undrained lab-test data. Once such data is obtained, the following equation, proposed by Matasovic and Vucetic (1993, 1995), can be used to determine the best-fit parameters to be used in the analysis.

The excess pore water pressure is generated using the following equation:

$$u_N = \frac{p * f * N_c * F * \left(\gamma_c - \gamma_{tvp}\right)^s}{1 + f * N_c * F * \left(\gamma_c - \gamma_{tvp}\right)^s}$$

Table 2 Description of Dobry/Matasovic Model Parameters

VARIABLE	DESCRIPTION
u_N	Normalized excess pore pressure (r_u).
N_{eq}	Equivalent number of cycles.
γ_c	The current reversal shear strain.
γ_{tvp}	Threshold shear strain value.
p	Curve fitting parameter.
s	Curve fitting parameter.
F	Curve fitting parameter.
f	Dimensionality factor.
v	Degradation parameter

Remarks:

The u_N parameter is defined as the normalized excess pore water pressure ratio ($r_u = u' / \sigma_v'$)

N_{eq} is the equivalent number of cycles calculated for the most recent strain reversal. For uniform strain cycles, the equivalent number of cycle is the same as number of loading cycles. For irregular strain cycles, since the cycle number does not increase uniformly, and N_{eq} is calculated at strain reversals using the u_N obtained from previous step and then incremented by 0.5 for the current step.

γ_{tvp} is the shear strain value below which reversals will not generate excess pore water pressure.

f is used to account for loading in multiple dimensions. f = 1 is used for 1D motion. f = 2 is used for 2D motion. Note that assigning a value of f = 2 does not double the excess pore water pressure because f is included in both the numerator and denominator of the equation.

F, s, and p are curve fitting parameters and can be obtained from laboratory tests.

The degradation parameter, v, is discussed in further detail in section 4.3.6

Suggested Values:

Carlton (2014) presents empirical correlations for the curve fitting parameters F and s for sands.

The best fit to the data is shown in Figure 21 and take the following functional forms:

$$F = 3810 * V_s^{(-1.55)}$$

$$s = (FC + 1)^{0.1252}$$

where V_s is the shear wave velocity in m/s and FC is the fines content in percent. The fit is produced using the data from Table 3.

Table 3 shows that the values of p stays within +-7.1% of 1 for different type and relative density of sands. For practical purposes, p = 1 is often assumed in the absence of laboratory data.

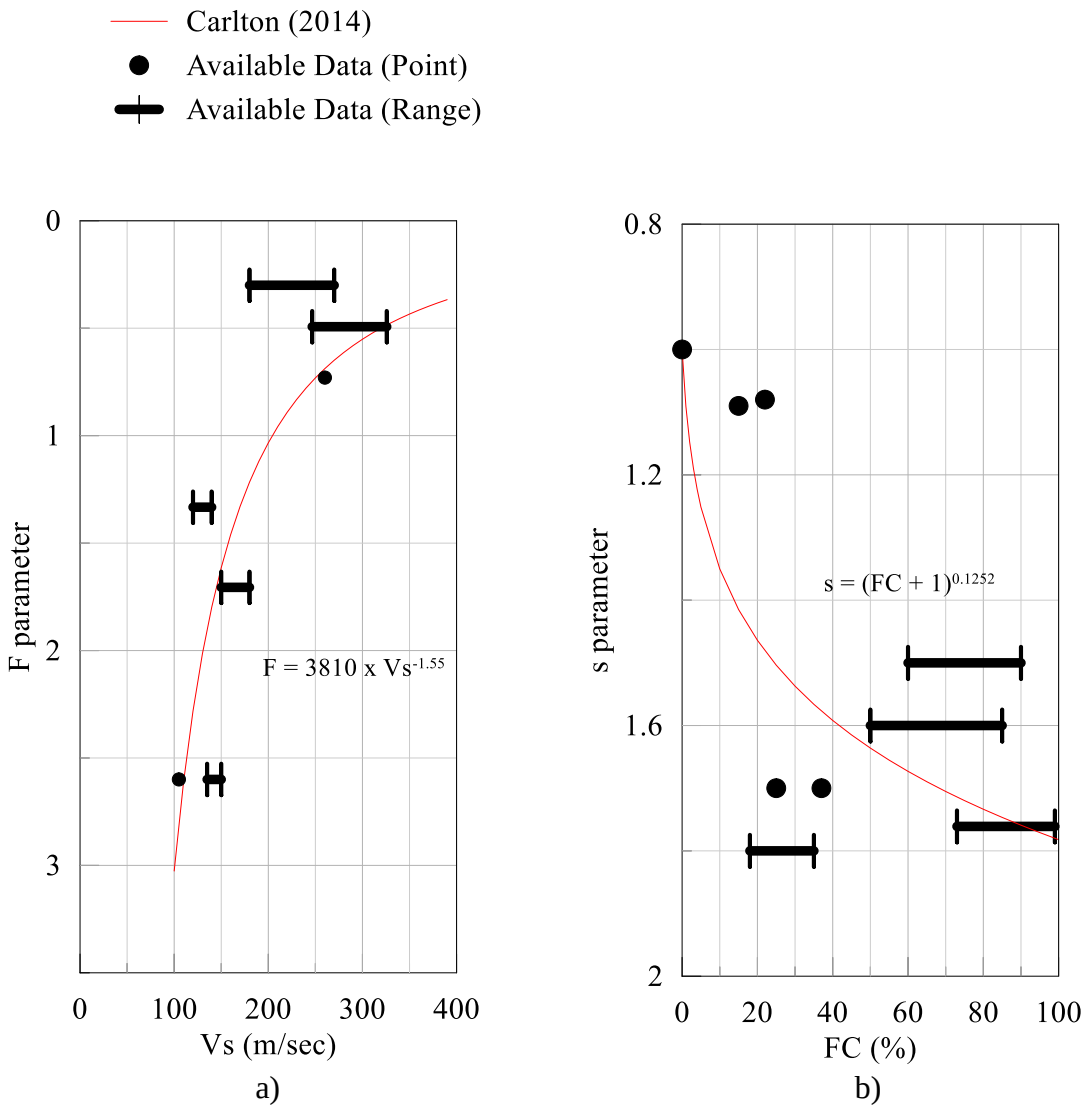


Figure 21: a) Carlton (2014), best fit correlating Vs (m/sec) to parameter F of Dobry pore water pressure model for sands. b) Carlton (2014), best fit correlating FC (%) to parameter s of Dobry pore water pressure model for sands.

Table 3: Material Parameters for Low Plasticity Silts and Sands for the Matasovic and Vucetic (1993) pore pressure generation model (From Carlton, 2014)

Material	Reference	k (ft/sec)	Pore Water Pressure Model Parameters					
			v	f	p	F	s	γ_{tv} (%)
Warrenton, Oregon Silt recovered from 130 to 248 ft b.g.s; 73%<fines<99%; 32.9%<water content<37.3%; 86.3<γdry< 88.9 pcf;882< Vs<1086 fps; OCR = 1.0; PI = 10, LL = 37	Dickenson (2008)	not reported	1	1	1	0.493	1.761	0.06
Stillaguamish River Silt, Washington; recovered from 30 to 95 ft b.g.s; 60%< fines< 90%; 600ft<Vs<900 ft/s; PI=8-10; LL=31-32	Anderson et al. (2010)	not reported	not reported	2	1.05	0.3	1.5	0.02
Bangding Sand (BS); poorly-graded commercially avaliable sane; Dγ＝40%；Dγ＝0.19；Cc＝0.9；Cu＝1.4；γd,min = 90pcf;γd,max=106pcf	Dobry et al. (1985)	$5.5x10^{-4}$	1	1	1	10.9	1	0.017
Wildlife Site Sand A(WSA); void ratio 0.84 to 0.85; 37% fines; N≈5;Vs≈350ft/s	Vucetic and Dobry (1988)	$9.8x10^{-4}$	1	2	1.04	2.6	1.7	0.02
Wildlife Site Sand B(WSB); void ratio 0.74 to 0.76; 25% fines; N≈6 to 13;Vs ≈ 450 to 500 ft/s	Vucetic and Dobry (1988)	$6.6x10^{-3}$	1	2	1.04	2.6	1.7	0.02
Heber Road Site Sand PB; void ratio 0.7; 15% fines; Vs ≈ 500 to 600 ft/s	Vucetic and Dobry (1989)	$1.4x10^{-4}$	1	2	1.05	1.706	1.09	0.024
Heber Road Site Sand PB; void ratio 0.7; 22% fines; Vs ≈ 400 to 466 ft/s	Vucetic and Dobry (1990)	$3.9x10^{-5}$	1	1	1.071	1.333	1.08	0.022
Santa Monica Beach Sand(SMB); clean uniform beach sand similar to Monterey No. 0; void ratio = 0.56; zero fines; dense; Vs ≈ 867 ft/s	Matasovic (1993)	$3.3x10^{-1}$	3.8	1	1	0.73	1	0.02
Owi Island Sand at depths from 6 to 14 m b.g.s.; silty fine sand placed as hydraulic fill; 18% <fines<35%	Thilakaratne and Vucetic(1987)	$6.6x10^{-3}$	1	2	1.005	3	1.8	0.025

Owi Island Sand at depths of 6 m; placed as hydraulic fill; 50% <fines<85%	Thilakarat ne and Vucetic(19 88)	$9.8x10^{-4}$	1	2	0.95	2.5	1.6	0.015

Mei et al. (2015) developed correlation for the curve fitting parameter F using 123 cyclic shear test results compiled from literature. Two soil index properties, relative density (D_r) and uniformity coefficient (C_u) are used in the correlation and it is applicable to sub-angular to sub-rounded clean sands.

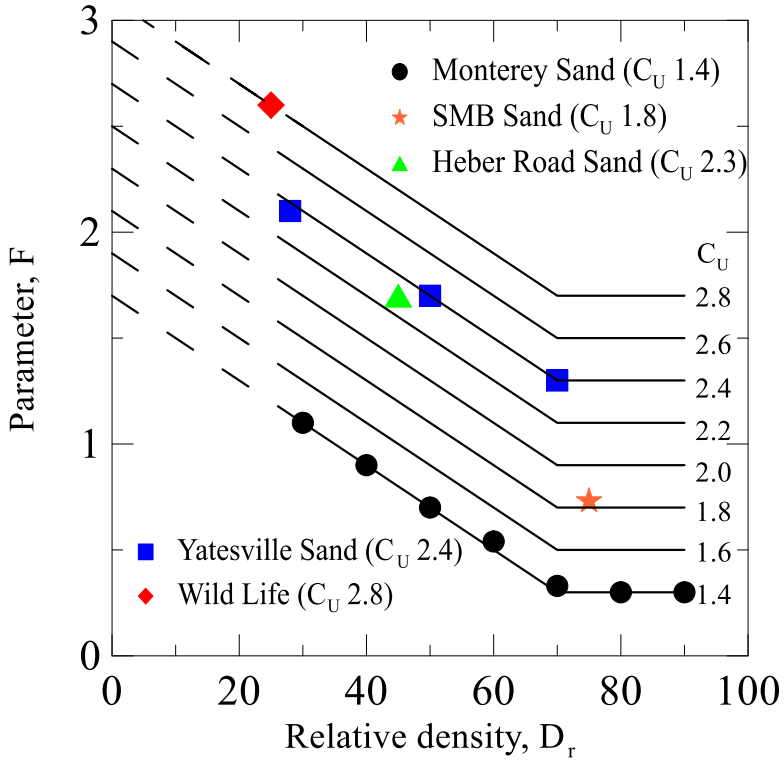


Figure 22: Proposed correlation to estimate curve-fitting parameter F (Mei et al. 2015)

4.3.2 Matasovic and Vucetic Model for Clays

Matasovic and Vucetic (1995) propose the following equation for the excess pore water pressure generation for clays:

$$u_N = AN_c^{-3s(\gamma_c-\gamma_{tvp})^r} + BN_c^{-2s(\gamma_c-\gamma_{tvp})^r} + CN_c^{-s(\gamma_c-\gamma_{tvp})^r} + D$$

Table 4: Description of Matasovic and Vucetic Model Parameters

VARIABLE	DESCRIPTION
u_N	Normalized excess pore pressure (r_u)
N_{eq}	Equivalent number of cycles
γ_c	The most recent reversal shear strain.
γ_{tvp}	Threshold shear strain value.
r	Curve fitting parameter.
s	Curve fitting parameter.
A	Curve fitting coefficients
B	Curve fitting coefficients
C	Curve fitting coefficients
D	Curve fitting coefficients

Remarks:

The u_N parameter is the same as normalized excess pore water pressure ratio ($r_u = u' / \sigma_v'$)

N_{eq} is the equivalent number of cycles calculated for the most recent strain reversal. For uniform strain cycles, the equivalent number of cycle is the same as number of loading cycles. For irregular strain cycles, since the cycle number does not increase uniformly, and N_{eq} is calculated using the u_N obtained from previous step and then incremented by 0.5 for the current step.

γ_{tvp} is the threshold shear strain value below which reversals will not generate excess pore water pressure.

Suggested Values:

Carlton (2014) presents empirical correlations for curve fitting parameters s, r, A, B, C, and D. Table 5 and Figure 23 (solid black lines) are used in the correlations. The parameter t in the figure corresponds to $s*(\gamma_c - \gamma_{tvp})^r$. The empirical correlations take the following functional forms:

$$s = 1.6374\ x\ PI^{-0.802}\ x\ OCR^{-0.417}$$

$$r = 0.7911\ x\ PI^{-0.113}\ x\ OCR^{-0.147}$$

$$A = \begin{cases} 7.6451\ for\ OCR < 1.1 \\ 15.641\ x\ OCR^{-0.242}\ for\ OCR \geq 1.1 \end{cases}$$

$$B = \begin{cases} -14.714\ for\ OCR < 1.1 \\ -33.691\ x\ OCR^{-0.33}\ for\ OCR \geq 1.1 \end{cases}$$

$$C = \begin{cases} 6.38\ for\ OCR < 1.1 \\ 21.45\ x\ OCR^{-0.468}\ for\ OCR \geq 1.1 \end{cases}$$

$$D = \begin{cases} 0.6922\ for\ OCR < 1.1 \\ -3.4708\ x\ OCR^{-0.857}\ for\ OCR \geq 1.1 \end{cases}$$

where OCR is the over consolidation ratio, and PI is the plasticity index.

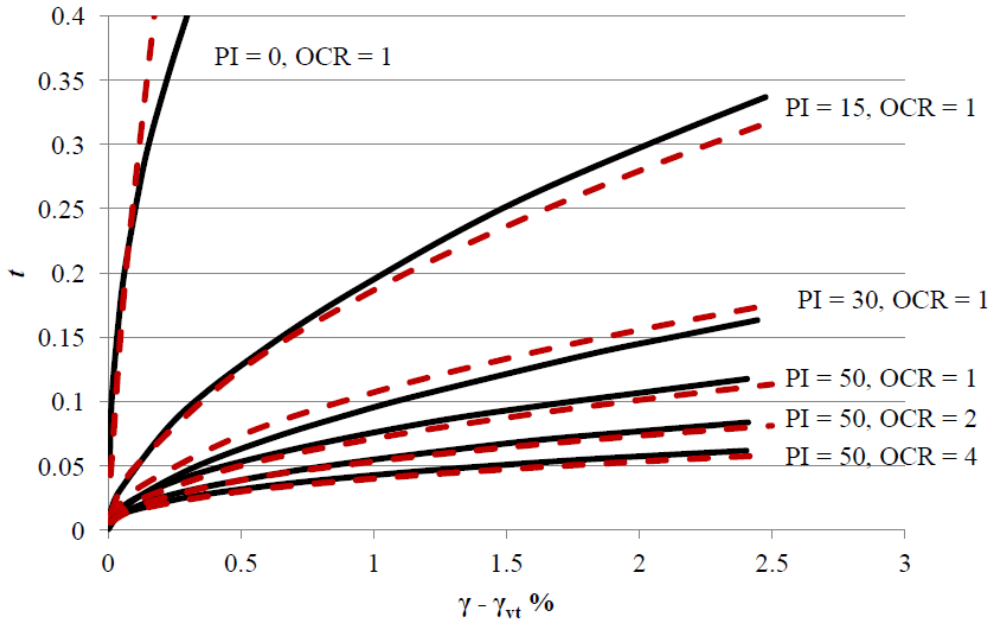


Figure 23: Comparison of the curves given by Matasovic (1993) and Vucetic (1992) (solid black lines) for t for different values of PI and OCR and the correlations presented (dotted red lines). (Carlton, 2014)

Table 5: Material parameters for the Matasovic and Vucetic (1995) clay pore pressure generation model (From Carlton, 2014)

Material	Reference	γ_{tvp} (%)	Pore Water Pressure and Degradation Model Parameter					
			s	r	A	B	C	D
Marine Clay (OCR = 1.0)	Matasovic and Vucetic (1995)	0.1	0.075	0.495	7.6451	-14.7174	6.3800	0.6922
Marine Clay (OCR = 1.4)	Matasovic and Vucetic (1995)	0.1	0.064	0.520	14.62	-30.5124	18.4265	-2.5343
Marine Clay (OCR = 2.0)	Matasovic and Vucetic (1995)	0.1	0.054	0.480	12.95	-26.3287	15.3736	-1.9944
Marine Clay (OCR = 4.0)	Matasovic and Vucetic (1995)	0.1	0.042	0.423	11.263	-21.4595	11.2404	-1.0443

4.3.3 GMP (Green, Mitchel and Polito) Model for Cohesioneless Soil

The GMP model (Green et al. 2000) is an energy-based pore pressure generation model. The excess pore pressure is calculated as follows:

$$r_u = \alpha \sqrt{\frac{W_s}{PEC}}$$

Table 6: Description of GMP Model Parameters

VARIABLE	DESCRIPTION
r_u	Normalized excess pore pressure.
W_s	Normalized dissipated energy per unit volume of soil.
PEC	Pseudo energy capacity.
α	Scale factor.
v	Degradation parameter

Remarks:

The dissipated energy, W_s, is calculated as the area beneath the current stress-strain path and has the following functional form:

$$W_s = \frac{1}{2\sigma_0'} \sum_{i=1}^{n} (\tau_{i+1} + \tau_i) * (\gamma_{i+1} - \gamma_i)$$

In DEEPSOIL, a scale factor "α" is introduced to allow for scaling of the generated excess pore water pressure to match laboratory or field data.

The GMP model is a special case of the Berrill and Davis model (Berrill and Davis, 1985) that has the form $r_u = \alpha \times W_s^{\beta}$. In GMP model, α and β values are replaced by $(1/PEC)^{0.5}$ and 0.5 respectively.

The degradation parameter is as described by Matasovic (1993) and uses the same functional form as defined in the Matasovic model for sands (see section 4.3.6).

Suggested Values:

The determination of the PEC calibration parameter can be conducted either via graphical procedure or by use of an empirical relationship. The graphical procedure is described in detail by Green et al. (2000). However, this causes an interruption in analysis as it requires the construction of the graphical procedure outside of site response analysis software.

Polito et al. (2008) derived an empirical relationship between PEC, relative density (D_r), and fines content (FC) from a large database of laboratory data on non-plastic silt-sand mixtures ranging from clean sands to pure silts. The use of this empirical relationship allows the use of the GMP

model directly in nonlinear site response analysis software by removing the need to find the value of PEC through graphical procedures. The empirical relationship is defined as:

$$\ln(PEC) = \begin{cases} FC < 35\%: e^{0.0139D_r} - 1.021 \\ FC \geq 35\%: -0.597 * FC^{0.312} + e^{0.0139D_r} - 1.021 \end{cases}$$

4.3.4 Generalized Energy-based PWP Generation Model

This model allows for a user-defined excess pore water generation model based on the framework adopted from Berrill and Davis (1985) and Green et al. (2000). The model is energy-based and the excess pore water pressure is calculated as follows:

$$r_u = \alpha * W_s^{\beta}$$

The model is a generalized form of GMP model, and uses the same general functional form presented in the Berrill and Davis (1985) formulation. α and β are curve fitting parameters and can be extracted from laboratory tests. W_s is the dissipated energy and calculated using the formulation defined in the GMP model.

The degradation parameter is as described by Matasovic (1993) and uses the same functional form as defined in the Matasovic model for sands (see section 4.3.6).

Table 7: Description of Generalized Model Parameters

VARIABLE	DESCRIPTION
α	Curve fitting coefficient
β	Curve fitting parameter
W_s	Normalized dissipated energy per unit volume of soil
v	Degradation parameter

4.3.5 Park and Ahn Model for Sands

The Park and Ahn (2013) model is a stress-based excess pore water pressure generation model that uses the concept of a damage parameter to account for the accumulation of stress. The excess pore water pressure is calculated as follows:

$$r_u = \frac{2}{\pi}\arcsin\left(\frac{D}{D_{ru=1.0}}\right)^{\left(\frac{1}{2\beta}\right)}$$

where the damage parameter D at each time step can be calculated as:

$$D_{i+1} = D_i + \Delta D$$

$$\Delta D = 2(CSR_{i+1} - CSR_t)^{\alpha}$$

In an incremental form, the generation model becomes:

$$dr_u = (r_u)_{i+1} - (r_u)_i = \frac{2}{\pi} arcsin\left[\left(\frac{D_{i+1}}{D_{r_u=1.0}}\right)^{\frac{1}{2\beta}}\right] - \frac{2}{\pi} arcsin\left[\left(\frac{D_i}{D_{r_u=1.0}}\right)^{\frac{1}{2\beta}}\right]$$

Table 8: Description of Park and Ahn Model Parameters

VARIABLE	DESCRIPTION
r_u	Normalized excess pore pressure.
D	Damage parameter.
$D_{ru = 1.0}$	Damage parameter at the initiation of liquefaction
CSR_t	Threshold shear stress ratio value.
α	A calibration parameter
β	Empirical constant
v	Degradation parameter

Remarks:

CSRt is the threshold shear stress ratio below which reversals will not generate excess pore water pressure.

The degradation parameter is as described by Matasovic (1993) and uses the same functional form as defined in the Matasovic model for sands (see section 4.3.6).

Suggested Values:

α is a calibration parameter that can be calculated using following formulation with the CSR-N curve obtained from laboratory tests:

$$\alpha_{ave} = \frac{1}{M} * \sum_{i=1}^{M-1} (\log(N_i/N_{i+1})/(\log(CSR_{i+1} - CSR_t) - \log(CSR_i - CSR_t))$$

where M is the total number of data points in CSR-N curve.

β is an empirical constant and for the clean sands, a value of 0.7 is suggested.

$D_{ru=1.0}$ is the value of damage parameter, D, at initiation of liquefaction and can be calculated from CSR-N curves that are obtained from laboratory tests using following formula:

$$D_{ru=1.0} = 4N(CSR - CSR_t)^{\alpha}$$

4.3.6 Porewater pressure degradation parameters

Matasovic (1993) represents the degradation of the shear strength and shear stiffness of the soil within the MKZ model by inclusion of two degradation indices. These degradation parameters have also been implemented (and have similar effects) within the GQ/H model. The degradation parameters are defined as:

$$\delta_G = \sqrt{1 - u^*}$$

$$\delta_\tau = 1 - (u^*)^v$$

Where $\delta_G$is the shear modulus degradation function, $\delta_\tau$is the shear stress degradation function, u^* is the excess porewater pressure normalized by initial effective overburden stress, and v is a curve-fitting parameter to better model the degradation of shear strength with excess pore pressure generation.

These degradation parameter formulations are implemented for all soil models except the Matasovic and Vucetic model for clays. The degradation parameters for the Matasovic and Vucetic model for clays are defined by Matasovic (1995) as:

$$\delta_G = \delta_\tau = N^{-1}$$

Where $\delta_G$is the shear modulus degradation function, $\delta_\tau$is the shear stress degradation function, and N is the number of equivalent cycles.

4.3.7 Porewater pressure dissipation

The pore water pressure dissipation model is based on Terzaghi 1-D consolidation theory:

$$\frac{\partial u}{\partial t} = C_v \left(\frac{\partial^2 u}{\partial z^2} \right)$$

where C_v is the consolidation coefficient.

Dissipation of the excess pore water pressure is assumed to occur in the vertical direction only. Porewater pressure generation and dissipation occur simultaneously during ground shaking.

5 Examples and Tutorials

The tutorial is intended to help users get familiar with DEEPSOIL. Six examples are prepared to guide the users through the various features of DEEPSOIL. It is recommended that the examples are followed in the order they appear. The example soil profiles and strain paths are stored in the "Examples" folder under the default DEEPSOIL working directory. The motions for use with example profiles are included under the default DEEPSOIL motion directory.

5.1 Example 1: Undamped Linear Analysis with Resonance

5.1.1 Soil Profiles:

Example 1 A:
Example_1A_DS-FL0.dp

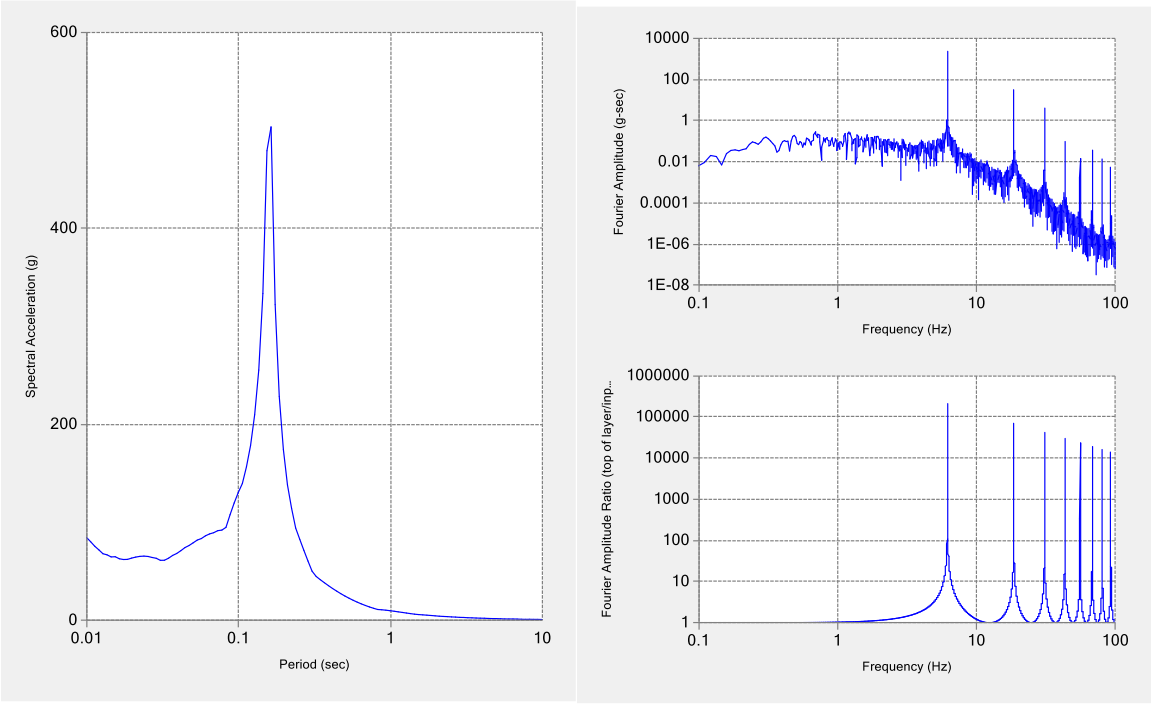
Example 1 B:
Example_1B_DS-TL0.dp

5.1.2 Input Motion:

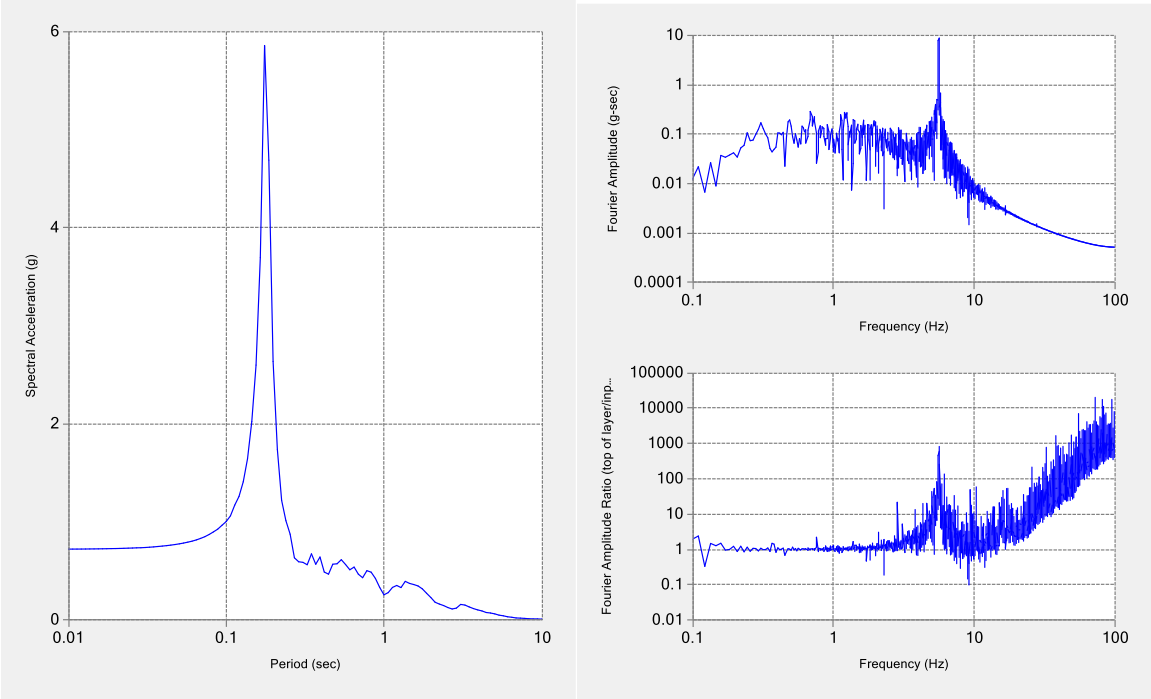
ChiChi.txt

5.1.3 Results:

Example 1 A:



Example 1 B:


Spectral Acceleration (g)
Period (sec)
Fourier Amplitude (g-sec)
Frequency (Hz)
Fourier Amplitude Ratio (top of layer/inp...
Frequency (Hz)

5.2 Example 2: Undamped Linear Analysis with Elastic Bedrock

5.2.1 Soil Profiles:

Example 2 A:
Example_2A_DS-FL0.dp

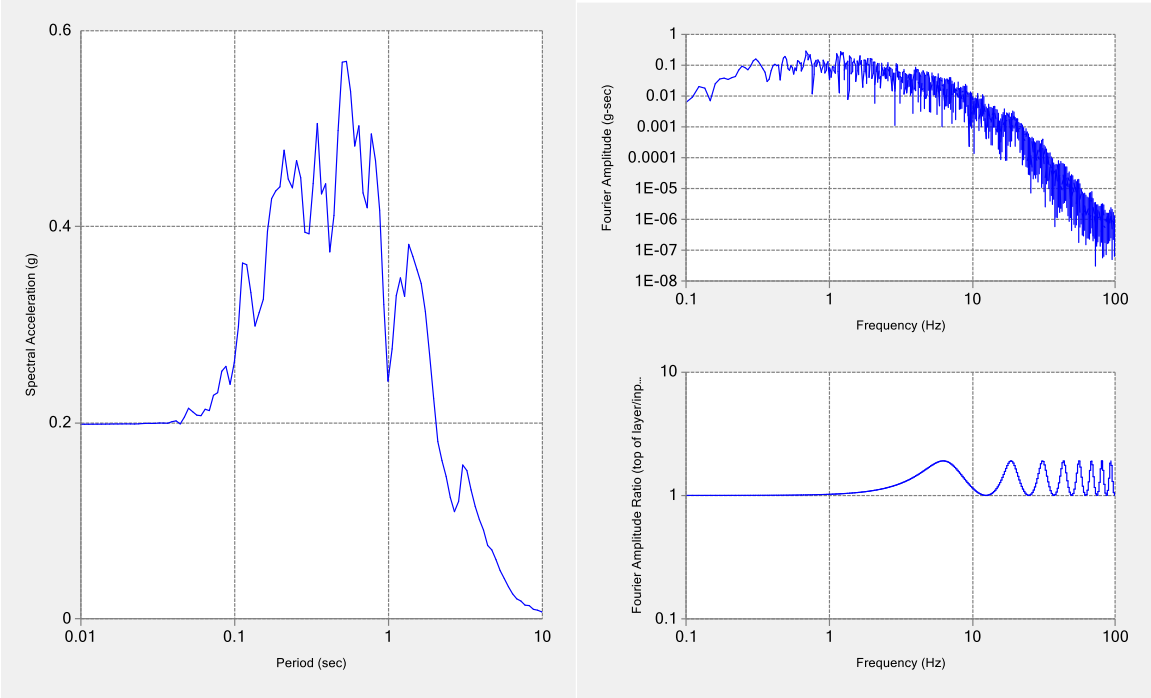
Example 2 B:
Example_2B_DS-TL0.dp

5.2.2 Input Motion:

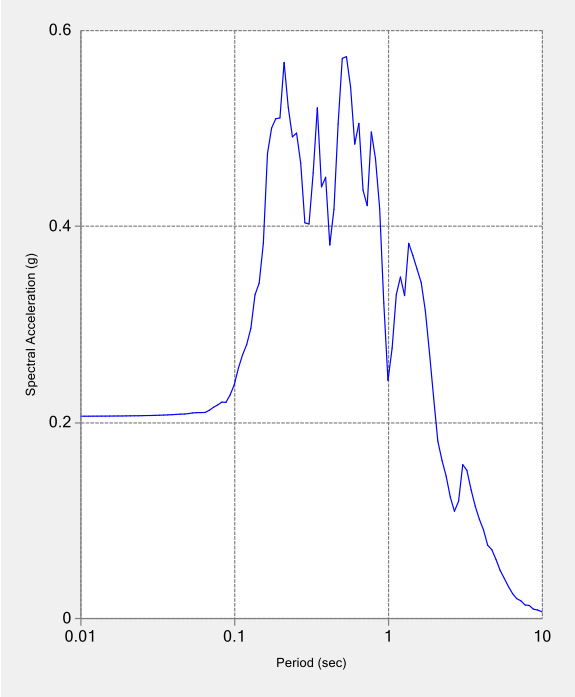
ChiChi.txt

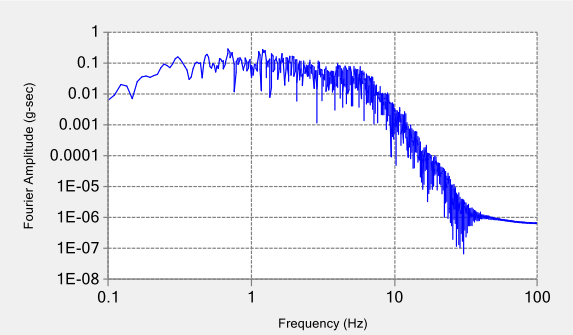
5.2.3 Results:

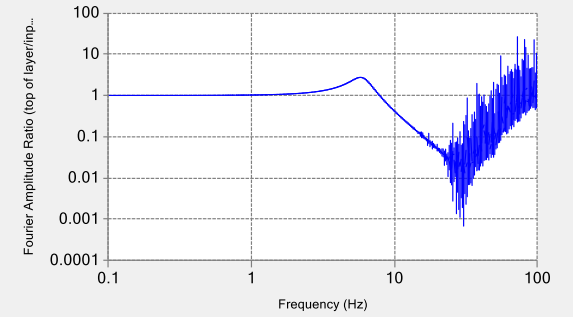
Example 2 A:



Example 2 B:


0.6
0.4
0.2
0
Spectral Acceleration (g)
0.01
0.1
1
10
Period (sec)


1
0.1
0.01
0.001
0.0001
1E-05
1E-06
1E-07
1E-08
Fourier Amplitude (g-sec)
0.1
1
10
100
Frequency (Hz)


100
10
1
0.1
0.01
0.001
0.0001
Fourier Amplitude Ratio (top of layer/inp...
0.1
1
10
100
Frequency (Hz)

5.3 Example 3: Damped Linear Analysis with Elastic Bedrock

5.3.1 Soil Profiles:

Example 3 A:
Example_3A_DS-FL0.dp

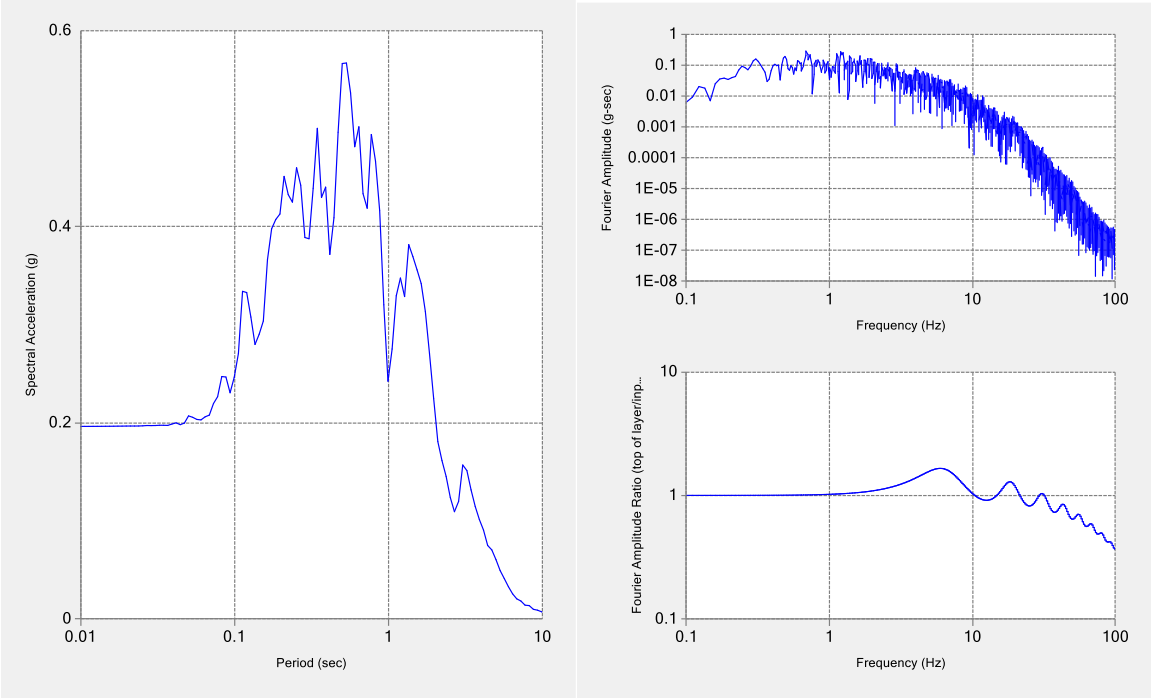
Example 2 B:
Example_3B_DS-TL0.dp

5.3.2 Input Motion:

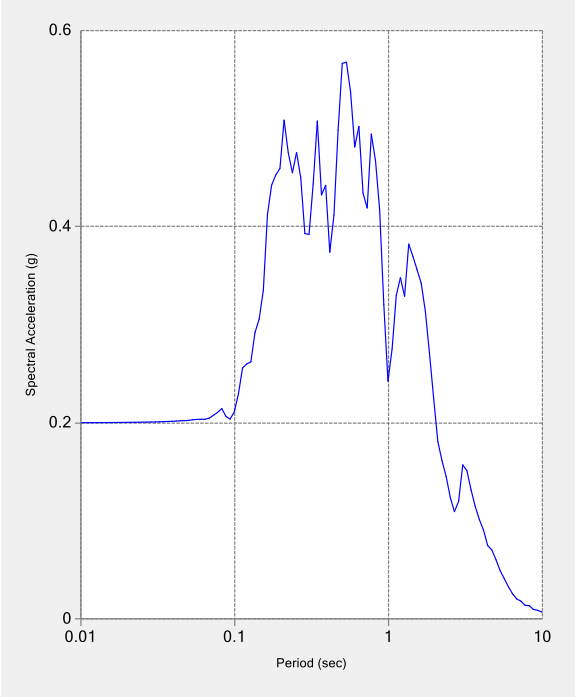
ChiChi.txt

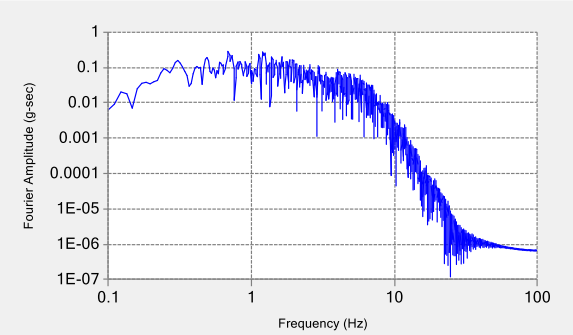
5.3.3 Results:

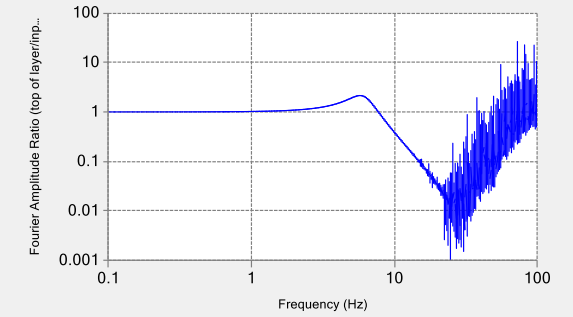
Example 3 A:



Example 3 B:


0.6
0.4
0.2
0
Spectral Acceleration (g)
0.01
0.1
1
10
Period (sec)


1
0.1
0.01
0.001
0.0001
1E-05
1E-06
1E-07
Fourier Amplitude (g-sec)
0.1
1
10
100
Frequency (Hz)


100
10
1
0.1
0.01
0.001
Fourier Amplitude Ratio (top of layer/inp...
0.1
1
10
100
Frequency (Hz)

5.4 Example 4: Equivalent Linear Analysis with Discrete Points

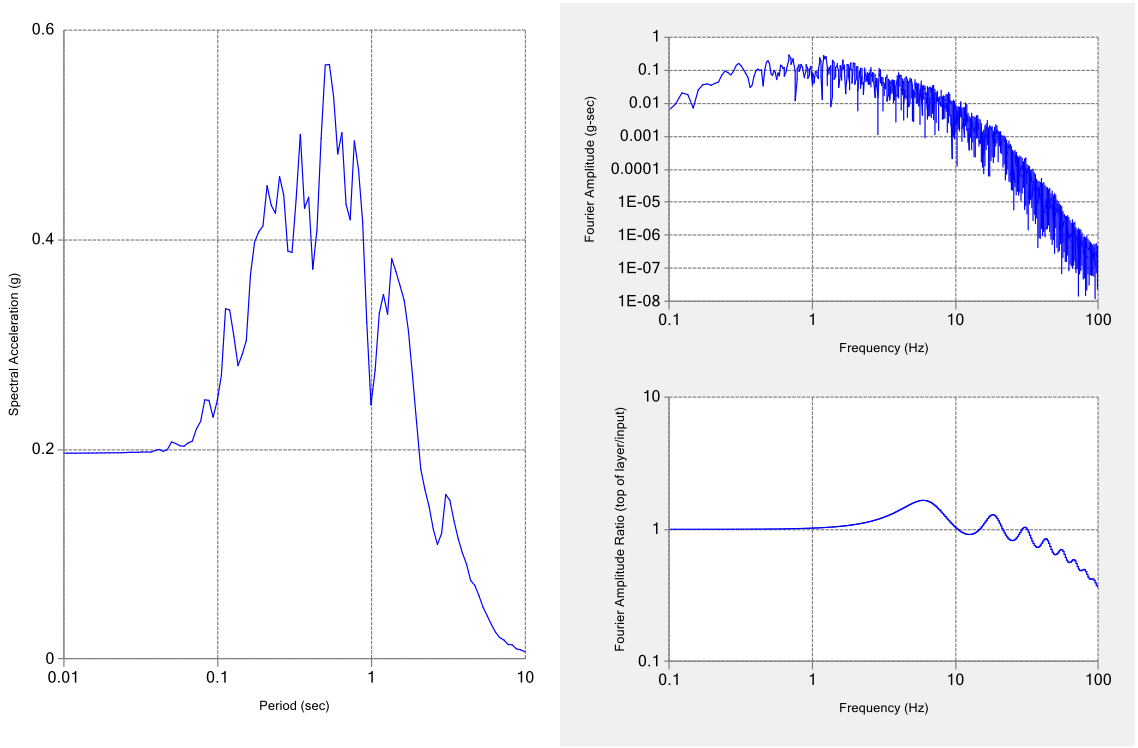
5.4.1 Soil Profile:

Example_4_DS-EL0.dp

5.4.2 Input Motion:

ChiChi.txt

5.4.3 Results:



5.5 Example 5: Nonlinear Analyses, MKZ with Masing Rules

5.5.1 Soil Profile:

Example 5 A:
Example_5_DS-NL1.dp

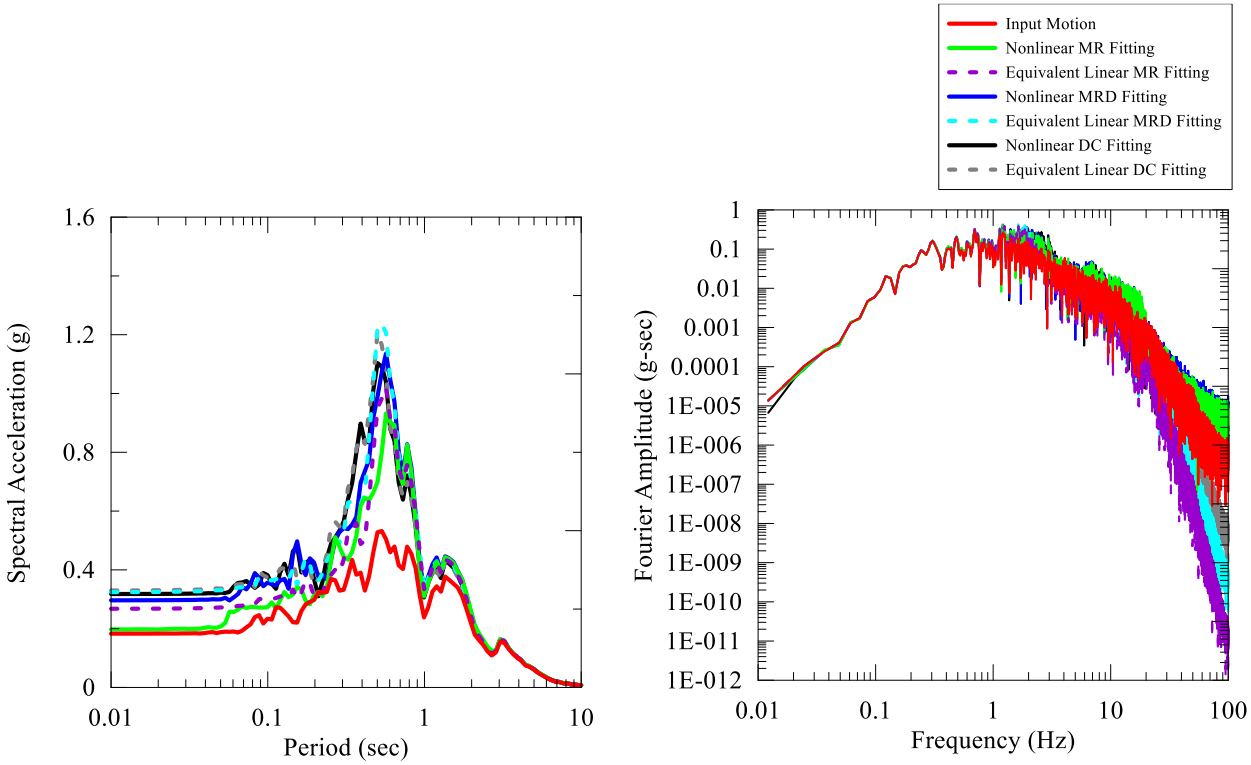
Example 5 B:

Example 5 C:

5.5.2 Input Motion:

ChiChi.txt

5.5.3 Results:



5.6 Example 6: Nonlinear Analysis, MKZ with Non-Masing Behavior

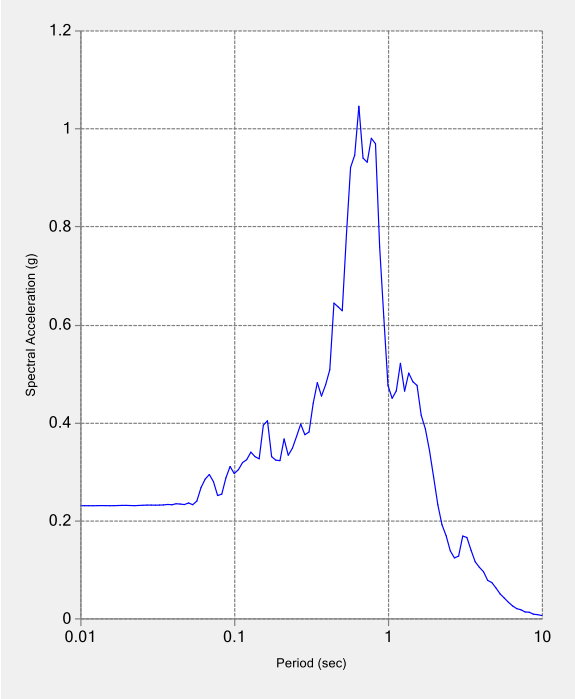
5.6.1 Soil Profile:

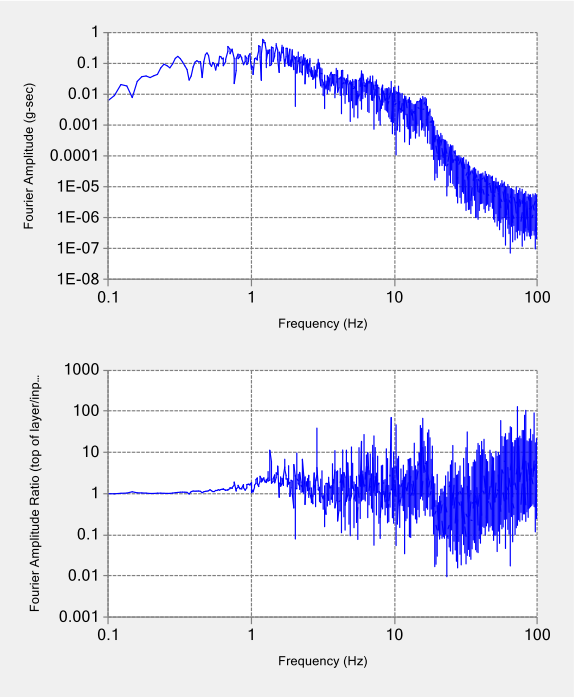
Example_6_DS-NL2.dp

5.6.2 Input Motion:

ChiChi.txt

5.6.3 Results:





5.7 Tutorial 1: Single Element Test

5.7.1 Soil Profile:

Example_6_DS-NL2.dp

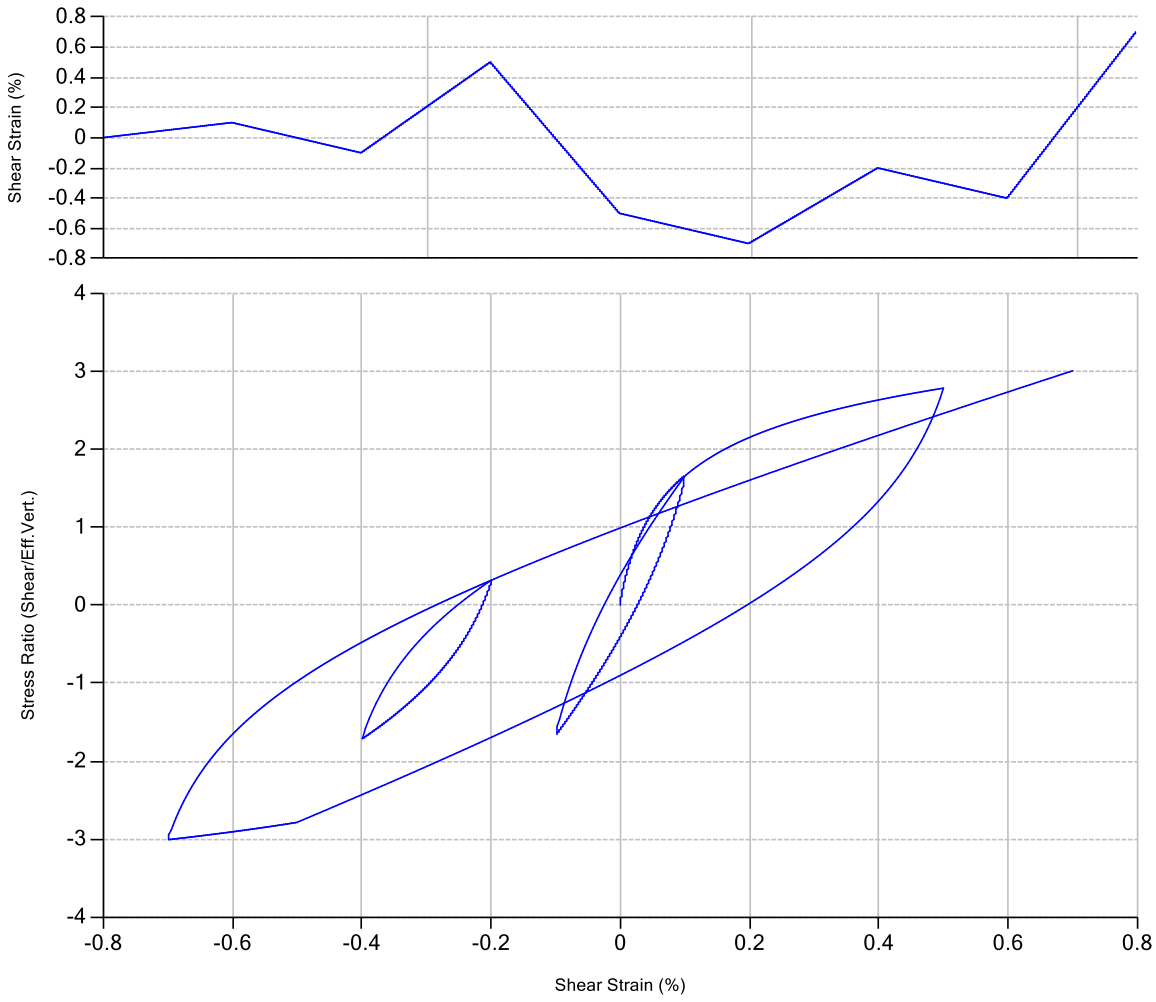
Selected Layer: Layer 3

5.7.2 Input Strain Path:

Single-Element-Test_Strain-Path.txt

Num. Increments: 199 (each step)

5.7.3 Results:



6 References

Amir-Faryar, B., M. Sherif Aggour & Richard H. McCuen (2016). Universal model forms for predicting the shear modulus and material damping of soils. Geomechanics and Geoengineering. http://dx.doi.org/10.1080/17486025.2016.1162332

Andrus, R. D., et al. (2003). Guide for Estimating the Dynamic Properties of South Carolina Soils for Ground Response Analysis, Clemson University.

Berrill, J.B. & Davis, R.O. (1985). Energy Dissipation and Seismic Liquefaction of Sands: Revised Model. JSSMFE Soils and Foundations 25(2): 106-118.

Carlton, B. (2014). "An Improved Description of the Seismic Response of Sites with High Plasticity Soils, Organic Clays, and Deep Soft Soil Deposits." PhD Thesis. University of California, Berkeley

Chopra, Anil K. (1995) Dynamic of Structures, Theory and applications to Earthquake Engineering Englewood Cliffs, New Jersey: Prentice Hall.

Clough, Ray W., and Joseph Penzien (1993) Dynamics of structures, New York: McGraw-Hill.

Darendeli, M. B. (2001). Development of a New Family of Normalized Modulus Reduction and Material Damping Curves, Department of Civil, Architectural and Environmental Engineering, The University of Texas, Austin, Texas.

Duncan, James M., and Chin-Yung Chang (1970) "Nonlinear analysis of stress and strain in soils," Journal of the Soil Mechanics and Foundations Division, Vol. 96, No. SM5, pp 1629-1653.

Finn, W. D. L., Lee, K. L, and Martin, G. R. (1977) "An effective stress model for liquefaction." Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT6, 517-533.

Green, R.A., Mitchell, J.K. and Polito, C.P. (2000). "An Energy-Based Pore Pressure Generation Model for Cohesionless Soils", Proceedings: John Booker Memorial Symposium, Melbourne, Australia, November 16-17, 2000.

Groholski, D., Hashash, Y., Kim, B., Musgrove, M., Harmon, J., and Stewart, J. (2016). "Simplified Model for Small-Strain Nonlinearity and Strength in 1D Seismic Site Response Analysis." J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)GT.1943-5606.0001496, 04016042.

Hardin, B. O. and Drnevich, V. P. (1972) "Shear modulus and damping in soils: Design equations and curves." Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM7, 667-692.

Hashash, Y. M. A., and D. Park (2002) "Viscous damping formulation and high frequency motion propagation in nonlinear site response analysis," Soil Dynamics and Earthquake Engineering, Vol. 22, No. 7, pp. 611-624.

Hashash, Youssef M. A., and Duhee Park (2001) "Non-linear one-dimensional seismic ground motion propagation in the Mississippi embayment," *Engineering Geology*, Vol. 62, No. 1-3, pp 185-206.

Hashash, Y.M.A., Phillips, C. and Groholski, D. (2010). "Recent advances in non-linear site response analysis", Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Paper no. OSP 4.

Hudson, M., Idriss, I.M., and Beikae, M. 1994. (1994) "QUAD4M - A computer program to evaluate the seismic response of soil structures using finite element procedures and incorporating a compliant base." Davis, CA: Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA.

Idriss, I. M. and Seed, H. B. (1968) "Seismic response of horizontal soil layers." Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 94, No. SM4, pp 1003-1031.

Idriss, I. M. and Sun, J. I. (1992) "User's Manual for SHAKE91, A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits"

Kramer, Steven Lawrence (1996) *Geotechnical earthquake engineering*, Upper Saddle River, N.J.: Prentice Hall.

Konder, R. L. and Zelasko, J. S. (1963) "A hyperbolic stress-strain formulation of sands." Proceedings of the 2nd Pan American Conference on Soil Mechanics and Foundation Engineering, Sao Paulo, Brasil, 289-324.

Lee, M. K. W. and Finn, W. D. L (1975) "DESRA-1, Program for the dynamic effective stress response analysis of soil deposits including liquefaction evaluation." Soil Mechanics Series No. 36, Department of Civil Engineering, University of British Columbia, Vancouver, Canada.

Lee, M. K. W. and Finn, W. D. L (1978) "DESRA-2, Dynamic effective stress response analysis of soil deposits with energy transmitting boundary including assessment of liquefaction potential." Soil Mechanics Series No. 36, Department of Civil Engineering, University of British Columbia, Vancouver, Canada.

Matasovic, Neven, and M. Vucetic (1993) "Cyclic Characterization of Liquefiable Sands," *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 119, No. 11, pp 1805-1822.

Matasovic, N. (1992) "Seismic response of composite horizontally-layered soil deposits." Ph.D. Thesis, University of California, Los Angeles.

Matasovic, Neven, and M. Vucetic (1995) "Generalized Cyclic Degradation-Pore Pressure Generation Model for Clays," ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 121, No. 1, pp 33-42.

Mei, X., Olson, S.M., and Hashash Y.M. (2015) "Empirical curve-fitting parameters for a porewater pressure generation model for use in 1-D effective stress-based site response analysis," *6th International Conference on Earthquake Geotechnical Engineering*, 1-4 November 2015, Christchurch, New Zealand.

Menq, Farn-Yuh (2003). Dynamic Properties of Sandy and Gravelly Soils, Department of Civil, Architectural and Environmental Engineering, The University of Texas, Austin, Texas.

Mugan, Ata, and Gregory M. Hulbe (2001) "Frequency-domain analysis of time-integration methods for semidiscrete finite element equations - part II: Hyperbolic and parabolic-hyperbolic problems," International Journal for numerical Methods in Engineering, Vol. 51, No. 3, pp 351-376.

Newmark, Nathan M. (1959) "A method of computation for structural dynamics," Journal of the Engineering Mechanics Division, Vol. EM 3, pp 67-94.

Park D., J.-K. Ahn. (2013) "Accumulated Stress Based Model for Prediction of Residual Pore Pressure," Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, pp 1567-1570.

Park, D., and Y. M. A. Hashash (2004) "Soil damping formulation in nonlinear time domain site response analysis," Journal of Earthquake Engineering, Vol. 8, No. 2, pp 249-274.

PEER (2010) "PEER Ground Motion Database Web Application," PEER.

Phillips, Camilo, and Youssef M. A. Hashash (2008) "A new simplified constitutive model to simultaneously match modulus reduction and damping soil curves for nonlinear site response analysis," Geotechnical Earthquake Engineering & Soil Dynamics IV (GEESD IV). Sacramento, California.

Phillips, C. and Hashash, Y. (2009) "Damping formulation for non-linear 1D site response analyses" Soil Dynamics and Earthquake Engineering, v. 29, pp 1143–1158.

Phillips, C., Kottke, A.R., Hashash, Y.M.A., and Rathje, E.M. (2012) "Significance of ground motion timestep in one dimensional site response analysis" Soil Dynamics and Earthquake Engineering, v. 43, pp 202–217.

Richart, F.E., Hall, J.R., and Woods, R.D. (1970). "Vibrations of Soils and Foundations," Prentice Hall, Englewood Cliffs, New Jersey, 401 pp.

Roblee, Cliff and Chiou, Brian. (2004) "A proposed geoindex model for design selection of non-linear properties for site response analyses." Caltrans Geo-Research Group. Sacramento, CA.

Sanderson, Conrad. (2010) "Armadillo: An Open Source C++ Linear Algebra Library for Fast Prototyping and Computationally Intensive Experiments." Technical Report, NICTA.

Sanderson, Conrad and Ryan Curtin. (2016) Armadillo: a template-based C++ library for linear algebra. Journal of Open Source Software, Vol. 1, pp. 26.

Schnabel, P. B., Lysmer, J. and Seed, H. B. (1972) "SHAKE: A computer program for earthquake response analysis of horizontally layered sites." Report No. EERC 72-12, Earthquake Engineering Research Center, University of California, Berkeley, California.

Seed, H. B. and Idriss, I. M. (1970) "Soil moduli and damping factors for dynamic response analyses." Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, California, 40p.

Udaka, Takekazu (1975) "Analysis of Response of Large Embankments to Traveling Base Motions," *Department of Civil and Environmental Engineering*. Berkeley: University of California, p 346.

Vucetic, M. (1992). "Soil Properties and Seismic Response." In *Proceedings of 10th World Conference of Earthquake Engineering*, July 19 – 24, Madrid, Spain, 1199 – 1204.

7 APPENDIX A: Included Ground Motions

All ground motions that are included with DEEPSOIL have been obtained from the PEER Strong Motion Database. The database is available at http://peer.berkeley.edu/smcat/. The table below summarizes the meta-data for the motions selected for DEEPSOIL.

Motion Name	Record Number	Date of Event	Magnitude	Distance to Fault Rupture (km)	USGS Site Class	PGA (g)
ChiChi	P1116	1999/09/20	7.6	15.29	B	0.183
Coyote	P0154	1979/08/06	5.7	17.2	B	0.124
Imperial Valley	P0165	1979/10/15	6.5	26.5	B	0.169
Kobe	P1043	1995/01/16	6.9	0.6	B	0.821
Kocaeli	P1087	1999/08/17	7.4	17.0	B	0.218
LomaGilroy	P0738	1989/10/18	6.9	19.9	B	0.170
LomaGilroy2	P0764	1989/10/18	6.9	11.6	B	0.357
MammothLake	P0232	1980/05/25	6.3	15.5*	A**	0.430
Nahnni	P0498	1985/12/23	6.8	16.0	A**	0.148
Northridge	P0885	1994/01/17	6.7	26.8	A	0.217
Northridge2	P1014	1994/10/17	6.7	43.4	A	0.098
Parkfield	P0034	1966/06/28	6.1	9.9	B	0.357
WhittierNarrows	P0666	1987/10/01	6.0	21.2	A	0.186

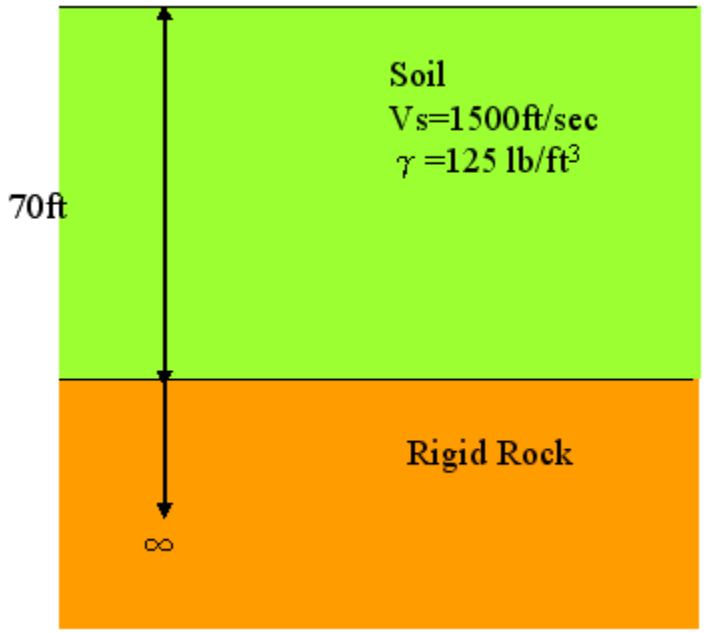
*Hypocentral distance
** Geomatrix Site Class

8 APPENDIX B: Archived Examples

The tutorial is intended to help users get familiar with DEEPSOIL. Seven examples are prepared to guide the users through the various features of DEEPSOIL. It is recommended that the examples are followed in the order that appears in the tutorial. The example files are stored in the "Saved Profiles" folder under the default DEEPSOIL working directory.

8.1 Example 1 Linear Frequency Domain Analysis / Undamped Elastic Layer, Rigid Rock

The first example considers a simple linear frequency domain analysis. The profile for Example 1 ("Ex1_Lin_Freq_Undamped_Rigid.dp") is shown below.



The profile consists of a 70-ft thick soil column overlying rigid bedrock. The soil layer is assumed to be undamped (zero damping) and linear elastic.

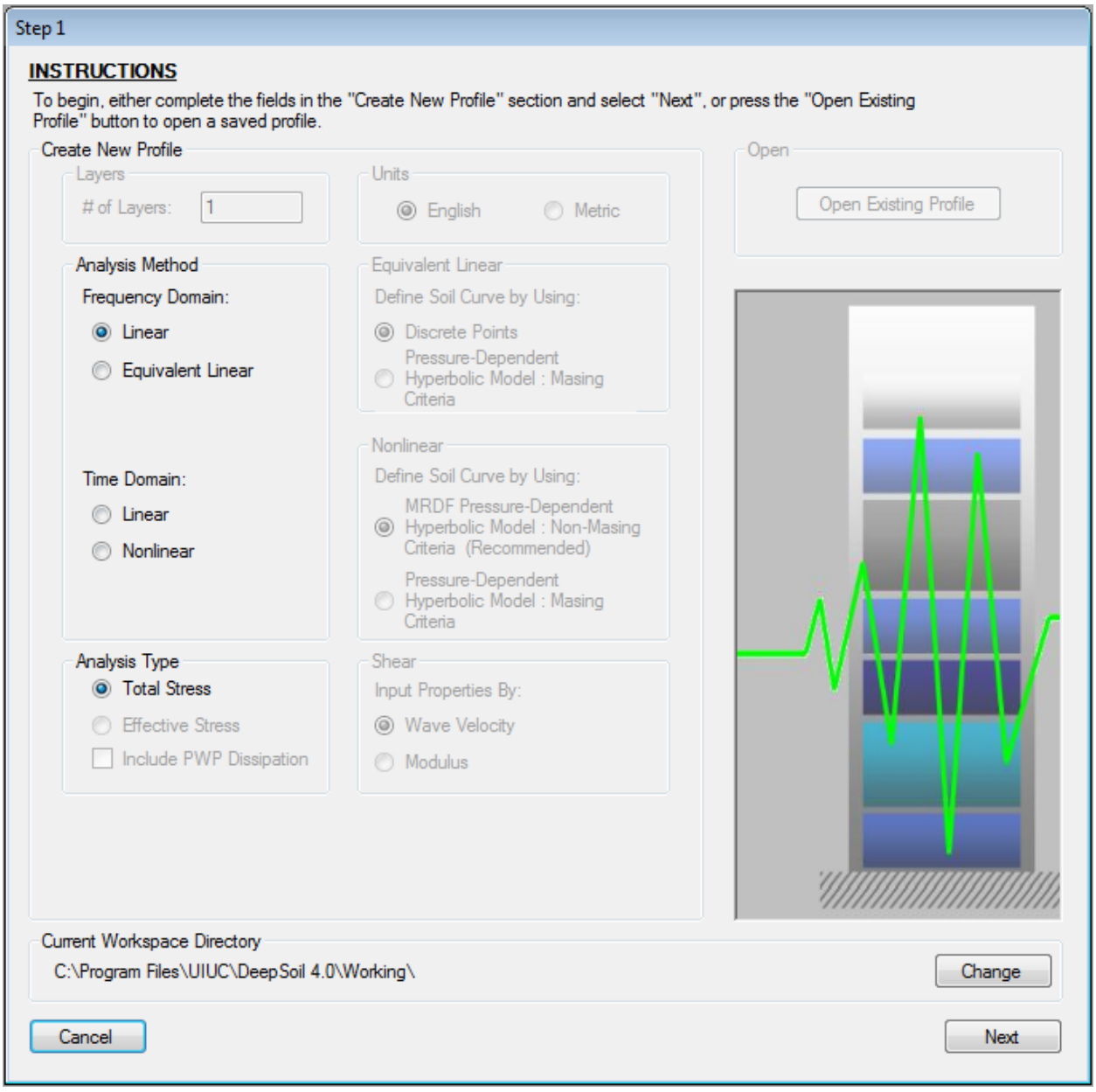
STEP 1/6

For Step 1/6, first choose the method of analysis by selecting Frequency Domain - "Linear Analysis."

For this example, the number of layers will be 1. Check that the value in the "# of Layers" input box is 1.

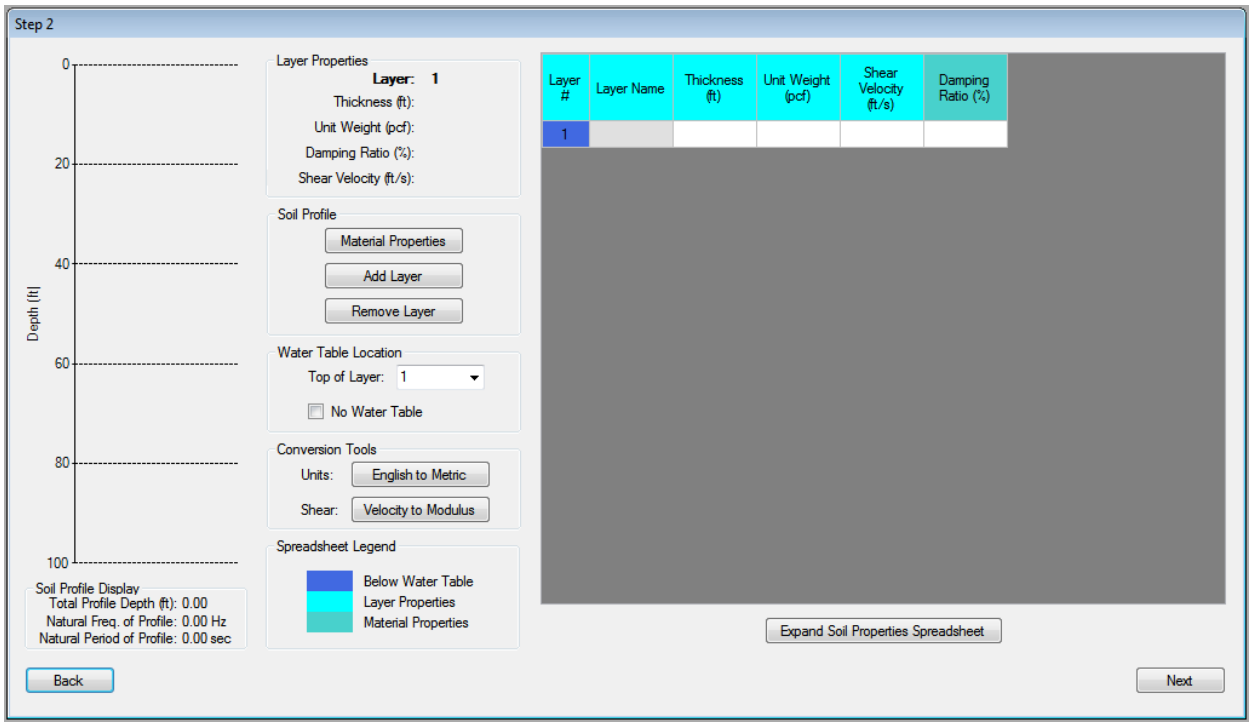
Now we must choose whether to define the stiffness of the layer in shear wave velocity or shear modulus. Select "Wave Velocity."

Finally, the analysis stress type will be "Total Stress Analysis." Check that "Total Stress Analysis" is selected and press the **Next** button.



STEP 2/6

In Step 2/6, the user must define the soil column and soil properties. The figure below shows the window that displays the soil properties.



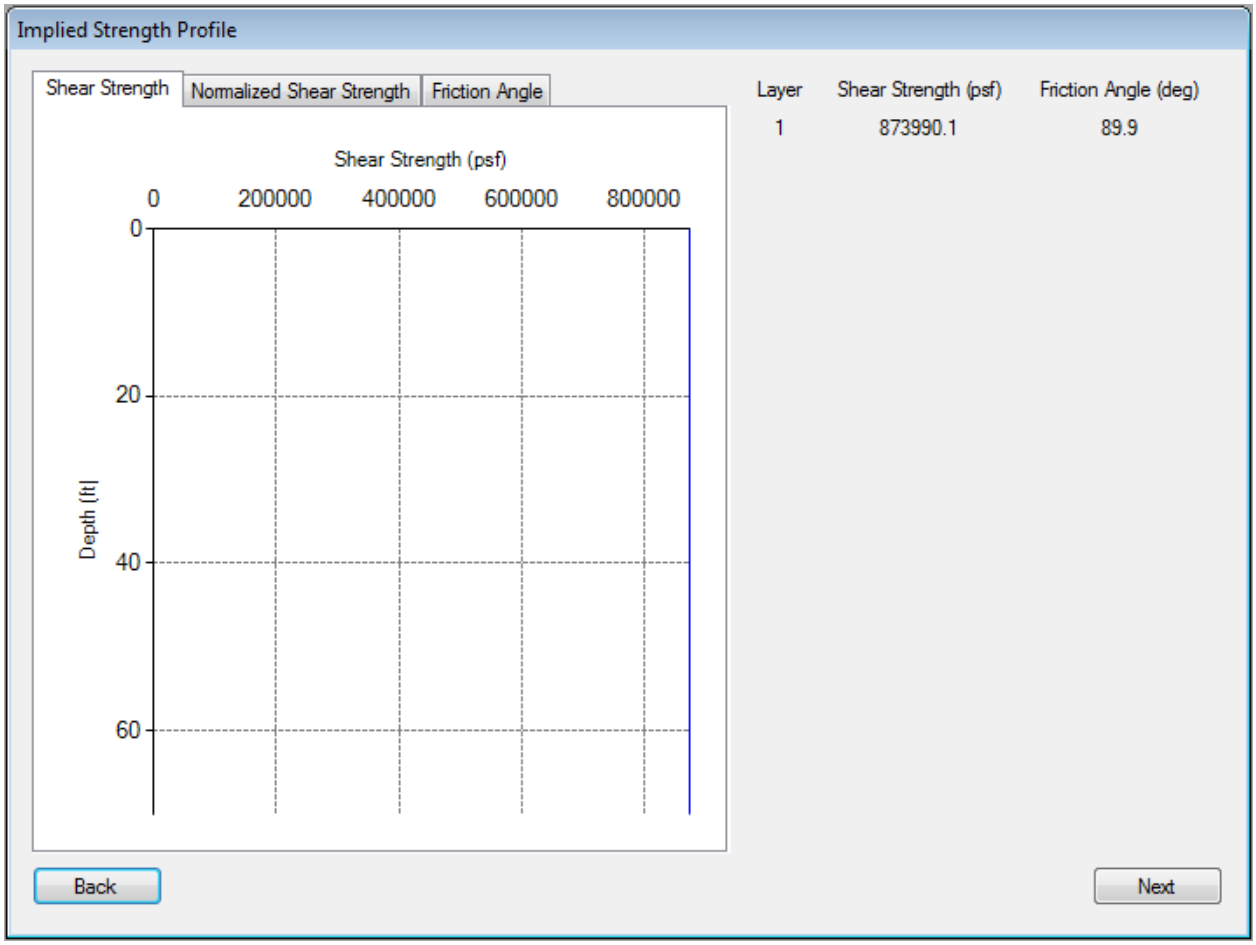
Specify the material properties of the layer as follows:

Layer #	Layer Name	Thickness (ft)	Unit Weight (pcf)	Shear Velocity (ft/s)	Damping Ratio (%)
1		70	125	1500	0

Press the **Next** button.

IMPLIED STRENGTH

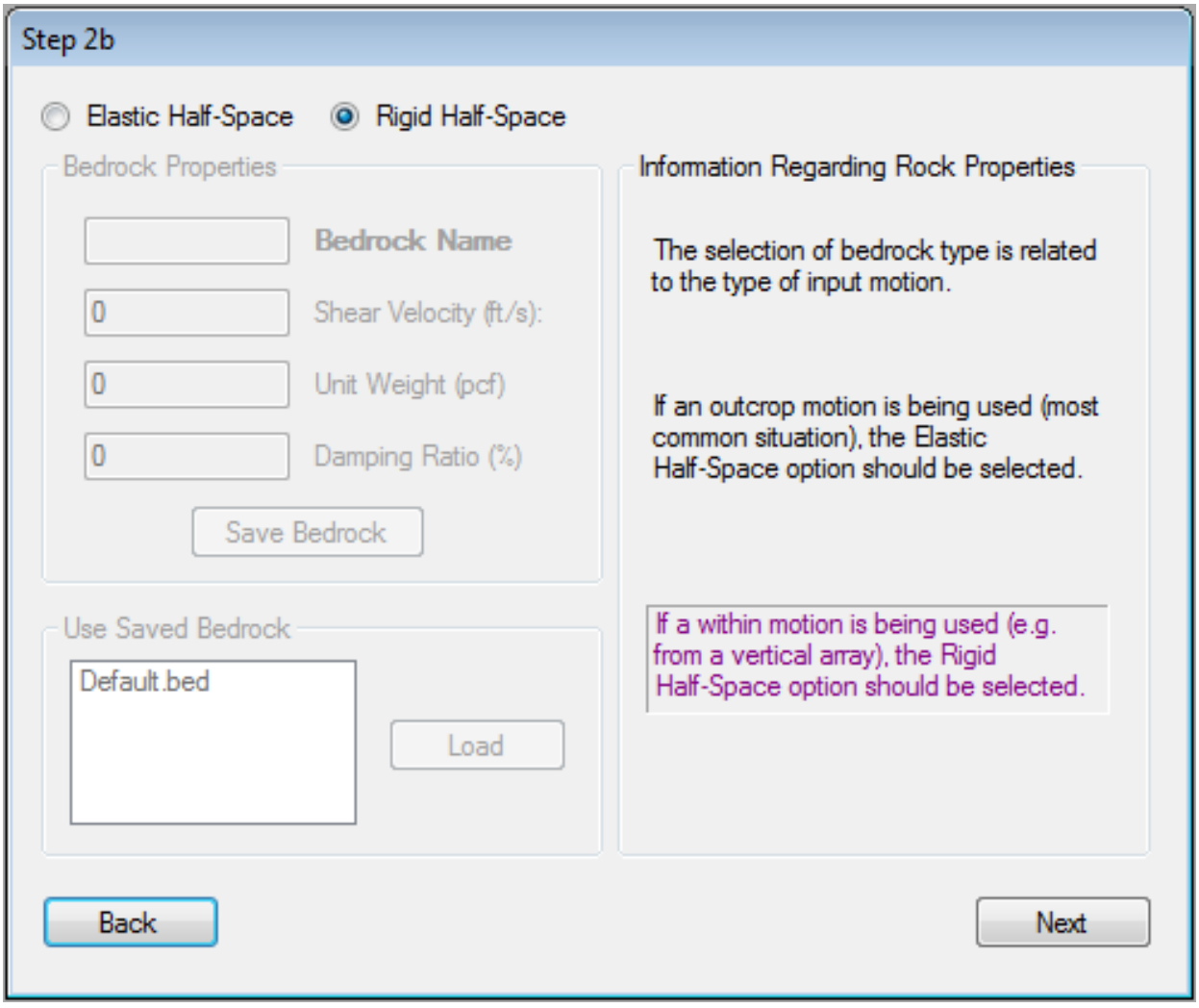
This step uses the material properties specified in step 2a to calculate the implied strength of the profile. Because this example in an idealized soil column, the values will seem very large. In a real analysis, the soil properties should be modified to reflect realistic strengths. For now, simply press **Next** to continue to step 2b.


Implied Strength Profile
Shear Strength
Normalized Shear Strength
Friction Angle
Shear Strength (psf)
0
200000
400000
600000
800000
Depth (ft)
0
20
40
60
Layer
Shear Strength (psf)
Friction Angle (deg)
1
873990.1
89.9
Back
Next

STEP 2b/6

In Step 2b/6, the properties of the bedrock are specified. In this case, the analysis considers rigid bedrock.

Specify the bedrock to be rigid by selecting the "Rigid Half-Space" option.



Press the **Next** button to continue.

STEP 3/6

In Step 3/6, the options for the Frequency Domain analysis must be specified.

First select the Fourier Transform Type you wish to use for analysis. There are two options which are the Fast Fourier Transform (FFT) and Discrete Fourier Transform (DFT). It is generally recommended that FFT be used for analysis. (Note: FFT and DFT will give the same results, but FFT is faster)

Select the Fast Fourier Transform (FFT).

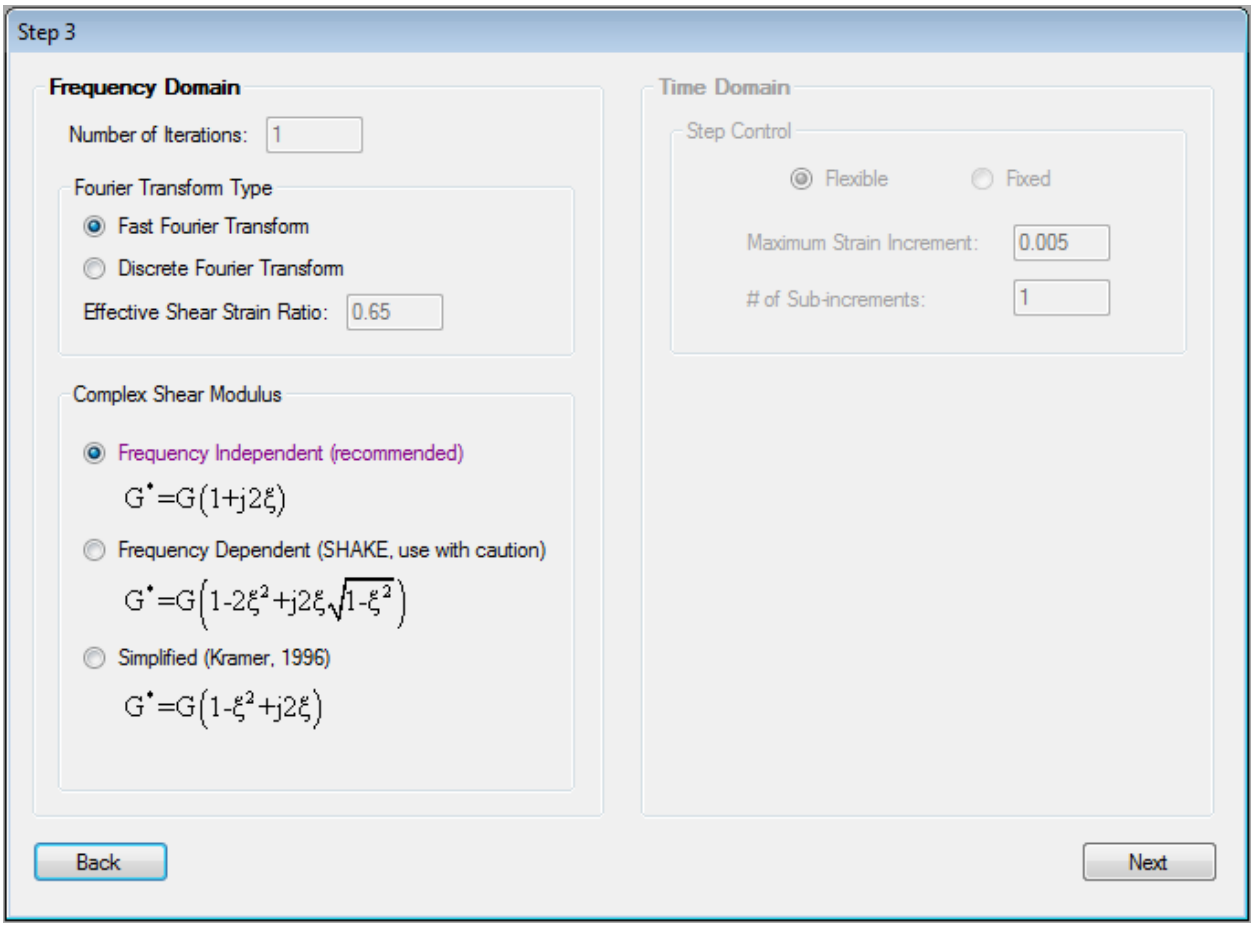
You'll notice that the "Effective Shear Strain" is disabled. This is because the effective shear strain is irrelevant for a linear analysis. Similarly, the "Number of Iterations" for a linear analysis is also irrelevant, so the default value of "1" does not need to be changed.

The final selection in this step is selecting the complex shear modulus. There are three options:

1. Frequency Independent
2. Frequency Dependent
3. Simplified (Kramer, 1996)

It is recommended that the "Frequency Independent" complex shear modulus be used for all analyses. The "Simplified" modulus is based on the "Frequency Independent" modulus, but modified to result in a simpler form (Kramer, 1996). The "Frequency Dependent" modulus is equivalent to the modulus used in SHAKE91.

Select the "Frequency Independent" modulus and press the **Next** button.



STEP 4/6

Step 4/6 involves the selection of a) input motion and b) layers for output.

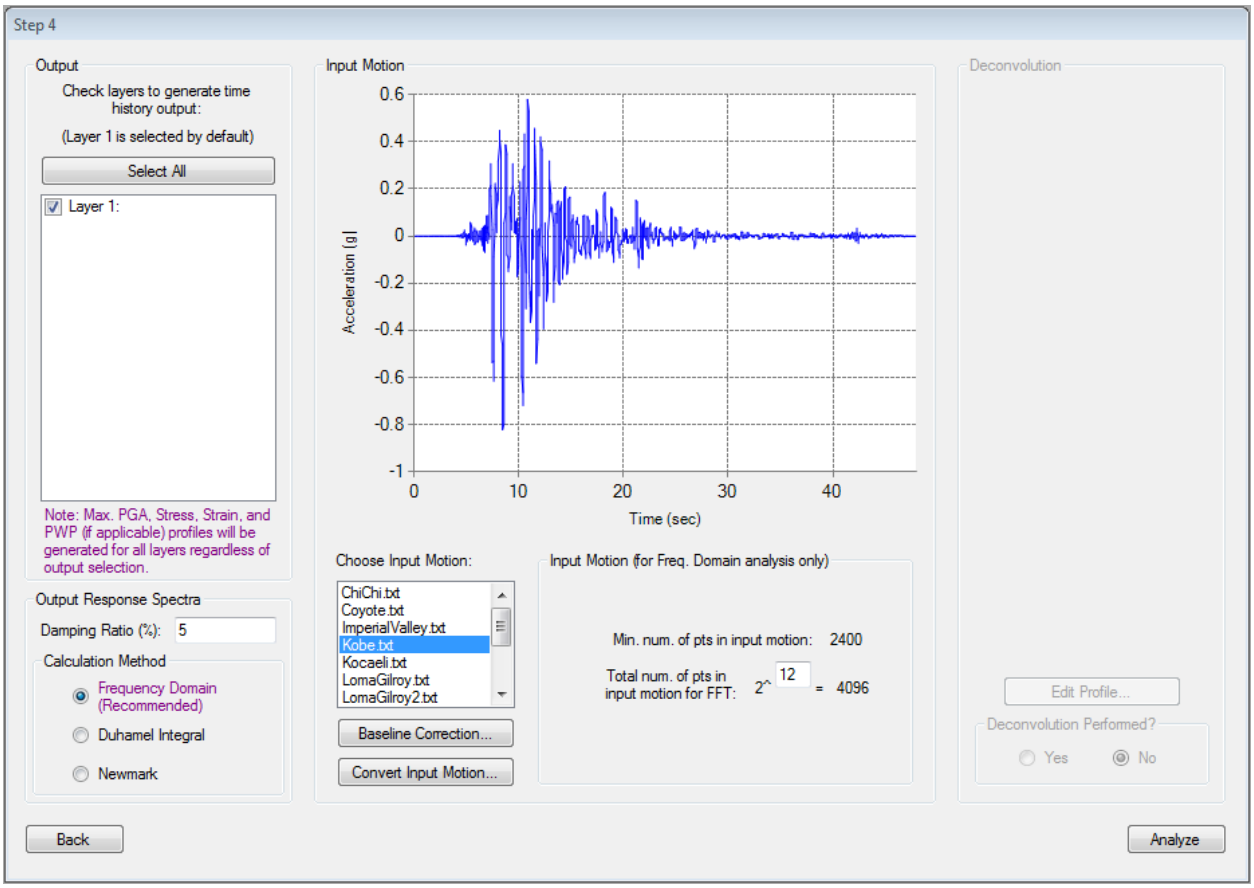
A motion library is provided which will automatically plot the selected motion for the user's inspection. Select the input motion "Kobe.txt" from the motion library.

In the frequency domain analysis, the number of points for the FFT must be defined. The number of points is a power of 2. DEEPSOIL will calculate the minimum number of points needed for the input motion and automatically sets the number of points to be used in the FFT to this minimum value. Note that the number of points for FFT should not be smaller than the minimum value recommended by DEEPSOIL.

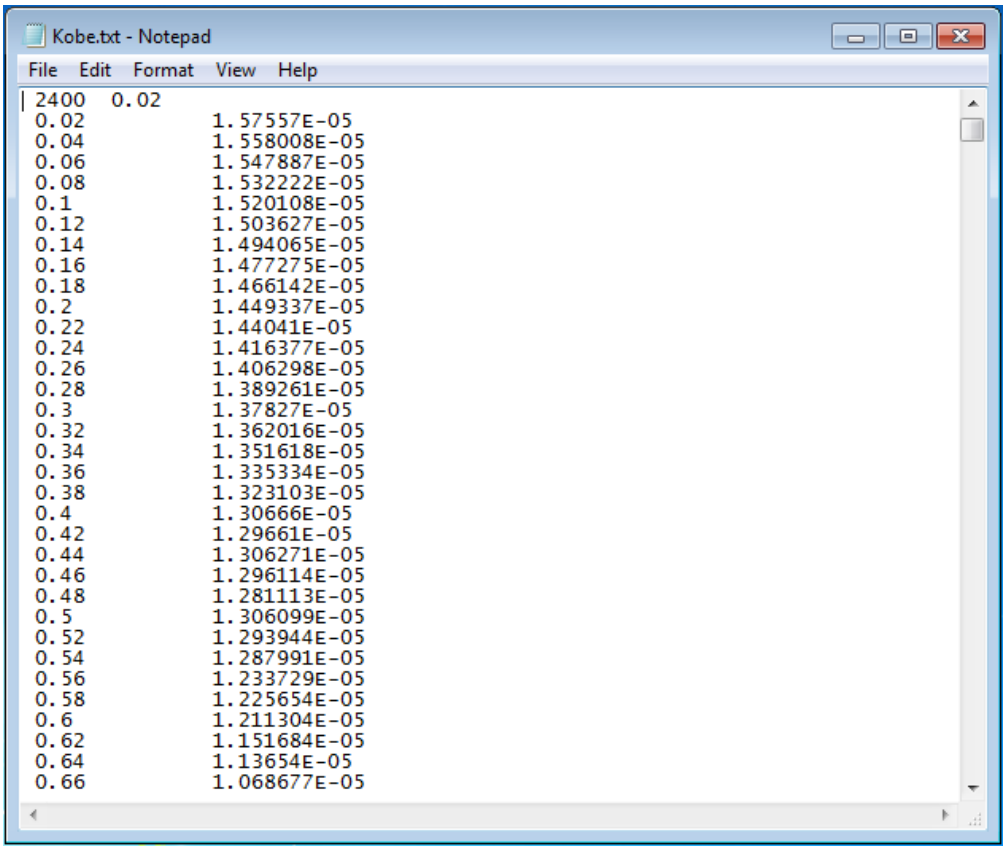
After selecting the input motion and associated parameters, select the layer(s) for output (shown in the left column). Layer 1 is selected by default.

Finally, select the calculation method to use for the response spectra, and enter a damping ratio for the output response spectrum (shown in the lower left corner). The recommended method is "Frequency Domain" and the recommended damping ratio is 5%.

Press the **Analyze** button to begin the analysis.



In case the user wishes to define new motions, the format of the ground motion file should be as follows:



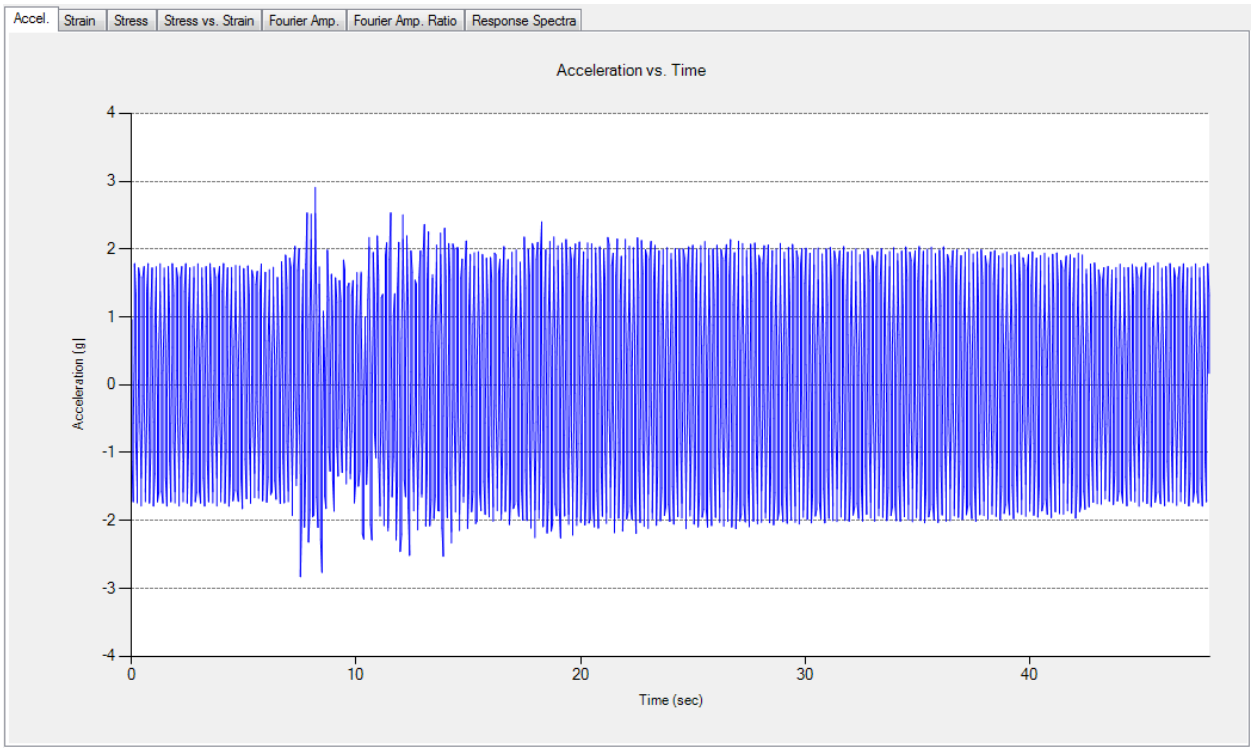
The first number is the total number of data points. The second number is the time step. The actual time history should be written in two columns, the first column is the time and the second column is the acceleration. The time should be in units of seconds, and the acceleration should be in units of g.

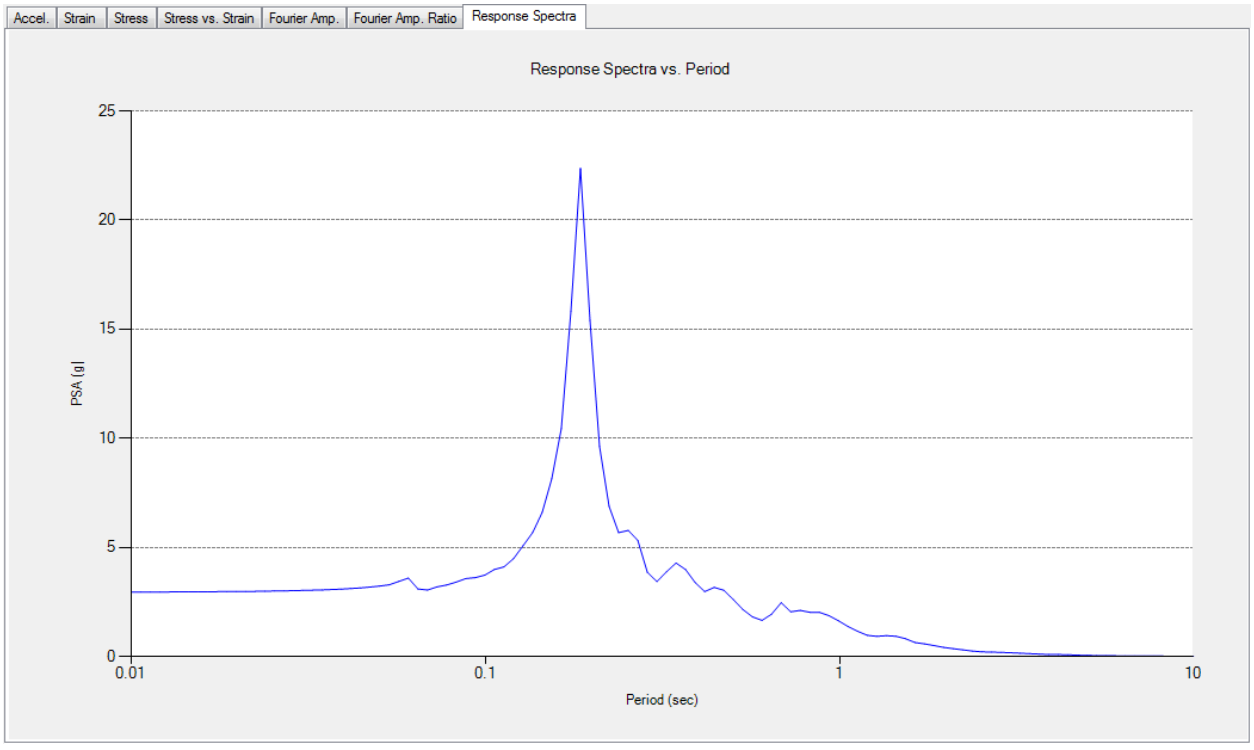
STEP 6/6

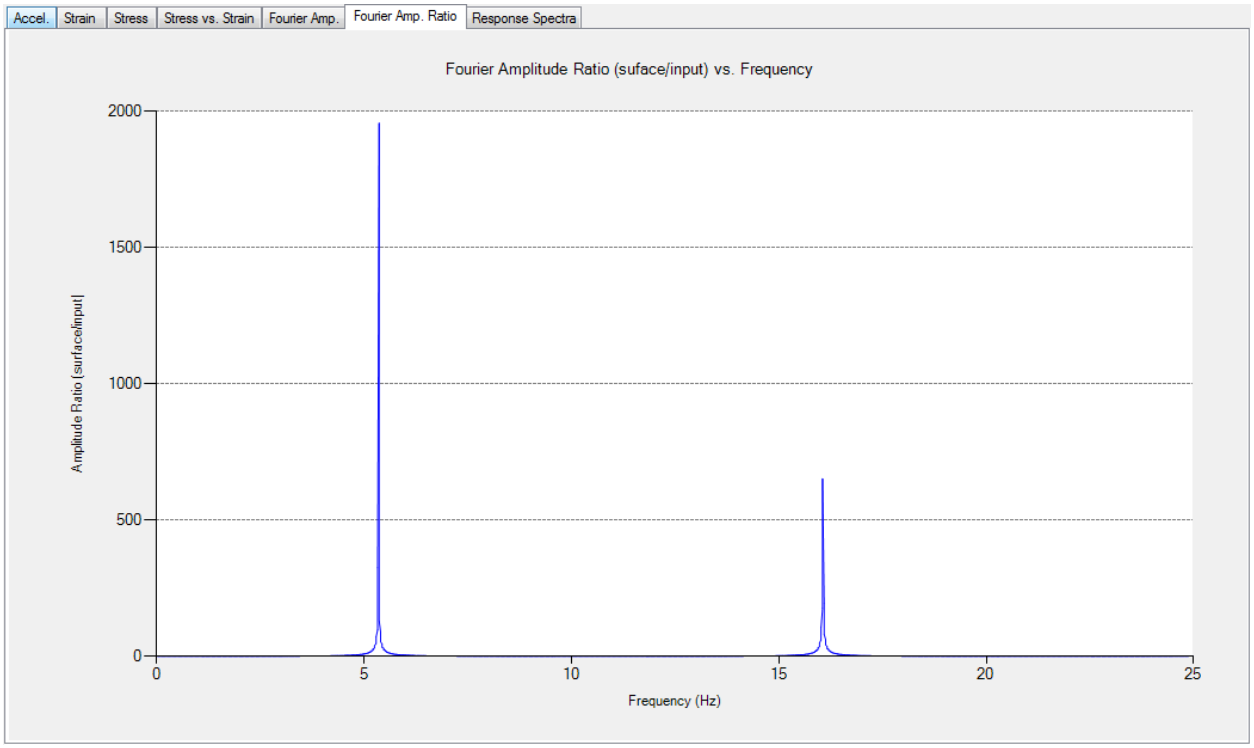
Upon completion of analysis, the user will be presented with the output window. The output window displays acceleration, strain, and stress time histories, in addition to stress vs. strain curves, Fourier amplitude spectrum, Fourier amplification ratio, and response spectra.

Compare your results with the figures shown below. The results should be exactly the same (note the scales).

The output data has been automatically exported to "Results - *Motion*.txt" in the user-specified working directory. To view the output text file, simply click the "Show analysis results in folder view…" link located above the Close button. This will open the user-defined working directory, which should contain the output text file.


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Acceleration vs. Time
Acceleration (g)
4
3
2
1
0
-1
-2
-3
-4
0
10
20
30
40
Time (sec)

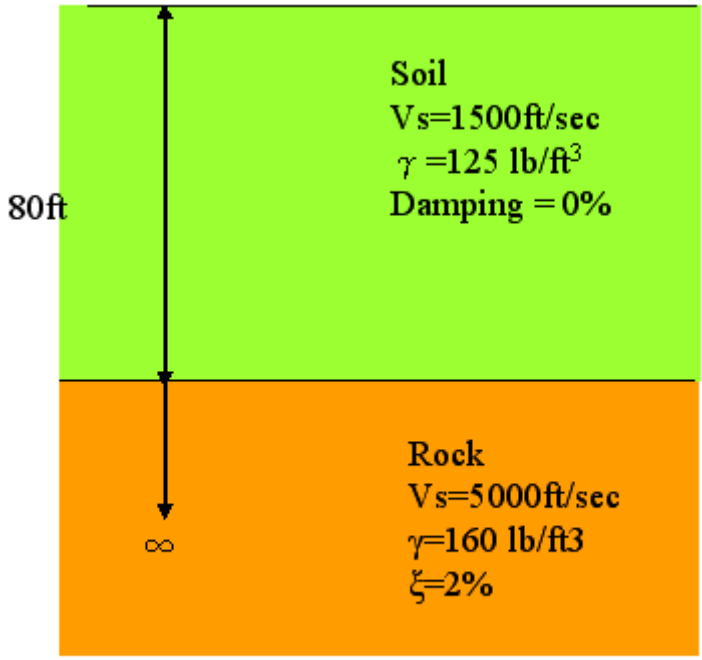

Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Response Spectra vs. Period
PSA (g)
25
20
15
10
5
0
0.01
0.1
1
10
Period (sec)



Note that resonance occurs at natural frequencies and therefore results in significant amplification of the motion at such frequencies.

8.2 Example 2 Linear Frequency Domain Analysis / Undamped Elastic Layer, Elastic Rock

Example 2 ("Ex2_Lin_Freq_Undamped_Elastic.dp") is similar to Example 1; the only differences being that the soil column is now 80 feet thick and the bedrock is elastic instead of rigid. As such, the steps of the analysis are the same as those outlined in Example 1 except where noted below.



STEP 1/6

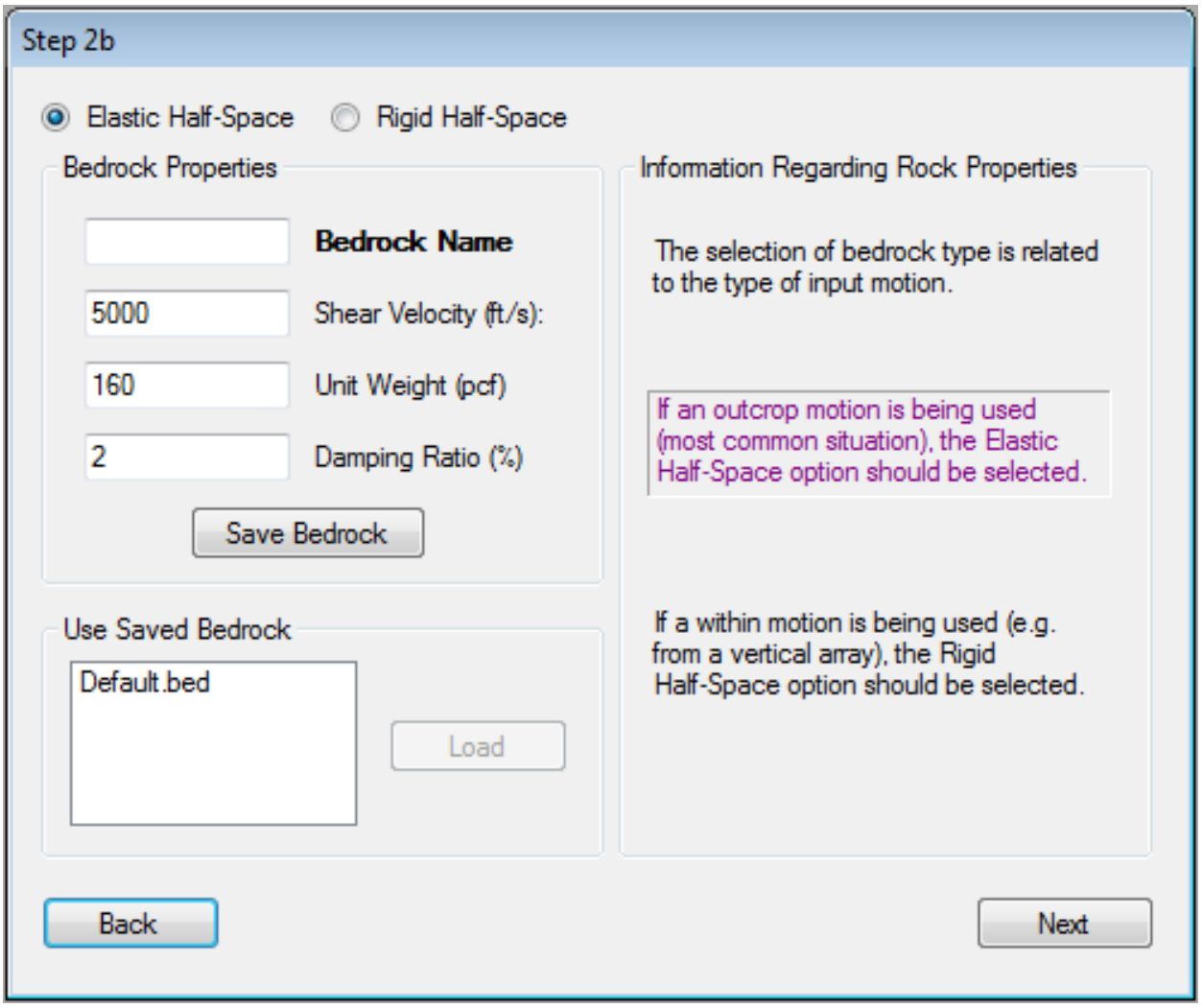
All options are the same as in Example 1. Press the **Next** button to proceed to the soil profile window.

STEP 2/6

Enter "80" for the thickness of the layer in the soil properties spreadsheet. All other values are the same as given in Example 1. Press the **Next** button to continue.

STEP 2b/6

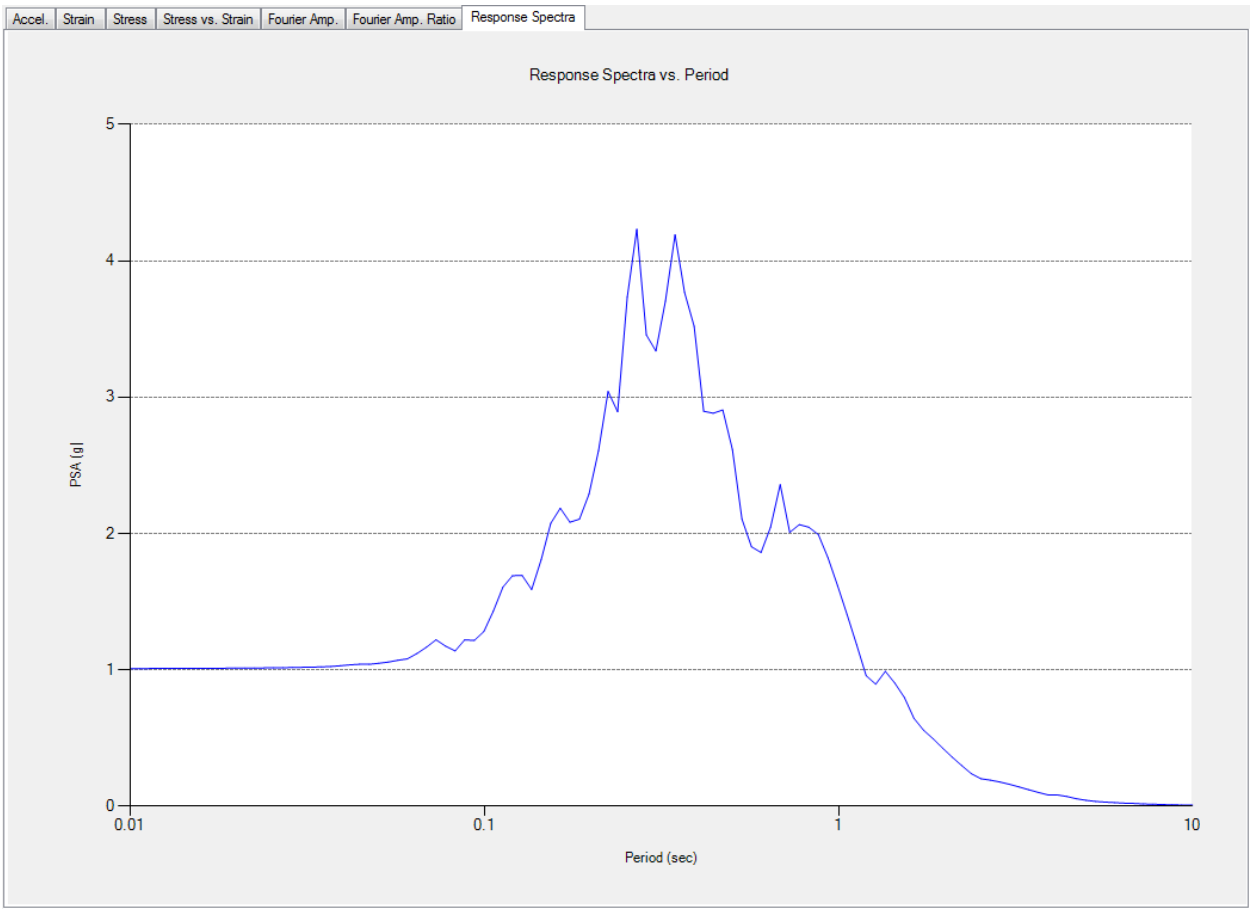
In this step, we will define the elastic properties of the bedrock. Select the "Elastic Half-Space" option to define the elastic bedrock properties. Enter the input for the Shear Velocity, Unit Weight, and Damping Ratio as 5000 ft/sec, 160 pcf, and 2% respectively. You can also save the bedrock properties by giving the bedrock a name and then clicking the **Save Bedrock**. Press the **Next** button to proceed to Step 3/6.

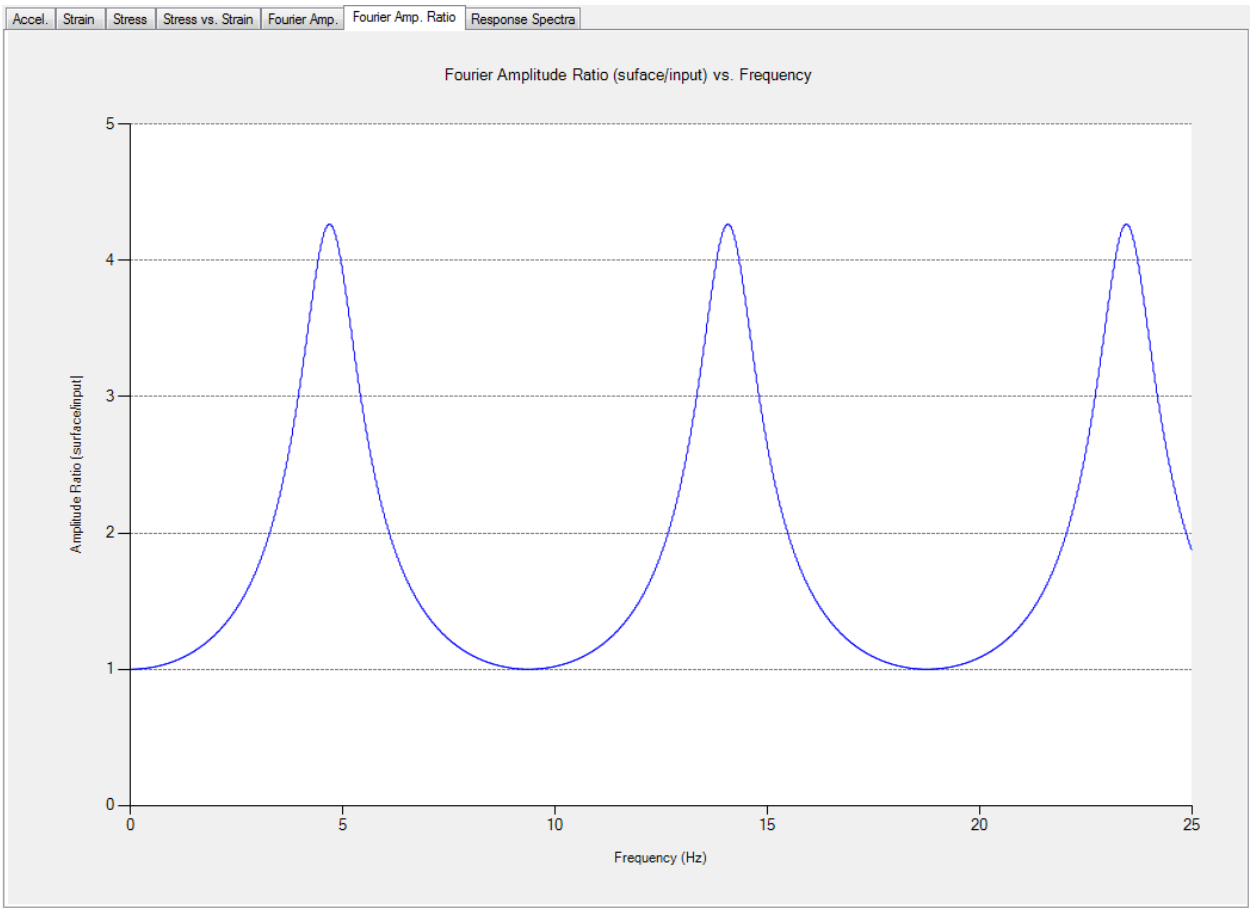


For the remaining steps, all options should be selected to be the same as in Example 1 (Input Motion→"Kobe.txt"; Frequency Independent Complex Shear Modulus; FFT).

After you have checked that all options are the same as in Example 1, click the **Analyze** button to begin the analysis.

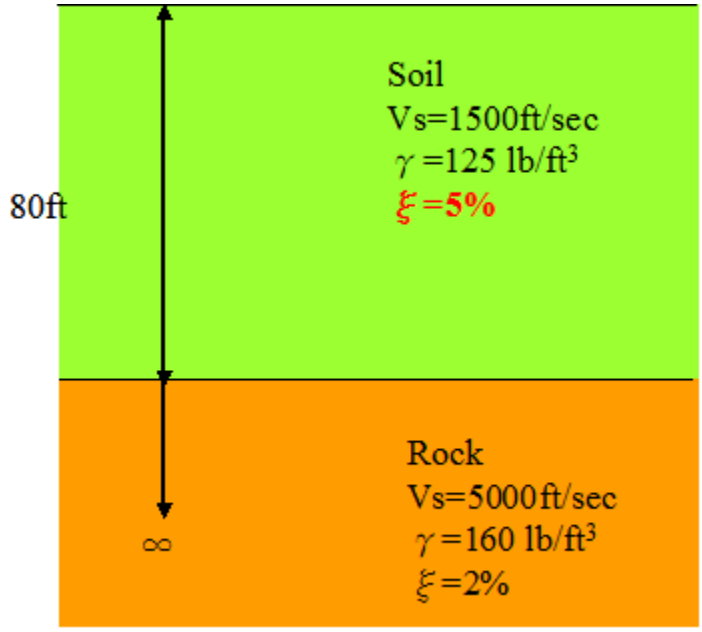
Check your analysis results with the figures shown on the following page. The first figure shows the calculated surface response spectrum. The elastic bedrock absorbs a significant amount of energy compared to the rigid bedrock and results in lower resonance.


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Response Spectra vs. Period
PSA (g)
5
4
3
2
1
0
0.01
0.1
1
10
Period (sec)


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Fourier Amplitude Ratio (suface/input) vs. Frequency
Amplitude Ratio [surface/input]
0
1
2
3
4
5
0
5
10
15
20
25
Frequency (Hz)

8.3 Example 3 Linear Frequency Domain Analysis / Damped Elastic layer, Elastic rock

Examples 1 and 2 assume that the soil layer has zero damping. This assumption is unrealistic because soils are known to exhibit damping even at very small strains. Example 3 ("Ex3_Lin_Freq_Damped_Elastic.dp") is similar to Example 2; the only difference being that the soil is damped instead of undamped. As such, the steps of the analysis are the same as those outlined in Example 2 except where noted below.



STEP 1/6

All options for Step 1/6 are exactly the same as those in Example 2.

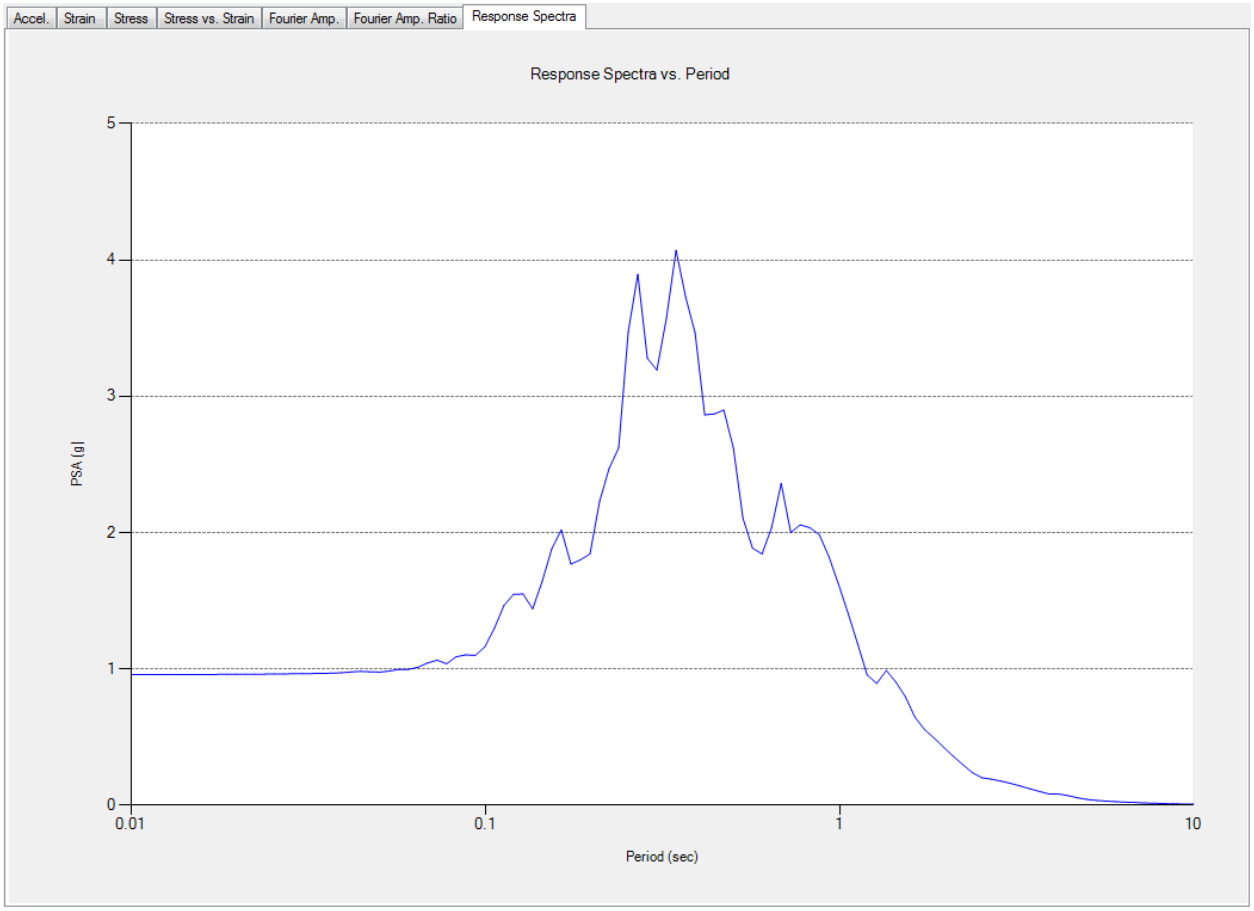
STEP 2/6

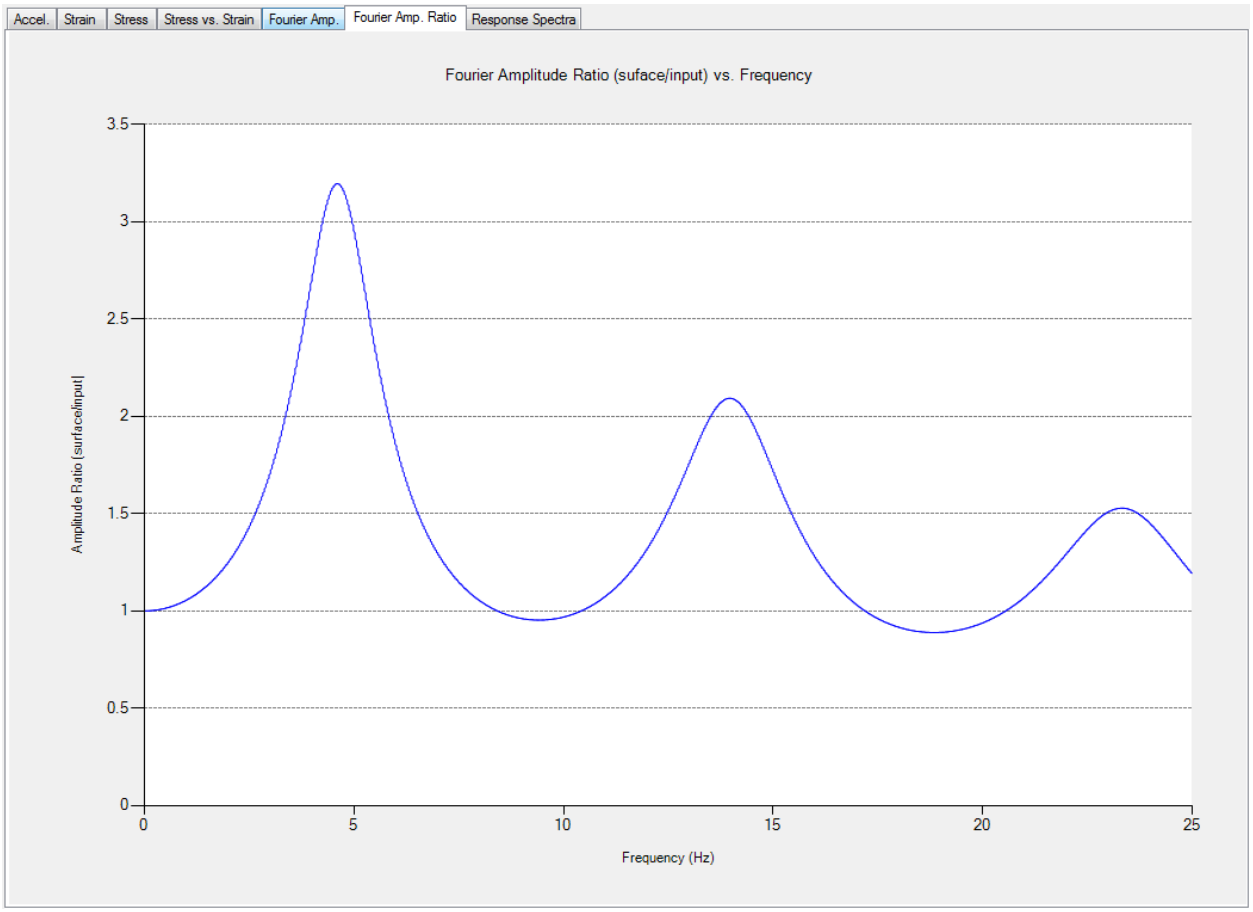
Damping of 5% is imposed on the soil layer. Enter "5" into the "Damping Ratio" column of the soil properties spreadsheet. Press the **Next** button to proceed to Step 2b/6.

Layer #	Layer Name	Thickness (ft)	Unit Weight (pcf)	Shear Velocity (ft/s)	Damping Ratio (%)
1		80	125	1500	5

Select all other options to be the same as Example 2 (Input Motion→Kobe.txt; Frequency Independent Complex Shear Modulus; FFT). After you have checked that all options are the same as in Example 2, click the **Analyze** button to begin the analysis.

The calculated surface response spectrum is shown in the figure on the following page. Note how the damping imposed on the soil results in lower resonance.




Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Fourier Amplitude Ratio (suface/input) vs. Frequency
Amplitude Ratio (surface/input)
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Frequency (Hz)

8.4 Example 4 Equivalent Linear Frequency Domain Analysis / Single Layer, Elastic Rock

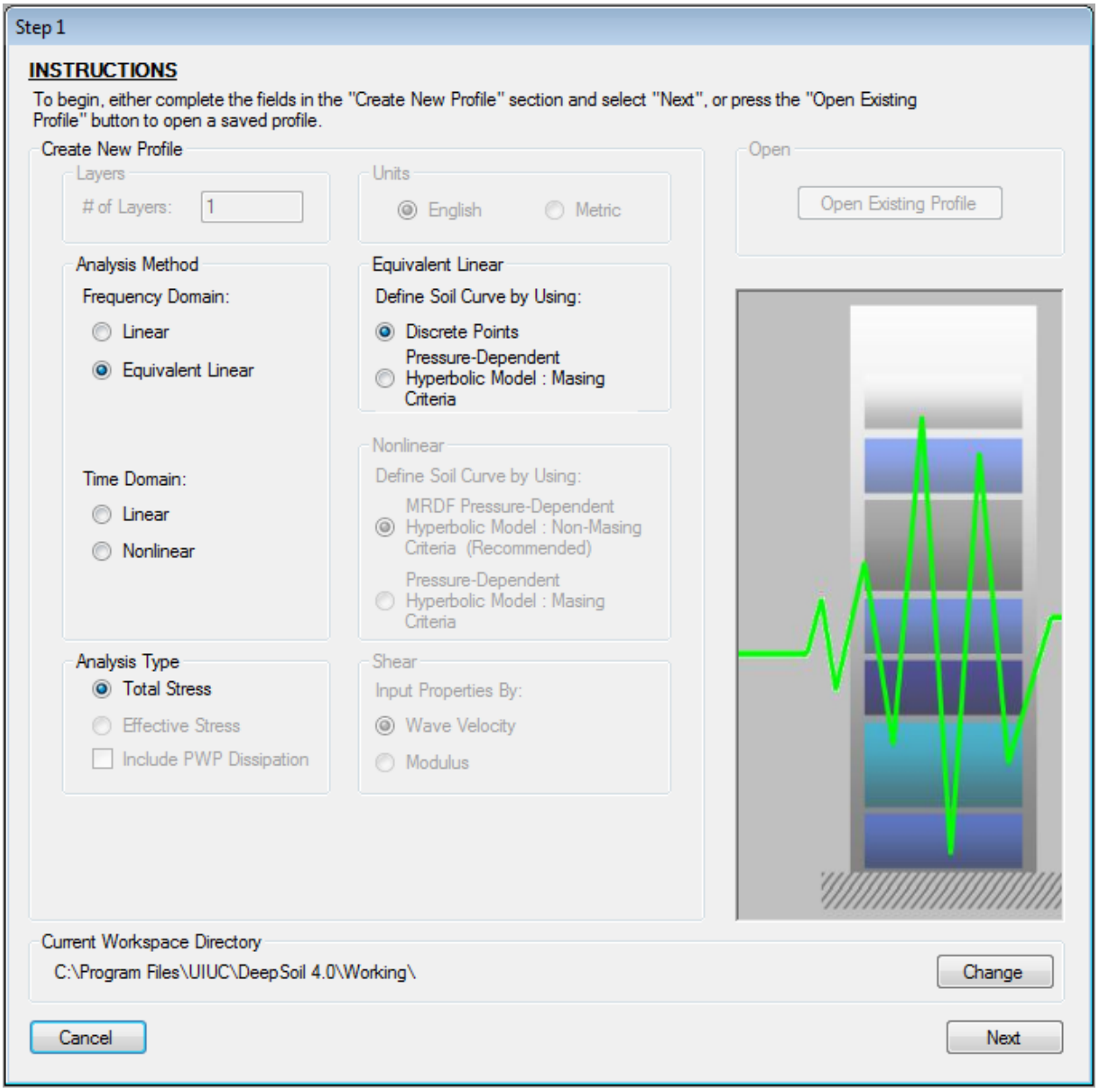
Example 4 ("Ex4_EQL_Single_Layer.dp") considers an equivalent linear analysis. The profile is the same as that of Example 3 with the exception that the material properties will be changed.

STEP 1/6

The input for Step 1/6 is similar to Example 3, with the following exceptions:

For "Analysis Type," select the Frequency Domain – "Equivalent Linear" analysis. This will enable the "Equivalent Linear" options.

For an equivalent linear analysis, the G/G_{MAX} and damping ratio curves can be defined using either a) Discrete Points or b) the Modified Hyperbolic Model.

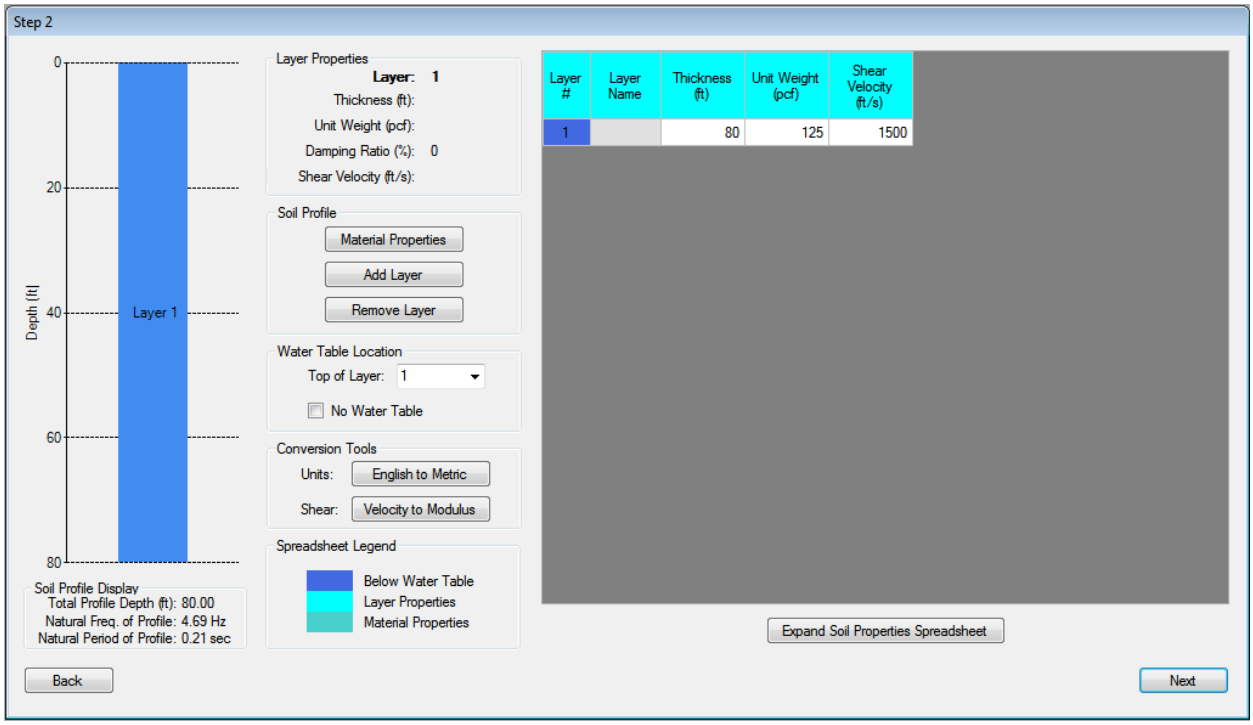


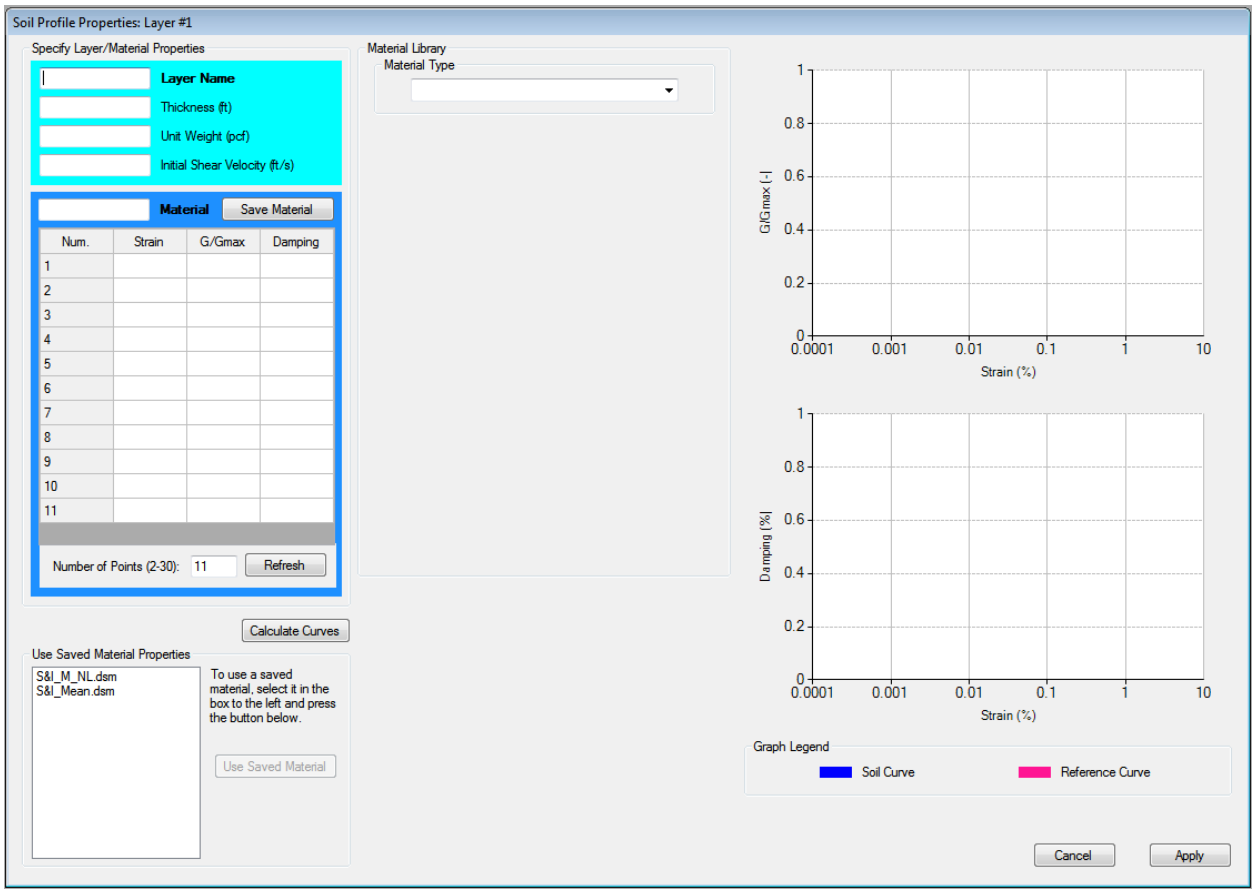
If discrete points are selected, the G/G_{MAX} and damping ratio will be defined in discrete points at various strain levels. It is also possible to define the G/G_{MAX} and damping curve using the modified hyperbolic model. In that case, the user needs to define the nonlinear parameters for the soil model. DEEPSOIL will automatically develop corresponding G/G_{MAX} and damping ratio curves.

For this example, select “Discrete Points” and then press the **Next** button.

STEP 2/6

The user can go directly to the spreadsheet, the graphical soil column, or use the "Material Properties" button to define the soil curves. From the spreadsheet, left-click any cell of the layer for which you want to define the soil curve to select that layer, and then press the **Material Properties** button. The user can also double-click any cell in the spreadsheet to open the Material Properties window for that layer. Similarly, double-clicking a layer in the graphical soil column will open the Material Properties window for that layer.

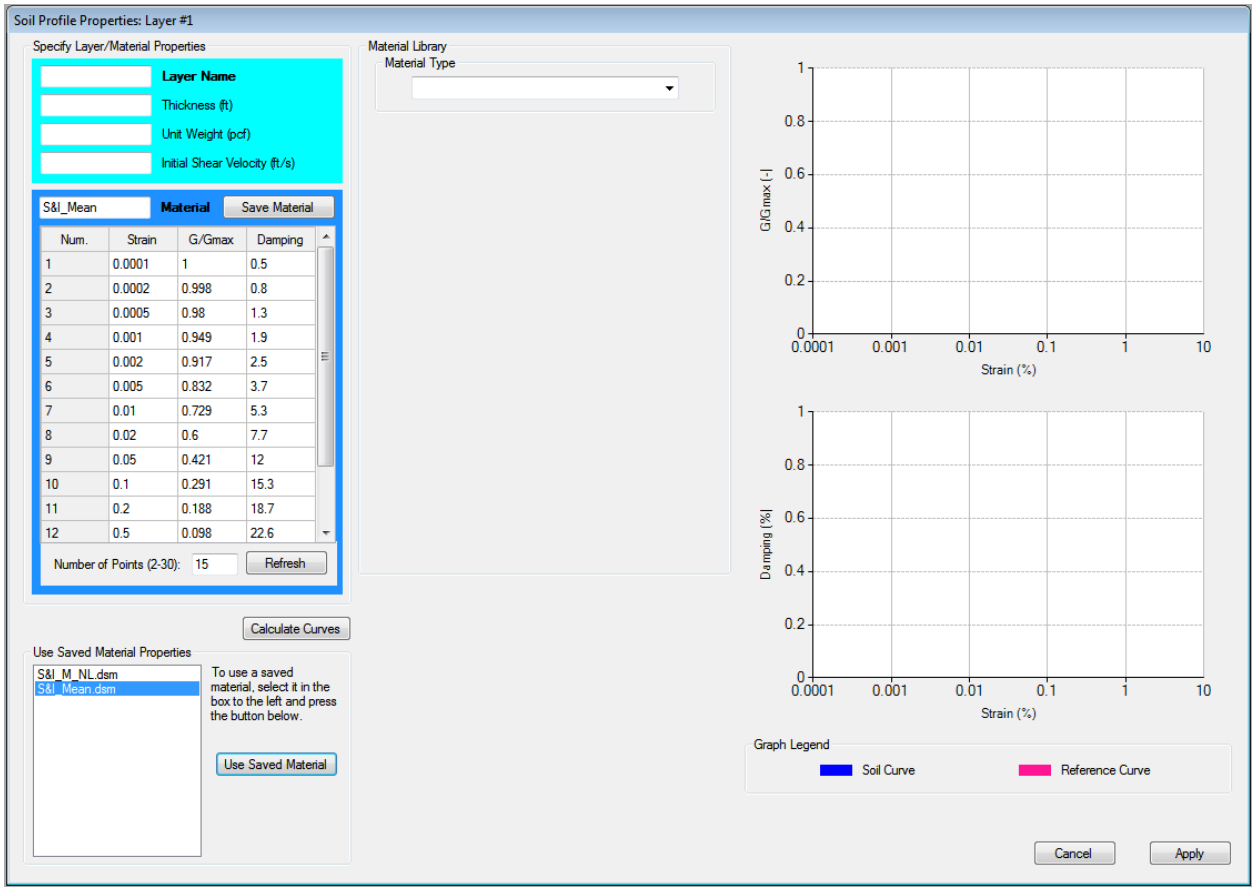




The user can define the G/G_{MAX} and damping properties by first defining the number of data points. Note that the number of data points should be identical for G/G_{MAX} and damping. The strain and damping values should be entered as a percent [%].

To save the data points, type a name to identify the properties and press **Save Material**. Once saved, the newly saved file will appear in the "Use Saved Material Properties" listbox.

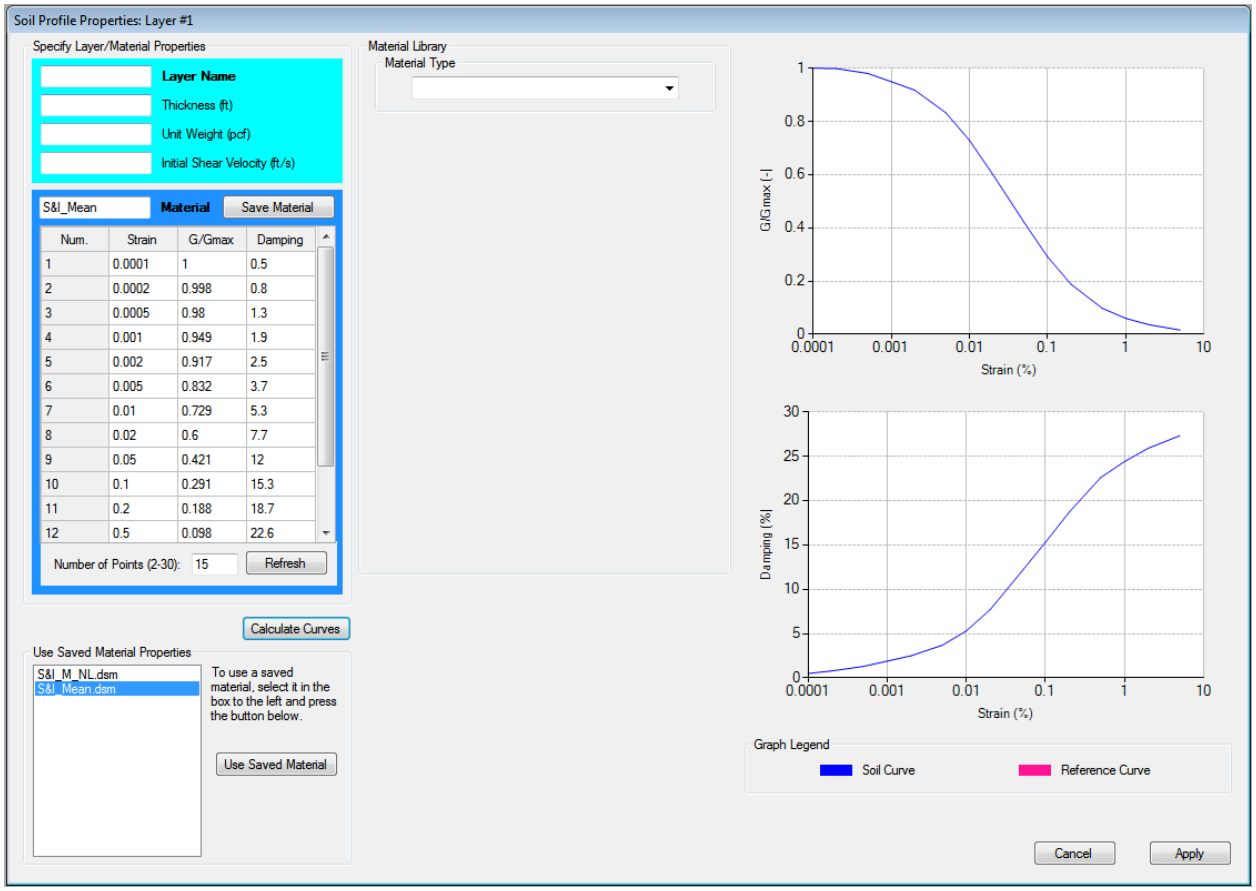
The user can also use saved material properties by selecting the appropriate file from the listbox and pressing the **Use Saved Material** button. We will use this method in this example. Select the saved material named "S&I_Mean.dsm" and click the **Use Saved Material** button. The discrete point data for this material should now be loaded in the spreadsheet as shown below.



To compare the selected material to a material from the material library, the user must define a) the Material Type, and b) the Target Curve.

Click on the Material Type drop-down menu and select "Sand". Two new items will appear: Basic Parameters and Target Curve. The Basic Parameters for this case simply displays the vertical stress at the midpoint of the layer. Now we must define the Target Curve.

Click on the Target Curve drop-down menu. A list of various models for sand will appear. Select the "Seed & Idriss, 1991 (Mean Limit)" item. The model soil curves will be plotted in pink for your reference. In addition, a new item appears labeled: "Data Points to Fit." These are the points that define the model curves. To use this model data, click the "Use Material Data" button. The discrete points of your soil model will be updated to match these points. Click "Calculate Curves" to verify that the models are the same.



Once you are satisfied with your soil curves, press the **Apply** button to apply the properties and return to the profile spreadsheet.

When you have finished checking the data, press the **Next** button to proceed.

STEP 2b/6

The entries for this step are the same as those specified in Example 3.

STEP 3/6

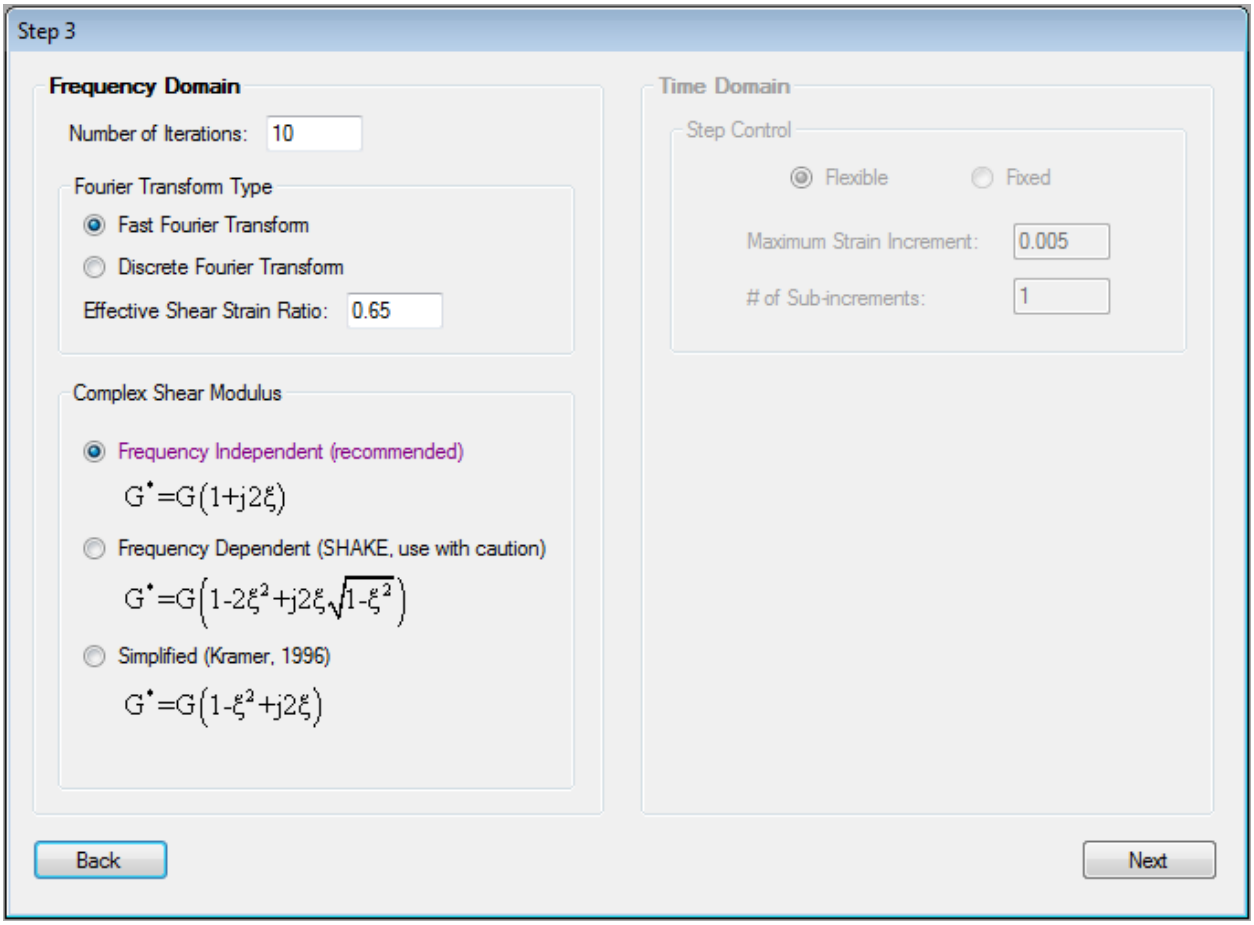
The third stage of analysis is the analysis control stage.

Equivalent linear analyses require a number of iterations to obtain more accurate results. The recommended number of iterations is 15. For the sake of accuracy, you should not choose less than 10 iterations. For this example, choose (at least) 10 iterations.

Select the Fast Fourier Transform (FFT).

The next step is selecting the effective shear strain ratio. The equivalent linear analysis selects shear modulus and damping ratio at a representative shear strain at an effective strain as a ratio of maximum shear strain. Enter an effective shear strain ratio of 0.65.

Select the Frequency Independent Complex Shear Modulus for use in this analysis.



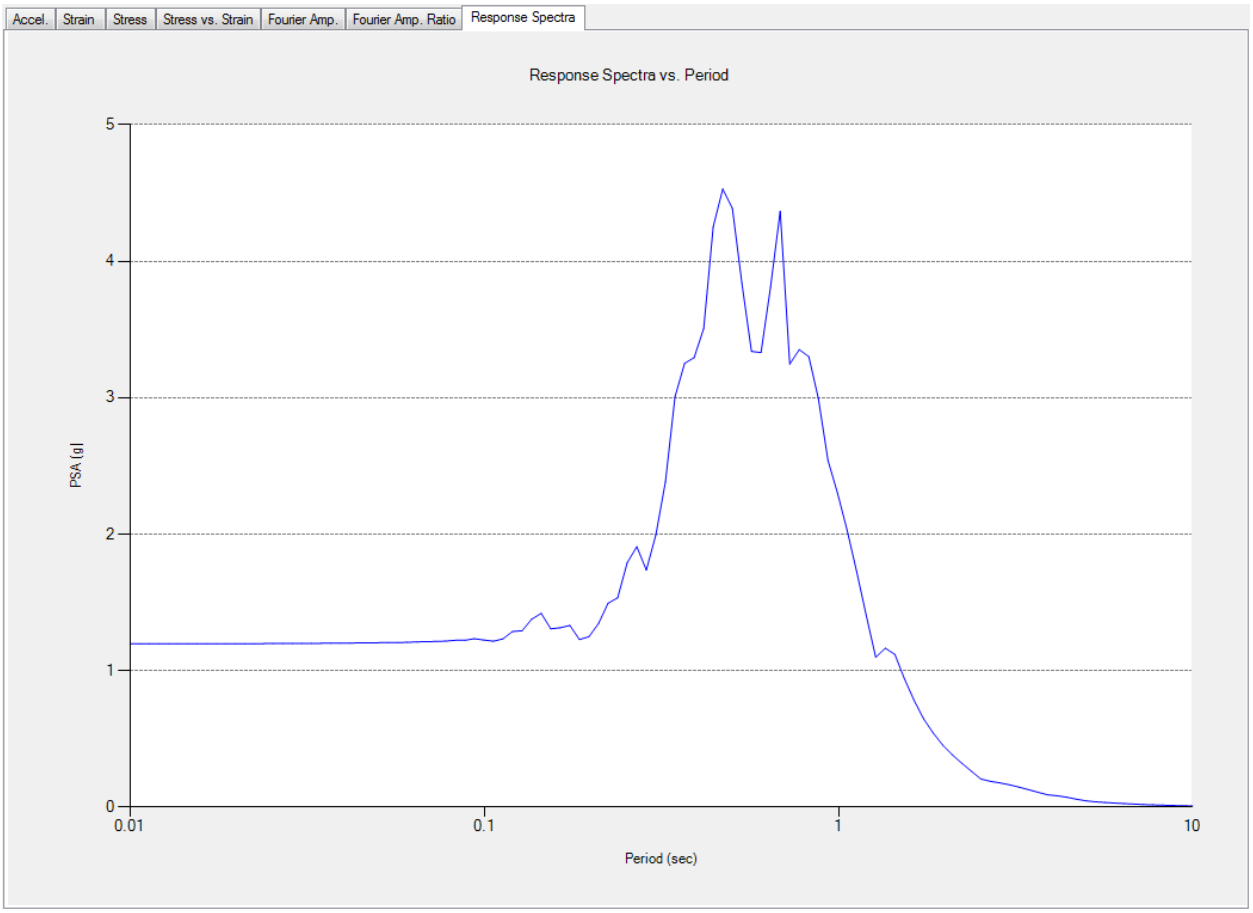
Finally, press the **Next** button to proceed to the input motion and output layer(s) selection window (Step 4/6).

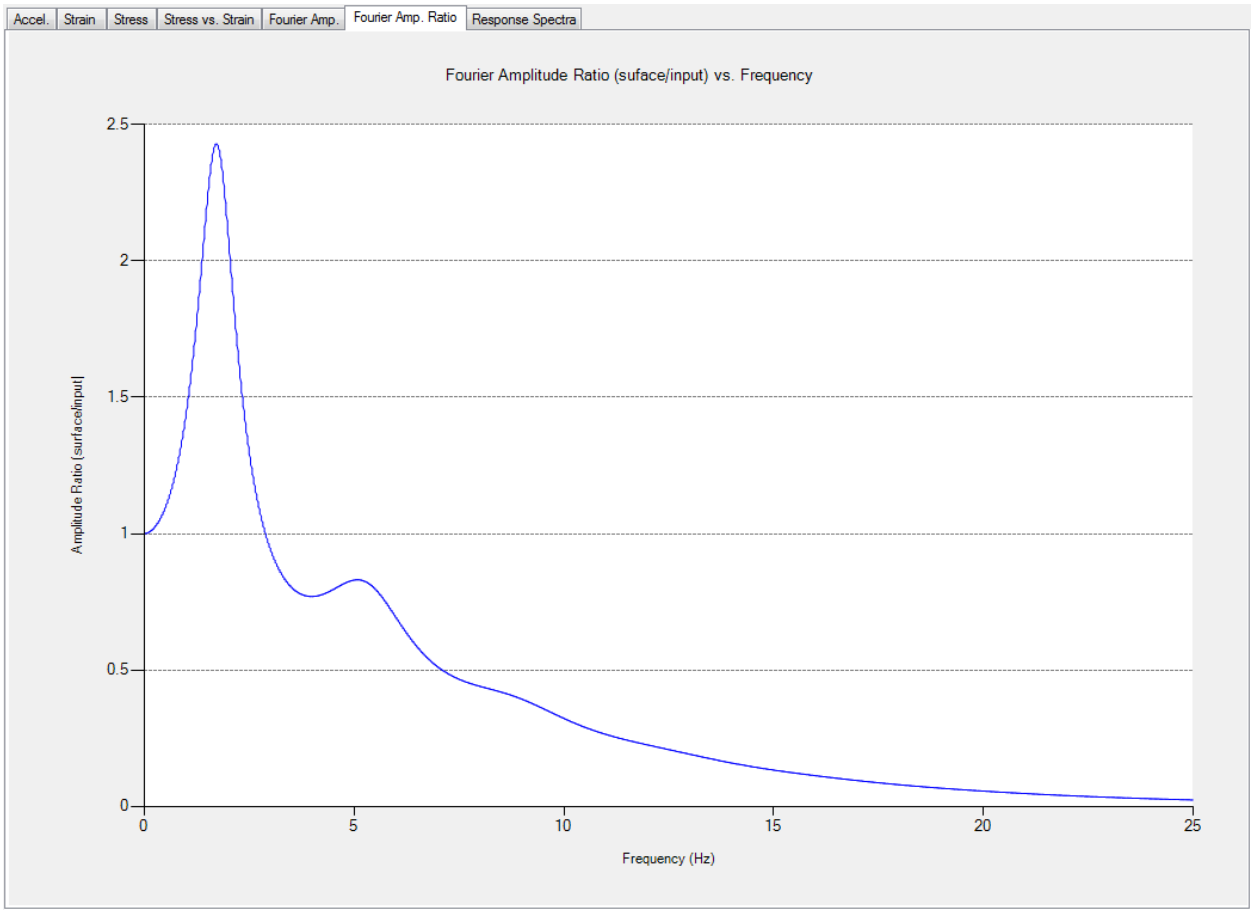
STEP 4/6

Similar to the previous examples, select "Kobe.txt" as the input motion and select the desired layers for output. Layer 1 is automatically selected by default. Press the **Analyze** button to begin the analysis.

STEP 6/6

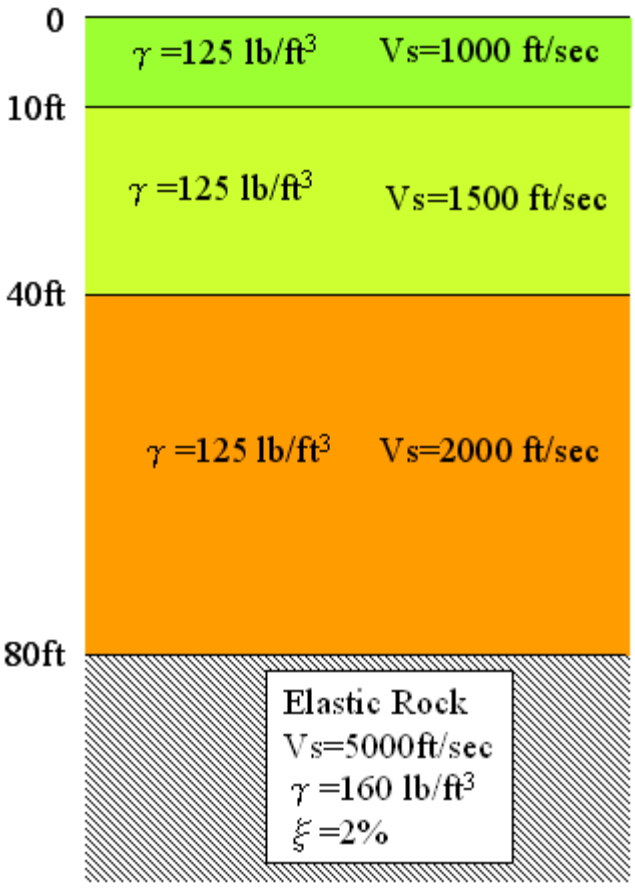
The figures below show the computed response spectrum at the surface. Check that your results match those presented in the figures.


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Response Spectra vs. Period
PSA (g)
5
4
3
2
1
0
0.01
0.1
1
10
Period (sec)


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
Fourier Amplitude Ratio (suface/input) vs. Frequency
Amplitude Ratio [surface/input]
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
Frequency (Hz)

8.5 Example 5 Equivalent Linear Frequency Domain Analysis / Multi-Layer, Elastic Rock

Example 5 ("Ex5_EQL_Multi_Layer.dp") considers an equivalent linear analysis for a multi-layer profile. This example will show you how to modify a previously saved profile by adding and removing layers.



STEP 1/6

Press the **Open Existing Profile** button and browse for Example 4. It should be located in the "Examples" directory. Once you find the appropriate directory, open Example 4 ("Ex4_EQL_Single_Layer.dp").

Press **Next** to proceed to Step 2/6.

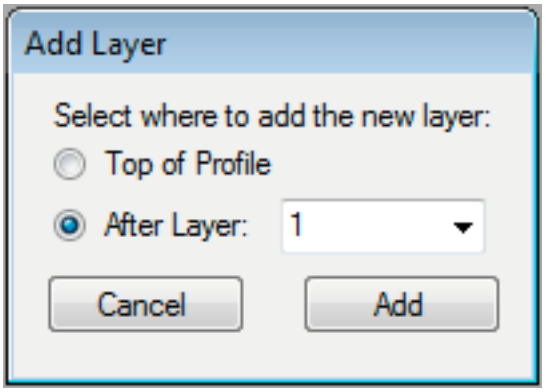
STEP 2/6

As you can see, all of the information for Layer 1 corresponds to Example 4. We will now modify this data and add two additional layers to the profile. First, change the Thickness and Shear Wave Velocity of Layer 1 to 10 ft and 1000 ft/sec, respectively.

There are two methods of adding a layer to the profile. We will use the first method to add the first layer, and the second method to add the second layer.

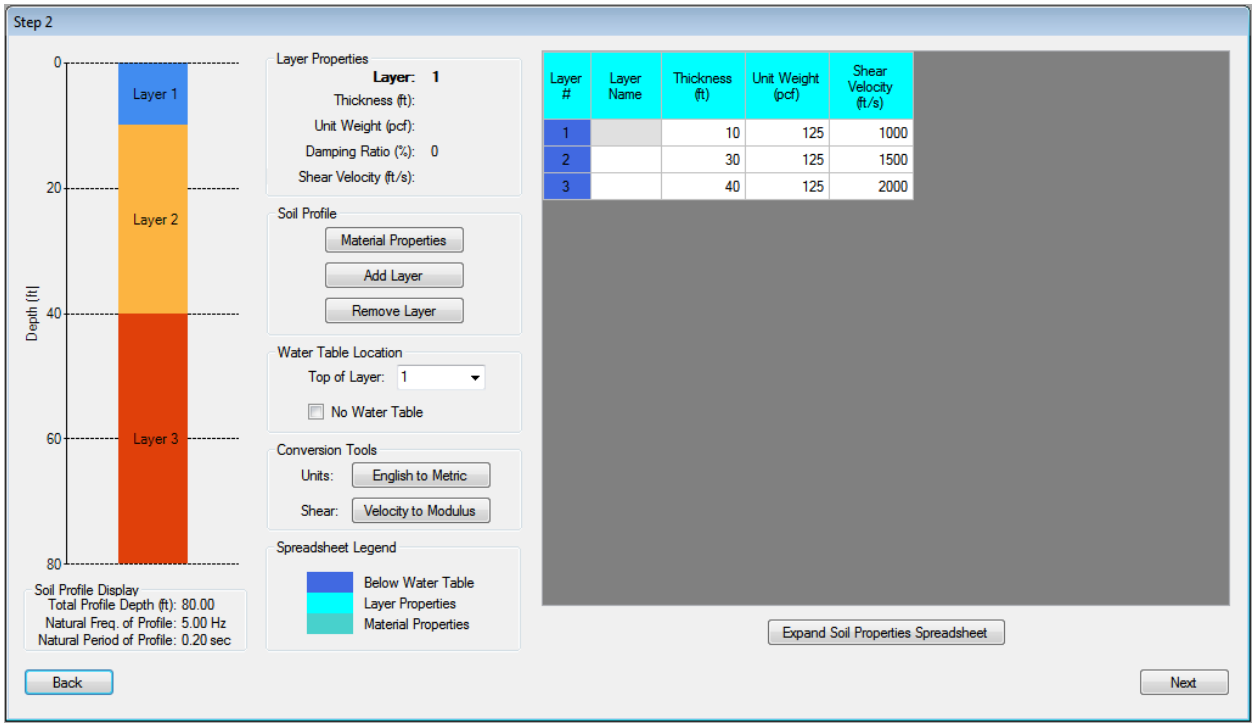
To add a layer to the profile by the first method, first select Layer 1 by left-clicking any of the cells in that row. Now, right-click to bring up the soil properties pop-up menu and select "Add Layer" from the list of commands. A new "Add Layer" window will appear.

In the "Add Layer" window, select the "After Layer" option and select Layer 1 from the drop-down list. After pressing **Add,** the new soil layer should be visible in the spreadsheet.



Enter the thickness (30 ft), unit weight (125 pcf), and shear wave velocity (1500 ft/sec) of the soil layer. Also apply the "Seed & Idriss, 1991 (Mean Limit)" curves for the layer as was done in Example 4.

To add the third layer, left-click one of the cells in the spreadsheet. Now click the **Add Layer** button in the Soil Profile group located in the middle of the form. Again select the "After Layer" option and select 2 using the drop-down box and press the **Add** button. Repeat the same process outlined above, but using a thickness of 40 ft and a shear wave velocity of 2000 ft/sec. Be sure that you check your input in the spreadsheet to confirm that it matches the one shown below.



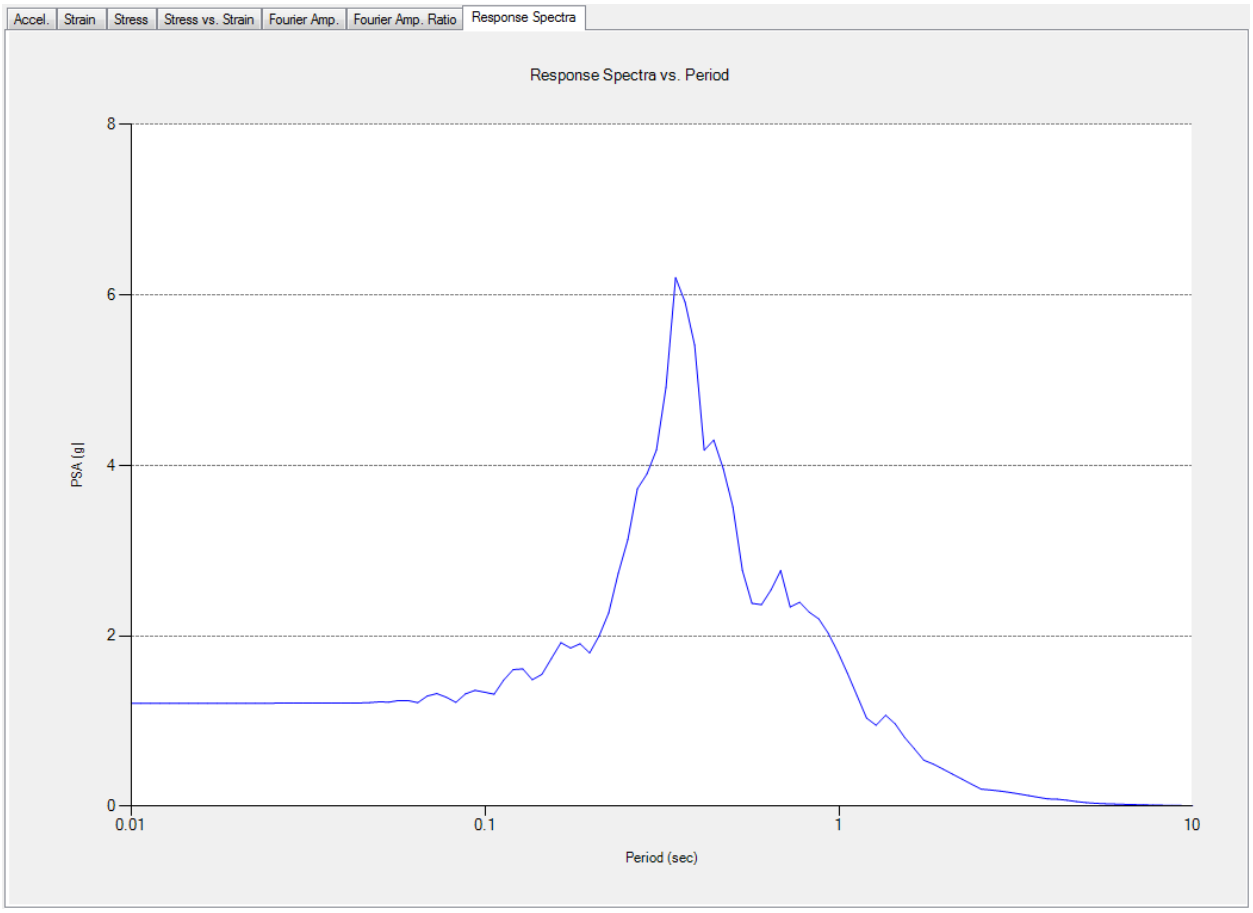
For Step 2b/6 and Step 3/6, keep all other options the same as Example 4.

STEP 4/6

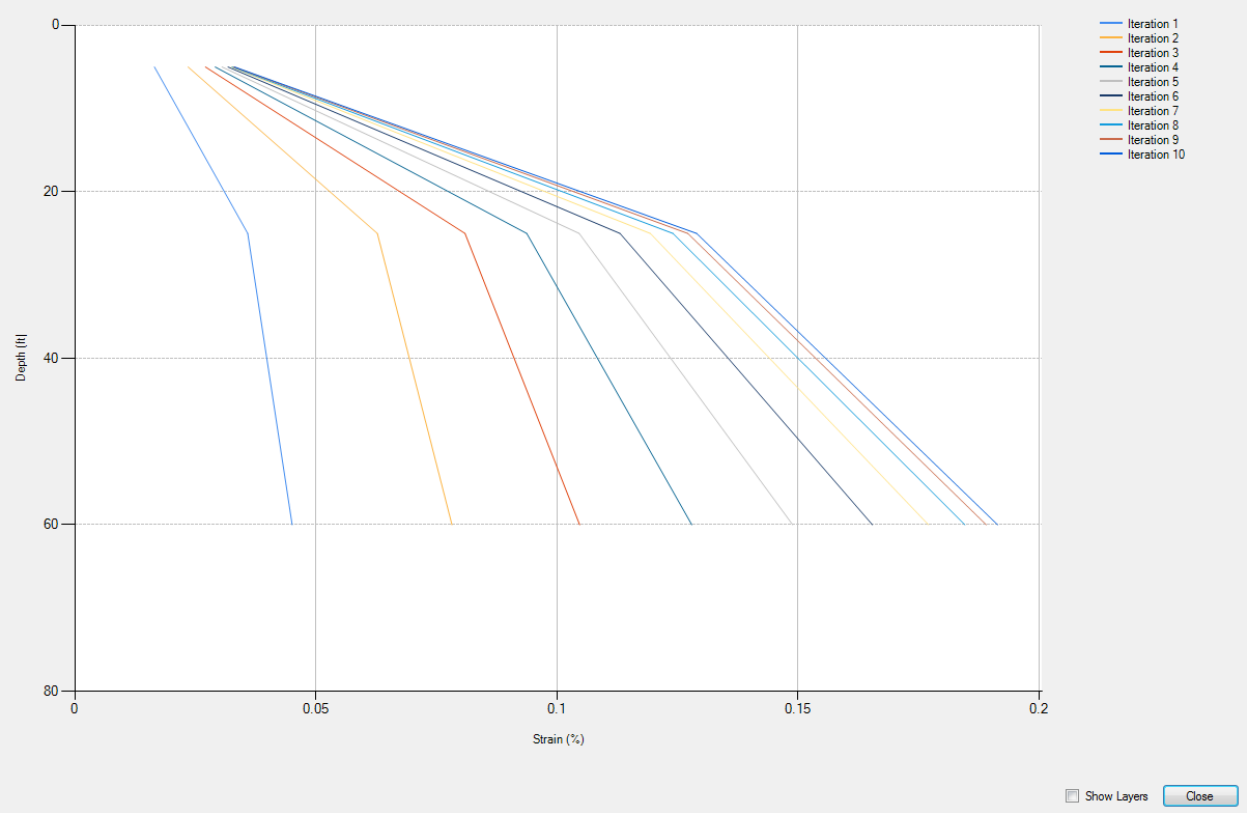
Keep all other selected options the same as in Example 4, including the input motion ("Kobe.txt"). If you like, you may select to analyze Layers 2 and 3 (Layer 1 is selected by default) by checking (double-clicking) each layer's corresponding checkbox located to the left of the input motion plot. Once you have checked your input and specified which layers are to be analyzed, press the **Analyze** button to run the analysis.

STEP 6/6

The figure below shows the computed surface acceleration. Check that your results match with those shown.



DEEPSOIL also allows checking the convergence of the equivalent linear analysis. You may do so by pressing the **Check Convergence** button located near the lower left corner of the form.



8.6 Example 6 Non-linear Analysis / Multi-Layer, Elastic Rock

Example 6 ("Ex6_Nonlin_Multi_Layer.dp") of this tutorial considers a Non-Linear analysis. This example will start with the profile defined in example 5 and then add additional layers.

In a non-linear analysis, the thickness of each layer has to be changed. This is because the thickness controls the maximum frequency that can be propagated by the layer. The greater is the thickness of the layer, the lower the maximum frequency that can be propagated by the same layer.

The equation that correlates the maximum frequency with soil thickness is as follows:

$$h = Vs/4f_{max}$$

Where h = thickness of the soil layer, V_s=shear wave velocity of the layer, and f_{max} is the maximum frequency that can be propagated.

It is a common practice to set the maximum frequency to 25 Hz in a non-linear site response analysis. This example will also use f_{max} = 25Hz.

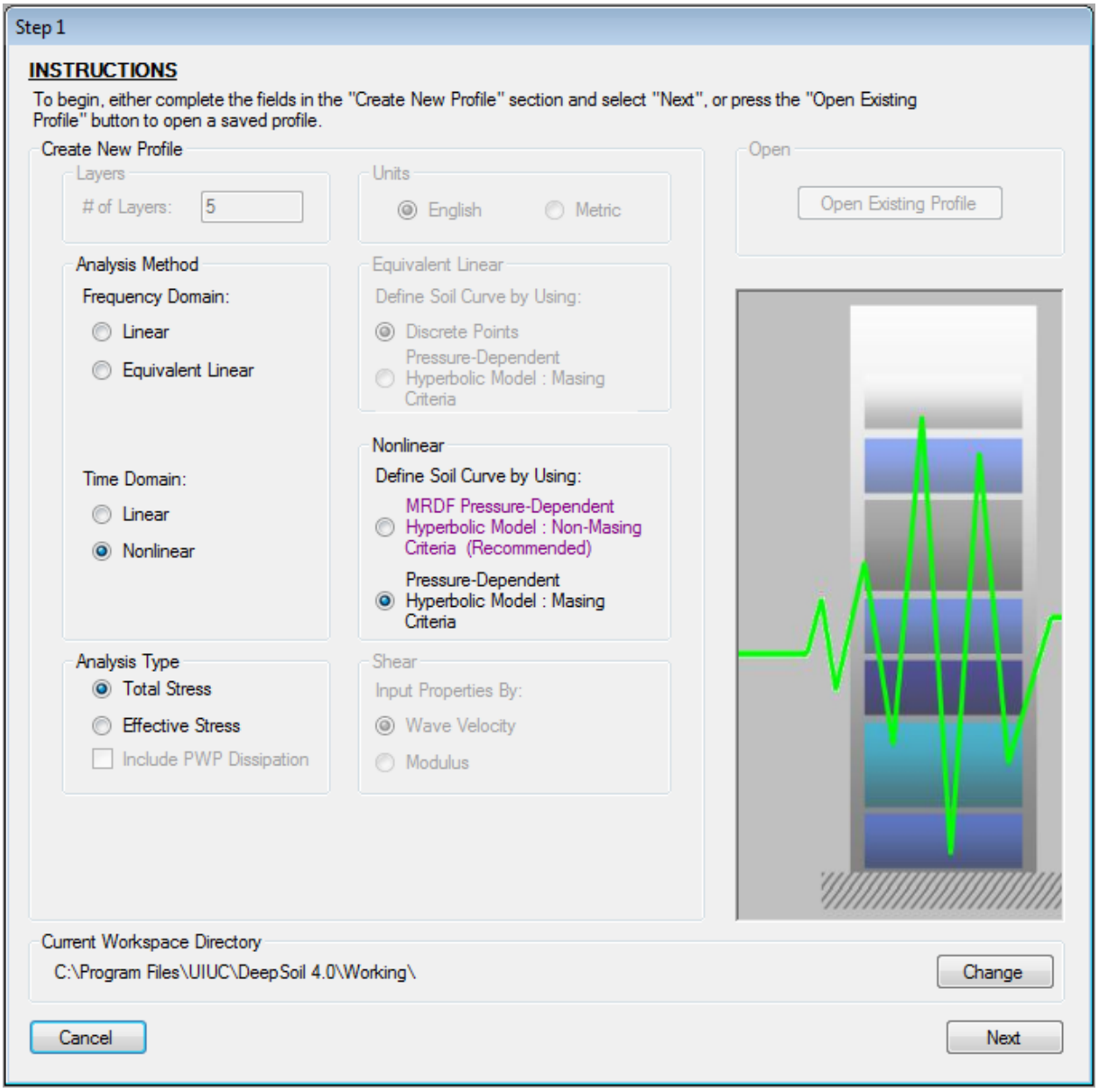
Simple calculations reveal that h for the layers should be 10 ft, 15 ft, and 20 ft for layers 1, 2, and 3 respectively. The first layer does not need to be changed, whereas the subsequent layers need to be subdivided into 2 thinner layers.

Now let's actually develop the input file for this example.

STEP 1/6

Open Example 5 ("Ex5_EQL_Multi_Layer.dp") from the examples directory.

Change the "Analysis Type" from "Equivalent Linear" to "Non-Linear." Then select "Pressure-Dependent Hyperbolic Model : Masing Criteria" in the "Nonlinear" section. Press the **Next** button to proceed to the soil properties input form.



STEP 2/6

Note that the basic properties of the layers (Thickness, unit weight, and shear velocity) are preserved.

Layer #	Layer Name	Thickness (ft)	Unit Weight (pcf)	Shear Velocity (ft/s)	Damping Ratio (%)	Ref. Strain (%)	Ref. Stress (MPa)	Beta	s	b	d
1		10	125	1000	0						
2		30	125	1500	0						
3		40	125	2000	0						

Subdivide Layers 2 and 3 into 2 thinner layers with each having a thickness equal to half of the original layer by adding layers as described in the previous example.

Layer #	Layer Name	Thickness (ft)	Unit Weight (pcf)	Shear Velocity (ft/s)	Damping Ratio (%)	Ref. Strain (%)	Ref. Stress (MPa)	Beta	s	b	d
1		10	125	1000	0						
2		15	125	1500	0						
3		15	125	1500	0						
4		20	125	2000	0						
5		20	125	2000	0						

For each layer, bring up the soil properties window using the "Soil Properties" button or by double-clicking the layer.

The default non-linear parameters are given as "S&I_M_NL.dsm." Find the file in the "Saved Materials" list box and press **Use Saved Material** to apply the material data to the layer.

Find the "Seed & Idriss, 1991 (Mean Limit)" curves in the Material Library as was done in previous examples. Now, press **Calculate Curves** to display the soil curves. Compare the calculated curves to the Seed and Idriss mean cohesionless curves. The Seed and Idriss curves, which are the reference curves, will be shown in pink.

To match the Seed and Idriss curves, the material constants need to be changed. The soil model incorporated in DEEPSOIL is the extended modified hyperbolic model:

$$\tau = \frac{G_{mo}\gamma}{1+\beta\left(\frac{G_{mo}}{\tau_{mo}}\gamma\right)^{s}} = \frac{G_{mo}\gamma}{1+\beta\left(\frac{\gamma}{\gamma_r}\right)^{s}}$$

$$\gamma_r = REF.strain\left(\frac{\sigma_v'}{REF.stress}\right)^{b} \qquad \xi = \frac{Damping\,ratio}{(\sigma_v')^{d}}$$

The parameters that control the shape of the backbone curve are β (beta), s, and γ_r.

The curve can be made confining pressure dependent by selecting the reference stress and the "b"-parameter. Select b = 0 to make the curve pressure independent. Note that γ_r = reference effective strain for b = 0 or σ_v' = reference stress.

The small strain damping properties can also be made pressure dependent by introducing the "d" parameter. The "d" parameter in the equation is the small strain damping in the user interface. Select d = 0 to make the curve pressure independent.

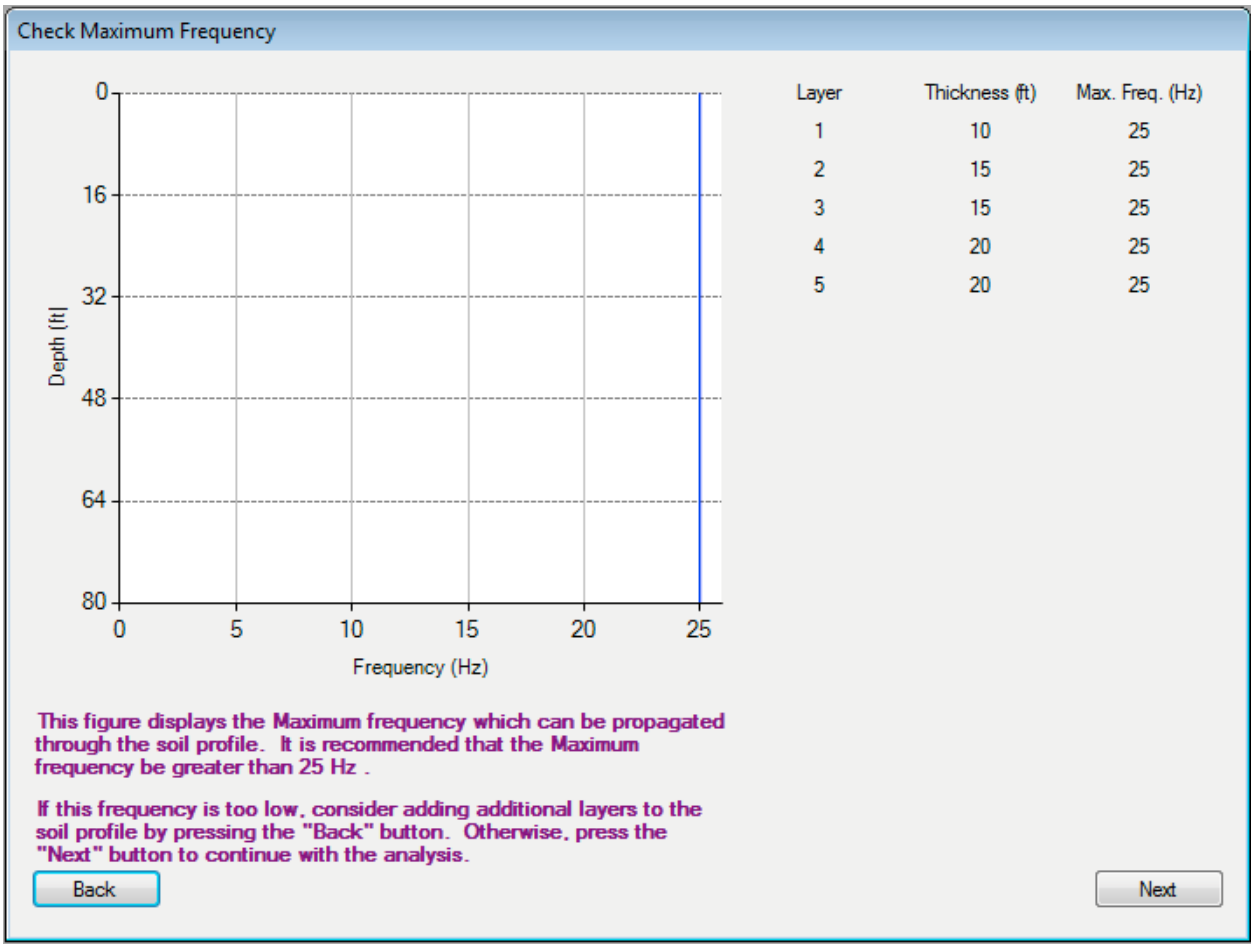
Try various combinations to get a good match with the Seed and Idriss reference curves. Once a satisfactory match is obtained, save the material in the material library. Then assign the selected parameters for all other layers.

For the purposes of this example, use the "S&I_M_NL.dsm" saved material for all layers.

After all of the input parameters have been specified, the spreadsheet should look like this:

Layer #	Layer Name	Thickness (ft)	Unit Weight (pcf)	Shear Velocity (ft/s)	Damping Ratio (%)	Ref. Strain (%)	Ref. Stress (MPa)	Beta	s	b	d
1	Nonlin S&I Mean	10	125	1000	0.5	0.03	0.18	0.8	0.7	0	0
2	Nonlin S&I Mean	15	125	1500	0.5	0.03	0.18	0.8	0.7	0	0
3	Nonlin S&I Mean	15	125	1500	0.5	0.03	0.18	0.8	0.7	0	0
4	Nonlin S&I Mean	20	125	2000	0.5	0.03	0.18	0.8	0.7	0	0
5	Nonlin S&I Mean	20	125	2000	0.5	0.03	0.18	0.8	0.7	0	0

For nonlinear analyses, DEEPSOIL will automatically check the maximum frequency of each layer. The Maximum Frequency vs. Depth will be plotted with a table of corresponding values given on the right. This check is to ensure that the maximum cut-off frequency is always greater than or equal to 25 Hz.



After checking the results, press the **Next** button to continue to Step 2b/6 of the analysis.

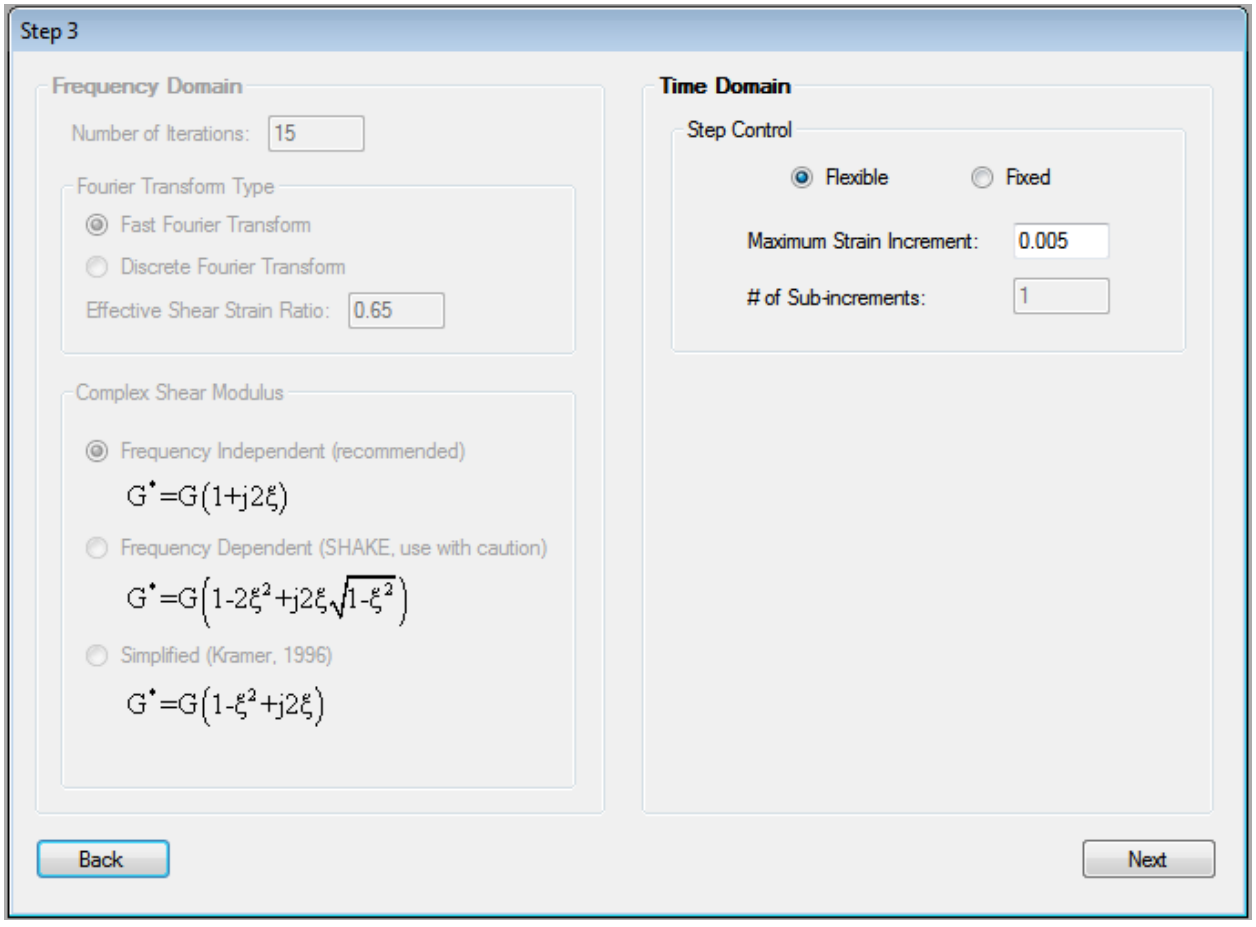
STEP 2b/6

The values to be entered in this step are the same as in Example 4.

STEP 3/6

The third stage of the analysis is the analysis control stage. In a time domain analysis, the user must specify a step control scheme. Choose either a "Flexible" (default) or "Fixed" sub-incrementation scheme. The "Flexible" sub-incrementation scheme subdivides a time interval into small steps if the calculated strain increment is higher than the user-defined maximum strain increment. The "Fixed" scheme sub-divides all time intervals into user-defined sub-increments.

For the purpose of this tutorial, select the "Flexible" sub-incrementation scheme and use the default value of 0.005. Press the **Next** button to continue.



STEP 4/6

This stage of analysis requires selection of the input ground motion and layers to be analyzed for output. As in previous examples, select "Kobe.txt" as the input motion. You may select the additional layers to be analyzed as well. Layer 1 is selected by default.

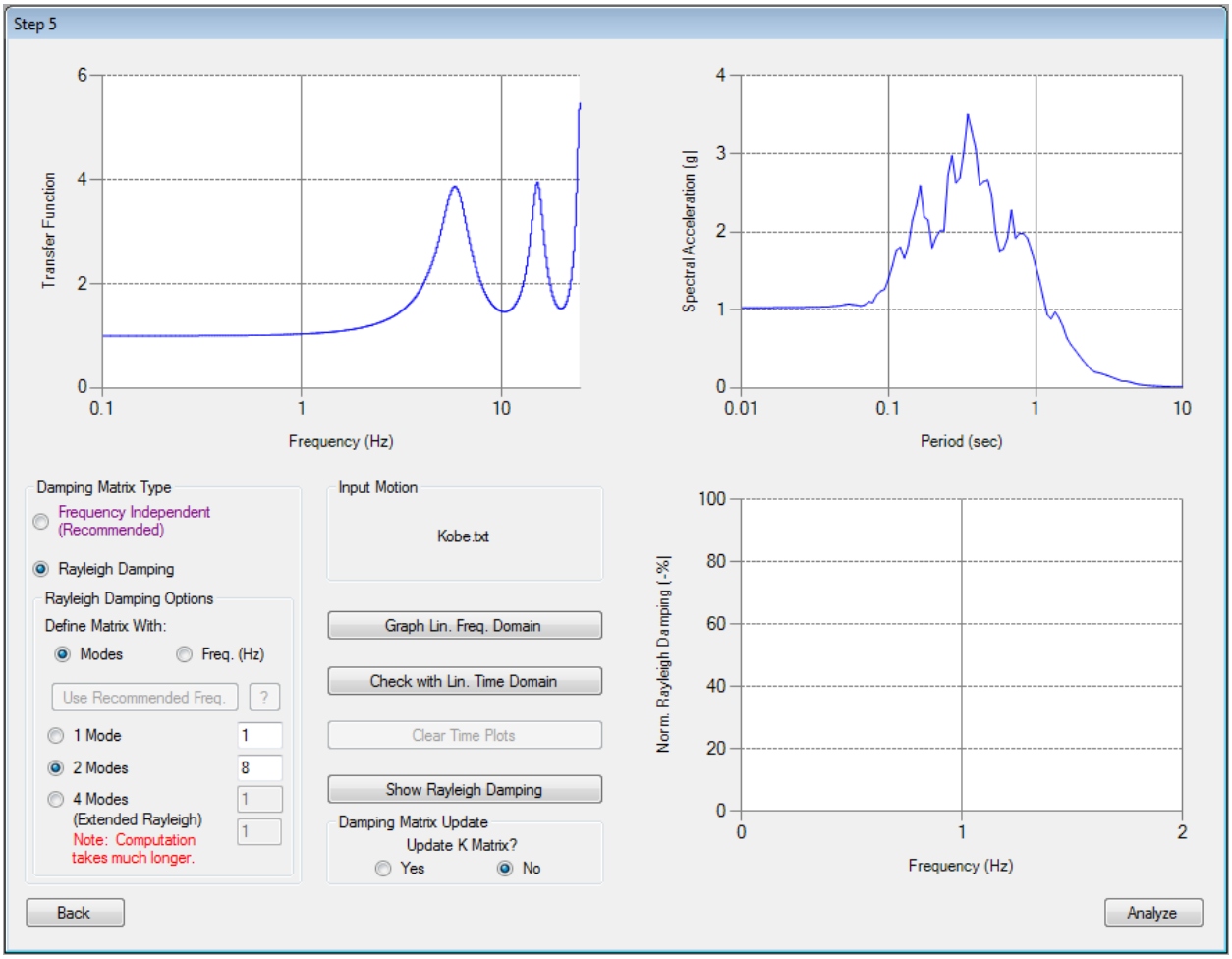
Press the **Next** button to continue to the fifth stage of analysis.

STEP 5/6

The fifth stage of analysis requires selection of the appropriate Rayleigh damping coefficients.

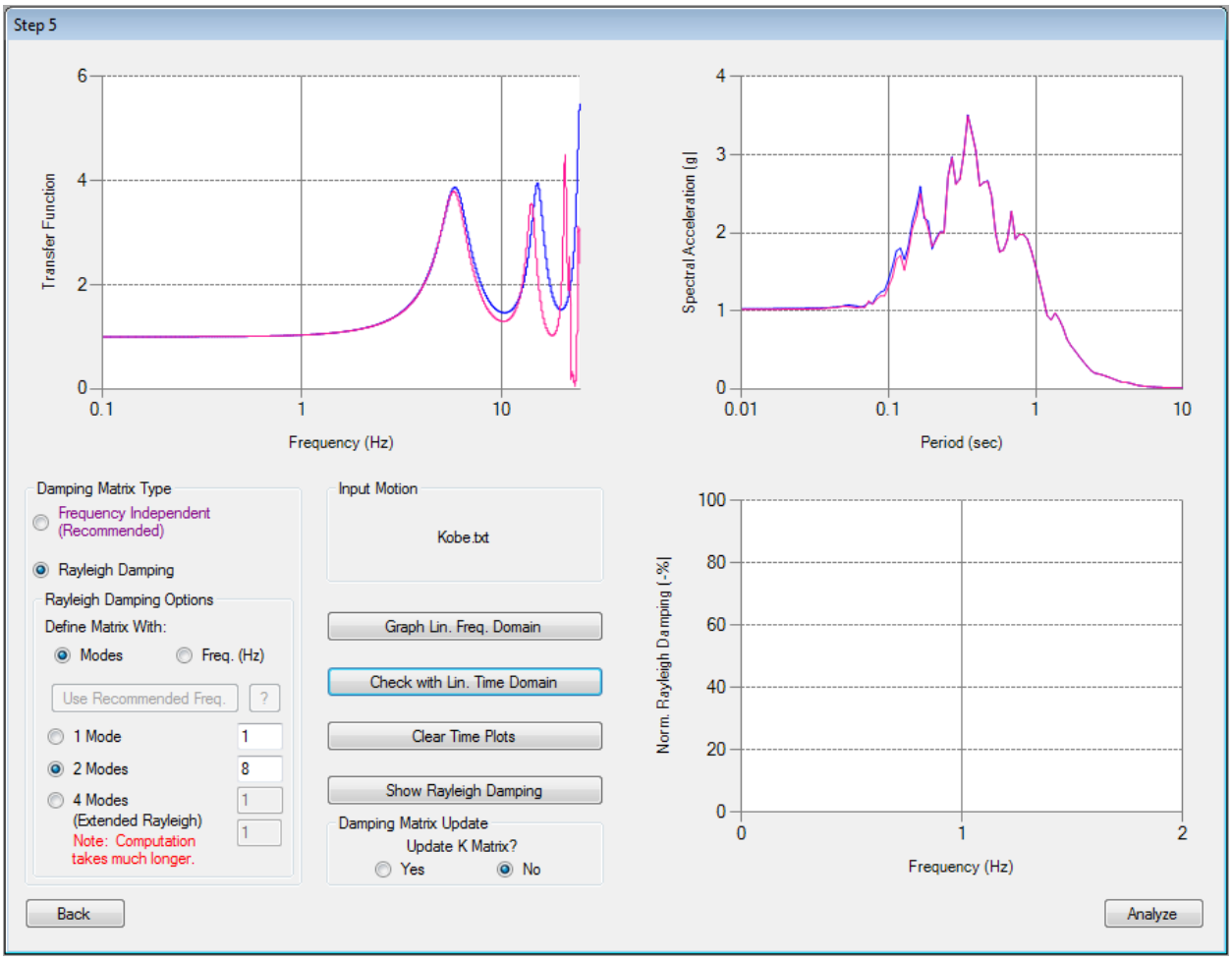
The purpose of this stage of analysis is to reduce frequency dependent damping introduced due to the viscous damping formulation. This stage allows selection of optimum coefficients by comparing the linear time domain solution with the linear frequency domain solution (Note: the linear frequency domain solution uses frequency independent damping).

First, click the **Graph Lin. Freq. Domain** button. DEEPSOIL will display the transfer function values and response spectrum plots corresponding to the linear frequency domain solution.



Next, choose modes/frequencies for the Rayleigh damping formulation. It is strongly recommended to use the frequency independent damping formulation, however this example will instruct you in using 2 modes to demonstrate all of the features available in this step. The selection process is an iterative trial-and-error procedure to get the best match with the frequency domain solution.

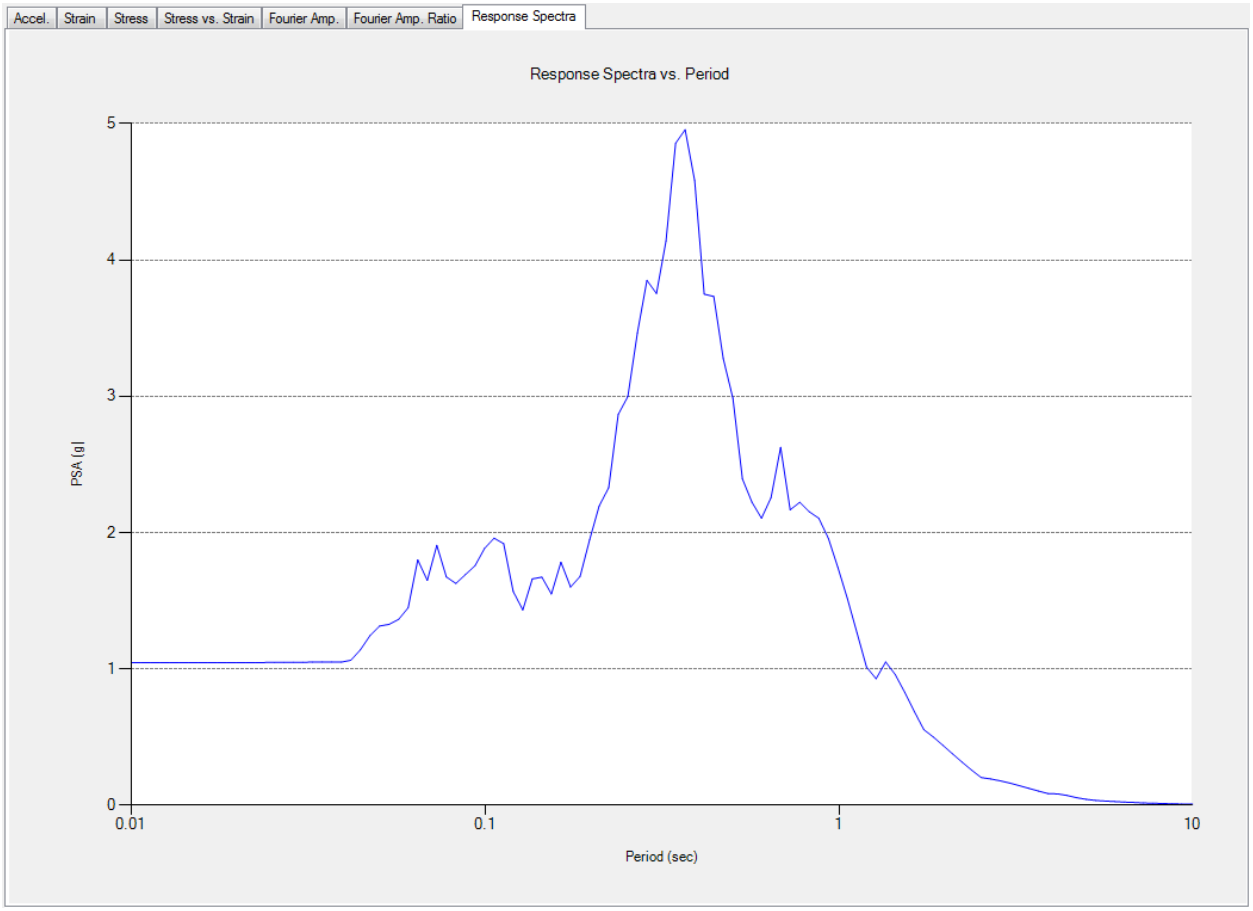
The default selections using 2 modes/frequencies are the 1st and 8th modes. Click the **Check with Lin. Time Domain** button to view the linear time domain solution. Using the default modes, a good match is obtained with the linear frequency domain solution.



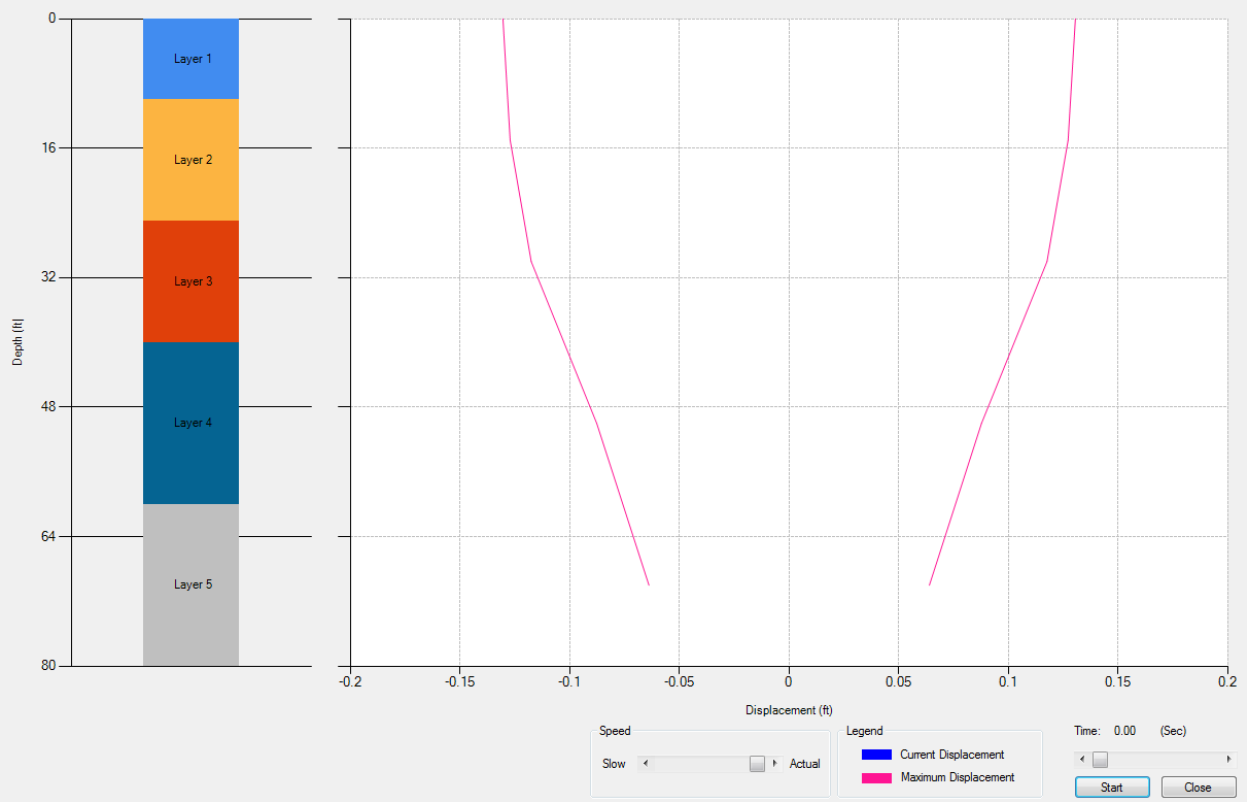
Finally, select the "Frequency Independent" option for the analysis. We have now optimized this analysis. Press the **Analyze** button to continue.

STEP 6/6

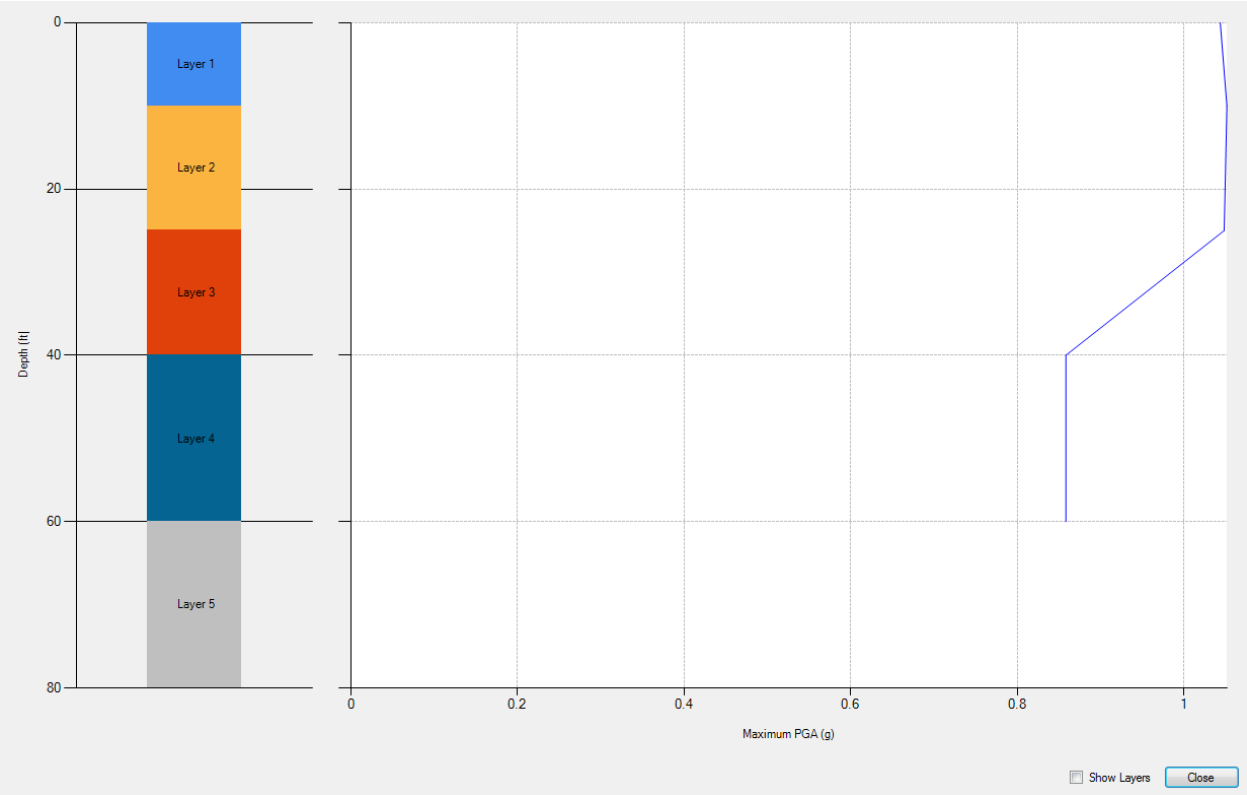
The figure shown below is the calculated surface response spectrum for Layer 1. Check that your results match those shown in this tutorial.



In a non-linear analysis, it is also possible to animate the column displacement time histories. You can do so by clicking the **Column Displacement Animation** button. The Column Displacement Animation Window allows the user to adjust the speed of the animation as well as to stop the animation and show the displacement at a given time. These options can be adjusted using the scroll bars below the plot. Click **Start** to start the animation or click **Close** to return to the output plots.



The PGA profile can also be displayed by clicking the **PGA Profile** button. The PGA Profile Window shows the PGA for each layer. Note that the PGA is calculated at the top of each layer, not the midpoint. To view the layers in the PGA plot, check "Show Layers." To change the color of the plotted layer lines, click the color box and select a new color. When you are finished, press **Close** to return to the output plots.



8.7 Example 7 Non-linear Analysis / Multi-Layer, Elastic Rock, Pore Water Pressure Generation and Dissipation

The next example ("Ex7_Nonlin_Multi_Layer_PWP.dp") of this tutorial considers the Non-Linear analysis of Example 6 as an effective stress analysis with generation and dissipation of pore water pressure. The steps in the analysis are the same as Example 6 except where noted below.

STEP 1/6

Open Example 6 ("Ex6_Nonlin_Multi_Layer.dp").

Change the "Analysis Type" from "Total Stress Analysis" to "Effective Stress Analysis." This will enable the option to "Include PWP Dissipation." Check the checkbox next to "Include PWP Dissipation" to allow for both pore water pressure generation and dissipation in the analysis.

When the "Include PWP Dissipation" option is selected, a new item appears labeled: "Boundary Conditions for Bottom of Profile." These options are used to specify whether the bottom of the profile is a permeable or impermeable boundary. For the purposes of this example, select the "Permeable" option.

Press the **Next** button to continue to the soil properties input form.

STEP 2/6

Note that the properties defined in Example 6 are preserved.

Using the horizontal scroll bar, we see that there are new parameters which must be defined for the pore water pressure generation and dissipation model. If the spreadsheet is too large for your window, press **Expand Soil Properties Spreadsheet** to open the spreadsheet in full-screen mode.

PWP Model (1=S-M/D) (2=C-M) (3=S-GMP)	f/s/f	p/r/Dr(%)	F/A/FC(%)	s/B/-	g/C/-	v/D/v	-/g/-	Cv (ft2/sec)

The first parameter that needs to be defined for each layer is the "PWP Model." The models that can be used in analysis are Sand (1), Clay (2), or GMP (3) which is another model that can be used for sands. Each layer may use a different PWP Model. For the purpose of this example, set each layer to use the Sand Model by entering 1 into each layer's corresponding cell.
The next parameter is "f/s/D_r (%)." The notation for the parameters including a "/" is that the first listed parameter is for the Sand Model, the second listed parameter is for the Clay Model, and the

third listed parameter is for the GMP Model. So, in the case of "f/s/D_r (%)," "f" must be defined if the Sand Model is selected, "s" must be defined if the Clay Model is selected, or "D_r (%)" must be defined if the GMP Model is selected. (Note that the parameters are defined in Section 4.2)

Dashed parameters such as "-/g/-" indicate that a certain model has no input for this column. In the case of "-/g/-", the Sand and GMP Models have no input for this column. You may leave the cell blank for the Sand and GMP Models.

Let us define the parameters as follows:

f/s/f → f = 1

p/r/Dr (%) → p = 1

F/A/FC(%) → F = 0.73

s/B/- → s = 1

g/C/- → g = 0.02

v/D/v → v = 3.8

-/g/- → (None; leave blank)

C_v = 0.1

The PWP section of the spreadsheet should look like the following figure.

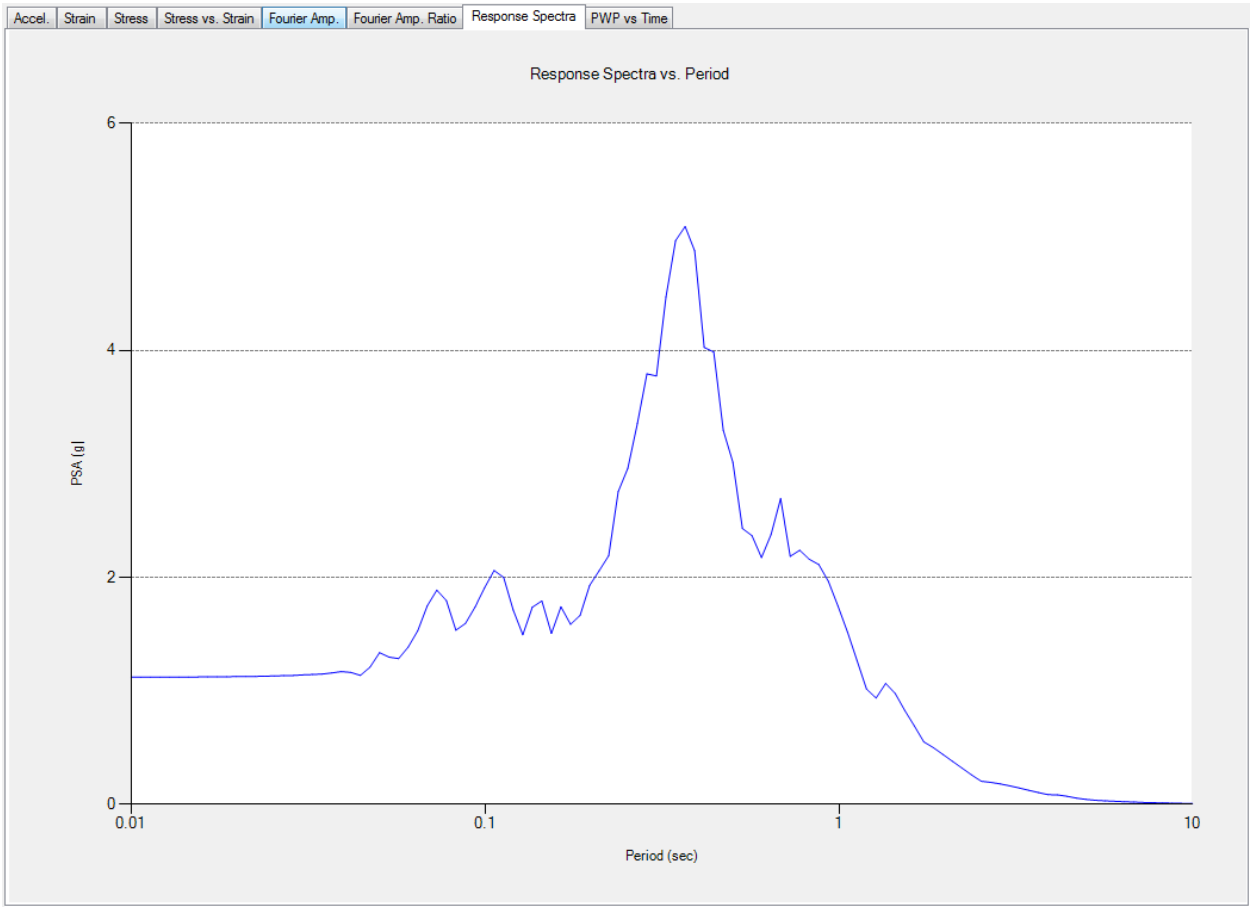
PWP Model (1=S-M/D) (2=C-M) (3=S-GMP)	f/s/f	p/r/Dr(%)	F/A/FC(%)	s/B/-	g/C/-	v/D/v	-/g/-	Cv (ft2/sec)
1	1	1	0.73	1	0.02	3.8		0.1
1	1	1	0.73	1	0.02	3.8		0.1
1	1	1	0.73	1	0.02	3.8		0.1
1	1	1	0.73	1	0.02	3.8		0.1
1	1	1	0.73	1	0.02	3.8		0.1

After checking your input, press the **Next** button to continue to the third stage of analysis.

The remaining steps of the analysis are exactly the same as in Example 6. Check that your input for Steps 3/6 – 5/6 are the same as in Example 6. In Step 4/6, be sure to select the "Kobe.txt" input motion for analysis.

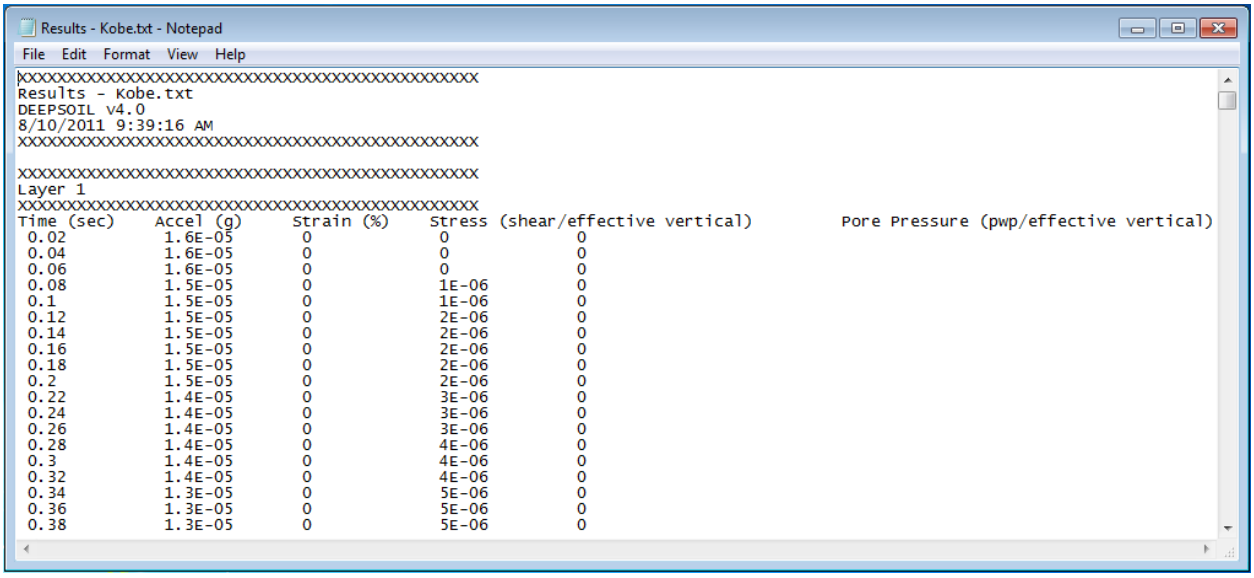
STEP 6/6

The figure shown on the following page is the calculated surface response spectrum for Layer 1. Check that your results match those shown in this tutorial.



Now let's take a look to see if any pore water pressure was generated in Layer 1 due to the input motion. You can do this by selecting the "PWP vs Time" tab for a quick visualization. For the purposes of this example, let's examine the exported output data. Use Windows Explorer to navigate to the folder you specified as your working directory when you started DEEPSOIL or press the "Show results in folder view…" link shown above the close button. If you kept the default directory suggested by DEEPSOIL, then navigate to the "Working" folder of the DEEPSOIL program path. The current working directory can also be found using the input summary. To view the input summary, click on the "View" menu and select "Input Summary." The working directory will be listed on the "Analysis Selection" tab of the form.

Open "Results – Kobe.txt." If you have completed other analyses with the Kobe motion, the results file will be "Results – Kobe#.txt," where # is simply an index referring to the most recent analysis.



Results - Kobe.txt - Notepad

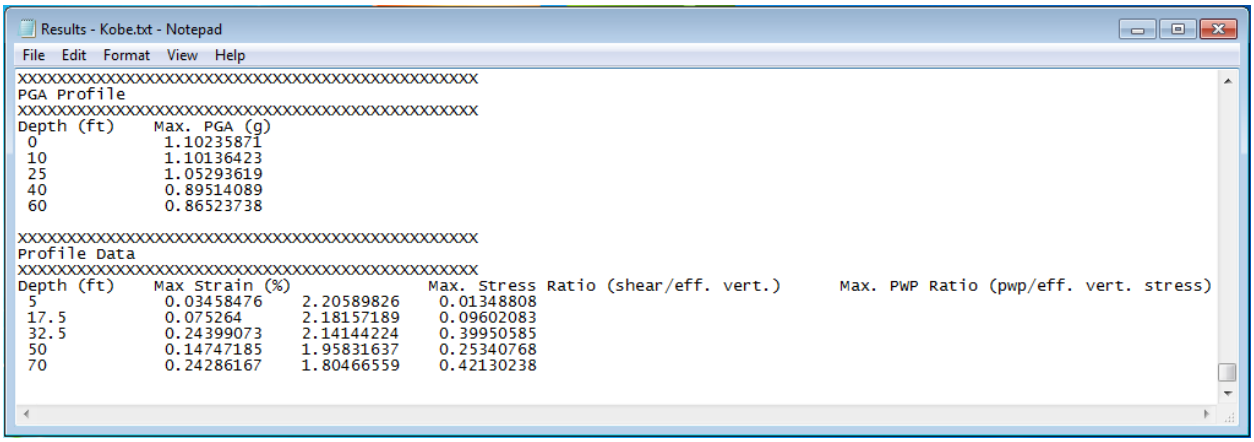
File Edit Format View Help

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Results - Kobe.txt
DEEPSOIL v4.0
8/10/2011 9:39:16 AM
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Layer 1
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Time (sec)     Accel (g)      Strain (%)     Stress (shear/effective vertical)        Pore Pressure (pwp/effective vertical)
 0.02           1.6E-05        0              0              0
 0.04           1.6E-05        0              0              0
 0.06           1.6E-05        0              0              0
 0.08           1.5E-05        0              1E-06          0
 0.1            1.5E-05        0              1E-06          0
 0.12           1.5E-05        0              2E-06          0
 0.14           1.5E-05        0              2E-06          0
 0.16           1.5E-05        0              2E-06          0
 0.18           1.5E-05        0              2E-06          0
 0.2            1.5E-05        0              2E-06          0
 0.22           1.4E-05        0              3E-06          0
 0.24           1.4E-05        0              3E-06          0
 0.26           1.4E-05        0              3E-06          0
 0.28           1.4E-05        0              4E-06          0
 0.3            1.4E-05        0              4E-06          0
 0.32           1.4E-05        0              4E-06          0
 0.34           1.3E-05        0              5E-06          0
 0.36           1.3E-05        0              5E-06          0
 0.38           1.3E-05        0              5E-06          0
```

"Results – Kobe.txt" contains all of the output data produced by DEEPSOIL. As can be seen from the figure above, the last column of data contains the pore water pressure in the layer at a given time.

Scroll down to the very bottom of "Results – Kobe.txt." Here you will find data regarding the PGA, Maximum Strain, Maximum Stress Ratio, and Maximum Pore Water Pressure Ratio Profiles.



Results - Kobe.txt - Notepad

File Edit Format View Help

```
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
PGA Profile
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Depth (ft)     Max. PGA (g)
 0              1.10235871
 10             1.10136423
 25             1.05293619
 40             0.89514089
 60             0.86523738

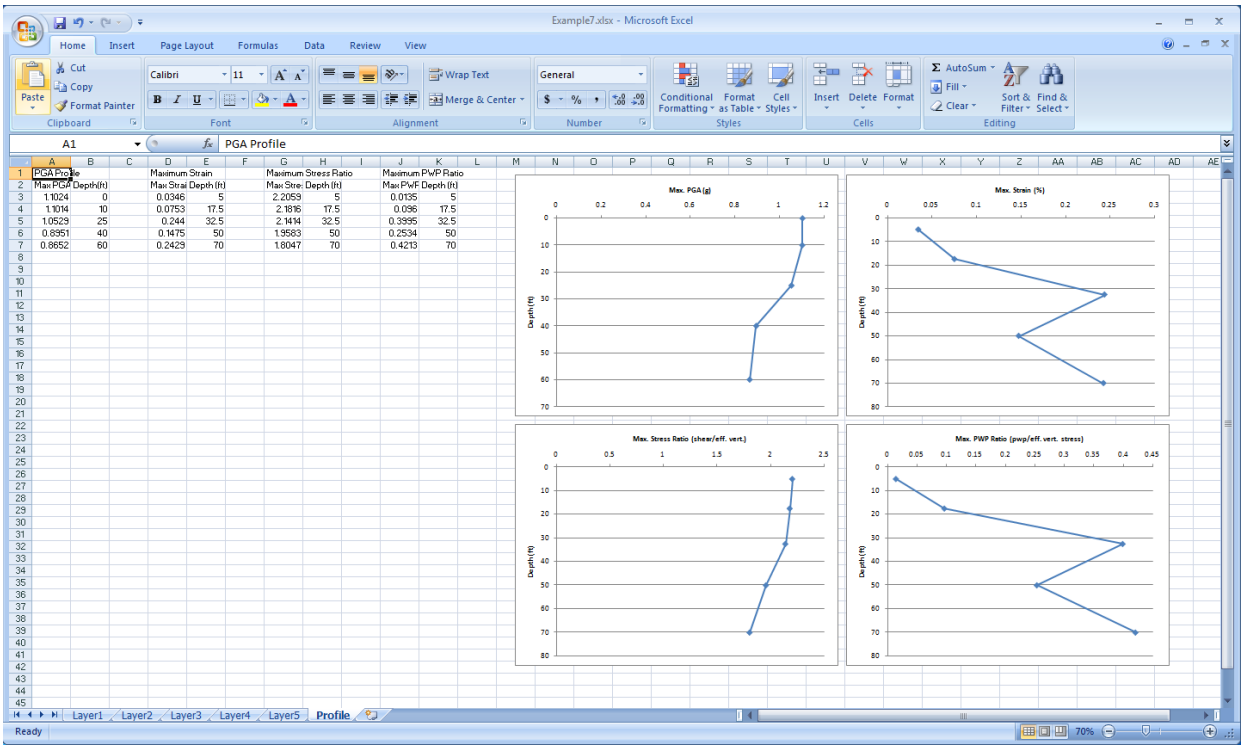
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Profile Data
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Depth (ft)     Max Strain (%)              Max. Stress Ratio (shear/eff. vert.)      Max. PWP Ratio (pwp/eff. vert. stress)
 5              0.03458476     2.20589826    0.01348808
 17.5           0.075264       2.18157189    0.09602083
 32.5           0.24399073     2.14144224    0.39950585
 50             0.14747185     1.95831637    0.25340768
 70             0.24286167     1.80466559    0.42130238
```

As you can see from the results, almost no pore water pressure was generated in Layer 1, and the largest pressures were generated in Layer 5.

Using "Results – Kobe.txt," we can determine the generation of pore water pressures with time, and also quickly identify which layer experiences the maximum generation of pore water pressure.

If you would prefer to view these results in the form of a Microsoft Excel file, simply click the **Export Output to Excel** button on the results form. This will create an Excel file that contains all of the data contained in "Results – Kobe.txt" in an easy to read and manipulate spreadsheet. It will also contain plots of the profile data. The user will be prompted to provide a file name and

location for the Excel file. The output file will be in .XLSX format, which requires Excel 2007 or greater to open.



	A	B	D	E	G	H	J	K
1	PGA Profile		Maximum Strain		Maximum Stress Ratio		Maximum PWP Ratio	
2	Max PGA	Depth (ft)	Max Strain	Depth (ft)	Max Stress	Depth (ft)	Max PWP	Depth (ft)
3	1.1024	0	0.0346	5	2.2059	5	0.0135	5
4	1.1014	10	0.0753	17.5	2.1816	17.5	0.096	17.5
5	1.0529	25	0.244	32.5	2.1414	32.5	0.3995	32.5
6	0.8951	40	0.1475	50	1.9583	50	0.2534	50
7	0.8652	60	0.2429	70	1.8047	70	0.4213	70

8.8 Example 8 Non-linear Analysis / Multi-Layer, Elastic Rock, Pore Water Pressure Generation and Dissipation

This example ("Ex8_Nonlin_Multi_Layer_PWP_with_GMP.dp") is identical to example 7, except that it uses the GMP PWP model (PWP model 3) instead of the Sand model (PWP model 1).

Open Example 7 and proceed to step 2.

Let us redefine the parameters as follows:

f/s/f → f = 2

p/r/Dr (%) → Dr = 0.95

F/A/FC(%) → FC = 15

s/B/- → (None; leave blank)

g/C/- → (None; leave blank)

v/D/v → v = 3.8

-/g/- → (None; leave blank)

C_v = 0.1

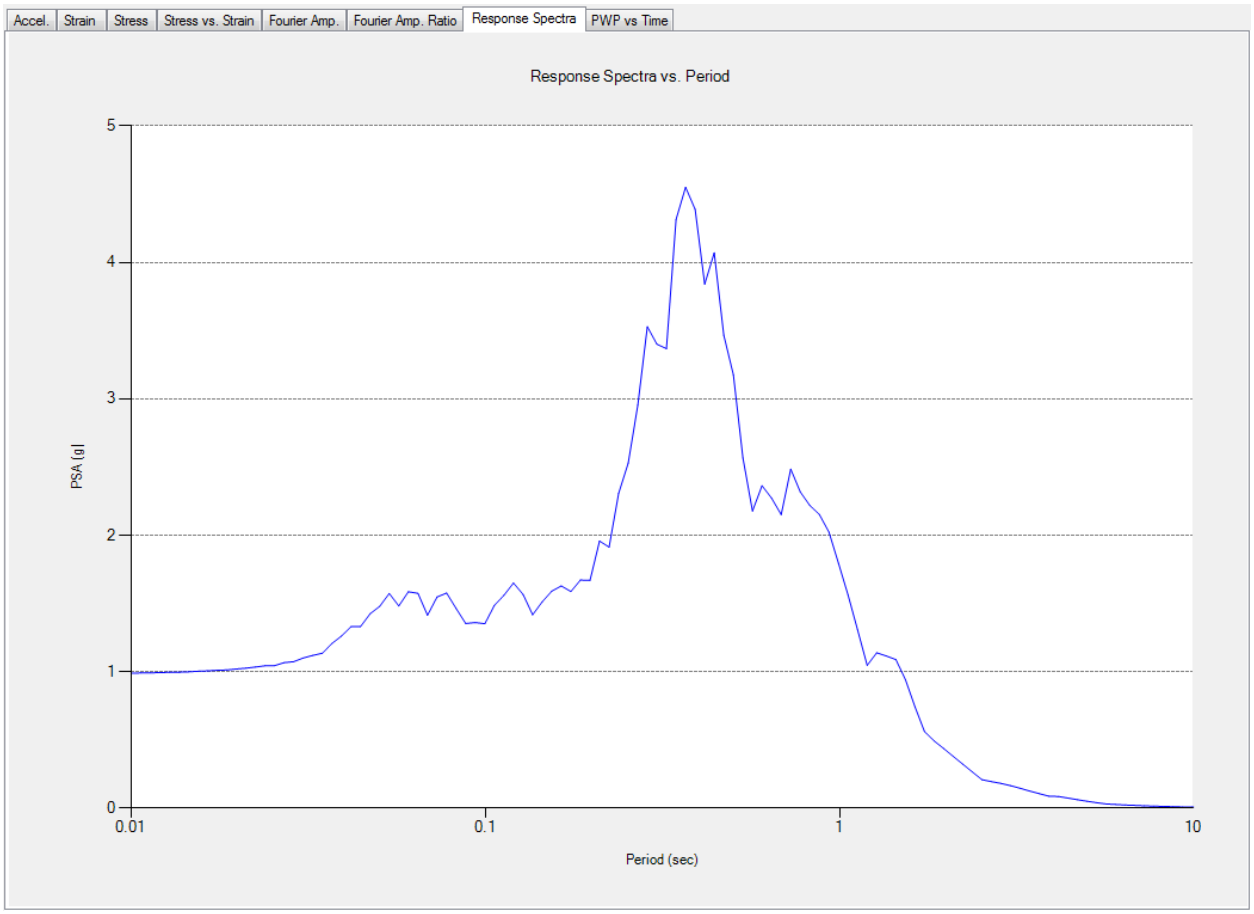
The PWP section of the spreadsheet should look like the following figure.

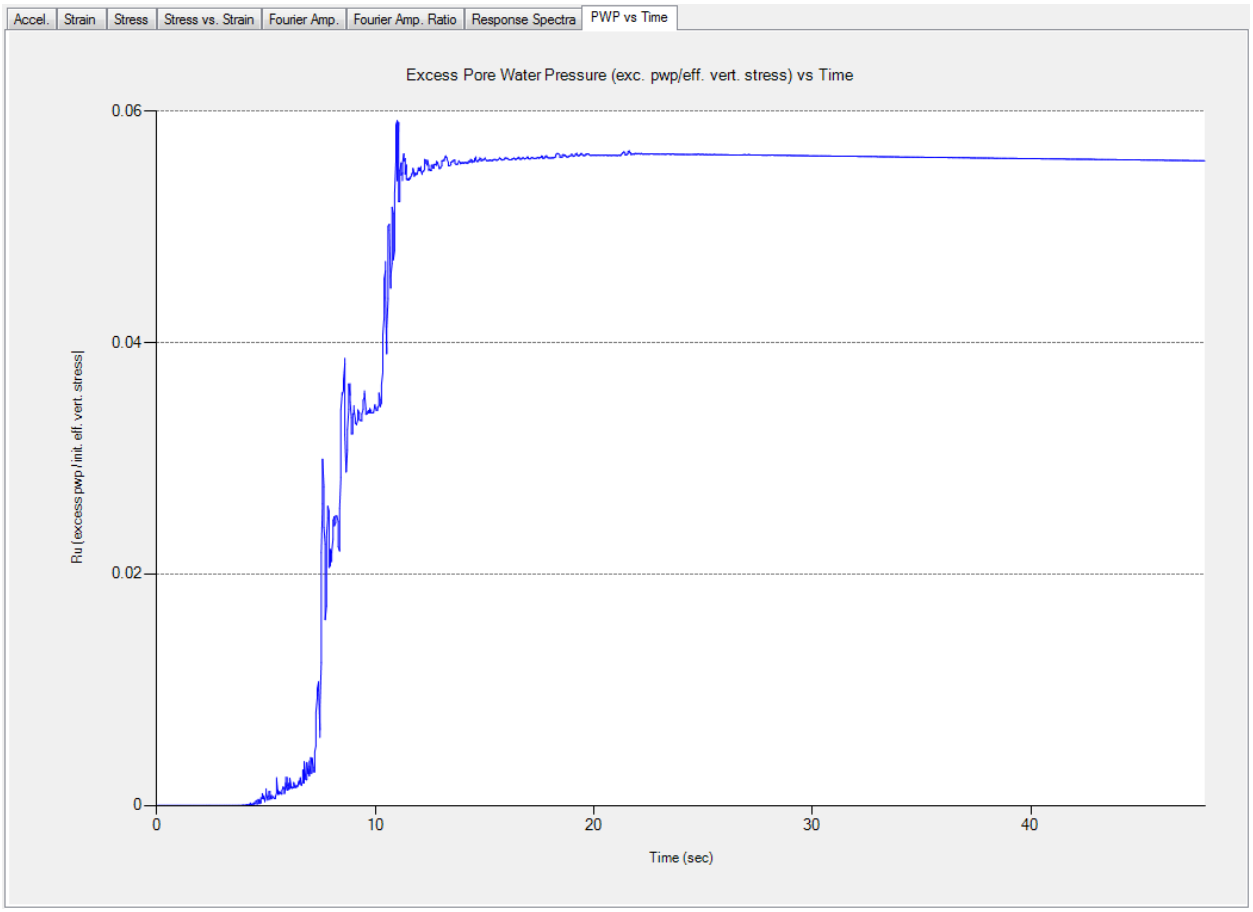
PWP Model (1=S-M/D) (2=C-M) (3=S-GMP)	f/s/f	p/r/Dr(%)	F/A/FC(%)	s/B/-	g/C/-	v/D/v	-/g/-	Cv (ft2/sec)
3	2	95	15			3.8		0.1
3	2	95	15			3.8		0.1
3	2	95	15			3.8		0.1
3	2	95	15			3.8		0.1
3	2	95	15			3.8		0.1

After checking your input, press the "Next" button to continue to the third stage of analysis.

The remaining steps of the analysis are exactly the same as in Example 6. Check that your input for Steps 3/6 – 5/6 are the same as in Example 7. In Step 4/6, be sure to select the "Kobe.txt" input motion for analysis.

The response spectra and excess pore pressure plots are shown below for your comparison.


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
PWP vs Time
Response Spectra vs. Period
PSA (g)
5
4
3
2
1
0
0.01
0.1
1
10
Period (sec)


Accel.
Strain
Stress
Stress vs. Strain
Fourier Amp.
Fourier Amp. Ratio
Response Spectra
PWP vs Time
Excess Pore Water Pressure (exc. pwp/eff. vert. stress) vs Time
Ru [excess pwp / init. eff. vert. stress]
0.06
0.04
0.02
0
0
10
20
30
40
Time (sec)

8.9 Example 9 Equivalent Linear Frequency Domain Analysis / Multi-Layer, Elastic Rock, Bay Mud Profile

Example 9 ("Ex9_Bay_Mud.dp") is similar to example 5 but includes 31 layers. This is a typical profile near San Francisco Bay. It is included to illustrate the capabilities of DEEPSOIL for more-realistic profiles. Recreation of this profile will not be discussed in this tutorial.

8.10 Example 10 Non-linear Analysis / Multi-Layer, Rigid Rock, Treasure Island Profile

Example 10 ("Ex10_Treasure_Island.dp") is similar to example 6 but includes 53 layers and is on rigid rock. This is a typical profile near Treasure Island. It is included to illustrate the capabilities of DEEPSOIL for more-realistic profiles. Recreation of this profile will not be discussed in this tutorial.

8.11 Example 11 Non-linear Analysis / Multi-Layer, Elastic Rock, MRDF

Example 11 ("Ex11_MRDF.dp") is an 80-layer profile on elastic rock. It is included to illustrate the capabilities of DEEPSOIL for more realistic profiles as well as the MRDF curve parameters. Recreation of this profile will not be discussed in this tutorial.

9 APPENDIX C: Description of the GQ/H Model

6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Evaluation of 1-D Non-linear Site Response Analysis using a General Quadratic/Hyperbolic Strength-Controlled Constitutive Model

D. R. Groholski [1], Y.M.A. Hashash [2,*], M. Musgrove [2], J. Harmon [2], B. Kim [3]

ABSTRACT

Reliable estimates of 1-D non-linear seismic site response due to strong ground shaking or in soft soils requires appropriate representation of soil strength in addition to small-strain nonlinearity and cyclic response. The focus on representing small-strain soil behavior resulted in the development of several modified hyperbolic models to define the monotonic stress-strain (i.e. backbone) curve coupled with unloading-reloading (i.e. damping) behavior. Though such models can accurately capture small-strain behavior, in some cases the shear strength of soil is underestimated while in others it is overestimated leading to inaccurate estimates of site response. The authors introduce a General Quadratic/Hyperbolic (GQ/H) model which allows the shear strength of soil at failure to be defined while still providing the ability to represent small-strain stiffness nonlinearity. The GQ/H model is verified in comparison with the existing model, and the effect of properly modeling soil shear strength is demonstrated through application to total-stress cases studies.

Introduction

Characterizing the non-linear cyclic response of soils under dynamic loading requires consideration of the initial stress-strain curve, the unloading-reloading behavior, and the generation of excess pore pressure. Much of the work over the past 50 years has focused on the development and refinement of hyperbolic models that define the monotonic stress-strain (i.e. backbone) curve coupled with unloading-reloading (i.e. damping) behavior. These models are then fit to reference curves of normalized shear modulus and damping values as functions of shear strain. While such models can adequately characterize the small-strain behavior, the large-strain shear strength is typically left uncontrolled, allowing for unrealistic shear stresses to be developed with increasing shear strains. Strength corrections have typically been made manually (Hashash et al., 2010, Chiu et. al, 2008) because the shear strength of soil is underestimated in some situations while overestimated in others. Such corrections are often time-consuming and are highly subjective. Yee et al (2013) proposed the use of composite hyperbolic curves to control for the shear strength. This paper introduces a General Quadratic/Hyperbolic (GQ/H) model which allows the shear strength at failure to be defined while still providing the flexibility to represent the small-strain soil behavior. The unload-reload stiffness uses a non-Masing criteria via inclusion of a damping reduction factor introduced in an earlier model (MRDF model in DEEPSOIL) to match laboratory-measured damping curves. The GQ/H model is implemented in the site response software DEEPSOIL, and comparative analyses have been made with the commonly-used Modified Kondner-Zelasko model (Matasovic, 1993).

[1] *Exponent, Inc., 475 14th Street, Ste. 400, Oakland, CA 94612, USA*
[2] *Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[3] *Risk Management Solutions, Inc., 7575 Gateway Boulevard, Newark, CA 94560, USA*
* *Corresponding author, E-mail address: hashash@illinois.edu*

General Quadratic Formulation

To capture the small-strain and large-strain behavior of a material, both the initial shear stiffness (G_{max}) and the shear strength at failure (τ_{max}) must be known. These values represent linear boundaries of stress-strain behavior in stress-strain space. A quadratic model can be used to join the two lines into a continuous curve because these linear boundaries are known to intersect at some reference shear strain. The proposed backbone curve has the form:

$$\frac{\tau}{\tau_{max}} = \frac{2\left(\gamma/\gamma_r\right)}{1 + \left(\gamma/\gamma_r\right) + \sqrt{\left\{1 + \left(\gamma/\gamma_r\right)\right\}^2 - 4\theta_\tau\left(\gamma/\gamma_r\right)}} \tag{1}$$

where τ is shear stress, τ_{max} is the shear strength at failure, γ is shear strain, γ_r is the reference shear strain, and θ_τ is a curve-fitting parameter. In this model, the reference shear strain maintains the original definition proposed by Kondner (1963) such that $\gamma_r = \tau_{max}/G_{max}$. The model is derived from a general quadratic equation that is simplified to a general hyperbolic equation. Hence the backbone curve is a general quadratic/hyperbolic form, and is labeled GQ/H model.

From consideration of several laboratory-obtained normalized shear modulus reduction curves, the proposed relationship for θ_τ has the form:

$$\theta_\tau = \theta_1 + \frac{\theta_2 \cdot \left(\frac{\gamma}{\gamma_r}\right)}{\theta_3 + \left(\frac{\gamma}{\gamma_r}\right)} \leq 1 \tag{2}$$

where θ_1, θ_2, and θ_3 are curve-fitting constants chosen to provide the best fit to the normalized shear modulus versus shear strain curves over a defined strain range. θ_1 and θ_2 must be selected such that $\theta_1 + \theta_2 \leq 1$.

Most commonly used nonlinear time-domain site response analysis codes use the extended unload–reload Masing rules to model hysteretic behavior. However, the hysteretic damping behavior calculated using the unloading-reloading stress-strain loops based on the Masing rules is known to overestimate the damping at large strains. The MRDF model (Phillips and Hashash, 2009) has been applied to the unloading-reloading relationship to provide better agreement with laboratory-measured damping curves. The model can also be used with porewater pressure generation models. The derivation and theoretical background of the GQ/H model are discussed in Groholski et. al (in preparation). The GQ/H model is implemented in DEEPSOIL. The performance of the model at the element level and in site response analysis is described in the following sections.

Calibration of Model Parameters

In the absence of site-specific data, empirical modulus reduction and damping curves such as EPRI (1993), Vucetic and Dobry (1991), and Darendeli (2001) are commonly used in site response analysis to represent dynamic soil behavior. Curves proposed by Darendeli (2001) have been used to demonstrate the application of the GQ/H model to site response analyses.

The fitted curves are compared to fits obtained using the Modified Kondner-Zelasko model (Matasovic, 1993), which is one of the most commonly used backbone formulations in 1-D site response analyses. Figure 1 shows the GQ/H model fitting procedure for a modulus reduction curve for a vertical effective stress of 169.9 kPa, PI of 25, OCR of 1, and shear strength of 40 kPa, which will be used for the station Apeel #2 (A02) in Redwood City, California site response analysis (described in the next section). The reference curve was obtained from Darendeli (2001) equations.

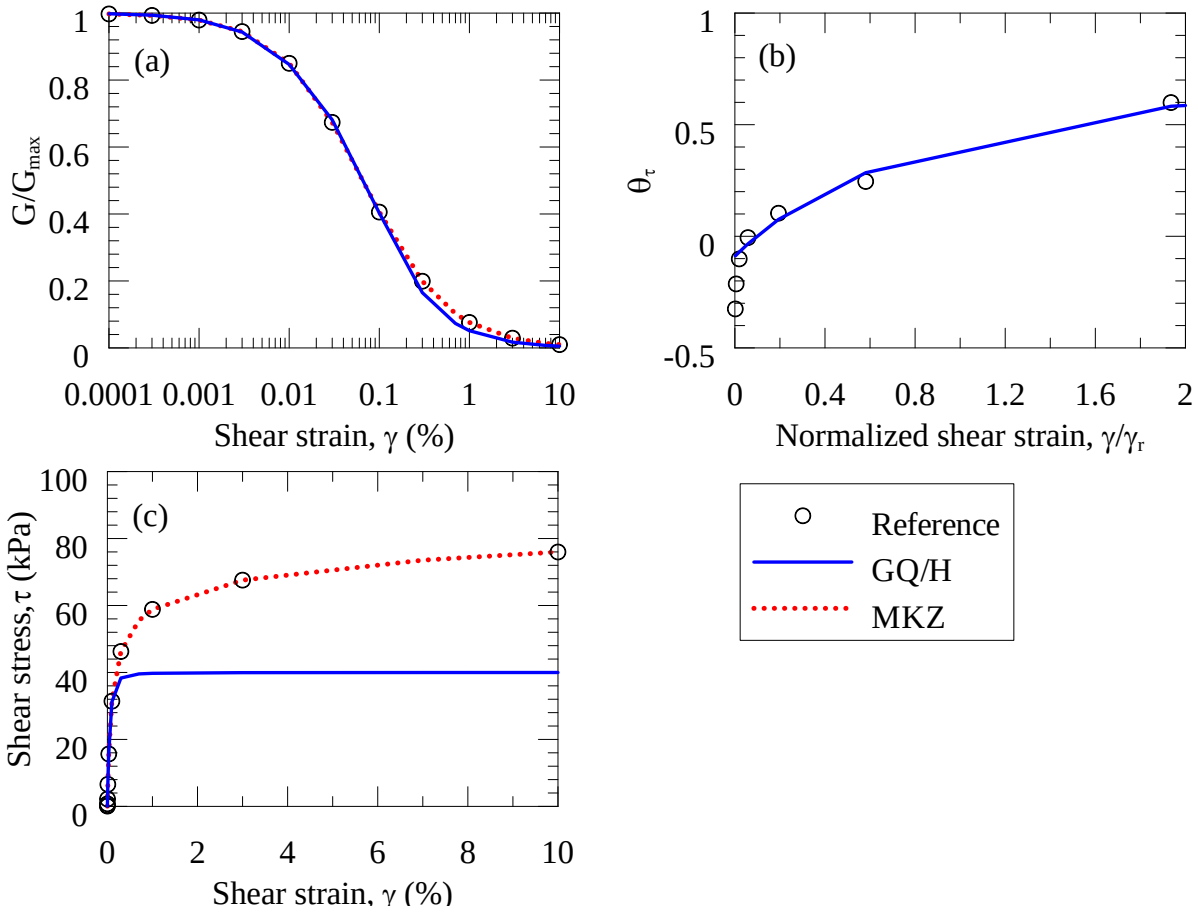


Figure 1 GQ/H model fitting procedure for clays with a vertical effective stress of 169.9 kPa, PI of 25, OCR of 1, and shear strength of 40 kPa (reference curve from Darendeli (2001)): (a) normalized shear modulus reduction; (b) θ_τ parameter relationship to normalized shear stress; and (c) shear stress-shear strain response.

The target shear stress (τ_{max}) is estimated to be 40 kPa. The parameter θ_τ is fitted by the hyperbolic relationship (Eq. 2) with coefficients θ_1, θ_2, and θ_3 of -0.09, 1.02, and 1, respectively. The MKZ and GQ/H models both match the reference G/G_{max} curve (Figure 1a). The MKZ model does not have the capability to match the target shear stress at large shear strains. However, the GQ/H model yields shear stress that approaches the target shear strength at large shear strains (Figure 1b).

Comparative Total-Stress Site Response Analyses

The performance of the GQ/H model in comparison with the MKZ model is demonstrated at two sites whose profiles correspond to Apeel #2 (A02) in Redwood City, California; and Service Hall array (SHA) at the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) in Japan. Figure 2 (a) and (b) show geology and shear wave velocity profiles, respectively, for station A02 (Baturay and Stewart 2003, http://www.cee.ucla.edu/faculty/stewart/research). The site consists of predominantly soft clay overlying stiff clays and shale.

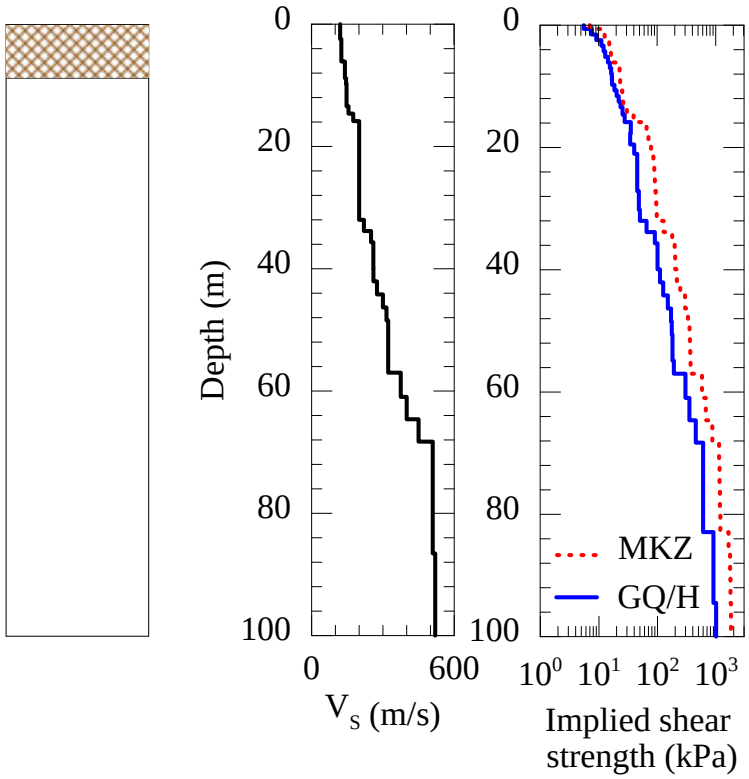


Figure 2 Profiles of (a) Geology and (b) shear wave velocity (V_S) of station Apeel #2 (A02) in California, and (c) implied shear strength for both MKZ and GQ/H models.

The assigned modulus reduction and damping curves for the soil column are derived from Darendeli (2001) relationships. Figure 3 shows normalized shear modulus, damping ratio, and shear stress -shear strain curves at three selected depths. The shear strengths are for the profile is defined as $0.22\sigma_v'$ above 16 m and below 16 m ranges from $0.3\sigma_v'$ *to* $1.0\sigma_v'$ increasing with depth. The use of the MKZ model fit of the modulus reduction curves results in significant over estimation of the shear strength. The GQ/H model adequately captures the target shear strength as this is a direct model input. No manual adjustment is required to achieve the shear strength profile as has been done so far when these types of conditions are encountered.

Figure 4 shows the results of site response analyses subjected to the strong ground motion (Record Sequence Number (RSN): 4876) obtained from the NGA-West2 database (Ancheta et al. 2014). For each of the MKZ and GQ/H models, equivalent linear (EL) and nonlinear (NL) site response analyses were conducted. Peak ground acceleration and peak shear strain versus depth are plotted. The computed surface response spectra as well as the input motion response spectrum are also plotted.

For both the EL and NL analyses the surface response computed with the GQ/H model is lower than that using the MKZ model especially around a period of 1 Hz and at high frequencies. As the GQ/H model has lower strengths than the MKZ model, larger strains are computed for the GQ/H model as would be expected.

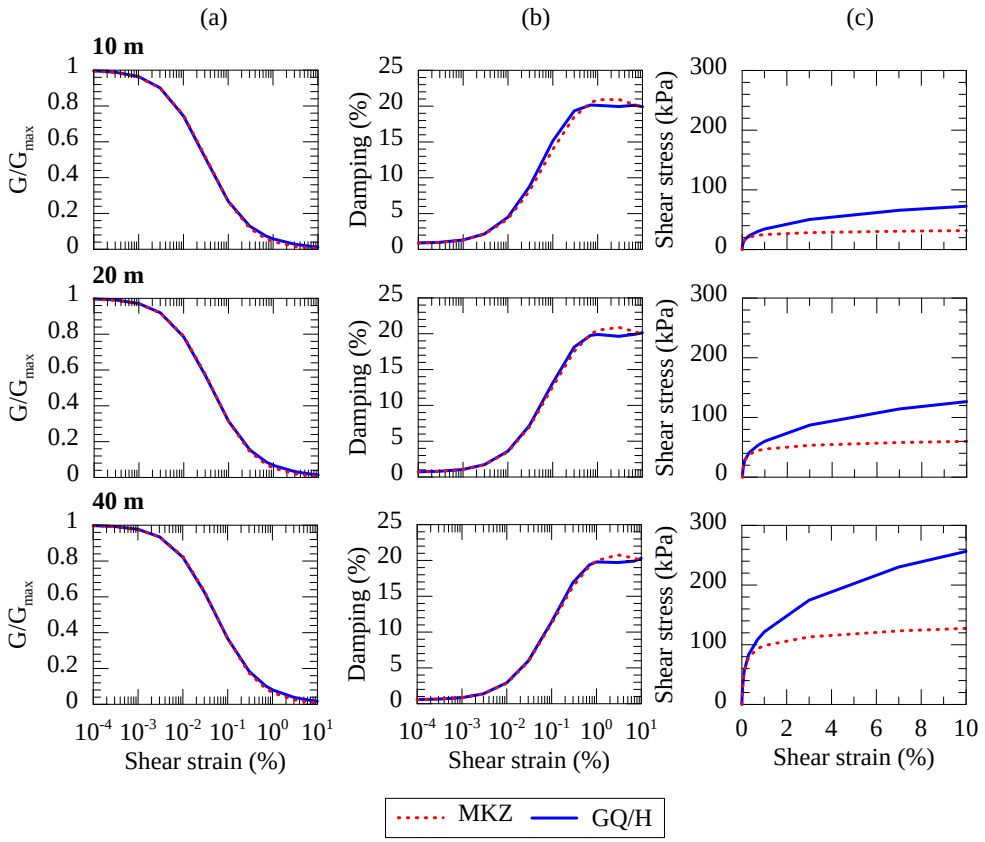


Figure 3 Normalized shear modulus (a), damping ratio (b), and shear stress (c) curves for station Apeel #2 (A02), California at selected depths (10, 20, and 40 m) for both MKZ and GQ/H models.

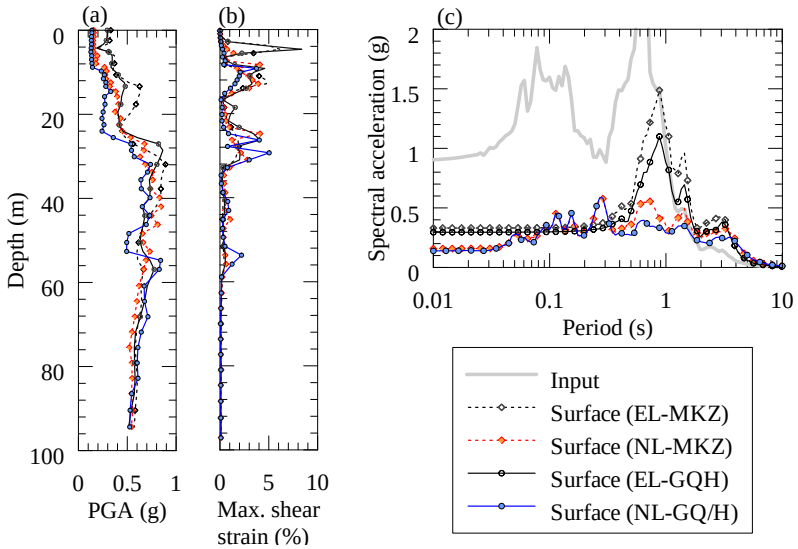


Figure 4 Results of site response analysis for station Apeel #2 (A02) subject to the NGA-West 2 strong ground motion measure (RSN: 4876): (a) PGA profiles; (b) maximum shear strain profiles; and (c) surface response spectra.

Figure 5 (a) and (b) show geology and shear wave velocity profiles, respectively, for station Service Hall array (SHA) at the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) in Japan (Yee et al. 2013). The implied shear strengths and friction angle of sand layers are corrected using the GQ/H model based on the friction angle measured by Yee et al. (2013) using consolidated-drained triaxial compression tests as shown in Figure 5 (c and d). Unlike the case of station A02, the strengths corrected by the GQ/H model are greater than those estimated by the MKZ model. Figure 6 shows the results of site response analyses for station SHA subject to the strong ground motion (RSN: 143) obtained from the NGA-West2 database (Ancheta et al. 2014). The maximum shear strains for nonlinear and equivalent-linear analyses using the MKZ model are approximately 9 % and 7 %, respectively, at depths less than 24 m. When the shear strengths are corrected using the GQ/H model, the maximum shear strains decrease to less than 2 % for both nonlinear and equivalent-linear analyses, respectively. There is also significant reduction in shear strains at depths between 50 m and 56 m. This reduction in shear strains is due to the increased shear strengths. As a result of the decreased maximum shear strain, the PGA values using the GQ/H model generally increased at depths less than 16 m compared to those using the MKZ model. The response spectra on the ground surface are shown in Figure 6 (c). The spectral accelerations for a nonlinear analysis using the GQ/H model are greater than those using the MKZ model at periods less than 5 s. The spectral accelerations for an equivalent-linear analysis using the GQ/H model are greater than those using the MKZ model at periods less than 2 s.

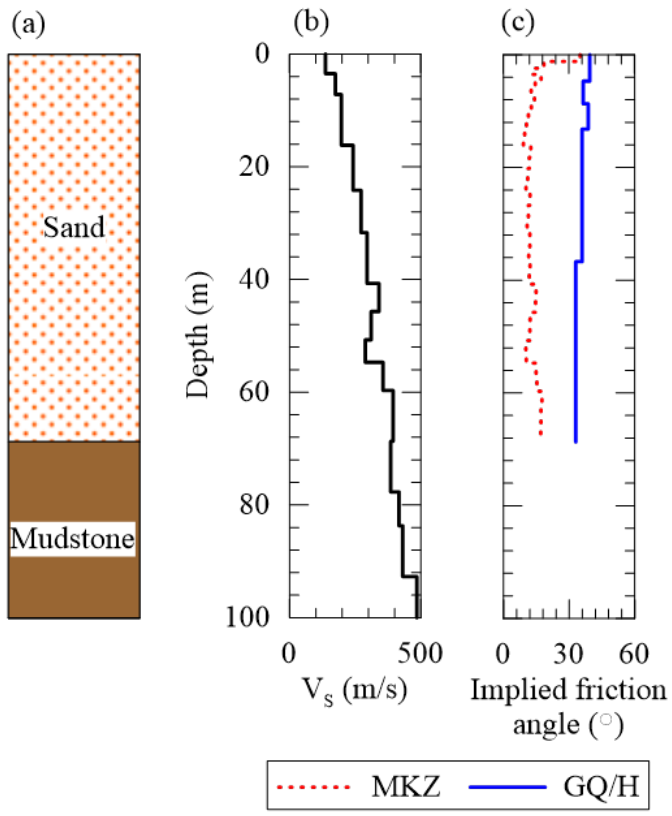


Figure 5 Profiles of (a) Geology and (b) shear wave velocity (V_S) of station Service Hall array (SHA) at the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) in Japan, and (c) implied friction angle for both MKZ and GQ/H models.

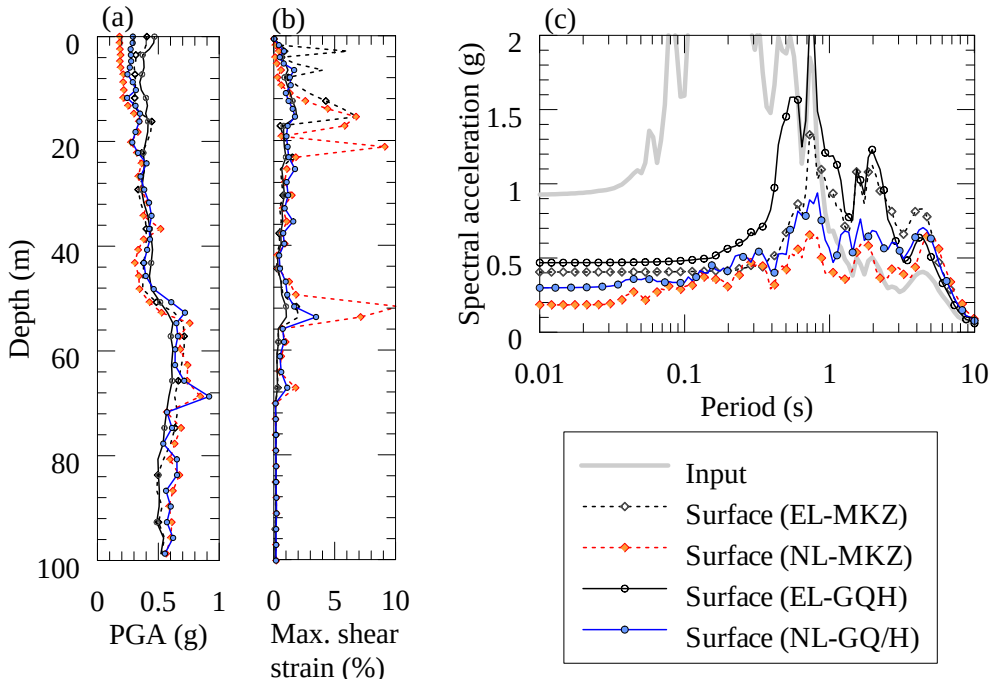


Figure 6 Results of site response analysis for the Service Hall array (SHA) at the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) subject to the NGA-West 2 strong

ground motion measure (RSN: 143): (a) PGA profiles; (b) maximum shear strain profiles; and (c) response spectra on the ground surface.

Conclusion

This paper introduces a new generalized quadratic/hyperbolic (GQ/H) model that can be used to represent both small strain nonlinear behavior and shear strength of the soil. The model is a simplified one dimensional shear stress-shear strain model that overcomes limitations of an available model widely used in nonlinear site response analysis. Site response analyses using the proposed model demonstrate that computed site response is quite sensitive to the implied shear strength in the soil model especially for soft soil sites. Validation of the proposed model using field measurements of soil shear strengths and ground motion recorded from vertical arrays is desirable in the future.

References

Ancheta et al. (2014) "*NGA-West2 database*," Pacific Earthquake Engineering Research Center, Berkelet, CA.

Chiu, P., Pradel, D. E., Kwok, A. O.-L., and Stewart, J. P. (2008) "Seismic Response Analyses for the Silicon Valley Rapid Transit Project." *Geotechnical Earthquake Engineering and Soil Dynamics IV* (GSP 181), Sacramento, CA.

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

EPRI (1993). *Guidelines for determining design basis ground motions*. Palo Alto, CA, Electric Power Research Institute.

Kondner, R. L., and Zelasko, J. S. "Hyperbolic stress-strain formulation of sands." *Second pan American Conference on Soil Mechanics and Foundation Engineering*, Sao Paulo, Brazil, 289-324.

Groholski, D.R., Y.M.A. Hashash, Kim, B., Musgrove, M., Harmon, J., Stewart, J.P. (2015). "A Simplified Non-Linear Shear Model to Represent Small-Strain Nonlinearity and Soil Strength in 1-D Seismic Site Response Analysis". (in preparation).

Hashash, Y.M.A., Musgrove, M, Groholski, D.R., Phillips, C.A., and Park, D. (2015) "*DEEPSOIL 6.0, User Manual*" 104 p.

Hashash, Y. M. A., C. Phillips and D.R. Groholski (2010). Recent advances in non-linear site response analysis. Fifth International Conference in *Recent Advances in Geotechnical Eartqhuake Engineering and Soil Dynamics*. San Diego, CA. CD-Volume: OSP 4.

Matasovic, N. (1993). *Seismic response of composite horizontally-layered soil deposits* Ph.D. Thesis, University of California, Los Angeles.

Phillips, C. and Y. M. A. Hashash (2009). "Damping formulation for non-linear 1D site response analyses." *Soil Dynamics and Earthquake Engineering* **29**(7): Pages 1143-1158.

Vucetic, M. and R. Dobry (1991). "Effect of soil plasticity on cyclic response." *Journal of Geotechnical Engineering* **117**(1): 87-107.

Yee, E., Stewart, J., and Tokimatsu, K. (2013). "Elastic and Large-Strain Nonlinear Seismic Site Response from Analysis of Vertical Array Recordings." *J. Geotech. Geoenviron. Eng.*, **139**(10), 1789–1801.