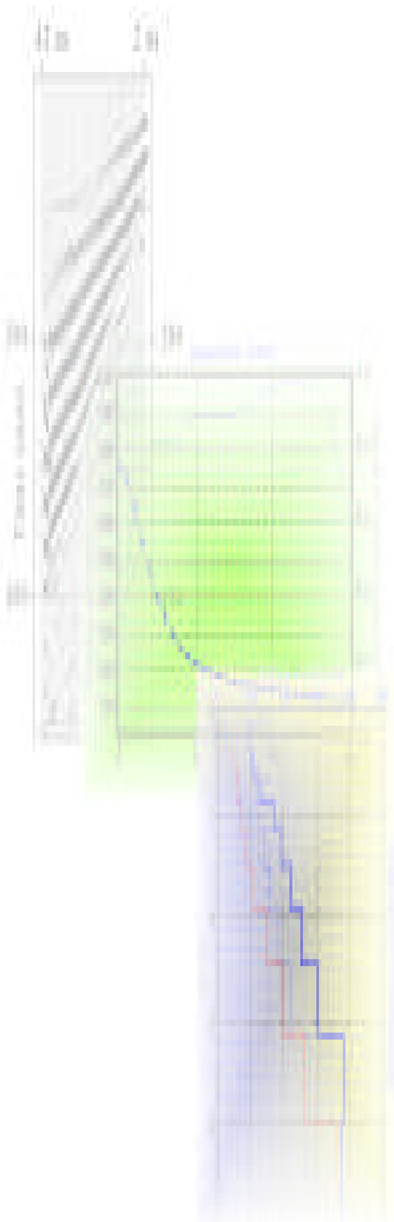


USING

SURFSEIS© 2000

For Multichannel Analysis of Surface Waves (MASW)

User's Manual

October, 2000

Written by Choon B. Park with assistance from

Rick Miller, Mary Brohammer, Jianghai Xia, and Julian Ivanov
of the
Kansas Geological Survey

Kansas Geological Survey
1930 Constant Avenue
Lawrence, Kansas 66047-3726
Phone: 785-864-3965
Fax: 785-864-5317
Email: SurfSeis@kgs.ukans.edu

Disclaimer of Warranty

The SurfSeis software has been extensively tested and its documentation, including the user's manual, has been carefully reviewed. **However, the Kansas Geological Survey makes no warranty or representation, either expressed or implied, with respect to the SurfSeis program and its documentation, its quality, performance, merchantability, or fitness for a particular purpose.** The SurfSeis software is licensed (not sold) on an "as is" basis, and the licensed user assumes all risk as to its quality, the results obtained from its use, and the performance of the program.

In no event will the Kansas Geological Survey be liable for any direct, indirect, special, incidental, or consequential damages resulting from any defect in the SurfSeis software, documentation, or program support.

This disclaimer of warranty is exclusive and in lieu of all others, oral or written, express or implied. No agent or employee is authorized to make any modification, extension, or addition to this warranty.

Credits

PROGRAMMING

Primary	Choon B. Park
Co-Programmers	Jianghai Xia and Julian Ivanov

PROJECT MANAGEMENT

Rick Miller and Mary Brohammer

GRAPHIC DESIGN

Julia Shuklaper and Choon B. Park

ADMINISTRATIVE AND TECHNICAL SUPPORT

Kathy Sheldon

Acknowledgments

SurfSeis has been developed in association with rigorous testing of the multi-channel analysis of surface waves (MASW) method developed at the Kansas Geological Survey. During this period, many people and organizations supported this program through encouragement, constructive comments, and funded projects. Firm and continuous support from the entire staff of the Kansas Geological Survey made realization of the MASW method possible. James Hunter, Ron Good, and their colleagues from Geological Survey of Canada provided an invaluable chance to refine the method during the field tests at Fraser River Delta, Vancouver, British Columbia. Rob Huggins and employees at Geometrics were also key supporters of the technique software development.

Contents at a Glance

Chapter 1

Introduction

The multichannel analysis of surface waves (MASW) method was first introduced into geotechnical and geophysical community in early 1999 although earlier development versions came out several years prior. MASW is a seismic method which generates a shear-wave velocity (Vs) profile (i.e., Vs versus depth) by analyzing Rayleigh-type surface waves on a multichannel record. The method utilizes multichannel recording and processing concepts widely used for several decades in reflection surveying for oil exploration. MASW utilizes energy commonly considered noise on conventional reflection seismic surveys. The fundamental mode of ground roll (the Rayleigh-type surface wave event) is without a doubt one of the most troublesome types of source-generated noise on reflection surveys. Rayleigh wave energy is defined as signal in MASW analysis, and needs to be enhanced during both data acquisition and processing steps. Because of this reversed definition of signal and noise in comparison to seismic reflection, the method requires slightly different considerations and approaches to data acquisition. Acquisition parameters are optimally determined using the approach described by Park et al. (1999a). It is suggeted that in most cases parameter design is favorable to body-wave (e.g., reflection and refraction waves) acquisition as well. This aspect could be beneficial in some situations when both methods—surface-wave and body-wave—analysis are required.

One of the most significant differences in data acquisition procedures with MASW when compared with the conventional body-wave survey is the enhancement of low frequency energy.

A sledgehammer is a common seismic source used for a MASW survey although many different types of seismic source can be used (see Miller et al., 1986; Keiswetter and Steeples, 1995). At most of the soil sites a sledgehammer with 10-kg mass usually assures optimum spectral characteristics for a target depth less than 10 m. A heavier (or lighter) one may need to be used to meet the required spectral characteristics as the primary target depth increases (or decreases). It is also important to use a low natural frequency geophone for most studies. A 4.5-Hz geophone is most often recommended.

SurfSeis is designed to generate a Vs profile using a simple 3-step procedure: preparation of a multichannel record (sometimes called a shot gather or a field file), dispersion-curve analysis, and inversion. The term “multichannel record” indicates a seismic data set acquired by using a recording instrument with more than one channel and, for most cases involving modern seismographs, at least 12 channels would be necessary. However, a multichannel record for use with the MASW method can be recorded in several different ways, with its assimilation not limited to the number of channels available on the recording device. For example, a 24-trace record can be obtained with a single-channel device by stepping the shot and/or receiver away from each other using a uniform increment. By repeating this procedure 24 times, following an appropriate acquisition sequence in which the distance between seismic source and receiver change in a consistent manner, a shot gather can be generated with 24 equally spaced traces (this is called a noise analysis, see Sheriff and Geldart, 1982). It can also be obtained with a 12-channel recording device by making the measurement twice, rolling the spread (12 receivers) out 12 intervals or moving the source 12 increments away. It is important to maintain the same receiver spacing for all the constituent traces and keep good field notes as to distances (source offset) between source and the closest-to-source receiver as well as receiver spacing. Once a record is prepared, it is ready to be converted into the processing format—modified SEG-Y (KGS)—and begin the next step: dispersion-curve analysis.

The next step begins the process to calculate a Vs profile from the dispersion-curve analysis performed on the multichannel record previously prepared. This step is the most critical because it has the greatest influence on the confidence in the Vs profile. In other words, the Vs profile will have, at best, as much confidence as the dispersion curve provided to the inversion step. The inversion uses the dispersion curve as the only empirical data with no reference to the original seismic record. Confidence in the dispersion curve can be estimated through a measure of signal-to-noise ratio (S/N) displayed along with the curve. The fundamental mode of the surface wave is the signal used for the analysis. There are several factors that interfere and disturb the analysis: body waves and higher-mode surface waves. These noise sources can be controlled to a limited extent during data acquisition, but never totally eliminated. Dominance of these types of noise is common with farther offset distance between source and receiver (see Park et al., 1999a and 1999b). To obtain an accurate dispersion curve, it is important to examine, without any bias, the spectral content and propagation velocity (called phase velocity) characteristics of both signal and noise waves. SurfSeis allows examination of these characteristics through a unique step called overtone analysis. Inversion of the calculated dispersion curve is performed with SurfSeis in a fully automated manner in which a most probable solution is sought in an iterative mode (see Xia et al., 1999).

Display of data during certain parts of the analysis is critical to insuring the optimum solution. It can sometimes become a necessary step for the assessment of optimum analysis parameters. All the display modules in SurfSeis can be used effectively to provide various types of images that can be used during the analysis as well as preparation of a project report.

A generalized flow chart for SurfSeis is displayed in Figure 1.1.

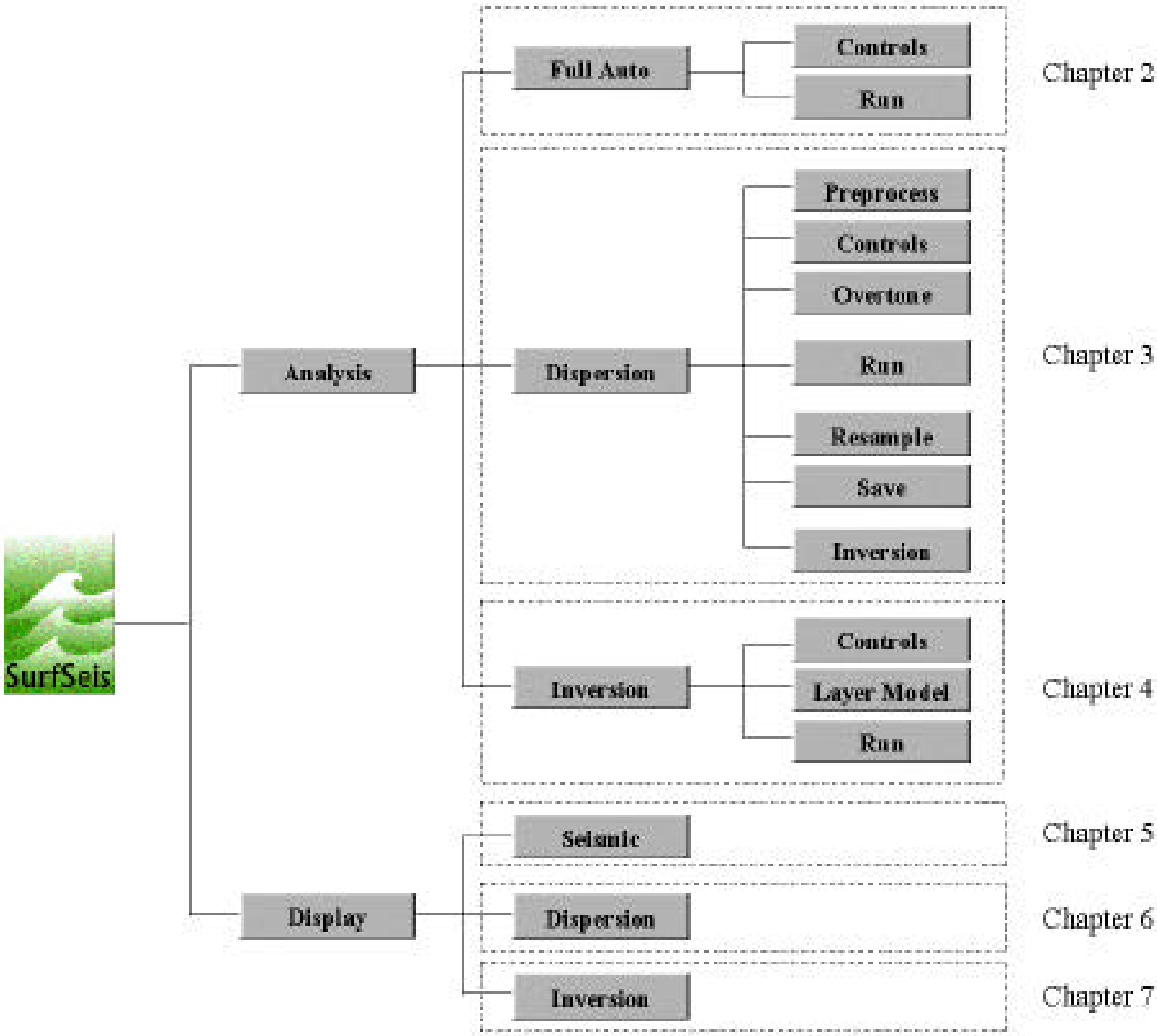

SurfSeis
Analysis
Display
Full Auto
Controls
Run
Chapter 2
Dispersion
Preprocess
Controls
Overtone
Run
Resample
Save
Inversion
Chapter 3
Inversion
Controls
Layer Model
Run
Chapter 4
Seismic
Chapter 5
Dispersion
Chapter 6
Inversion
Chapter 7

Figure 1.1

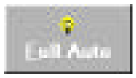
Chapter 2

Full Auto

A single multichannel seismic record is processed to produce one S-wave velocity profile when fully automatic mode is selected. All the processing parameters such as optimum frequency and depth ranges are automatically determined based on predetermined "normal or average" data characteristics. This option of analysis is best suited for seismic data with a good signal-to-noise ratio (S/N). The following files are generated and saved during and at the end of process:

- One dispersion curve (*.DC)
- One file containing all the processing parameters used for inversion (*.IND).
- One output file from the inversion process that contains the theoretical dispersion data and layer model.
- Another output file from inversion processes that contains the processing history followed during the iterative inversion steps.

Note: If the seismic file input contains more than one record, the first record in the file is processed.

2.1 Main ¾ 

When the "Full Auto" button is selected, a dialog box (Figure 2.1.1) pops up that allows selection of a multichannel seismic record(s)† file. All intermediate files resulting from the processing flow: dispersion curve (*.DC), inversion input (*.IND), and output (*.IVO and *.LST) files, will be displayed with appropriate extensions. These names, however, can be overwritten as desired.

Once an input seismic file is selected and displayed, a "preprocess" step is applied to the input data. This quick look process provides an approximate range of surface wave arrivals in a display area detected and marked by the program as shown in Figure 2.1.2. This range is determined by lower and upper bounds of phase velocity. Phase velocities of the dispersion curve will usually fall in this range. If the marked zone encompasses most of the surface wavefield, the remainder of the process will proceed effectively. If the marked zone is not consistent with the surface wave arrivals, the process may need to proceed through the "step-by-step" procedure (see Chapter 3).

†If the input seismic file contains more than one multichannel record, the first record will be selected for processing.

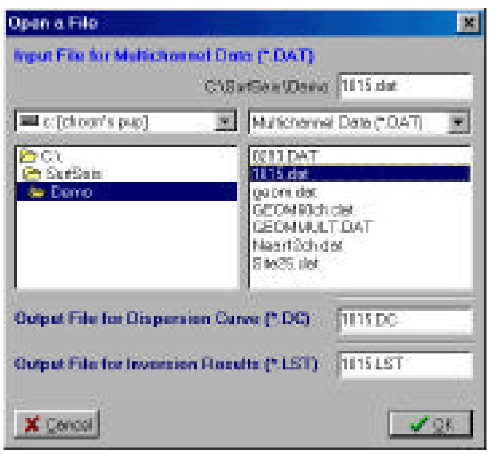


Figure 2.1.1

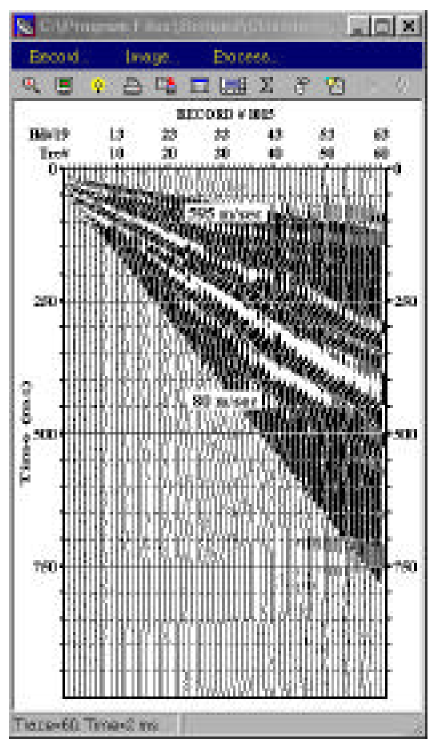


Figure 2.1.2

2.2 Controls

"Full Auto" analysis is designed to perform the entire process of generating an S-velocity profile without intervention, using the parameters determined either during the process or user-defined default values. Some key parameters can be manually set before processing ("run") begins. In any case, the default values shown in the controls dialog box represent the most optimum values.

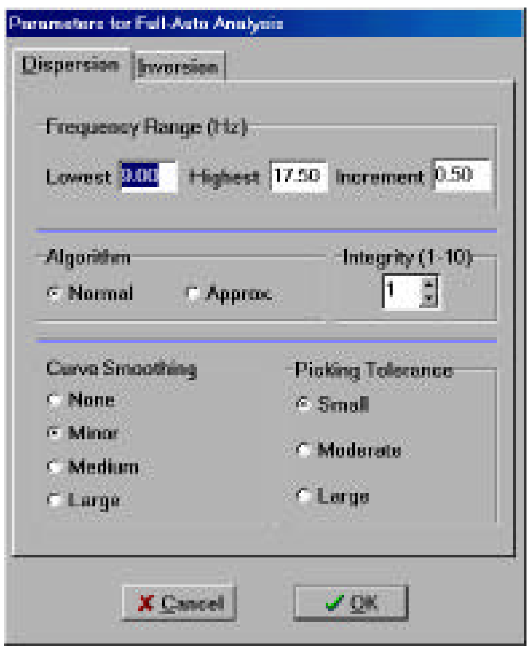


Figure 2.2.1

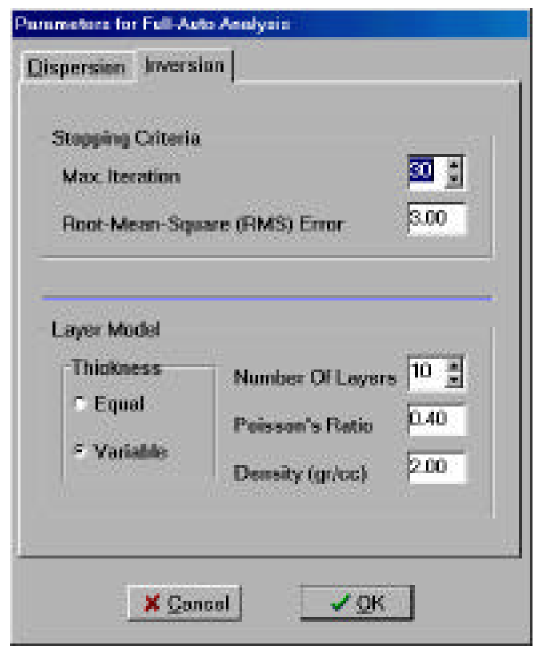


Figure 2.2.2

2.2.1 Controls ¾ Dispersion (Figure 2.2.1)

Options	Description
Frequency Range	Frequency range of dispersion curve (Section 3.3.2).
Algorithm	Phase velocity calculation method (Section 3.3.3).
Integrity	Shown only in case of “Normal” algorithm (Section 3.3.3).
Curve Smoothing	Degree of dispersion-curve smoothing (Section 3.3.4).
Picking Tolerance	Tolerance in phase velocity calculation (Section 3.3.3).

2.2.1 Controls ¾ Inversion (Figure 2.2.2)

Options	Description
Stopping Criteria	Criteria upon which the iteration of inversion stops. Inversion will stop when it reaches either the maximum number (Max. Iteration) or the minimum root-mean-square (RMS) error.
Layer Model	Parameters for the earth layer model. “Thickness” will select the earth model with either equal (“Equal”) or depth varying (“Variable”) thickness. Constant values of “Poisson’s Ratio” and “Density” will be assigned to all the layers.

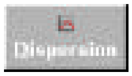
Chapter 3

Dispersion Analysis

"Full Auto" in Chapter 2 provides an effective way to produce one S-wave velocity profile from a single multichannel record. However, it is only truly effective when the record has a high signal-to-noise ratio (S/N). This means that the input data should be as free as possible of body waves and higher-mode surface waves. Also, the full auto option assumes that the main purpose of the analysis is to produce an S-wave profile from a single input record. Although the inclusion of strong body waves is usually obvious when a record is displayed (Chapter 5), that is not true of higher-mode surface waves (Chapter 8). In addition, it is sometimes necessary to process multiple records to produce multiple Vs or dispersion profiles from the same processing flow to allow comparative examination of processing parameters relative to previous processing results.

The "Dispersion" option in the analysis section gives complete flexibility to determine key processing parameters. A complete range of options are available between full-automatic and full-manual modes. It also provides a way to construct dispersion-curve images for all types of dispersive waves regardless of whether they are body or surface waves. Contamination by higher-mode surface waves and body waves can be clearly examined using these images. Following is a summary of the features of this option:

- Control of key processing parameters (e.g., frequency range, increment, etc.).
- Construction of dispersion-curve images through the wavefield-transformation method.
- Dispersion analysis of multi-record input data.

3.1 Main ¾ 

When the “Dispersion” button is clicked, a dialog box (Figure 3.1.1) pops up that allows you to select a file containing multichannel seismic record(s). The file may contain one or more records and you can process one record at a time or sequentially as a group.

Once an input seismic file is selected and displayed, the first record in the file is ready to be processed. If, based on the data displayed, this is not the record you want to process, you can choose another record by clicking the “Next Record” or “Jump” button (Chapter 5) in the display. Figure 3.1.2 shows a panel of buttons displayed on left side of the screen as a tool bar at this stage. Only buttons that can be executed currently are enabled and all others are disabled. The set of both enabled and disabled buttons will change according to the stage of the analysis. Only two buttons (excluding the “Back” button) are enabled: “Preprocess” and “Controls” buttons.

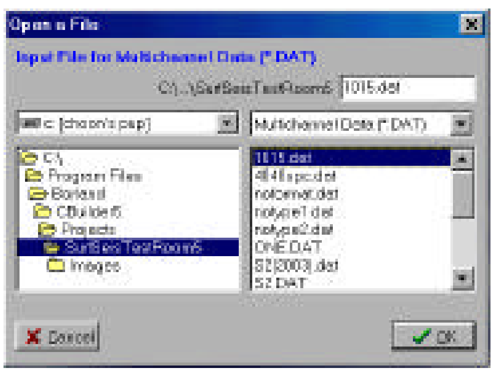


Figure 3.1.1

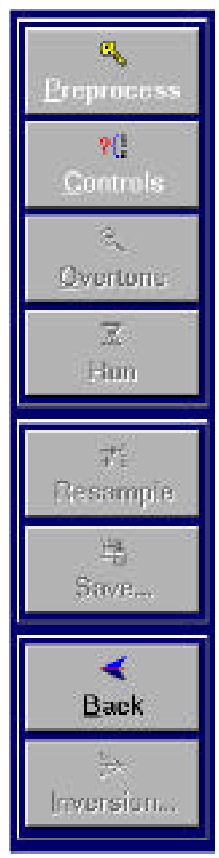


Figure 3.1.2

3.2 Preprocess ¾ 

When this button is clicked, the program tries to estimate the following two data characteristics:

1. Optimum range and increment of frequency.
2. Optimum (upper and lower) bounds of phase velocity.

These operations are performed first by examining frequency spectra of all the constituent traces and, then, by examining energy distribution in time of each trace. The phase-velocity bounds are calculated through a best-fit method applied to the trend of the 2-D energy distribution in the time domain. These bounds are marked on the displayed record (see Figure 3.2.1). The phase velocities in the analyzed dispersion curve will usually fall into this range. If the marked zone encompasses most of the surface wavefields, the process will usually proceed effectively using these automatically determined parameters. This means you can proceed to the next stage of processing: "Run." Otherwise, based on your judgment, you need to check the parameters and change them appropriately by clicking the "Controls" button discussed in Section 3.3.

By right-clicking the "Controls" button a dialog box will pop up (see Figure 3.2.2) showing a couple of control parameters. You can instruct the program to either broaden ("Wide") or shorten ("Narrow") the frequency range. You can also select the offset range to be used for the automatic determination. "Near," "Middle," "Far," and "Full" options will respectively use only those half traces nearest to source, in the middle of the receiver spread, furthest from source, and all the traces. This control should be set whenever traces in specific offset ranges have questionable surface-wave quality.

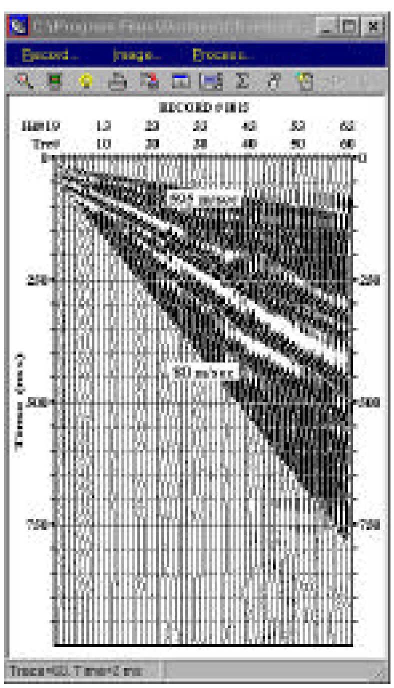
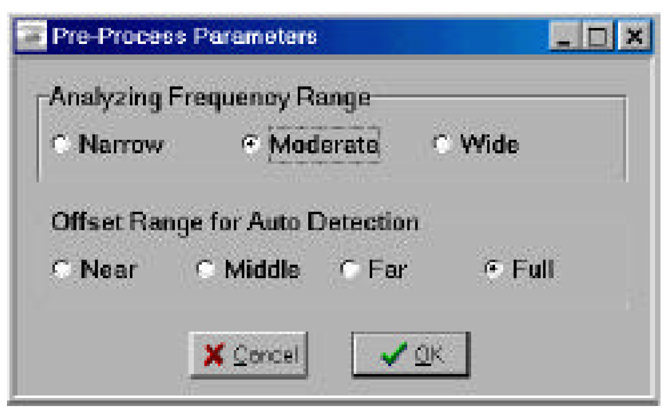


Figure 3.2.1

Figure 3.2.2



3.3 Controls ¾ 

This option enables you to control all parameters used during the dispersion analysis. Controls parameters are grouped into four types: "Analysis Type," "Parameters," "Computation," and "Curve." By clicking this button a tabbed dialog box (Figure 3.3.1) will pop up displaying each group of parameters in a tab. If the "Preprocess" button has not been clicked, the dialog box will only have one tab—"Analysis Type." This is because all other parameters will be determined after the preprocessing has been executed.

3.3.1 Controls ¾ Analysis Type

There are two types analysis: "Normal" and "Pilot Aided" (Figure 3.3.1).

Normal Analysis

This analysis type does not use a reference dispersion curve obtained from a previous processing. For that reason, this type of analysis has minimal bias when calculating phase velocities. You can control most of the key parameters and examine the influence of each parameter on the performance. Normal analysis is recommended in any of the following situations:

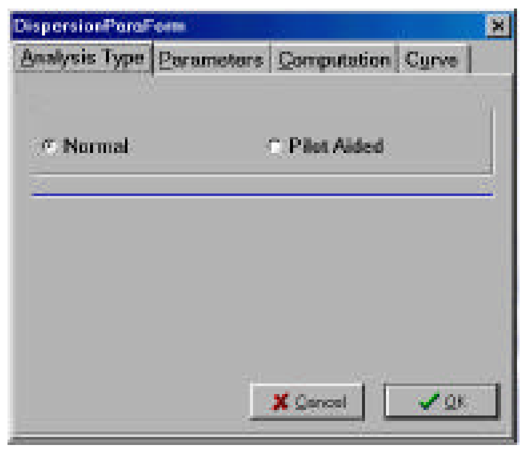


Figure 3.3.1

1. You have an input data set consisting of multiple records collected in a continuous or roll-along mode* and they have not been processed to obtain a dispersion curve before. In this case, you may need a high confidence dispersion curve to use as reference for generating other dispersion curves.
2. Your input records in general have a low S/N.
3. You have a good understanding of the processing parameters to use regardless of the S/N.

**This means that shot records are obtained along the same linear survey line, moving source and receivers in a regular fashion so as to maintain a consistent source-to-receiver offset and spread geometry (e.g., a roll-along mode in CDP survey).*

Pilot Aided Analysis

This analysis type uses a reference dispersion curve usually obtained from a previous process. In contrast to normal analysis, pilot aided analysis has the greatest bias during the calculation of phase velocities. This type is recommended for any of the following situations:

1. Your input data set consists of multiple records collected in a continuous or roll-along mode and at least one of those records has been processed to calculate the dispersion curve using "Normal" analysis as described above.
2. A reference dispersion curve exists that is known to be "typical" from the area your current data were collected.

If this type of analysis is chosen, SurfSeis will prompt you to choose a file with a reference (pilot) dispersion curve.

3.3.2 Controls ¾ Parameters

Options	Description
Frequency Range*	Frequency range and dispersion curve increment.
Apparent Phase Velocity*	Upper and lower bounds on phase velocity, which will be used by the phase-velocity calculation as an approximate reference.

**Values assigned immediately following "Preprocessing" which have been determined by the program to be the optimum values.*

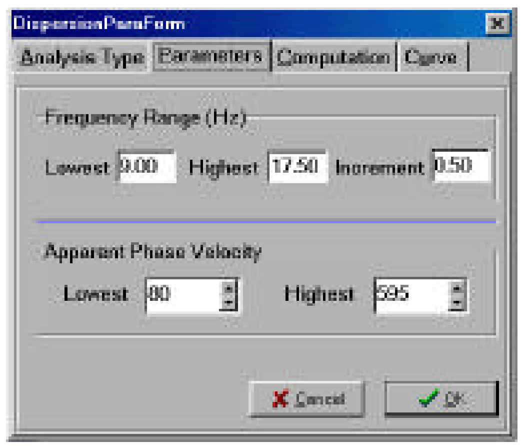


Figure 3.3.2

3.3.3 Controls ¾ Computation

Reference

A reference phase velocity is necessary and represents a starting point for the program to calculate phase velocities for all frequencies within the "Frequency Range" as specified in parameters discussed in Section 3.3.2. The phase velocity will be calculated at this particular frequency using the specified phase velocity as a starting point to begin the downward progression through each frequency. At each new frequency the calculation will begin again, using the phase velocity calculated from the previous frequency as the reference. The program

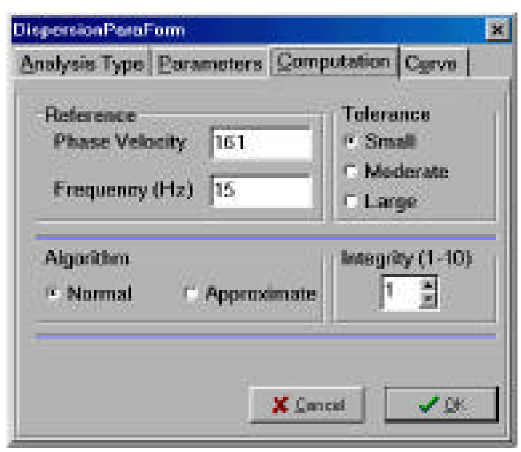


Figure 3.3.3

will continue doing this until it reaches the lowest frequency. At that point it will move on to the frequency immediately higher than the reference frequency.

The reference phase velocity and frequency displayed in this panel of the dialog box (Figure 3.3.3) are the values the program determined automatically and considers to be most reliable references with which to begin the calculations.

Tolerance

This operation establishes the range of phase velocities to examine when calculating the phase velocity at a specific frequency. Intuitively, "Small" sets a narrow range and "Large" represent the biggest range possible. If a certain portion of the calculated dispersion curve appears to be influenced by the inclusion of higher modes, the "Small" option will provide the most desirable results.

Algorithm

Two types of dispersion analysis algorithms are available: "Normal" and "Approximate." Fundamental principles of these two algorithms can be found in Park et al. (1996).

"Normal" is most accurate and is used whenever the input record has a high S/N or all the key parameters (e.g., reference phase velocity and frequency, frequency range and increment, etc.) are properly set (either automatically or through your own determination). When this option is selected, another subparameter called "Integrity" is initiated. "Integrity" controls how intensely the program tries to establish the most "probable" value of phase velocity. A value of 3 is a good choice for most situations. Increasing it by one usually doubles the computation time.

"Approximate" is best when S/N is not as good or you are not confident in or unable to select the optimum parameters. The advantage of this algorithm is that any perturbations (including noise) introduced during the acquisition of surface-wave data are usually averaged out and will not cause the whole analysis to fail. The disadvantage to this approach is that the dispersion curve will be an "average" curve, possibly lacking the integrity possible with high S/N and good estimations of the optimum parameters.

3.3.4 Controls ¾ Curve

Smoothing

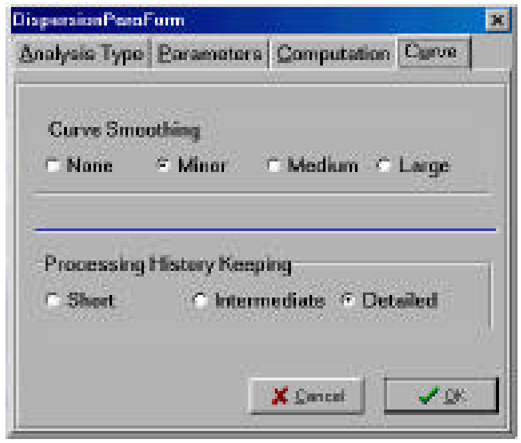
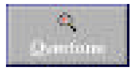


Figure 3.3.4

Once all the phase velocities in the specified frequency range are calculated, the program can apply variable degrees of smoothing to the curve. Since the calculated phase velocities usually contain a certain degree of perturbation caused by numerical truncation, random noise, field and equipment noise, etc., this smoothing will usually average out the perturbation effect. A smoothed curve will usually converge better to a final solution during the iterative inversion process (see Chapter 4).

Processing History Keeping

This option sets the degree of detail retained in the processing history file. The processing history file will be appended when the dispersion curve file (*.DC) is output. This file can be viewed using a text editor (Section 6.1) when the dispersion curve is displayed.

3.4 Overtone ¾ 

Overtone analysis is the best way to observe the dispersive nature of any type of seismic wave without the bias associated with event interpretations. Fundamental principles of this analysis (Park et al., 1996) are quite straightforward. This type of analysis basically attempts to construct a wiggle-trace image where local amplitude maxima trends represent possible dispersive energy (i.e., fundamental and higher modes). This is accomplished by examining all possible phase velocities for all frequencies being considered.

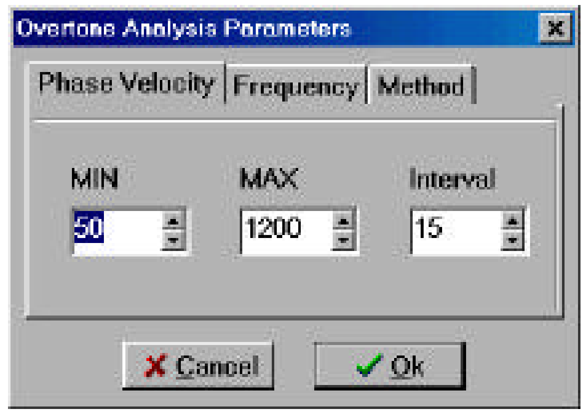


Figure 3.4.1

For most dispersion-curve analysis it is recommended that "Overtone" analysis be performed right after the "Preprocess" step. Many times critical information such as phase-velocity range and optimum frequency range, presence of strong higher modes, and any body wave noise may already be reasonably well known.

There are two parameters to define for this analysis: frequency and phase velocity. Default values determined by the program will usually be sufficient for most cases. But, you have access to these values through the right mouse button (which displays the dialog box in Figure 3.4.1). The "Algorithm" operation in the "Method" tab is the same operation as described in Section 3.3.3. Examples from different algorithms: "Approximate" (Figure 3.4.2), "Normal" with Integrity = 1 (Figure 3.4.3), and "Normal" with Integrity = 3 (Figure 3.4.4) demonstrate the functional range of these options. The seismic data input into these overtone analyses (Figure 3.2.1) were obtained by using 4.5-Hz geophones. From these examples it is evident that the optimum frequency range is around 5-20 Hz. This range is estimated by noting that the higher mode (possibly the first overtone) starts to dominate at frequencies higher than 20 Hz with the low (5 Hz) of the optimum frequency range chosen consistent with the geophone natural frequency. This range can be wider than suggested here, depending on the closeness of source to the receivers, on near-surface materials, and frequency characteristics of the source.

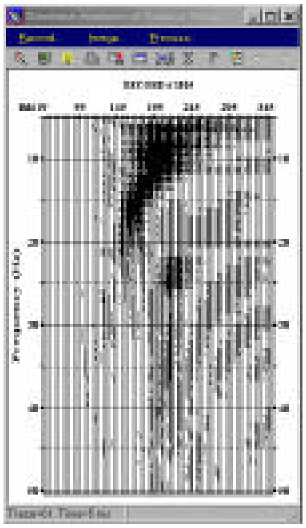


Figure 3.4.2

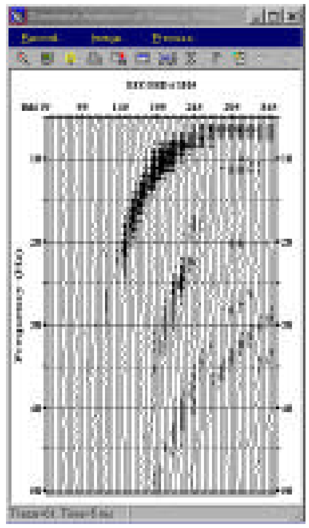


Figure 3.4.3

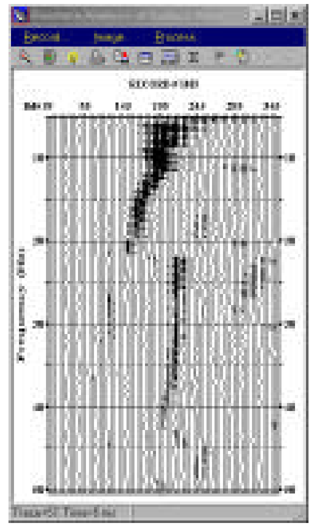


Figure 3.4.4

3.5 Run ¾ 

Clicking the “Run” button starts the program calculating phase velocities within the specified frequency range. This calculation can be run multiple times using different values and sets of parameters, examining the output curves until an optimum solution is identified. In general, the curve with the highest signal-to-noise ratio (S/N) represents the best choice. Output curves for the three cases illustrated in Figures 3.4.2 through 3.4.4 are displayed in Figure 3.5.1.

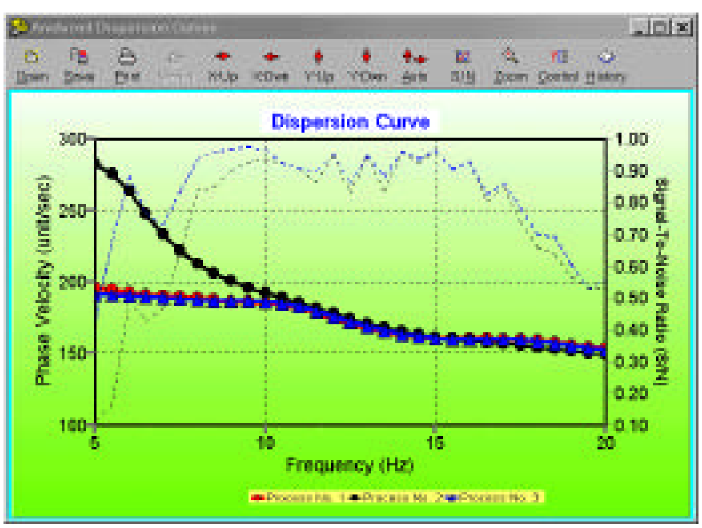
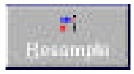


Figure 3.5.1

3.6 Resample ¾ 

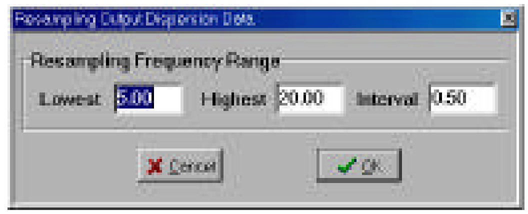


Figure 3.6.1

This option makes it possible to truncate the end portion(s) of the calculated dispersion curve(s) that seem unreliable. It also makes it possible to change the frequency increment of the curve so that adjusting the number of data points within the phase-velocity data set permits the inversion process to function properly. The dialog box for this option is shown in Figure 3.6.1. Usually an excessive number of data points (more than needed) will simply take more computation time during the inversion process without benefit to the accuracy.

3.7 Save ¾ 

Figure 3.7.1

Any one of the last three calculated curves can be saved (Figure 3.7.1). After saving a curve, the program automatically brings up the next record in the input file or moves to the inversion process, depending on whether the file being processed contains multiple records or only one record.

Chapter 4

Inversion Analysis

Inversion of the calculated dispersion curve uses the phase velocity with frequency curve as a reference to estimate the vertical S-velocity (Vs) structure of near-surface materials. The inversion algorithm in SurfSeis has been adopted from Xia et al. (1999).

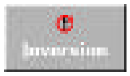
The most commonly used inversion method uses an initial model before actually beginning to search (iterate) for the answer. An initial model consists of several key parameters: S-velocity (v_s), P-velocity (v_p), density (ρ), and thickness (h) of the layers in the earth model. Using this set of parameters, the program begins searching for a solution, continuously converging in an iterative fashion on the most probable values. The S-velocity (v_s) is most sensitive and influential to the surface wave phase velocity. Influence of all other types of parameters can usually be neglected as long as they have been reasonably estimated.

The initial S-velocity (v_s) model is approximated from the measured dispersion curve. The initial P-velocity (v_p) model is determined using this v_s model and a constant Poisson's ratio of 0.4. A density of 2.0 g/cc is assigned to all layers of the earth model. The maximum depth of investigation is determined from the longest surface wave wavelength measured from the dispersion curve. The thickness or layer model is then created by successively increasing the thickness of each layer as its depth increases, to the maximum depth of investigation. A ten-layer model is initially assigned.

The iterative inversion procedure can continue uninterrupted unless a stopping criterion is imposed. Two types of criteria are used: maximum number of iteration (I_{max}) and maximum root-mean-squre error (RMSE). That is, the inversion process will stop when either of the two is met.

The following summarizes the features of this module:

- Invert for S-velocity (v_s) profile with all parameters automatically determined (default).
- Change of the stopping criterion.
- Change of the number of layers.

4.1 Main ¾ 

When the "Inversion" button is selected, a dialog box appears, allowing selection of dispersion curve file(s). A single file or multiple files to be processed in succession can be defined.

Once an input file is selected, an initial model is created using phase velocities in the input file and the preset parameters. The initial S-velocity (v_s) model is displayed along with the input dispersion curve (Figure 4.1.1). The dispersion curve is also displayed, but with an inverted frequency axis so that general trend in the S-velocity (v_s) model and dispersion curve match in an approximate sense. The P-velocity (v_p) model and other parameters (e.g., density) can be displayed using appropriate buttons and tabs. A detailed explanation of the display features can be found in Chapter 7. Actual parameters values can be viewed and changed using the "Layer Model" option (Section 4.3). Buttons available at this stage of the process include Run, Controls, Layer Model, and Back.

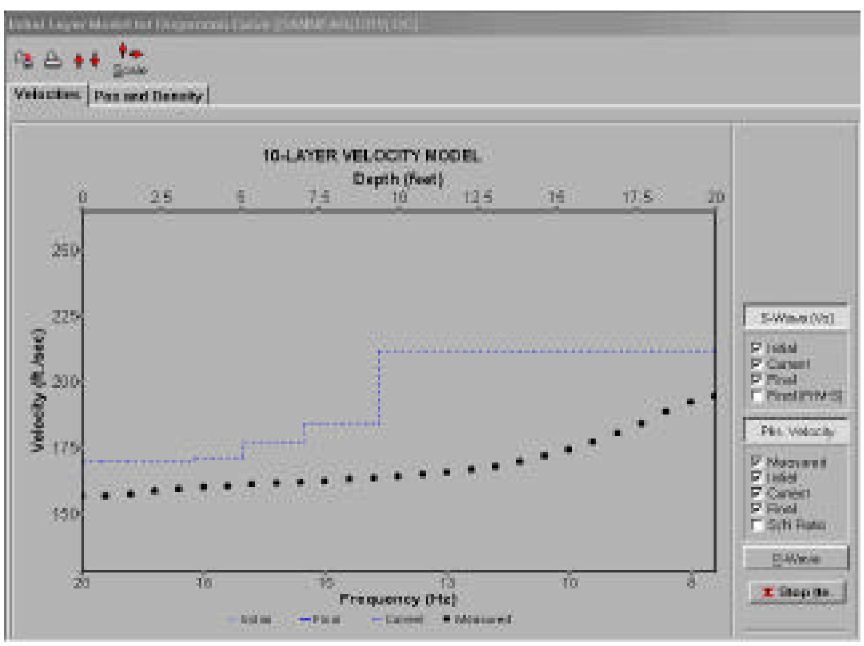


Figure 4.1.1

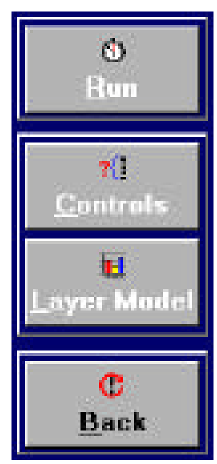
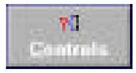


Figure 4.1.2

4.2 Controls ¾ 

The “Controls” operation allows changes to be made in the iteration stopping criteria, type of initial S-velocity (v_s) model, and weighting of phase velocities (Figure 4.2.1).

Stopping Criteria

The inversion is halted when one of the criteria is met: the root-mean-square error (RMSE) or maximum number of iteration (*Imax*).

The RMSE default setting is 3.0, but the optimum value may change based on the input dispersion curve. A more detailed explanation of the optimum criteria can be found in Chapter 1, “Working with Example Data.” The *Imax* default value is set to 30, which will usually exceed the number of iterations necessary to obtain a reasonable solution for S-velocity (v_s) profile.

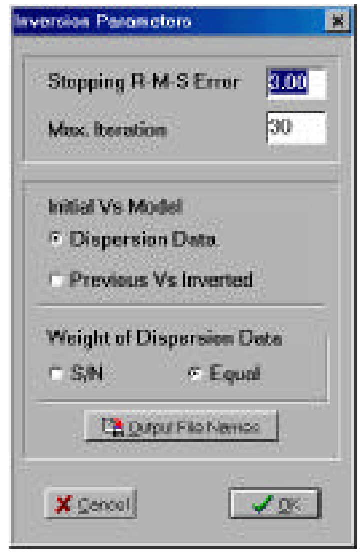


Figure 4.2.1

Initial v_s Model

The initial v_s model is usually calculated from phase velocities in the input dispersion curve (“Dispersion Data” option). This is the only option available if only one dispersion curve is to be inverted. However, if multiple consecutive dispersion-curve files have been selected, the inversion results of a previous record can be used as a “good” approximation of the initial model for the current inversion. Using a previous profile (“Previous v_s Inverted” option) as an initial v_s model, a more accurate result is more likely with fewer examinations (i.e., iterations).

If the “Previous v_s Inverted” option is selected, it is necessary that all input dispersion curve files be selected in the consecutive order of acquisition.

Weighting of Dispersion Data

Each phase velocity in the dispersion curve can be treated with equal confidence (“Equal” option) or weighting can be selected in proportion to the signal-to-noise ratio (S/N) (“S/N” option).

4.3 Layer Model ¾ 

The initial S-velocity (v_s) model is approximated from the measured dispersion curve. The initial P-velocity (v_p) model is defined from this v_s model by assuming a constant Poisson's ratio of 0.4. A default density value of 2.0 g/cc is assigned into all layers (default is 10 layers) in the earth model. The maximum depth (Z_{max}) of investigation is assigned based on the longest surface wave wavelength (λ_{max}) measured from the input dispersion curve. A proper thickness model is then created within this depth range with the last layer assumed to be the half space. From the "Layer Model" option a manual change can be made to any of the default values (Figure 4.3.1).

Parameters

Six kinds of parameters are displayed and can be manually changed: depth (Z), thickness (H), S-velocity (Vs), P-velocity (Vp), Poisson's ratio (S), and density (R).

Depth (Z) represents the depth from the ground surface to the bottom of the associated layer. Changing any depth (Z) will result in changes in thickness (H). Since the deepest depth (Z_{max}) is constrained by the longest surface wave wavelength (λ_{max}) measured, it is not allowed to change.

A change in S-velocity (Vs) will result in a consequent change in P-velocity (Vp) in accord with the value of Poisson's ratio (S). Changes in P-velocity (Vp) will result in a change in Poisson's ratio (S).

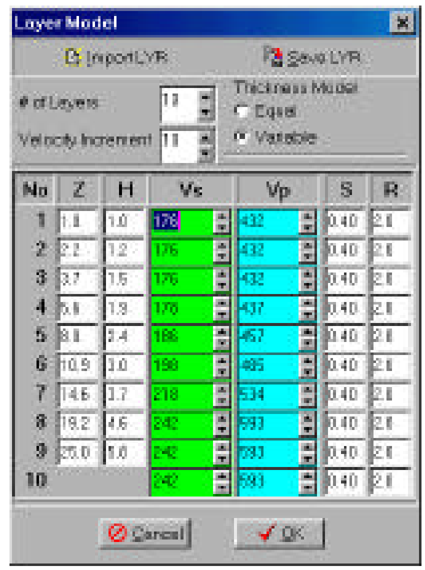


Figure 4.3.1

A change in density (R) will not result in change in any other parameters.

Others

The total number of layers in a model can be changed using the up (or down) arrow in the "# of Layers" edit box. Currently the maximum number is set to 20 layers. The "Thickness Model" option enables a choice of "Equal" and "Variable" models. The "Equal" option generates a model consisting of all layers with equal thickness and the "Variable" option generates a model with layers whose thickness increases with depth. The "Velocity Increment" option defines the amount values in the edit boxes of Vs and Vp are changed when up or down arrows are clicked.

"Import LYR" and "Save LYR" options import previously saved files containing all previously worked layer parameter values and save the current set of values, respectively.

4.4 Run ¾ 

"Run" starts the program searching for a Vs profile whose theoretical dispersion curve matches the experimental dispersion curve obtained from the "Dispersion" analysis. The "match" will be evaluated on the root-mean-square error (RMSE) between the two curves (Xia et al., 1999). The inversion algorithm first calculates the theoretical curve using the initial Vs profile (along with other layer parameters previously explained), then compares the theoretical curve with the experimental curve (from the RMSE perspective). If this RMSE is greater than the minimum RMSE (*Emin*) specified in the "Controls" dialog (Figure 4.2.1), the inversion algorithm will automatically modify the Vs profile (see Xia et al., 1999) and repeat the procedure by calculating a new theoretical curve. Each round of this searching procedure is called an "iteration," and iterations continue until either *Emin* or maximum number of iterations (*Imax*) is reached.

The theoretical dispersion curve ("Current") that is being compared with the experimental curve ("Measured") and its associated Vs profile being compared with the initial profile ("Initial") are displayed for each iteration (Figure 4.4.1). The changing trend of RMSE is displayed in the upper righthand corner of the display. If the experimental curve is reasonably accurate (or makes sense from a theoretical point of view), the RMSE usually drops dramatically during the first several iterations. Sometimes later iterations may reach a level beyond which no noticeable change in RMSE can be observed (see Section 8.4). In this case, the iterations can be stopped manually by clicking the "Stop Ite" button in lower-right hand corner of the display.

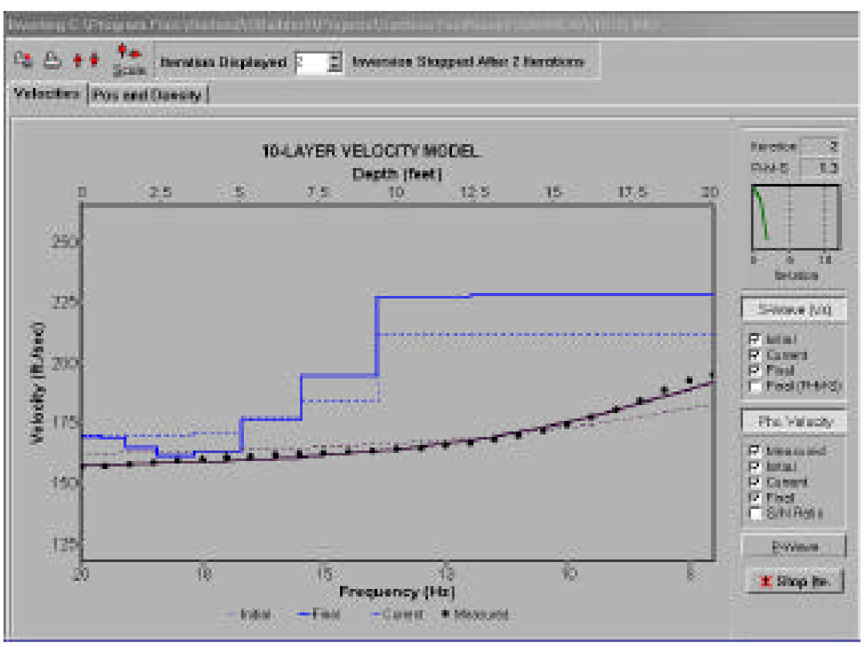


Figure 4.4.1

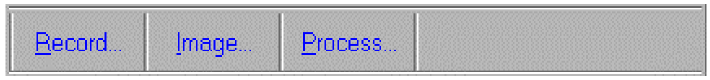
Chapter 5

Seismic Data Display (SDD)

Multichannel seismic data collected in the field are in the native data format of the seismograph and need to be converted into KGS format using conversion routines in the icon “Headers and Conversions.” Converted data can contain single or multiple shot gathers (“records”), depending on acquisition parameters and seismograph settings. SurfSeis includes a variety of display options, including:

- **Record** Checking
- Image **Display**
- Seismic Data **Processing**

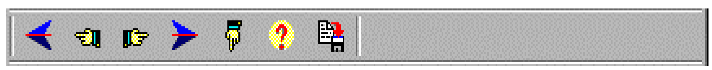
5.1 Main Tool Bar ¾

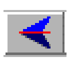
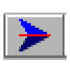
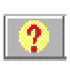
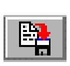


Button	Name	Mouse Button* L	Mouse Button* R	Description
Record...	Record	A		Toggle to display/hide the seismic-record tool bar.
Image...	Image	A		Toggle to display/hide the wiggle-image tool bar.
Process...	Process	A		Toggle to display/hide the data-processing tool bar.

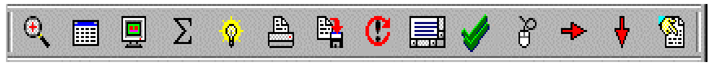
* **L:** Left Click **R**: Right Click **A**-Action Button, **D**-Dialog Button

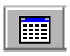
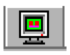
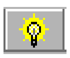
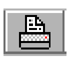
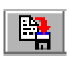
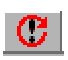
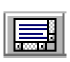
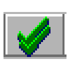
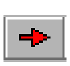
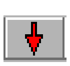
5.2 Record Tool Bar ¾



Button	Name	Mouse Button* L	Mouse Button* R	Description
	First	A		Selects and displays first record of input data.
	Previous	A		Selects and displays previous record.
	Next	A		Selects and displays next record.
	Last	A		Selects and displays last record.
	Jump	D		Selects user-defined record and displays it.
	Info	A		Displays seismic data information.
	Save	D		Saves displayed seismic record as individual file (*.DAT).

* **L:** Left Click **R:** Right Click **A**-Action Button, **D**-Dialog Button

5.3 Image Tool Bar ¾ 

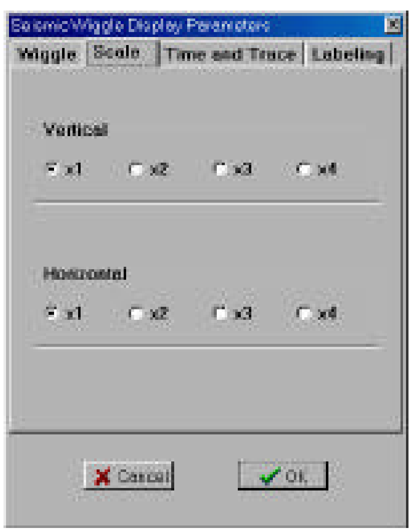
Button	Name	Mouse Button* L	Mouse Button* R	Description
	Zoom	A		Displays zoom of the data selected by mouse.
	Dialog	D		Displays a dialog box for viewing and changing display controls simultaneously (Sections 5.3.1–5.3.4).
	Full Size	A		Displays maximized view of record in current window.
	Normalize	A		Toggle trace normalization on/off.
	Gain	A	A	Changes gain (L = up, R = down).
	Print	D		Prints displayed image after responding to a dialog box (based on print setup).
	Save	D		Saves displayed image in a bitmap file (*.BMP) after responding to an option dialog box.
	Restore	A		Restores original unprocessed record. Available to user only after the data has been processed in some way.
	Scroll Bar	A		Displays both horizontal and vertical scroll bars. Both *Horizontal* and *Vertical* buttons below are enabled.
	Select	A		Selects one or more traces for processing.
	Mouse	A		Clears any mouse-generated marks or symbols.
	Horizontal	A	A	Changes horizontal scale (L = up, R = down). Enabled only when *Scroll Bar* button  is clicked.
	Vertical	A	A	Changes vertical scale (L = up, R = down). Enabled only when *Scroll Bar* button  is clicked.
	Position	A		Toggle on/off displayed location of the position of mouse cursor in trace number and time.

* **L:** Left Click **R:** Right Click **A**-Action Button, **D**-Dialog Button

5.3.1 Image Tool Bar ¾ Dialog (Wiggle)

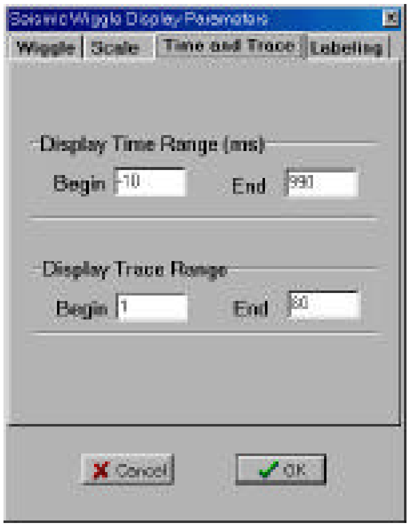
Option	Description
Size	Determines scale of each seismic trace. "Amplitude" will determine the maximum horizontal deflection (in trace spacing) of the maximum amplitude value of a trace (or entire record if "Normalization" option below is Off). "Gain" increases or decreases the display amplitude, or gain, in decibel.
Type	+ Fill: Right side (positive values), - Fill: left side (negative values), and No Fill: neither side of wiggle will be filled.
Normal-ization	Scales entire trace relative to the maximum value of each trace.

5.3.2 Image Tool Bar ¾ Dialog (Scale)



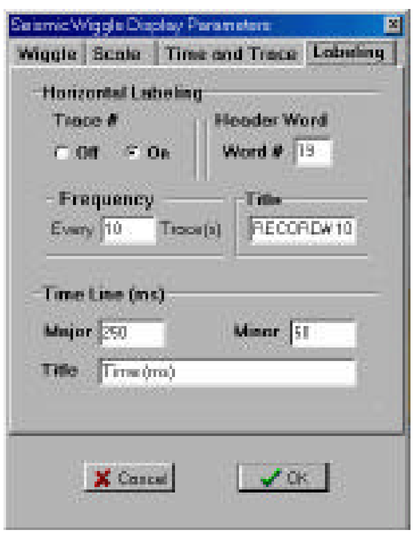
Option	Description
Vertical	Increases vertical size of displayed image by the specified multiplier.
Horizontal	Increases horizontal size of displayed image by the specified multiplier (increases trace spacing).

5.3.3 Image Tool Bar ¾ Dialog (Time and Trace)



Option	Description
Display Time Range	Selects range of time displayed.
Display Trace Range	Selects range of traces displayed.

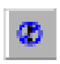
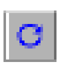
5.3.4 Image Tool Bar ¾ Dialog (Labeling)



Option	Description
Trace #	Option for annotating trace number.
Header Word	Options for annotating specified header word data sorted ascending to.
Fre-quency	Identifies how often the specified labels appear along the top of the image.
Title	"Title" of the displayed image.
Time Line	Separation between "major" (solid line) and "minor" (dotted line) time lines. "Title" of the time axis.

5.4 Process Tool Bar ¾ 

Note: A more detailed description is listed in a separate section titled "Processing With Multichannel Seismic Data."

Button	Name	Mouse Button*		Description
		L	R	
	Filter	A	D	L = (double click) starts filtering process. R = displays dialog box with parameters (Section 5.5.1).
	Mute	A	D	L = (double click) starts muting process. R = displays dialog box with parameters (Section 5.5.2).
	AGC	A	D	L = (double click) starts AGC (automatic gain control) process. R = displays dialog box with parameters (Section 5.5.3).
	Spctrm	A	D	L = (double click) starts spectral analysis process. R = displays dialog box with parameters (Section 5.5.4).
	Raw	A		Toggle between original and processed records. Enabled only after processing has been applied to an original record.
	Proc	A		Toggle between current and last processed records. Enabled only after at least two processing steps have been completed.

* **L:** Left Click **R:** Right Click **A**-Action Button, **D**-Dialog Button

5.5 Processing Seismic Data

Signal processing techniques sometimes need to be applied to displayed records before dispersion-curve analysis to enhance signal-to-noise ratio (S/N). Four different kinds of record-specific processing steps are available: filtering, automatic gain control (AGC), mute, and spectral analysis.

The following procedure begins a specific process:

1. Click the appropriate button (e.g., ),
2. execute the "parameter action by mouse (PAM)" when necessary (see table below),
3. double click the appropriate part (or a specific part depending upon type of process you are applying) within the displayed record.

The actual processing applied to the entire displayed record will be based on automatically determined parameters (default values) and/or parameters determined through PAM. This procedure is outlined in the table below.

To manually change any or all the processing parameters, right click the button (e.g., ) and select from a dialog box containing a list of parameters you wish to enable or disable and associated value change for each individual parameter (see "Controls" section).

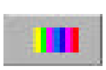
Click Button	Parameter Action by Mouse (PAM)	"Double Click" Displayed Image
	**Option A:** Place mouse cursor approximately in the middle of the noise to attenuate ("filter out"). **Option B:** Click to drag-and-draw a rectangular region around the noise to attenuate ("filter out").	Band-reject filtering is applied to attenuate noise identified by PAM. In the case of Option A in PAM, a rectangular region (centered at the mouse cursor position) with an area one-fifth the displayed image window is chosen as noise.
	Click on the image to drag-and-draw a straight line that specifies a time boundary.	Seismic energy above (earlier than) the specified time boundary is zeroed with a smooth tapering at the boundary.
	Unnecessary	Gain is applied using a scaling window one-fifth the displayed record length.
	Unnecessary	Amplitude spectrum of each trace is displayed separately.

Figure 5.1

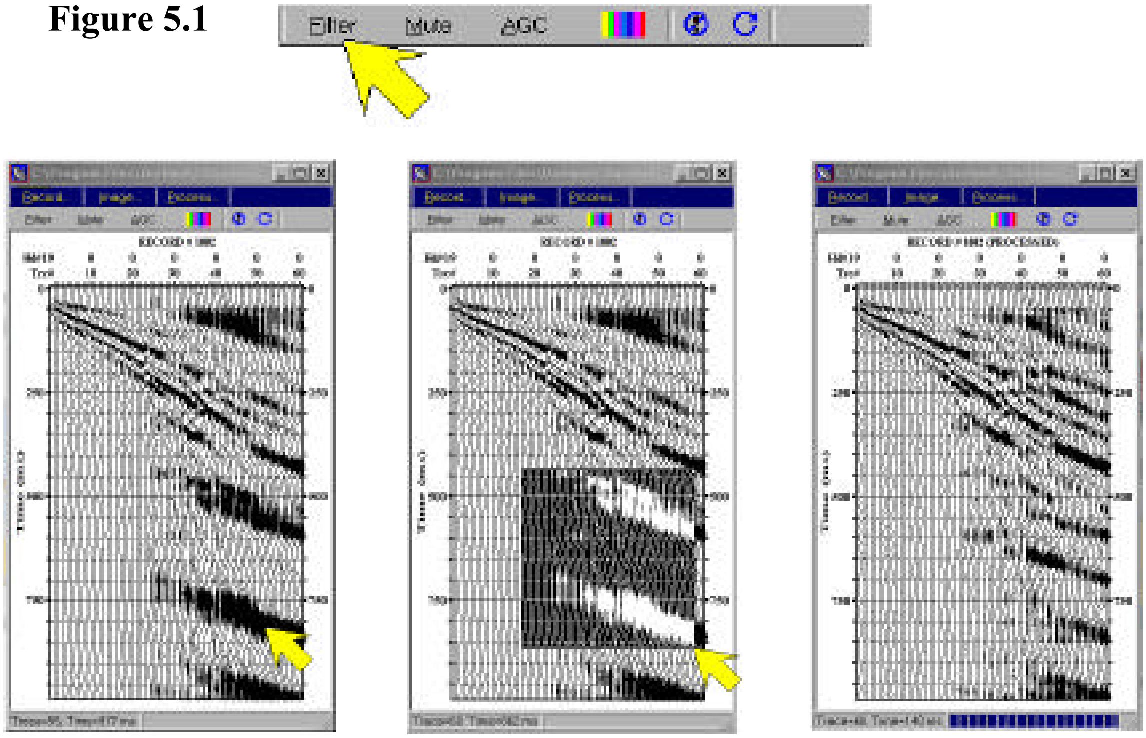


Figure 5.2

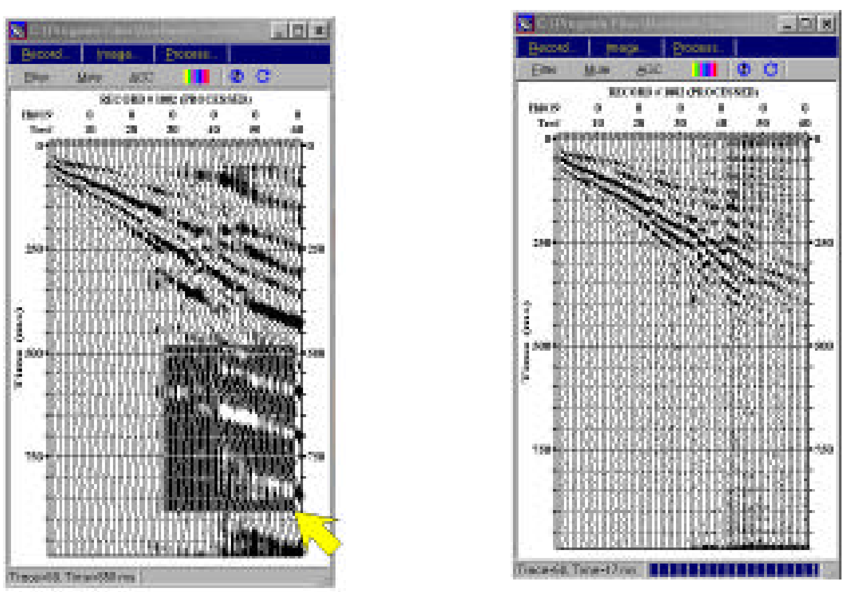
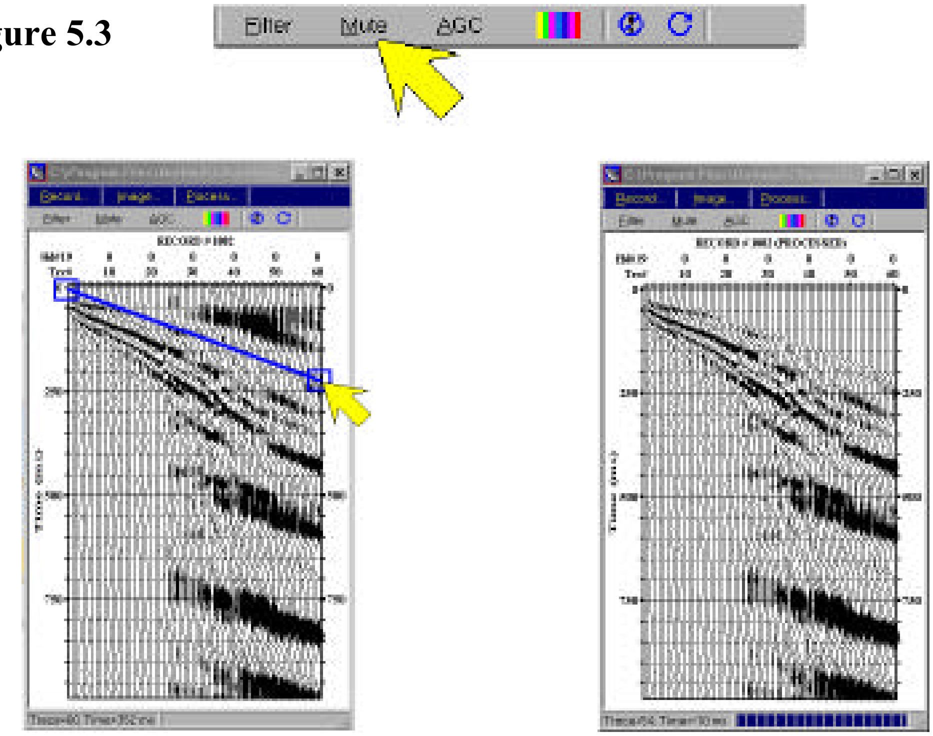


Figure 5.3



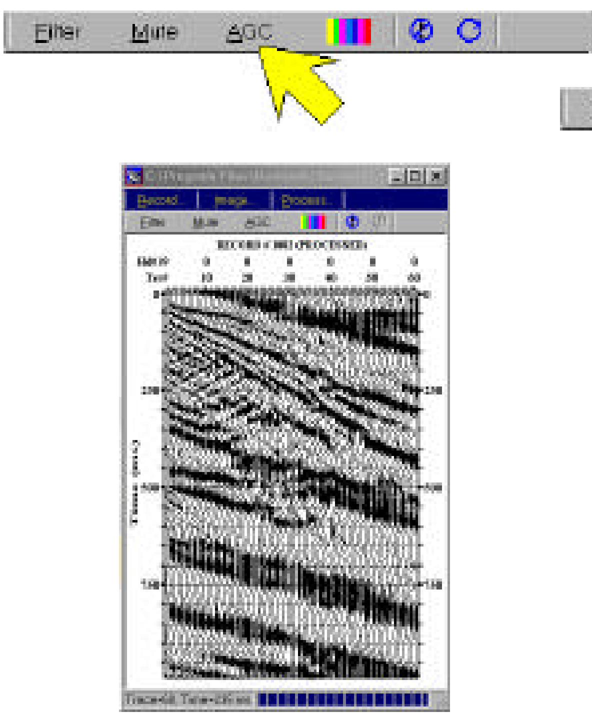
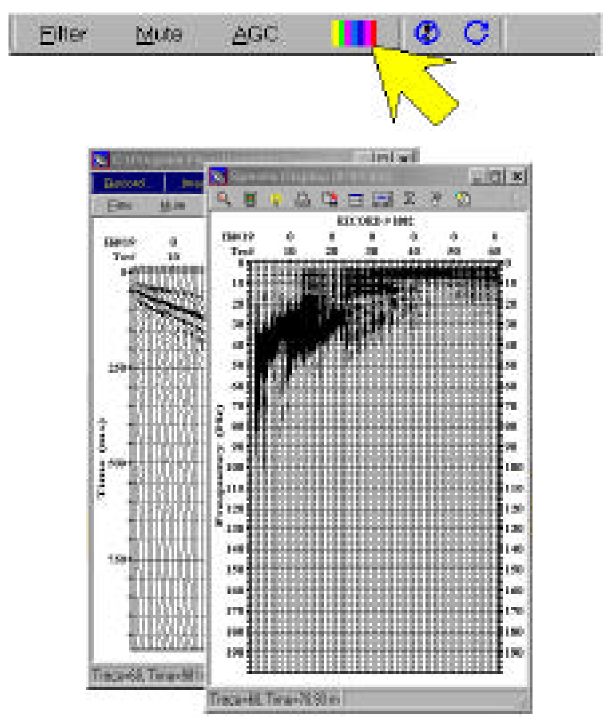
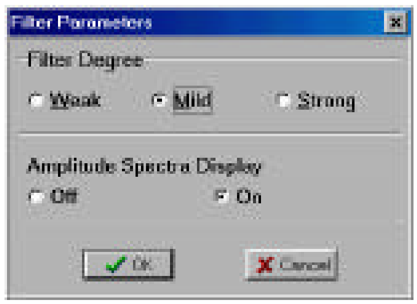


Figure 5.4

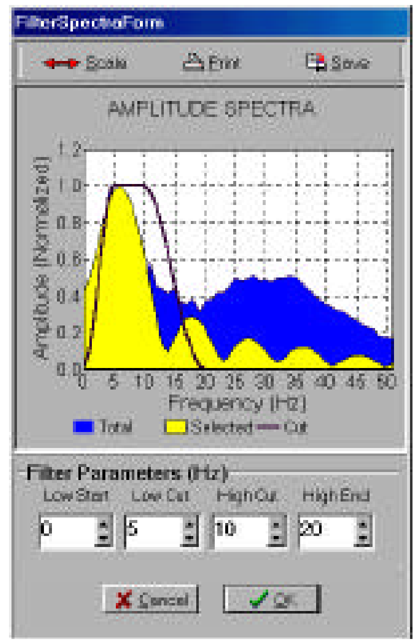
Figure 5.5



5.5.1 Process ¾ Filter Controls



Dialog 1



Dialog 2

Dialog 1

Option	Description
Filter Degree	Controls degree of filtering. "Weak" filtering indicates the narrowest bandwidth filter centered on the noise, whereas "strong" signifies the widest bandwidth.
Amplitude Spectra Display	Allows "Amplitude Spectra Display" dialog box to pop up before actual filtering takes place to allow the user to change filter parameters based upon displayed spectra.

Dialog 2

Option	Description
Filter Parameters (Hz)	Specifies four filter parameters that define the frequency range for filter (i.e., band-reject filtering). The shape of the filter operator is a solid graph on the displayed spectra.
Scale	Changes horizontal scale of displayed spectra (left click = increase, right click = decrease).
Print	Prints displayed spectra.
Save	Saves displayed spectra image (*.BMP).

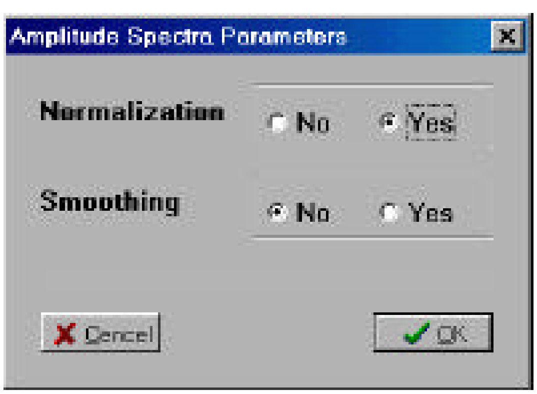
5.5.2 Process ¾ Mute Controls

Option	Description
Mute Type	Defines the portion above ("Top") or below ("Bottom") the drawn straight line that is to be zeroed.
Tapering	Determines degree of smoothing along the edge of cutting boundary. "Weak" tapering will result in a relatively abrupt edge while "strong" tapering results in a very smooth ramp. Actual length of smoothing window can be manually specified.

5.5.3 Process ¾ AGC Controls

Option	Description
AGC Degree	Defines the length of the automatic gain control (AGC) scaling window. The window length under the "Mild" option is equal to 20 percent of displayed time axis. Actual length of the window can be manually specified by changing the value in the spin edit.

5.5.4 Process ¾ Spectra Controls



Option	Description
Normalization	Normalize amplitude spectra.
Smoothing	Smoothing amplitude spectra.

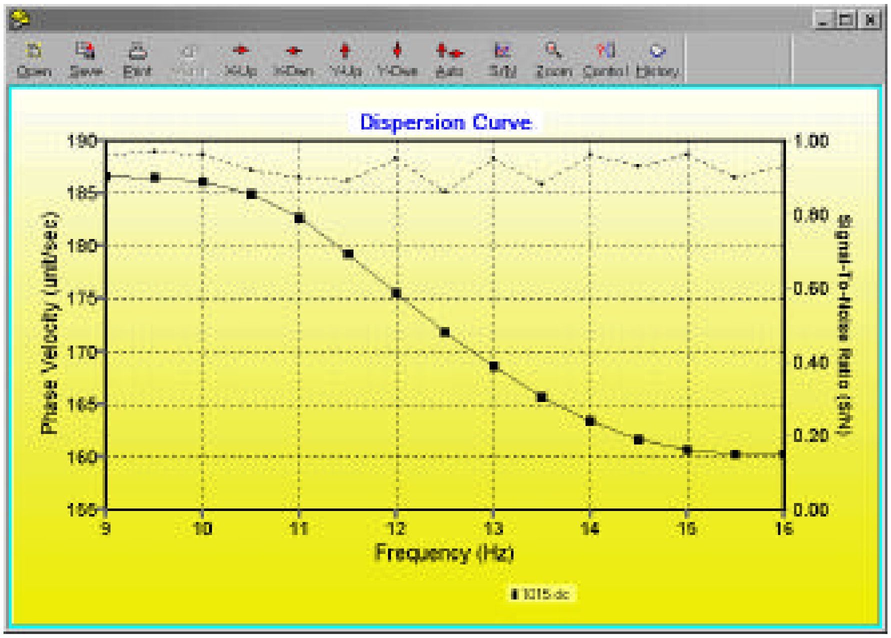
Chapter 6

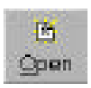
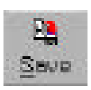
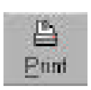
Display of Dispersion Curve

Dispersion curves, saved into a text file (*.DC), possess frequency vs. phase velocity domain and signal-to-noise ratio curves. This data can be examined, manipulated, and handled using moduli discussed in this chapter. This chapter includes:

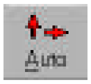
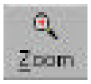
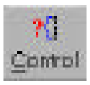
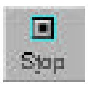
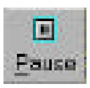
- Displaying dispersion and signal-to-noise ratio (S/N) curves
- Printing curves
- Saving images of curves as a bitmap file (*.BMP)

6.1 Button Controls



Button	Name	Mouse Button* L	R	Description
	Open	A		Opens a file for display.
	Save	A		Saves displayed image as a bitmap file (*.BMP).
	Print	A		Sends displayed graph to a printer (based on print setup).
	March	A		Continuously displays sequential files. Enabled only when multiple files are open.
	X-Up	A		Increases horizontal scale of displayed graph (increases Hz/inch).
	X-Dwn	A		Decreases horizontal scale of displayed graph (decreases Hz/inch).
	Y-Up	A		Increases vertical scale of displayed graph (increases Hz/inch).
	Y-Dwn	A		Decreases vertical scale of displayed graph.

(Continued)

Button	Name	Mouse Button* L	R	Description
	Auto	A		Automatically scales both horizontal and vertical axes to fill screen.
	S/N	A		Toggle on/off display of signal-to-noise ratio curve.
	Zoom	A		Zooms in on particular portion of display.
	Control	A		Brings up a dialog box enabling various display parameters to be changed (see Section 6.2).
	History	A		Presents processing history of current dispersion curve.
	Stop	A		Stops processing (available only during “Pilot Analysis,” see Section 3.3.1).
	Pause	A		Pauses processing (available only during “Pilot Analysis,” see Section 3.3.1).

*** L:** Left Click **R:** Right Click **A**-Action Button, **D**-Dialog Button

6.2 Dialog Controls

Dialog controls enable changes to be made in display attributes and can be activated by either clicking the “Control” button or by right-clicking the mouse. There are four categories in this option: Data Points, Axis, Labeling, and Panel.

6.2.1 Data Points

Display attributes of data points (line and mark) are important when multiple files are displayed simultaneously. A specific file to change can be indicated in the “Apply to File” box.

In the “Line” tab, the style, thickness, and color of the line connecting data points can be changed. In the “Mark” tab, the style, size, and color of the data point marks can be modified. You can select dispersion and/or S/N curves to apply the indicated changes to.

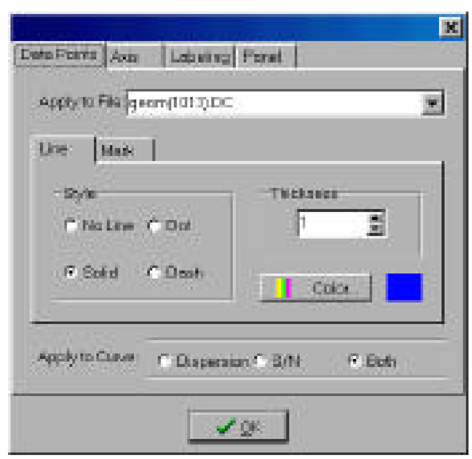


Figure 6.2.1

6.2.2 Axis

Attributes of the horizontal and vertical axes are controlled under the "Axis" tab. Upper and lower data bounds for axes can be specified with the desired increment.

"Auto Scale Axes" automatically adjusts the scale of all active axes. This is especially useful when the original scales need to be adjusted after display changes have been applied within the visible window.

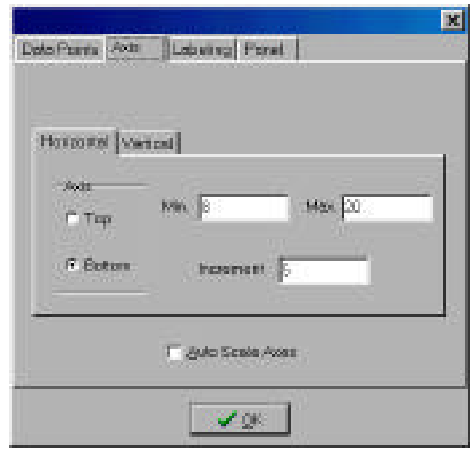


Figure 6.2.2

6.2.3 Labeling

The "Labeling" tab controls the characteristics of title and legend. The title of the graph can be manually typed in, and changes to title or legend position and font characteristics can be made.

The legend for displayed curves can be turned off or on by checking the "Visible" box under the "Legend" tab.

A specific curve can be selected and highlighted by clicking it in the legend. This is especially useful when several curves are displayed together and a specific curve needs to be distinguished for comparison purposes.

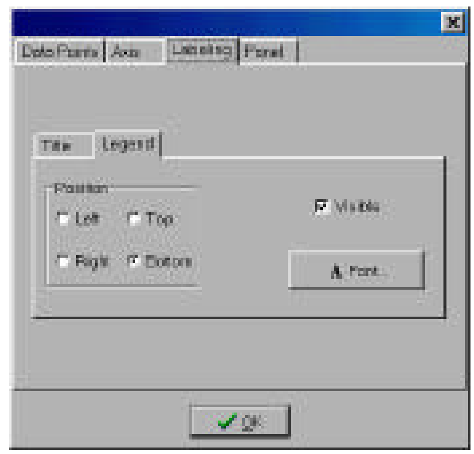


Figure 6.2.3

6.2.4 Panel

The "Panel" tab controls bevel and color of the entire displayed panel. Under the "Bevel" tab, the inner and outer bevel type and width can be designated. Under the "Gradient" tab, the background color can be changed in a continuous/gradual mode from a "Start Color" to a "End Color" in a specified "Direction." When the "Visible" box is not selected, the "Panel Color…" option appears, which enables the selection of a constant background color.

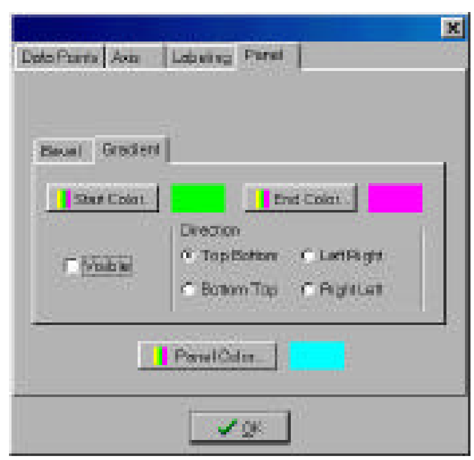


Figure 6.2.4

Chapter 7

Inversion Results Display

Inversion results are saved into two different files. One file (*.IVO) contains the final results of inversion. The other file (*.LST) contains the final as well as intermediate iteration results. The module displaying the entire inversion process iteration by iteration through all the defined layer parameters can be instrumental in confidence determinations. Included with this module are:

- Theoretical layer model display at each iteration.
- Theoretical dispersion curve display corresponding to the layer model.
- Printing and saving (*.BMP) displayed image.

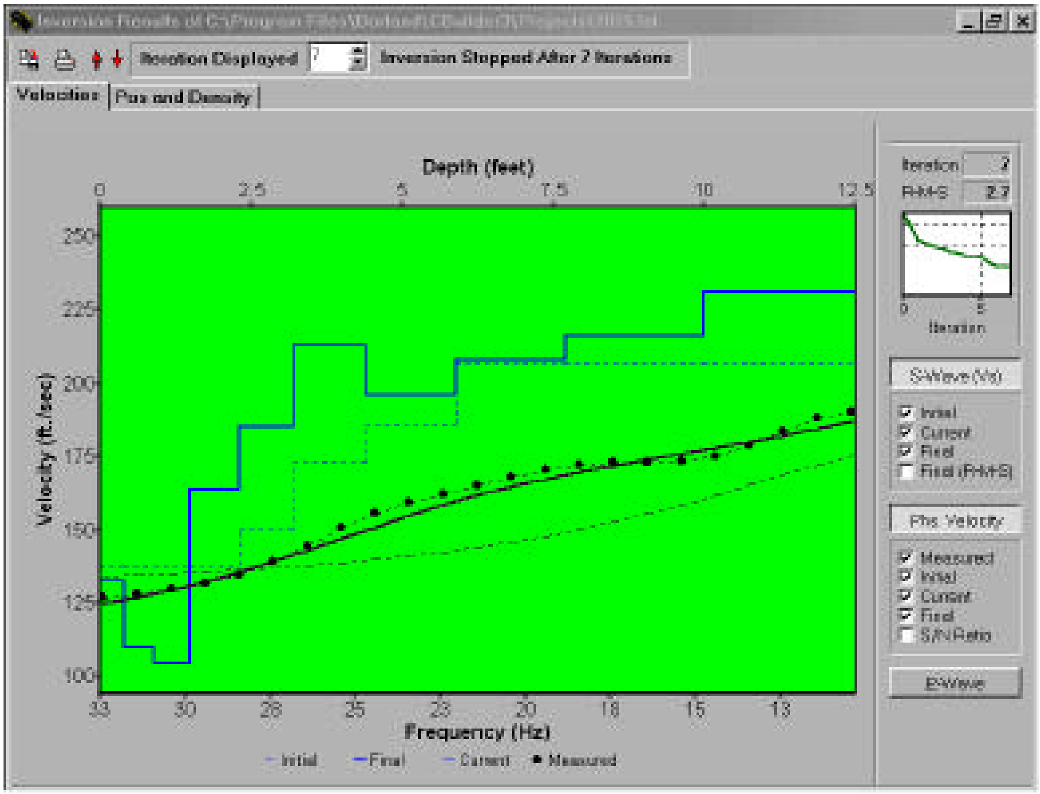
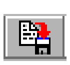
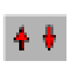


Figure 7.1

7.1 Main

Button	Name	Mouse Button* L	Mouse Button* R	Description
	Save	A		Saves displayed image as a bitmap file (*.BMP).
	Print	A		Sends displayed graph to printer according to printer setup.
	Scale	A	A	Changes vertical scale of displayed graph (L=increase, R=decrease).
	Ite.	A		Changes which data iteration is displayed.

*** L:** Left Click **R:** Right Click **A**-Action Button, **D**-Dialog Button

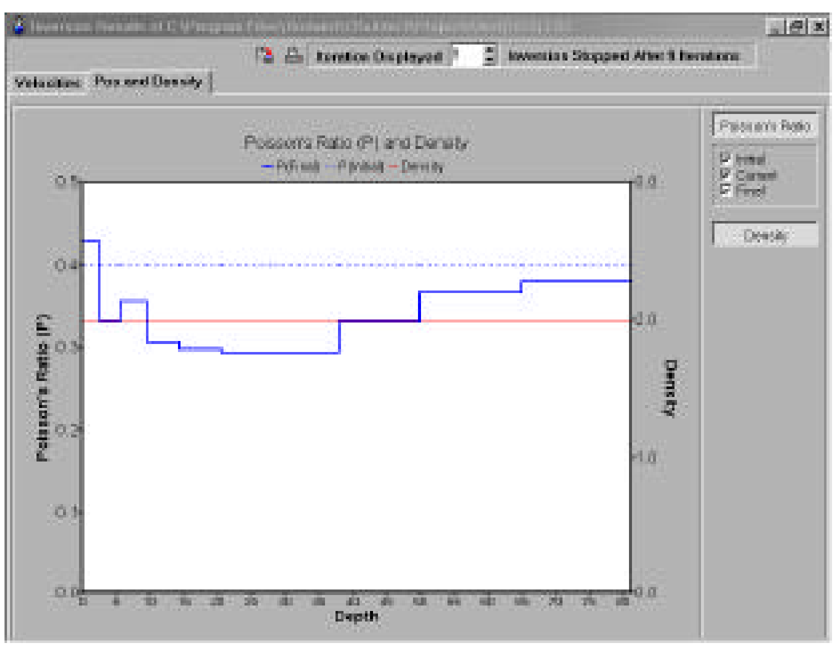
7.2 Velocities

Button	Name	Mouse Button* L	Mouse Button* R	Description
S-Wave (Vs)	Vs	A		Toggle on/off to display S-wave velocities with layer model. When this button is toggled to the on position, a separate panel appears. Inside this panel are check boxes for selecting the Initial model, Current model (iteration), Final model, and R-M-S shear velocities.
Phs. Velocity	Phs.	A		Toggle on/off to display phase velocities. When this button is on, a separate panel appears. Inside the panel are check boxes for selecting curves for the Measured, Initial, Current (iteration) and Final phase velocities and the Signal-to-Noise Ratio (S/N) curve.
P-Wave	P	A		Toggle on/off to display P-wave velocities based on selected Poisson's ratio.

* **L:** Left Click **R:** Right Click **A**-Action Button, **D**-Dialog Button

7.3 Poisson's Ratio (Pos) and Density

Figure 7.2



Button	Name	Mouse Button* L	R	Description
Poisson's Ratio	Pos	A		Toggle on/off to display Poisson's ratio for the layer model. When this button is on, a separate panel appears. Inside the panel are check boxes for selecting the Initial, Current (iteration), and Final Poisson's ratios.
Density	Density	A		Toggle to display density curve based on user selection.

*** L:** Left Click **R**: Right Click **A**-Action Button, **D**-Dialog Button

7.3.1 Animated Zoom

By pointing, dragging, and drawing a rectangular area (see Figure 7.3), which includes part of the displayed curves, a selected zone can be zoomed in on using animation mode. The original display can be restored by double clicking any place within the curve-display area.

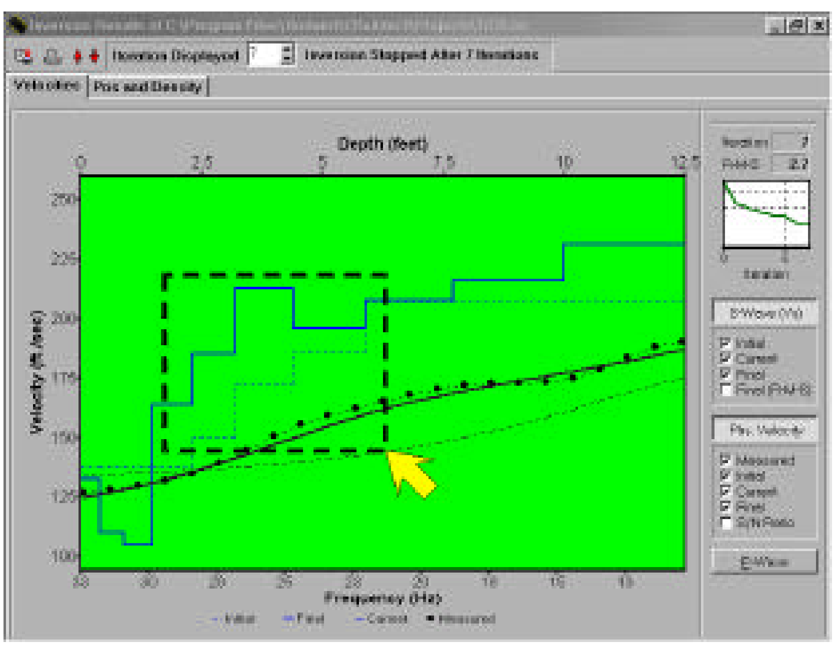


Figure 7.3

Chapter **8**

Working with *SurfSeis*

This chapter discovers practical issues associated with using SurfSeis for specific projects. Previous chapters have explained specific parts of the software in relation to their functions and capabilities.

In this chapter, actual demonstration data sets that come with the software can be used to help understand the process and functions of this software and method. All the demonstrations focus on included data sets.

In this chapter the following are addressed:

- How to acquire multichannel seismic data and prepare it for processing with SurfSeis.
- How to obtain an S-velocity profile from the analysis of a single record.
- How to appropriately process data before starting dispersion curve analysis.

8.1 Data Acquisition

MASW requires a multichannel record with at least 12 traces to produce reliable results. A multichannel record can be obtained in either of two methods: acquisition with a seismograph with at least 12 channels, or acquiring single-channel data with the source and receiver incrementally separated a predetermined distance after each trace is recorded and then gather up all the traces in source-offset order to construct a 12-channel record. Because low frequency components of surface waves increase the maximum depth (Z_{max}) of investigation and make the inversion process more stable, it is critical that no analog filtering be applied during data acquisition.

A weight drop, specifically a sledge hammer, is normally employed as the seismic source. Although its weight and impact velocity can vary depending on the desired Z_{max}, a hammer of 5 to 10 kilograms is usually sufficient for investigations within a few tens of meters of the ground surface.

Low-frequency geophones (from an engineering perspective) are essential. Usually 4.5-Hz geophones are adequate for investigation in the few tens of meters.

The source offset (X_1) (distance between source and the first closest geophone) needs to be great enough (X_n) to assure efficient generation of surface waves that extend down to the primary depth range of interest. The negative characteristics of the "near-field effect" are controlled by Z_{max} and near-surface velocity. To avoid these undesirable attributes, a good rule of thumb is to insure X_1 is greater than Z_{max}. Geophone spacing (dX) can be determined after the maximum offset (X_{max}) and total number of traces (N) are established: $dX = (X_{max} - X_1) / N$. X_{max} is usually at a source offset beyond which ambient noise begins to dominate the source-generated surface waves (see Figure 8.1.1). More detailed information about the selection of X_1 and dX can be found from Park et al. (1999).

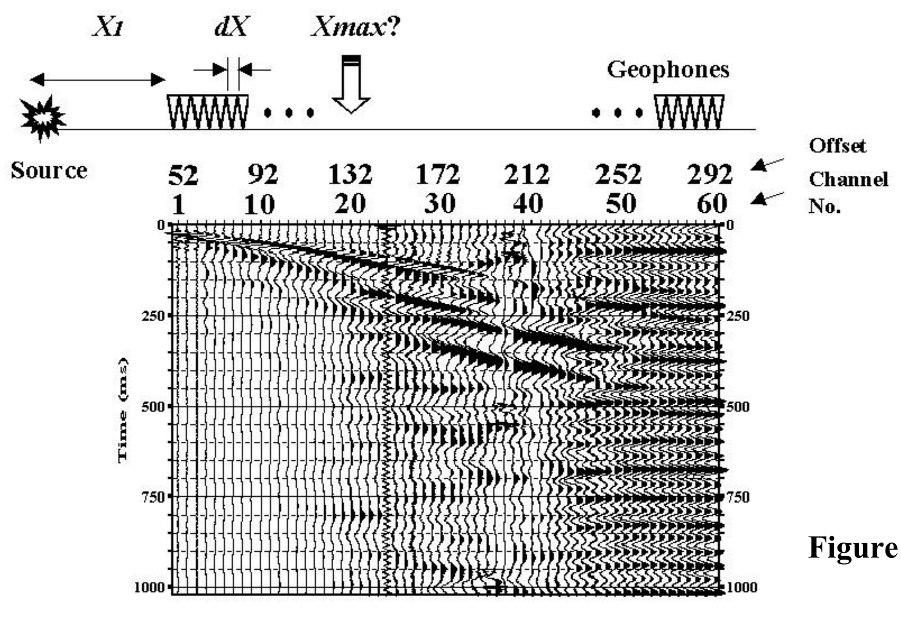


Figure 8.1.1

8.2 Data Format

Most engineering seismographs output SEG-2 natively. Other output options will generally include SEG-D or, in a rare instance, SEG-Y. Processing seismic data requires organization of information within the trace in a very structured form. Most seismic processing packages use data in SEG-Y or a slightly modified version of SEG-Y. SurfSeis uses the same modified SEG-Y data format used by WinSeis and WinSeis Turbo. This modified form of SEG-Y is trace-by-trace sequential and possesses a fixed header length followed by data. Conversion routines are available for most seismograph and processing formats.

Trace headers, sample resolution, and data order are what designate the format of a seismic data file. SurfSeis reads and writes data in the KGS-modified SEG-Y format. This data format is unique and requires conversion before anything can be done with or to data, regardless of whether it came directly from a seismograph or other processing software. Several data formats are presently being used by commercial seismograph manufacturers. The engineering "standard" is designated as SEG-2 (Pullan and Hunter, 1990). Conversion of data files requires the user to double click the format/header icon and select the appropriate conversion routine. Because the majority of modern engineering seismographs are using SEG-2, reference will be made primarily to that format. The general flow of all conversion routines is the same, so little would be gained by going through each individually. Information required from the user includes input file names (usually one file name for each shot gather or field file), output file name (SurfSeis, as most processing routines, handles all the field files from a particular line as a single file), and source sequence number (SSN). The source sequence number allows files collected with non-sequential file names/numbers (such as a missing file number) or with extensive or alpha character file names to be renumbered, renamed, and regrouped. The function of any conversion routine is to reorganize and update trace headers in such a way as to allow a specific processing algorithm to recognize and operate on data.

Formatting seismic data for processing with SurfSeis involves organization of trace headers and data bytes into specific fixed-length patterns and sequences. The formatting utilities (conversion routines) are designed to operate on raw data input from and output to the hard disk. Getting the raw data from the seismograph's preferred storage media (hard drive, floppy disk, 9 track tape, DAT cassette, data tape cartridges, RAM, etc.) onto the hard disk requires procedures, software, and/or hardware that can be supplied or recommended by the seismograph manufacturer. Often the transfer of raw unformatted data to a computer's hard disk requires nothing more than the MS-DOS COPY command or Windows' copy procedures. The following programs are currently available with SurfSeis:

Program	Format converted **from**
90002FPT	Bison 9000
BISCONVF	Bison GeoPro
70002FPT	Bison 7000
EASI2FPT	EG&G Easidisk

SV2KGS	EG&G Seisview
GEOF2KGS	EG&G GeoFlex
SEG22FPT	SEG-2 (EG&G 2401, StrataView, ABEM MarkVI, OYO DAS1, and most modern seismographs)
ABEM2FPT	ABEM Terraloc
OYO2FPT	OYO Models 5-8
OYO160FP	OYO McSeis 160
OYO170FP	OYO Model 170
QSEISFPT	OYO 1500 Q'Seis
SCIN2FPT	Scintrex
SEGY2FPT	SEG-Y (most types)
KGS2FPT	KGS integer

These reverse translators are also included.

Program	Format converted **to**
9000SEGY	SEG-Y
FPT2SEGY	SEG-Y
SEG2SEGY	SEG-Y

The particular formatting routine necessary for your data depends on the seismograph it was collected on. Most new engineering seismographs read and write SEG-2. SEG-2 format accommodates variable header lengths, maximizing the flexibility of the trace headers to store information during the acquisition of seismic data; however, once the multi-data files are organized into a single-file, multi-record configuration, a fixed trace header length is necessary. SurfSeis uses a data format that is modeled after SEG-Y.

Raw unformatted data must be copied onto the computer hard drive and will likely be represented by a series (generally in some sequential order) of similar, yet unique file names. Each unique name represents a saved record. For CDP or common offset data each field file is generally a unique shot gather. The process of file naming is usually accomplished during the downloading of data onto the processing computer or at the time the file was collected/recorded.

The conversion programs are within the format/header user interface icon. To convert SEG-2 data clicking on that sub-icon will be necessary. This will open the SEG2->KGS conversion window, which has a general layout that is consistent with operational windows throughout the SurfSeis processing package. By highlighting the Files heading, input data files can be selected using a standard Windows style file/directory server. When the complete list of files has been highlighted and the OK button clicked, the screen will return to the basic window with all the selected files listed. The output file can then be selected again under the Files heading. Once the output file name has been assigned, both the input and output should be listed in the original window. During the conversion process it is possible to decimate the data (resample), delete the files as they are converted (space-saving measure only), and/or shorten the record length. Any of these operations can be selected in the Options menu. When the input file name and output file name have been selected and any options designated, the Convert heading should be clicked on. This will begin the conversion process by requesting a source sequence number. Once that number is assigned, the conversion will proceed. During the conversion process the file being converted is displayed. When the conversion process has terminated a complete listing of each file and any problems encountered during the conversion are listed. The resulting data file will be 32-bit floating point with all traces/samples assembled in a modified SEG-Y format.

8.3 Dispersion Curve Analysis

The following are the most influential factors affecting the dispersion analysis:

1. approximate phase velocity range,
2. optimum frequency range for depth of interest,
3. ease in identifying higher modes, and
4. identification and reduction of noise events.

The influence of these factors on the analysis is highly dependent on the data quality (signal-to-noise). A "good" quality data set suggests the surface-wave event is the most prominent seismic event (i.e., the highest S/N), whereas a "bad" quality data set is usually contaminated by noise. In dispersion-curve analysis the fundamental mode surface waves are signal and everything else is noise. Noise includes all higher-mode surface waves as well as all body-wave events.

There are a variety of ways to obtain a dispersion curve. The following sequence is recommended.

Data Quality

Figures 8.3.1 and 8.3.2 are examples of good-quality data. The data set in Figure 8.3.1 (SanJose.DAT) was obtained at a soil site near San Jose, California, whereas the one in Figure 8.3.2 (HardRock.DAT) was acquired on a limestone bench within a limestone-shale cyclothem sequence in Kansas. In Figure 8.3.1, highly dispersive surface waves dominate the seismic energy with no other seismic events identifiable. A non-dispersive surface-wave event is also evident in Figure 8.3.2 as well as an air-wave event. Since the air-wave event can be clearly identified as a separate event and represents much less total energy than the surface-wave event, the analysis will run smoothly with no problematic step(s). Data shown in Figure 8.3.1 can be regarded as good quality although far-offset traces may be contaminated with noise due to low surface-wave energy and may require special handling.

Figures 8.3.3 and 8.3.4 are examples of poor-quality data. Data in Figure 8.3.3 were acquired in Kansas where the surface topography was irregular and irregular voids of various dimensions were known to exist in the near surface. Noise waves possibly generated as a result of the irregularity of the surface and presence of voids are obvious on far-offset traces (about half of the recorded traces). This data set needs editing to remove the far-offset traces before it is input into the analysis (see Section 8.5). Data in Figure 8.3.4 were recorded at a site where heavy construction vehicles were in close proximity to the line and moving all around the survey area. Most of the energy on this record is the surface waves generated by these moving vehicles and is therefore considered noise. This data set cannot be processed properly due to a complete lack of any identifiable surface wave signal. Some adjustments or enhancements that can help improve the quality of bad data are explained in Section 8.5.

Sometimes even a data set that appears good during acquisition may need to go through an adjustment based on the results of a more careful examination post-acquisition.

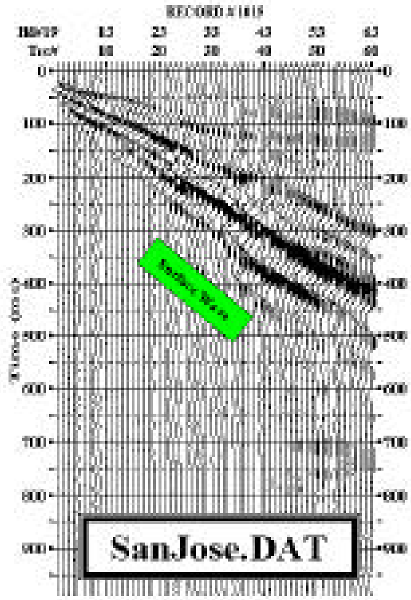


Figure 8.3.1

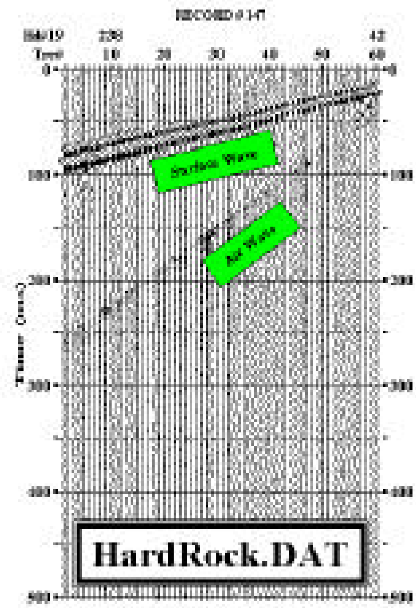


Figure 8.3.2

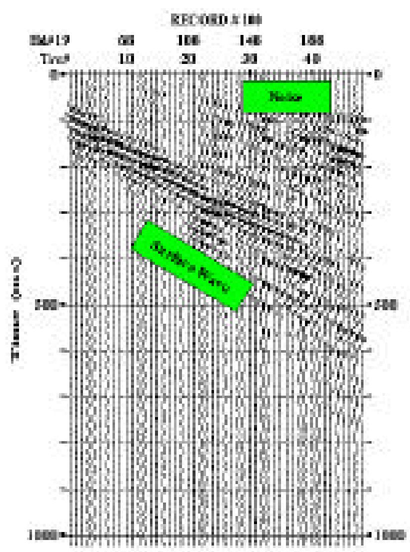


Figure 8.3.3

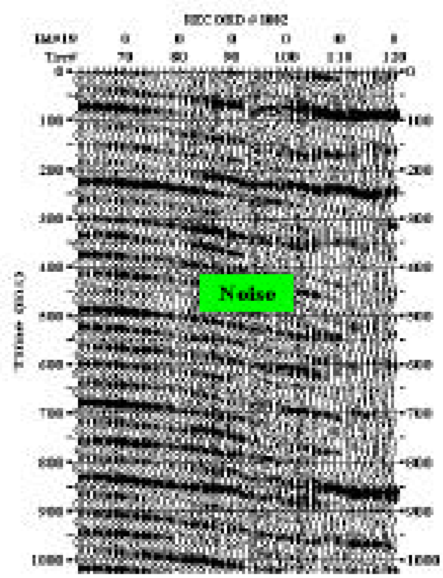


Figure 8.3.4

Phase Velocity Range

A good estimate of an approximate phase velocity (Vphs) range for the surface wave is critical. Vphs will generally range from as low as 10 m/sec to as high as 3000 m/sec depending on material type. This information is used by the program to initiate the analysis by searching within this range for a phase velocity corresponding to a particular surface wave frequency with the greatest coherency throughout the entire range of offset and highest S/N. This frequency is called the "Reference Frequency" in the computation tab of the Control dialog box (Figure 8.3.5). This range of phase velocities is called the "Apparent Phase Velocity" in the parameter tab (Figure 8.3.6). This "beginning" information is also critical for the program to accurately track changing trends in the phase velocity at other frequencies.

If data are of good quality, automatic detection of the phase velocity range is usually reasonably accurate (Figure 8.3.8). If the data have a poor S/N, this automatic detection can result in erroneous findings (Figure 8.3.9). In Figure 8.3.9, a strong body-wave event (a guided wave within a water layer) is identified incorrectly as a surface-wave event. This data set needs to undergo preliminary processing to insure an accurate analysis (see Section 8.5). Figure 8.3.10 illustrates how an apparent phase velocity is calculated from a specific linear trend of arrivals.

As long as the program properly identifies surface-wave events, the analysis will go smoothly by doing nothing more than selecting the "Run" command. Curves resulting from fully automatic analysis should be taken as preliminary with the potential that they may have been adversely affected by noise events sometimes difficult to detect on raw data.

Frequency Range

Proper selection of the frequency range to analyze is also critical. Since different types of seismic events (e.g., body-wave, fundamental- and higher-mode events) usually have characteristic frequency bands, improper selection of this range can result in the analysis of noise events rather than the fundamental mode surface-wave event. An approximate range of surface waves (both fundamental and higher modes) is usually accurately detected automatically once "Preprocess" has been appropriately applied (Figure 8.3.7). Automatic detection can also be controlled or limited by right clicking the "Preprocess" button (see Section 3.2).

Analysis of the amplitude spectra is another way of estimating this frequency range (Figure 8.3.11). When surface-wave events dominate the record, the amplitude spectra will predominantly show the offset-varying spectral characteristics of surface waves. The largest amplitude arrival bands on the traces (as illustrated in Figure 8.11) define the optimum frequency range.

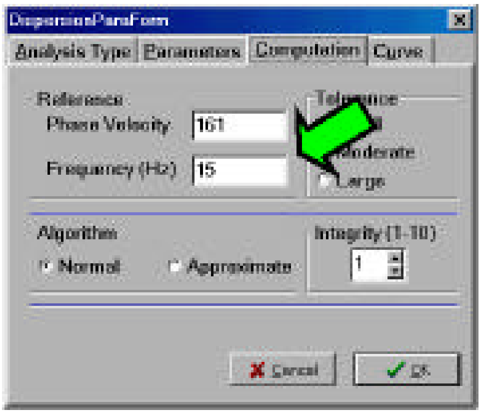


Figure 8.3.5

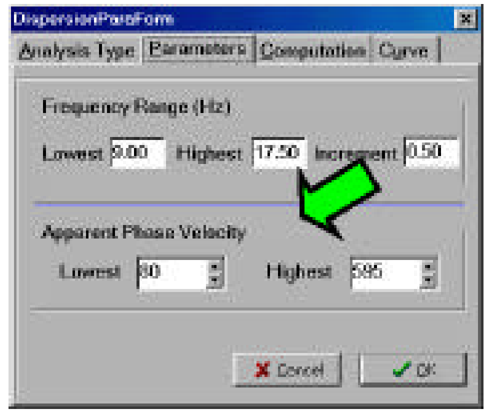


Figure 8.3.6

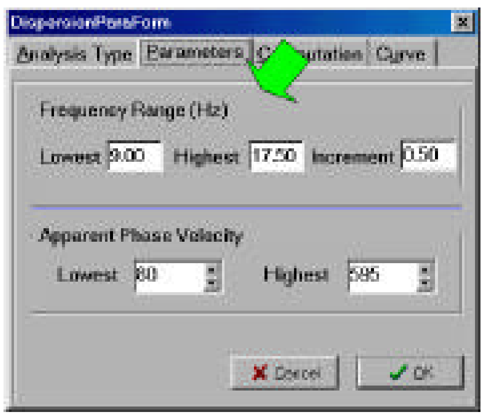


Figure 8.3.7

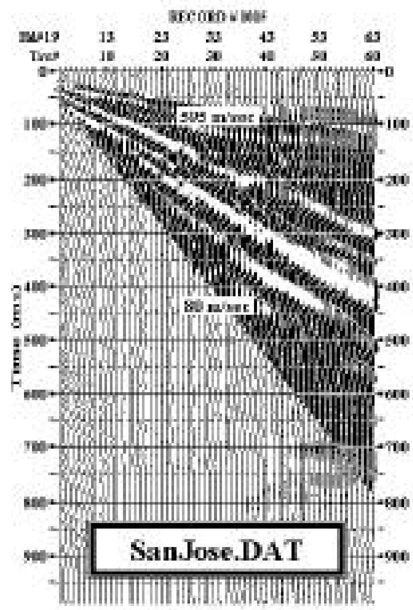


Figure 8.3.8

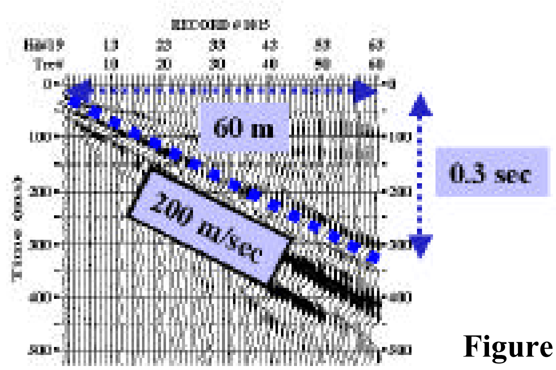


Figure 8.3.9

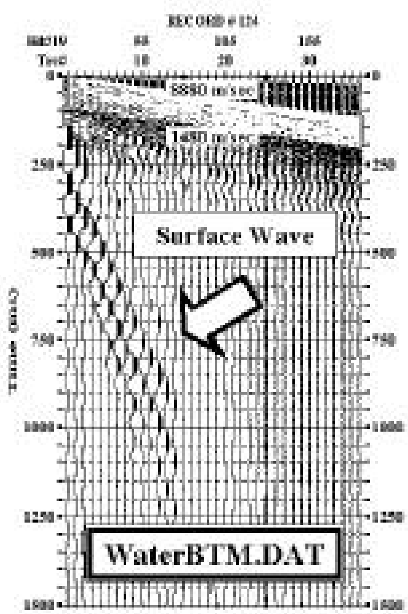


Figure 8.3.10

Overtone Analysis

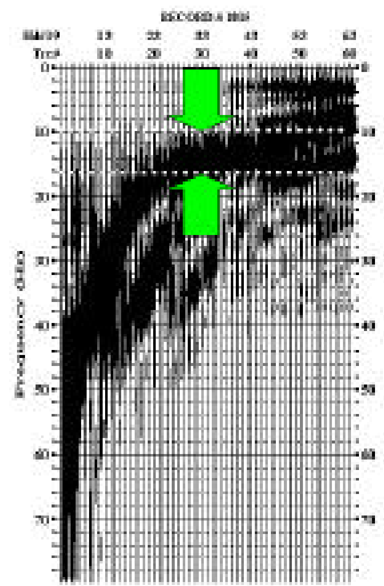


Figure 8.3.11

Overtone analysis is a tool for identifying changing propagation velocity patterns with frequency for all types of seismic events (both signal and noise events). This method is based on 2-D pattern recognition (Park et al., 1996) and is by far the most-unbiased way of delineating phase velocity information. It is probably most useful in identifying surface wave higher modes (overtones).

A seismic record contains surface waves and body waves. A good quality record has been defined as a record in which the surface wave energy dominates any body wave. However, there is always some body-wave energy coincident with the surface waves. Identification of body-wave events and their association to frequency and phase velocity ranges is important for the following reasons:

1. An approximate P-wave velocity (Vp) function can be obtained from either refraction or reflection analysis. An approximate range of surface-wave phase velocities can be estimated from these data using general rules of thumb.
2. Correlation of Vp with Vs (from surface-wave analysis) for unique layers is always useful information (e.g., Poisson's ratio) on geotechnical investigations.
3. Proper identification of body-wave events enhances the confidence of surface wave dispersion-curve analysis. For example, it can be used to confirm that the final dispersion curve was not mistakenly obtained from a body-wave event. Or, it can make it possible to evaluate the influence of body-wave events on the surface wave dispersion curve analysis.

If you select the "Overtone" button after "Preprocessing," overtone analysis will be initiated with the default parameters defined for frequency and phase velocity range. These default parameters are chosen such that the dispersive nature of surface waves can be most effectively delineated, whereas body-wave events are excluded from the image. The default values are much broader than values determined automatically during preprocessing. The reason for this increased range is to assure a wider coverage during pattern recognition. For that reason, resultant images usually contain the remnants of noise events as well as signal patterns (Figure 8.3.12). Once this initial image has been examined and evaluated, another overtone analysis can be run with ranges and parameters more focused on the fundamental mode energy only (Figure 8.3.13). The image in Figure 8.3.13 was obtained by using a narrower range of phase velocity and wider range of frequencies than the image in Figure 8.3.12. To achieve a higher resolution image, a smaller increment (5 m/sec) of phase velocity was used than in the initial analysis run (15 m/sec).

Body-wave events can be identified by enlarging the frequency and phase velocity range beyond that optimum for surface waves during overtone analysis. Usually, body-wave events will have frequencies and phase velocities several times higher than surface waves.

For example, the direct, refraction, and reflection events at most soil sites usually possess frequencies that range across a couple hundred Hz (e.g., 50-300 Hz). An air-wave event usually has frequencies even higher than direct, refracted, or reflected energy (e.g., 100-500 Hz). Phase velocities (horizontal propagation speed) of body waves are generally in the range from 300 to 5000 m/sec. They are, however, usually non-dispersive with just a slight dispersive character observable on some refraction events (Clayton and McMechan, 1981). Back- and side-scattered body waves can also appear dispersive when they have more than one azimuth angle with respect to the survey line (Park et al., 2000).

There are two types of body-wave events generally evident on shot records recorded to optimize surface wave energy: air-wave and the first-arrival (refraction or direct) events. Since air-wave events can possess a significant amount of energy and a phase velocity (343 m/sec in 20°C) close to (or sometimes within) the phase-velocity of many surface waves, phase velocity calculations of surface wave energy can be unreliable unless the air-wave event is identified, its influence assessed, and removed if possible. When the frequency range for the surface waves being analyzed is lower than about 100 Hz, the air-wave event will not likely affect the surface wave analysis because air waves generally have frequencies higher than 100 Hz. On the other hand, refraction events usually have velocities many times (say, five times) higher than surface waves in the same setting. This large difference is in part due to a much greater penetration depth of refracted energy compared to surface waves at the same source. In the case of direct-wave events, however, the velocity will generally be four or five times higher than surface wave velocities since the direct wave is sampling the same overburden material the surface wave is.

Figures 8.3.14 and 8.3.15 show overtone images obtained using frequency and phase velocity ranges appropriate for body waves. It is sometimes important that these ranges overlap those of surface waves so that both types of waves can be examined on the same display in a comparative manner. Overtone analysis shown in Figure 8.3.14 focuses on examination of an air-wave event, whereas the one in Figure 8.3.15 targets the first-arrival events. A frequency range of 5-250 Hz (with 1 Hz increment) and a phase-velocity range of 50-450 m/sec (with 5 m/sec increment) are usually optional for air-wave analysis. The phase-velocity range is enlarged to 50-6000 m/sec (with 50 m/sec increment) for first-arrival analysis. In Figure 8.3.14, the normal air-wave event is clearly non-dispersive (with about 345 m/sec velocity) at frequencies higher than 100 Hz. Dispersive air-wave events that were either side- or back-scattered (or combination of both) from surface objects near the survey line are also identified. It is apparent that air-wave events do not interfere with surface-wave analysis due to frequency characteristics that are uniquely different and in part due to only minor overlap in velocity ranges. The frequency and phase-velocity characteristics of air-wave events can be determined using “Filter” processing (see Section 5.5) (Figure 8.3.16). Overtone analysis shown in Figure 8.3.15 focuses on examination of the first-arrival. A narrow-band (about 50-60 Hz) body-wave event with a phase velocity of about 2000 m/sec is identified. This shows a slight dispersion, possibly indicating a refraction from bedrock surface. The presence of this refraction on the seismic record can be confirmed on the raw record by using the “Filter” option (Figure 8.3.17).

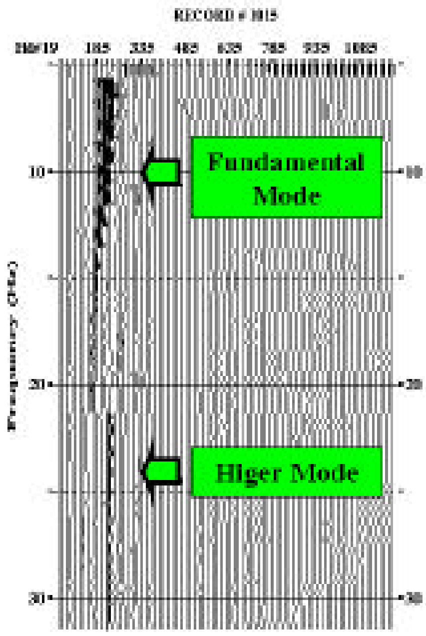


Figure 8.3.12

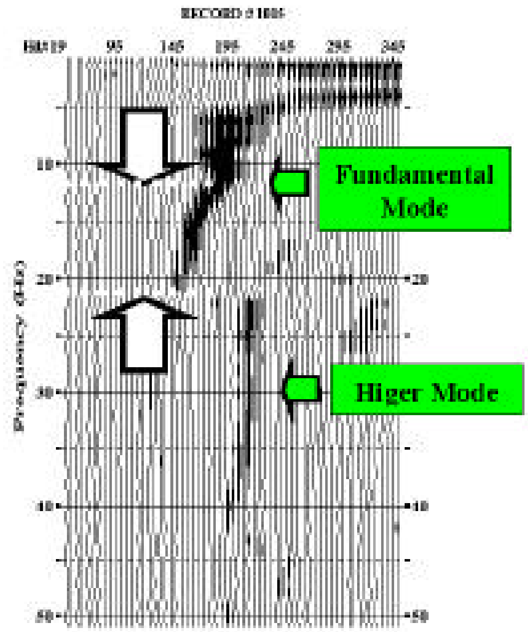


Figure 8.3.13

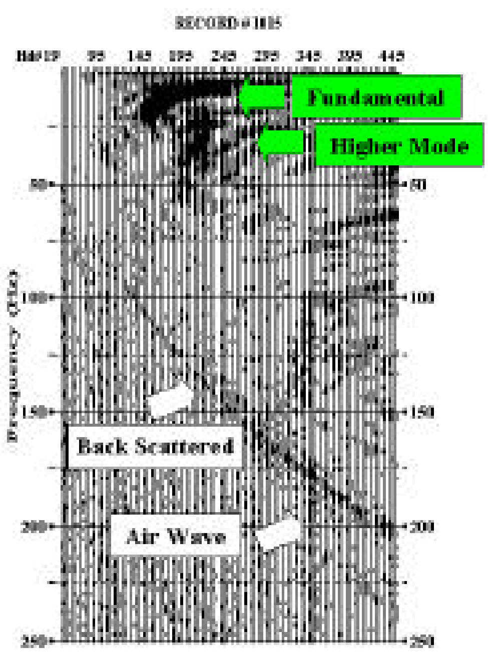


Figure 8.3.14

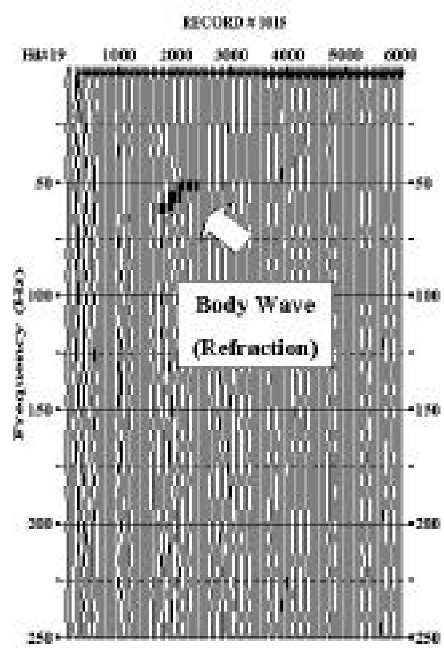


Figure 8.3.15

Controls

After one or more overtone analyses have been completed, frequency and phase-velocity characteristics of all wave types should be well understood and reasonably well determined. Using this information, the dispersion-curve for the fundamental mode surface wave can be constructed. This is done by first properly setting the frequency range in the parameters tab of the "Control" dialog box (Figure 8.3.7). Using automatic mode during the "Preprocess" step will usually come up with optimum values. However, occasionally the highest frequency selected may extend beyond the overtone frequencies. For this case, the value determined automatically needs to be manually changed to a lower value determined using the overtone image. On the other hand, the lowest frequency automatically selected may be so low it includes frequencies in which the phase velocity becomes either non-dispersive or unstable (e.g., 5-10 Hz range in Figure 8.3.13). The nondispersive range is represented by a flat curve. An "unstable" range is represented on the dispersion curve by an irregular image. This usually occurs within the frequency range suffering from "near-field" effects (Stokoe et al., 1994). In other words, the surface waves in this frequency range were not developed sufficiently to become well-behaved plane-wave events. This usually indicates longer offsets (between source and receivers) need to be used during acquisition to avoid this effect. From the overtone image in Figure 8.3.13, the optimum frequency range would be selected to be 11-21 Hz.

After properly setting the frequency range, the phase velocity needs to be checked at a reference frequency (Figure 8.3.5). Automatic selection usually assigns values to these parameters within 20% deviation. (However, a deviation as much as 100% may be acceptable as long as there is no significant higher mode energy observed at the reference frequency [Figure 8.3.13].)

The "Tolerance" option under the computation tab in the "Control" dialog box (Figure 8.3.18) sets the range of velocities to search at a particular frequency. Once an accurate phase velocity has been calculated for the reference frequency, the process moves to adjacent frequencies. At this point the range of phase velocity searched through is updated according to the phase velocity values estimated during the previous calculation. The tolerance option sets the upper and lower bounds for this searching range. The existence of higher modes needs to be evaluated to properly set this option. The tolerance option has no effect on the calculation when no higher mode energy (or any body-wave event) is observed within a velocity range with an upper limit at least two times higher than the phase velocity of the fundamental mode. It is critical to properly set this option if higher modes are present at energy levels comparable to the fundamental-mode and in the same frequency range as the fundamental mode. The significance of this option is dependent on the difference in phase velocity (dVphs) between the fundamental (V0) and next higher mode (V1) observed in the overtone image. The following guides describe how to properly choose an option:

1. "Small" if dVphs < 0.25 x V0,
2. "Moderate" if dVphs < 0.50 x V0,
3. "Large" if dVphs > 0.50 x V0.

The “Algorithm” setting under the computation tab in the “Control” dialog box (Figure 8.3.19) provides the opportunity to select a couple of slightly different algorithms for overtone and dispersion-curve analyses. Selecting the “Approximate” algorithm option will usually provide a good preliminary representation of overtone images. This is an especially effective option when working with noisy data. This option can effectively delineate higher modes when more than one higher mode exists within a given frequency range during the overtone analysis (Figure 8.3.20). The “Normal” algorithm option, on the other hand, focuses on the mode with the highest energy levels (Figure 8.3.21). Because of this approach, the “Normal” option will usually produce an overtone image with greater resolution than the “Approximate” option. In Figure 8.3.21 the fundamental mode clearly dominates energy in the 10-20 Hz range, where the first higher mode dominates energy in 20-40 Hz range.

Once the optimum frequency range for the fundamental mode has been identified, it is always best to use the “Normal” algorithm. The “Integrity” option in normal algorithm controls how intensively the phase velocity search is undertaken at each calculation frequency. Optimum integrity can be obtained by successively increasing the integrity value and examining the phase velocity change and its effect on the calculated dispersion curve. An integrity value of 3 is generally optimum.

Run

After all the parameters have been properly set, clicking the “Run” button starts the calculation of the phase velocities followed by the display of one dispersion curve. Based on the displayed curve quality, a few trials may be necessary with different parameter settings (Figure 8.3.22). “Process No. 1” in Figure 8.3.22 has been obtained by using “Approximate” algorithm, “Process No. 2” by using “Normal” algorithm with integrity 1, and “Process No. 3” by using integrity 3. For demonstration purposes the highest analysis frequency has been increased to 35 Hz from the default selection of 17.5 Hz. A slight difference can be observed between all three curves in the lower half of the analyzed frequency range. The most prominent difference occurs in frequencies higher than about 23 Hz.

The quality of a dispersion curve is judged according to two criteria: signal-to-noise ratio (S/N) and general dispersion curve trend. A high S/N indicates high confidence in the obtained phase velocity. S/N higher than 0.5 is usually acceptable. The S/N curve will, in general, show a roughly “down-going” trend. This means that S/N will generally decrease with frequency, which is due to the relative increase in noise events at the higher frequencies (Park et al., 1999). This down-going trend in S/N should be examined in much a broader perspective than possible with dispersion curves done.

The trend of a dispersion curve is generally “down-going” phase velocity as frequency increases. Unless the upper-most layer of the surveyed area consists of material with a high seismic velocity (or stiffness) in comparison to materials below it (e.g., pavement), it is unlikely the dispersion curve will contain phase velocities that increase significantly with frequency (“up-going” trend). Therefore, whenever an up-going trend is observed within a certain frequency range, interference by noise must be suspected. The most common source for this type of noise interference is the higher mode energy. When the dispersion curves in Figure 8.3.22 are compared to the overtone image previously obtained (Figure 8.3.21), it is obvious that the up-going trend of the two curves is the result of the first higher mode. Although it is tempting to consider the normal "down-going" trend of the other curve (Process No. 2) in the higher frequency range as "good," it would be best discarded because its corresponding image is not confirmed in the overtone image shown in Figure 8.3.21. The low (< 0.5) S/N curves at these higher frequencies are also indicative of unreliable results. Careful examination of S/N curves at frequencies higher than 20 Hz reveals that the two "up-going" curves have higher S/N than the normal curve. This is the result of higher mode energy being considered signal during the analysis.

Figure 8.3.23 shows the comparison of results from the different algorithms. With the "Normal" algorithm, dispersion curves change somewhat noticeably as the integrity increases. The change soon becomes negligible after a certain value (e.g., 3). When data are not noisy, a value of 3 is usually the optimum. With noisy data the value needs to be increased proportionally with the noise levels. Improvement in the quality of dispersion curves with different integrity values is usually quantified by changes in S/N curves, although changes in the general trend of the dispersion curves should also be considered. With good quality data, the "Approximate" algorithm usually produces a dispersion curve comparable to that obtained using the normal algorithm with optimum integrity (Figure 8.3.23).

Figure 8.3.24 shows dispersion curves obtained using different degrees of "Tolerance." It demonstrates that the higher mode is picked in the high frequency range when "Moderate" and "Large" tolerances are used. This is due to the larger phase velocity searching range as previously described.

Once a judgment has been made as to the best curve, the curve must be saved before proceeding to the "inversion" step. By checking the processing history ("History" button), all the displayed curves can be studied (Figure 8.3.25). This step can also assist in judging which curve should be taken as final/representative through examination of a few key processing parameters. If only part of the curve is reliable and to be saved, the "Resample" button provides options to edit the curves (see Section 3.6).

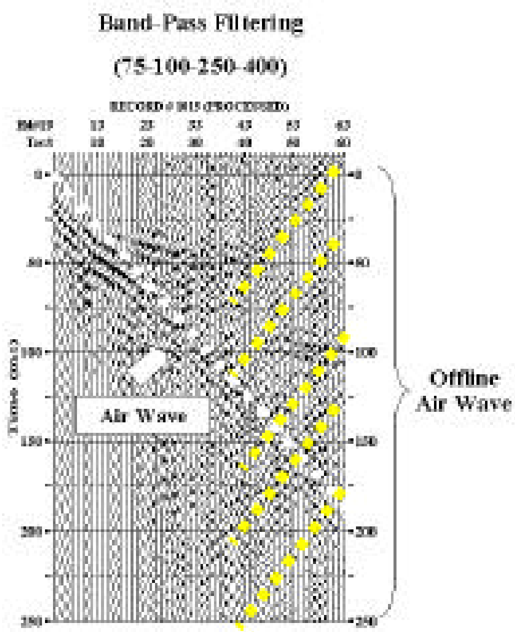


Figure 8.3.16

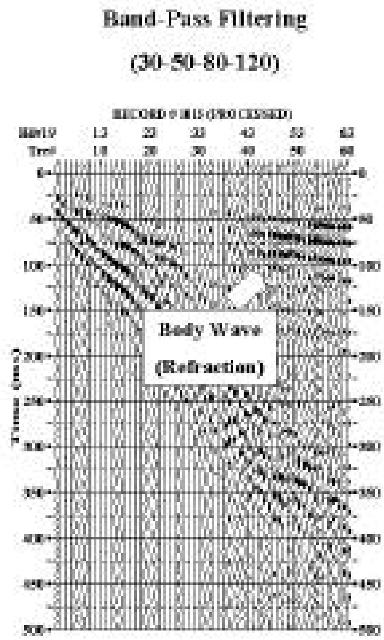


Figure 8.3.17

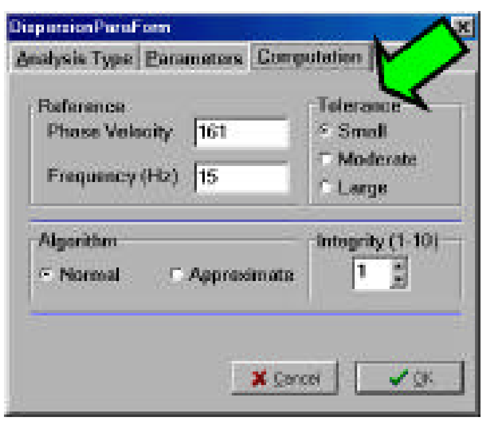


Figure 8.3.18

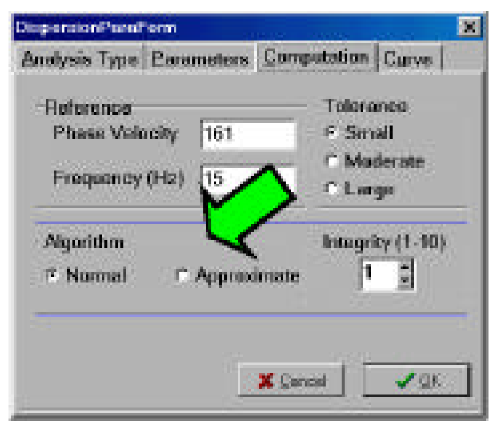


Figure 8.3.19

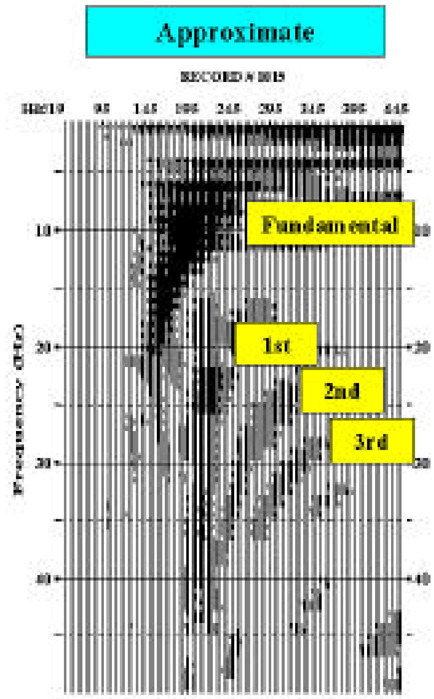


Figure 8.3.20

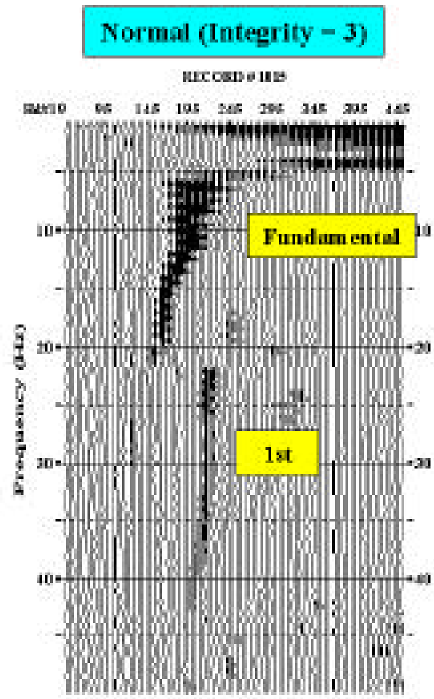


Figure 8.3.21

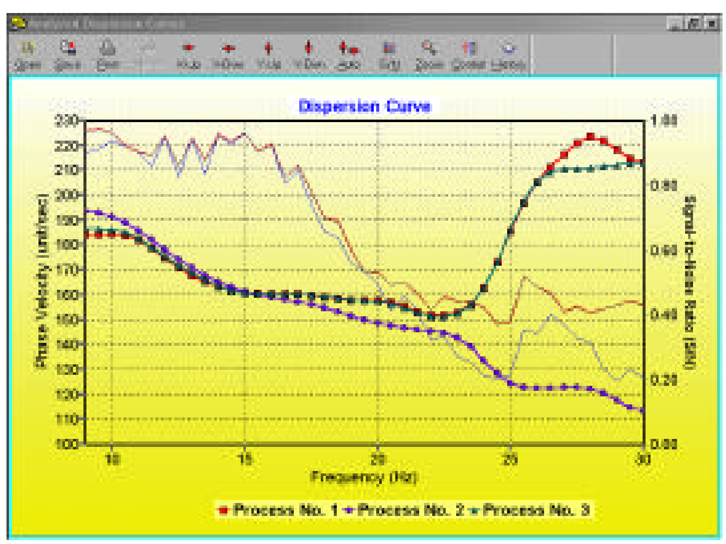


Figure 8.3.22

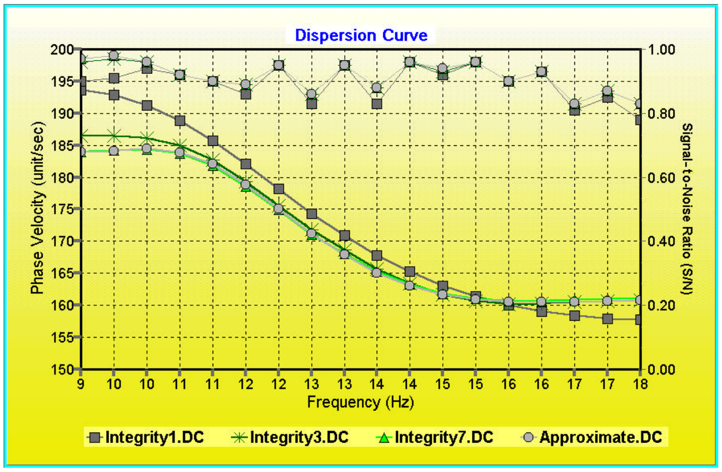


Figure 8.3.23

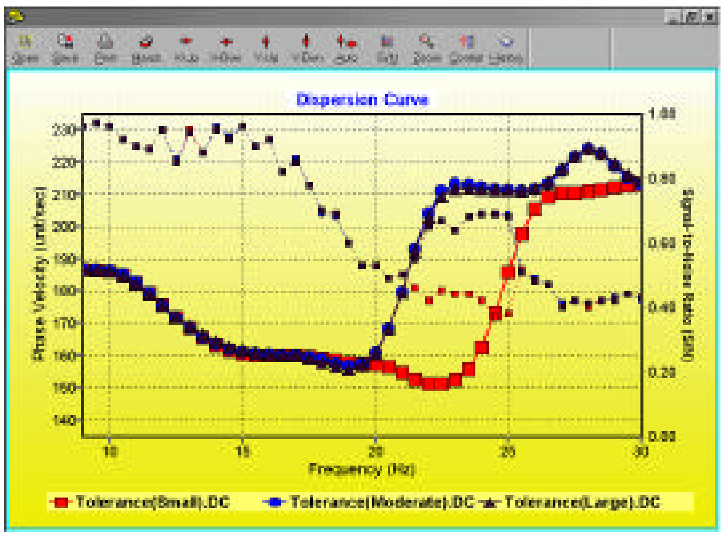


Figure 8.3.24

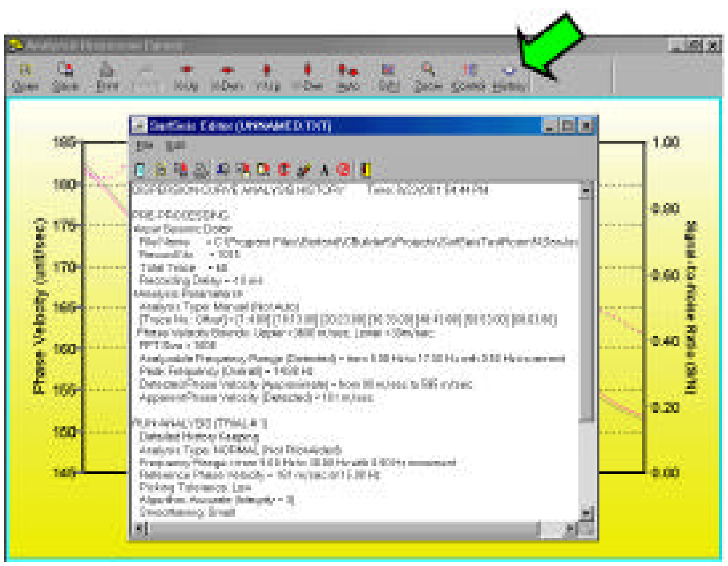


Figure 8.3.25

8.4 Inversion Analysis

Once a final dispersion curve has been selected and saved as a *.DC file, the program will prompt to proceed to either “Inversion” analysis for the saved curve or “Dispersion” analysis to move on to the next seismic record (depending, of course, on whether the input seismic data contains only one or multiple records). For “Dispersion” analysis the analysis for each record would be similar to the previously described procedure. As well, with the “Dispersion” analysis option the previous dispersion curve can be used as a “Pilot” curve. Moving one step further, the “Pilot Aided” analysis type in the “Controls” dialog box (see Section 3.3) prompts automatic analysis for all remaining records in input file.

Figure 8.4.1 displays the beginning stage of the inversion analysis. Two other button options are available besides the “Run” button: “Controls” and “Layer Model.” The “Controls” button enables the changing of some parameters that relate to the inversion process (e.g., stopping criteria) (see Section 4.2). The “Layer Model” button makes it possible to change individual items in the initial earth layer model (see Section 4.3).

The “Run” button begins the inversion process searching for a Vs profile whose theoretical dispersion curve best matches the calculated dispersion curve using the root-mean-square error (RMSE) as a guide and constraint (Xia et al., 1999). Each time a theoretical curve is calculated based on a layer model and compared with the experimental curve is called an “iteration.” After each iteration, the theoretical (marked as “Current”) curve is compared to the experimental (marked as “Measured”) curve and the Vs profile for the theoretical curve is compared with the initial Vs profile (Figure 8.4.2). The frequency axis for the dispersion curve is inverted during display to allow approximate comparison of the phase velocity to the Vs profile. Iterations will continue until either the minimum RMSE (*Emin*) is met or the maximum number of iteration (*Imax*) is reached, whichever occurs first.

If the experimental curve is fairly accurate (or makes sense from theoretical point of view), then the RMSE usually drops rapidly during the first several iterations (Figure 8.4.2). A high quality dispersion curve usually will be characterized by a consistent and smooth change in phase velocity with frequency. For these high quality dispersion curves, *Emin* is usually reached after just a few iterations and the analysis is completed. Once a level is reached beyond which no noticeable drop in RMSE is observed (Figure 8.4.3), the iteration should be stopped manually by selecting the “Stop Ite” button in the lower righthand corner of the display.

A prolonged inversion usually occurs when the measured dispersion curve trend “does not make sense” from theoretical perspective (Xia et al., 1999) either in whole or in part. This type of dispersion curve usually has an abnormal trend, where phase velocity increases (instead of decreases) with frequency across a significant portion of the curve or the curve flattens at low frequencies. The dispersion curve shown in Figure 8.4.3 represents an example of this abnormal trend at both high and low frequencies. The inversion process did not drop below the specified *Emin* (= 3.0) even after the specified *Imax* (= 30) was reached as a result of this trend. Whenever the inversion is prolonged, calculated Vs profiles usually contain one or more velocity reversals. These reversals are noticeable in this example at depths of about 3 m and deeper than 10 m (Figure 8.4.3). If the reversals are a result of prolonged inversion, they should be considered suspicious and could be numerically exaggerated. In Figure 8.4.4 the inversion of a dispersion curve with a “reverse” dispersion trend (phase velocity increases with frequency in a consistent manner) is typical for seismic data acquired over pavement (therefore, nothing is wrong with the curve). The inversion analysis still had a large RMSE even after 30 iterations due to this “abnormal” trend. This type of “reverse” dispersion curve needs a separate inversion algorithm for a proper handling of layer parameters (Nazarian et al., 1982). This algorithm is not part of this version of SurfSeis, however, it will be part of SurfSeis 2, soon to be released.

A prolonged inversion can also occur when the stopping RMSE (*Emin*) is set unrealistically low (Figure 8.4.5). Although the input dispersion curve possesses good quality, the inversion was prolonged because the *Emin* was too low (= 0.3). Therefore, the observed velocity reversal (2–5 m deep) is likely more exaggerated than actual.

The RMSE of each unique layer in the final Vs profile can be viewed by selecting “Final (R-M-S)” (Figures 8.4.6 and 8.4.7). This RMSE is a measure of relative error for each layer in comparison to theoretical criteria (Xia et al., 1999) and can be used as a measure of confidence. A prolonged inversion will usually result in a profile with a large RMSE (i.e., small confidence) for most layers (Figure 8.4.6). Small RMSE values (i.e., big confidence) should be expected for a normal inversion where the process is stopped after several iterations (Figure 8.4.7).

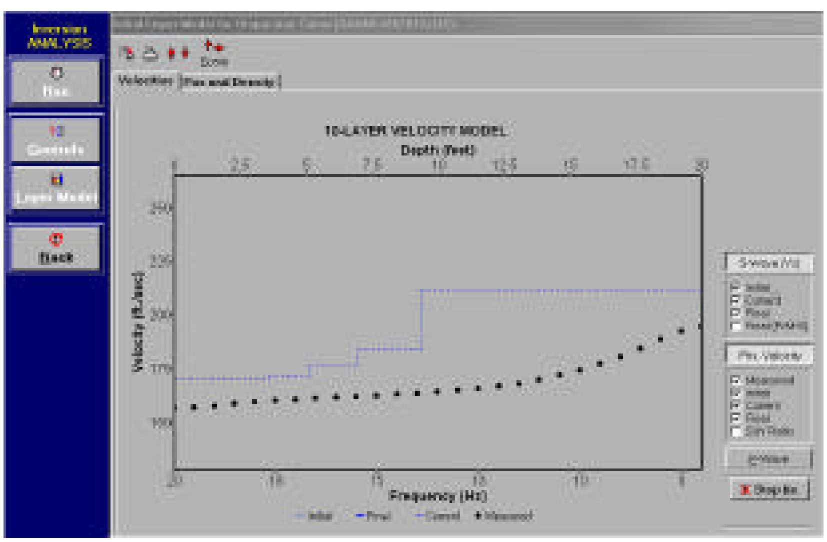


Figure 8.4.1

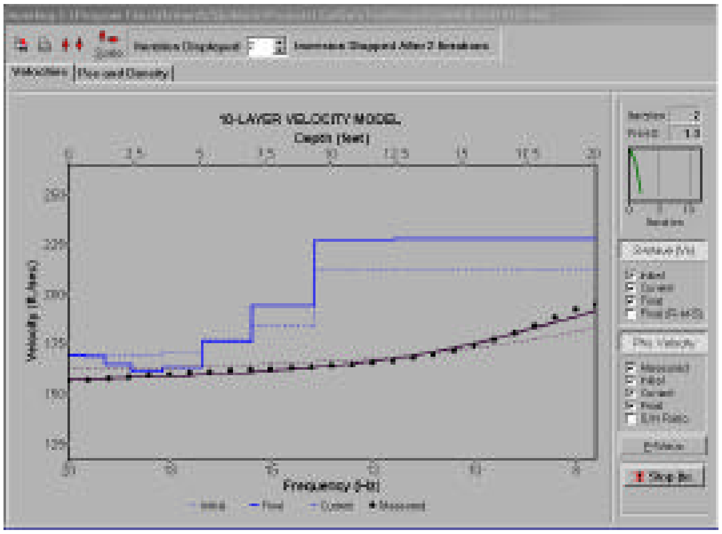


Figure 8.4.2

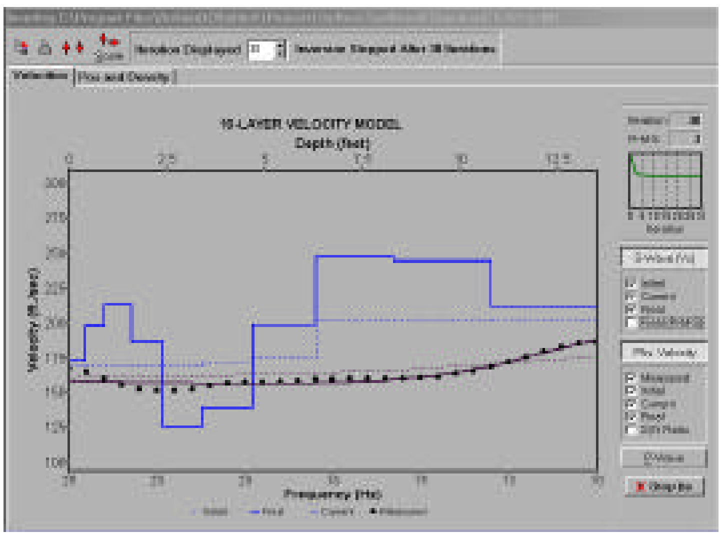


Figure 8.4.3

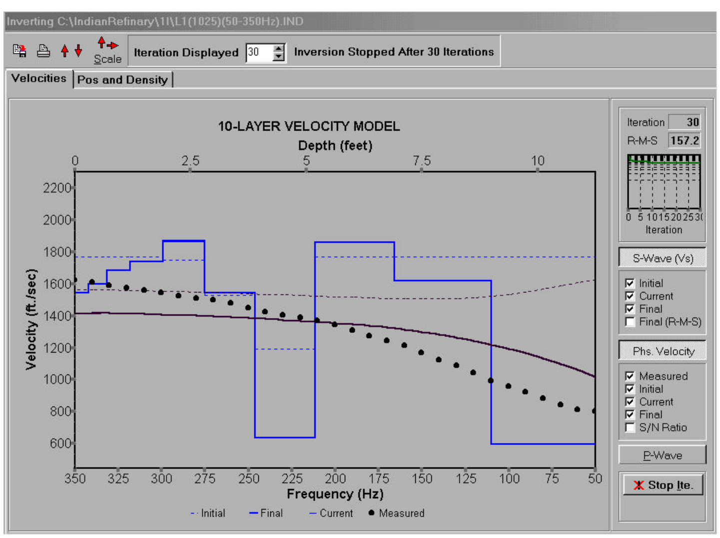


Figure 8.4.4

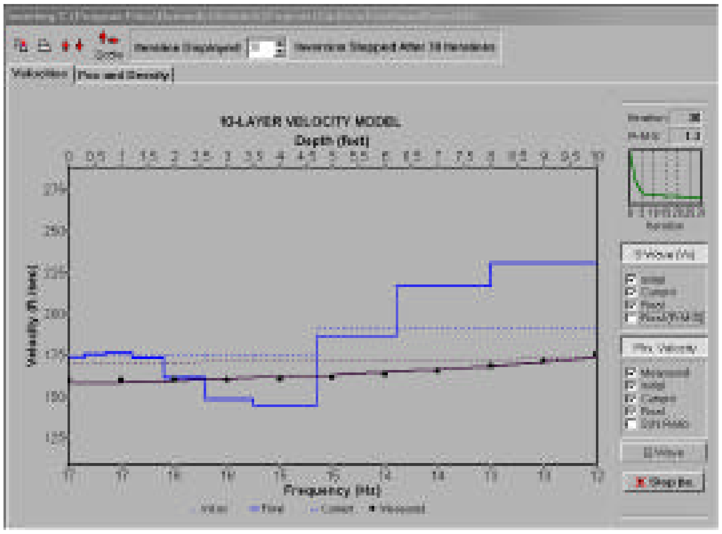


Figure 8.4.5

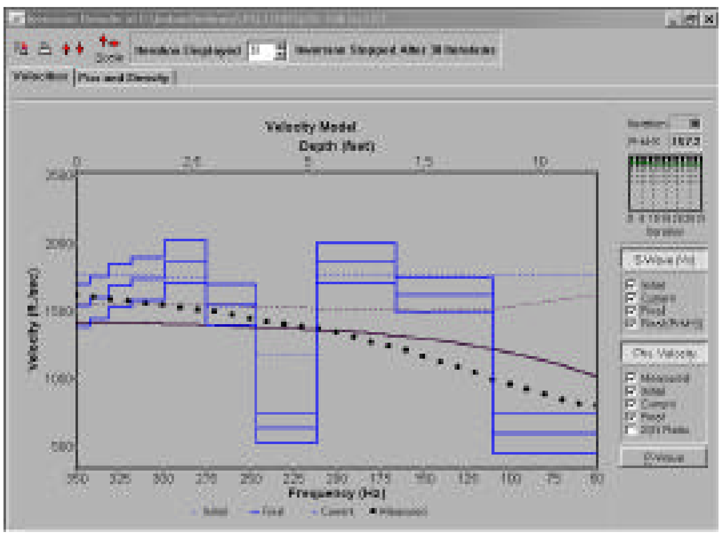


Figure 8.4.6

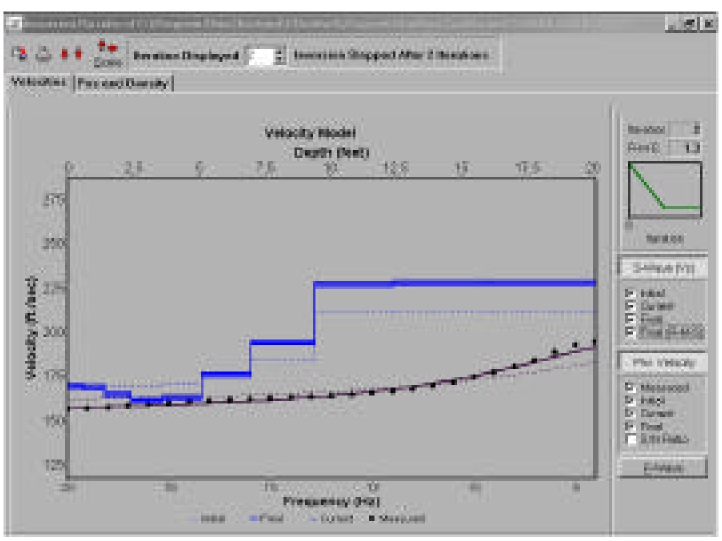


Figure 8.4.7

8.5 Preadjustment of Data

It may be necessary to preprocess seismic data prior to dispersion-curve analysis. There are usually two reasons for this: First, to enhance the signal-to-noise ratio (S/N), resulting in a broader-band dispersion curve, increasing investigation depth and confidence; and second, to help identify more effectively the different types of seismic events within the frequency and phase velocity range of interest. This, in turn, can help optimize estimates of some key processing parameters (e.g., frequency range) for the dispersion analysis.

A strong first-arrival event can be troublesome in two different ways. First, automatic detection can mistake it as a surface-wave event if its energy is equal to or greater than the surface-wave (Figure 8.3.7). For this case, a dispersion curve calculated using the default parameters will be erroneous because the dispersive nature of the body-wave event (in this case, a guided-wave event) will be of equal or greater influence over the surface-wave event. Secondly, the first arrival can alter the phase relationship of surface waves at frequencies dominated by first arrival energy. Again, for this case, the calculated phase velocities will deviate from actual to an extent proportional to the degree the first arrival energy dominates. A strong first-arrival event can be effectively removed using the "Mute" process (see Section 5.5).

Underwater data shown in Figure 8.5.1 have significantly more pronounced surface-wave (in this case, the Scholte wave) energy after the high amplitude body-wave events (guided and refraction events) are muted (Figure 8.5.2). With this proper preprocessing of the data, the overtone image (Figure 8.5.4) of the fundamental-mode is much better defined across a broader bandwidth than the raw data without editing (Figure 8.5.3). The dispersion curve has, in general, a higher S/N and broader frequency range (Figure 8.5.5).

Another problem source in dispersion-curve analysis is scattered energy, or energy arriving from a source outside the 2-D plane of the survey. Scattered energy can come from any place in the survey area. Off-line anomalies (e.g., voids and building foundations) can produce coherent energy with an apex related to the anomaly location. Anomalies in line can cause back-scattered arrivals, which are the sound equivalent of waves on a pond when they "bounce" off a fixed object in the water. Depending on the relative energy of these scattered-wave events, the dispersion relationship of surface waves can be significantly altered. Sometimes they create a separate dispersion curve (usually reverse dispersion) on the overtone image (e.g., the back-scattered air-wave event shown in Figure 8.3.14). The scattered-wave noise problem is usually offset-dependent, such that the noise tends to represent a large portion of the recorded energy at further offset traces (due to attenuation) where the source-generated surface waves are weaker relative to near-offset traces. For this reason, the far-offset traces need to be examined carefully before analysis. Figure 8.5.6 shows a sample data set (SanJose.DAT) with a gain that makes it obvious that the far-offset traces are contaminated with body- and surface-wave noise events. When this data set is separated into near-offset and far-offset traces, overtone analysis of the near-offset traces (Figure 8.5.7) reveals a fundamental-mode dispersion curve that is better defined, especially at low frequencies, than that obtained from full-offset analysis (Figure 8.3.13). The dispersion image for the far-offset traces (Figure 8.5.8) suffers noticeably from the noise problem. Even with the noise problem on far-offset traces, the dispersion image is of an even better quality than the image obtained by using full-offset traces. The two analyzed dispersion curves are displayed in Figure 8.5.9 and show that the near-offset curve has a higher S/N in general.

Although higher modes are complicated with dependence on a variety of parameters, such as layer geometry and receiver location (Tokimatsu et al., 1992), they tend to become more significant at further offsets (Park et al., 1999). This reinforces the need to carefully examine the far-offset traces and their effects on the analysis.

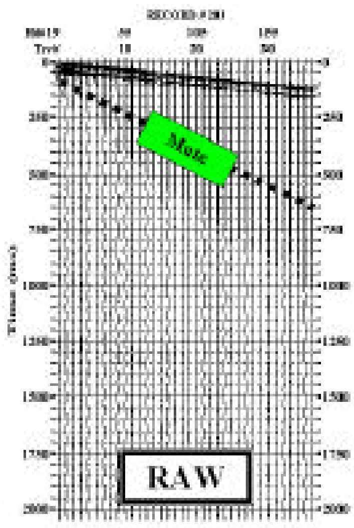


Figure 8.5.1

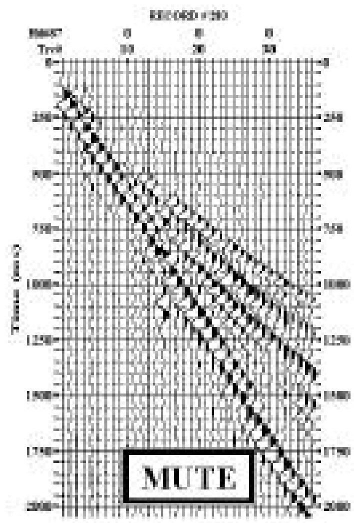


Figure 8.5.2

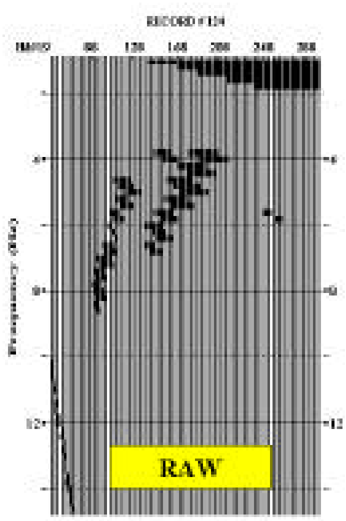


Figure 8.5.3

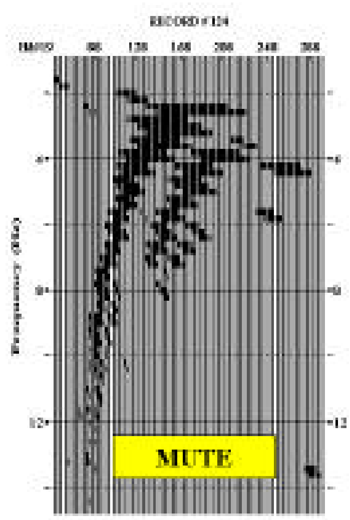


Figure 8.5.4

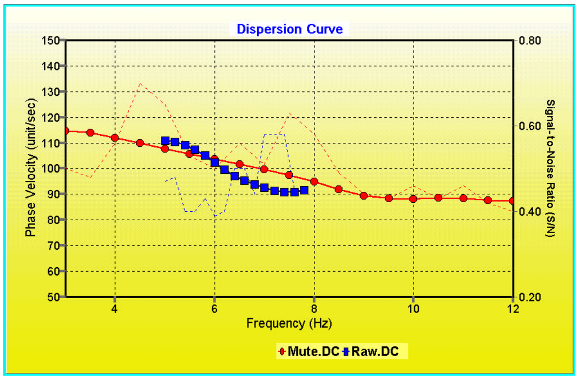


Figure 8.5.5

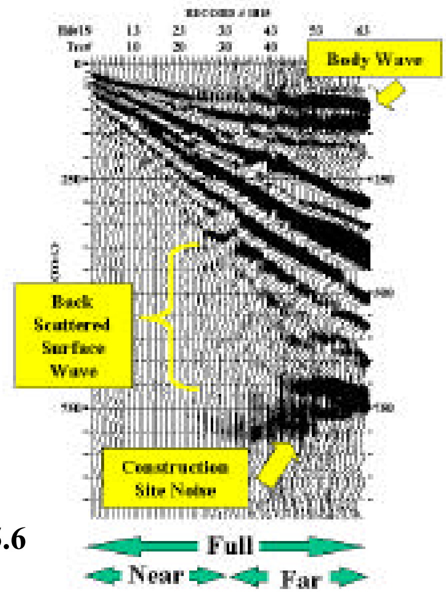


Figure 8.5.6

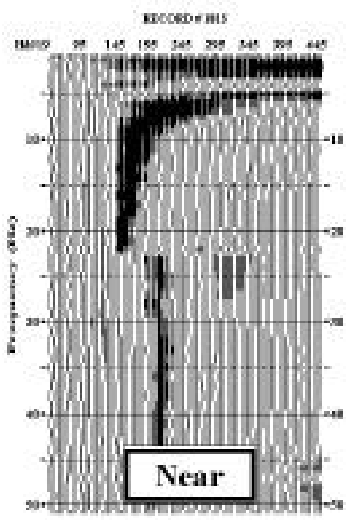


Figure 8.5.7

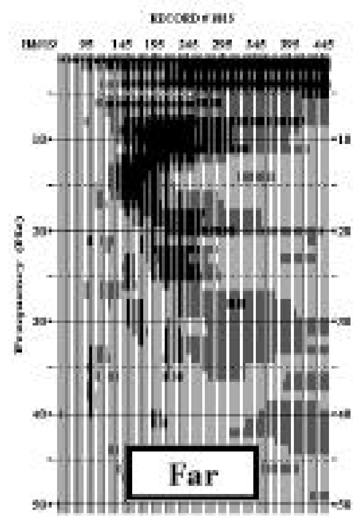


Figure 8.5.8

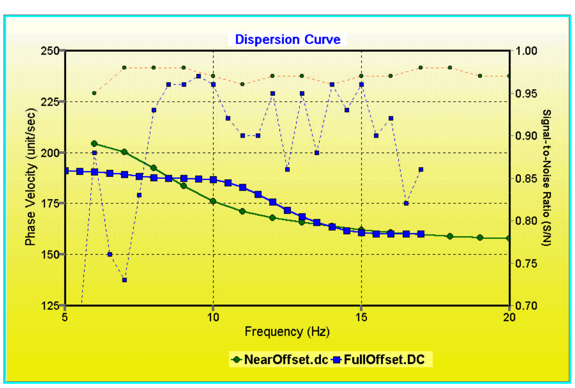


Figure 8.5.9

Appendices

Appendix __ — Index

Bullen, K.E., 1963, An introduction to the theory of seismology: Cambridge University Press, 381 pp.

Coruh, C., 1985, Stretched automatic amplitude adjustment of seismic data: Geophysics, v. 50, p. 252–256.

Gucunski, N., and Woods, R.D., 1991, Instrumentation for SASW testing, in Geotechnical special publication no. 29, Recent advances in instrumentation, data acquisition and testing in soil dynamics, edited by S.K. Bhatia and G.W. Blaney, American Society of Civil Engineers, p. 1–16.

Heukelom, W., and Foster, C.R., 1960, Dynamic testing of pavements: Journal of the soil mechanics and foundations division, v. 86, n. SM1, 1–28.

Ivanov, J., Park, C.B., Miller, R.D., and Xia, J., 2000, Mapping Poisson's Ratio of unconsolidated materials from a joint analysis of surface-wave and refraction events: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2000), 11-19.

Ivanov, J., Park, C.B., Miller, R.D., Xia, J., Hunter, J., Good, L., and Burns, R., 2000, Joint analysis of surface-wave and refraction events from river-bottom sediments [Exp. Abs.]: Soc. Explor. Geophys., p. 1307-1310.

Mari, J.L., 1984, Estimation of static corrections for shear-wave profiling using the dispersion properties of Love waves: Geophysics, v. 49, p. 1169–1179.

McMechan, G.A., and Yedlin, M.J., 1981, Analysis of dispersive waves by wave field transformation: Geophysics, v. 46, p. 869–874.

Miller, R.D., Xia, J., Park, C.B., and Ivanov, J.M., 1999, Multichannel analysis of surfaces waves to map bedrock: Leading Edge, v. 18, n. 12.

Miller, R.D., J. Xia, C.B. Park, and J. Ivanov, 1999, Using MASW to map bedrock in Olathe, Kansas [Exp. Abs.]: Soc. Explor. Geophys., p. 433-436.

Miller, R.D., J. Xia, C.B. Park, J.C. Davis, W.T. Shefchik, and L. Moore, 1999, Seismic techniques to delineate dissolution features in the upper 1000 ft at a power plant site [Exp. Abs.]: Soc. Explor. Geophys., p. 492-495.

Miller, R.D., J. Xia, C.B. Park, and J.M. Ivanov, 1999, Multichannel analysis of surfaces waves to map bedrock: Leading Edge, v. 18, n. 12.

Miller, R.D., J. Xia, C.B. Park, and J. Ivanov, 1999, Shear wave velocity field to detect anomalies in the subsurface [Abs.]: Proceedings of the Int'l Conference on Applications of Geophysical Technologies, Dec. 11-15, 2000, St. Louis, Missouri.

Miller, R.D., J. Xia, and C.B. Park, 1999, MASW to investigate subsidence in the Tampa, Florida area: Kansas Geological Survey Open-file Report 99-33.

Miller, R.D., J. Xia, C. Park, J. Ivanov, N. Geier, and D. Laflen, 1999, Using MASW to map bedrock in Olathe, Kansas: Kansas Geological Survey Open-file Report 99-9.

Moore, R.C., 1964, Paleoecological aspects of Kansas Pennsylvanian and Permian Cyclothems: Kansas Geological Bull. 169, v. 1, p. 287–380.

Nazarian, S., Stokoe II, K.H., and Hudson, W.R., 1983, Use of spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems: Transportation Research Record No. 930, p. 38–45.

Nazarian, S., 1984, In situ determination of elastic moduli of soil deposits and pavement systems by spectral-analysis-of-surface-waves method: Ph.D. Dissertation, The University of Texas at Austin.

Park, C.B., Miller, R.D., and Xia, J., 1999, Multichannel analysis of surface waves: Geophysics, v. 64, n. 3, p. 800-808.

Park, C.B., Xia, J., and Miller, R.D., 1998, Surface waves as a tool to image near-surface anomaly: 68th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, p. 874–877.

Park, C.B., Miller, R.D., Xia, J., Ivanov, J., Hunter, J., Good, L., and Burns, R., 2000, Multichannel analysis of underwater surface waves near Vancouver, B.C., Canada [Exp. Abs.]: Soc. Explor. Geophys., p. 1303-1306.

Park, C.B., R.D. Miller, and J. Xia, 2000, Detection of higher mode surface waves over unconsolidated sediments by the MASW method: in Proceedings of Symposium on the application of geophysics to engineering and environmental problems (SAGEEP 2000), Arlington, Va., p. 1-9.

Park, C.B., R.D. Miller, J. Xia, J.A. Hunter, and J.B. Harris, 1999, Higher mode observation by the MASW method [Exp. Abs.]: Soc. Explor. Geophys., p. 524-527.

Park, C.B., Miller, R.D., and J. Xia, 1999, Multimodal analysis of high frequency surface waves: Proceedings of Symposium on the application of geophysics to engineering and environmental problems (SAGEEP 99), Oakland, Calif., March 14-18, p. 115-121.

Park, C.B., Miller, R.D., and J. Xia, 1999, Detection of near-surface voids using surface waves: Proceedings of Symposium on the application of geophysics to engineering and environmental problems (SAGEEP 99), Oakland, Calif., March 14-18, p. 281-286.

Park, C.B., Miller, R.D., and Xia, J., 1998, Imaging dispersion curves of surface waves on multi-channel record: [Exp. Abs.]: Soc. Explor. Geophys., 1377-1380.

Park, C.B., Miller, R.D., and Xia, J., 1998, Ground roll as a tool to image near-surface anomaly: [Exp. Abs.]: Soc. Explor. Geophys., 874-877.

Park, C.B., Miller, R.D., and Xia, J., 1997, Multi-channel analysis of surface waves (MASW)—“A summary report of technical aspects, experimental results, and perspective”: Kansas Geological Survey Open-file Report 97-10.

Park, C.B., Miller, R.D., and Xia, J., 1996, Multi-channel analysis of surface waves using Vibroseis (MASWV): [Exp. Abs.]: Soc. Explor. Geophys., 68-71.

Pullan, S.E., and J.A. Hunter, 1990, Delineation of buried bedrock valleys using the optimum offset shallow seismic reflection technique: Society of Exploration Geophysicists, Investigations in Geophysics no. 5, S.H. Ward, ed., Volume 3: Geotechnical, p. 75-87.Richart, F.E., Hall, J.R., and Woods, R.D., 1970, Vibrations of soils and foundations, Prentice-Hall, Inc., New Jersey, 414 pp.

Rix, G.J., and Leipski, E.A., 1991, Accuracy and resolution of surface wave inversion, in Geotechnical special publication no. 29, Recent advances in instrumentation, data acquisition and testing in soil dynamics, edited by S.K. Bhatia and G.W. Blaney, American Society of Civil Engineers, p. 17–32.

Sheu, J.C., Stokoe II, K.H., and Roesset, J.M, 1988, Effect of reflected waves in SASW testing of pavements: Transportation Research Record No. 1196, p. 51–61.

Stokoe II, K.H., Wright, G.W., James, A.B., and Jose, M.R., 1994, Characterization of geotechnical sites by SASW method, in Geophysical characterization of sites, ISSMFE Technical Committee #10, edited by R.D. Woods, Oxford Publishers, New Delhi.

Tokimatsu, K., Tamura, S., and Kojima, H., 1992, Effects of multiple modes on Rayleigh wave dispersion characteristics: Journal of Geotechnical Engineering, American Society of Civil Engineering, v. 118, n. 10, p. 1529-1543.

Vardoulakis, I., and Vrettos, Ch., 1988, dispersion law of Rayleigh-type waves in a compressible Gibson half space: International Journal for Numerical and Analytical Methods in Geomechanics, v. 12, p. 639–655.

Waters, K.H., 1978, Reflection seismology: John Wiley and Sons, Inc.

Xia, J., and Miller, R.D., 2000, Fast estimation of parameters of a layered-dipping earth model by inverting reflected waves: Accepted for publication in Journal of Environmental and Engineering Geophysics.

Xia, J., R.D. Miller, C.B. Park, and J. Ivanov, 2000, Construction of 2-D vertical shear-wave velocity field by the multichannel analysis of surface wave technique: in Proceedings of Symposium on the application of geophysics to engineering and environmental problems (SAGEEP 2000), Arlington, Va., p. 1197-1206.

Xia, J., R.D. Miller, and C.B. Park, 2000, Advantages of calculating shear-wave velocity from surface waves with higher modes: [Exp. Abs.]: Soc. Explor. Geophys., 1295-1298.

Xia, J., Miller, R.D., and Park, C.B., 1999, Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves: Geophysics, v. 64, no. 3, p. 691-700.

Xia, J., R.D. Miller, C.B. Park, J.A. Hunter, and J.B. Harris, 1999b, Evaluation of the MASW technique in unconsolidated sediments [Exp. Abs.]: Soc. Explor. Geophys., p. 437-440.

Xia, J., R.D. Miller, C.B. Park, E. Wightman, and R. Nigbor, 1999c, A pitfall in shallow shear-wave refraction surveying [Exp. Abs.]: Soc. Explor. Geophys.p. 508-511.

Yilmaz, O., 1987, Seismic data processing: Doherty, S. M., Ed.: Investigations in Geophysics, no. 2, Soc. of Expl. Geophys.