

# ProShake

Ground Response Analysis Program

**Version 1.1**

## **User's Manual**

EduPro Civil Systems, Inc.  
Redmond, Washington

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## Introduction

Welcome to ProShake, a new computer program for seismic ground response analysis of horizontally layered soil deposits. ProShake was developed from EduShake, a public domain program developed to help engineering students understand the mechanics of seismic ground response. ProShake features a Windows graphical user interface that both simplifies and speeds the analysis and interpretation of seismic ground response.

If you have used EduShake, you will find that ProShake is virtually identical, except that the restrictions that prevent EduShake from being used for general problems are removed. If you are an experienced user of SHAKE (or SHAKE85 or SHAKE91), you will find that ProShake allows you to input and check data faster and more easily, perform analyses more quickly, and interpret your results much more easily and efficiently than previous versions of SHAKE. If you are new to ground response analysis, you will find the intuitive interface of ProShake easy to learn and use.

## Background

ProShake evolved from an attempt to provide a user-friendly interface to SHAKE for geotechnical earthquake engineering students. Many current students have only been exposed to C or other programming languages, and are not familiar with FORTRAN and its formatting conventions. When first using SHAKE, therefore, they often encounter difficulties in preparing their input (getting the right number in the right column) and reformatting their output (to put it in a form that spreadsheets or graphics programs can recognize). As a result, many students spend more time worrying about input and output than they do learning about ground response.

Initially, a relatively simple system consisting of a front end (preprocessor) and back end (postprocessor) for SHAKE91 was envisioned. As the programming effort proceeded, however, it became clear that much greater capabilities could be achieved by developing a single, integrated program. At that point, the computational portion of the program was written from scratch (in FORTRAN) and the interface developed (in Visual Basic). As the program began to take shape, its potential benefits to practicing engineers became apparent. At that point, two versions of the program were developed - EduShake and ProShake. EduShake fulfills the original goal of the developers - it is a full-featured program that is available at no cost to students, faculty, and other interested parties. EduShake is limited, however, to the use of only two input motions; this is sufficient for well-constructed assignments to provide students with a good understanding of seismic ground response, but not sufficient to allow the program to be used for commercial purposes.

The development of EduShake evolved through several stages and was eventually beta tested by graduate students, researchers, and practicing engineers. After a few modifications in response to the comments of the beta testers, EduShake was made available in the public domain. Shortly

thereafter, the restrictions of EduShake were removed and a few additional features added to produce ProShake.

## **ProShake Features**

ProShake offers many features that make it easy and efficient to use - features not found in other ground response analysis software packages. Some of the most significant of these features are listed below:

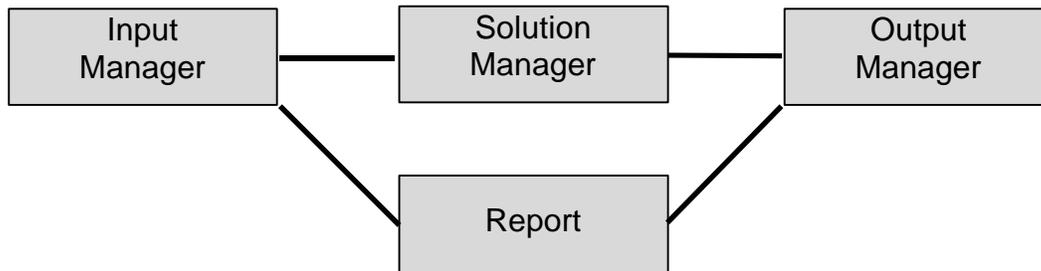
- English or metric units can be used, and the units can be entered in whatever format is most convenient during input.
- A number of built-in soil models can be selected from pulldown menus. ProShake will interpolate as necessary to the conditions of your analysis, and will allow you to add your own soil models and store them for later use.
- Soil profile data can be entered quickly using drag-and-drop techniques, and can be checked graphically for errors prior to analysis.
- Input motions can be viewed graphically in many different ways - as time histories, as spectra, and in terms of a variety of ground motion parameters.
- The number of input motions that can be analyzed at a time is limited only by available RAM, and the results from all input motions can be plotted together. Each input motion can have up to 16,384 acceleration values.
- The progress of the program is displayed graphically during execution. Plots showing the variation of shear strain and modulus/damping errors during iteration toward convergence can help illustrate site response as well as identify possible errors in input data.
- A wide variety of output parameters from any depth within the soil profile can be plotted with the click of a button. The plots include time histories of acceleration, velocity, displacement, shear stress, and shear strain; response spectra, Fourier spectra, power spectra, and phase spectra; and plots of the maximum amplitudes of various parameters with depth.
- Scalar parameters such as peak acceleration, peak velocity, peak displacement, RMS acceleration, Arias Intensity, predominant period, and bracketed duration can be computed for any depth within the soil profile.
- ProShake can display an animation of the horizontal displacements of a soil profile excited by earthquake shaking. The animation provides greatly improved intuitive understanding of the response of the soil profile, and can help the user identify potential hazards that might otherwise go undetected.

- ProShake has a built-in word processor that is linked to the program in a way that allows analyses to be documented thoroughly and easily in a ProShake Report. The ProShake Report can include text, tables, and graphics - all of which can be cut-and-pasted into more powerful word processors for final report preparation.

These are only some of the features that ProShake offers to simplify and speed the process of performing and interpreting the results of ground response analyses. As you become more familiar with the program, other helpful features will become apparent.

## Program Structure

ProShake is designed to provide an intuitive interface that simplifies and speeds the process of performing and interpreting the results of ground response analyses. The program is organized into three “managers” - an Input Manager, a Solution Manager, and an Output Manager - and a Report. In the normal sequence of operations, the user will move from the Input Manager to the Solution Manager and then on to the Output Manager, as indicated graphically below. The Report can be accessed from both the Input Manager and the Output Manager.



The program structure is designed to allow complete flexibility. For example, users may bypass the normal sequence to go directly to the Output Manager to examine the results of previous analyses. The basic functions of the three managers and the Report are described below.

### Input Manager

The Input Manager allows all input data to be entered, checked, and saved prior to program execution. The required input data consists of soil profile data and input motion data. The Input Manager provides a series of forms on which the required data can be entered, and on which the desired output can be specified. The Input Manager allows input data to be viewed graphically, a valuable aid in checking for data entry errors. All input data and plots generated in the Input Manager can be copied to the Report. The input data is saved in a file with a .dat extension.

### Solution Manager

The Solution Manager performs the actual ground response analysis. It requires that the user specify a valid input data file (with the .dat extension) and then performs the required computations. While the program is executing, the Solution Manager presents a graphical display

that allows the user to track the progress of the analysis. Upon completion of the analysis, the Solution Manager saves the results in a file with a .lyr extension.

### **Output Manager**

The Output Manager allows the user to generate a wide range of plots of the results of the analysis. It requires that the user specify a valid output data file (with the .lyr extension), and then provides a number of forms for plotting time histories, spectra, variations of parameters with depth, and for computation of scalar parameters. The Output Manager also allows the user to view an animation of the horizontal displacements throughout the soil profile - many users find this feature very helpful for developing an intuitive understanding of the response of the soil profile. All plots generated in the Output Manager can be copied to the Report.

### **Report**

The Report produced by a word processor that is built into ProShake. The Report allows the user to keep a record of each analysis. All input data is automatically written to the Report and updated when the Report is accessed. All plots generated in the Input Manager and Output Manager can be copied to the Report and saved in a format that can be read by other, more powerful word processors. Many users find the Report useful for internal documentation of their analyses, and for preparation of project reports for their clients.

## **Installing ProShake**

The first step in using ProShake is to install the program. ProShake comes on two 3.5" disks, labelled Disk 1 and Disk 2, and with a hardware key that fits into the parallel port of your computer. The hardware key will protect your investment in ProShake by preventing unauthorized use or copying of the program. In order to run ProShake, the hardware key must be installed on your computer. The hardware key is otherwise transparent to the computer; if you are already using the parallel port for a particular device, you may insert the hardware key in the parallel port and plug your device into the other end of the hardware key.

ProShake runs under the Windows 95 or NT 4.0 operating system - it will not run under earlier versions of Windows (e.g. Windows 3.1). To install ProShake:

1. Start your computer.
2. Start the Windows 95 operating system.
3. Place ProShake Disk 1 in the a:\ drive.
4. Click on the Windows 95 Start button and select Run.
5. Type the following in the command line:

a:\setup.exe

and click on OK.

6. Follow the instructions on the screen.

ProShake will be installed in a directory called ProShake (unless you specify otherwise). An Uninstall program will also be installed in that directory in the event that you need to remove ProShake from your computer. After installation, ProShake can be accessed using the Windows 95 Start button (then to Programs and on to ProShake).

## **Tutorial**

The easiest way to learn the basics of ProShake's organization and operation is to complete the tutorial exercise detailed in this section. The tutorial will take you through nearly all of ProShake's functions; it should take you about 20 minutes to complete.

The first step in the tutorial exercise is to start the ProShake program. Click on the Windows 95 Start button, move to Programs, to ProShake, and then click on the ProShake icon to start the program. After it has started, you can work your way through the tutorial.

The first screen ProShake displays shows the ProShake symbol and six menus - (from left to right) Input Manager, Solution Manager, Output Manager, Utilities, Help, and Exit. Let's look at the last three first.

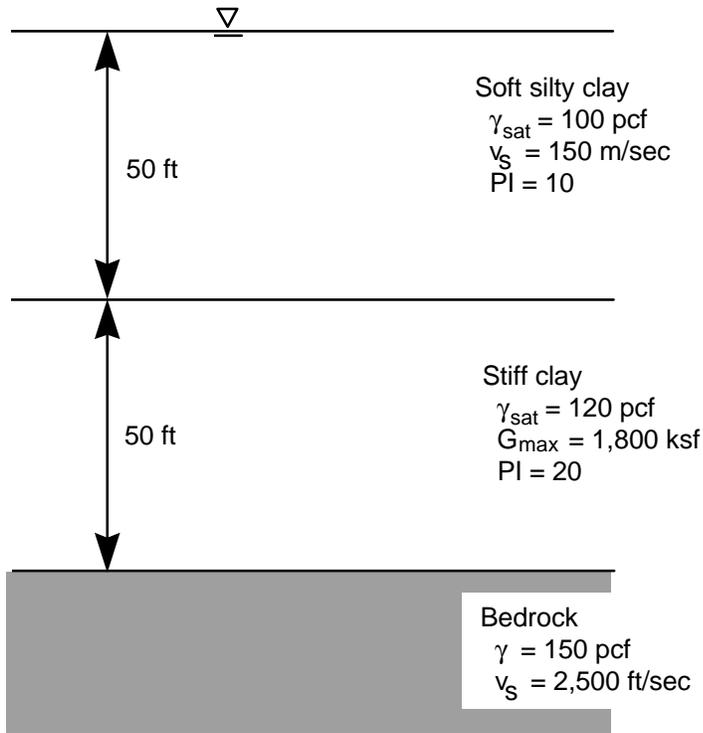
ProShake includes two utilities. One allows you to add new modulus reduction and damping curves or to modify existing curves. These can be useful when the library of built-in modulus reduction and damping curves are not appropriate for one or more of the soil types you need to analyze. The other allows you to convert digitized earthquake records to ProShake format. Use of these utilities is described later in the User's Manual.

ProShake has an extensive help system that operates like most conventional Windows help systems, and can be accessed in two ways. First, clicking on the Help menu will allow you to choose between working your way through the contents of the ProShake help system and searching for the specific item you are interested in. The second way of accessing the help system is through its context-sensitive capability - simply move the cursor to the field you want information for, then press F1.

The Exit command is self-explanatory - clicking on it will end the program.

### **Setting Up an Analysis**

Setting up a ProShake analysis involves defining the properties of all soil layers within the profile to be analyzed, specifying the characteristics of the input motion that will be applied to the soil profile, defining the quantities to be computed, and documenting the input data. Follow the steps in the following sections to set up, run, and view the results of a typical ground response analysis.



The tutorial will set up and solve for the response of the soil profile shown to the left when subjected to a bedrock motion equal to that recorded at Yerba Buena Island in the 1989 Loma Prieta earthquake. The soil profile consists of a 50 ft thick layer of soft silty clay over a 50 ft thick layer of stiff clay underlain by bedrock. The groundwater level is at the ground surface. The input motion is to be applied at the top of bedrock.

The tutorial will take you through the main steps in a typical ProShake analysis - definition of layer properties, specification of input motion, documentation of input, running the analysis, and documenting the results of the analysis. Each of these steps are

described in detail in the following sections. Completion of the tutorial will provide a very good introduction to the structure and operation of ProShake.

### *Definition of Layer Properties*

1. Select the Input Manager from the initial ProShake screen. This will bring up a form that allows you to define a soil profile, select an input motion, and keep a record of your input data in a report. If you wanted to open an existing input file, you could do so under the File menu on this screen (there is an input file named shake.dat that you may want to look at when you've completed this tutorial - it contains the example soil profile used in the original SHAKE user's manual).
2. Type in a title for the soil profile. This title should identify the soil profile to you and other potential users - it will be echoed on subsequent screens and in output files. Hit the Tab key after entering the title to automatically move the cursor to the next field, or move to the next field using the mouse.
3. Enter the number of layers for the analysis. For this example, enter 16 (then hit Tab) - this will provide 15 soil layers plus the underlying halfspace. Note how ProShake provides 16 tabs when the number of layers is entered - each tab will allow you to input the appropriate data for the corresponding layer.
4. Enter the depth of the groundwater table. Because ProShake performs total stress analyses, the groundwater table depth is not needed for the ground response analysis - rather, it is used when vertical effective stresses need to be computed. For this example, enter 0.0 in either the ft or m box (the other will automatically be calculated). ProShake allows you to enter input data in either US or SI units, and to mix and match units.

5. Now you are ready to enter input data for the first layer. Making sure that the tab for Layer 1 is active (it should be at the front of the stack of tabs with the layer number displayed in blue), enter a material name for Layer 1. This can be any alphanumeric string - for this example, call the first layer Soft Silty Clay.
6. The next step is to select a modulus reduction curve. ProShake has a series of built-in modulus reduction curves extracted from the geotechnical earthquake engineering literature. To see the list of built-in curves, click on the button at the right side of the modulus reduction curve field. For this example, select Vucetic-Dobry. The Vucetic-Dobry model describes modulus reduction (and damping) behavior as a function of plasticity index. When you select this model, ProShake will prompt you for a plasticity index - enter 10 for the plasticity index. ProShake will interpolate between the modulus reduction (and damping) curves presented by Vucetic and Dobry to obtain curves that correspond to the plasticity index you enter.
7. Note that ProShake initially sets the damping model as identical to the modulus reduction model by default. If you want to change the damping model, you may do so by selecting a different model in the same manner used to select the modulus reduction model.
8. Check your modulus reduction and damping curves by clicking on the button labeled Plot Modulus and Damping Curves. This will show the curves you specified in yellow and the curves of the Vucetic-Dobry model in green. Note that the two left-most green curves represent plasticity indices of 0 and 15, respectively. You should see that the yellow (PI=10) curve is in the appropriate position relative to the PI=0 and PI=15 curves.
9. Place the cursor anywhere on the plot and click the right mouse button. The forms that pop up allow you to change the characteristics of the plot. This feature is available for all of the plots that ProShake generates.
10. Now return to the Soil Profile form and move the cursor to either of the Thickness fields - again, you can enter the thickness in ft or in m, whichever is more convenient. For this example, enter a thickness of 5 ft for Layer 1.
11. Enter the unit weight (100 pcf) for Layer 1.
12. Now you need to specify the low-strain stiffness of Layer 1. This can be done either by entering the maximum shear modulus,  $G_{max}$ , or by entering the shear wave velocity. Using whatever units are most convenient, enter one or the other in the appropriate field. For this example, enter the shear wave velocity of Layer 1 (150 m/sec). Note that striking the Enter key after entering the shear wave velocity causes ProShake to compute the maximum shear modulus corresponding to the shear wave velocity and unit weight of the material. Now Layer 1 has been defined, and it is time to move on to the other layers.
13. Though the properties of the other layers can be defined in the same way, it will be faster for our example to enter subsequent data using the Summary Data tab. Click on that tab (just to the left of the tab for Layer 1). You will then see the Layer 1 input data displayed in a compact tabular form. For our example, the silty clay is actually 50 ft

thick and we will represent it in our ProShake analysis by ten 5-ft-thick layers. Rather than type all of this data in 10 times, we will use the drag-and-drop feature of the Summary Data form. To do this, put the cursor anywhere within the area that defines Layer 1 on the Summary Data form. Press and hold the left mouse button, then move the cursor down to the area that defines Layer 2. Release the mouse button and you will see that all of the data from Layer 1 has been assigned to Layer 2. Now repeat this process to define the properties of Layers 3-10.

14. For our example, the silty clay layer is underlain by 50 ft of very stiff clay which we will represent using five 10-ft-thick layers. To enter the data for Layer 11, first copy the properties of Layer 10 to Layer 11 by dragging and dropping. Now change the thickness of Layer 11 from 5 ft to 10 ft - click on the thickness cell for Layer 11 and type 10 followed by the Tab key. Using the same procedure, change the material name to Stiff Clay, the unit weight to 120 pcf,  $G_{\max}$  to 1,800 ksf, and the modulus and damping parameters to 20 (indicating  $PI=20$ ).
15. Now use the drag-and-drop feature to copy the properties of Layer 11 to Layers 12 through 15.
16. Finally, the properties of the half-space (bedrock) must be specified. Working either on the Summary Data form or on the tab for Layer 16, enter the input properties for bedrock with a unit weight of 150 pcf and shear wave velocity of 2500 ft/sec. Assign the Rock modulus reduction and damping curves to Layer 16.
17. Now we must specify what information is to be computed during the ground response analysis. Go to the tab for Layer 1 and click on the Select Output button. On the form that appears, check the boxes for acceleration and velocity. Also, check the box for acceleration response spectrum and enter damping ratios of 5, 10, and 20%. Repeat this process for Layers 2 and 11, but now requesting plots of shear strain and shear stress for those layers.
18. Now that all of the layers are defined, check for obvious errors (such as a misplaced decimal point) by clicking the View Profile button. The profile shows the variation of unit weight and shear wave velocity with depth - our example shows significant impedance (product of shear wave velocity and density) contrasts at the boundaries between the silty clay and the stiff clay (at the bottom of Layer 10) and between the stiff clay and bedrock (bottom of Layer 15). As we will see, these impedance contrasts will have a strong influence on the seismic response of our soil profile. The locations at which output is to be computed are indicated by green ovals - you should see these at the tops of Layers 1, 2, and 11.

### *Specification of Input Motion*

19. Now the input motion must be specified. Click on the large Input Motion button on the main Input Manager form. This will bring up a form that allows you to select an input motion, define its characteristics, view it graphically, and compute various ground motion parameters associated with the motion.

20. Enter 1 for the number of motions. ProShake allows you to analyze a soil profile using many different input motions in an individual run. For this example, leave the strain ratio, maximum number of iterations, and error tolerance at their default values.
21. Click the Open button on the tab form for Motion 1. From the Open File menu that appears, select the file named "yerba.eq." This file contains a strong motion record obtained at a rock outcrop on Yerba Buena Island in San Francisco Bay during the 1989 Loma Prieta earthquake. The characteristics of the record will be displayed in the Object Motion box (the peak acceleration, time step, and cutoff frequency can be changed, if desired). Various plots and common ground motion parameters for the object motion can be obtained by clicking on the buttons at the right side of this form - you should spend a little time playing with these.
22. Assign the object motion to the top of bedrock by entering 16 in the Layer field within the Object Motion Location box. Specify this motion as an outcrop motion by checking the appropriate box.
23. Select "Yes" in the Animation box. This will instruct ProShake to compute the response at the locations necessary to produce an animated view of ground response that can be viewed in the Output Manager.
24. The soil profile and input motion have now been completely characterized. Save the input data file with the name "tutorial.dat."

#### *Documentation of Input*

25. Click on the large Report button on the main Input Manager form. This will open a dedicated word processor with a template that shows all of the input data in tabular form. The report can be printed directly from ProShake, or saved (in Rich Text Format) for subsequent editing using a more powerful word processor.
26. Graphics can also be copied to the report. Go back to the Input Motion form and plot the time history of acceleration of the input motion. Click the button labeled Copy to Report, and then go back to the Report. You should see that the input motion has been copied to the report at whatever location the report cursor was in. Any ProShake plot can be copied to the report to provide documentation of a ground response analysis.
27. Now, save the report with the name "tutorial.hed."

#### **Running the Analysis**

28. To run the ProShake analysis, select the Solution Manager.
29. The Solution Manager will analyze any input data file you desire. The default extension for ProShake input files is .dat, though other filename extensions can also be used. To run the analysis you have just set up, select the data file tutorial.dat.

30. ProShake will then perform the analysis. You will see how the program iterates toward strain-compatible soil properties during the analysis - this feature will help you develop a better understanding of the response of your soil deposit. The word "Running" will appear in the lower left corner of the screen, and will be replaced by the word "Finished" at completion of the analysis and a dialog box will appear. When the analysis is completed, click OK on the dialog box that appears to exit Solution Manager. The results of the analysis performed by the Solution Manager will automatically be written to a file with the same name as your data file, but with the extension .lyr - in this case tutorial.lyr.

### **Examining the Results of the Analysis**

31. To view the results of your analysis, select the Output Manager.
32. Go to the File menu in the Output Manager and open the file tutorial.lyr.
33. There are many options for viewing the results of your analysis in the Output Manager. The primary plot types are organized on a series of six tabs - Ground Motion Plots, Stress and Strain Plots, Response Spectrum Plots, Depth Plots, Other Parameters, and Animation.
34. The Ground Motion Plots form allows you to plot time histories and Fourier spectra at the tops of the layers you selected in Step 17 of the tutorial. You may plot one or more motions on the same graph by checking the desired boxes. Go ahead and create a couple plots of your output. Note that these plots can be copied to the Report from the Output Manager just as they could from the Input Manager.
35. The Stress and Strain Plots form allows plotting of time histories and spectra of shear stress and shear strain - for our example, plots should be available at the tops of Layers 2 and 11.
36. The Response Spectrum Plots form allows you to plot any or all of the response spectra that you requested in Step 17. For this example, ground surface response spectra with 5%, 10%, and 20% damping were requested - select them all and plot them on the same graph, then copy the graph to the Report.
37. The Depth Plots form can be used to plot the variation of several quantities with depth for one or more input motions. Since our analysis used only one input motion, check the box for Motion 1 and try plotting some of these quantities with depth.
38. The Other Parameters form offers the opportunity to compute a variety of useful ground motion parameters at the tops of any of the layers selected in Step 17. Highlight the layer you are interested in, and then click on the Calculate button to see the numerical values of the parameters. This information can be copied in tabular format to the Report.
39. Finally, the Animation form allows you to view the variation of horizontal displacements with both depth and time for each input motion that an animation was requested for (you

did this for the single input motion of this example in Step 23). Click on the Prepare Animation button - it will take a few moments for ProShake to load and integrate the computed motions at the tops of all layers in the profile.

40. When the animation form appears, select the slow speed for best resolution. Immediately below the animation axes is a plot of the input motion; you can use it along with the Current Record Time display to track the progress of the animation. Select the desired Start Record Time - for this record, enter a value of 8 sec to eliminate the first 8 sec of the motion where nothing much is happening.
41. Click on the Start button to begin the animation. You will view a yellow line that represents the position of an originally vertical plane passing through your soil profile. Note the response at the impedance contrast between the soft silty clay and the stiff clay. The small displacements at the end of the time history result from a slight drift in the input motion.
42. Finally, take a look at the Report. You should see the input data for the analysis summarized in tabular form, and any plots you copied to the Report. You may print the Report from ProShake and/or save it for later reference.

You have now completed a ProShake analysis. To see how easy it is to work with ProShake, go back to the Input Manager, open tutorial.dat, and make some changes to your input file. As you will see, making the changes, running the analysis again, and viewing the results can all be accomplished very quickly and easily.



## ProShake Utilities

ProShake has two utilities that allow users to reformat digitized ground motions to be used with ProShake and to input their own soil models by adding new modulus reduction and damping curves. Both utilities save new data in a form recognizable to ProShake for future analyses.

### Convert Ground Motion File

Digitized earthquake ground motions are available from many different sources, and the formats in which they are provided by those sources are often different. ProShake, like any other ground response analysis program, expects to see the ground motion values in a particular format. To allow the user to specify any ground motion as a ProShake input motion, ProShake includes a utility for converting and saving ground motions in the format required by ProShake.

To use the Convert Ground Motion File utility, follow these steps:

1. Select Convert Ground Motion File from the Utilities menu.
2. An Open File Dialog Box with the title Earthquake File Name will appear on the screen. Select or enter the name of the ground motion file you wish to convert to ProShake format.
3. A Convert Ground Motion File form will then appear on the screen. The upper part of the box will display the first five lines of the ground motion file you plan to convert. Below that display is a series of text boxes that allow you to specify the format of the file.
4. Specify the name of the output file for the ProShake-formatted file you are creating. You can use any filename you wish, but ProShake will look first for files with the .eq extension.
5. Enter the number of header lines. This is the total number of lines at the top of the file *before* the actual ground motion data. The header lines often contain alphanumeric descriptions and/or numerical information about the motion (number of data points, time step, maximum value, etc.).
6. Enter the number of values - the number of data points in the ground motion file. This information is often shown in the header lines.
7. Enter the number of values per line. Ground motion data files are written in many different formats, but usually consist of 6 - 8 acceleration values written on each line. Determine how many individual acceleration values are on each line of your ground motion file and enter it here.
8. Enter the field width. The ground motion file will allot a certain number of characters for each acceleration value. Note that the field width includes negative signs, the decimal point, and any blank spaces. Determine the field width and enter it here.
9. Enter the time interval. Each of the acceleration values in the ground motion file will be separated by a certain time interval, usually 0.005, 0.01, or 0.02 sec. The time step is often shown in one of the header lines.

10. Select the units of acceleration in the file you are converting. Choose from fraction of gravity (g), cm/sec<sup>2</sup>, m/sec<sup>2</sup>, in/sec<sup>2</sup>, or ft/sec<sup>2</sup>. Most ground motion files will express accelerations in g's, but some use other units. Note that 1 gal = 1 cm/sec<sup>2</sup>.
11. After providing all of the required information, click on OK. ProShake will read your file and write a new file with the same acceleration data (expressed in g's) arranged in ProShake format. Your original file will be unchanged.

## Modulus-Damping Curve Editor Utility

ProShake approximates the nonlinear, inelastic behavior of soils using an iterative, equivalent linear approach. This approach requires that the variation of secant shear modulus and damping ratio with shear strain be specified. This behavior is described by modulus reduction and damping curves.

A modulus reduction curve illustrates the variation of normalized secant shear modulus (secant shear modulus divided by maximum shear modulus, or  $G/G_{\max}$ ) with strain. A damping curve illustrates the variation of equivalent viscous damping ratio with strain. The modulus reduction and damping behavior of many soils is well understood, and several models have been proposed to characterize them. ProShake has a number of built-in modulus reduction and damping models, but users may wish to add new models using the modulus-damping curve editor.

To add a new modulus reduction or damping curve, follow these steps:

1. Select Modulus-Damping Curve Editor from the Utilities Menu. A Modulus-Damping Curve Library Editor box will appear on the screen displaying modulus and strain values for Model No. 1 - the Vucetic-Dobry model. Note that there are 6 curves in the Vucetic-Dobry model (each corresponding to a different plasticity index), and that each curve is defined at 16 different strain levels. Individual modulus reduction values can be changed, but any changes should be documented (or preferably saved with a different model name).
2. If you want to create a new damping curve, select Damping in the upper box. If not, leave Modulus selected.
3. Click the Add button. You will now have a blank form on which to enter the modulus reduction data for your new model.
4. Give the model a name. You may use any alphanumeric name, but make sure that it is different than the names of the existing models. The length of the name is limited to 50 characters.
5. Enter the number of curves defining your new model. If modulus reduction behavior depends only on strain level in your model, you will only need one curve. If modulus reduction behavior depends on a second parameter (e.g. plasticity index in the Vucetic-Dobry model), enter the number of values of that parameter for which modulus reduction data will be entered (6 in the case of the Vucetic-Dobry model).

6. Enter an alphanumeric description of the second parameter.
7. Enter the number of points defining each curve; this is equal to the number of strain values at which modulus reduction ratio is to be specified.
8. If you specified more than one curve (for a model in which modulus reduction behavior depends on another parameter in addition to strain level), enter the values of that parameter for which modulus reduction curves are to be entered in each column of the first row of the data grid.
9. Enter the desired strain values in the left-most column, and the corresponding modulus reduction ratio values in the appropriate Modulus columns.
10. When the data is entered and you have checked it, click OK.
11. To add additional curves, repeat steps 3 to 10 for each curve.
12. Click Save. The data you have entered will be saved and be available for subsequent use via the pulldown menu in the Input Manager. The pulldown menu will display the model name you entered in Step 4 and, if applicable, the parameter name you specified in Step 6.

## **ProShake Help**

ProShake has extensive help capabilities. The ProShake help system follows standard Windows help file protocol. Each screen that ProShake displays provides access to the Help system through a pull-down menu. Also, context-sensitive help is available by clicking on the item for which more information is desired, then pressing the F1 key.

There are two options for navigating through the Help system. The first is initiated by selecting Contents from the Help menu. This selection will allow you to explore the structure of ProShake by working your way through the Input Manager, Solution Manager, or Output Manager. Each selection takes you through the various managers and has explanations for each item on each form that ProShake displays. The second option for using the Help system is through the use of the index, activated by selecting 'Search for Help on' from the Help menu. The index is particularly helpful if you know what you're looking for - either scroll down through the alphabetical list of help topics or begin typing the name of the item you are looking for. When you have found the item you want, either double-click on it or highlight it and click on Display.

## The ProShake Interface

The ProShake interface is designed to be intuitive, efficient, and easy to use. As previously described, ProShake is organized into three main components - the Input Manager, the Solution Manager, and the Output Manager. Within each of these managers, ProShake displays a series of forms on which data can be entered and/or results displayed. The following sections illustrate the most significant forms displayed by ProShake, and describes the items that appear on those forms.

### Input Manager

The input manager is used to prepare input files that can be executed by ProShake, specifically definition of the Soil Profile and specification of all Input Motions

#### Soil Profile

The Soil Profile form is accessed by clicking on the Profile button in the Input Manager. The screen that appears is shown below, and the information entered on the Soil Profile form described in the following paragraphs.

##### Profile Information

The upper part of the Soil Profile window requests global information that applies to the entire profile, rather than to individual material layers

##### *Profile Title*

Enter the alphanumeric title of your choice here, or leave it blank. The title will be displayed whenever the Soil Profile window is activated. It will be stored when you save your soil profile data and it will also be written into the Report. The length of the title is limited to 80 characters.

##### *Number of Layers*

ProShake allows you to define an unlimited number of material layers, including a half-space layer at the bottom of the profile (the memory capacity of your computer may introduce a practical upper limit to the number of layers, but it is likely to be larger than the number of layers that you would choose to use). Enter the number of layers you want to use and ProShake will provide that number of tab forms on which you can enter soil profile data. An individual soil

The screenshot displays the 'ProShake Input Manager' window with the 'Profile' tab selected. The form contains the following fields and controls:

- Profile Title:** Example -- 150-R layer
- No. of Layers:** 17
- Depth to Water Table:** 10.0 ft, 3.0 m
- Summary Data:** A tabbed interface with tabs numbered 1 through 17, where tab 1 is currently selected.
- Material Name:** Sand
- Modulus Reduction Curve:** Sand (Seed and Idriss 1970)
- Damping Curve:** Sand (Idriss 1990)
- Plot Modulus and Damping Curves:** A button to generate a plot.
- Thickness:** 5.0 ft, 1.5 m
- Unit Weight:** 125.0 pcf, 19.6 kN/m<sup>3</sup>
- Max. Shear Modulus:** 3882.0 ksf, 185.9 MPa
- Shear Wave Velocity:** 1000.0 ft/sec, 304.8 m/sec
- Select Output** and **View Profile** buttons are located at the bottom of the form.

layer may be represented by more than one material layer. As an alternative, users may find it more efficient to enter material data directly on the Summary Data form.

#### *Depth to Water Table*

Enter the depth to the water table, if any. Use U.S. or metric units - the other will be calculated automatically when you move to the next data field. ProShake uses this depth, along with the layer thickness and unit weight data, to compute effective vertical stresses. If left blank, ProShake will assume that no groundwater exists in the entire profile. ProShake will compute initial porewater pressures as zero above and hydrostatic below the water table.

### **Layer Information**

The main portion of the Soil Profile window contains a series of tabbed forms that allow you to enter material property data for each material layer. The active material layer form is indicated by the tab label.

#### *Material Name*

Enter the alphanumeric description of your choice, or leave it blank. The material name will be stored in the Analysis Summary in the Report. The length of the description is limited to 20 characters.

#### *Thickness*

Enter the layer thickness in feet or in meters - the other will be calculated automatically. Because ProShake computes ground motions at layer boundaries, you'll want to select layer thicknesses to provide a layer boundary at each depth at which ground motions are to be computed. This may require specification of adjacent layers with identical properties.

#### *Unit Weight*

Enter the unit weight in pcf or in kN/m<sup>3</sup> - the other will be calculated automatically. Moist unit weights should be used for layers above the water table. Because porewater moves with the soil during earthquake shaking, saturated unit weights should be used below the water table.

#### *Maximum Shear Modulus*

Enter the maximum shear modulus, if available, either in ksf or in MPa - the other will be calculated automatically. If you enter unit weight and maximum shear modulus, the corresponding shear wave velocity will be computed from

$$v_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{G\gamma}{g}}$$

where  $G_{\max}$  is maximum shear modulus,  $\rho$  is density,  $\gamma$  is unit weight, and  $g$  is the acceleration of gravity.

*Shear Wave Velocity*

Enter the shear wave velocity, if available, in ft/sec or in m/sec - the other will be calculated automatically. If you enter unit weight and shear wave velocity, the corresponding maximum shear modulus will be computed from

$$G_{\max} = r \nu_s^2$$

*Modulus Reduction Curve*

The modulus reduction curve describes the manner in which the shear modulus varies with shear strain amplitude. The curve itself expresses the modulus ratio, defined as the secant shear modulus divided by the maximum shear modulus, as a function of shear strain amplitude. The secant shear modulus used in the ground response calculations is computed as the product of the modulus reduction factor and the maximum shear modulus.

Because soils exhibit nonlinear stress-strain behavior, their secant shear moduli decrease with increasing strain level. The shape of the modulus reduction curve indicates how nonlinear the material is - a linear material would have a horizontal modulus reduction curve; the modulus reduction factor would be 1.0 at all strains. In general, soil nonlinearity increases with decreasing plasticity index.

A number of investigators have studied the modulus reduction behavior of different soils and proposed standard modulus reduction curves for those soils. ProShake provides a list of modulus reduction curves to choose from, and also allows you the option of defining your own modulus reduction curve. To view the list, simply click on the drop-down arrow to the right of the data field. If the modulus curve you select requires additional data (for example, the Vucetic-Dobry curve requires that you specify the plasticity index), the required data fields will appear to the right. To select a modulus reduction curve from the menu, just click on it. See Modulus-Damping Curve Editor Utility section to define your own modulus reduction curve.

ProShake offers the following modulus reduction curve options:

Vucetic-Dobry	Gravel
Sun, Golesorkhi, and Seed	Linear
Ishibashi-Zhang	Rock
Seed-Idriss	Custom

A more detailed description of the models may be found in the subsequent section titled Built-In Soil Models.

*Damping Curve*

The damping curve describes the manner in which the damping ratio varies with shear strain amplitude. Because soils exhibit nonlinear, inelastic stress-strain behavior, their equivalent damping ratios increase with increasing strain level. Different types of soil exhibit different damping characteristics. In general, soil damping increases with decreasing plasticity index.

A number of investigators have studied the damping behavior of different soils and proposed standard damping curves for those soils. ProShake provides a list of damping curves to choose from, and also allows you the option of defining your own damping curve. To view the menu, simply click on the drop-down arrow to the right of the data field. If the damping curve you select requires additional data (for example, the Vucetic-Dobry curve requires that you specify the plasticity index), the required data boxes will appear to the right. To select a damping curve from the list, just click on it. See Modulus-Damping Curve Editor Utility section to define your own damping curve.

ProShake offers the following damping curve options:

- |                           |          |
|---------------------------|----------|
| Vucetic-Dobry             | Constant |
| Sun, Golesorkhi, and Seed | Rock     |
| Ishibashi-Zhang           | Custom   |
| Seed-Idriss               |          |

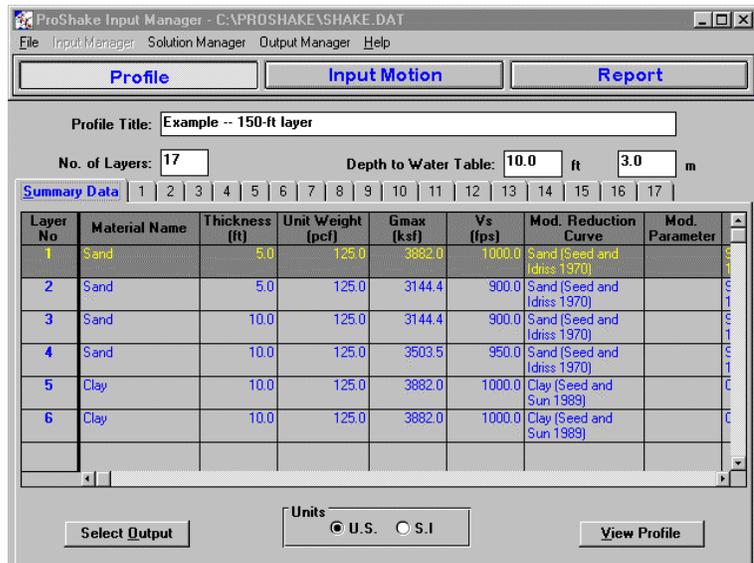
A more detailed description of the models may be found in the subsequent section titled Built-In Soil Models.

*Plot Modulus Reduction and Damping Curves*

ProShake allows you to view the modulus reduction and damping curves graphically. These graphs also feature Copy to Report and Write Data to File capabilities.

*Summary Data*

The Summary Data form allows the soil profile data to be entered and/or edited in a tabular format. Experienced ProShake users may find this format more efficient for data entry. The Summary Data form has a drag-and-drop feature that allows all of the characteristics of one layer to be assigned to another layer. The drag-and-drop feature can be very useful for entering data when multiple material layers have similar properties - the properties of one layer can be input and then assigned to the other layers by dragging and dropping. Individual properties of the other layers can then be changed by editing as necessary. To drag-and-drop, place the cursor anywhere on the line (data for each layer is displayed on an individual line) that you want to copy, then press the left mouse button and hold it as you move the cursor down to the layer you want to paste the information to. Then, release the mouse button. The data for one layer will be copied to the other layer.



### Select Output

Output can be requested for the top of any soil layer in the profile prior to program execution. Output is divided into three main categories that are displayed on the Select Output form:

### Time History

Time histories of acceleration, velocity, displacement, shear strain, and shear stress can be selected for any layer. The exception is that shear stress and shear strain cannot be selected for Layer 1 because their values are always zero at the ground surface.

### Response Spectrum

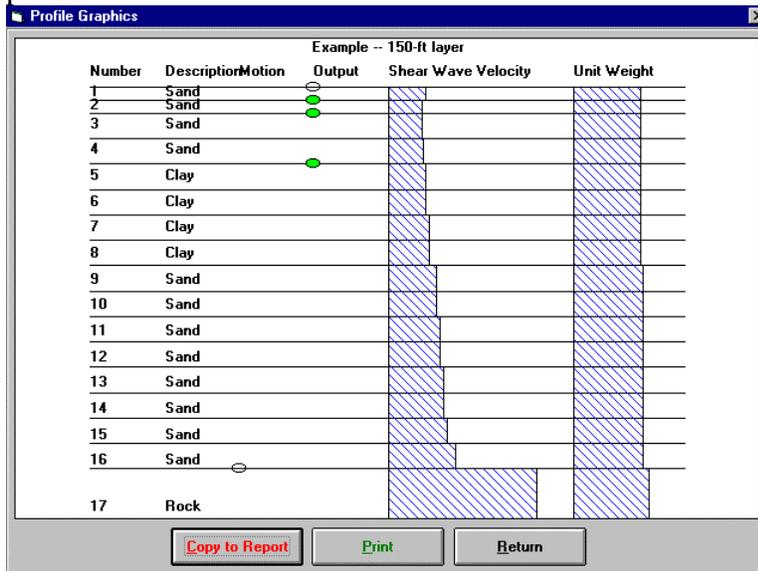
Acceleration, velocity, and/or displacement response spectra can be computed at up to three structural damping ratios. Response spectra are computed at 95 structural periods ranging from 0 to 10 seconds.

### Spectra

Fourier spectra, phase spectra, and power spectra can be computed for acceleration, velocity, and/or displacement.

### View Profile

ProShake's Input Graphics allow you to view the soil profile and input parameters assigned to various material layers. This feature is very useful for detecting errors or other problems with the input data - mis-typed parameters or misplaced decimal points will show up very clearly in the profile.



The profile shows the name, thickness, unit weight, and shear wave velocity for each material layer. The profile indicates the depths at which the input motions are applied (with solid red ovals for motions within the profile and open ovals for outcrop motions) and the depths at which output is calculated (with solid green ovals for motions within the profile and open ovals for outcrop motions). The profile plot can be copied to the Report.

The profile is also useful for visualizing impedance contrasts at layer boundaries. Because impedance ratios control the partitioning of wave energy (reflected and transmitted) at layer boundaries, it is useful to know where the highest impedance ratios are located.

## Input Motion

Proper specification of an input motion is an important part of any ground response analysis. ProShake allows you to view a variety of potential input motions and select the ones that are most appropriate for the analysis. The selection and review of input motions takes place on the Input Motion form. The upper part of the Input Motion form requests global information that applies to all of the input motions you select; the lower part requests information for each individual input motion.

### Number of Motions

ProShake places no limit on the number of input motions that can be specified for a given run (the memory capacity of your computer will place a practical limit on the number of motions, but it will generally be larger than the number that most users will wish to use). Enter the number of input motions you want to use and ProShake will provide that number of tab forms on which you can select and/or enter input motion data.

### Maximum Number of Iterations

ProShake approximates nonlinear soil behavior by iterating toward strain-compatible soil properties. You can specify the maximum number of iterations here - ProShake will continue until it reaches this limit or until the tolerance criterion is satisfied. ProShake uses a procedure to adjust the soil properties that converges more quickly and reliably than that used in previous versions of SHAKE. For most soil profiles, strain-compatible properties will be reached in a few iterations. During execution, the number of iterations is displayed by ProShake's Solution Graphics.

### Error Tolerance

As ProShake iterates toward strain-compatible modulus and damping values, the difference between the modulus and damping values from one iteration to the next becomes smaller and smaller. You can specify any error tolerance defined as the maximum percentage change in shear modulus or damping ratio between successive iterations. ProShake will iterate toward strain-compatible soil properties until the tolerance criterion is satisfied for all layers or until the maximum number of iterations is reached. The results of many ground response analyses do not change much at tolerance levels below about 5% and ProShake will use this as a default value. During execution, the variation of modulus and damping error with depth is illustrated by ProShake's Solution Graphics.

### **Strain Ratio**

The strain ratio is the ratio of effective shear strain to maximum shear strain in each layer. ProShake takes transient input motions and computes transient output motions. The computed shear strain is an important output parameter because of the strain-dependence of the shear modulus and damping ratio. The process of iteration toward strain-compatible modulus and damping values requires comparison of the strains computed in each iteration of ProShake with the strains on which the modulus and damping values are based. Because equivalent linear modulus and damping characteristics are based on laboratory tests with uniform harmonic loading, the transient shear strain computed by ProShake must be converted to an effective shear strain for this comparison. Historically, the strain ratio has often been taken as 0.65, but can better be selected as  $(M-1)/10$  where  $M$  is the magnitude of the earthquake that produced the input motion.

### **Object Motion**

An object motion is an input motion read from a data file and assigned to a particular layer boundary in the soil profile. ProShake computes the response at other points in the soil profile to the object motion. In this section you will select and specify the characteristics of each individual input motion.

### **File Name, Open, Remove**

Enter the complete name of the input motion file here, or use the Open command button to browse through all Windows 95 directories.

### **Description**

Enter the alphanumeric description of your choice here. This description will be attached to all pertinent data and graphics copied to the Report or written to your Data File. The length of the description is limited to 128 characters.

### **Number of Acceleration Values**

ProShake uses digitized earthquake records. This term indicates the number of acceleration values in the current input file. The number of acceleration values in a ProShake earthquake record cannot exceed 16,384.

### **Peak Acceleration**

The maximum (absolute) acceleration of the current input file is displayed here. You can change this value if you want to scale the accelerations to a different maximum acceleration for your analysis - the input motion data file will not be changed. By changing the maximum acceleration, you will change all acceleration values in the input motion by the same factor. The frequency content and duration of the input motion will not be affected by amplitude scaling.

### **Time Step**

The time step that separates the acceleration values in the input motion data file is displayed here. You can change this value if you want to change the frequency content or duration of the input motion for your analysis - the input motion data file will not be changed. By changing the time step, you will change both the frequency content and the duration (but not the amplitude) of the input motion. This is a rather crude way of modifying the frequency content - time step changes of more than about 20% should be considered very carefully.

### **Cutoff Frequency**

The equivalent linear mode of ProShake computes ground response in the frequency domain. Briefly, it represents an input motion as the sum of a series of sine waves of different amplitudes, frequencies, and phase angles. Because most of the energy in an earthquake motion is concentrated in a range of relatively low frequencies (and because high frequency motions have little effect on most civil structures), ProShake doesn't require you to spend time on the higher frequencies that contribute little to the total response. The cutoff frequency specifies the upper limit of frequencies that ProShake will consider - cutoff frequencies of 15 to 20 Hz are usually adequate for most soil profiles. The speed of the analysis will increase as the cutoff frequency is decreased, but the execution time is generally not long enough to justify low cutoff frequencies.

### **Number of Terms in Fourier Series**

ProShake uses a Fast Fourier Transform (FFT) to convert the input motion (time domain) into a Fourier series (frequency domain). After computing the response in the frequency domain, it uses an inverse FFT to transform the solution back to the time domain.

The FFT is a very efficient numerical procedure, but it requires the total number of acceleration values to be an integer power of 2 (e.g. 1024, 2048, 4096, etc.). ProShake allows up to 16,384 ( $=2^{14}$ ) terms in the object motion. If the number of acceleration values in your input motion file is less than some power of 2, ProShake will add the required number of trailing zero acceleration values to bring the total length to the number of terms you specify for the Fourier series. Because the Fourier series implies periodicity (it assumes that the total time history, including the trailing zeros, repeats itself indefinitely), you need to make sure you have enough trailing zeros to form a quiet zone sufficiently long to allow the response to die out before the next motion begins. The best results are usually obtained when the last third or more of the total time history is quiet.

### **Object Motion Location**

The input motion can be applied at the top of any layer in your soil profile, from the ground surface to the bottom half-space layer. Enter the layer number at which your input motion is to be applied here.

The input motion may be applied as an outcrop motion or as a motion within the soil profile. Your selection here depends on your input motion. If the input motion was recorded by an instrument located on the ground surface, or if it was obtained by computation at a point on the ground surface of some numerical model, it should be specified as an outcrop motion.

### **Animation**

ProShake's animation feature needs to be selected individually for individual input motions. When you select the animation feature, ProShake will automatically compute acceleration time histories at the tops of all layers. These accelerograms are then double-integrated in the Output Manager to obtain the animated displacements.

### **Object Motion Plots**

It is often helpful to examine the characteristics of potential input motions graphically before using them. ProShake allows you to look at your input motions in a variety of ways. Many of these graphs include a crosshair function which allows you to see the numerical value of a particular point on the graph.

#### ***Acceleration vs Time***

Select for a graph of acceleration vs time. The graph can be copied to the Report and/or the data written to the Data File. After viewing, click on Return to go back to the Input Motion form.

#### ***Velocity vs Time***

Select for a graph of velocity vs time. The graph can be copied to the Report and/or the data written to the Data File. After viewing, click on Return to get back to the Input Motion form.

#### ***Displacement vs Time***

Select for a graph of displacement vs time. The graph can be copied to the Report and/or the data written to the Data File. After viewing, click on Return to get back to the Input Motion form.

#### ***Husid Plot***

A Husid plot shows how the energy of the ground motion is distributed in time. Mathematically, it is a plot of normalized cumulative squared acceleration, i.e.

$$H_n(t) = \frac{\int_0^t [a(t)]^2 dt}{\int_0^{\infty} [a(t)]^2 dt}$$

vs time. The Husid plot can be used for some measures of ground motion duration (see Trifunac duration).

#### ***Fourier Spectrum***

A transient input motion can be represented, using a Fourier series, as the sum of a series of sine waves with different amplitudes, frequencies, and phase angles. A Fourier amplitude spectrum is a plot of amplitude vs frequency for each of these sine waves. The Fourier amplitude spectrum illustrates the frequency content of the motion.

#### ***Phase Spectrum***

A phase spectrum is a plot of phase angle vs frequency for all of the sine waves that make up a Fourier series. The phase spectrum controls the manner in which ground motion energy is distributed in time; the overall shape of a time history is related to the phase spectrum. Unlike Fourier spectra, phase spectra have no discernible structure.

***Power Spectrum***

A power spectrum shows how the power of a ground motion signal is distributed with respect to frequency. The power spectrum really provides the same information as the Fourier spectrum - its values are the squares of the values of the Fourier spectrum.

***Response Spectrum***

A response spectrum presents the maximum absolute response (acceleration, velocity, or displacement) of single-degree-of-freedom oscillators of different natural periods. As such, it gives a good indication of the potential effects of the ground motion on different structures. For object motion response spectra, ProShake assumes 5% structural damping.

***Crosshairs***

ProShake screen graphs include a crosshair feature that allows you to identify the coordinates of any point on the graph. By moving the cursor onto the graph, the arrow turns into a set of crosshairs. The coordinates of the center of the crosshairs is given in the Crosshair Position box. The x- and y-coordinates are those on the horizontal and vertical axes of the graph, respectively, and the units are the same as those of the graph.

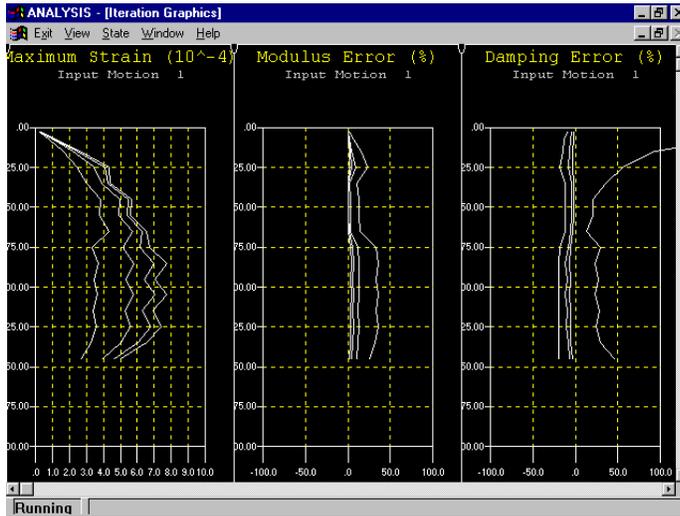
***Other Parameters***

ProShake will allow you to compute other characteristics of an input motion. Clicking on this button allows you to compute any of the following ground motion parameters.

- |                   |                             |
|-------------------|-----------------------------|
| Peak Acceleration | Response Spectrum Intensity |
| Peak Velocity     | Predominant Period          |
| Peak Displacement | Bracketed Duration          |
| RMS Acceleration  | Trifunac Duration           |
| Arias Intensity   |                             |

## Solution Manager

The solution manager is used to execute the equivalent linear analysis of ProShake. The user must select a valid ProShake data file for execution. The solution manager will save the selected output in a file with a .lyr filename extension, e.g. PSRUN.lyr upon execution of the data file PSRUN.dat.



The solution manager will display solution graphics during execution of the equivalent linear analysis. The solution graphics will display three plots for each input motion. The leftmost plot will illustrate the variation of effective shear strain with depth for each iteration - the effective shear strain values should converge to a constant profile with increasing numbers of iterations. The center and rightmost plots illustrate the variation of modulus error and damping error with depth for each iteration. As the program iterates toward strain-compatible

soil properties, the errors should decrease. When the errors decrease below the error tolerance specified on the Input Motion form of the Input Manager at all depths, or when the maximum number of iterations has been reached, the program will cease iterating.

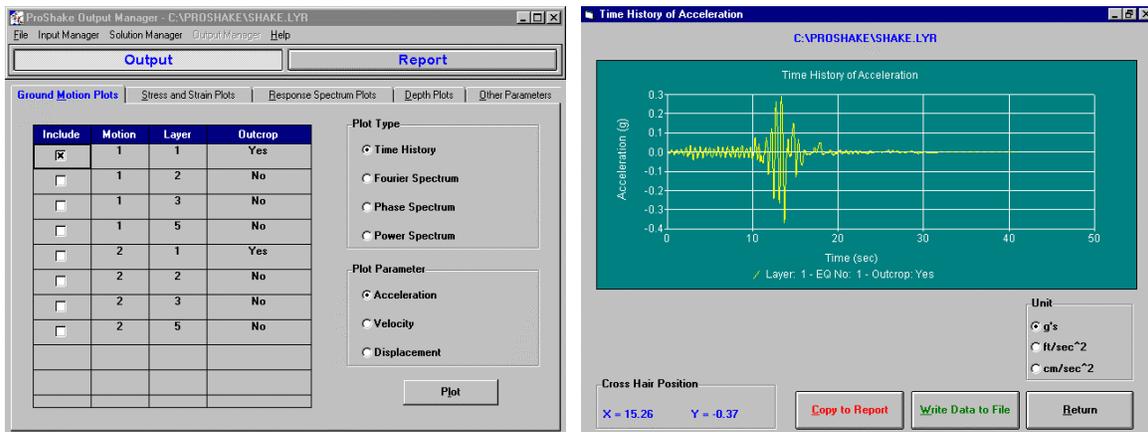
The solution graphics are intended to help the user better understand the behavior of the soil deposit being analyzed, and to help identify and correct potential problems with the analysis. ProShake uses iteration logic that is more advanced than that used in previous versions of SHAKE; as a result, it converges more quickly and more reliably than previous versions. Soil profiles with extraordinarily soft layers or extraordinarily high impedance ratios, however, may converge slowly or not at all - such behavior often indicates an error in the input.

## Output Manager

The output manager processes all output and allows all results to be plotted graphically. Several types of plots, including ground motion plots, stress and strain plots, response spectrum plots, and depth plots are available. The output manager also allows computation of other parameters. Finally, the output manager can be used to view an animation of the ground response. Each of these can be selected by clicking on the appropriate tab.

## Ground Motion Plots

A variety of plots can be constructed from the Ground Motion Plots tab which is selected by clicking on the labeled tab. Three ground motion parameters - acceleration, velocity, and displacement - can be plotted as functions of time or frequency. Four different plot types are available: Time History, Fourier Spectrum, Phase Spectrum, and Power Spectrum plots. Any of these plots can be copied to the Report, or have their data written to the Data File.

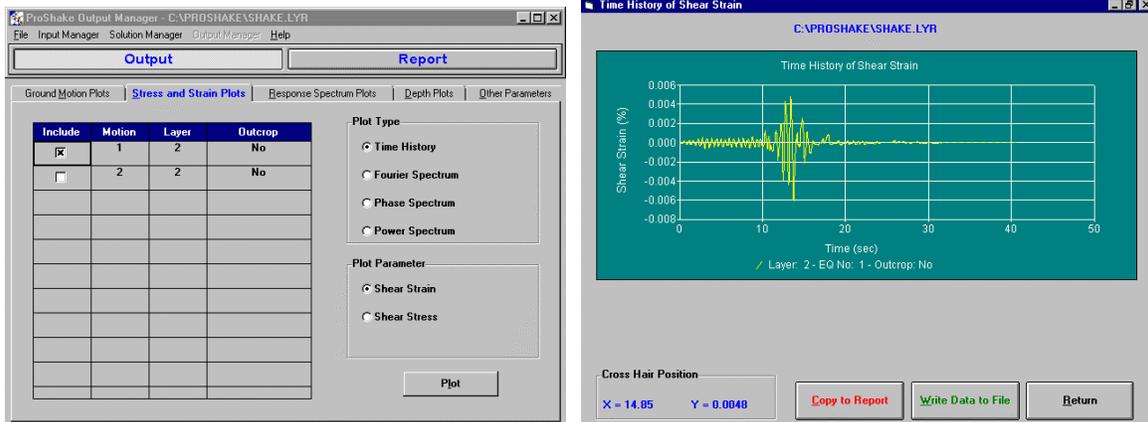


Ground motion parameters from multiple depths, or from multiple input motions, can be selected for a single plot using the check boxes in the Include column. While it is unlikely that users will want to plot multiple time histories or phase spectra on the same plot, plots of multiple Fourier or power spectra on the same graph can illustrate differences in frequency content effectively.

Time history of accelerations can also be saved to a file in PsoShake Input Motion Format for use as input motion for future analysis by clicking on the Save As button. You will be prompted for file name(s).

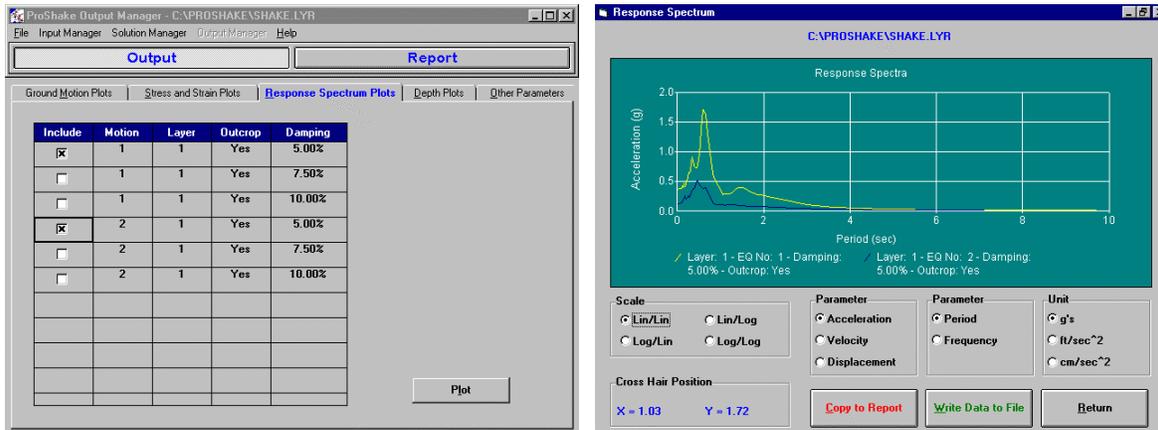
## Stress and Strain Plots

Time histories of shear stress and shear strain can be constructed from the Stress and Strain Plots tab. Any of these plots can be copied to the Report, or have their data written to the Data File.



## Response Spectrum Plots

Response spectra can be plotted using the Response Spectrum Plots tab which is selected by clicking on the labeled tab. Multiple response spectra, from different depths and/or for different damping ratios or input motions, can be selected for a single plot using the check boxes in the Include column.

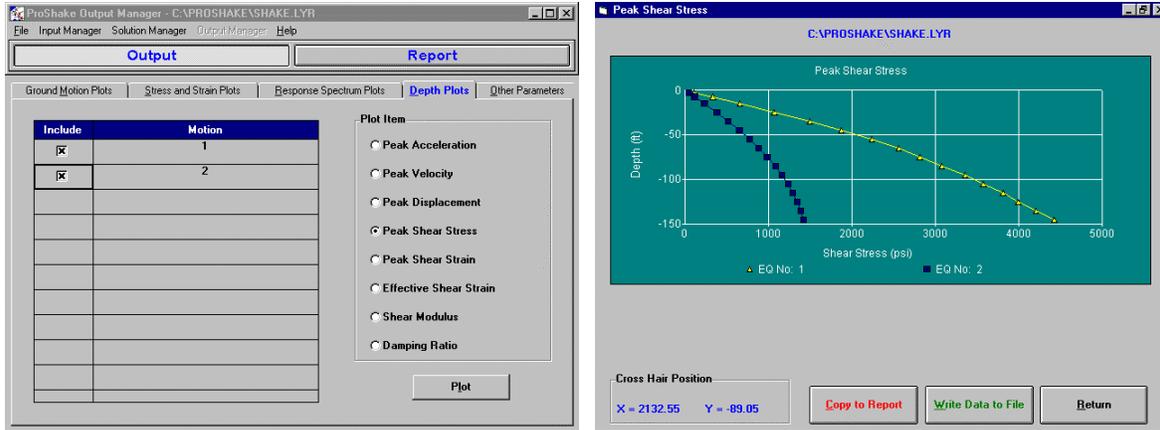


Upon clicking the Plot button, acceleration spectra are plotted as a function of period on arithmetic scales by default. However, velocity and displacement spectra can be plotted from the plot form. Also, the abscissa can be changed to frequency and the scales to logarithmic from the plot form.

All response spectrum plots can be copied to the Report, or have their data written to the Data File.

## Depth Plots

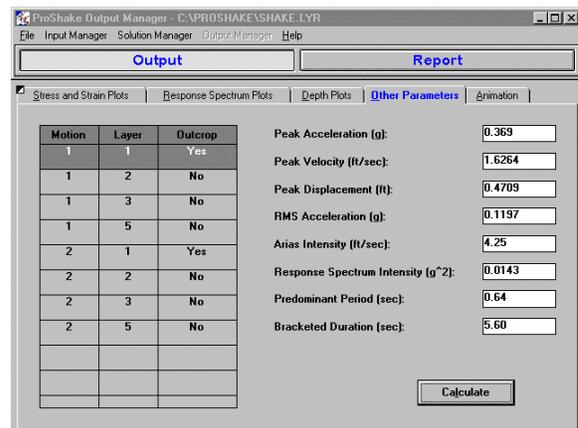
It is often useful to examine the variation of ground motion amplitudes with depth; the Depth Plot form allows ProShake users to do this. Parameters that can be plotted as functions of depth include peak acceleration, peak velocity, peak displacement, peak shear stress, peak shear strain, effective shear strain, shear modulus, damping ratio, and cyclic stress ratio. Parameters from multiple input motions can be combined on the same plot using the check boxes in the Include column.



Parameters can also be copied to the report in tabular form by clicking Copy to Report button.

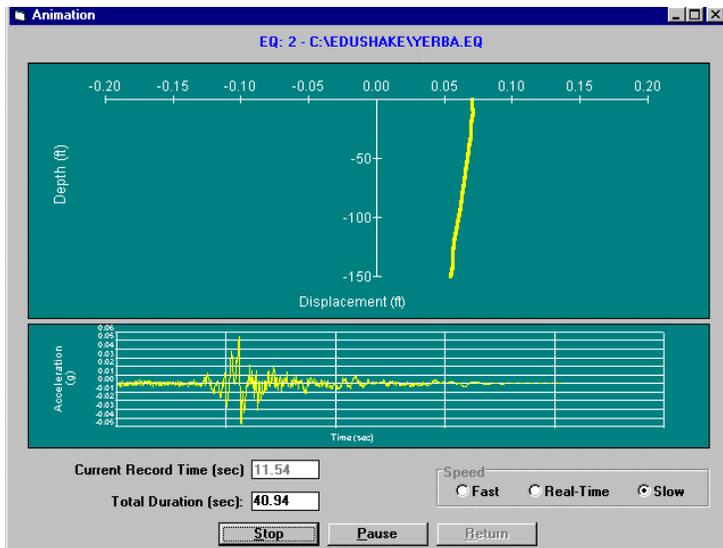
### Other Parameters

ProShake will allow you to compute other characteristics of the computed motion at the top of any layer at which acceleration data has been computed. Clicking on the Calculate button on the Other Parameters tab allows computation of the ground motion parameters shown on the Other Parameters form to the right. Calculated parameter values can also be copied to the report in tabular form by clicking Copy to Report.



### Animation

The Animation feature allows ProShake users to view the horizontal displacements of an originally vertical line throughout an input motion. An animation can be viewed for each input motion for which animation was selected on the Input Motion form in the Input Manager. To view an animation, highlight the desired input motion and click on the Prepare Animation button.



ProShake will take a few moments to load the data for the animation. The animation is based on the computed displacements at the top of each layer, with linear interpolation of displacements between layer boundaries. As a result, more realistic animations can be achieved by increasing the number of soil layers in a profile; however, the increased computational requirements will slow program execution somewhat.

ProShake animations scale the computed displacements so that the

maximum computed displacement is slightly less than the full-scale value of the horizontal axis. This was done in order to clearly illustrate the pattern of the displacements; in most cases, the amplitudes of the displacements will be greatly exaggerated. When used with input motions that have not been baseline corrected, some apparent residual displacements may occur - these displacements are relics of drift in the input motion and should not be taken to imply the existence of residual strains (or stresses) in the equivalent linear analysis.

The ProShake animation can be played at three speeds - fast, real-time, and slow - and can be started at any time during the record. Due to the speed limit of the Visual Basic graphics routine that displays the animation, the fast and real-time speeds are accomplished by skipping different numbers of time steps; hence, animations of some records may appear to “jump” a bit at those speeds. Viewing the animation at the slow speed setting will provide a smoother view of the displacement profile. For the example shown above, selecting a starting time of about 8 sec would allow the most interesting part of the animation to be viewed in a reasonable amount of time when the slow speed is selected.

### Transfer Function Plots

A transfer function describes the relationship between two motions in the frequency domain. Consider two motions, A and B, with Fourier Series  $A(f)$  and  $B(f)$ , respectively. The motions can be related by

$$A(f) = H(f) * B(f)$$

where  $H(f)$  is a transfer function. Therefore, the transfer function can be written as the ratio

$$H(f) = A(f)/B(f)$$

When damping is present, transfer functions are complex-valued.

ProShake allows plotting of transfer functions between any two layers for any of the motions used in the analysis from the Transfer Function form in Output Manager. A maximum of six different transfer functions can be computed and plotted at one time using the check boxes in the Include column. Transfer functions are computed using strain compatible modulus and damping values obtained in the Solution Manager for the particular motion being used.

To plot the Transfer Functions, follow these steps:

1. Specify the Number of Frequencies (default = 201) and the Frequency Step (default = 0.1 Hz) for computing the transfer functions. Transfer function values will be computed and plotted from 0 Hz to 20 Hz ( = [201-1]\*0.1 Hz); the default values should provide satisfactory resolution in most cases.
2. Click a check box in the "Include" column to specify a transfer function plot.
3. Click in the adjacent cell (in the Motion column). Use the drop down list box to select the motion you want to use. The strain-compatible modulus and damping values for this motion will be used to compute the transfer function.
4. Click in the next cell to the right (in the Layer A column). Select the Layer number you want to use in the numerator of the transfer function equation.
5. In the column labeled Outcrop A, select whether to treat "Layer A" as an outcrop or within profile motion.
6. Repeat Steps 4 and 5 for Layer B which will be in the denominator of the transfer function equation.

Repeat Steps 2 through 6 to define additional transfer functions to be plotted. Any of the layers can be defined as an outcrop or within profile for computing transfer functions. Then simply click on the Plot button to create the transfer function plots.

Transfer functions, like all complex-valued functions, have real and imaginary part. The transfer function can be expressed in terms of its real and imaginary parts as

$$H(f) = \text{Re}[H(f)] + i * \text{Im}[H(f)]$$

where  $\text{Re}[H(f)]$  and  $\text{Im}[H(f)]$  are the real and imaginary parts of  $H(f)$ , respectively, and  $i^2 = -1$ . ProShake allows the transfer function to be plotted in four different ways:

*Amplitude* shows the ratios of the amplitudes of the motions at different frequencies. Numerically, given by the square root of the sum of the squares of the real and imaginary parts of the transfer function.

*Phase angle* shows the phase angles between the two motions at different frequencies. Numerically, given by the arctangent of the ratio of imaginary part to the real part of the transfer function. Can be expressed in radians or degrees.

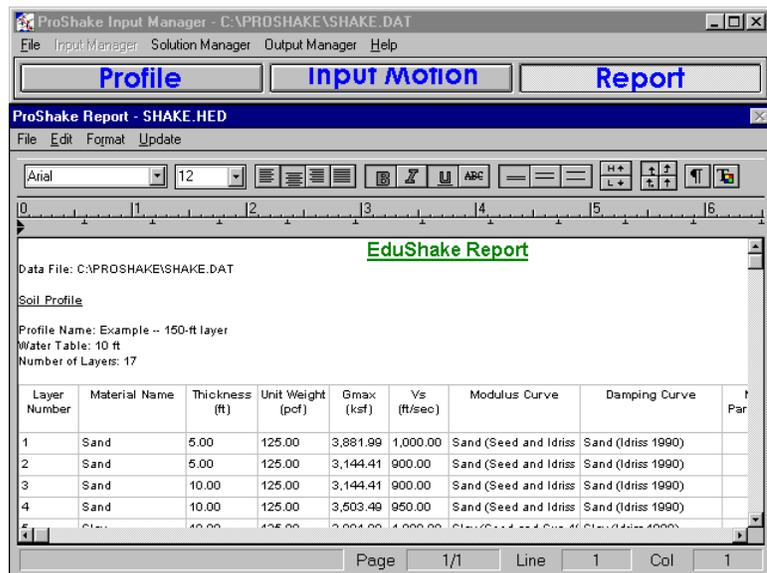
*Real part* shows the real part of the transfer function at different frequencies.

*Imag. part* shows the imaginary part of the transfer function at different frequencies.

## Report

ProShake allows you to save numerical and graphical data in the form of a report - because ProShake comes with its own Windows-based word processor. While the ProShake word processor will serve the needs of many, it is not as powerful as Microsoft Word™ or WordPerfect™. If you prefer to use more powerful word processors, use the ProShake word processor for temporary storage, save the report file in Rich Text Format using the Save As menu item of the report form and later open the Rich Text Format file using the Windows-based word processor of your choice. The report feature allows you to easily paste data and graphics into the document of your choice.

One of the main features of the ProShake report is the analysis summary. As you enter input data from the Soil Profile and Input Motion forms in the Input Manager, the data is stored in arrays that are linked to the report. Input motion and output location data are also stored in linked arrays. By selecting Update menu from the ProShake report, the soil profile, input motion, and output location data will be displayed in a compact table in the report. This feature will allow you to keep a written record of each analysis you perform; of course, you can use the word processor to add comments of your own to the report.



By default, the report contains an Analysis Summary of the Soil Profile, Input Motion, and output selections. Whenever you select "Copy to Report" the item of interest will be copied into the report. Although items are copied sequentially, it is often advisable to type labels into the report so that the items can be identified at a later time. Text items (usually numbers) are written in column format. Graphics items are displayed black-on-white in the report, even if they are displayed differently within ProShake.



## ProShake Graphics

ProShake allows rapid generation of many different types of plots. In the Input Manager, users can plot modulus reduction and damping curves, various time histories and spectra for input motions, and a graphical view of the soil profile. In the Output Manager, plots of time histories, spectra, and depth variations are all available. Some of the common elements of these plots are described in the following paragraphs.

For clarity on the computer monitor, the plots are displayed as light (generally yellow or white) curves and axes on a darker background. The axes are selected to cover the entire range of data and clearly illustrate the variation of the parameter being plotted. Nevertheless, some users may want to change the characteristics of the plots - this is easily accomplished in ProShake.

To modify a plot, place the cursor anywhere on the plot and click the right mouse button. This will produce a Graph Control dialog with tabs labeled Style, Data, Titles, Axis, Fonts, Markers, Background, and System. These tabs allow virtually any characteristic of the plot to be modified as the user desires.

The forms on which all ProShake plots are displayed also contain two buttons - one titled Copy to Report and the other titled Write Data to File. The first copies the plot and pastes it into the ProShake Report. The copy that goes to the report is formatted with black lines and axes on a white background, even though the plot displayed on the screen is formatted differently. Users may also want to save some data (e.g. ground motions or response spectra) for subsequent use or additional processing. ProShake allows you to write data to an output file. The data is written sequentially and labeled in the same manner as in the report.

Many of the ProShake plots have a Crosshair feature. This feature simply allows the user to see the numerical values of the parameters that are being plotted. When the cursor is moved to the plot area, it changes from an arrow to crosshairs and the values of the parameters at the locations of the crosshairs are displayed.

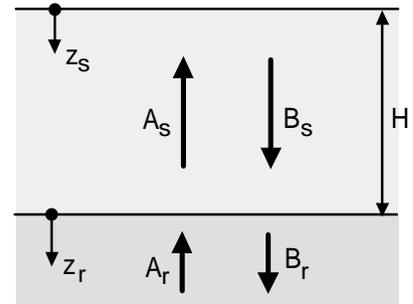
## Theory

ProShake uses a frequency domain approach to solve the ground response problem. In simple terms, the input motion is represented as the sum of a series of sine waves of different amplitudes, frequencies, and phase angles. A relatively simple solution for the response of the soil profile to sine waves of different frequencies (in the form of a transfer function) is used to obtain the response of the soil deposit to each of the input sine waves. The overall response is obtained by summing the individual responses to each of the input sine waves. This section describes the basic mathematics of the process for a problem involving a single soil layer, illustrates how that problem can be solved using a widely available mathematical programming language, and extends the approach to layered systems.

### Single Soil Layer

The following paragraphs describe the basis of the analysis used in ProShake and follow the general approach of Kramer (1996). That reference provides substantial background material and a more detailed description of ground response analyses than is presented in this User's Manual.

To illustrate the basic approach used in ProShake, consider a uniform soil layer lying on an elastic layer of rock that extends to infinite depth, as illustrated to the right. If the subscripts  $s$  and  $r$  refer to soil and rock, respectively, the horizontal displacements due to vertically propagating harmonic s-waves in each material can be written as



$$u_s(z_s, t) = A_s e^{i(\omega t + k_s^* z_s)} + B_s e^{i(\omega t - k_s^* z_s)} \quad (1)$$

$$u_r(z_r, t) = A_r e^{i(\omega t + k_r^* z_r)} + B_r e^{i(\omega t - k_r^* z_r)} \quad (2)$$

where  $\omega$  is the circular frequency of the harmonic wave and  $k^*$  is the complex wave number. No shear stress can exist at the ground surface ( $z_s=0$ ), so

$$\mathbf{t}(0, t) = G_s^* \mathbf{g}(0, t) = G_s^* \frac{\partial u_s(0, t)}{\partial z_s} = 0 \quad (3)$$

where  $G_s^* = G(1 + 2i\alpha)$  is the complex shear modulus of the soil. Substituting Equation (1) into Equation (3) and differentiating gives

$$G_s^* i k_s (A_s e^{i k_s(0)} - B_s e^{-i k_s(0)}) e^{i \omega t} = G_s^* i k_s (A_s - B_s) e^{i \omega t} = 0 \quad (4)$$

which is satisfied when  $A_s = B_s$ . Compatibility of displacements and continuity of stresses at the soil/rock boundary require

$$u_s(z_s = H) = u_r(z_r = 0) \quad (5)$$

$$\mathbf{t}_s(z_s = H) = \mathbf{t}_r(z_r = 0) \quad (6)$$

Substituting Equations (1) and (2) into Equation (5)

$$A_s \left( e^{ik_s^* H} + e^{-ik_s^* H} \right) = A_r + B_r \quad (7)$$

From Equation (6) and the definition of shear stress ( $\mathbf{t} = G_s^* \mathbf{u}/\mathbf{z}$ )

$$A_s i G_s^* k_s^* \left( e^{ik_s^* H} - e^{-ik_s^* H} \right) = i G_r^* k_r^* (A_r - B_r)$$

or

$$\frac{G_s^* k_s^*}{G_r^* k_r^*} A_s \left( e^{ik_s^* H} - e^{-ik_s^* H} \right) = A_r - B_r \quad (8)$$

The ratio

$$\frac{G_s^* k_s^*}{G_r^* k_r^*} = \mathbf{a}_z^*$$

where  $\mathbf{a}_z^*$  is known as the complex impedance ratio. Solving Equations (7) and (8) simultaneously gives

$$A_r = \frac{1}{2} A_s \left[ (1 + \mathbf{a}_z^*) e^{ik_s^* H} + (1 - \mathbf{a}_z^*) e^{-ik_s^* H} \right] \quad (9a)$$

$$B_r = \frac{1}{2} A_s \left[ (1 - \mathbf{a}_z^*) e^{ik_s^* H} + (1 + \mathbf{a}_z^*) e^{-ik_s^* H} \right] \quad (9b)$$

If a vertically propagating shear wave of amplitude,  $A$ , traveled upward through the rock and the soil was not present, the free surface effect at the rock outcrop would produce a bedrock outcropping motion of amplitude  $2A$ . If the soil was present, the free surface motion amplitude would be

$$2A_s = \frac{4A}{(1 + \mathbf{a}_z^*) e^{ik_s^* H} + (1 - \mathbf{a}_z^*) e^{-ik_s^* H}}$$

The transfer function,  $F(\mathbf{w})$ , defined as the ratio of the soil surface amplitude to the rock outcrop amplitude, is given by

$$F(\mathbf{w}) = \frac{2}{(1 + \mathbf{a}_z^*)e^{ik_s^*H} + (1 - \mathbf{a}_z^*)e^{-ik_s^*H}}$$

Obviously, the transfer function is a complex function. It can be rewritten using Euler's Law as

$$F(\mathbf{w}) = \frac{1}{\cos k_s^*H + i\mathbf{a}_z^* \sin k_s^*H} \quad (10)$$

### Solution of Single Layer Problem

Because the transfer function is defined as the ratio of the soil surface amplitude to the rock outcrop amplitude, the soil surface amplitude can be obtained as the product of the rock outcrop amplitude and the transfer function. Therefore, the response of the soil layer to a periodic input motion can be obtained by the following steps:

1. Express the input (rock outcrop) motion in the frequency domain as a Fourier series (as the sum of a series of sine waves of different amplitudes, frequencies, and phase angles). For an earthquake motion, this Fourier series will have both real and imaginary parts.
2. Define the transfer function (Equation 10). The transfer function will have both real and imaginary parts.
3. Compute the Fourier series of the output (ground surface) motion as the product of the Fourier series of the input (bedrock) motion and the transfer function. This Fourier series will also have both real and imaginary parts.
4. Express the output motion in the time domain by means of an inverse Fourier transform.

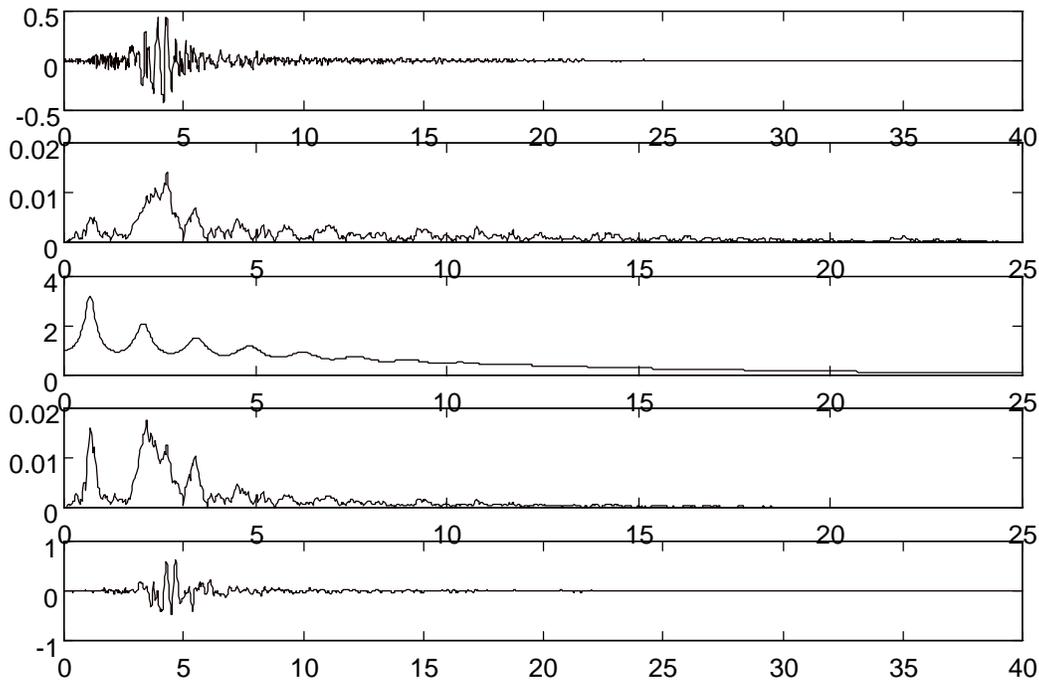
These steps are coded into a program using the mathematical processing program MATLAB in the box located below. The syntax of a MATLAB program is similar to common languages such as FORTRAN and BASIC, but MATLAB contains high-level functions that allow many complicated calculations and graphics commands to be processed in a single line of text. The MATLAB program is well-commented, and should be relatively easy to follow.

```

% EX73.M - A MATLAB script for computing the seismic response of a uniform
% damped soil layer on elastic bedrock. Input data corresponds to
% Example 7.3 in Kramer, S.L. (1996), Geotechnical Earthquake
% Engineering, Prentice Hall, 653 pp.
%
height=540; % soil layer thickness
vss=1500; % soil shear wave velocity
vsr=5000; % rock shear wave velocity
rho_s=125; % soil unit weight
rho_r=160; % rock unit weight
xs=0.05; % soil damping ratio
xr=0.02; % rock damping ratio
load gle.dat % load input motion
n=length(gle);
for j=2:n+1
    a(j)=gle(j-1)/981; % shift and convert input motion to g's
end
a(1)=0.0;
dt=0.02; % time step
df=1./(n*dt); % frequency increment
t=0.0:dt:n*dt; % set up time vector
f=0.0:df:n*df; % set up frequency vector
afft=fft(a)/n;
absfft=abs(afft);
for j=1:n/2+1 % set up single-sided FAS
    b(j)=2.*absfft(j);
    ff(j)=f(j);
end
alpha_z=(rho_s*vss*(1+i*xs))/(rho_r*vsr*(1+i*xr)); % complex impedance ratio
h(1)=1.0;
for j=2:n/2+1
    ksH(j)=2*pi*f(j)*height/(vss+xs*i*vss); % wave number x thickness
    h(j)=1./(cos(ksH(j))+i*alpha_z*sin(ksH(j))); % left half of transfer function
    h(n+3-j)=conj(h(j)); % right half of transfer function
end
for j=1:n/2+1
    habs(j)=abs(h(j)); % modulus of transfer function (for plotting)
end
subplot(5,1,1)
plot(t,a) % plot input motion (time domain)
subplot(5,1,2)
plot(ff,b) % plot FAS of input motion (frequency domain)
subplot(5,1,3)
plot(ff,habs) % plot modulus of transfer function (freq. domain)
for j=1:n+1
    acc(j)=afft(j)*h(j); % compute output motion in frequency domain
end
for j=1:n/2+1
    acc1(j)=2.*abs(acc(j)); % compute FAS of output motion
end
subplot(5,1,4)
plot(ff,acc1) % plot FAS of output motion (frequency domain)
atime=n*real(ifft(acc));
subplot(5,1,5)
plot(t,atime) % plot output motion (time domain)

```

The variables defined in the first part of the MATLAB program correspond to Example 7.3 in Kramer (1996). This example considers the response of a 540 ft thick soil layer of soil ( $v_{ss}=1500$  ft/sec,  $\gamma=125$  pcf, and  $\xi=5\%$ ) overlying bedrock ( $v_{sr}=5000$  ft/sec,  $\gamma=160$  pcf, and  $\xi=2\%$ ). The MATLAB program generates the plots shown below.



The first of these plots shows a time history of acceleration of the 40-sec input motion in the time domain. Immediately below this is the Fourier amplitude spectrum of the input motion - the Fourier amplitude spectrum shows the variation of amplitude with frequency for each of the frequencies in the Fourier series. The abscissas of the second, third, and fourth plots are frequency in Hz. The third plot shows the modulus (the square root of the sum of the squares of the real and imaginary parts) of the transfer function. The transfer function is clearly seen to have a series of local peaks that illustrate the nature of amplification that will take place at the natural frequencies of the soil layer; note that the greatest amplification will take place at the lowest natural frequency (where the transfer function reaches its global maximum). The fourth plot shows the Fourier amplitude spectrum of the output (ground surface) motion which is numerically equal to the product of the input motion (second plot) and the transfer function (third plot). The origin of this spectrum is clearly seen by comparing the second, third, and fourth plots - the peaks in the fourth plot (the output motion) are related to the peaks in the second plot (the input motion) and the third plot (the transfer function). Finally, the last plot shows the output (ground surface) motion in the time domain as obtained by taking the inverse Fourier transform of the output motion in the frequency domain.

## Multiple Soil Layers

The basic approach described in the preceding sections is also used to analyze layered soil deposits in ProShake - the only difference is that the transfer function is different for a layered soil deposit. The transfer function for a layered soil deposit must account for the transmission and reflection of waves at boundaries between adjacent layers, much as those factors were accounted for at the soil/rock boundary in the previous section.

Consider the soil deposit shown to the right. Within a given layer, say layer  $j$ , the horizontal displacements will be given by

$$u_j(z_j, t) = (A_j e^{ik_j^* z_j} + B_j e^{-ik_j^* z_j}) e^{i\omega t} \quad (11)$$

At the boundary between layer  $j$  and layer  $j+1$ , compatibility of displacements requires that

$$A_{j+1} + B_{j+1} = A_j e^{ik_j^* h_j} + B_j e^{-ik_j^* h_j} \quad (12)$$

Continuity of shear stresses requires that

$$A_{j+1} - B_{j+1} = \frac{G_j^* k_j^*}{G_{j+1}^* k_{j+1}^*} (A_j e^{ik_j^* h_j} - B_j e^{-ik_j^* h_j}) \quad (13)$$

Note that Equations (12) and (13) are analogous to Equations (7) and (8), respectively. Defining  $\mathbf{a}_j^*$  as the complex impedance ratio at the boundary between layers  $j$  and  $j+1$ , the wave amplitudes for layer  $j+1$  can be obtained from the amplitudes of layer  $j$  by solving Equations (12) and (13)

$$A_{j+1} = \frac{1}{2} A_j (1 + \mathbf{a}_j^*) e^{ik_j^* h_j} + \frac{1}{2} B_j (1 - \mathbf{a}_j^*) e^{-ik_j^* h_j} \quad (14a)$$

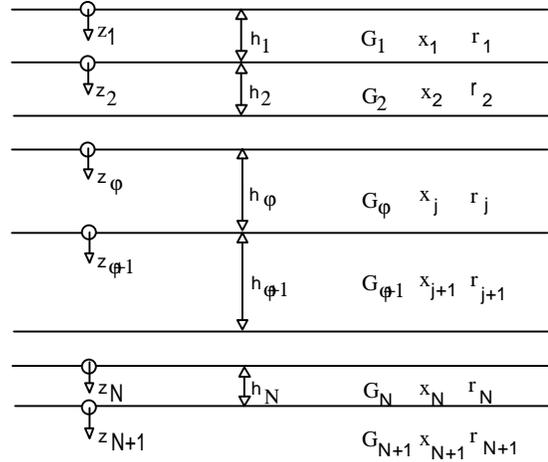
$$B_{j+1} = \frac{1}{2} A_j (1 - \mathbf{a}_j^*) e^{ik_j^* h_j} + \frac{1}{2} B_j (1 + \mathbf{a}_j^*) e^{-ik_j^* h_j} \quad (14b)$$

At the ground surface ( $z_1 = 0$ ), the requirement that the shear stress must be zero means that  $A_1 = B_1$ . Applying Equations (14) recursively for  $j = 1, 2, 3, \dots, N$ , the coefficients  $A_{j+1}$  and  $B_{j+1}$  can be related to  $A_j$  and  $B_j$  by

$$A_{j+1} = a_{j+1}(\omega) A_1 \quad (15a)$$

$$B_{j+1} = b_{j+1}(\omega) B_1 \quad (15b)$$

where the functions  $a_{j+1}(\omega)$  and  $b_{j+1}(\omega)$  represent the effects of the wave interactions that take place at all of the layer interfaces above layer  $j+1$ . Then, a transfer function relating the motions at the tops of any two layers, say layers  $i$  and  $j$ , can be expressed as



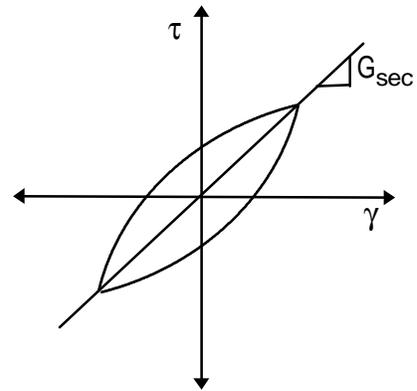
$$F_{ij}(\mathbf{w}) = \frac{a_i(\mathbf{w}) + b_i(\mathbf{w})}{a_j(\mathbf{w}) + b_j(\mathbf{w})} \quad (16)$$

This transfer function can become quite complicated, but it is used in exactly the same way as the much simpler transfer function developed for the single layer case. In fact, the MATLAB program that illustrated the single layer case could be used to compute the response for a multi-layered problem by changing only one line - the line where the transfer function is defined (with the comment % left half of transfer function).

## Equivalent Linear Analysis

The nonlinear and inelastic behavior of soil is well established in geotechnical engineering. The nonlinearity of soil stress-strain behavior means that the shear modulus of the soil is constantly changing. The inelasticity means that the soil unloads along a different path than its loading path, thereby dissipating energy at the points of contact between particles. Rigorous analysis of the mechanical response of soils to any type of loading, dynamic or otherwise, would require that the stress-strain behavior of each element of soil be tracked directly in the time domain. The method of analysis used in SHAKE (and ProShake) cannot allow for nonlinear stress-strain behavior because its representation of the input motion by a Fourier series and use of transfer functions for solution of the wave equation rely on the principle of superposition - which is only valid for linear systems.

To approximate the actual nonlinear, inelastic response of soil, an equivalent linear approach can be utilized. In the equivalent linear approach, linear analyses are performed with soil properties that are iteratively adjusted to be consistent with an effective level of shear strain induced in the soil. In the equivalent linear approach, the shear modulus is taken as the secant shear modulus which, as shown to the right, approximates an "average" shear modulus over an entire cycle of loading. As the level of shear strain increases, the secant shear modulus decreases. The relationship between secant shear modulus and shear strain amplitude can be characterized by means of a modulus reduction curve. The nature of this curve, which has an ordinate of modulus ratio ( $= G/G_{max}$ ) and an abscissa of  $\log$  (shear strain), has been well established for many soils. ProShake has a library of modulus reduction relationships that can be selected in the Input Manager. The solution algorithm used in SHAKE (and ProShake) assumes viscous soil damping which it represents using a complex shear modulus. Viscous damping implies behavior that would be characterized by elliptical stress-strain loops. Because actual stress-strain loops are seldom elliptical, an equivalent damping ratio is used - the equivalent damping ratio is equal to the damping ratio that would be computed based on the area within the hysteresis loop, the secant shear modulus, and the maximum shear strain. The relationship between this equivalent damping ratio and shear strain is characterized by means of a damping curve. The nature of this curve, which has an ordinate of damping ratio and an abscissa of  $\log$  (shear strain), has been well established for many soils. ProShake has a library of damping



curves that can be selected in the Input Manager.

In an equivalent linear analysis, the first iteration is performed using shear modulus and damping ratios that correspond to some initially estimated level of shear strain. In ProShake, the first iteration is based on an assumed shear strain of 0.001%. Following the first iteration, the effective shear strain, defined as

$$\mathbf{g}_{eff} = R_g \mathbf{g}_{max}$$

where  $R_g$  is a strain reduction factor often taken as

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

is computed. The shear modulus and damping ratio corresponding to  $\gamma_{eff}$  is then used for the next iteration. This process is repeated until the computed effective strain does not change much from one iteration to the next. At this point, the equivalent linear process is said to have converged.

While the equivalent linear approach allows the most important effects of nonlinear, inelastic soil behavior to be approximated, it must be emphasized that it remains a linear method of analysis. The strain-compatible shear modulus and damping ratio remain constant throughout the duration of an earthquake - when the strains induced in the soil are small and when they are large. Permanent strains cannot be computed and porewater pressures cannot be computed. However, the equivalent linear approach has been shown to provide reasonable estimates of soil response under many conditions of practical importance.

## Verification

As stated earlier in the User's Manual, ProShake was written from scratch using the same computational procedure used in the original version of SHAKE (Schnabel et al., 1972). Though the basic procedures are the same, some aspects of their numerical implementation were different. As a result, verification of the accuracy of ProShake and comparison of its results with the results from previous versions of SHAKE are required.

### Verification Using Analytical Solutions

ProShake has been verified against exact analytical solutions for the simple loading cases for which such solutions are available and found to produce accelerations that match the exact solutions perfectly to at least the first six decimal points (with acceleration measured in g's).

### Comparison with SHAKE

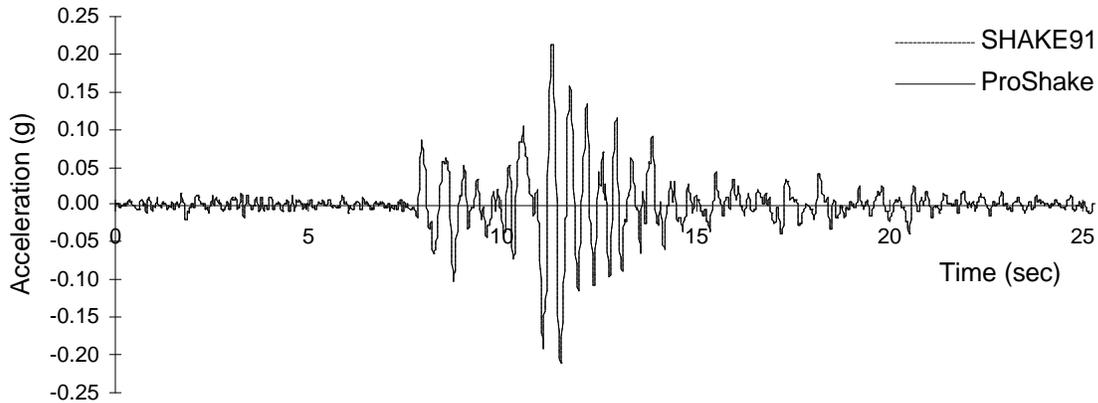
Additional verification of the numerical implementation of ProShake can be obtained by comparing its results with those of previous versions of SHAKE when both are applied to the same problem. Because SHAKE91 is the most commonly used version of SHAKE in current geotechnical earthquake engineering practice, a number of such comparisons between ProShake and SHAKE91 have been performed; the results of a typical comparison are described in this section.

The numerical implementation of ProShake differs from that of SHAKE91 in the following ways:

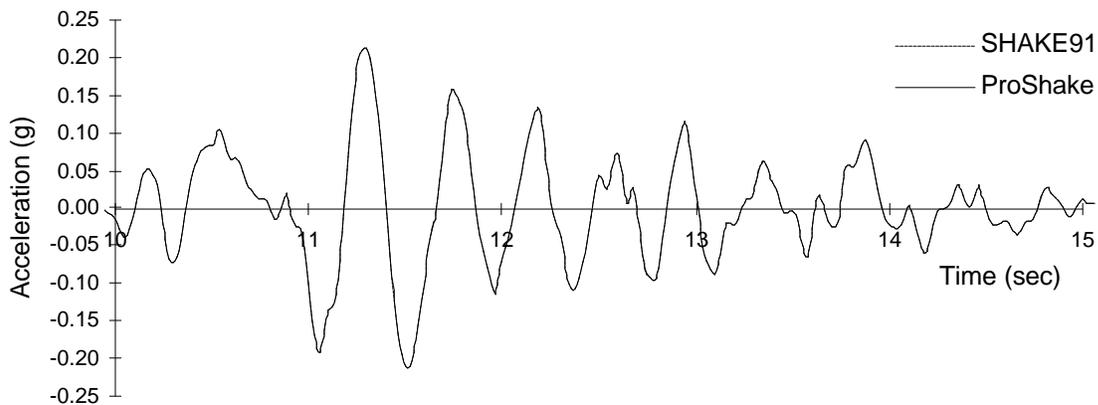
1. ProShake uses 32-bit arithmetic rather than the 16-bit arithmetic used in SHAKE91. This is primarily a result of recent advances in development platforms - 32-bit Fortran became available for personal computers after the development of SHAKE91 and before the development of ProShake.
2. ProShake uses a different Fast Fourier Transform (FFT) routine. The routine used in ProShake, taken from the International Mathematical Software Library (IMSL), represents a more recent and efficient implementation of the FFT.
3. ProShake uses a more efficient and robust procedure to iterate toward strain-compatible soil properties. For most analyses, the last iteration required to drop the modulus and damping error below the specified error tolerance in ProShake will produce smaller final errors than the last iteration for the same error tolerance in SHAKE91.
4. ProShake handles cutoff frequencies slightly differently than SHAKE91. SHAKE91 applies its cutoff frequency *after* scaling the input motion to the specified peak acceleration; as a result, the actual peak acceleration used in the analysis can be different than the desired peak acceleration. ProShake applies the cutoff frequency *before* any required scaling - in this way, the accelerations that are actually used as input in the analysis are equal to the desired accelerations. The

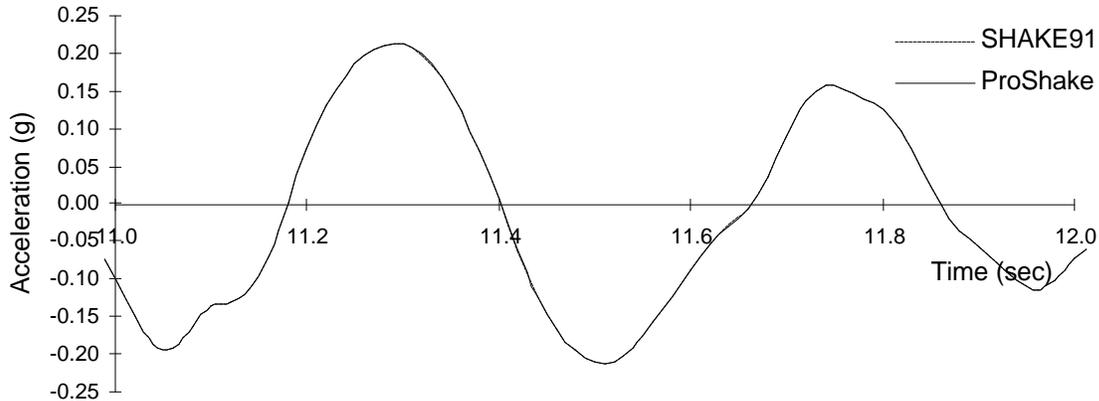
difference between these approaches is small for reasonably high cutoff frequencies, but the approach taken in ProShake is considered to be more appropriate.

The relative performance of ProShake and SHAKE91 can be illustrated using the example problem from the original SHAKE User's Manual (Schnabel et al., 1972). This problem, for which the input file is contained in the file shake.dat, involves the response of a 150-ft-thick soil deposit. Analyzing the deposit using both ProShake and SHAKE91 produces the time histories of ground surface acceleration shown below:



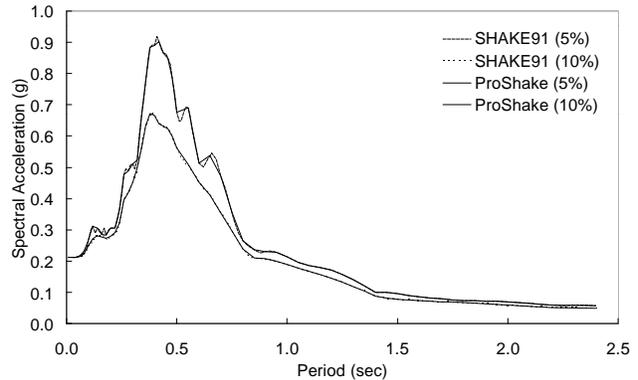
The differences between the ground surface accelerations produced by ProShake and SHAKE91 are very small. To make these differences more apparent, portions of the time histories are expanded in the two plots shown below:



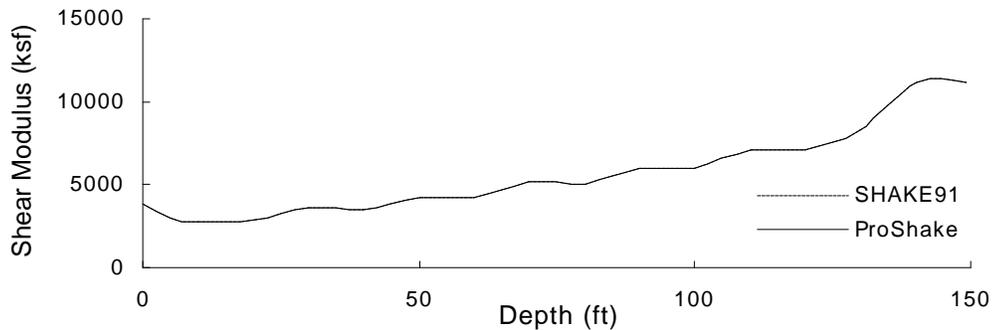


Even when the time scale is expanded tremendously, the strongest part of the computed response shows very close agreement between the two programs.

The programs can also be compared from the standpoint of response spectra - the computed ground surface response spectra for structural damping ratios of 5% and 10% are illustrated to the right. Again, the response spectra are very similar (in fact, part of the differences in these plots is explained by the fact that ProShake and SHAKE91 compute spectral accelerations at different periods).

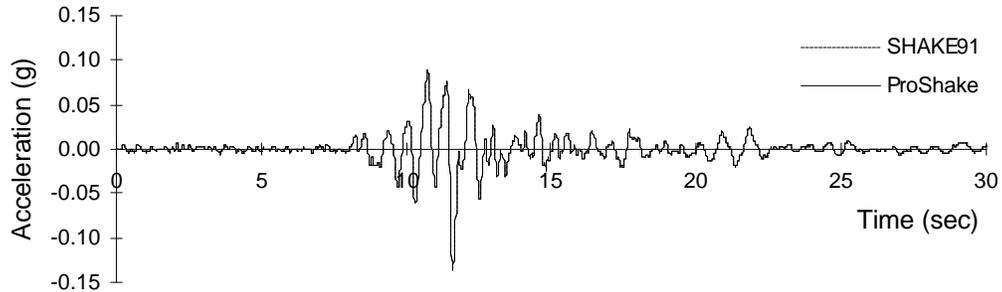


Another comparison can be made with respect to the equivalent linear properties that both programs converge to. The equivalent linear shear moduli from the final iteration of ProShake and SHAKE91 are shown below. Again, the very close agreement between the moduli from the two programs verifies their consistency.

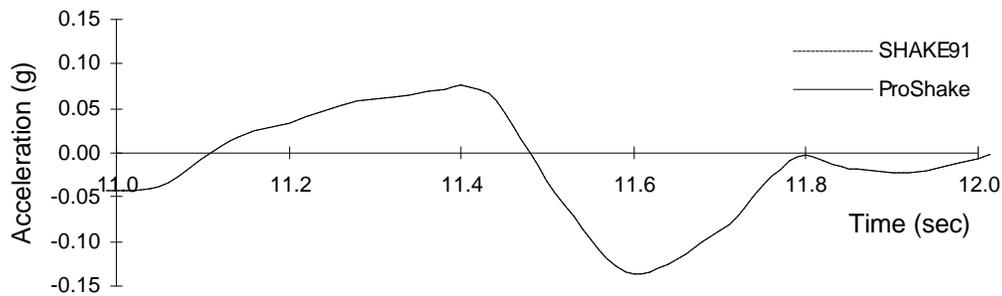
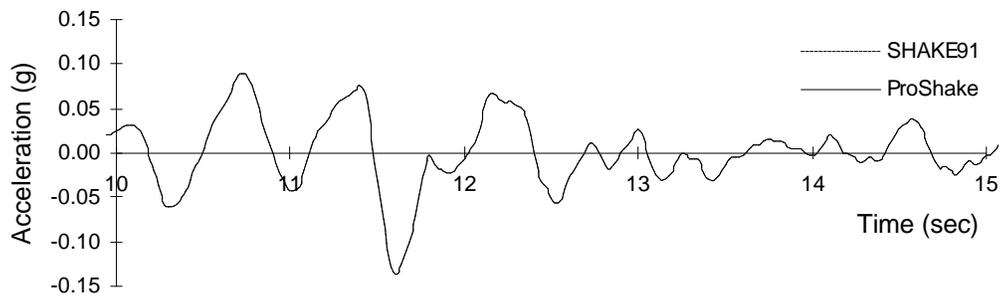


The same set of comparisons can be made for other ground response problems. The following plots compare the responses predicted by ProShake and SHAKE91 when both are applied to the

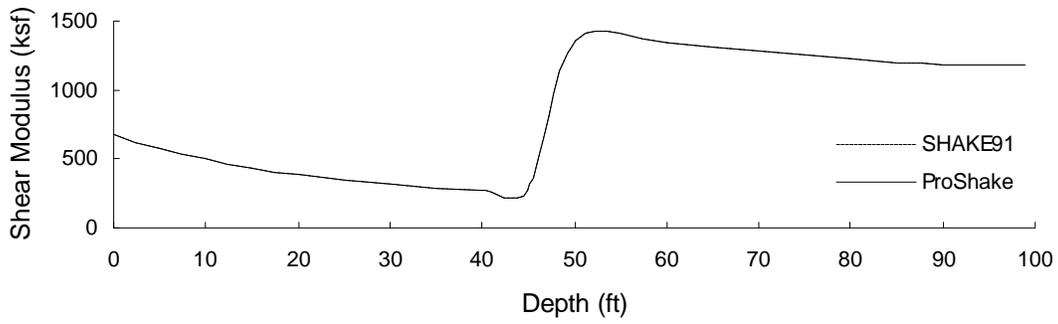
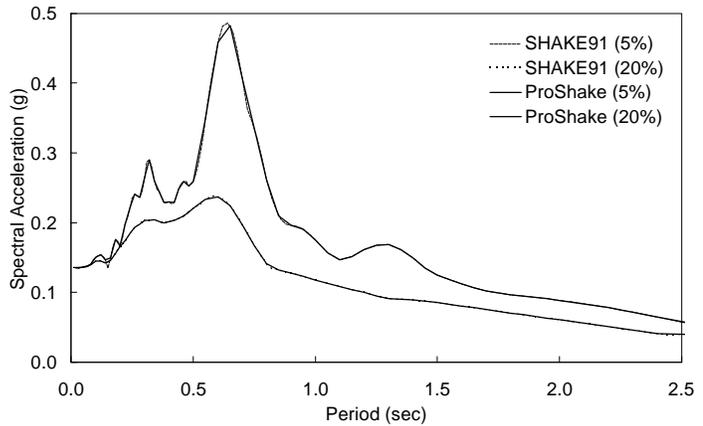
problem described in the Tutorial section of this User's Manual. The tutorial problem involved a 50 ft thick layer of soft silty clay overlaying a 50 ft thick layer of stiff clay. The thick, soft nature of the silty clay layer also produces ground surface motions with relatively low accelerations and long periods. The following plot illustrates this response:



Again, the differences between the ground surface accelerations produced by ProShake and SHAKE91 are very small, even when the time scale is expanded as shown below:



Response spectra are also very similar as illustrated (for structural damping ratios of 5% and 20%) to the right. The distinguishing feature of the tutorial problem, from the ground response standpoint, is the presence of the strong impedance contrast at the boundary between the soft silty clay and the stiff clay. This impedance contrast causes large strains near the bottom of the soft silty clay layer that lead to low shear moduli in the equivalent linear model.



## Strong Motion Parameters

### Arias Intensity

The Arias Intensity (Arias, 1970), also influenced by amplitude, frequency content, and duration, is defined as

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

The Arias Intensity has units of velocity and is usually expressed in meters per second. Since it is obtained by integration over the entire duration, rather than over the duration of strong motion, its value is independent of the method used to define the duration of strong motion.

### Bracketed Duration

The bracketed duration is the time interval between the first and last exceedances of a threshold acceleration (Bolt, 1969). The threshold acceleration is set at 0.05g in ProShake.

### Peak Acceleration

The maximum absolute value of acceleration. The peak acceleration provides a useful measure of the strength of the higher frequency components of a ground motion.

### Peak Velocity

The maximum absolute value of velocity. The peak velocity provides a useful measure of the strength of the intermediate frequency components of a ground motion.

### Peak Displacement

The maximum absolute value of displacement. The peak displacement provides a useful measure of the strength of the lower frequency components of a ground motion.

### Predominant Period

The predominant period is the period corresponding to the maximum value of the Fourier spectrum. Because Fourier spectra are typically quite jagged, the period corresponding to the highest peak in a raw spectrum may not correspond well to the strongest part of the motion. For that reason, some users may want to obtain predominant periods from smoothed spectra. The cross-hair feature can be used to estimate predominant period from ProShake Fourier spectrum plots.

### Response Spectrum Intensity

The response spectrum intensity (Housner, 1959) is defined as

$$SI(\mathbf{x}) = \int_{0.1}^{2.5} PSV(\mathbf{x}, T) dT$$

i.e., the area under the pseudo-velocity response spectrum between periods of 0.1 second and 2.5 seconds. In ProShake, the response spectrum intensity is computed for a structural damping ratio of 5%. It captures important aspects of the amplitude and frequency content (in the range of primary importance for structures) in a single parameter.

### **RMS Acceleration**

The RMS acceleration is a single parameter that includes the effects of the amplitude and frequency content of a strong motion record

$$a_{RMS} = \sqrt{\frac{1}{T_d} \int_0^{T_d} [a(t)]^2 dt}$$

where  $T_d$  is the duration of the motion. Because the integral is not strongly influenced by large, high frequency accelerations (which occur only over a very short period of time) and because it is influenced by the duration of the motion, the rms acceleration can be very useful for engineering purposes. ProShake uses the Trifunac duration for computation of the RMS acceleration.

### **Trifunac Duration**

The Trifunac duration (Trifunac and Brady, 1975) is defined as the time interval between the points at which 5% and 95% of the energy in a ground motion have been delivered. Numerically, it corresponds to the time between the 5% and 95% points on a Husid plot.



## Built-In Soil Models

### Vucetic-Dobry

Vucetic and Dobry (1991), building on the work of Kokoshu (1980) in an investigation motivated by the performance of Mexico City clay in the 1985 Michoacan earthquake, showed clearly how modulus and damping behavior are influenced by soil plasticity. Vucetic and Dobry developed families of modulus reduction and damping curves as functions of plasticity index. ProShake allows you to specify any plasticity index - the program will determine the corresponding curves by interpolation. The curves originally proposed by Vucetic and Dobry are shown on the plots in green; from left to right, they represent  $PI = 0$ ,  $PI = 15$ ,  $PI = 30$ ,  $PI = 50$ ,  $PI = 100$ , and  $PI = 200$ . The curve for the selected  $PI$  is obtained by linear interpolation and shown in yellow. See also Dobry and Vucetic (1987).

### Sun, Golesorkhi, and Seed

Sun, Golesorkhi, and Seed (1988) developed a series of modulus reduction and damping curves for different ranges of plasticity index. Separate curves for  $5 < PI < 10$ ,  $10 < PI < 20$ ,  $20 < PI < 40$ ,  $40 < PI < 80$ , and  $PI > 80$  were developed. ProShake will ask for the plasticity index of the soil, and use it to assign the proper curve (i.e., it does not interpolate).

### Ishibashi-Zhang

Modulus reduction and damping characteristics, particularly for low-plasticity soils, are also influenced by effective confining pressure. Ishibashi and Zhang (1993) proposed expressions for shear modulus and damping ratio that accounted for plasticity index and effective confining pressure. ProShake will compute the effective confining pressure, but you must provide the plasticity index. In calculating the effective confining pressure an at rest earth pressure coefficient ( $K_0$ ) of 0.5 is assumed. It should be noted that the actual Ishibashi and Zhang equations predict  $G/G_{max}$  values slightly greater than 1 over a range of low strains. ProShake sets  $G/G_{max} = 1.0$  for these values. ProShake does not modify the damping curves, however, for the effects of this limiting value. See also Ishibashi (1992).

### Seed-Idriss Sand

Seed and Idriss (1970) developed the first widely used modulus reduction and damping curves for sand. Their curves showed a range of modulus reduction behavior. ProShake allows you to select the average of that range, or the upper or lower bounds.

### Gravel

Seed et al. (1984) developed modulus reduction and damping curves for gravel. These curves are based on the average behavior of 12-inch diameter cyclic triaxial tests on four different gravels.

### Rock

Modulus reduction and damping curves for rock were included in sample data files for the original SHAKE program (Schnabel et al., 1970).

**Linear**

ProShake allows you to specify a linear elastic or linear viscoelastic material. When you select this material, ProShake will use the maximum shear modulus and prompt you to enter a damping ratio. You should note that the transfer function for an undamped linear elastic layer will have singularities at the natural frequencies of the layers; these can lead to numerical problems that prevent program execution.



## Definitions

**Analysis Summary** - a summary of the soil profile, input motion, and output selections for the analysis. The analysis summary is written to the Report - from there, it can be printed and placed in a project or assignment file.

**Cyclic Stress Ratio** - the ratio of the peak shear stress to the vertical effective stress.

**Damping Error** - the difference between damping ratio values in successive iterations divided by the damping ratio value used in the most recent iteration (expressed as a percentage).

**Drag-and-Drop** - By holding the left mouse button down, any line (corresponding to a particular material layer) can be copied and placed at the location of the cursor at the time the left mouse button is released.

**Effective Shear Strain** - The amplitude of a harmonic (sinusoidal) shear strain time history that would be equivalent to the time history of shear strain from an actual earthquake record. The effective shear strain is equal to the product of the maximum shear strain and the strain ratio.

**Frequency Content** - the distribution of acceleration amplitudes in the frequency domain. The frequency content can be obtained from the shape of the Fourier spectrum of the motion.

**Impedance Ratio** - the ratio of specific impedances of two adjacent soil layers, where the specific impedance is defined as the product of the density and shear wave velocity of a material.

**Input Motion Format** - ProShake input motion files are formatted in a certain way. The two input motion files included in the distribution of ProShake, yerba.eq and treas.eq, are in the proper format. Input motion files in any other format can be converted to ProShake Input Motion Format by using the Convert Ground Motion File utility.

**Modulus Error** - the difference between shear modulus values in successive iterations divided by the shear modulus value used in the most recent iteration (expressed as a percentage).

**Peak Acceleration** - the maximum (absolute) value of acceleration in an acceleration time history.

**Peak Displacement** - the maximum (absolute) value of displacement in a displacement time history.

**Peak Shear Strain** - the maximum (absolute) value of shear strain in a shear strain time history.

**Peak Shear Stress** - the maximum (absolute) value of shear stress in a shear stress time history.

**Peak Velocity** - the maximum (absolute) value of velocity in a velocity time history.

**Quiet Zone** - a portion of an input motion with zero (or very small) accelerations. Because the frequency domain solution of ProShake implies periodicity (i.e., that the input motion repeats itself indefinitely), a quiet zone may be required for the computed response to an individual application of the input motion to be distinct.

**Tab Label** - the label found on the protruding portion of a tab form. The tab label shows which of the tab forms is active. Only one tab form can be active at a time.

**Trailing Zeroes** - acceleration values of 0.0 that are appended to the end of an input motion file to bring the total number of acceleration values to an integer power of 2.



## References

- Dobry, R. and Vucetic, M. (1987). "Dynamic properties and seismic response of soft clay deposits," *Proceedings, International Symposium on Geotechnical Engineering of Soft Soils*, Mexico City, Vol. 2, pp. 51-87.
- Housner, G.W. (1959). "Behavior of structures during earthquakes," *Journal of the Engineering Mechanics Division*, ASCE, Vol. 85, No. EM14, pp. 109-129.
- Idriss, I.M. and Sun, J.I. (1992). "SHAKE91: A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits," *User's Guide*, University of California, Davis, California, 13 pp.
- Ishibashi, I. (1992). Discussion to "Effect of soil plasticity on cyclic response," by M. Vucetic and R. Dobry, *Journal of Geotechnical Engineering*, ASCE, Vol. 118, No. 5, pp. 830-832.
- Ishibashi, I. and Zhang, X. (1993). "Unified dynamic shear moduli and damping ratios of sand and clay," *Soils and Foundations*, Vol. 33, No. 1, pp. 182-191.
- Kokoshu, T. (1980). "Cyclic triaxial test of dynamic soil properties for wide strain range," *Soils and Foundations*, Vol. 20, No. 2, pp. 45-60.
- Kramer, S.L. (1996). *Geotechnical Earthquake Engineering*, Prentice Hall, Upper Saddle River, New Jersey, 653 pp.
- 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.
- Seed, H.B., Wong, R.T., Idriss, I.M., and Tokimatsu, K. (1986). "Moduli and damping factors for dynamic analyses of cohesionless soils," *Journal of Geotechnical Engineering*, ASCE, Vol. 112, No. 11, pp. 1016-1032.
- Sun, J.I., Galesorkhi, R., and Seed, H.B. (1988). "Dynamic moduli and damping ratios for cohesive soils," *Report No. EERC-88/15*, Earthquake Engineering Research Center, University of California, Berkeley.
- Vucetic, M. and Dobry, R. (1991). "Effect of soil plasticity on cyclic response," *Journal of Geotechnical Engineering*, ASCE, Vol. 117, No. 1, pp. 89-107.