SeisImager/SW-Pro^{TM} Manual

Windows Software for Analysis of Surface Waves

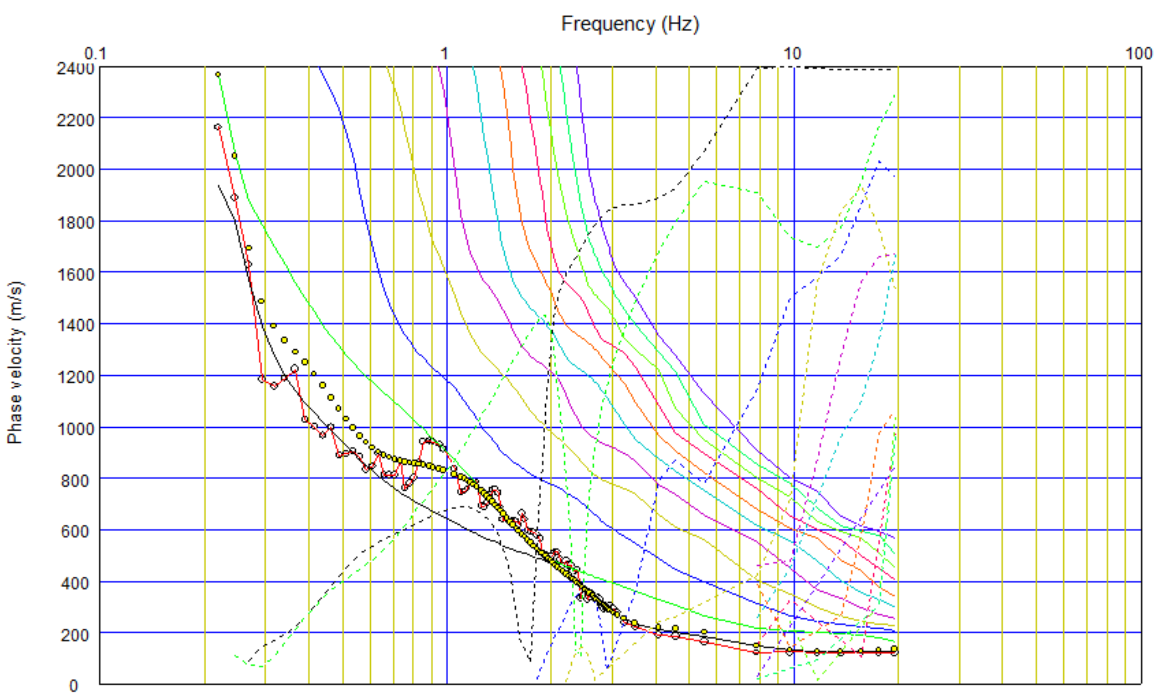
Pickwin^{TM} v. 5.2.1.3

WaveEq^{TM} v. 4.0.1.0

GeoPlot^{TM} v. 10.0.1.4

Manual v. 1.2

Apr. 2016



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1. Introduction

Welcome to SeisImager/SW-Pro™! SeisImager/SW-Pro is an upgrade of SeisImager/SW 1D or 2D that provides a suite of new and improved inversion options. Main improvements of SeisImager/SW-Pro include the integration of H/V data and higher modes in inversion.

Traditional analysis of surface wave data generally assume that a dispersion curve mainly consists of a fundamental mode. Higher modes may dominate in several types of velocity structures, such as a model in which a high-velocity layer overlays a low-velocity layer or a model in which a high-velocity layer is embedded in low-velocity layers. In order to include higher modes in inversion, SeisImager/SW-Pro introduced several new algorithms, such as a Genetic Algorithm (GA) and inversion with variable layer thickness.

A three component micro-tremor measurement at a single station has been widely used for estimating site characterization of earthquakes. This method has been referred to as Nakamura's method, HVSR (Horizontal Vertical Spectral Ratio) or H/V. This manual will refer to "H/V" when addressing three component micro-tremor measurements. Over the last few decades, theory of H/V has been the subject of controversy. Conventional theory of H/V considered microtremors mainly to consist of body waves and the peak frequency of H/V corresponded to the resonance frequency of a site. Recently, there is a new consensus that microtremors are dominated by surface-waves and H/V data correspond to ellipticity of Rayleigh waves. SeisImager/SW-Pro assumes the later theory and has introduced an inversion of H/V in which observed H/V data is compared with theoretical ellipticity of Rayleigh waves. In a calculation of theoretical H/V, higher modes of Rayleigh and Love waves can be considered. Conventional and latest theories of H/V are comparatively illustrated in Figure 1.1.

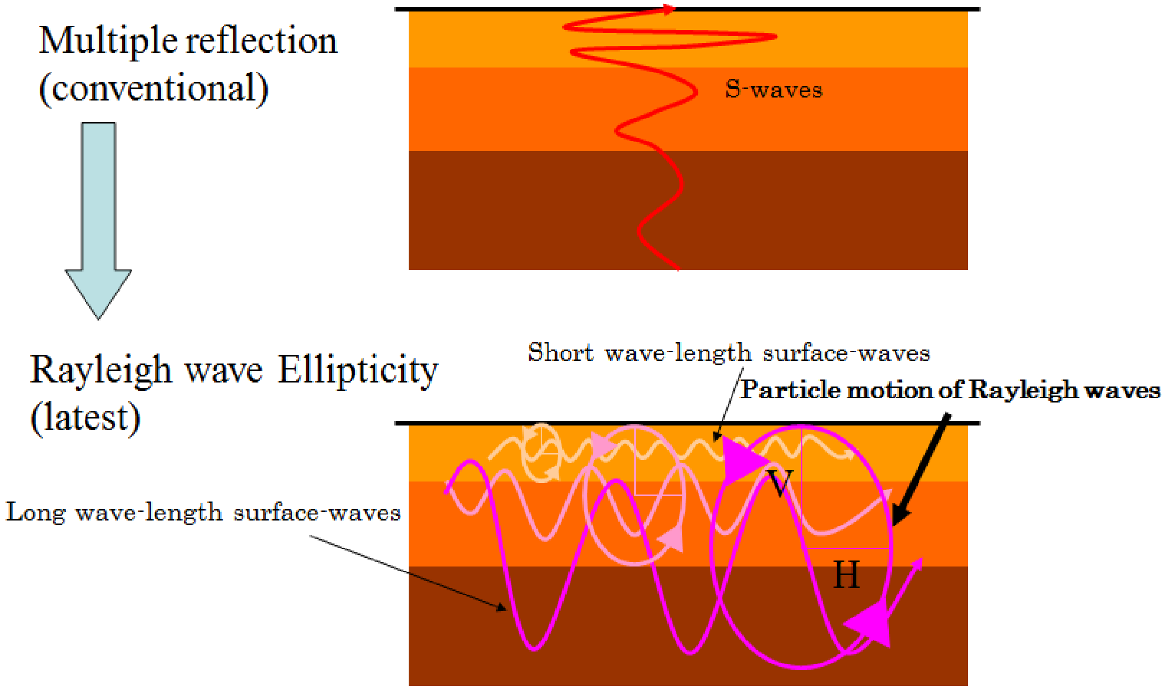


Figure 1.1. Conventional (top) and latest (bottom) theories of H/V

2. Outline of new functions available in SeisImager/SW-Pro

SeisImager/SW-Pro enables you to use a wide variety of inversion methods for dispersion curves obtained from surface-wave methods and H/V data obtained from three-component microtremor measurements. All available inversion methods are listed alongside their place in the menu in Table 2.1. Main new functions available in SeisImager/SW-Pro and newly introduced analysis theory can be summarized as follows.

2.1 Inversion of H/V

In SeisImager/SW-Pro, an H/V curve can be used for inversion of S-wave velocity as similar to a dispersion curve. Currently, H/V curve processing is only available for one-dimensional analysis. It should be noted that inversion of the H/V curve is not as robust as inversion of dispersion curve data. So, it is difficult to obtain accurate S-wave velocity models from H/V data alone. However, prior information may be used to estimate an appropriate initial model and to increase inversion accuracy. H/V data can also be integrated with dispersion curves data to carry out joint inversion. Integrating H/V data can increase the accuracy and penetration depth in the dispersion curve inversion.

Table 2.1 Available inversion methods and SeisImager/SW menu structure

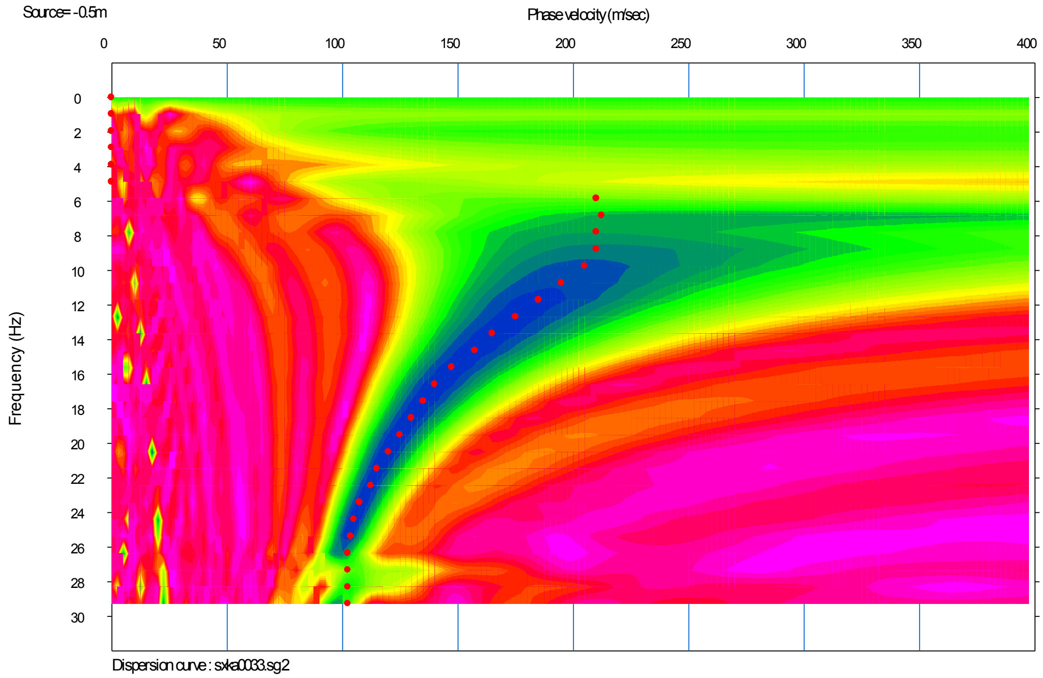
		Non-linear least square method		Genetic Algorithm	
		1D	2D	1D	2D
Dispersion curve	Layer velocity	SW-1D MASW1D, Inversion (LSM)	SW-2D MASW2D, Inversion (2D:All data)	SW-Pro MASW1D, Advanced inversion, GA (VS only)	SW-Pro MASW (2D), Advanced inversion, GA (2D)
	Layer thickness	SW-Pro MASW1D, Advanced inversion, LSM (thickness only)			
	Velocity and thickness	SW-Pro MASW1D, Advanced inversion, LSM (thickness only)		SW-Pro MASW1D, Advanced inversion, GA (VS and thickness)	
H/V	Layer velocity	SW-Pro H/V curves, Inversion, LSM (VS only)		SW-Pro H/V curves, Inversion, GA (VS only)	
	Layer thickness			SW-Pro H/V curves, Inversion, GA (thickness only)	
	Velocity and thickness			SW-Pro H/V curves, Inversion, GA (VS and thickness)	
Joint inversion	Layer velocity	SW-Pro MASW1D, Inversion (LSM)		SW-Pro MASW1D, Advanced inversion, GA (VS only)	
	Layer thickness				
	Velocity and thickness			SW-Pro MASW1D, Advanced inversion, GA (VS and thickness)	

2.2 Inversion using higher modes

As mentioned previous section, main improvement of SeisImager/SW-Pro is inclusion of higher modes in inversion. SeisImager/SW-Pro allows users to include higher modes in inversion and to therefore more accurately analyze complex velocity structures. Observed and theoretical phase-velocity modes are not identified by SeisImager/SW-Pro analysis.

2.2.1 Basic idea of higher modes in surface wave methods

In an active surface wave method, observed data is defined as the maximum amplitude phase velocity calculated at each frequency using multi-channel analysis of surface waves (MASW) method (Park et al., 1999). In a passive surface wave method, observed data is defined as the phase velocity that yields minimum error between observed coherence and the Bessel function calculated through Spatial Autocorrelation (SPAC) method (Aki, 1957). Examples of phase velocity images for active and passive surface-wave data are shown in Figure 2.1.



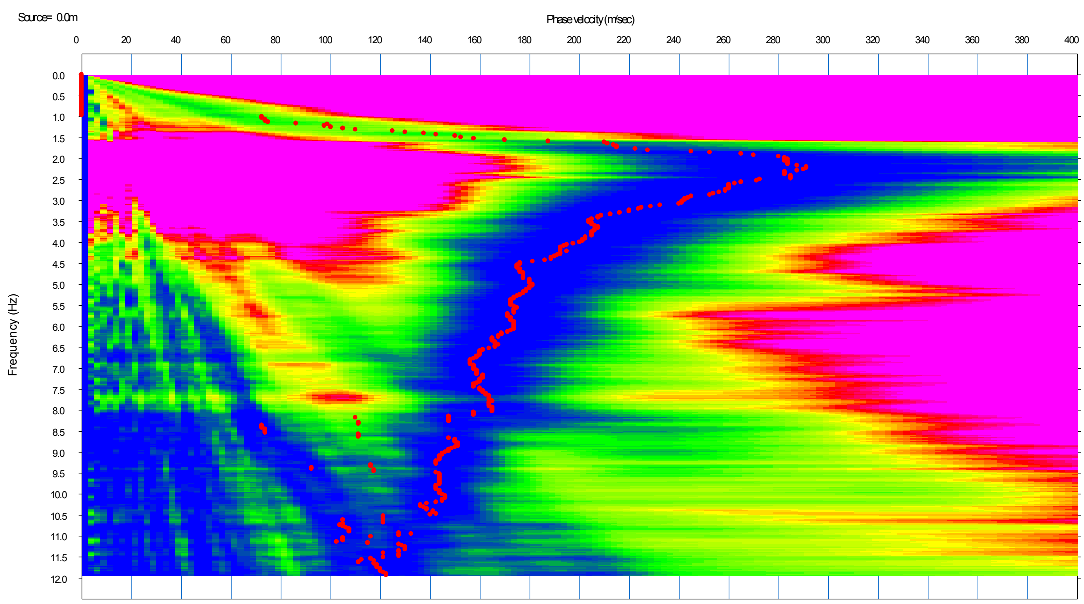


Figure 2.1. Examples of phase velocity images for active (top) and passive (bottom) surface-wave data.

In calculation of higher mode phase velocities, both phase velocity and its relative amplitude (medium response) are calculated simultaneously. Theoretical phase velocity is defined in the following two ways. First, the phase velocity is defined as the velocity that has maximum relative amplitude at each frequency. Secondly, the phase velocity is defined as the weighted average of all modes. The relative amplitude is used for calculating weighted average data. "Maximum" will correspond to phase velocities calculated with the first method, and "averaged" will refer to phase velocities calculated with the second method. In WaveEq, maximum amplitude calculated phase velocities are shown as right blue circles and averaged phase velocities are shown as yellow circles in case of Rayleigh wave. They are shown as blue and green respectively in case of Love waves. Figure 2.3 shows example of theoretical "maximum" and "averaged" phase velocities for the velocity model shown in Figure 2.2. See Hayashi (2012) for some example of higher modes.

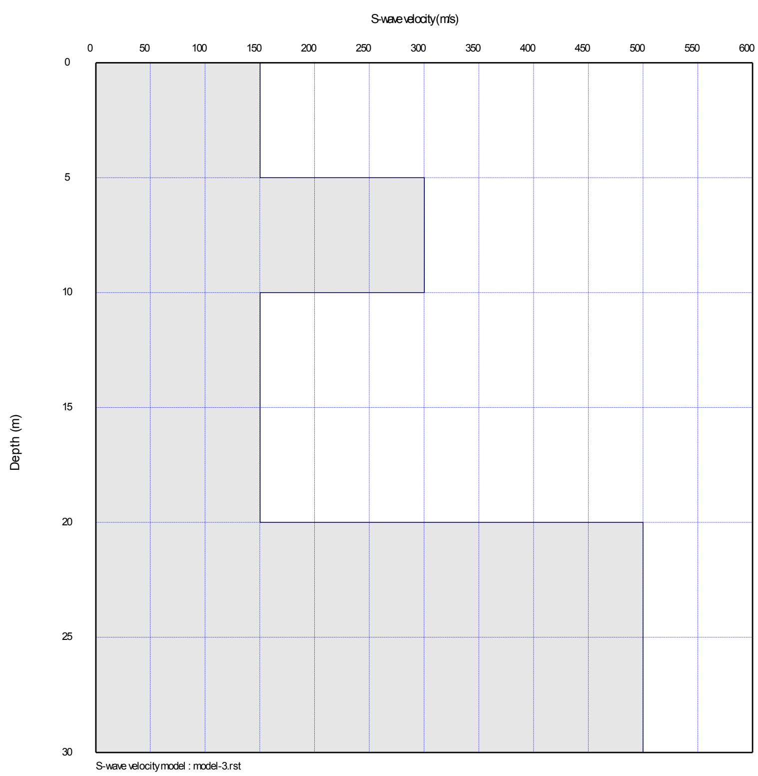


Figure 2.2 Example of velocity model

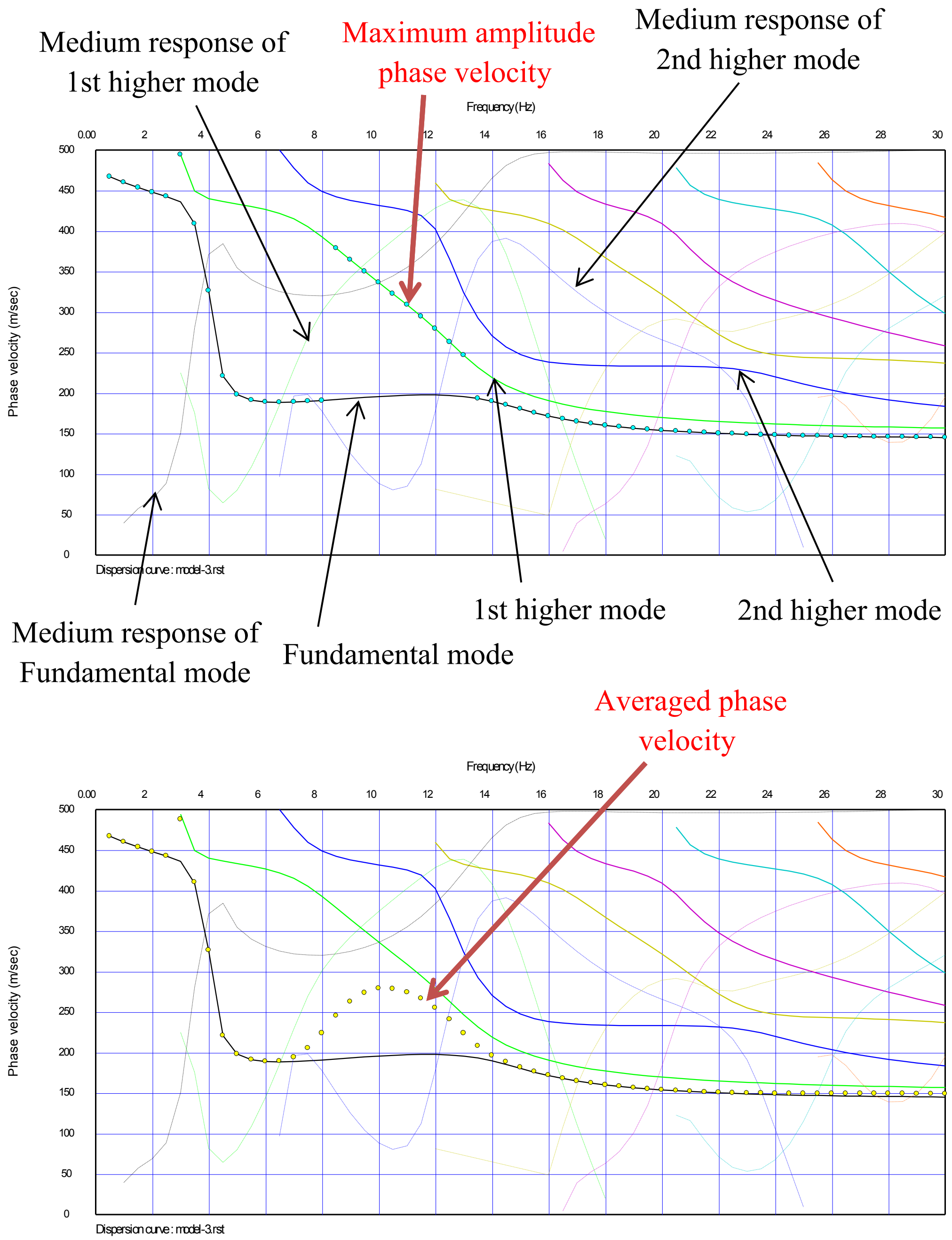


Figure 2.3 Example of theoretical “maximum (top)” and “averaged (bottom)” phase velocities for the velocity model shown in Figure 2.2. Medium response curves shown in the top image correspond to the relative amplitude of the designated mode with respect to the fundamental mode.

There is no established rule for how to calculate theoretical phase velocities including higher modes. In observed data, different modes can be isolated if the geophone array size is relatively bigger than the wave length of interest. Generally speaking, an active surface wave methods use relatively bigger arrays in terms of wave length of interest compared to passive methods. Therefore, we propose using “maximum” phase velocity for active method processing and “averaged” phase velocity for passive surface wave data.

Figure 2.4 shows theoretical phase velocity images for the velocity model shown in Figure 2.2. The top and bottom figures correspond to the dispersion curve calculated with Multichannel Analysis of Surface Waves (MASW) and passive method (SPAC) respectively. MASW data was acquired with 96m a linear array and SPAC data was acquired with a 10m triangular array. It is clear that MASW dispersion curves appear similar to “maximum” phase velocities and SPAC results are more similar to “averaged” phase velocities. Figure 2.5 shows an example of phase velocity change due to array size or geometry. In the example, synthetic data for the velocity model shown in Figure 2.2 is used. It is obvious that an increase in array size results in clear separation of different mode phase velocities.

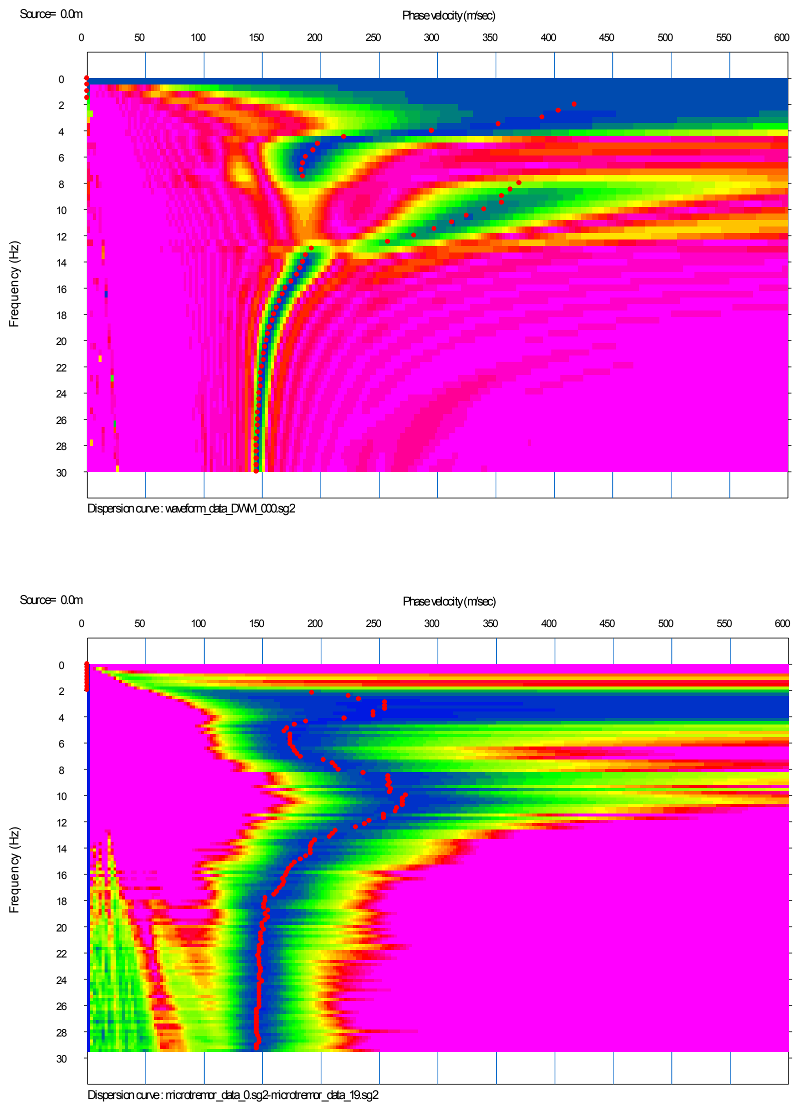
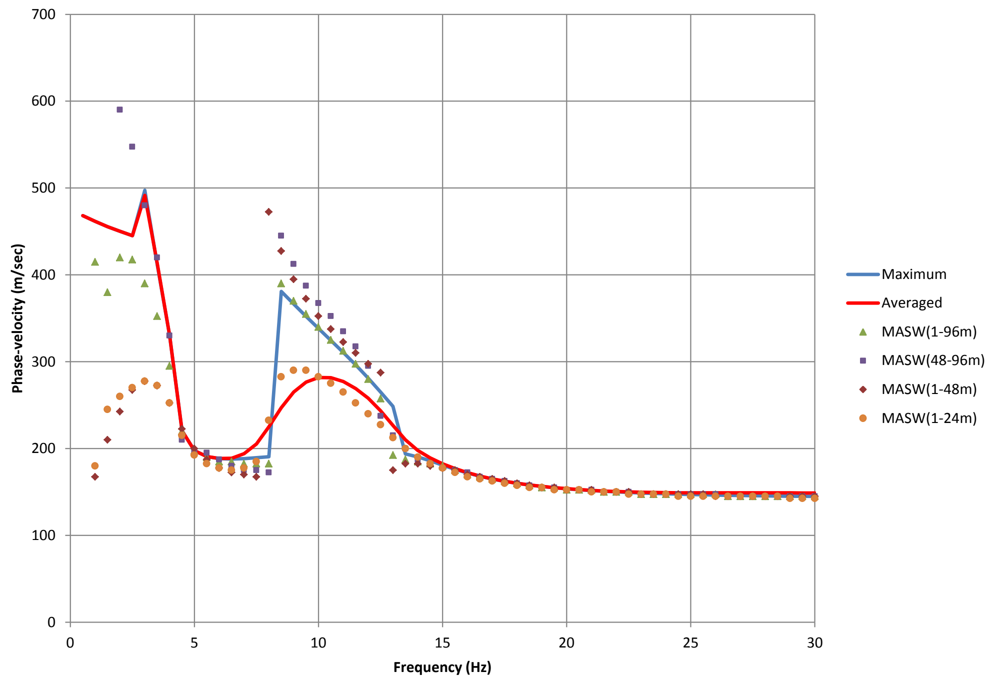


Figure 2.4. Theoretical phase velocity images for the velocity model shown in Figure 2.2. Top image corresponds to phase velocity curve derived from the active method (MASW) and bottom is that of passive method (SPAC).



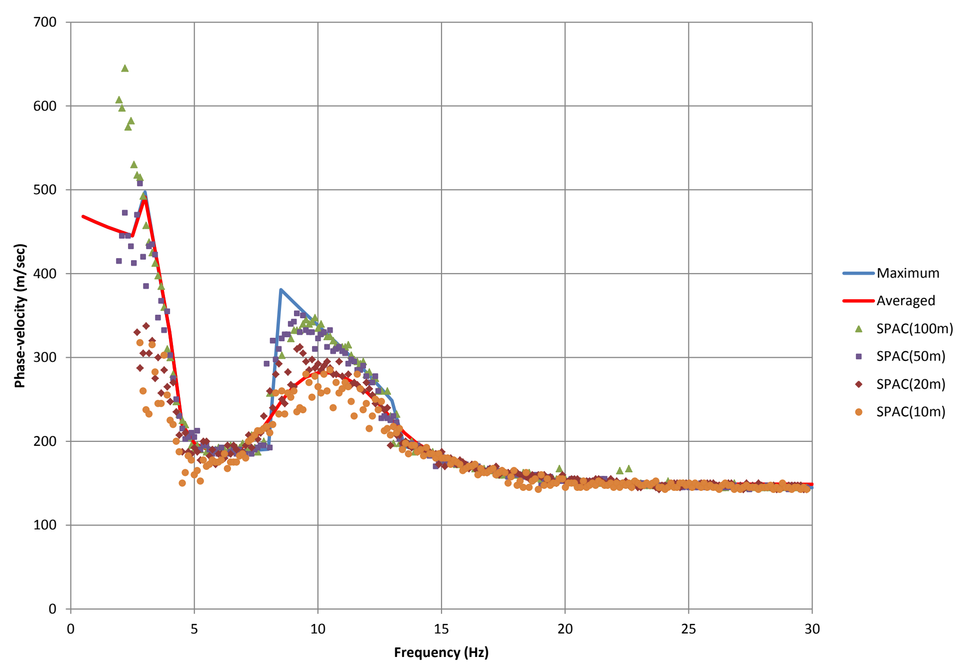


Figure 2.5. Change of phase velocities calculated by MASW and SPAC due to array sizes or geometry. Synthetic data for the velocity model shown in Figure 2.2 is used in the calculation.

Higher mode data is also important in a calculation of theoretical H/V. In SeisImager/SW, theoretical H/V is defined in two ways. The first definition of H/V is corresponds to the Rayleigh wave fundamental mode and is the second method assumes Rayleigh and Love wave higher modes. In the higher order method, the ellipticity of Rayleigh wave and medium response (relative amplitude) of Rayleigh and Love waves are calculated for each mode. Horizontal and vertical amplitudes are calculated from the ellipticity and medium response values. Figure 2.6 shows an example of theoretical H/V. A solid black line indicates an H/V of Rayleigh wave fundamental mode and yellow circles indicate Rayleigh and Love wave higher modes.

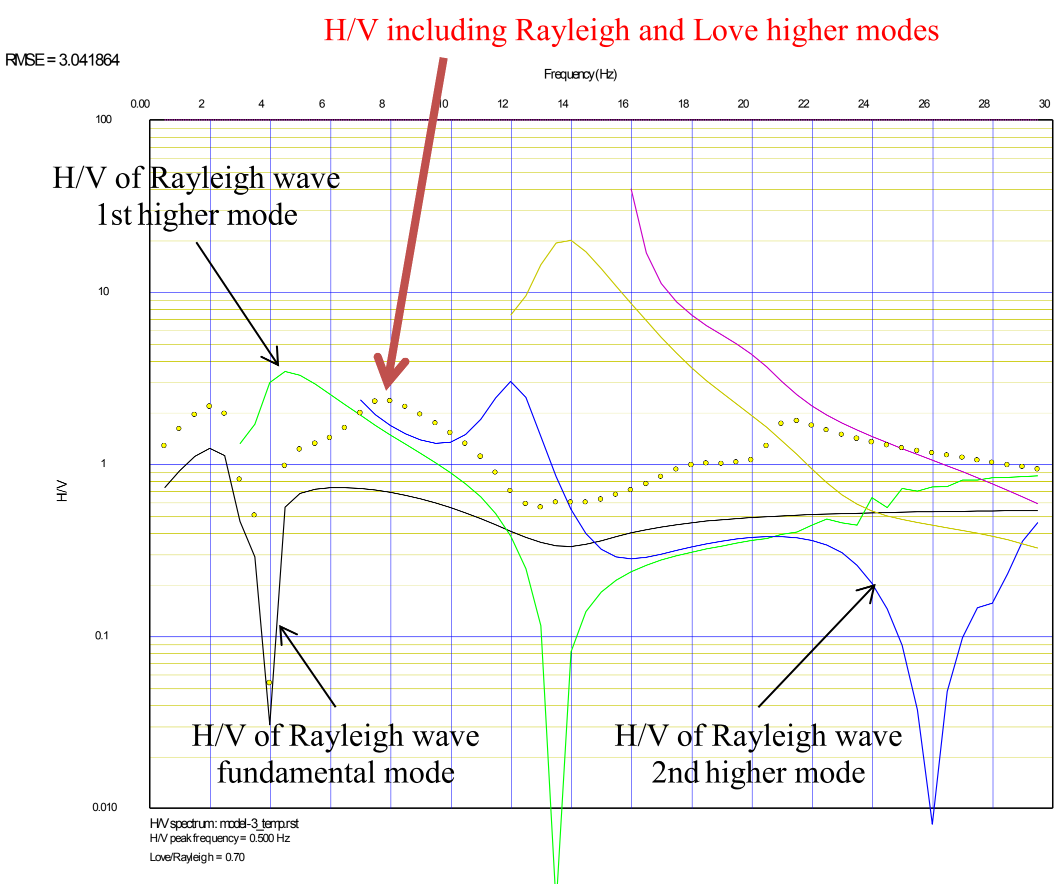
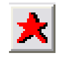
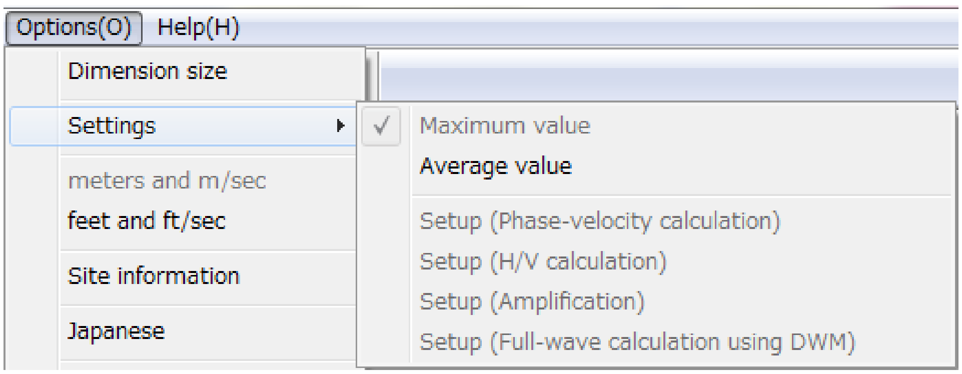


Figure 2.6. Example of theoretical H/V for the velocity model shown in Figure 2.2.

2.2.2 How to handle higher modes in SeisImager/SW

Calculation of the fundamental and higher modes can be activated by selecting the  and  buttons on the tool bar. Once the fundamental mode or higher mode button is activated, select the *Calculate theoretical dispersion curves*  button and WaveEq calculates the designated mode. Note that the setting for the *Calculate theoretical dispersion curves* is applied to forward modeling the theoretical data used in inversion processing as well.

The detailed setting of higher modes calculation can be changed in *Settings* in *Options* menu.

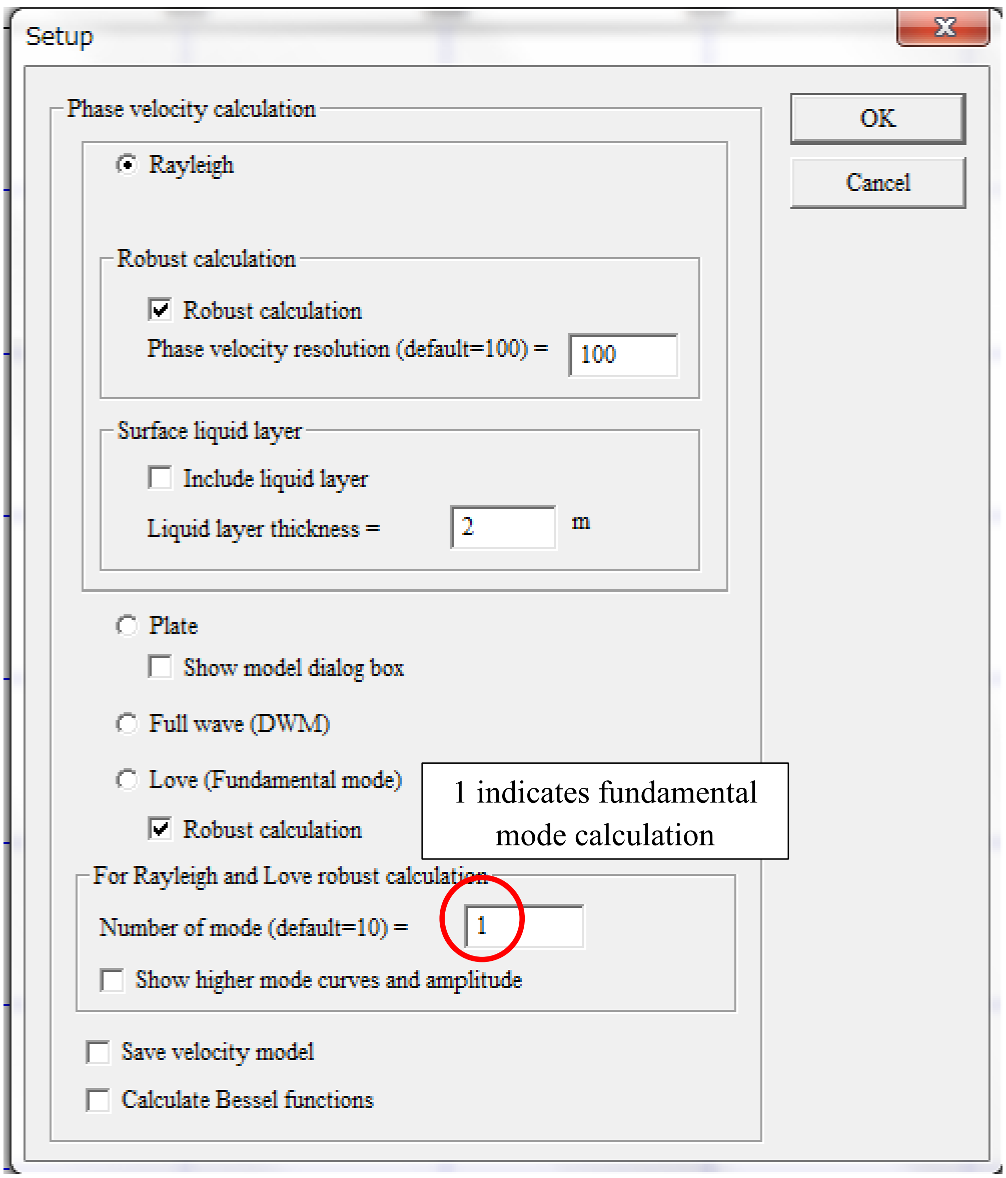


2.2.2.1 Maximum and average value

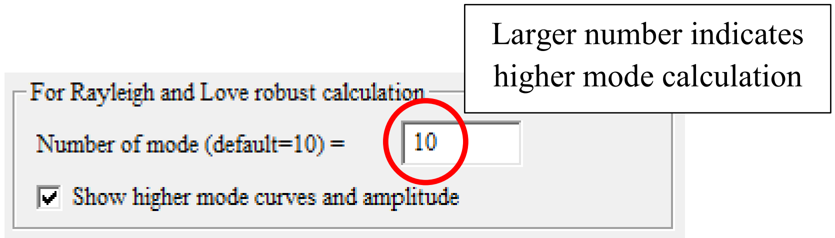
As mentioned earlier, theoretical phase velocity may be calculated under “averaged” or “maximum” dispersion curve assumptions. Activate *Maximum value* or *Average value* in *Settings* menu to switch methods. We recommend using *Maximum* value or *Average value* for MASW and SPAC respectively.

2.2.2.2 Setup (Phase-velocity calculation)

Select *Setup (Phase-velocity calculation)* in *Settings* menu to change settings for higher mode calculations of phase velocity. A following dialog box appears when the fundamental mode calculation is selected. Note that the *Number of modes (default=10)* is one. Default values are suitable for most cases.



When the higher mode calculation is selected, *Number of modes (default=10)*will not be equal to one. Use 5 to 20 for the number of modes. The number of modes integrated is proportional to computation time. Calculating five to ten modes is suitable for most cases. Use large number 20 to 50 if the data includes significant higher modes that are due to a high velocity thin layer underlying a low velocity layer.



2.3 Inversion changing thickness

In SeisImager/SW, S-wave values are calculated while assuming a fixed number of layers and thicknesses. Inversion requires many layers, typically 10 to 20, and it has restricted the flexibility of inversion. In SeisImager/SW-Pro, thickness of each layer can also be optimized in inversion. Parameterizing layer thickness allows you to use a velocity model with small number of layers, such as 2 to 5 layers. You can choose an appropriate velocity model parameterization and inversion method depending on the data characteristics and purpose of investigation. Table 1.2 summarizes the suggested selection of model parameterization and inversion methods.

Table 1.2. Suggested selection of unknowns in inversions depending on model parameterization

		Model parameterization	
		Small layer number (<7 layers)	Multi-layer model (10 <)
Data	1D dispersion curve	VS and thickness	VS only
	1D H/V	VS and thickness Thickness only	VS only
	1D dispersion curve and H/V	VS and thickness	VS only
	2D dispersion curves	VS only	VS only

2.4 Inversion using Genetic Algorithm

2.4.1 Basic idea of Genetic Algorithm

As mentioned before, in complex velocity structures, higher modes may dominate in a particular frequency range and cause dispersion curves to look discontinuous. Higher modes can be represented as “maximum” and “averaged” phase velocities. As shown in Figure 1.4, “averaged” phase velocity is generally smooth and continuous while “maximum” phase velocity is discontinuous. Previously, SeisImager/SW used a non-linear least squares method (LSM) for inversion and could not handle discontinuous dispersion curves, such as those in “maximum” phase velocity curves, which may contain higher modes. It is generally difficult to separate the fundamental mode and the higher modes correctly, and traditional inversion methods based on the Jacobian matrix cannot be applied.

In order to overcome these difficulties, SeisImager/SW-Pro introduced a new inversion method using a Genetic Algorithm (Yamanaka and Ishida, 1995). Genetic Algorithm (GA) is a search method that mimics the process of natural evolution and is routinely used to generate useful solutions to optimization and search problems. The method is characterized as a global search method and can mitigate convergence upon local minima. One clear disadvantage of GA is that the method requires a large amount of forward modeling compared to the conventional iterative non-linear least squares method.

Computation time of inversion generally increases as number of data increases, number of layers increases, GA is used, and higher modes are included. Select the appropriate inversion method depending on character of data, model parameterization, and purpose of investigation. Summary of calculation methods of dispersion and H/V curves are shown in Table 2.3. General guidelines for selection are summarized in Table 2.4.

Table 2.3 Calculation methods of dispersion and H/V curves

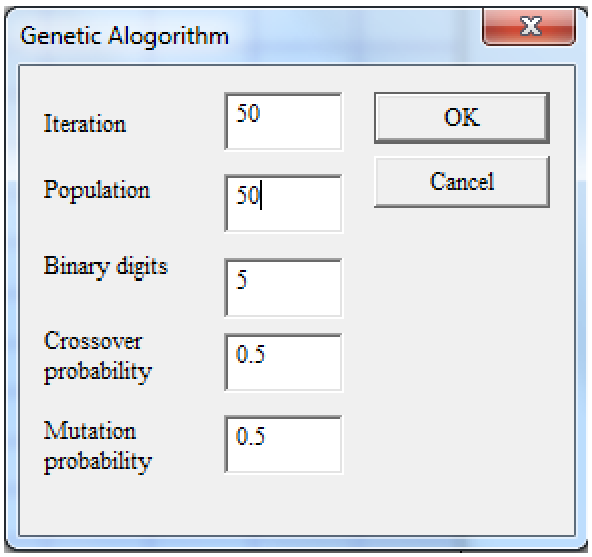
Data	Acquisition method	Modes	Appearance	Forward modeling	Inversion
Dispersion curve	Active (MASW)	Fundamental	Discontinuous	Fundamental	LSM
		Higher	Continuous	Maximum	GA
	Passive (MAM)	Fundamental	Discontinuous	Fundamental	LSM
		Higher	Continuous	Averaged	LSM or GA
H/V	Passive	Fundamental	Discontinuous	Fundamental	GA
		Higher	Discontinuous	Averaged	GA

Table 2.4. Selection of inversion methods depending on model parameterization and higher mode

Data	Data acquisition	Forward modeling	Model	
			Small layer number (<7 layer)	Multi-layer model (10 layer <)
1D dispersion curve (fundamental mode)	MASW or MAM	Fundamental	LSM, GA	LSM
1D dispersion curve (higher mode)	MASW	Maximum	GA	GA
	MAM	Averaged	LSM, GA	LSM
1D H/V	H/V	Fundamental	GA	GA
	H/V	Averaged	GA	GA
1D dispersion curve and H/V	MAM and H/V	Fundamental	GA	GA
		Averaged	GA	GA
2D dispersion curve (fundamental mode)	MASW	Fundamental	LSM	LSM
2D dispersion curve (higher mode)	MASW	Maximum	GA	GA

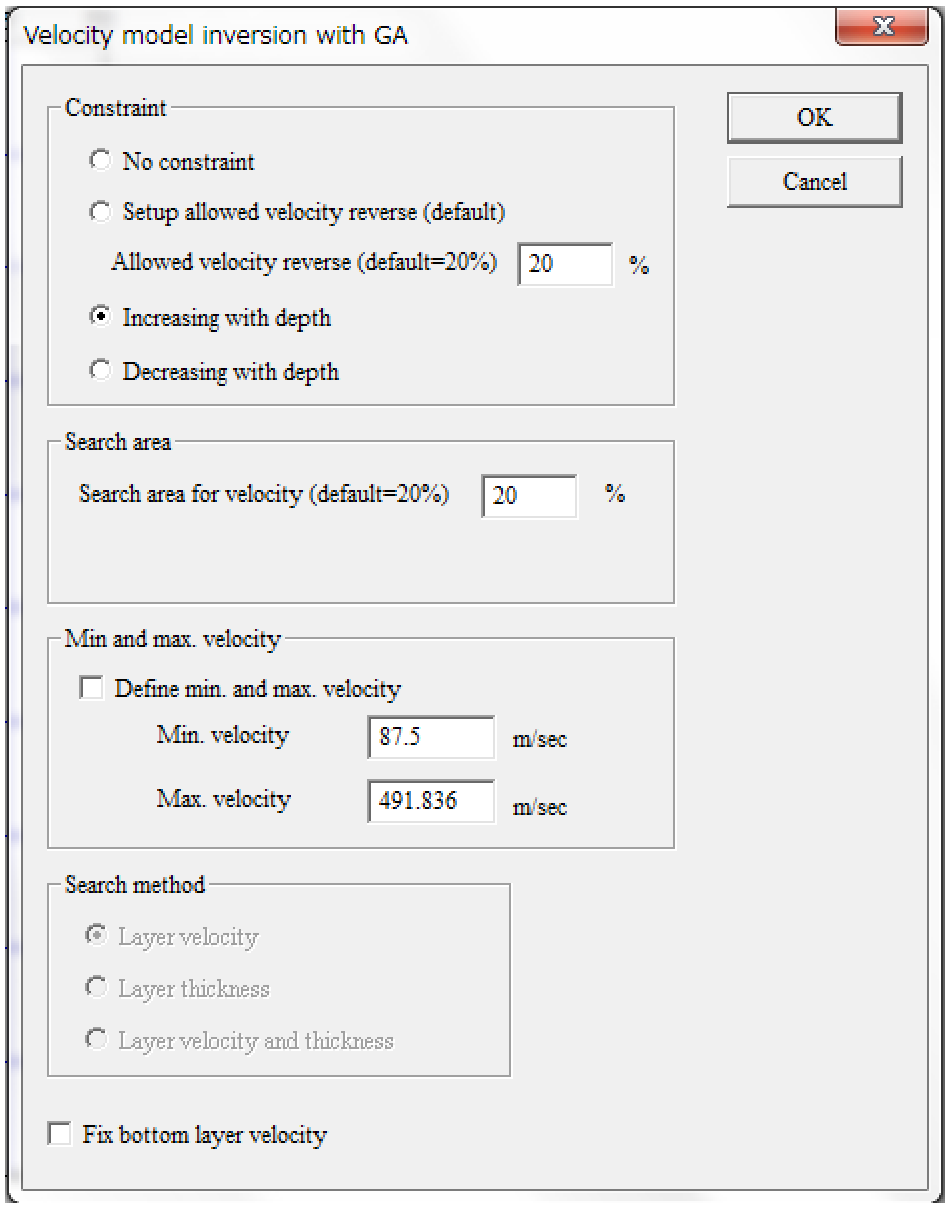
2.4.2 Parameters for inversion using Genetic Algorithm

The following dialog box appears when carrying out inversions using the Genetic Algorithm (GA). The GA is basically random search in which many models are randomly created. The degree to which the final model fits the observed data depends on how many models were used in the inversion and several other factors. Total number of models calculated in the GA is equal to the number of "Iteration" times "Population". Computation time of the GA is directly proportional to the total number of models incorporated. Both the number of iterations and the number of populations can be between 20 and 100. Default values (50) are suitable for most cases.



2.4.3 Constraint for inversion using Genetic Algorithm

Subsequently to initial GA parameter setup, the following dialog appears.



A) Constraint

Four different velocity models can be assumed. Typical dispersion curve and velocity models considered are summarized in figures shown below. Note that the bottom layer (the deepest layer) must have the highest velocity in all models.

A-1) No constraint

The velocity of each layer can be any value except the bottom layer. The inversion with no constraint tends to be unstable and it is advised to use this option with caution.

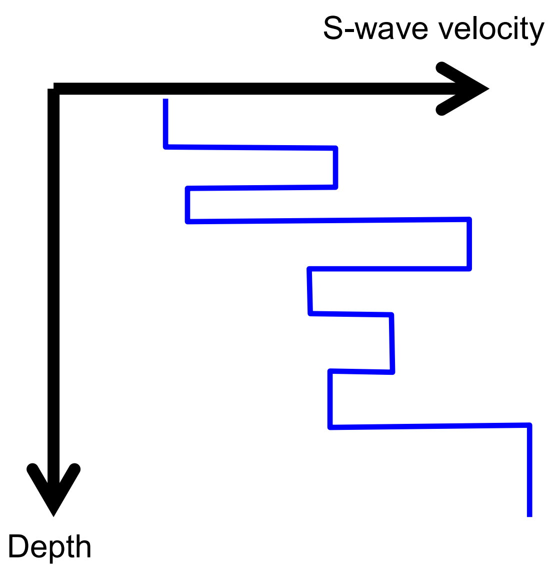


Figure 2.7 S-wave velocity model with no constraint illustrated above.

A-2) Setup allowed velocity reverse

Define the total velocity reversal (inversion) against the maximum velocity in percent. The total velocity reversal (inversion) is the summation of velocity decrease (a+b+c). The *Allowed velocity reverse* (P) is expresses as the following equation using the maximum velocity d.

$$\mathrm{P}(\%) = \frac{a+b+c}{d} \times 100$$

The *Allowed velocity reverse* (P) option allows a percentage of velocity inversion. Generally speaking, natural ground may have slight velocity reversal particularly in shallow (shallower than 100 m) region. So, a default value of 20 % of the *Allowed velocity reverse* is selected. S-wave velocity is generally increasing at greater depths and it is recommended to use the *Increasing with depth* option if the investigation depth is greater than 100 m.

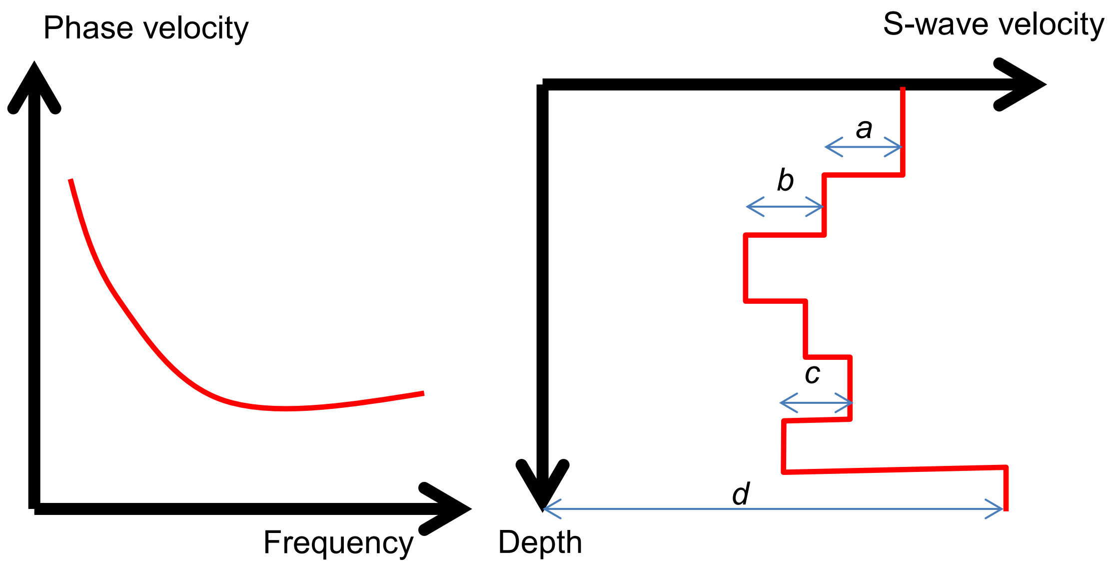


Figure 2.8 S-wave velocity model with allowed velocity inversion illustrated above.

A-3) Increasing with depth

Velocity has to increase with depth in this option. This option is suitable when phase velocity smoothly increases as frequency decreases or investigation is greater than a depth of 100 m.

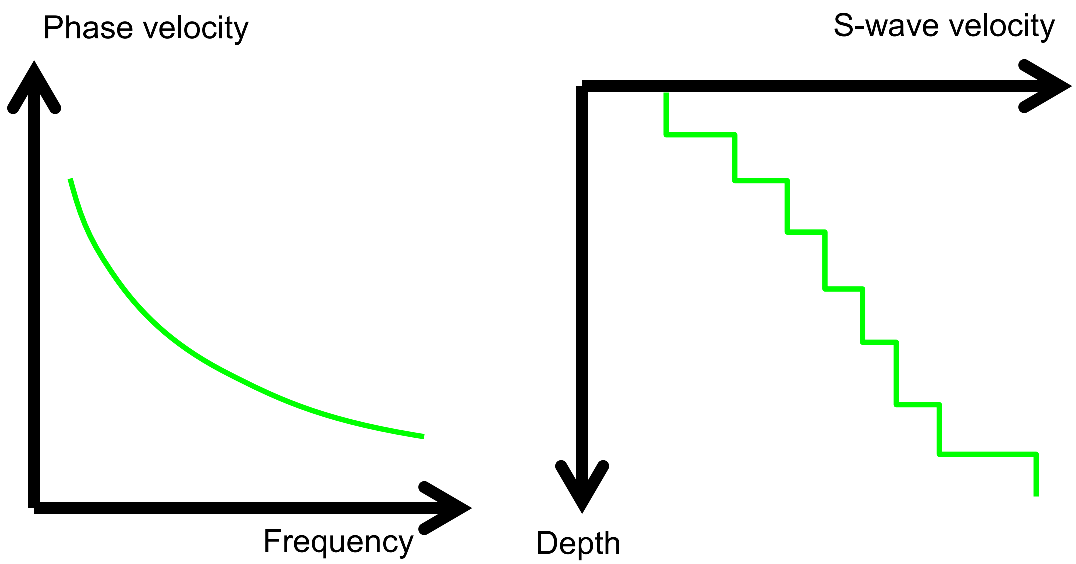


Figure 2.9 S-wave velocity model with increasing velocity with depth.

A-4) Decreasing with depth

Velocity has to decrease with depth in this option except for the bottom layer. Use this option when phase velocity increases as frequency increases. S-wave velocity generally increases with depth in the natural ground, so phase velocity is usually inversely proportional to frequency. Dispersion curves and S-wave velocity structures associated with this option are quite unusual. S-wave velocity values that decrease with depth are usually associated with artificial structures such as paved surfaces, embankments, soil modification, etc.

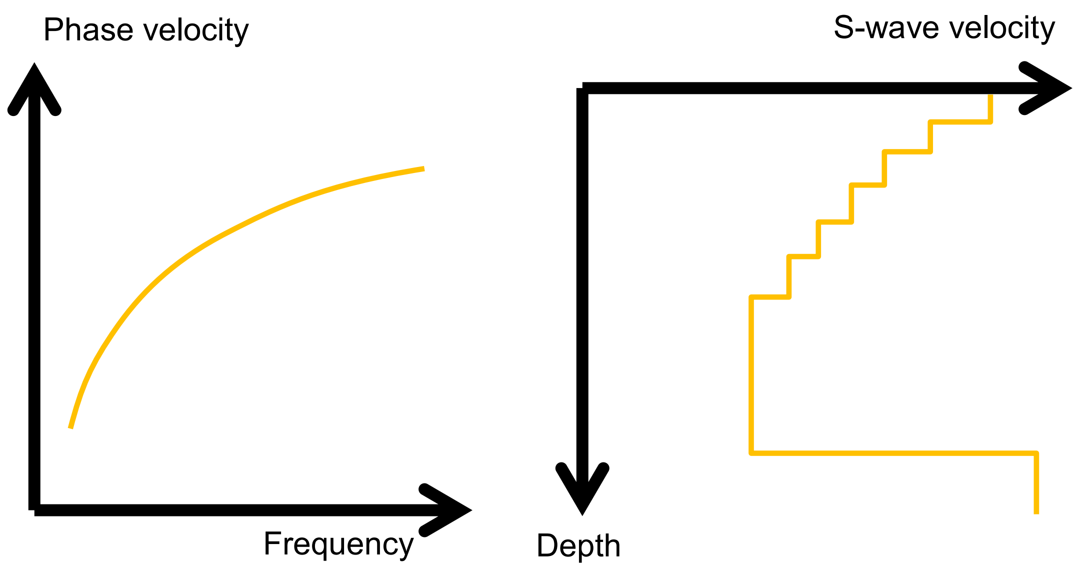


Figure 2.10 S-wave velocity model with decreasing velocity with depth illustrated above. All methods assume the bottom layer has the highest S-wave velocity.

2.5 Joint inversion of dispersion curve and H/V

Phase-velocity data and H/V data can be used in inversion simultaneously to further constrain the model (Suzuki and Yamanaka, 2010). As mentioned before, it is difficult to obtain accurate velocity model from H/V data alone. Dispersion curve inversion solutions are generally non-unique and may not be always accurate. Incorporating H/V and phase velocity data in a join inversion scheme allows for the production of a more constrained final model and may also increase depth of investigation.

Generally speaking, information contained in H/V data is limited compared to dispersion curve data. Therefore, if there are both phase velocity and H/V data, it is better to use phase-velocity data to construct the S-wave velocity model, until data misfit is sufficiently low. Once error between observed and theoretical phase velocities is deemed small enough, H/V data may be incorporated into the inversion process. Suggested processing flow is shown below (Figure 2.11).

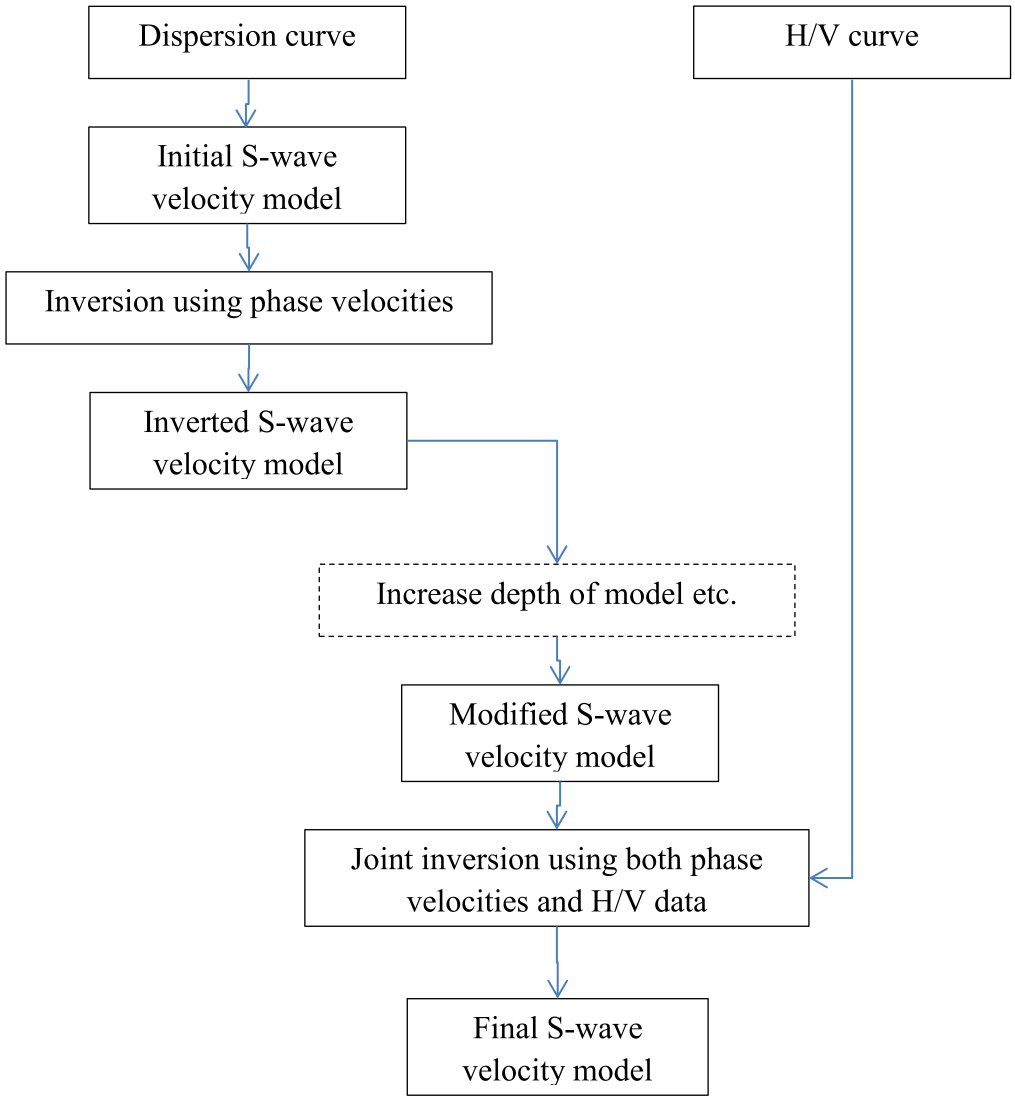


Figure 2.11 Suggested processing flow for joint inversion.

2.6 2D Inversion including higher modes using Genetic Algorithm

Genetic Algorithm is the recommended inversion procedure for incorporating higher mode data. As mentioned in Section 2.4, higher mode dispersion curves are discontinuous and may not be handled optimally by traditional inversion procedures. Genetic Algorithm may handle discontinuous higher mode data more optimally.

Since Genetic Algorithm is time consuming compared to a non-linear least square method, SeisImager does not simply apply it to all dispersion curves. Genetic Algorithm is only applied to one location, one dispersion curve and associated 1D model, out of all data along a survey line. Velocity models at other locations are modified with calculation result of Genetic Algorithm applied to one location. For this reason, it is better to call the inversion as “pseudo 2D inversion”. Figure 2.12 shows a processing flow of a 2D inversion using Genetic Algorithm. Inversion procedure is summarized as follows.

At first, theoretical phase velocities are calculate for dispersion curves and associated 1D velocity models at all locations (Figure 2.13). Observed and theoretical phase velocities are compared and residuals (RMSE: root mea square error) are calculated for all locations. A dispersion curve and an associated 1D velocity model that has the biggest residual (RMSE) is selected. An inversion using Genetic Algorithm is applied to the 1D model that has the biggest residual. Genetic Algorithm randomly generates many velocity models and calculates theoretical phase velocities for the models. All velocity models and associated theoretical phase velocities are stored in memory during the inversion (Figure 2.14). A result of Genetic Algorithm for the 1D model that has the biggest residual is used for that location. For other locations, memorized theoretical phase velocities are compared with each observed dispersion curve and an 1D model that yields minimum error is used for the model at each location (Figure 2.15).

Refer to Section 2.4. for further details of inversion using Genetic Algorithm.

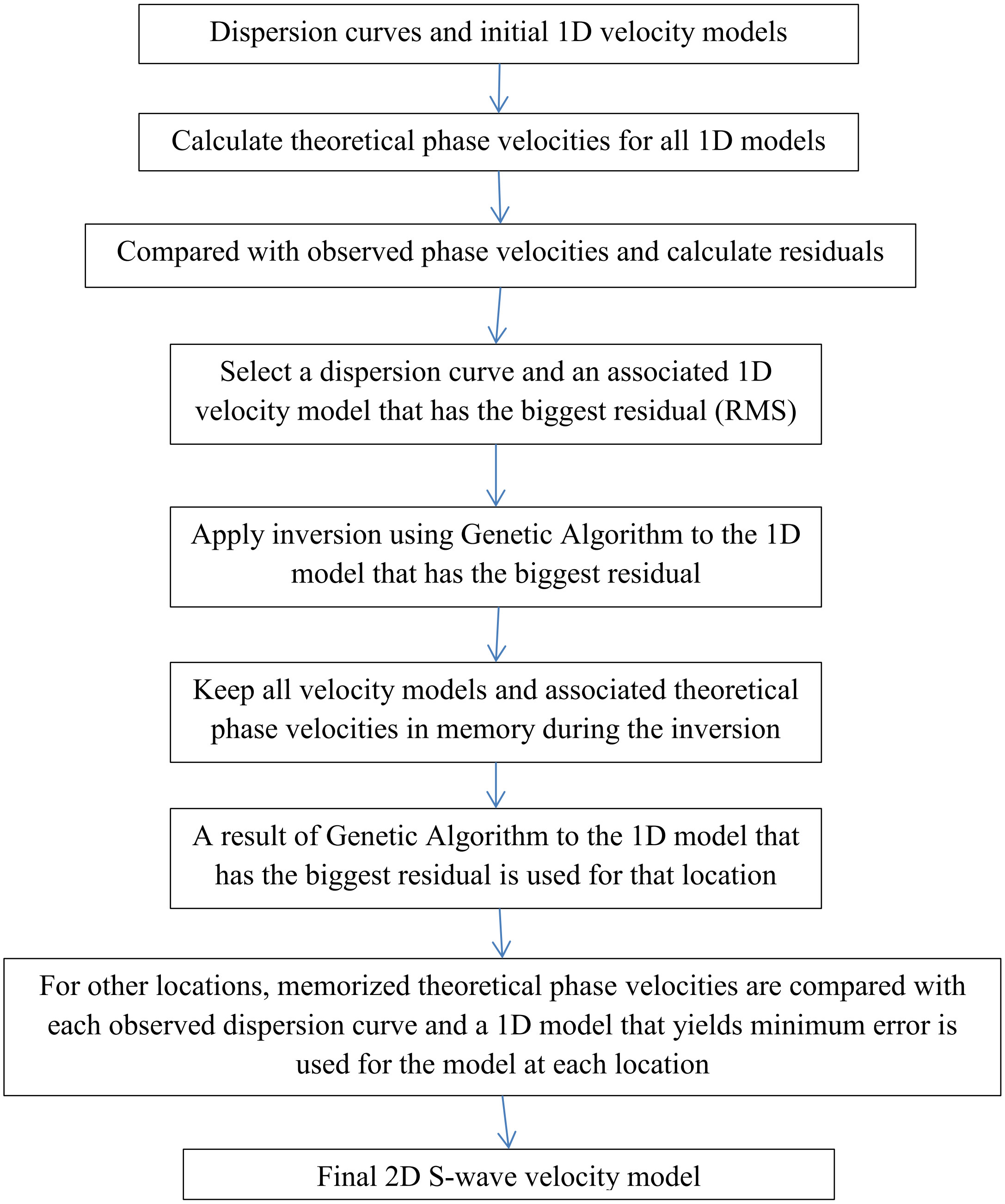


Figure 2.12 Processing flow of a 2D inversion using Genetic Algorithm.

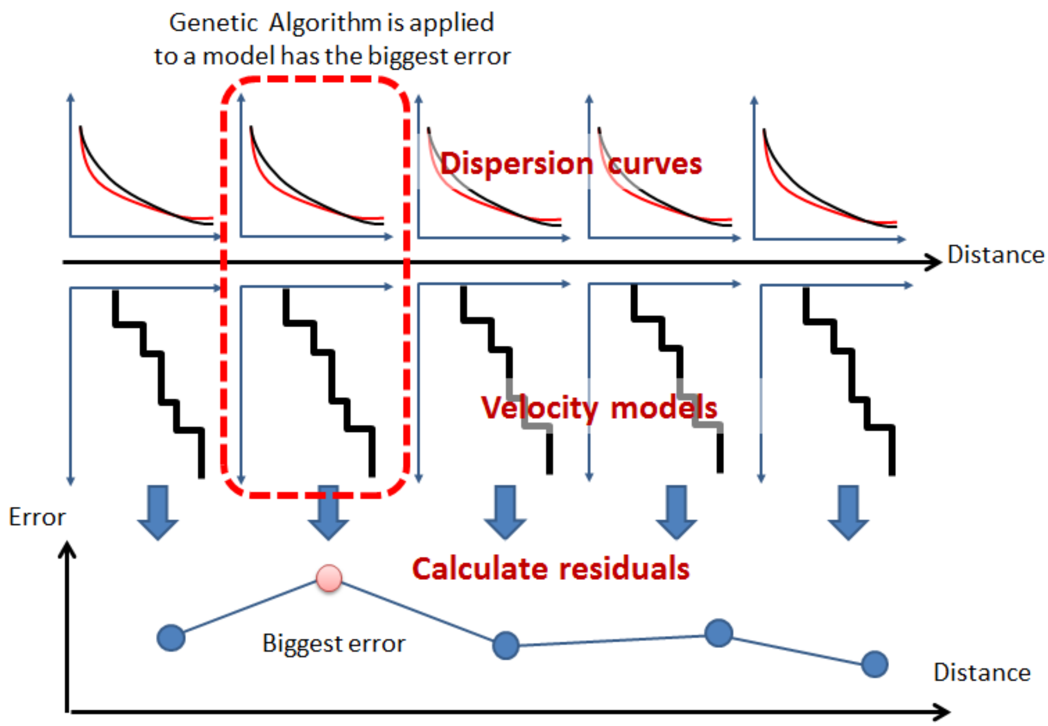


Figure 2.13 Selection of dispersion curve and velocity model for Genetic Algorithm in 2D.

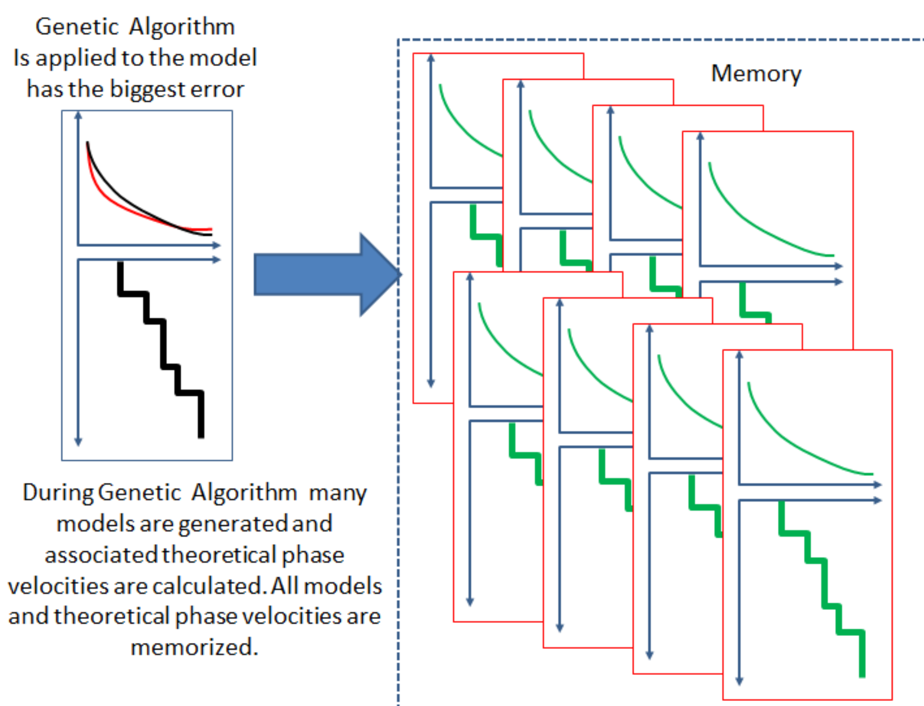


Figure 2.14 All velocity models and associated theoretical phase velocities are kept in memory during inversion using Genetic Algorithm.

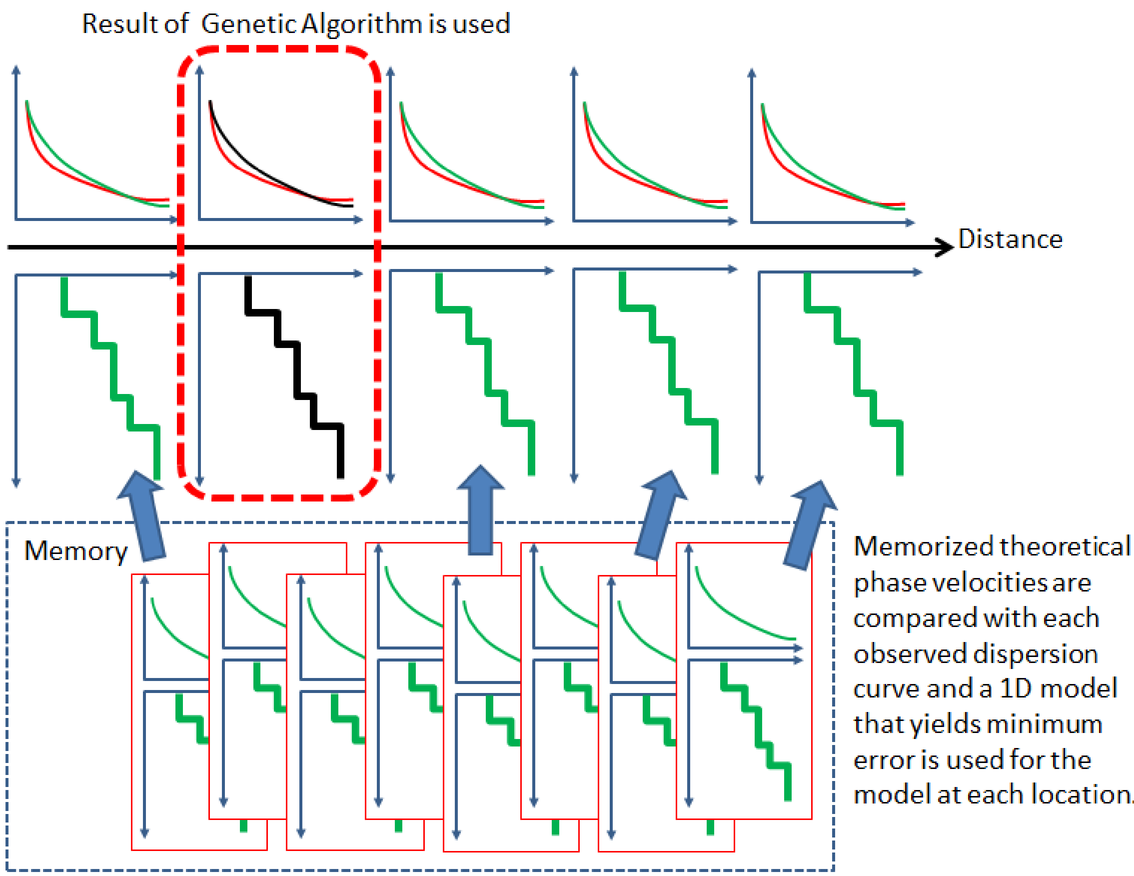
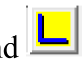


Figure 2.15 Memorized theoretical phase velocities are compared with each observed dispersion curve and an 1D model that yields minimum error is used for the model at each location.

2.7 Higher mode of Love waves

The higher modes of Love waves can be calculated and used in inversions. Rayleigh and Love waves can be switched by buttons on toolbar ( for Rayleigh waves and  for Love waves). The fundamental mode of Love waves is shown as a blue line. For higher mode calculation, “maximum” and “averaged” modes are shown as blue and green respectively.

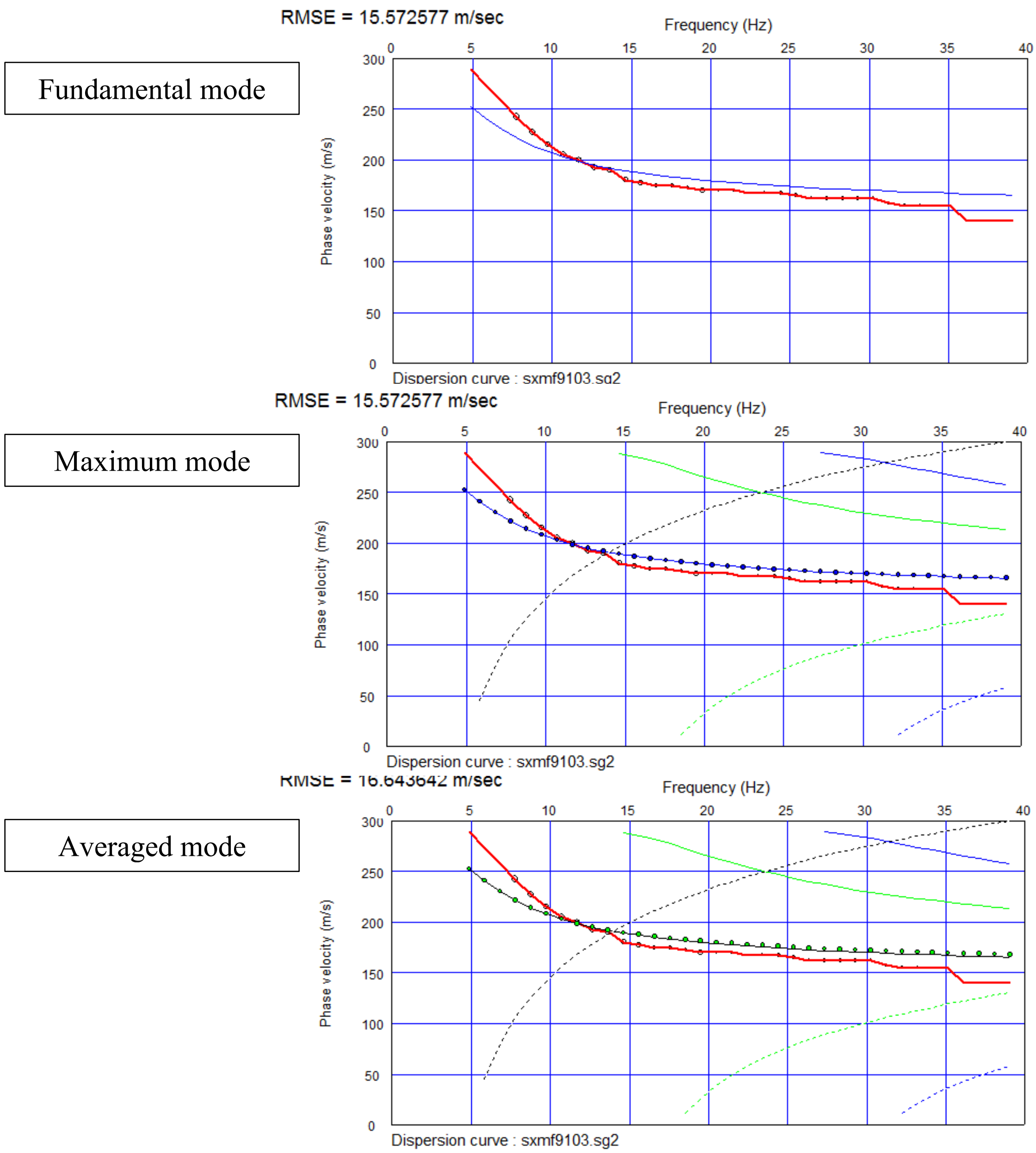
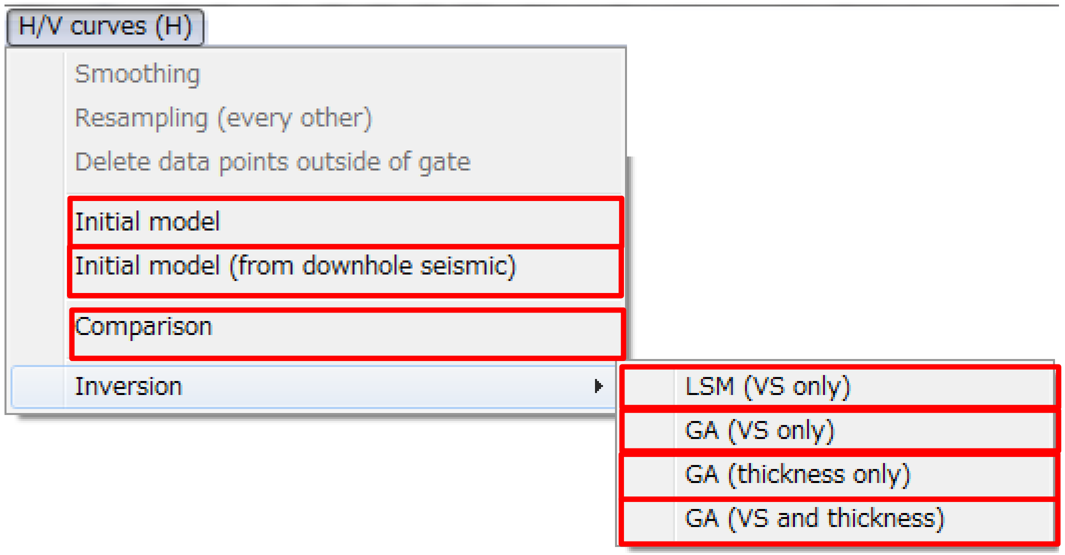


Figure 2.16 Display of theoretical dispersion curve for Love waves.

3. Available new functions in SeisImager/SW-Pro

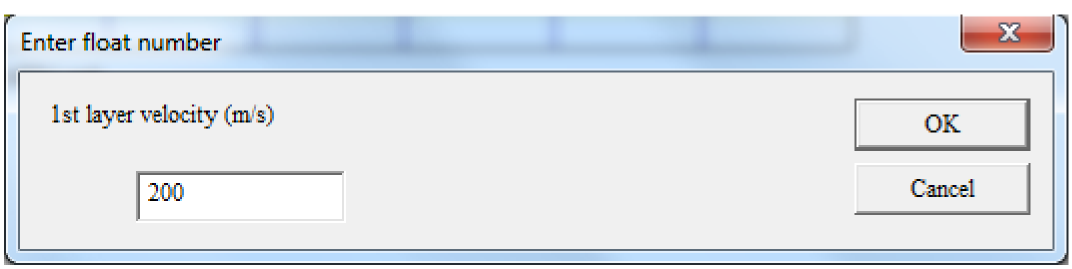
In this section, new functions available in SeisImager/SW-Pro will be described. New functions are framed in red.

3.1 H/V curves Menu



3.1.1 H/V curves Menu: Initial model

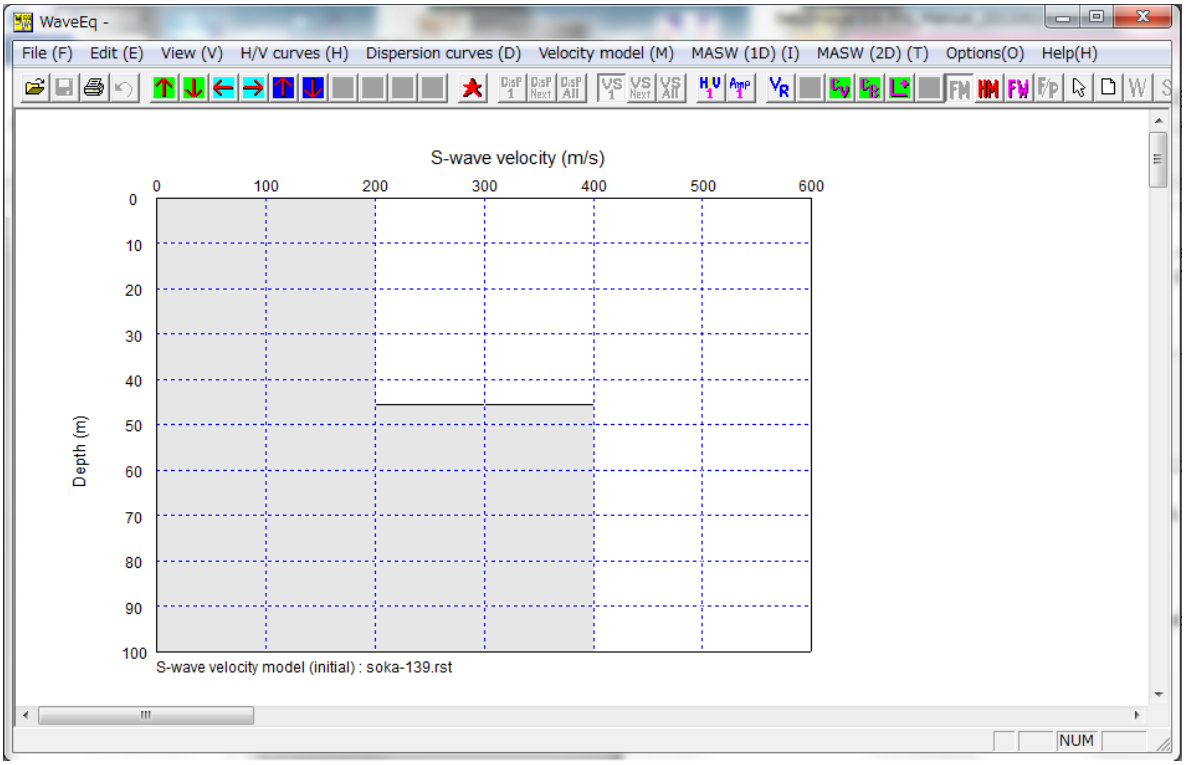
To make an initial velocity model for H/V analysis, select *Initial model*. The initial model is a two-layer velocity model. Set S-wave velocity for first layer (Vs_1).



Depth to a second layer (D_2) is calculated with peak frequency of H/V (f) as follows:

$$D_2 = \mathrm{Vs}_1 \div f \div 4. \qquad (1)$$

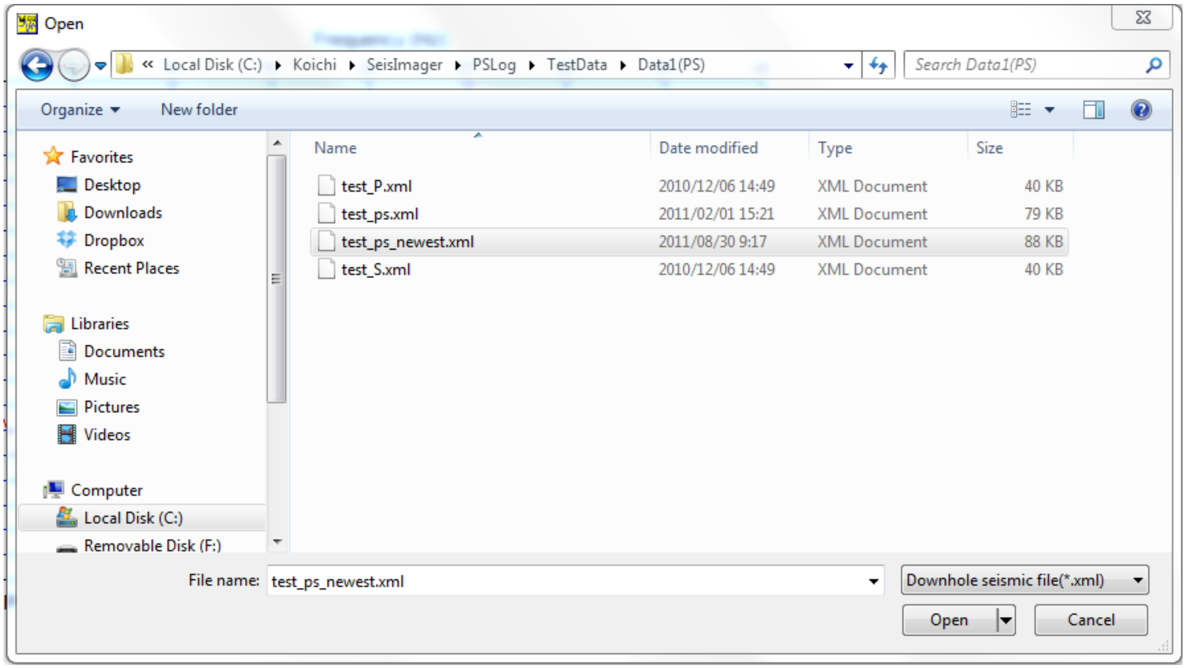
S-wave velocity for second layer (Vs_2) is automatically set to double of Vs_1. Click OK and the initial S-wave velocity is displayed.



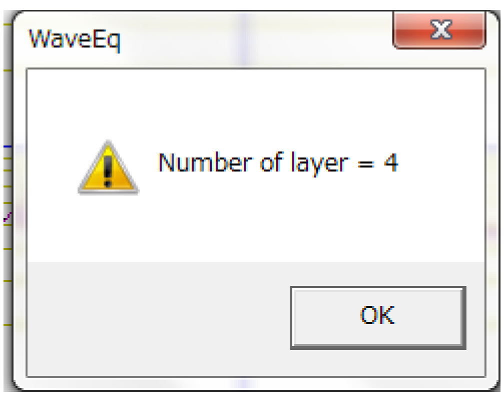
Note that an inversion using only H/V data is essentially non-unique and unstable. Do not rely on the inversion of H/V data alone, and we recommend incorporating other information, such as phase velocity data, drilling logs, and geological information.

3.1.2 H/V curves Menu: Initial model (from downhole seismic)

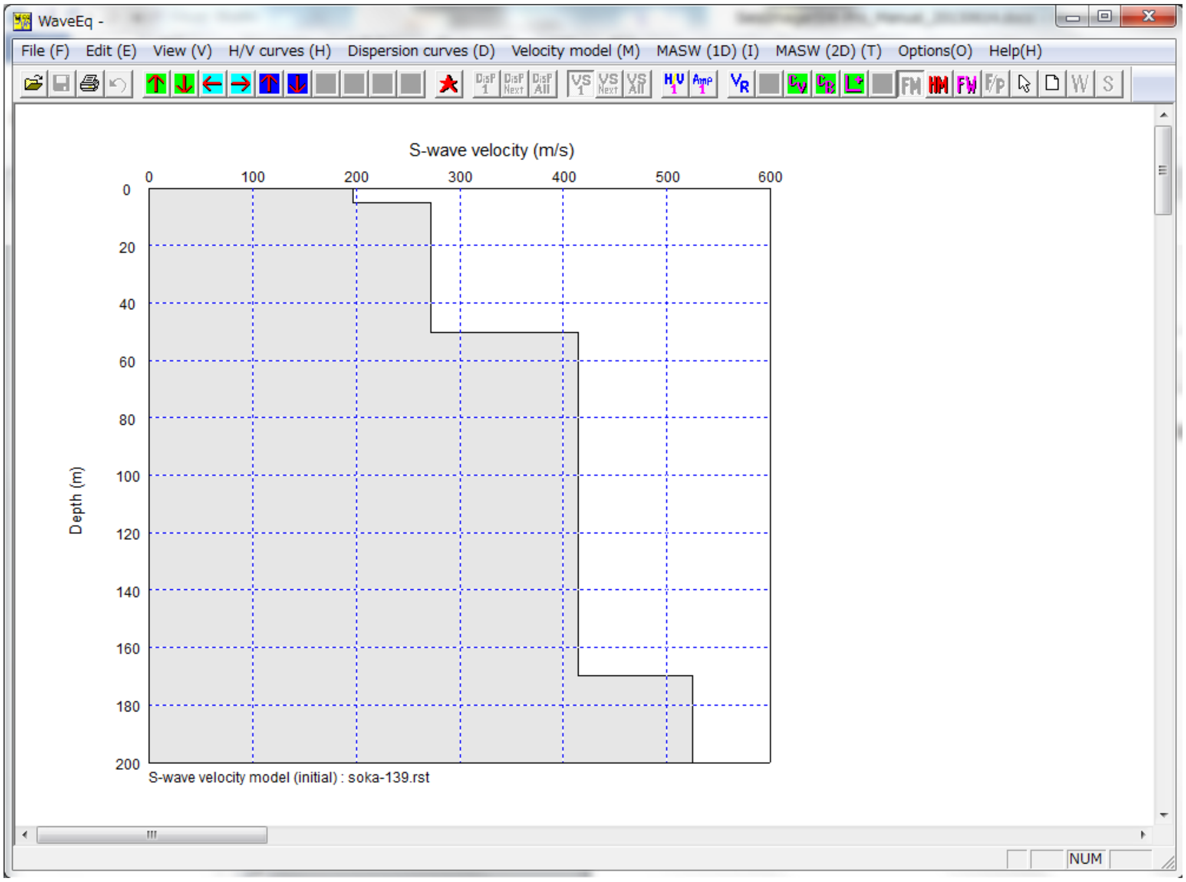
To make an initial velocity model for H/V analysis based on a seismic logging, select *Initial model (from downhole seismic)*. An XML file saved by SeisImager/DH (PSLog) can be used as a velocity model. Highlight the file and click *Open*.



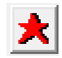
After confirmation that the number of layers is displayed, click *OK*.

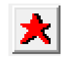


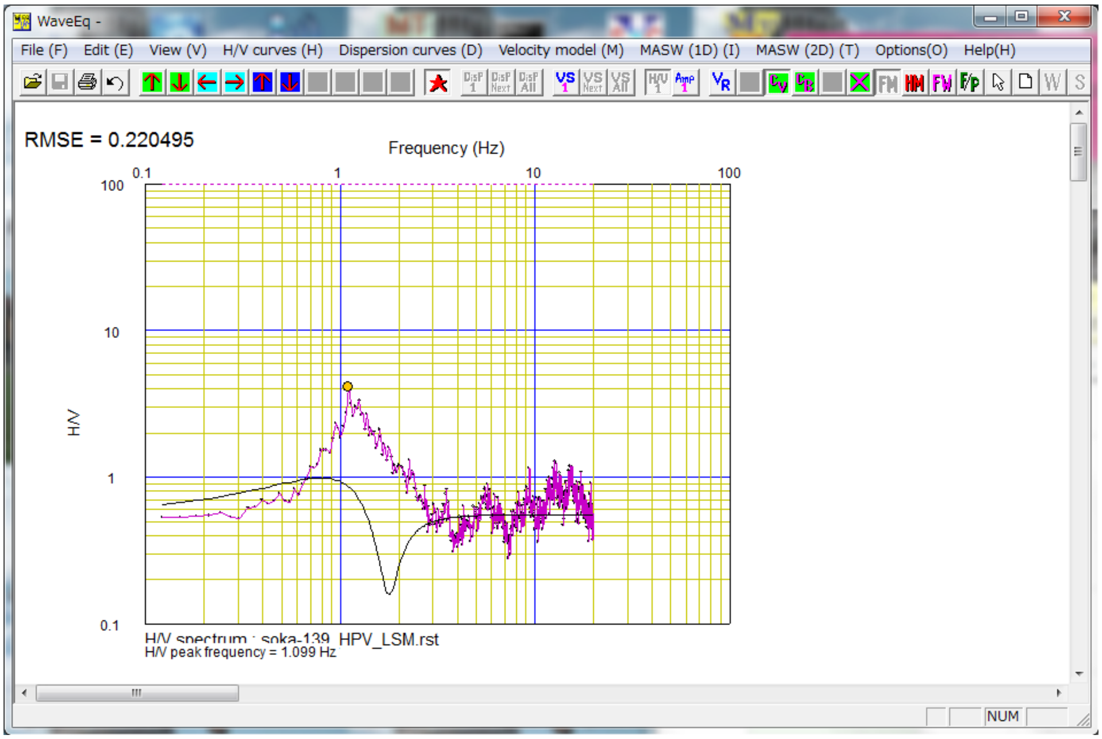
A velocity model is displayed.



WaveEq -
File (F) Edit (E) View (V) H/V curves (H) Dispersion curves (D) Velocity model (M) MASW (1D) (I) MASW (2D) (T) Options(O) Help(H)
S-wave velocity (m/s)
0 100 200 300 400 500 600
Depth (m)
0 20 40 60 80 100 120 140 160 180 200
S-wave velocity model (initial) : soka-139.rst
NUM

3.1.3 H/V curves Menu: Comparison 

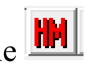
To calculate and overlay a theoretical H/V curve over an observed H/V curve, select *Comparison* or click the *Calculate theoretical dispersion curves*  button. The calculated curve is shown as a black line. To remove the calculated H/V curve from the display, unclick the *Calculate theoretical dispersion curves* button.



3.1.4 H/V curves Menu: Inversion

The *Inversion* menu includes functions for inversion of H/V data. Several different inversion methods can be selected. Use an appropriate method depending on observed data, site conditions, and investigation purposes. Remember, the inversion of H/V data is unstable compared to the inversion of dispersion curve data. We suggest using a small number of iterations and checking the validity of results carefully.

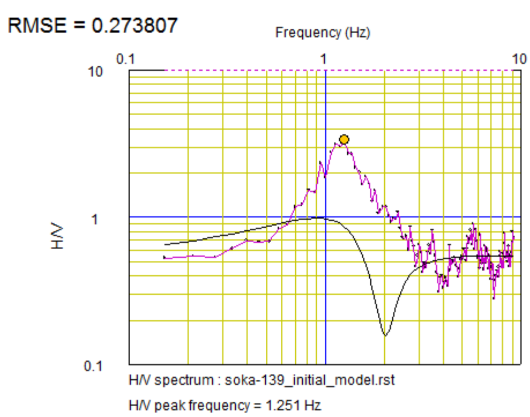
All inversion functions may be carried out with data from fundamental mode only or fundamental and higher mode H/V curves. Inversions use only fundamental mode when the 

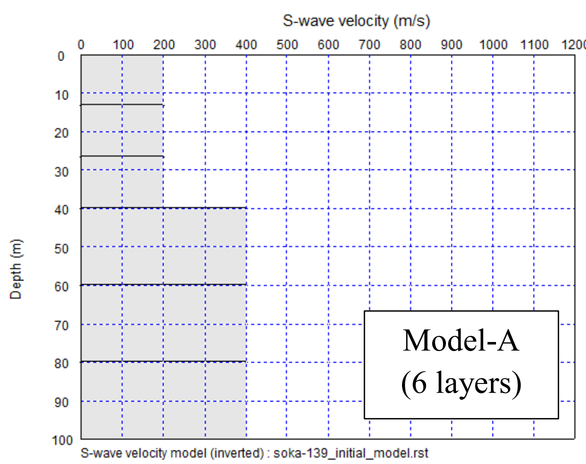
button is selected and use both fundamental and higher modes when the 

button is selected.

Joint inversions of a dispersion curve and a H/V spectrum may be performed if the user has phase velocity and H/V measurements. Use functions in *Advanced inversion* in the *MASW (1D)* menu to perform the joint inversion functions.

An example of observed and theoretical H/V data (left) and initial velocity model (right) will be used in the following explanation. The initial model (model-A) is a six layer model. The theoretical H/V data is calculated for the initial model.

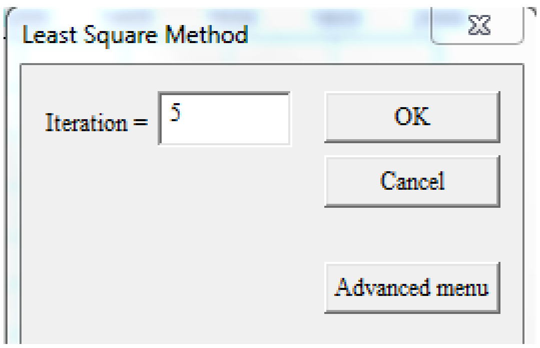




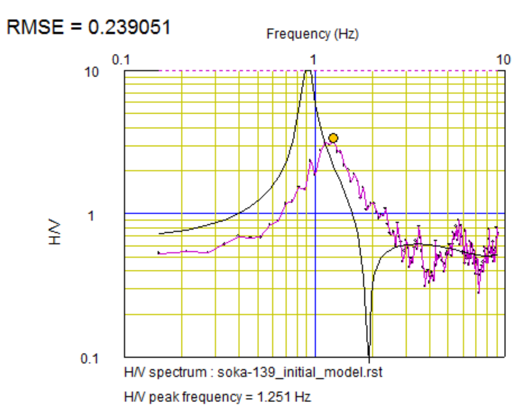
3.1.4.1 H/V curves Menu: Inversion: LSM (VS only)

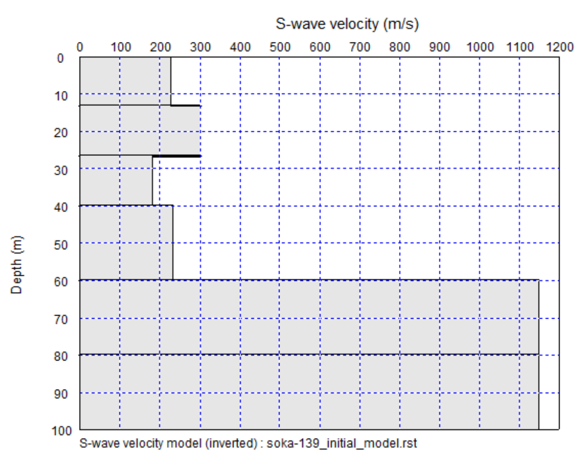
S-wave velocity model is estimated by non-linear least square methods, and layer thickness is held constant under this inversion process. Observed data in the inversion is H/V data and unknown parameters in the inversion are S-wave velocity of each layer.

Set the number of iterations for the inversion. The default value of 5 for *Iteration* is suitable for most cases.



An example of inverted result is shown below. Error between obsreved and thoretical H/V is smaller than the initial model (model A).

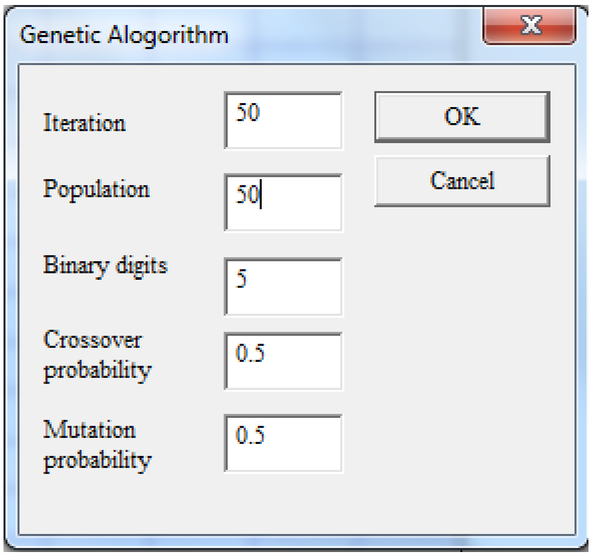




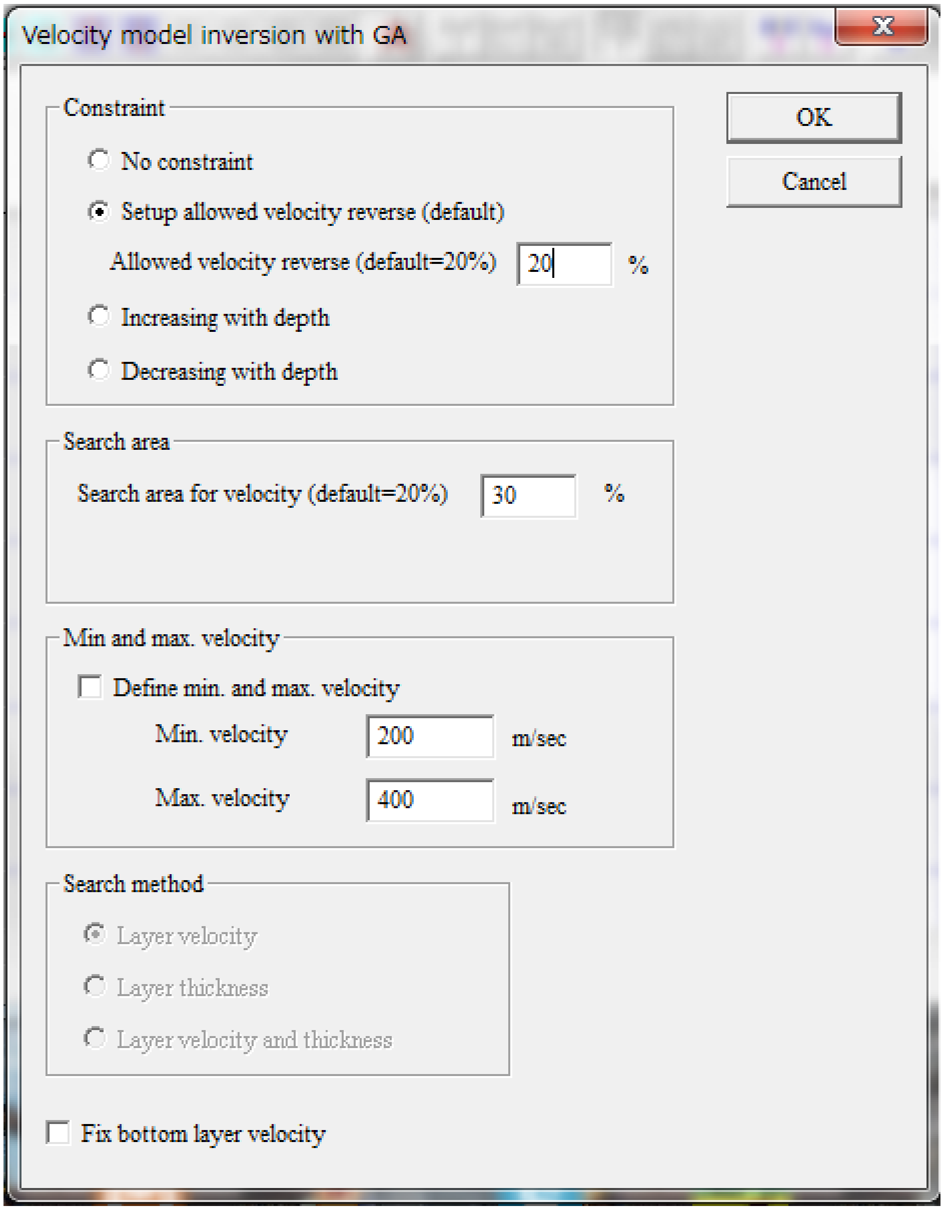
3.1.4.2 H/V curves Menu: Inversion: GA (VS only)

S-wave velcity model is estimated by Genetic Algorithm. Observed data in the inversion is absolute H/V values and peak frequency of H/V spectrun. Unknown parameters in the inversion are S-wave velocity of each layer.

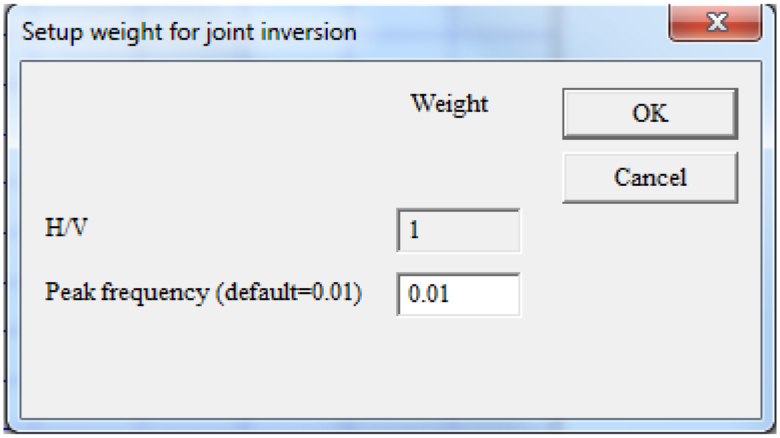
Set the parameters for the Genetic Algorithm. The default values (Iteration=50, Popuration=50, Binary digits=5, Crossover probability=0.5, Mutation probability=0.5) are suitable for most cases. Click the *OK* button to proceed.



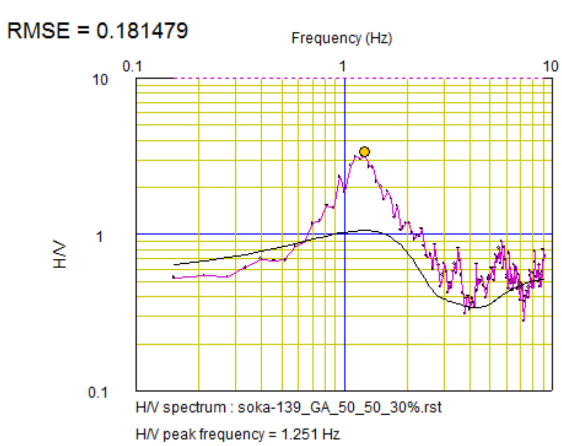
Set the parameter for constraint. Change the parameters depending on site conditions. Click the *OK* button to proceed.

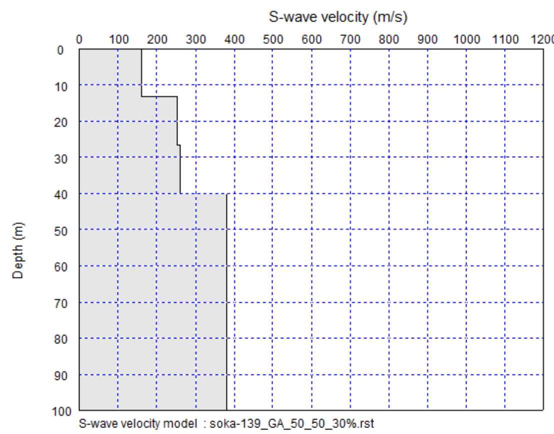


Set the weight for observed data. The default value of 0.01 for *Peak frequency* is suitable for most cases. Click the *OK* button to start the inversion.



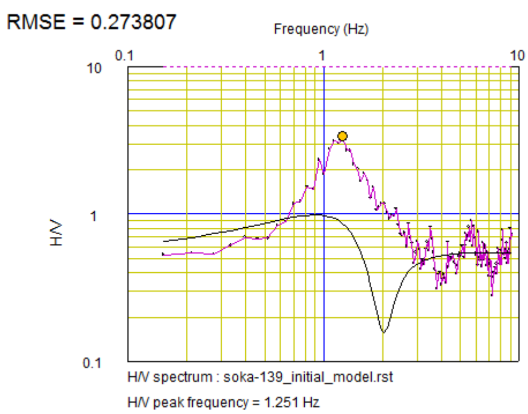
An example of inveted result is shown below. Error between obsreved and thoretical H/V is smaller than the initial model (model A).

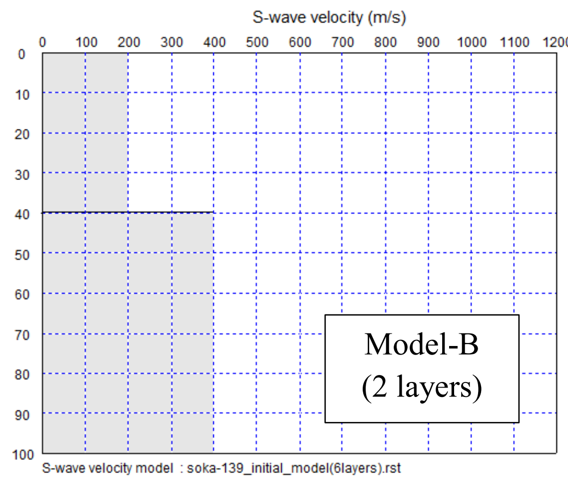




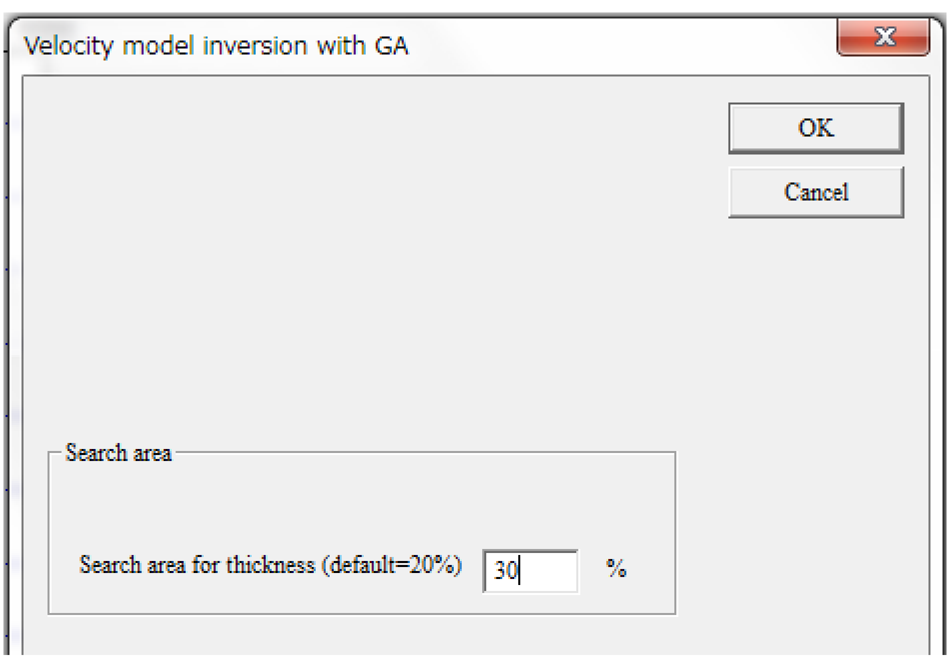
3.1.4.3 H/V curves Menu: Inversion: GA (thickness only)

S-wave velcity model is estimated by Genetic Algorithm. Observed data in the inversion is absolute H/V values and peak frequency of H/V spectrun. Unknown parameters in the inversion are thickness of each layer. Thickness of layer is difficult to estimate compared with S-wave velocity. Keep the number of layers as small as possible. A two layer model is used as initial model (model-B).

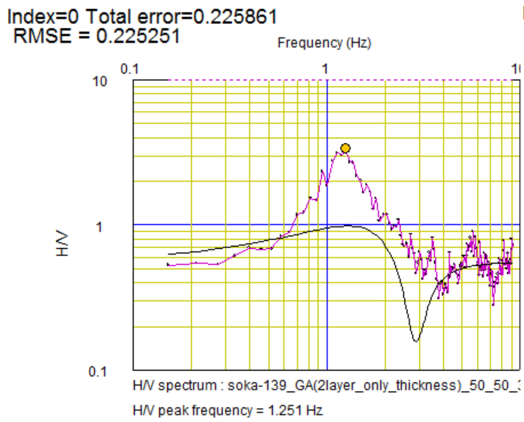


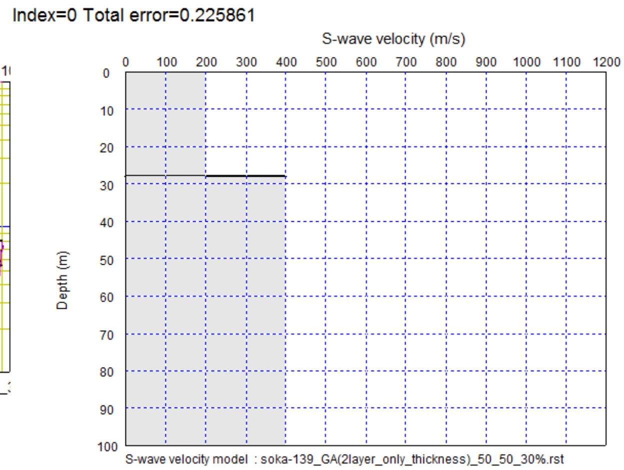


Set the parameter for constraint. Change the parameters depending on site conditions. Click the *OK* button to proceed.



An example of inveted result is shown below. Error between obsreved and thoretical H/V is smaller than the initial model (model B).





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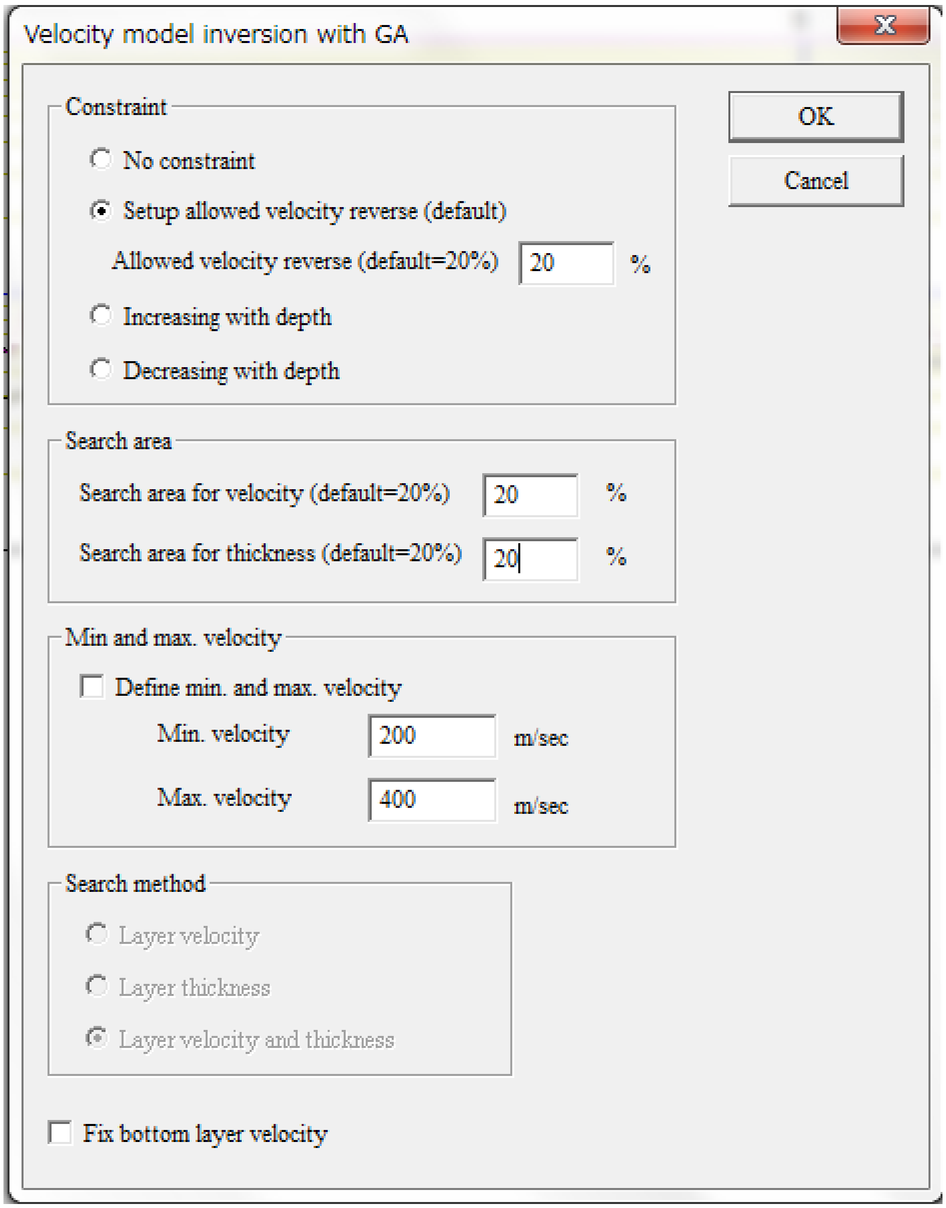
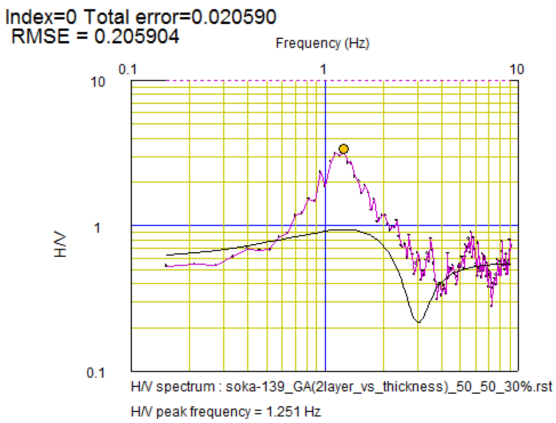
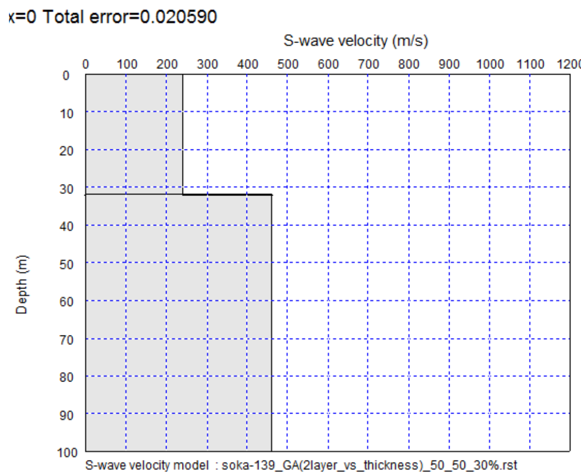
3.1.4.4 H/V curves Menu: Inversion: GA (VS and thickness only)

S-wave velcity model is estimated by Genetic Algorithm. Observed data in the inversion is absolute H/V values and peak frequency of H/V spectrun. Unknown parameters in the inversion are thickness and S-wave velocity of each layer. Estimating thickness and S-wave velcocity of layer simeltaneously is difficult compared with the inversion estimating S-wave velocity only. Keep number of layers as small as possible. The two layer model (model-B) mentioned in the previous section is used as an initial model.



An example of inverted result is shown below. Error between obsreved and thoretical H/V is smaller than the initial model (model B).



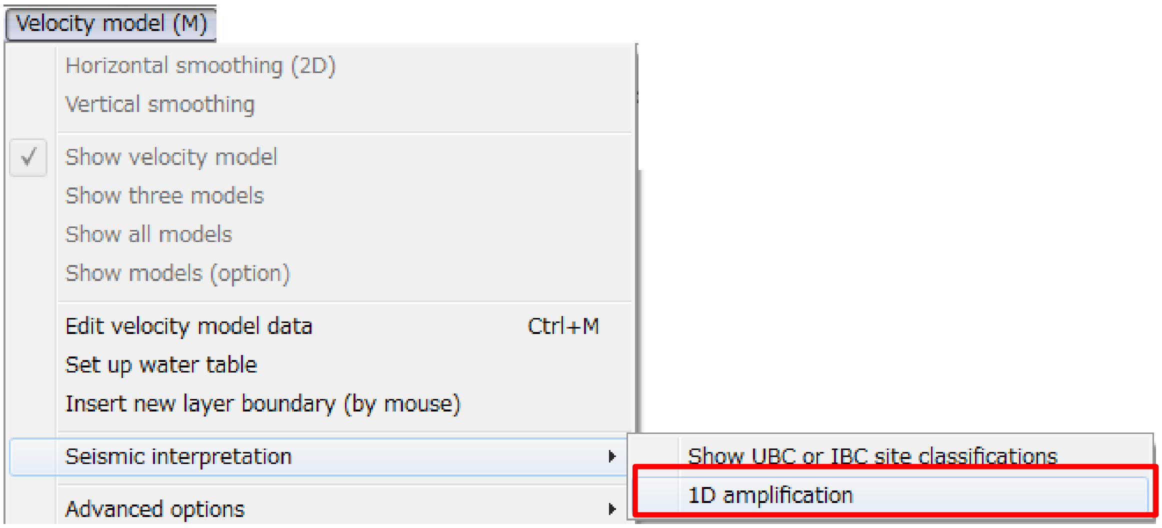


3.2 Velocity model Menu

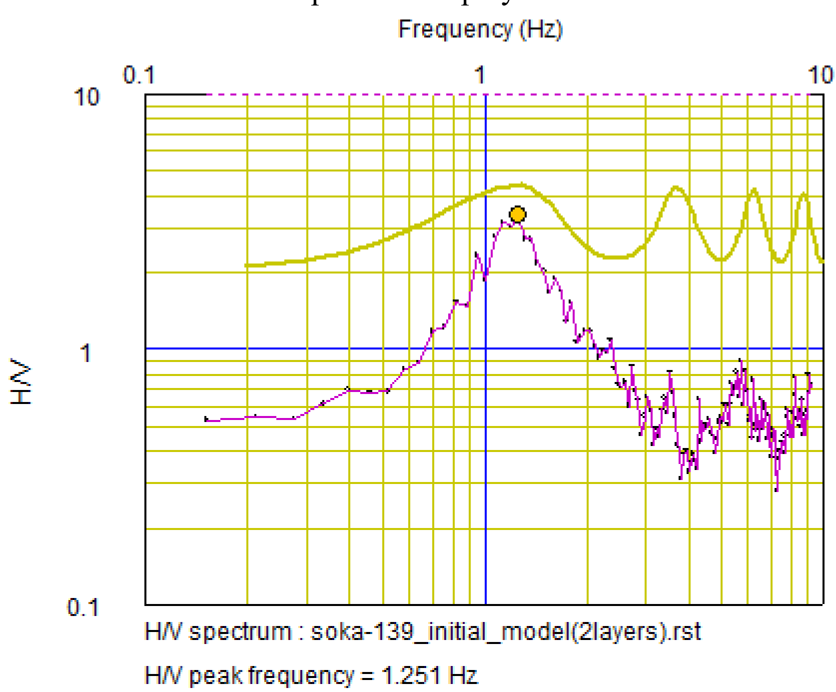
3.2.1 Velocity model Menu : Seismic interpretation

Select *1D amplification* in the *Seismic interpretation* menu or click the *1D amplification* 

button to calculate amplification of SH waves based on multiple reflections.

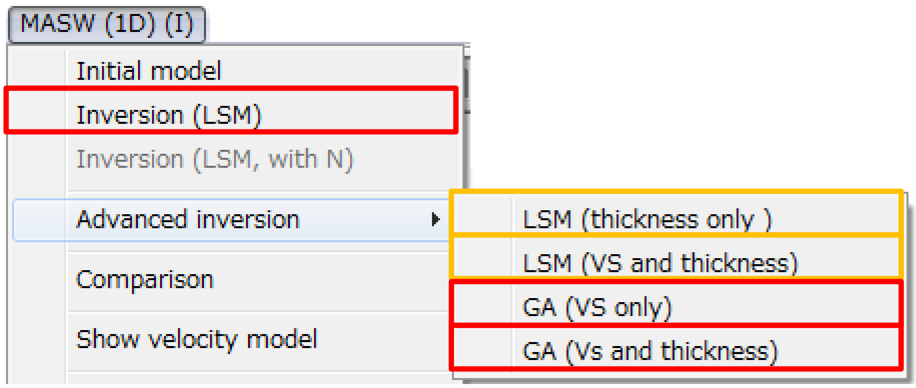


An example of amplification for the Model-B is shown below. Amplification is shown as a thick ocher line on H/Vspectrum display.



3.3 MASW (1D) Menu

MASW (1D) menu and *Advanced inversion* in the *MASW (1D)* menu includes following inversion functions available in the SW-Pro.

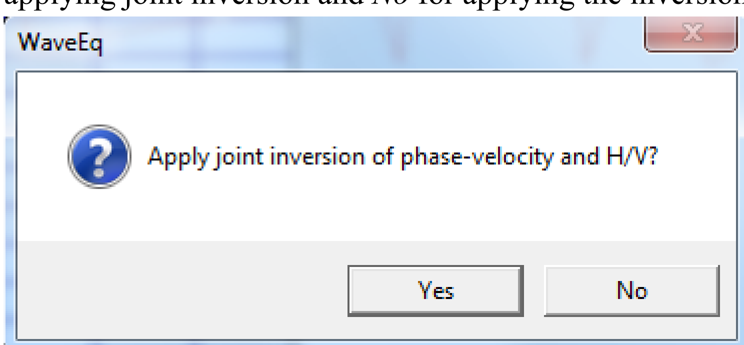


All inversion functions can take accounts both fundamental mode only or fundamental and higher modes. Inversions use only fundamental mode when the 

button is being selected and use both fundamental and higher modes when the 

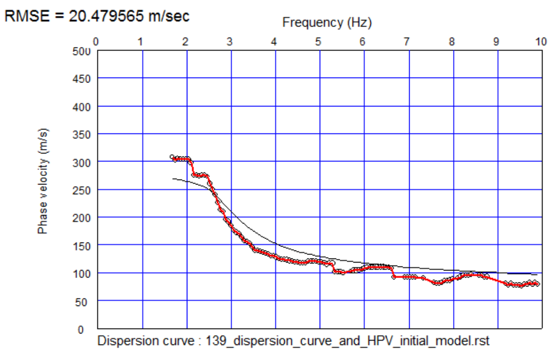
button is being selected.

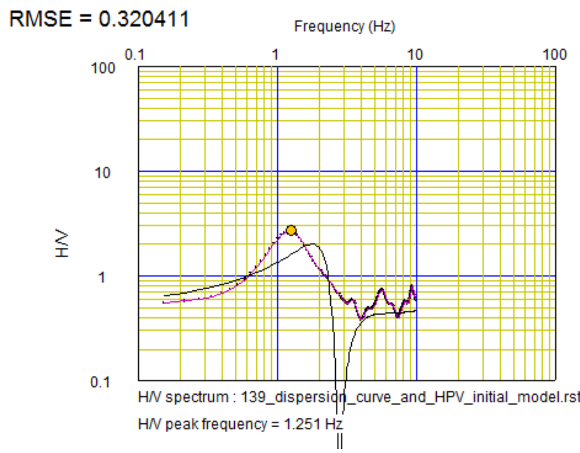
The inversion functions surrounded by red line (*Inversion (LSM), GA (VS only), GA (VS and thickness)*) can be used for the inversions of a dispersion curve or the joint inversions of the dispersion curve and an H/V spectrum. After selecting inversion menu, following dialog is displayed when data includes both dispersion curve and H/V. Click *Yes* for applying joint inversion and *No* for applying the inversion using only phase velocity data.

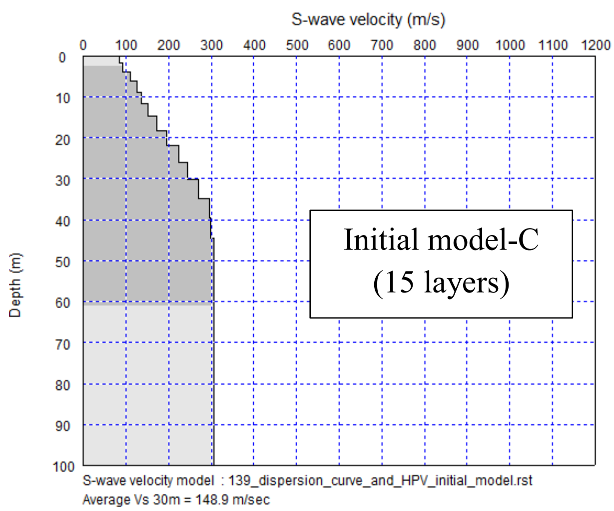


3.3.1 MASW (1D) Menu : Inversion (LSM)

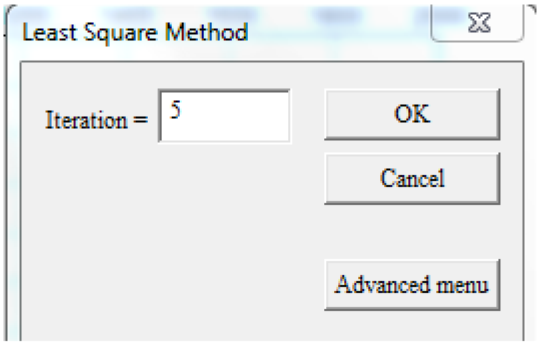
Select *Inversion (LSM)* to perform an inversion in which S-wave velocity of each layer is changed. An inversion that only uses a dispersion curve and a joint inversion that uses both a dispersion curve and a H/V spectrum can be performed by this menu. Following dispersion curve, H/V spectrum, and an initial model are used for example. The inversion performed by this menu only changes S-wave velocity of each layer and a number of layers in the initial model has to be large (10 to 20).



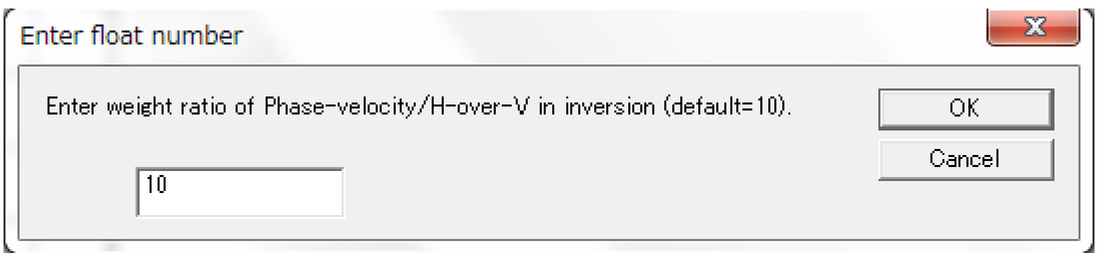




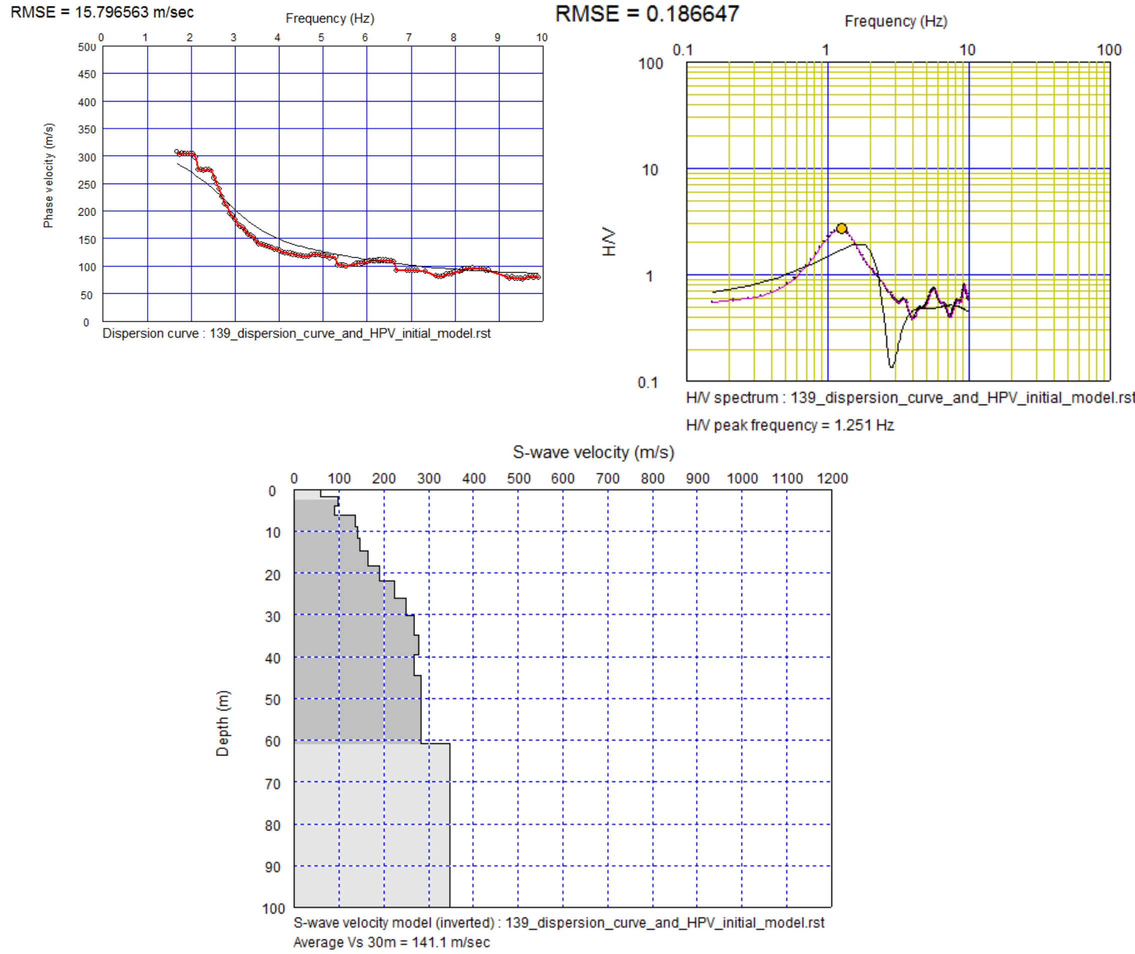
Set the number of iterations for the inversion. The default value of 5 for *Iteration* is suitable for most cases.



Set the weight ratio of Phase-velocity and H/V in the inversion. Larger values give presidence to dispersion curve data. Default value is 10.



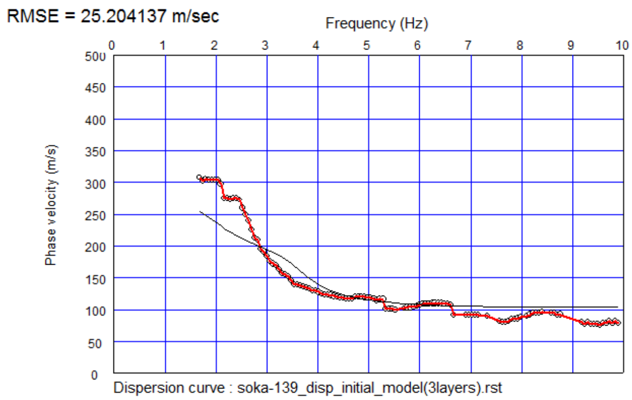
An example of inverted result is shown below. Error between observed and theoretical phase velocities and H/V is smaller than the initial model (model C).

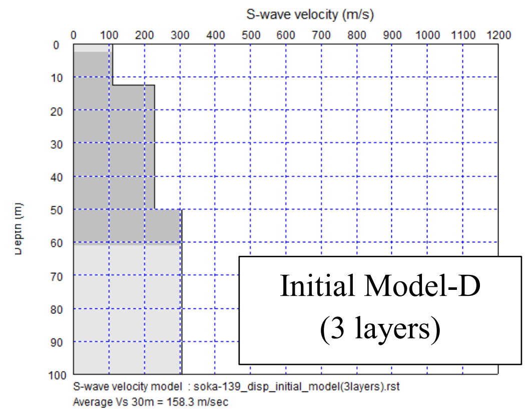


3.3.2 MASW (1D) Menu: Advanced inversion

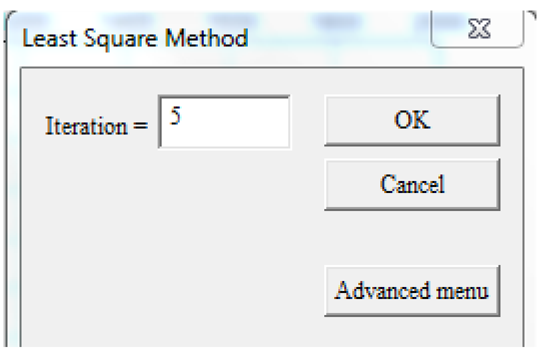
3.3.2.1 MASW (1D) Menu: Advanced inversion: LSM (thickness only)

Select *LSM (thickness only)* to perform an inversion in which thickness of each layer is changed. Following dispersion curve and an initial model (Model-D) are used for example. The inversion performed by this menu only changes thickness of each layer and it is better to keep a number of layers to be small (3 to 7). The Initial Model-D is used for example.

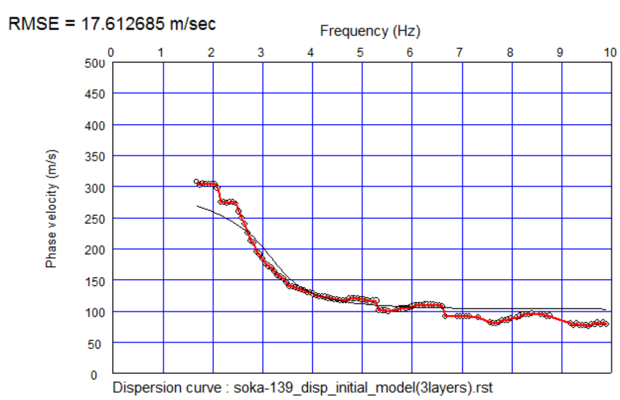


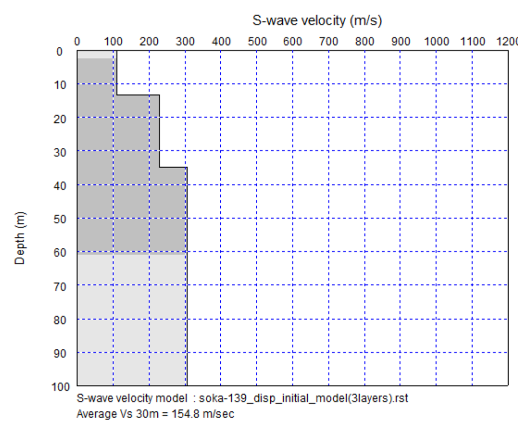


Set the number of iterations for the inversion. The default value of 5 for *Iteration* is suitable for most cases.



An example of inverted result is shown below. Error between observed and theoretical phase velocities is smaller than the initial model (model D).

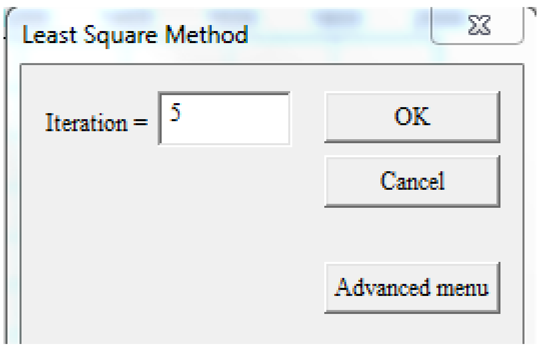




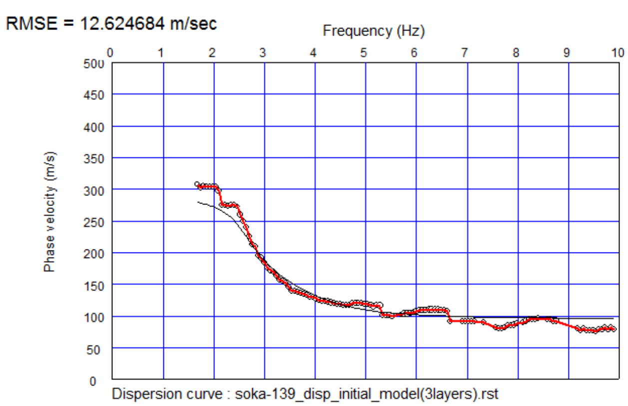
3.3.2.2 MASW (1D) Menu: Advanced inversion: LSM (VS and thickness)

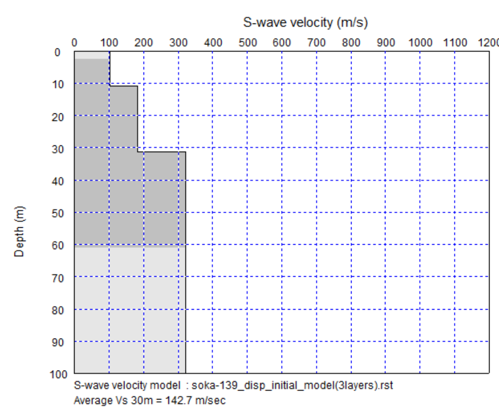
Select *LSM (VS and thickness)* to perform an inversion in which both S-wave velocity and thickness of each layer are changed. The inversion performed by this menu changes both S-wave velocity and thickness of each layer and it is better to keep a number of layers to be small (3 to 7). The Initial Model-D is used for example.

Set the number of iterations for the inversion. The default value of 5 for *Iteration* is suitable for most cases.



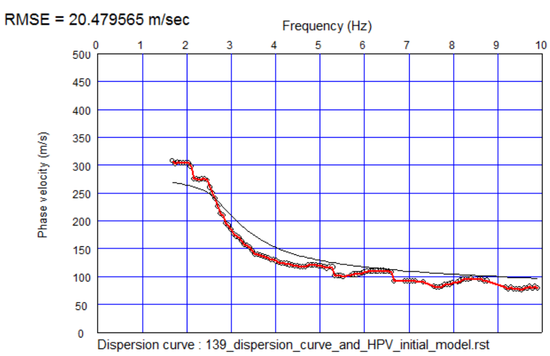
An example of inverted result is shown below. Error between observed and theoretical phase velocities is smaller than the initial model (model D).

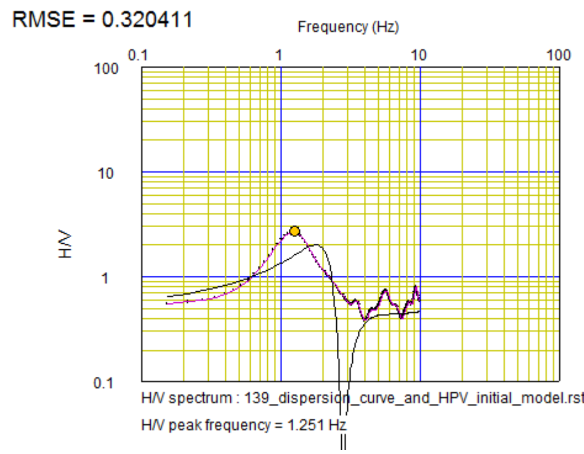


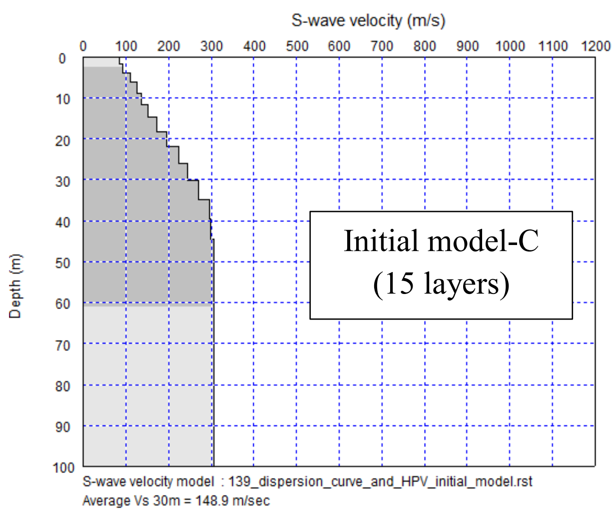


3.3.2.2 MASW (1D) Menu: Advanced inversion: GA (VS only)

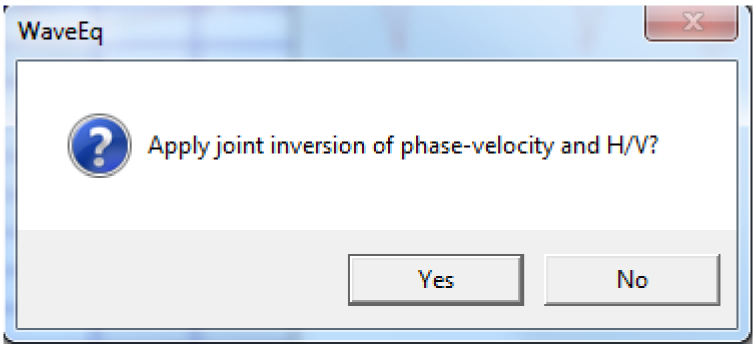
Select *GA (VS only)* to perform an inversion in which only S-wave velocity is changed. An inversion that only uses a dispersion curve and a joint inversion that uses both a dispersion curve and an H/V spectrum can be performed by this menu. The inversion applied by this menu changes S-wave velocity of each layer, and the number of layers in the initial model has to be large (10 to 20). The Model-C is used for example.



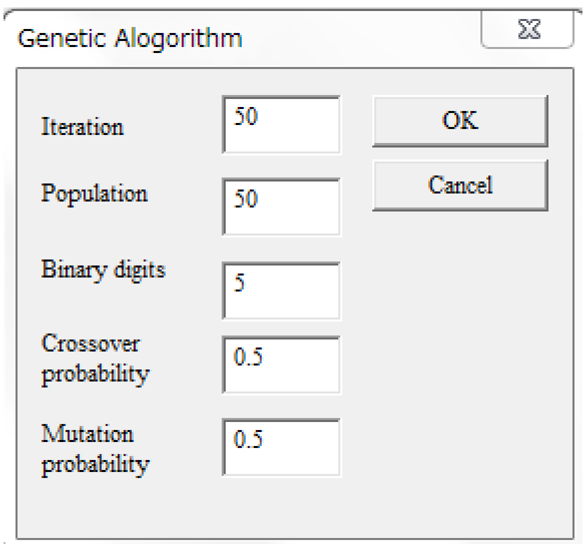




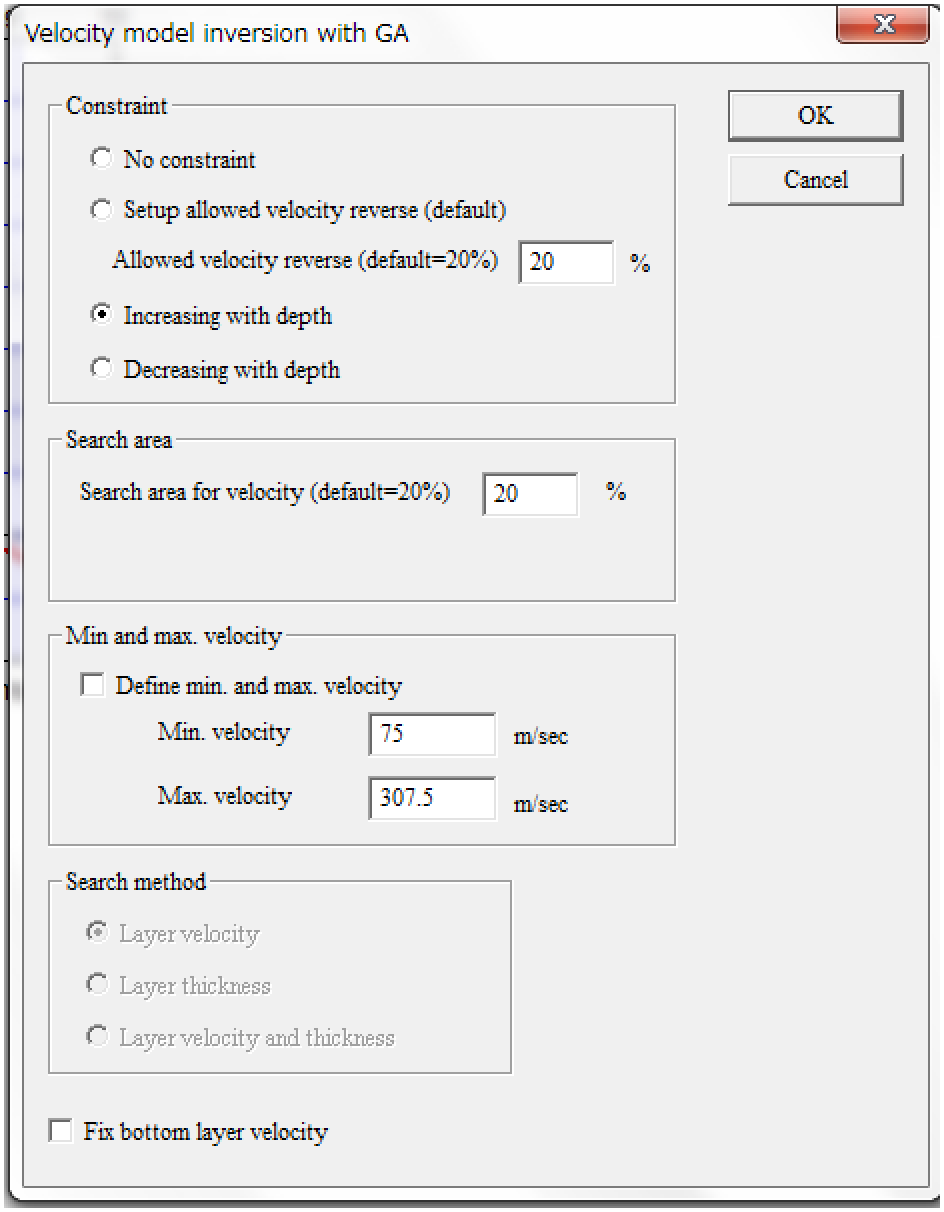
The dialog box shown bellow would appear when the data contains both phase velocity and H/V data. Click *Yes* if you intend to apply the joint inversion of phase velocity and H/V data. Click *No* to apply the inversion of phase velocity data.



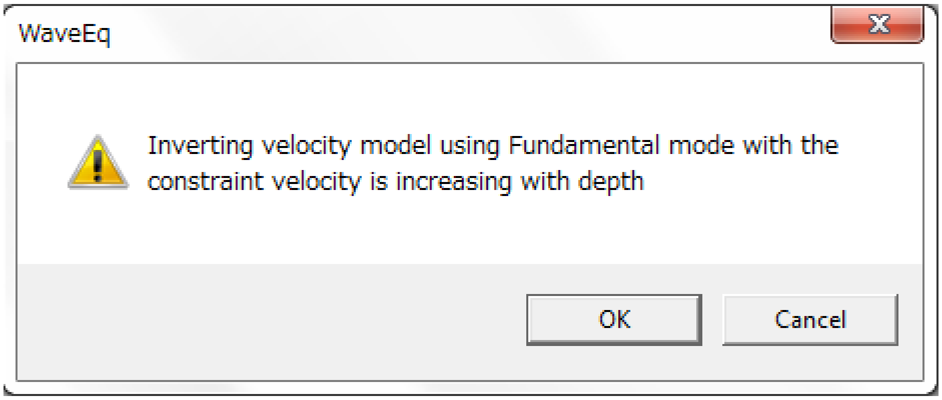
Set the parameters for the Genetic Algorithm. The default values (Iteration=50, Popuration=50, Binary digits=5, Crossover probability=0.5, Mutation probability=0.5) are suitable for most cases. Click the *OK* button to proceed.



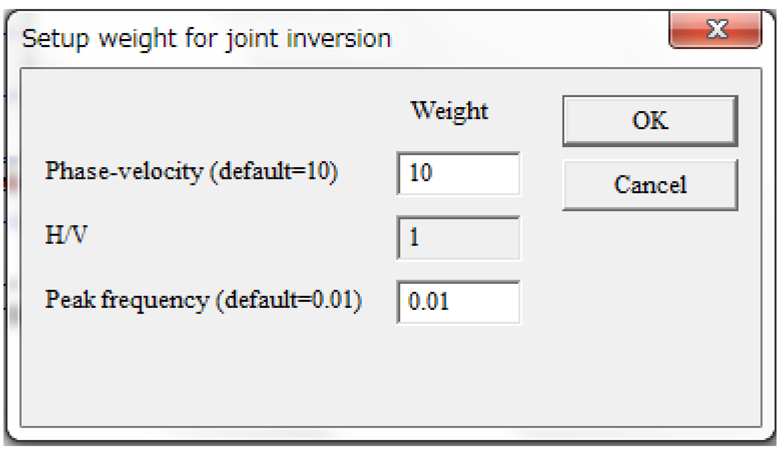
Set the parameter for constraint. Change the parameters depending on site conditions. Click the *OK* button to proceed.



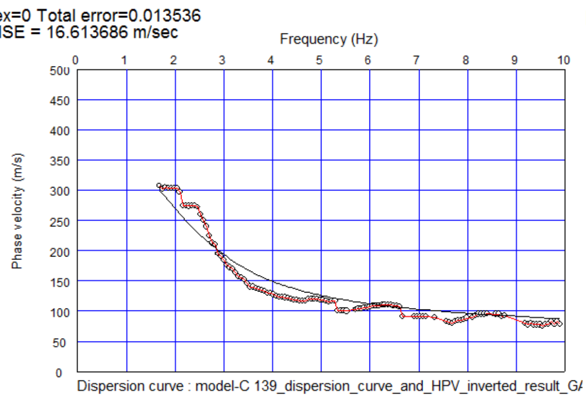
Confirm the setup for the inversion. Click OK to continue.

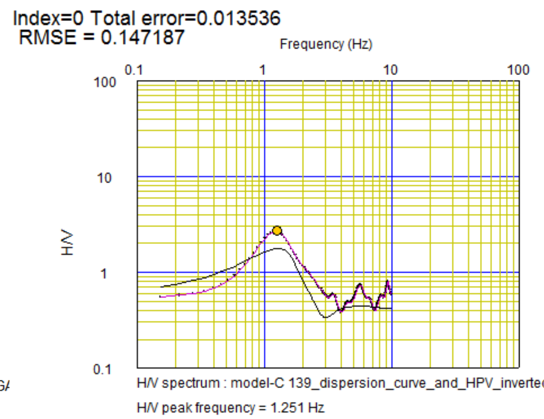


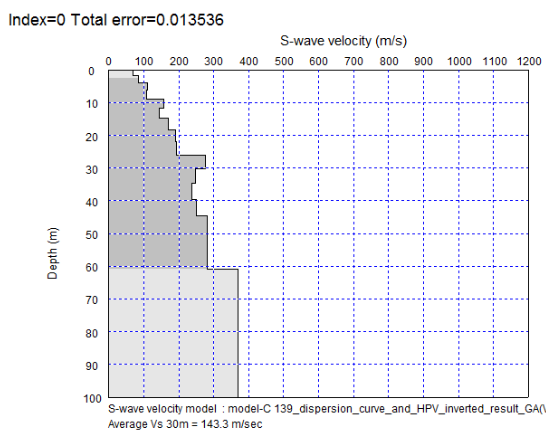
Set the weight ratio of Phase-velocity, H/V and peak frequency of H/V in the inversion. Larger value give presidence to dispersion curve data. The default values (10 and 0.01) are suitable for most cases.



An example of inverted result is shown below. Error between observed and theoretical phase velocities is smaller than the initial model (model C).





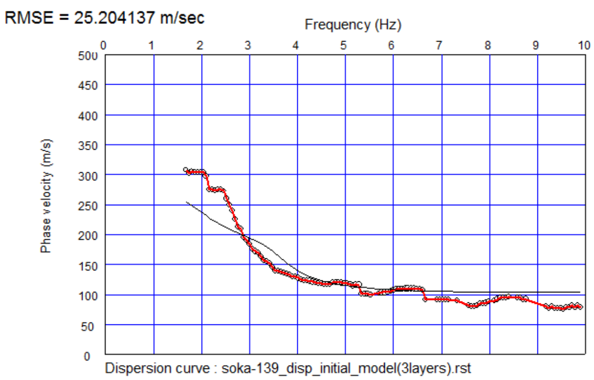


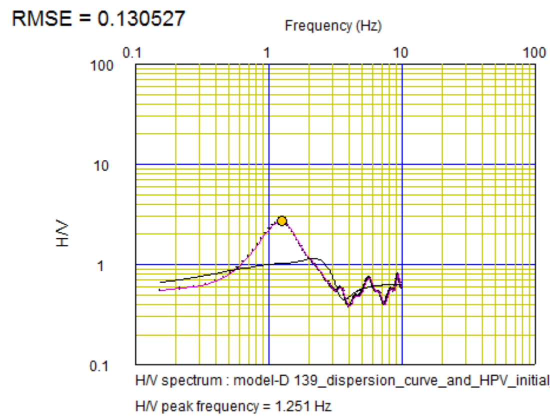
3.3.2.3 MASW (1D) Menu: Advanced inversion: GA (VS and thickness)

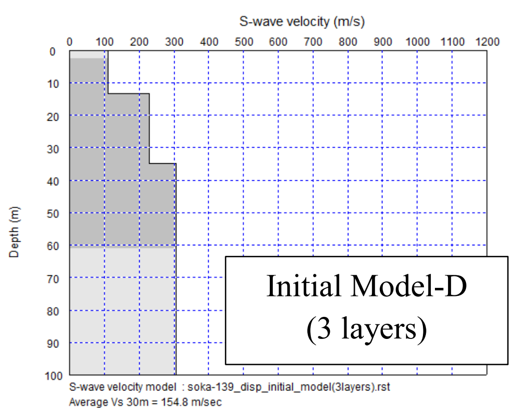
Select *GA (VS and thickness)* to perform an inversion in which both S-wave velocity and thickness of each layer are changed. An inversion that only uses a dispersion curve and a joint inversion that uses both a dispersion curve and an H/V spectrum can be performed by this menu. The inversion performed by this menu changes both S-wave velocity and thickness of each layer and it is better to keep a number of layes to be small (3 to 7).

A) Example using a fundamental mode

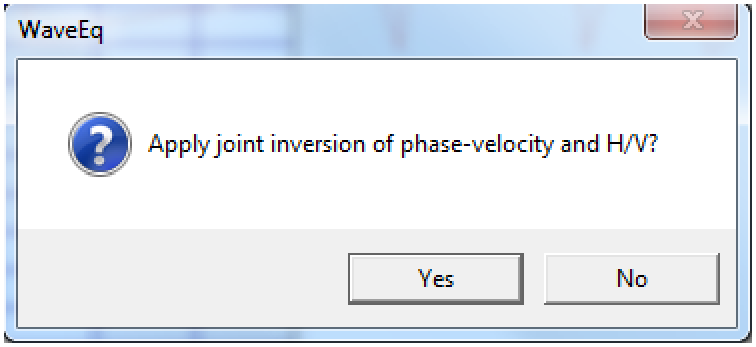
The Initial Model-D is used for example.



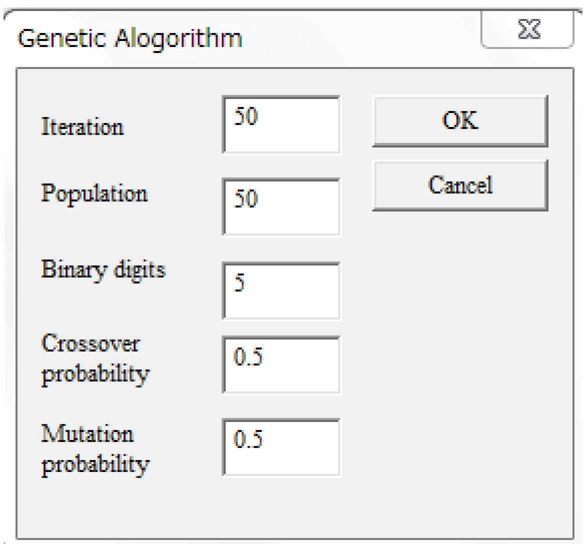




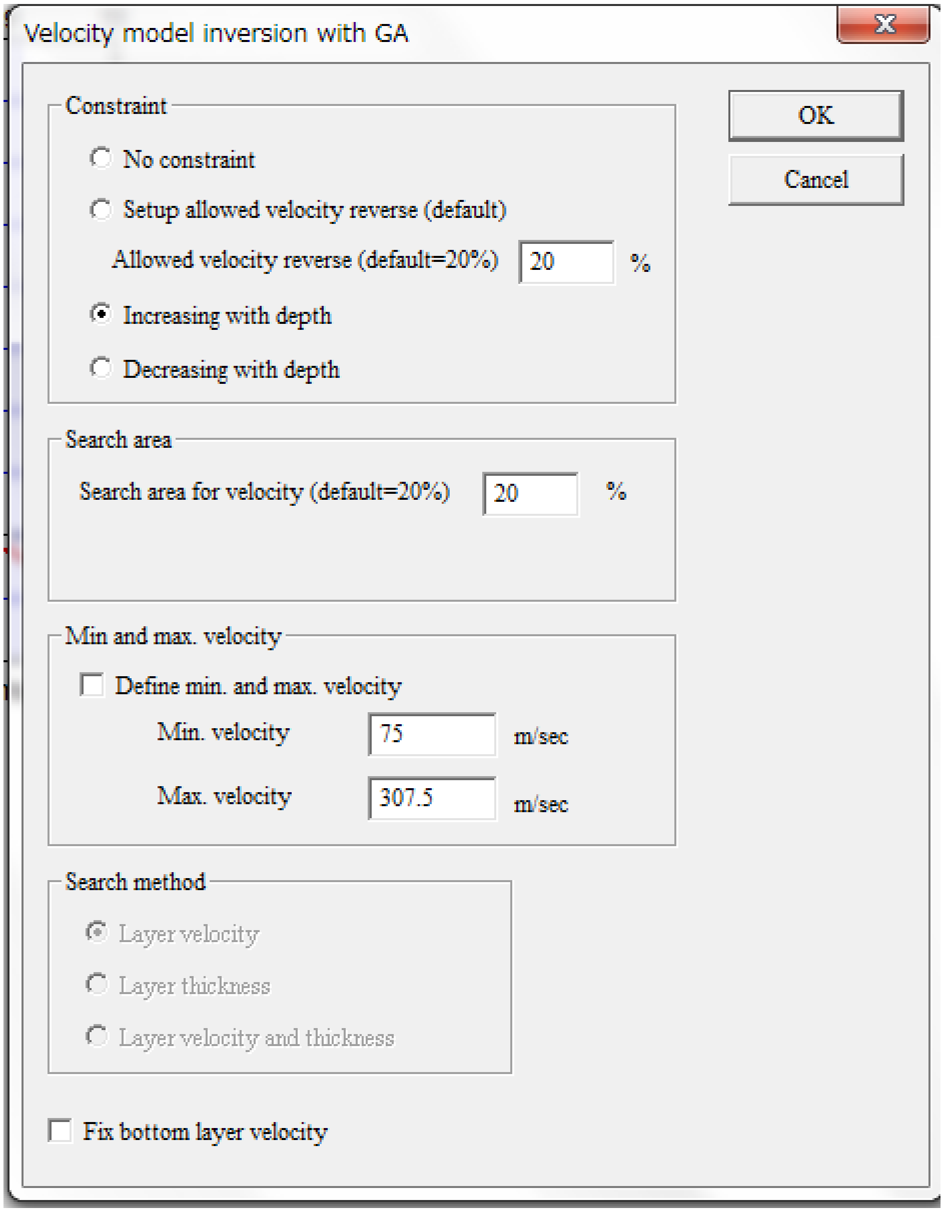
The dialog box shown bellow would appear when the data contains both phase velocity and H/V data. Click *Yes* if you intend to apply the joint inversion of phase velocity and H/V data. Click *No* to apply the inversion of phase velocity data.



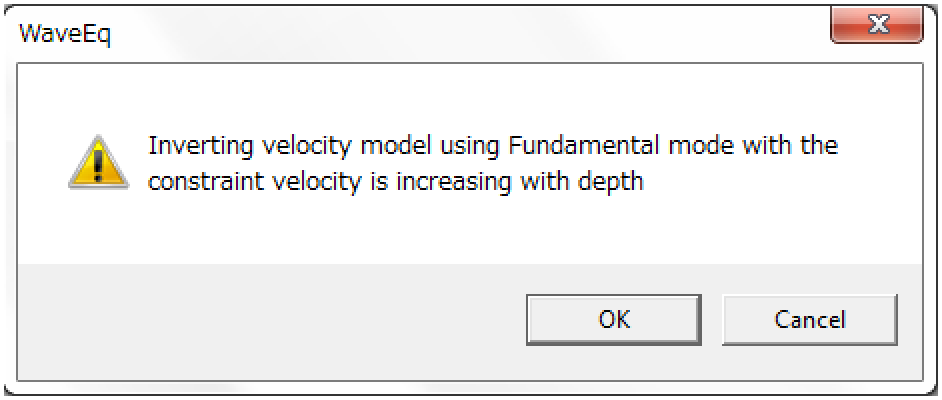
Set the parameters for the Genetic Algorithm. The default values (Iteration=50, Popuration=50, Binary digits=5, Crossover probability=0.5, Mutation probability=0.5) are suitable for most cases. Click the *OK* button to proceed.



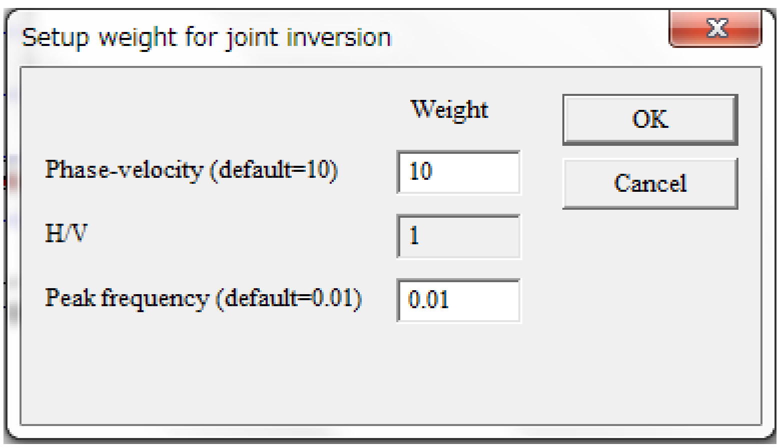
Set the parameter for constraint. Change the parameters depending on site conditions. Click the *OK* button to proceed.



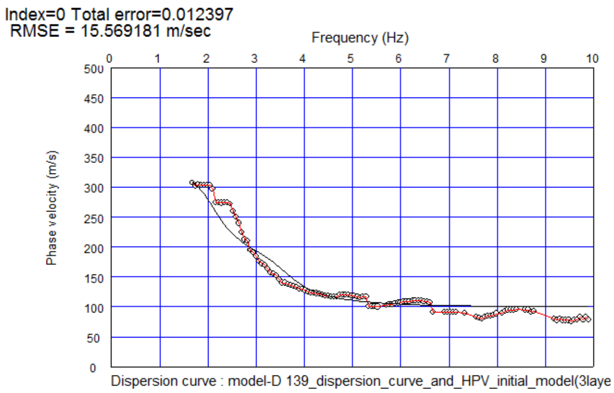
Confirm the setup for the inversion. Click OK to continue.

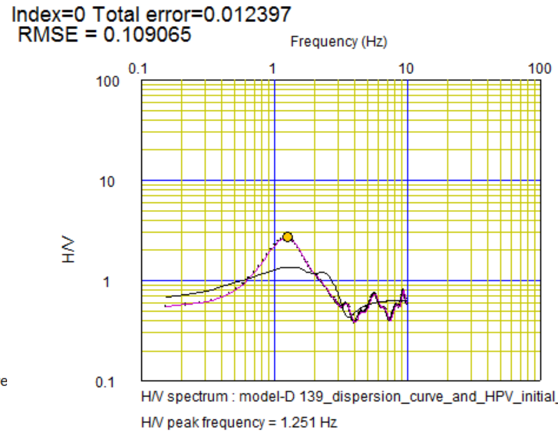


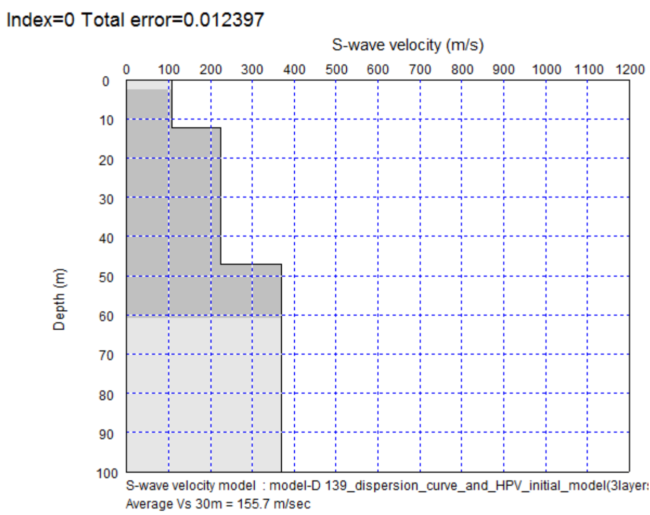
Set the weight ratio of Phase-velocity, H/V and peak frequency of H/V in the inversion. Larger value give presidence to dispersion curve data. The default values (10 and 0.01) are suitable for most cases.



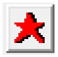
An example of inverted result is shown below. Error between observed and theoretical phase velocities is smaller than the initial model (model D).

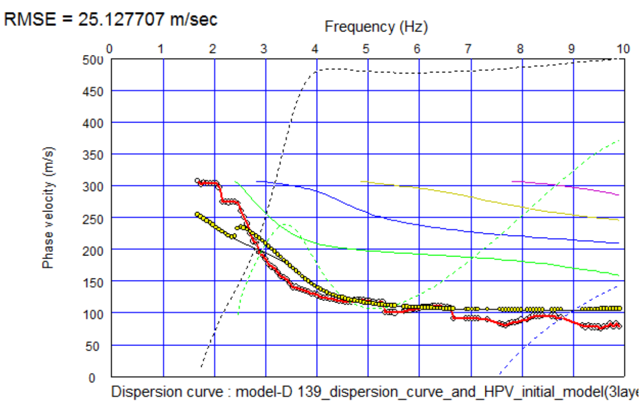


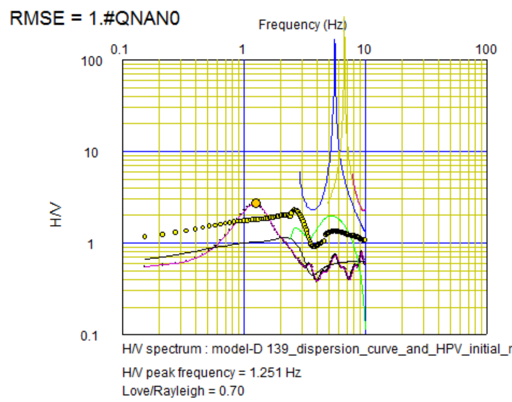


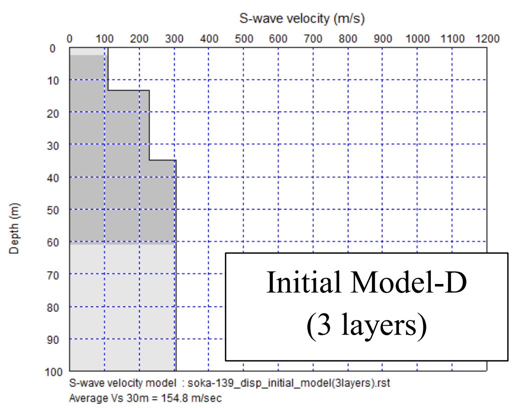


B) Example using higher modes

Click  button to apply the inversion using higher modes. The Initial Model-D is used for example. Click  and the theoretical dispersion curves (or H/V) of fundamental and higher modes appear together with averaged (effective mode) or maximum phase velocities (or H/V). The inversion takes account higher modes when the  is selected.

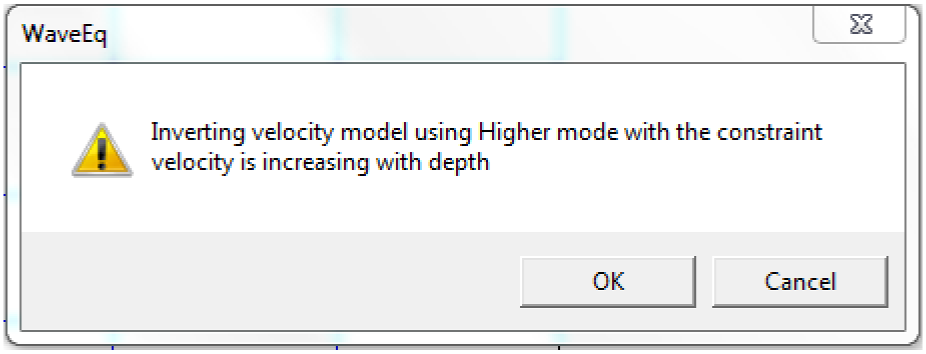




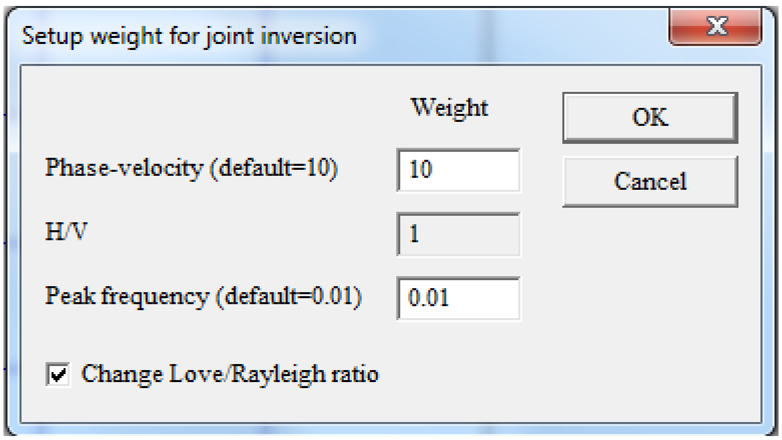


The procedure of inversion is the exactly same as the inversion using a fundamental mode.

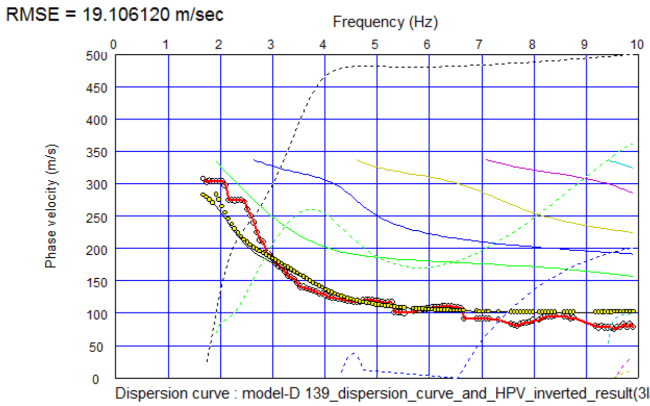
Make sure it uses higher modes in a dialog box shown below.

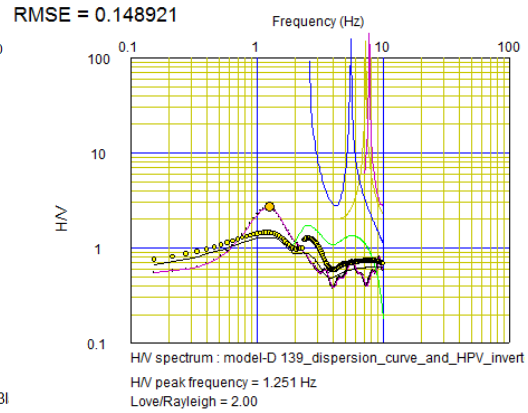


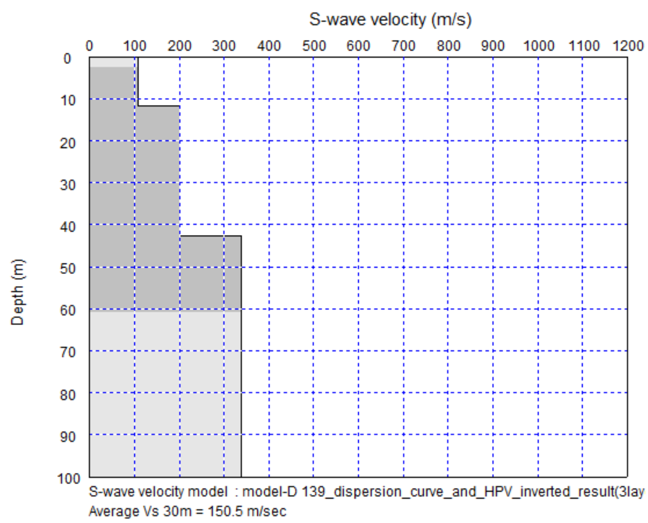
You can change Love/Rayleigh ratio automatically during the inversion.



An example of inverted result is shown below. Error between observed and theoretical phase velocities is smaller than the initial model (model D).

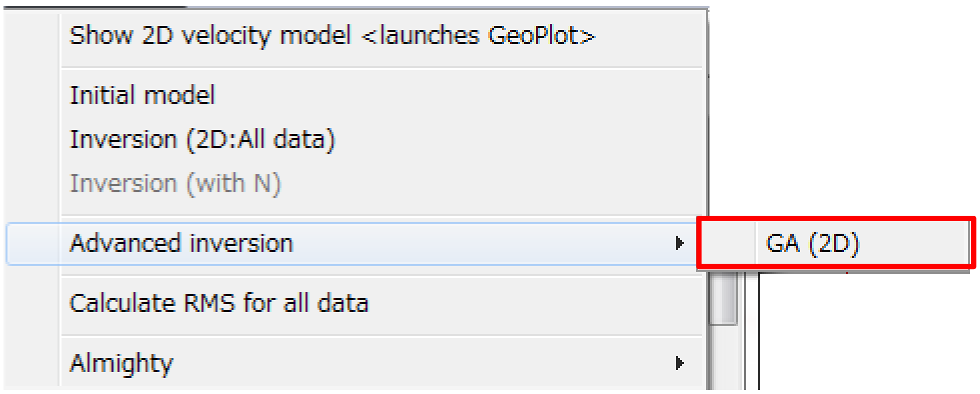




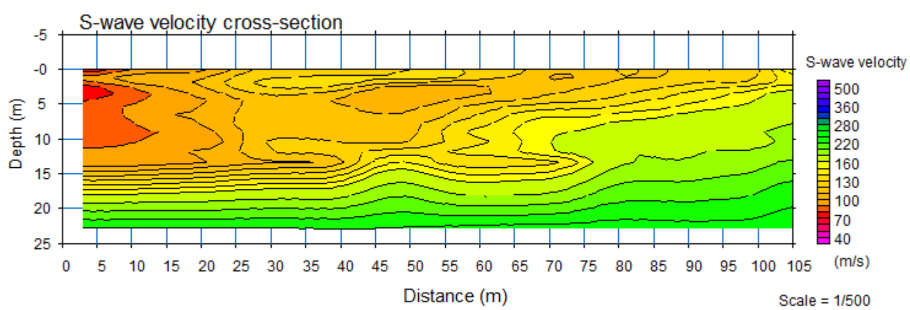


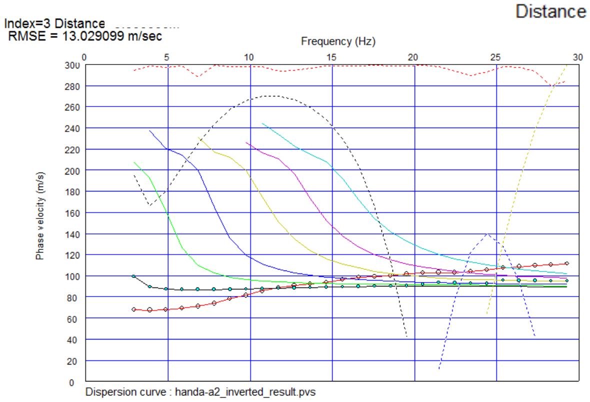
3.4 MASW (2D) Menu

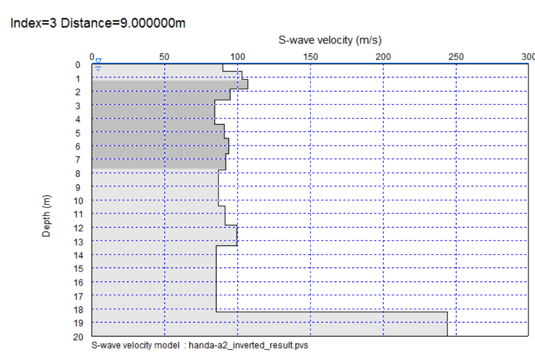
Select *GA (2D)* to apply the inversion using Genetic Algorithm (GA) to two-dimensional data.



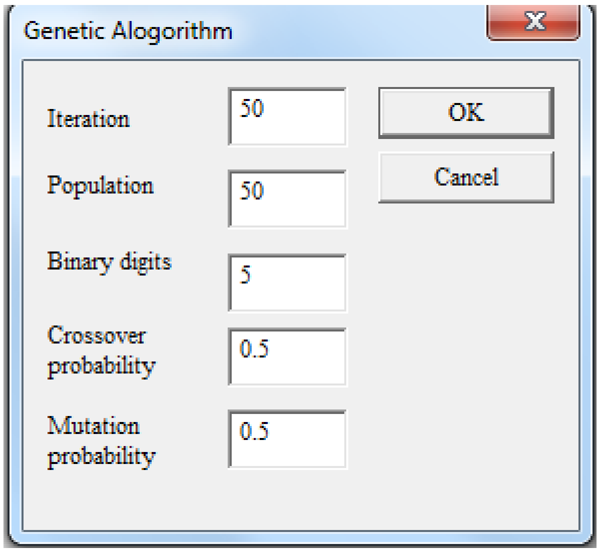
A 2D velocity section of the initial model, example of 1D dispersion curve and velocity model are shown below.



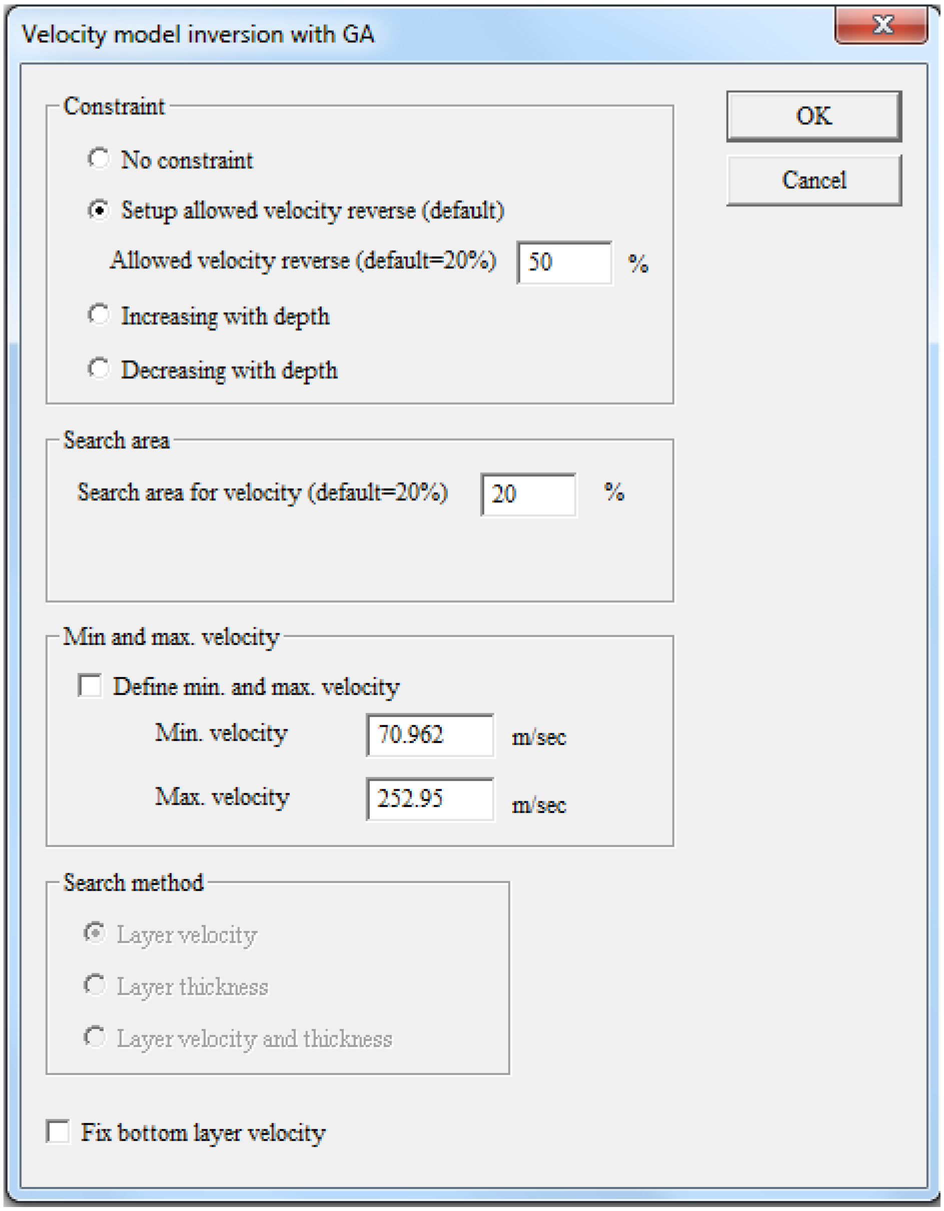




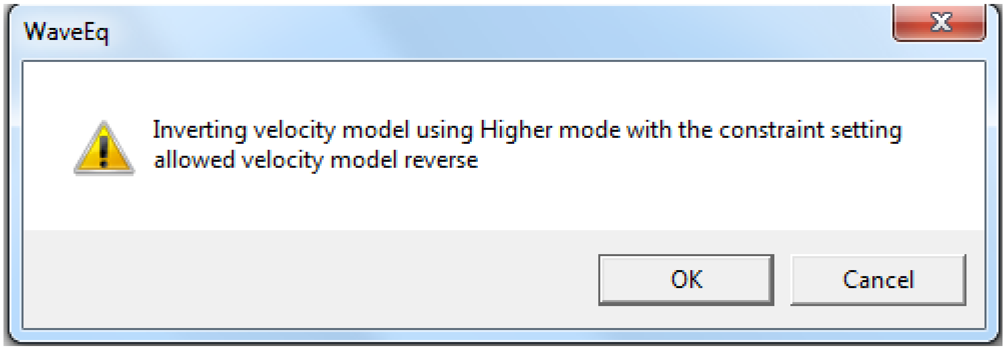
Set the parameters for the Genetic Algorithm. The default values (Iteration=50, Popuration=50, Binary digits=5, Crossover probability=0.5, Mutation probability=0.5) are suitable for most cases. Click the *OK* button to proceed.



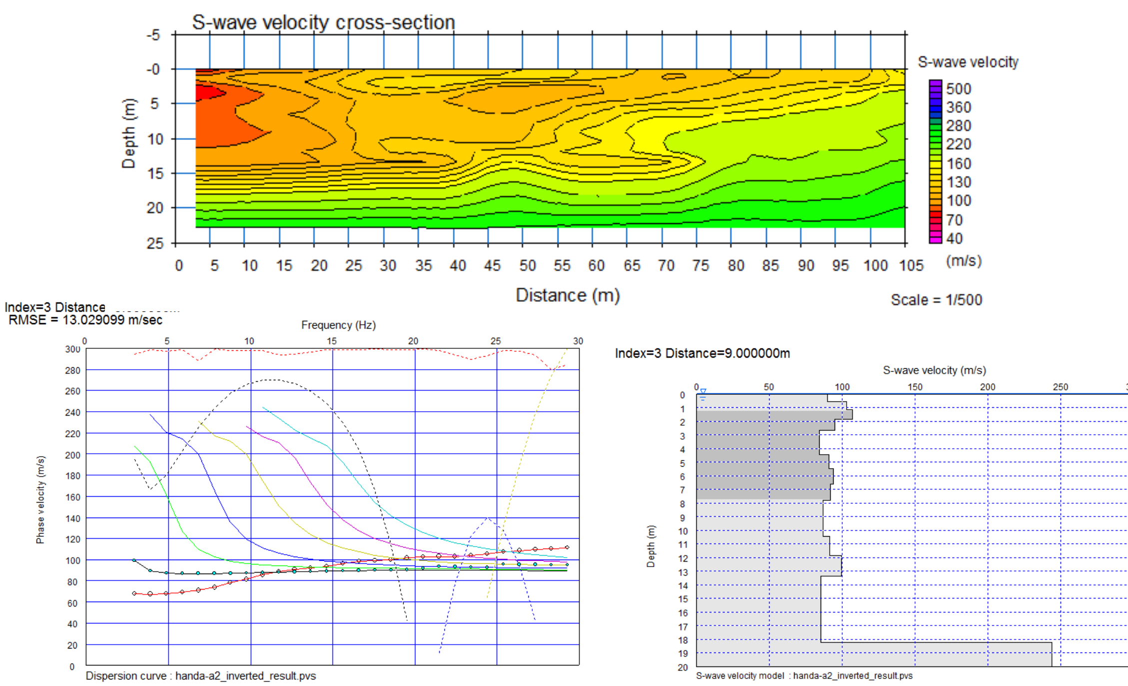
Set the parameter for constraint. Change the parameters depending on site conditions. Click the *OK* button to proceed.



Make sure it uses higher modes in the pop-up dialog box.



An example of inverted result is shown below. Error between observed and theoretical phase velocities is smaller than the initial model.



4. Examples

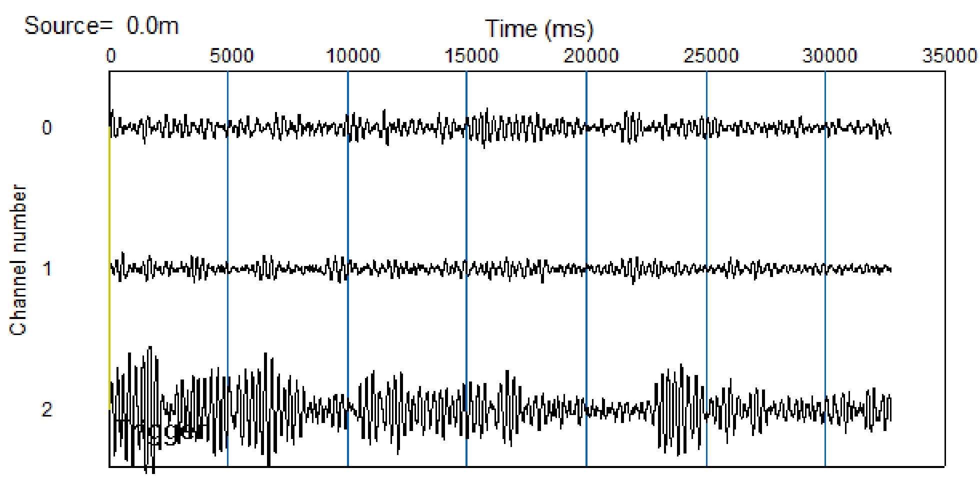
This section shows several data examples and discusses signal quality. Please refer to SeisImager/SW Manual for active/passive surface wave data and dispersion curves.

4.1 Dispersion Curve Data.

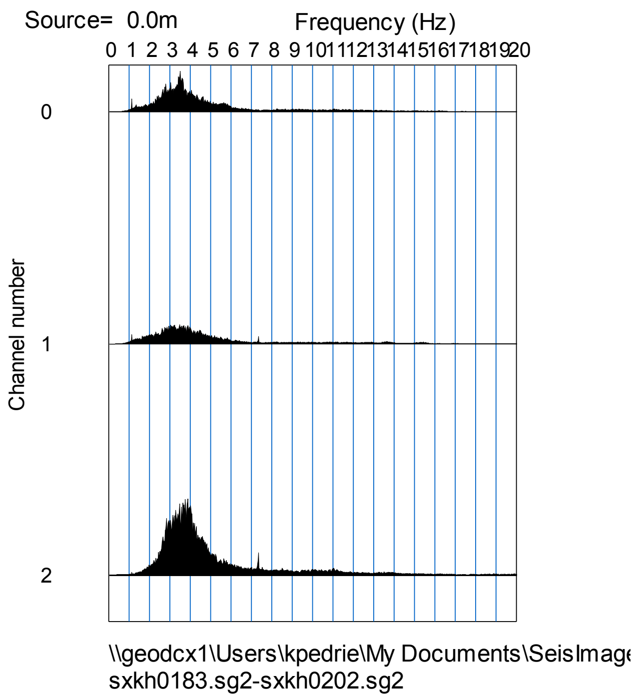
Please refer to Section 8 of the SeisImager/SW manual for examples of active and passive surface wave data. Section 8 contains examples of varying quality data and discussion on how to assess signal quality.

4.2 H/V Data

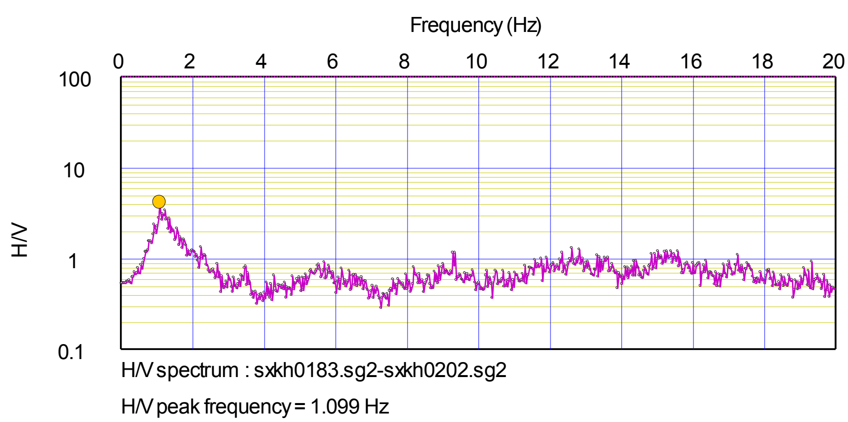
H/V method requires 3-component passive data as seen below. Signal quality is proportional to the trace-to-trace stationarity.



The data are then transformed. The data below are higher quality, as fairly consistent frequency content is observed throughout all channels. Signal quality may be gauged by the amplitude at coherent frequencies.



After the data are transformed, the H/V spectral ratio is calculated. A clear peak frequency is observed in the figure above. High signal quality peak frequency is observed in the Figure below. Low signal quality peak frequencies appear more subtle than the example provided.



5. Appendices

5.1 H/V

5.1.1. Theory

Theory and methods of the Horizontal to Vertical Spectral Ratio Method, or H/V method, are summarized from the USGS publication, “ESTIMATION OF BEDROCK DEPTH USING THE HORIZONTAL-TO-VERTICAL (H/V) AMBIENT-NOISE SEISMIC METHOD” by Lane et al.

H/V method uses passive seismic data to evaluate a site’s resonance frequency. Three component ambient seismic data are collected, and used to calculate the horizontal to vertical spectral ratio. The method has primarily been used for microzonation studies in order to characterize earthquake site response, and also to estimate depth to bedrock.

The theoretical seismic resonance frequency may be estimated for a two-layer model according to the equation below. Where n, Vs, and Z correspond to mode, average shear wave velocity of the upper layer in m/s, and sediment thickness respectively.

$$fn = (2n + 1)(\frac{Vs}{4Z})$$

Nakamura (1989) demonstrated how the fundamental resonance frequency of a site can be approximated from the horizontal to vertical spectral ratio. The horizontal to vertical spectral ratio is calculated as follows.

$$H/V(w) = ((S^2(w)_{NS} + S^2(w)_{EW})/2S^2(w)_V)^{\frac{1}{2}}$$

The method assumes an acoustic impedance contrast equal or greater than 2 between the bedrock and overlying sedimentary layer. Case studies have shown the inability of the method to accurately determine depth to bedrock where this assumption does not hold (Lane et al., 2008). The assumption may not hold if gradational cementation, strong heterogeneity, or deep weathering exists.

Please see the referenced article for further discussion on H/V theory.

6. References

Aki, K., 1957, Space and time spectra of stationary stochastic waves, with special reference to microtremors: Bulletin of the Earthquake Research Institute, 35, 415-456.

Hayashi, K., 2012, Analysis of surface-wave data including higher modes using the Genetic Algorithm, GeoCongress 2012: American Society of Civil Engineers, 2776-2785.

Park, C. B., Miller, R. D., and Xia, J., 1999, Multimodal analysis of high frequency surface waves, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems '99, 115-121.

Suzuki, H., and Yamanaka H., 2010, Joint inversion using earthquake ground motion records and microtremor survey data to S-wave profile of deep sedimentary layers, BUTSURI-TANSA 2010, 65, 215-227 (in Japanese).

Yamanaka, H. and Ishida, J., 1995, Phase velocity inversion using genetic algorithms, Journal of Structural and Construction Engineering 468, 9-17 (in Japanese).

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