

AN INTRODUCTION TO THE SURFACE WAVES PHASE VELOCITY SPECTRA MODULE IN *Grilla*

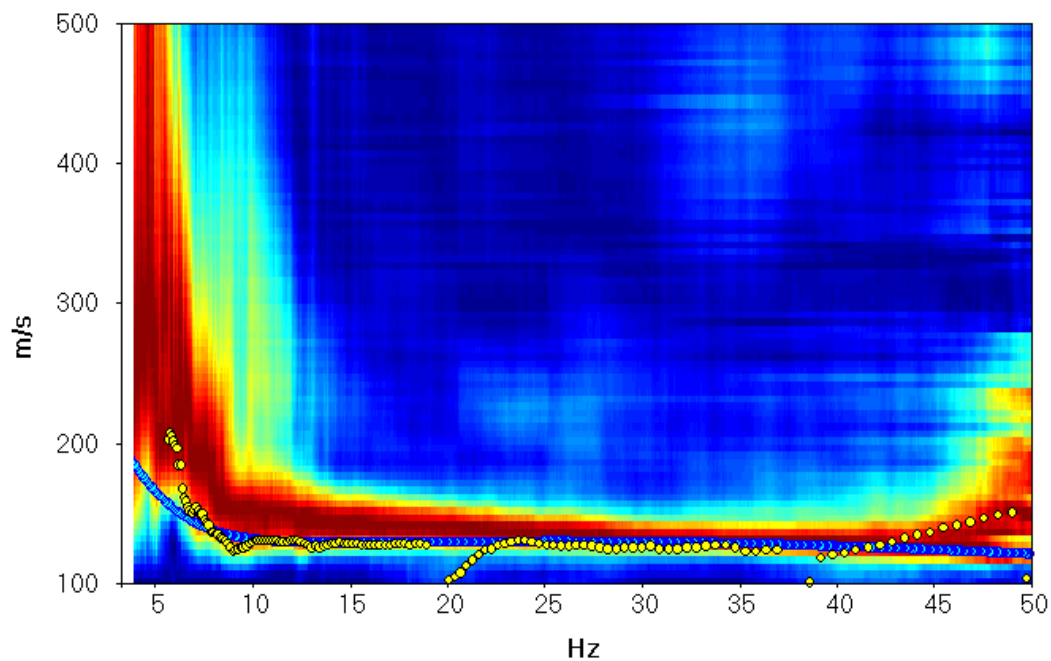


Table of contents

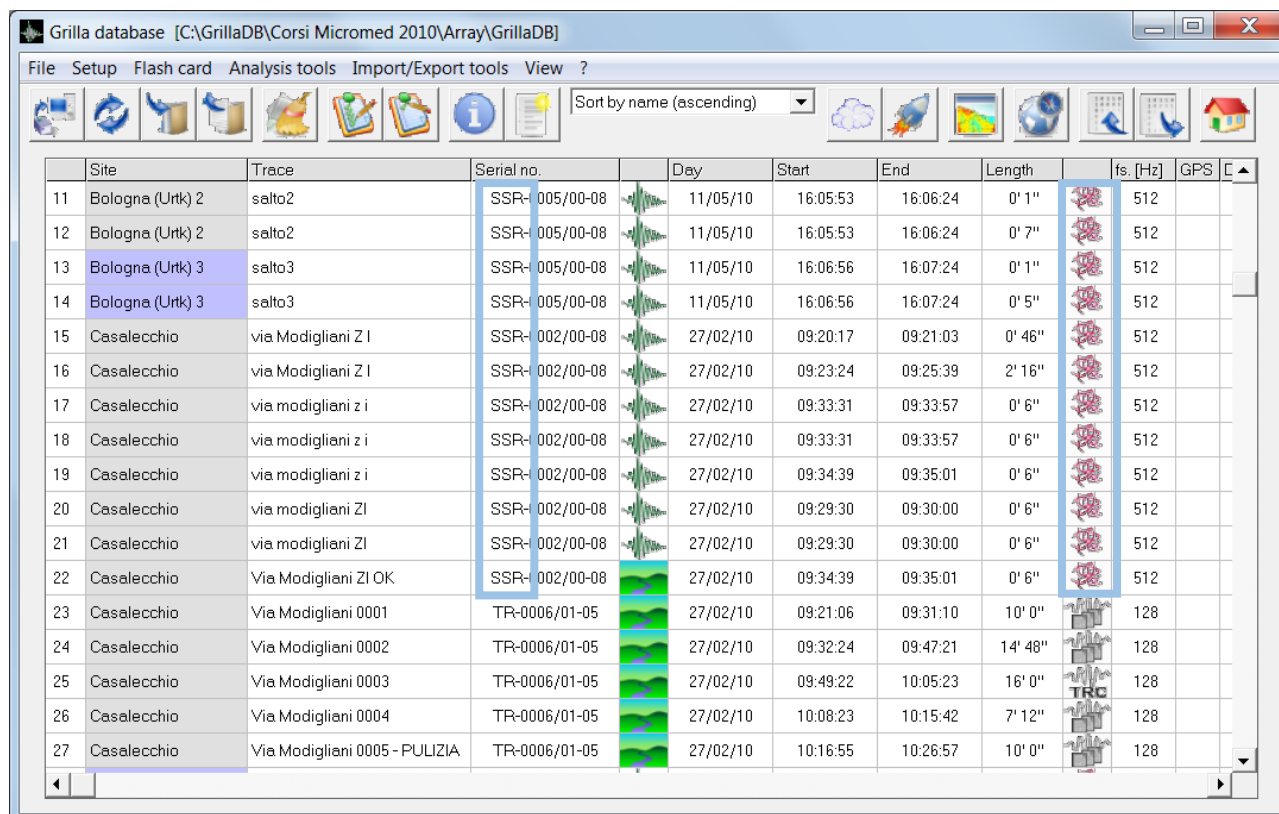
Table of contents	2
Introduction	3
Phase velocity spectra.....	5
Basic principles (passive seismic approach).....	5
Basic principles (active seismic approach).....	6
Recommendations	6
First settings	7
How to produce the phase velocity spectra	10
Joint fit of dispersion and H/V curves	13
Keep your database clean	13
Limits of the model	13
Final recommendations	14
Forward modelling of dispersion curves with Grilla	15
Joint fit of H/V and dispersion curves with <i>Grilla</i>	22

DISCLAIMER. The code described herein is provided on an “as is” basis, without warranty of any kind, to the fullest extent permitted by law. The usage of the code is intended for qualified personnel only, capable to understand the meaning of the input and output data. The code developers and distributors disclaim all warranties, express or implied and will not be liable for any direct, indirect or consequential damages or costs of any type arising out of any action taken by you or others related to the code.

Introduction

Recordings acquired through the multichannel seismic acquisition system SoilSpy produced by MoHo s.r.l. can be stored in the *Grilla* database as TROMINO® recordings, by simply copying them in the *Grilla* database. SoilSpy recordings can be distinguished from TROMINO® recordings for:

- 1) the serial number of SoilSpy, which always starts with “SSR-”,
- 2) the flower icon (blue frames in Figure 1).



	Site	Trace	Serial no.		Day	Start	End	Length		fs. [Hz]	GPS	
11	Bologna (Urtk) 2	salto2	SSR- 005/00-08		11/05/10	16:05:53	16:06:24	0' 1"		512		
12	Bologna (Urtk) 2	salto2	SSR- 005/00-08		11/05/10	16:05:53	16:06:24	0' 7"		512		
13	Bologna (Urtk) 3	salto3	SSR- 005/00-08		11/05/10	16:06:56	16:07:24	0' 1"		512		
14	Bologna (Urtk) 3	salto3	SSR- 005/00-08		11/05/10	16:06:56	16:07:24	0' 5"		512		
15	Casalecchio	via Modigliani Z I	SSR- 002/00-08		27/02/10	09:20:17	09:21:03	0' 46"		512		
16	Casalecchio	via Modigliani Z I	SSR- 002/00-08		27/02/10	09:23:24	09:25:39	2' 16"		512		
17	Casalecchio	via modigliani z i	SSR- 002/00-08		27/02/10	09:33:31	09:33:57	0' 6"		512		
18	Casalecchio	via modigliani z i	SSR- 002/00-08		27/02/10	09:33:31	09:33:57	0' 6"		512		
19	Casalecchio	via modigliani z i	SSR- 002/00-08		27/02/10	09:34:39	09:35:01	0' 6"		512		
20	Casalecchio	via modigliani ZI	SSR- 002/00-08		27/02/10	09:29:30	09:30:00	0' 6"		512		
21	Casalecchio	via modigliani ZI	SSR- 002/00-08		27/02/10	09:29:30	09:30:00	0' 6"		512		
22	Casalecchio	Via Modigliani ZI OK	SSR- 002/00-08		27/02/10	09:34:39	09:35:01	0' 6"		512		
23	Casalecchio	Via Modigliani 0001	TR-0006/01-05		27/02/10	09:21:06	09:31:10	10' 0"		128		
24	Casalecchio	Via Modigliani 0002	TR-0006/01-05		27/02/10	09:32:24	09:47:21	14' 48"		128		
25	Casalecchio	Via Modigliani 0003	TR-0006/01-05		27/02/10	09:49:22	10:05:23	16' 0"		128		
26	Casalecchio	Via Modigliani 0004	TR-0006/01-05		27/02/10	10:08:23	10:15:42	7' 12"		128		
27	Casalecchio	Via Modigliani 0005 - PULIZIA	TR-0006/01-05		27/02/10	10:16:55	10:26:57	10' 0"		128		

3

Figure 1. Recordings of the multichannel digital seismic acquisition system SoilSpy are stored in the *Grilla* database as TROMINO® recordings and are distinguished from the latter by 1) the serial number of the instrument (SoilSpy always starts with “SSR-”) and the flower icon (blue frames in figure).

To view a SoilSpy recording, double-click the item you are interested in and you will be forwarded to the trace window. In Figure 2 and Figure 3 examples of passive and active 16 channels and 24 channels recordings are given.

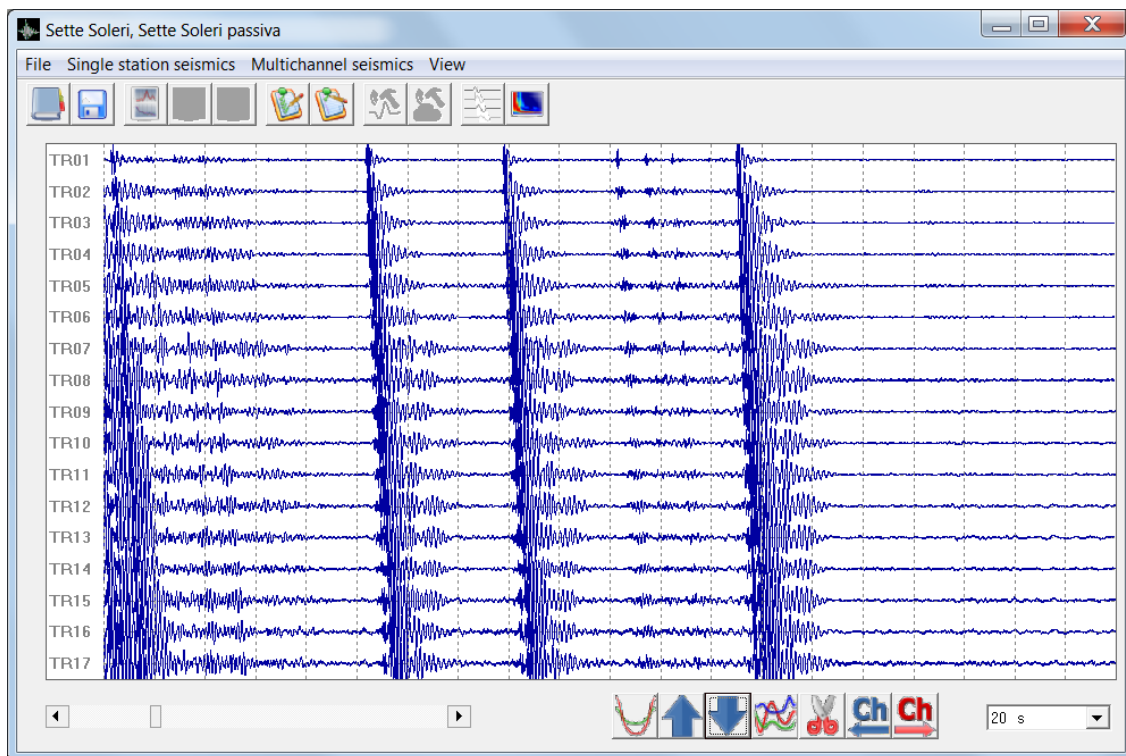


Figure 2. Example of passive recording.

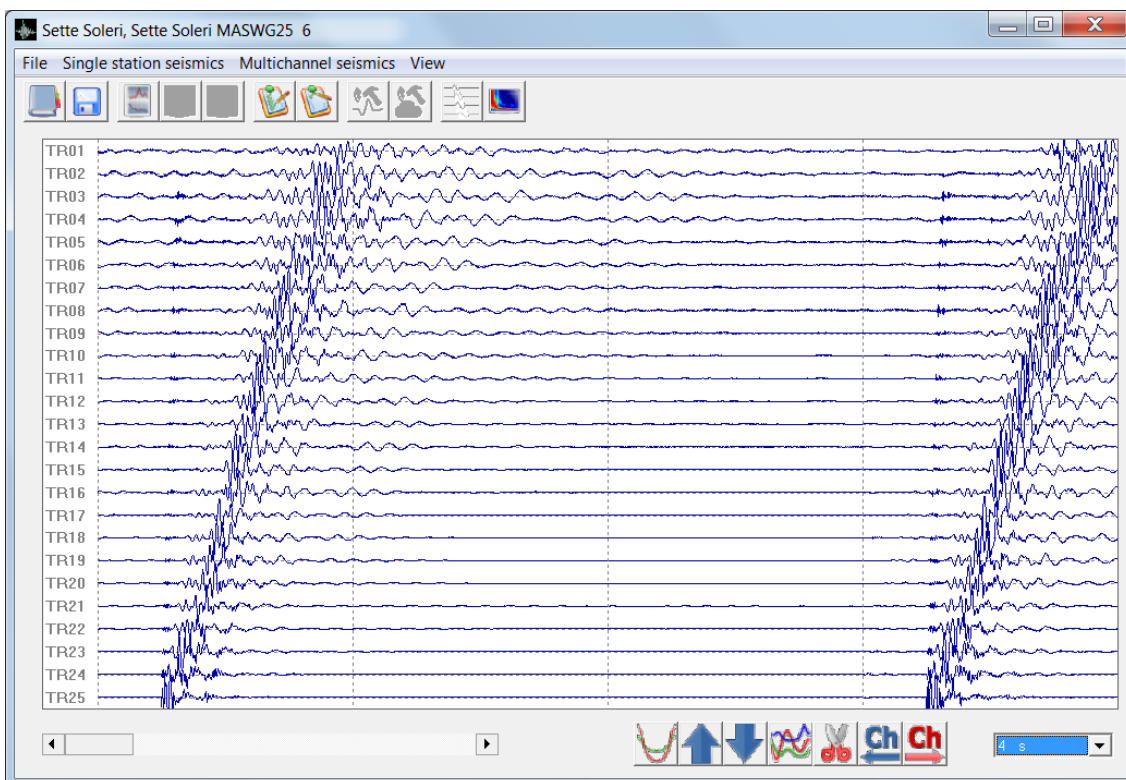


Figure 3. Example of active recording (2 shots).

Phase velocity spectra

Basic principles (passive seismic approach)

In 1D passive seismic surveys (e.g., ReMi™, passive MASW) it is highly recommended that you produce and inspect *several* phase velocity spectra before deciding how to operate the fit with the synthetic model.

Seismic arrays are antennas that, according to their specific geometry, are tuned to a fixed set of frequencies and source azimuth. The statistical definition of sources in a seismic noise wavefield produces wavetrains with fluctuating composition and azimuth, which, on a fixed array, results in a picture unstable in time. This is clear in Figure 4, where the frequency-velocity analysis of 4 consecutive 10 s windows recorded by the same array at the same site gives 4 completely different images.

Panel A) shows a dispersion curve where the fundamental mode is visible. Panel B) shows a dispersion curve where only a higher mode (or an apparent velocity if the wavefront is not parallel to the array) is visible. Panel C) shows a dispersion curve where several fragments of several modes are visible. Panel D) does not show any clear dispersion curve. Obviously, if noise were recorded only at the time of panel B), the dispersion curve inverted for the fundamental Rayleigh mode would give a Vs profile a factor of 2 larger than real.

In practice, tremor must be recorded for several minutes and at least some tens dispersion curves should be calculated on different time-windows in order to understand the modal pattern of the dispersion curve. Dispersion curves may vary so largely in time that 'blind' averaging may result in an inconsistent variety of pictures depending on the details of the averages.

Grilla can produce several phase velocity spectra from a SoilSpy recording. If you sampled noise for a few minutes along the array, you can produce a phase velocity spectrum for each N seconds window, where N is selected by the user ("Win. Length" parameter in Figure 6).

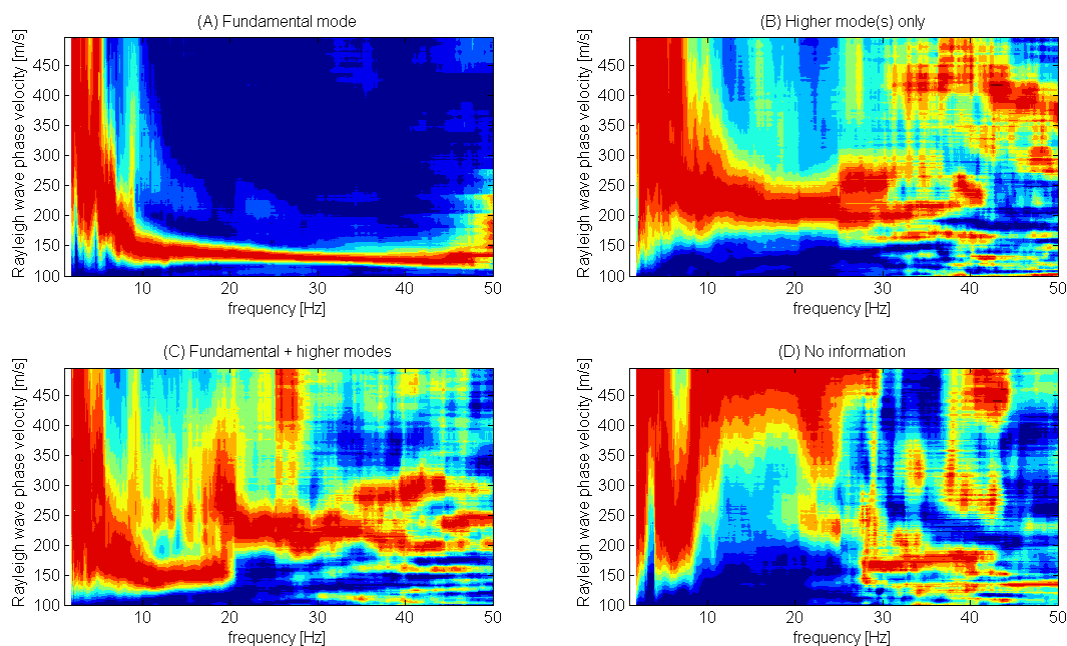


Figure 4. Example of phase velocity spectra obtained exactly at the same site, by the same array, at different times. Only different signal sources may be responsible for the different observed dispersion curves. Each image is produced

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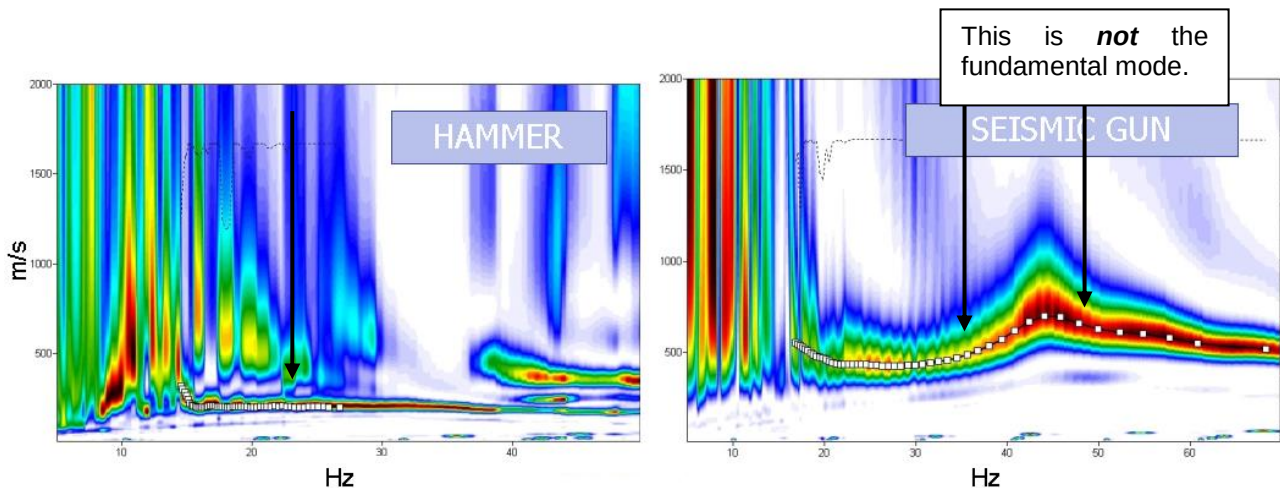
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using 10 s time-windows. A) fundamental mode only; B) higher mode(s) (or apparent velocities) only; C) fundamental + higher mode(s); D) no clear dispersion curve.

Basic principles (active seismic approach)

Understanding the modal pattern of dispersion curves is essential also in active seismic prospection (e.g. active MASW). For a number of reasons linked to the source spectrum, the stratigraphy and the array geometry, higher modes are commonly observed and they are sometimes so powerful that the fundamental mode cannot (or can hardly) be recognized.

It also happens that different seismic sources show different energy distribution among modes. This is illustrated in Figure 5, where a seismic hammer and a seismic gun produced two different surface wave velocity spectra and the picking shown in the second case does not follow the dispersion curve fundamental mode.



6

Figure 5. Example of phase velocity spectra obtained exactly at the same site, from the same array, using two different sources (seismic hammer and seismic gun). The energy content of the different modes is completely different. The dispersion curve picking on the right does not follow the fundamental mode.

Recommendations

In light of the above observations, we recommend to sample:

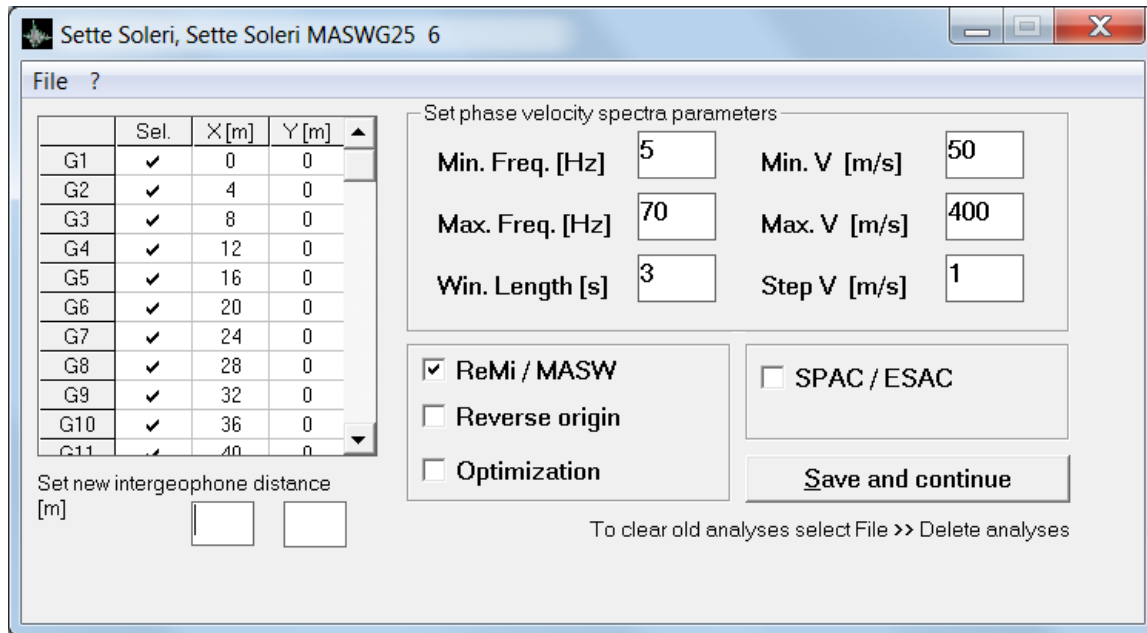
- 1) passive signal for a few minutes and
- 2) active signal (a jump on the ground on one end of a linear array is a reasonable vertical point source and you can avoid bringing seismic hammers or guns) for a few seconds

and to analyse all the phase velocity spectra (passive and active) before deciding how to fit the dispersion curves.

First settings

To produce a phase velocity spectra click the *Open dispersion curve module* button  from the trace toolbar, or select MULTICHANNEL SEISMICS > SURFACE WAVES > DISPERSION CURVES from the menu (Figure 2, Figure 3).

The parameter setting window (Figure 6) will open.



Sette Soleri, Sette Soleri MASWG25 6

File ?

	Sel.	X [m]	Y [m]
G1	✓	0	0
G2	✓	4	0
G3	✓	8	0
G4	✓	12	0
G5	✓	16	0
G6	✓	20	0
G7	✓	24	0
G8	✓	28	0
G9	✓	32	0
G10	✓	36	0
G11	✓	40	0

Set new intergeophone distance [m]

Set phase velocity spectra parameters

Min. Freq. [Hz] Min. V [m/s]

Max. Freq. [Hz] Max. V [m/s]

Win. Length [s] Step V [m/s]

☒ ReMi / MASW ☐ SPAC / ESAC

☐ Reverse origin

☐ Optimization

Save and continue

To clear old analyses select File >> Delete analyses

Figure 6. Parameter setting window for a 1D array.

In this window, you need to specify:

- 1) THE ACTIVE CHANNELS. To select all channels click the SEL. column header. To exclude/include channels, click the relative line.
- 2) THE ARRAY GEOMETRY (X [m] AND Y [m] COLUMNS). Values are distances from the first geophone (G1) of the array and must therefore be increasing in a linear array. These values are automatically read in the SoilSpy file header. Should they be incorrect, you can enter new values in the single cells.

As an example, let us consider a 16-channel 2D array deployed as in Figure 7, with 12 geophones set at 3 m interdistance on the long leg and 4 geophones at the same interdistance on the short leg. The corresponding geometry (X, Y) values to enter in *Grilla* are shown in Figure 8. To consider only the 12 channels of the long leg (geophones 1 to 12) in the analysis, uncheck geophones from 13 to 16, as shown in Figure 8. The first geophone is always number 1 (the closest to the acquisition PC) and all geophones up to the number specified will be considered in sequential order¹.

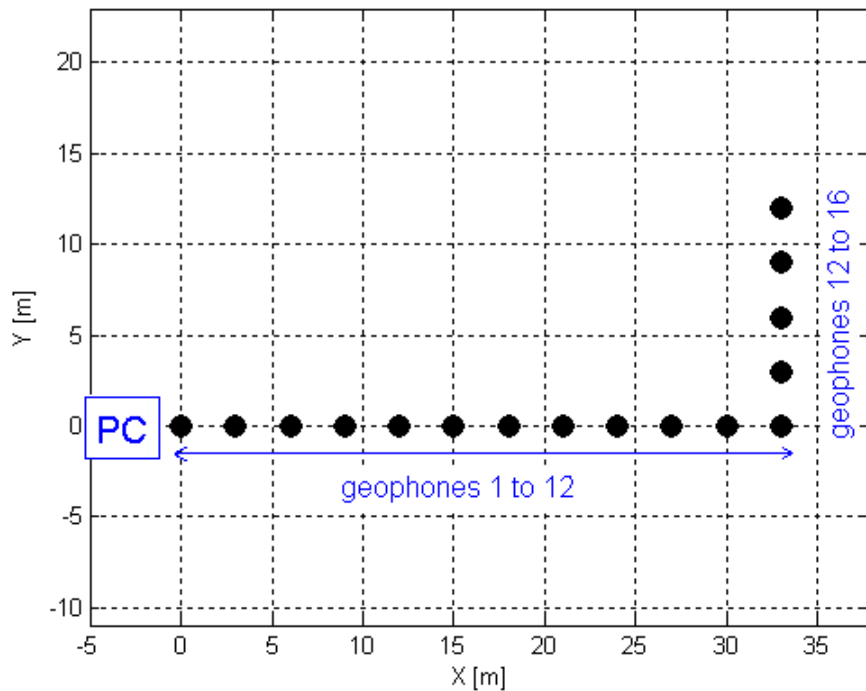


Figure 7. Array geometry specified in Figure 8.

File ?

	Sel.	X [m]	Y [m]
G7	✓	18.0	0
G8	✓	21.0	0
G9	✓	24.0	0
G10	✓	27.0	0
G11	✓	30.0	0
G12	✓	33.0	0
G13		33	3
G14		33	6
G15		33	9
G16		33	12
G17		33	15

Set new intergeophone distance [m]:

Set phase velocity spectra parameters

Min. Freq. [Hz]: Min. V [m/s]:

Max. Freq. [Hz]: Max. V [m/s]:

Win. Length [s]: Step V [m/s]:

☒ ReMi / MASW ☐ SPAC / ESAC

☐ Reverse origin

☐ Optimization

Save and continue

To clear old analyses select File >> Delete analyses

Figure 8. Array geometry for the deployment of Figure 7.

- 3) THE PARAMETERS FOR THE PHASE VELOCITY SPECTRA. These are the parameters to set in the frame *Set phase velocity spectra parameters*:
- MIN. FREQ. [Hz] is the lower bound frequency of computation of the phase velocity spectra (e.g., 1 Hz in Figure 8),
 - MAX. FREQ. [Hz] is the higher bound frequency of computation of the phase velocity spectra (e.g., 80 Hz in Figure 8),

- MIN. VEL. [m/s] is the lower bound velocity of computation of the phase velocity spectra (e.g., 100 m/s in Figure 8),
- MAX. VEL. [m/s] is the higher bound frequency of computation of phase velocity spectra (e.g., 500 m/s in Figure 8),
- STEP V. [m/s] is the Vs step of computation of the phase velocity spectra (this means that spectra will be computed from MIN. VEL. to MAX. VEL., step STEP V.) (e.g., 2 m/s in Figure 8),
- WIN. LENGTH [s] is the length in seconds of the windows on which the phase velocity spectra will be calculated. Example: if you set WIN. LENGTH. [s] = 10 and your recording lasted 5 minutes, you will get 30 phase velocity spectra.

To refine the analysis by selecting only a part of the recorded signal, click the button



from the toolbar of the trace window (or click MULTICHANNEL SEISMICS > SURFACE WAVES > SELECT AREA) and set the 4 vertices of the polygon to analyse. Click the keyboard key 1 and click on the trace window to set vertex 1 (top-left). Click the keyboard key 2 and click on the trace window to set vertex 2 (bottom-left). Click the keyboard key 3 and click on the trace window to set vertex 3 (bottom-right). Click the keyboard key 4 and click on the trace window to set vertex 4 (top-right). The dispersion analysis of surface waves will be performed only inside the selected polygon. This operation can improve the results, e.g. by removing the body wave (near field) contribution from the recorded signal or by cleaning noise.

9

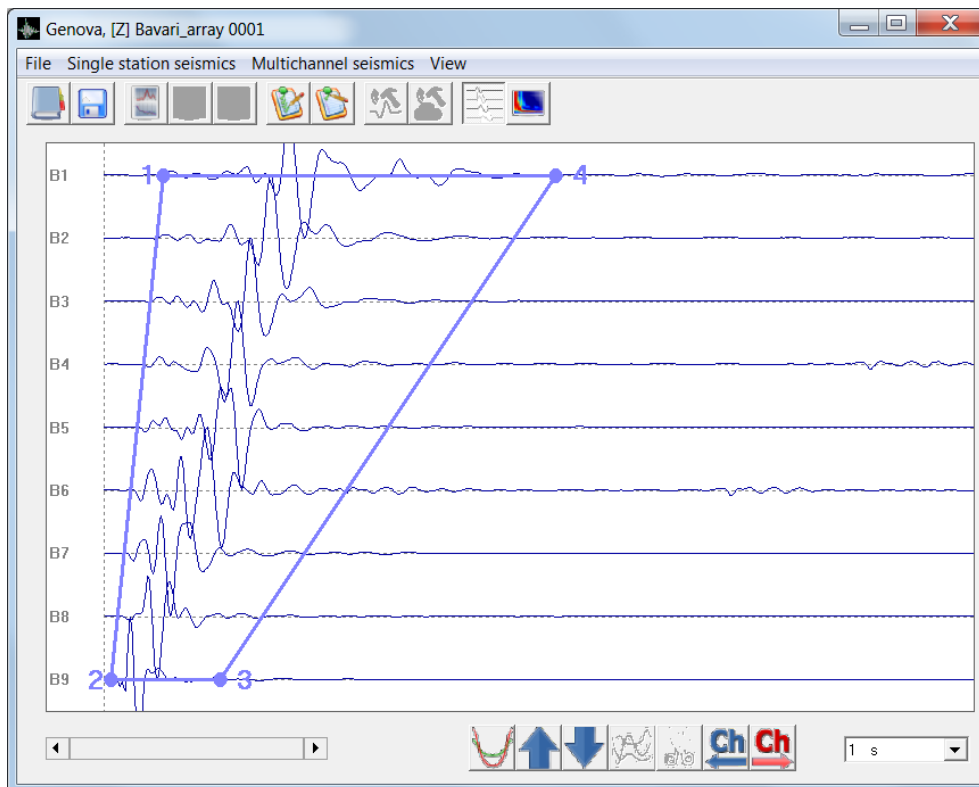




Figure 9. To analyse a defined part of the recording, click the button  and set the 4 vertices of the polygon by clicking the key 1 (to set vertex 1), 2 (to set vertex 2), 3 (to set vertex 3) and 4 (to set vertex 4). Respect the order: top-left is vertex 1, bottom-left is vertex 2, bottom-right is vertex 3 and top-right is vertex 4.

- 4) REVERSE ORIGIN, this option should be enabled when the seismic source is located at the end of the array. This applies also to passive seismic prospection, where the source location is not known. In the passive seismic approach, you should first inspect all the velocity spectra without enabling this option and second inspect all the velocity spectra enabling this option.
- 5) REMI/MASW, enable this option to produce phase velocity spectra from passive/active 1D linear arrays,
- 6) SPAC/ESAC, enable this option to produce dispersion curves from 2D passive acquisitions,
- 7) OPTIMIZATION, this option is meant to optimize the phase velocity spectra from deployments with small numbers of sensors.

When you are done with the settings, click *Save and continue* to proceed.

How to produce the phase velocity spectra

On the phase velocity spectra window (Figure 12) you will find the following commands:



ALL WINDOWS. By clicking this button, *Grilla* starts computing the phase velocity spectra¹⁰ for all N second length windows specified by the user in the WIN. LENGTH field of the parameter window (Figure 6). Example: if you set WIN. LENGTH. [s] = 10 and your recording lasted 5 minutes, you will obtain 30 phase velocity spectra. All spectra are saved in the same folder of the .trc recording² under a subfolder named N SEC, where N is the window length in seconds as specified above.

When the REVERSE ORIGIN option is selected, phase velocity spectra are saved in the same folder of the .trc recording² under a subfolder named N SEC R, where N is the window length in seconds as specified above and R indicates REVERSE ORIGIN.

You can inspect all the velocity spectra figures produced by *Grilla* by using the Windows[®] resource manager PREVIEW tool (Figure 13).



This command computes a single-phase velocity spectrum among those available. Example: if you set WIN. LENGTH [s] = 10 and your recording lasted 5 minutes, you will obtain 30 phase velocity spectra. If you select WIN. 6, the seconds [50, 60[of your recording will be used to produce the phase velocity spectrum.



This command allows to compute the phase velocity spectra on a selection of windows chosen by the user. Select those to retain in the analysis, which will be averaged (AVG). The selection is performed by ticking the corresponding check boxes in the SELECTION

² See VIEW TRACE PROPERTY in *Grilla* help for the path of the database folders.

WINDOW form (Figure 10).

Use FILE > (DE)SELECT ALL to select/deselect all windows.

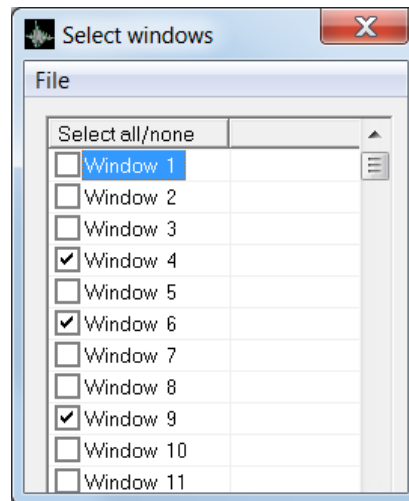


Figure 10. Select windows form.



This button enables the surface wave modelling tool. Please refer to the *Grilla* SINGLE STATION (TROMINO) > SYNTHETIC H/V MODULE or to the tutorials at the end of this document for instruction on how to fill the subsoil model table.

The synthetic dispersion curve can be produced both for Rayleigh and Love waves. If you acquired the signal by using vertical geophones, then set the Rayleigh wave option from the right frame in Figure 13. If you acquired the signal by using horizontal geophones, set parallel to an SH wave source, then set the Love wave option from the right frame in Figure 13.

To adjust the parameters of the synthetic curves, click SYNTHETIC MODEL > SETTINGS from the subsoil model window (Figure 11). Here you can set the frequency interval for the synthetic curves, the frequency step to compute and plot the synthetic curves and the number of modes to show (fundamental and higher modes).

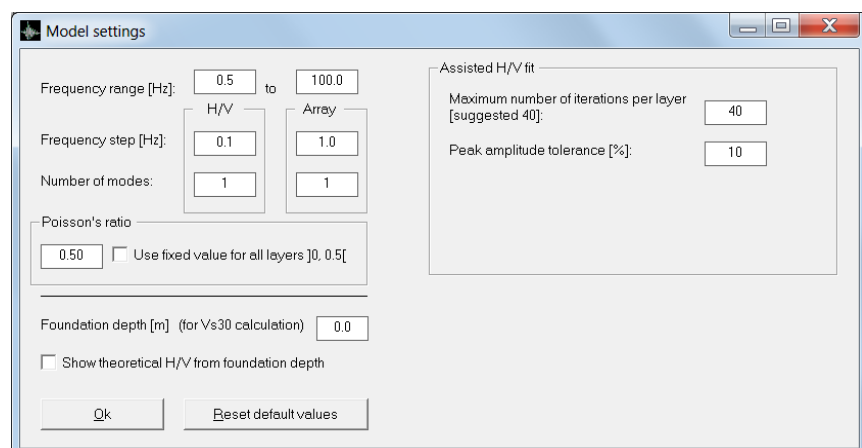


Figure 11. Model settings window.



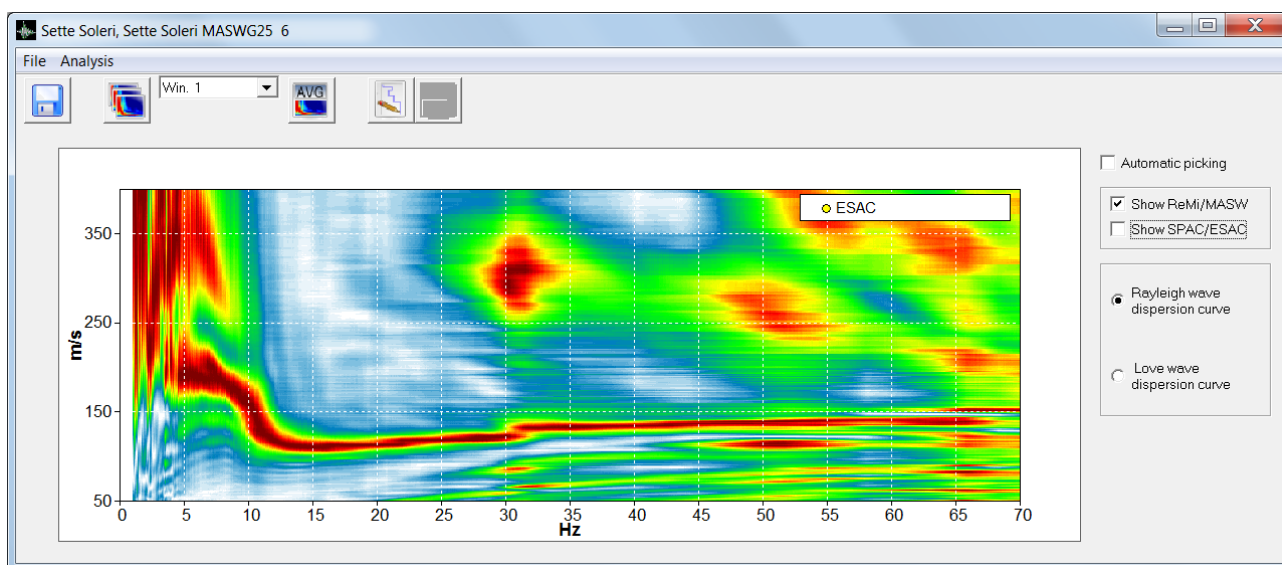
Click SAVE to save the phase velocity spectrum (and/or the synthetic curves) displayed on the screen.



Select/deselect the check boxes to show/hide the phase velocity spectra (ReMi™, MASW) and/or the SPAC/ESAC dispersion curves.

ANALYSIS >
CREATE REPORT

Compiles an automatic report in MS Word® compatible format.



12

Figure 12. The surface wave phase velocity spectra window.

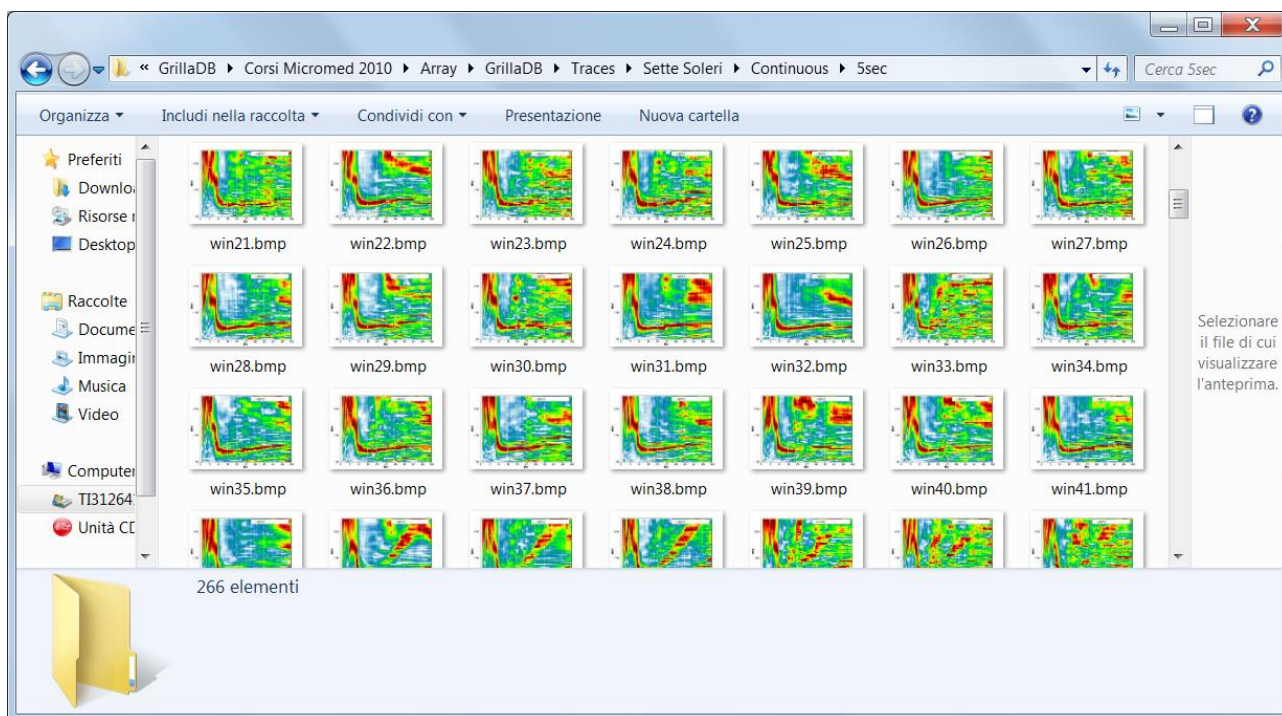
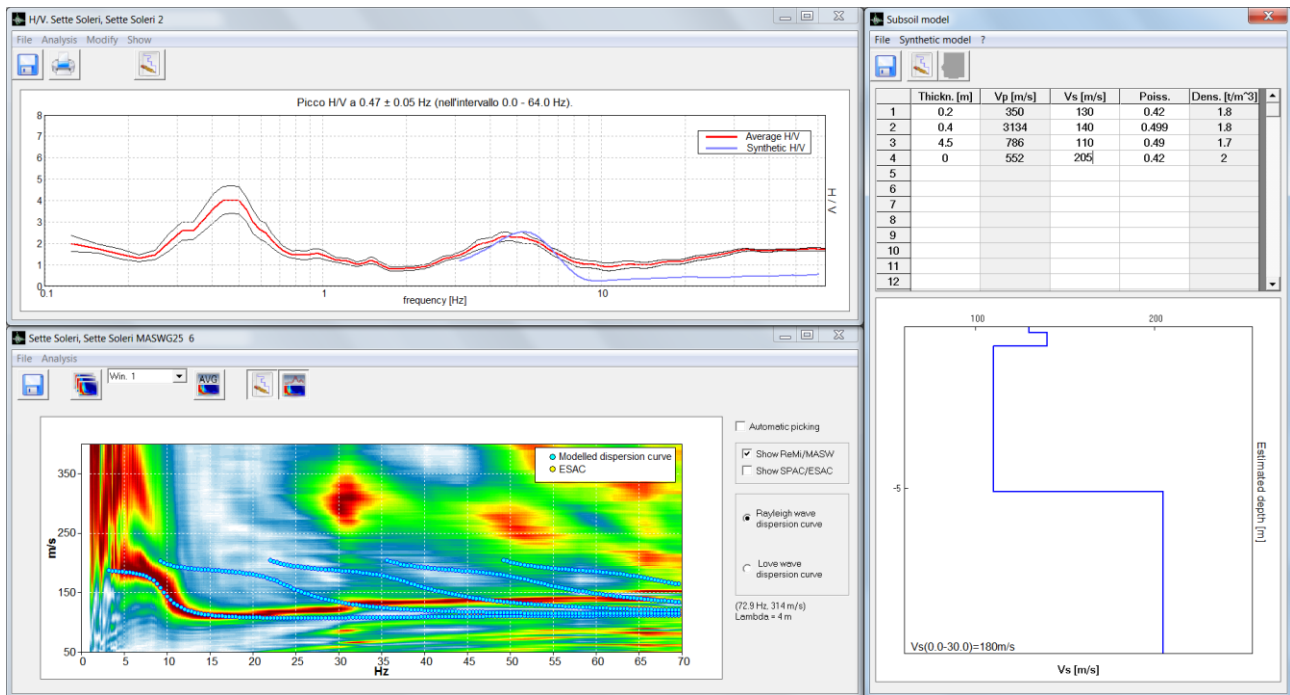


Figure 13. Use the Windows® resource manager PREVIEW tool to inspect all the velocity spectra available for the site.

Joint fit of dispersion and H/V curves



This button allows viewing synthetic dispersion curves and synthetic H/V curves for the same subsoil model. You will be asked to load a single *existent* H/V curve saved in the *Grilla* database and you will be redirected to the set of windows displayed in Figure 14.



13

Figure 14. Example of joint fit of a H/V curve collected with TROMINO® (top left panel) and of the phase velocity spectra collected with SoilSpy (bottom left pane) at the same site. The synthetic curves are displayed in blue and are obtained from the subsoil model shown on the right.

Keep your database clean



To remove the phase velocity spectra figures produced by using the ALL WINDOWS command, select FILE > DELETE ANALYSES from the PARAMETER window (Figure 6). This clears the N SEC and N SEC R folders but does not remove the SoilSpy .trc recording. The latter can only be deleted by using the *ad hoc* functions in the *Grilla* database.

Limits of the model

The synthetic modelling tool introduced in *Grilla* is based on the assumption of plane-parallel layers. In many practical cases, the geologic setting is not so simple, as the comparison between H/V recordings collected at the same time and at short distance can show. An advantage of the H/V technique is that it allows to recognize lateral heterogeneities which could not be resolved from array techniques based on surface waves.

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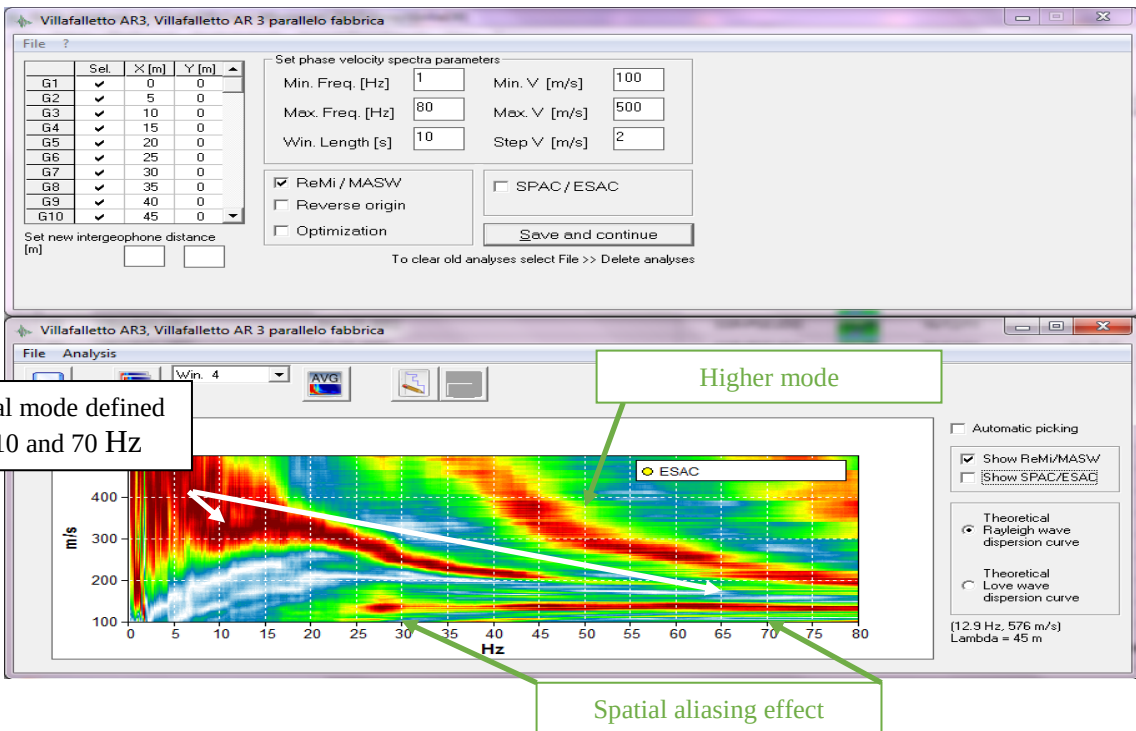
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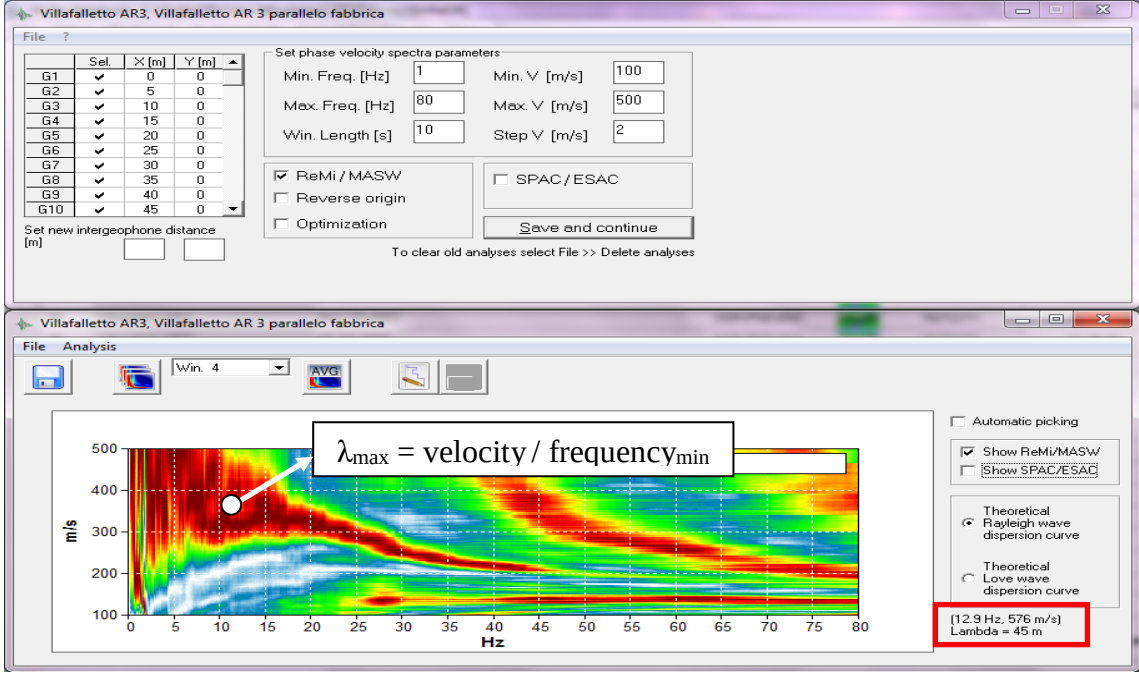
Final recommendations

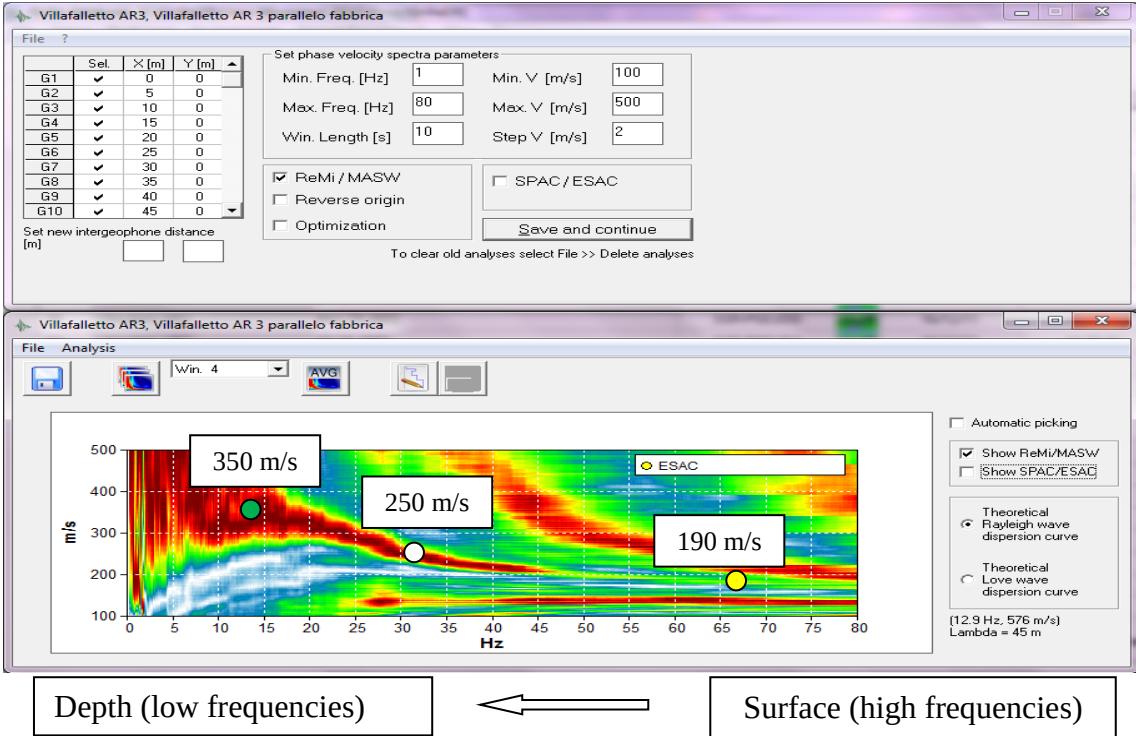
- i. The code described herein is provided on an “as is” basis, without warranty of any kind, to the fullest extent permitted by law. The code developers and distributors disclaim all warranties, express or implied and will not be liable for any direct, indirect or consequential damages or costs of any type arising out of any action taken by you or others related to the code.
- ii. In no case the model can provide V_p and density profiles.
- iii. Particular care should be paid to the recognition of different modes in the phase velocity spectra. This is often a difficult task, for which we address to the specialized literature. A joint H/V – phase velocity spectrum fit could help in these cases.

Forward modelling of dispersion curves with *Grilla*

TUTORIAL VIDEO 01

Timing [mm:ss]	
00:00	In this video we will see how to model a dispersion curve.
00:05	<p>On the screenshot here below we see a diagram called <i>Velocity Phase Spectra of Rayleigh waves</i> (vertical components). In this kind of diagram high energy zones (red) represent the dispersion curves of the fundamental and/or higher modes of Rayleigh waves. In this example, the dispersion curve of the fundamental mode is defined between frequencies of 10 and 70 Hz.</p>  <p>Fundamental mode defined between 10 and 70 Hz</p> <p>Higher mode</p> <p>Spatial aliasing effect</p>
00:46	<p>The white arrows in the previous image delimit the interval where the fundamental mode of the dispersion curve can be recognized. For a specified frequency, high spectral content areas (red color shades) with higher velocity compared to the fundamental mode are usually higher modes. Other curves with high spectral content can be spatial aliasing. These normally show an opposite trend (increasing velocity with increasing frequency) compared to the dispersion curves.</p> <p>It is really important to identify the fundamental mode because numbering the higher modes is a very difficult task: their visibility is highly dependent on the source type, the receiver geometry and the specific ground properties.</p> <p>Among all curves with high spectral content – excluding spatial aliasing – the fundamental mode is the one presenting, for each frequency, the lowest velocity values.</p> <p>In some cases it is possible that the fundamental mode is not visible at all and that only higher modes are visible but let us now assume that we are lucky and that what is displayed between the white arrows in the figure above is the fundamental mode.</p>
01:39	<p>This will be for us the fundamental mode, defined in the interval between 10 and 70 Hz.</p> <p>First of all it is necessary to know what is the maximum and the minimum depth of</p>

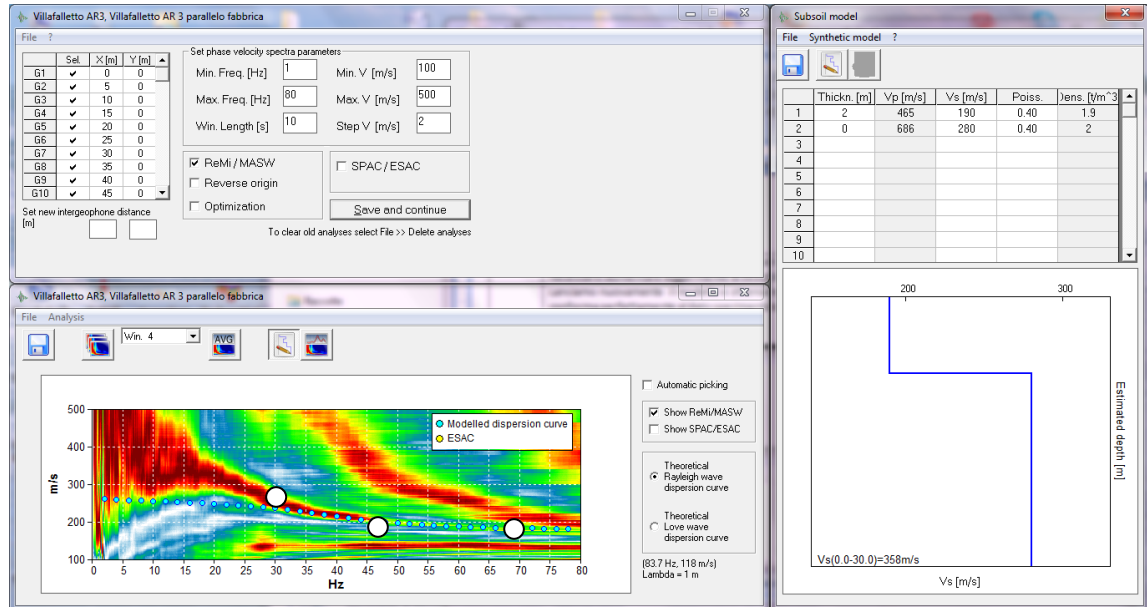
	<p>investigation that has been achieved with the survey. Calculating those values as a first approximation is quite simple.</p> <p>Generally speaking, high frequencies refer to shallow depth, low frequencies refer to larger depths.</p>
02:22	<p>To calculate the maximum depth of investigation it is necessary to define the phase velocity at which the minimum frequency of the dispersion curve is defined.</p> <p>In this case the minimum frequency is approximately 12 Hz and the corresponding velocity is around 350 m/s. By dividing 350 m/s times 12 Hz we obtain: $350 \text{ m/s} / 12 \text{ Hz} \approx 29 \text{ m}$.</p> <p>This is the maximum Rayleigh wavelength λ that can be recognized.</p> 
03:10	<p>By following the curve with the mouse it is possible to read the velocity, frequency and wavelength values at every point (red rectangle on the bottom right of the picture above).</p>
03:35	<p>This is the maximum wavelength of investigation but the maximum wavelength of investigation is not the maximum depth of investigation. Rayleigh waves in fact induce the major part of the ground displacement at a depths between $1/3$ and $1/2$ of their wavelength. It is therefore generally assumed that the velocity at which a Rayleigh wave is moving refers to a depth between $\lambda/3$ and $\lambda/2$.</p> <p>In this case, by dividing the maximum wavelength times 2, we have an estimation (by excess) of the maximum depth of investigation achieved by the survey.</p> $\lambda = \text{wavelength}$ $z = \text{depth}$ $\lambda_{\max} = \text{velocity}_{\max} / \text{frequency}_{\min}$ $z_{\max} = [\lambda / 3, \lambda / 2]$
04:18	<p>The subsoil depth to which a velocity value of a Rayleigh wave with given wavelength λ refers to is approximately included in the $[\lambda/3, \lambda/2]$ range.</p> <p>In this example we can create a subsoil model only down to 15 m depth. No more than 15 m</p>

	<p>because we do not have any information below this level ($\lambda_{\max} = 29 \text{ m}$, $z_{\max} < 29/2 \text{ m}$). We will be able to create a model reaching higher depths only combining the array technique with the H/V technique. This is what we will see in the next example/video.</p>
04:53	<p>To start creating the model let us get an idea about the seismic stratigraphy of the subsoil. By following the fundamental mode from the right to the left, i.e. from surface to depth, we see that we are dealing with a phase velocity of the Rayleigh wave starting from 190 m/s (minimum depth of investigation), increasing up to 250 m/s and then up again to 350 m/s (maximum depth of investigation).</p>  <p>Estimating as a first approximation at what depth the velocity changes, is quite simple: let us move the mouse pointer on the knee (changing point of the slope) of the curve and calculate the corresponding λ. We already know that the reference depth for this velocity value is included between $[\lambda/3, \lambda/2]$.</p> <p>Basically, by observing a dispersion curve the first thing to do is to understand the maximum depth (green circle in the picture) and the minimum depth (yellow circle in the picture) of investigation and the second thing to do is to identify the changing point of the slope (white circle in the picture), that indicate changes in the velocity gradient.</p>
06:37	<p>Now we are ready to start compiling our model. To open the modeling tool, press this icon  in the dispersion curve window.</p> <p>Moving from left to right along the dispersion curve we can notice that the initial velocity is around 190 m/s. Moving the mouse at the first knee (white circle in the picture) we read a wavelength λ of about 4 m. It means that we have less than $\lambda/2$ (less than 2 m) of subsoil with a velocity of 190 m/s.</p> <p>This is our first layer: $V_s \approx 190 \text{ m/s}$, thickness $\approx 2 \text{ m}$.</p>

We fill in the table on the right with these velocity and thickness values and we insert a reasonable density value and Poisson's ratio. The Poisson ratio can be very high when V_s is low and sediments are saturated, because in this case $V_p \approx 1500$ m/s.

In this case let's assume that there is no water and that a Poisson ratio value of 0.4 is

reasonable. To obtain the theoretical dispersion curve, click  in the window of the subsoil model.

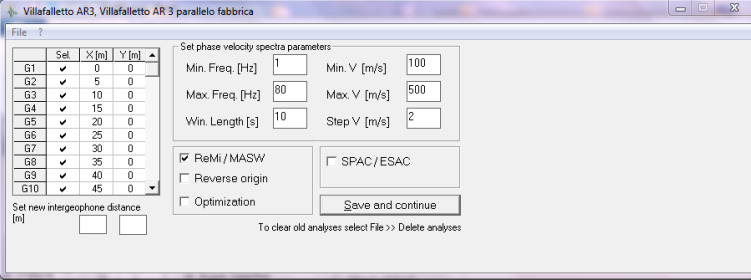
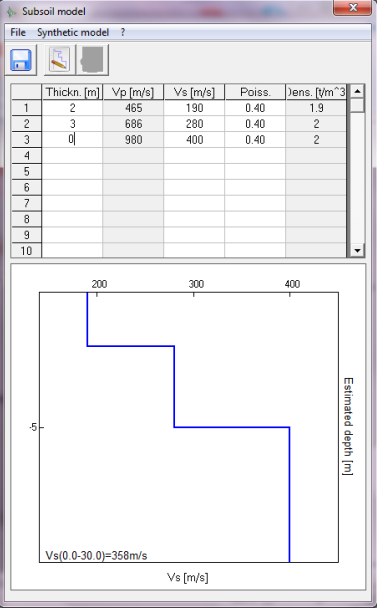


07:38

So far we have observed a first part of the subsoil with a velocity of 190 m/s, then a first slope changing point (knee) where the velocity increase from 190 m/s up to about 280 m/s. The velocity remains unchanged until the following knee (green circle) which occurs at the wavelength $\lambda = 10$ m (that is at a depth $< \lambda/2$, i.e. 5 m, from which we must subtract the 2 m thickness of the first layer, thus getting 3 m).

This is our second layer: $V_s \approx 280$ m/s, thickness ≈ 3 m. To obtain the theoretical dispersion

curve of this model, click  in the subsoil model window.

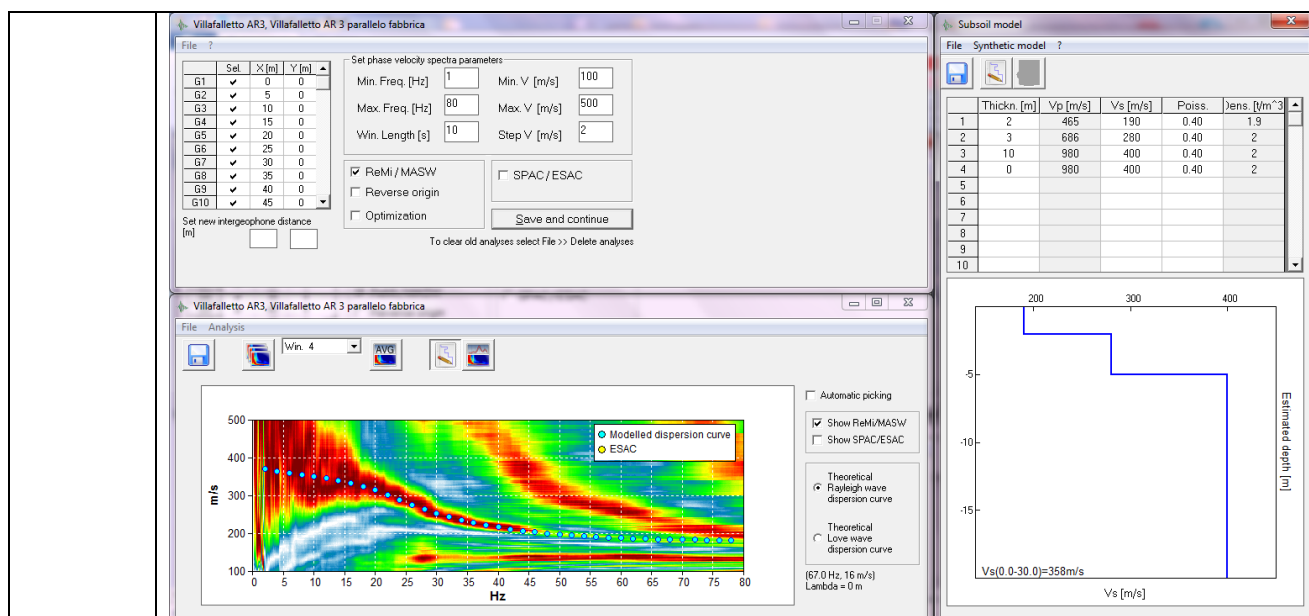



08:35 Finally, we know that our model will end at about 15 m depth, therefore we have the last 10 m subsoil with a velocity increasing again up to at least 350 m/s.
We write the velocity value in the table and to indicate the half-space (last layer) we write 0 (zero) in the thickness cell.
This is our third layer: $V_s \approx 350$ m/s, half-space (leave blank or write zero).
Summing up, we have a 3 layer model. To obtain the theoretical dispersion curve related to this model, click  in the subsoil property table.

We remind that dividing the velocity times the frequency and then again times a number between 2 and 3 is just a rule of thumb to estimate approximately the depth associated to each Rayleigh wave phase velocity value. To solve the problem in a more accurate way, one needs to model the surface wave propagation in multi-layered media, as we just did.
In the example under examination in order to obtain a good fit between the experimental and the theoretical curve it is necessary to increase slightly the velocity of the last layer from 350 to 400 m/s.

This discrepancy in velocities is due to the fact that the phase velocity spectra and the related dispersion curves show the Rayleigh wave phase velocity as a function of frequency while the subsoil model (table on the right in the figure below) accepts as input values the shear wave velocity V_s . Shear waves have velocities 10-15% larger than Rayleigh wave phase velocities (the exact percentage is a function of the Poisson's ratio), therefore it is normal to find in the V_s table values slightly larger than those suggested from the Rayleigh wave dispersion curves.

We run the theoretical model for the last time by clicking  in the subsoil property table and we obtain the theoretical dispersion curve shown below that matches perfectly the experimental data.



10:18

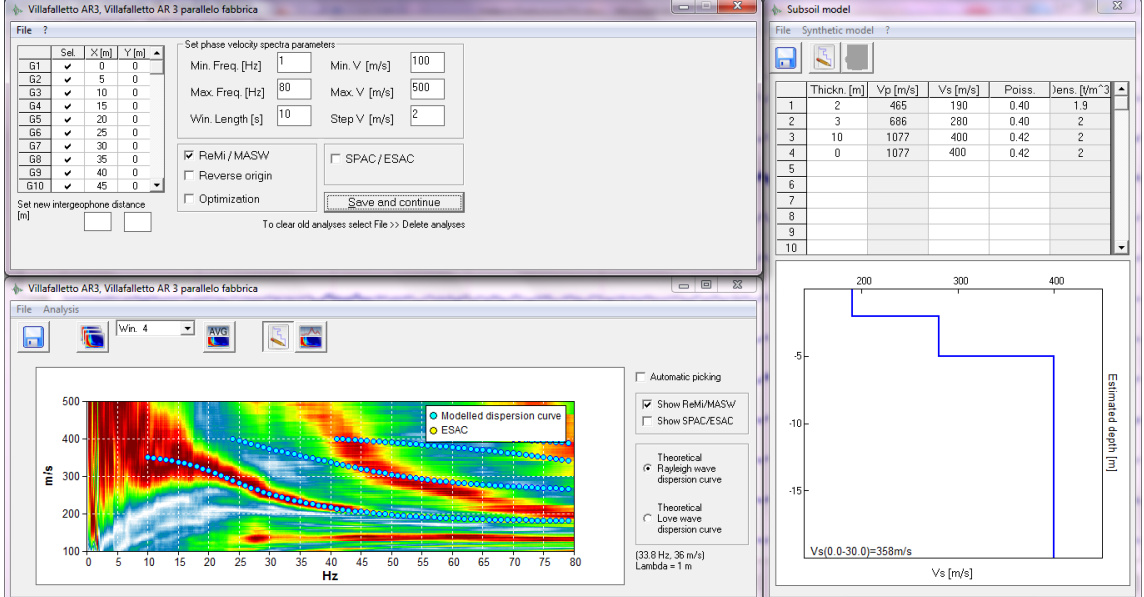
To display the theoretical higher modes click the menu “Synthetic Model”, then “Settings” and write the number of desired modes in the text box labeled “Number of modes”. Then re-launch

the model by always clicking .

Remind that identifying the fundamental mode is crucial and its visibility is strongly dependent on the source used as well as on a number of other parameters.

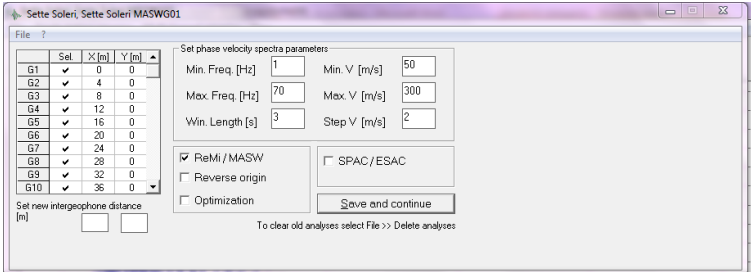
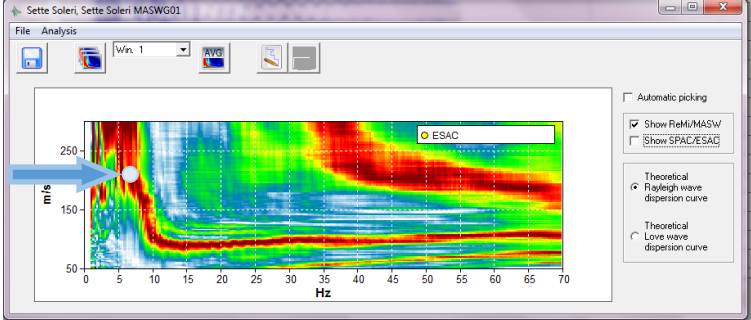
Correctly numbering higher modes is unfortunately an even harder task, therefore it is recommended not to rely exclusively on their interpretation.

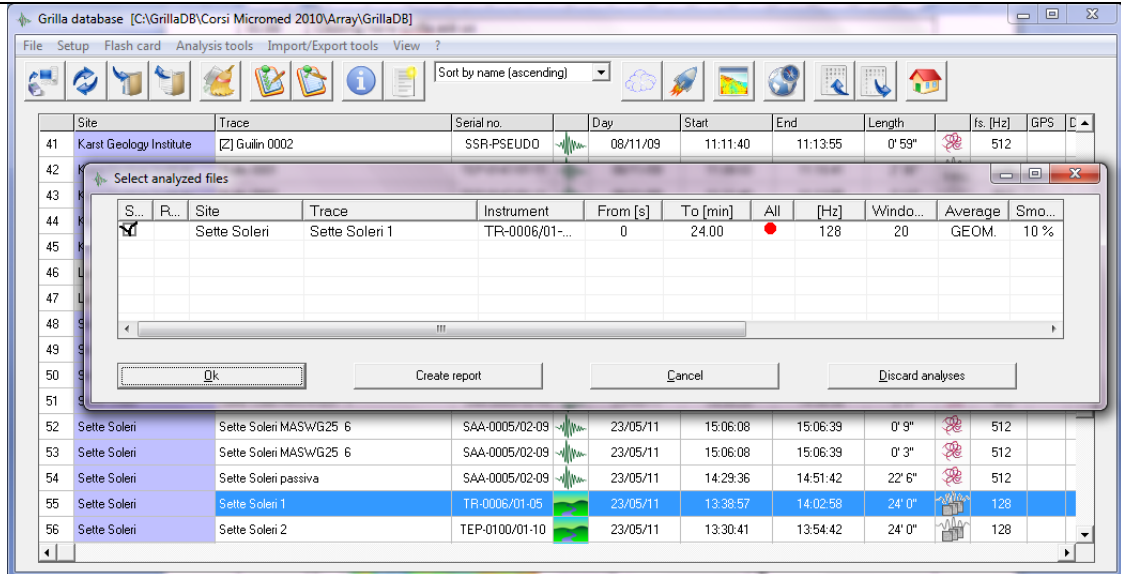
Note: the so called “effective” dispersion curve, which is theoretically capable to describe what mode is dominant in each frequency interval, is based on specific assumptions about the source type (usually an ideal point source with vertical load), which are systematically violated with real sources. Therefore, once more, we recommend to attempt to identify the fundamental model and work on its modeling.

	
11:10	<p>Let us delete the higher modes for the moment.</p> <p>To display less points in the theoretical curves, increase the field “Frequency Step”.</p> <p>To show the theoretical dispersion curves only in the frequency interval in which the dispersion curve is experimentally visible (procedure which is always correct), set the said interval in the “Frequency Range” field from the “Model Settings” window shown above.</p> <p>In the case that we examined, the blue points of the theoretical curve will be traced only from 10 Hz to 80 Hz, which is the only interval in which it makes sense to trace them.</p>
12:00	<p>Concluding: identify the fundamental mode and the slope changing points (knees). Divide the λ corresponding to the first knee times 2 to obtain the approximated maximum thickness of the first layer.</p> <p>Move to the second knee. Divide the corresponding λ times 2 to obtain the approximated maximum thickness of the second layer and so on until the maximum depth obtained from the survey.</p> <p>Adjust the modeling frequency intervals of the theoretical dispersion curve to reproduce only the intervals where there exists a real experimental dispersion curve.</p>

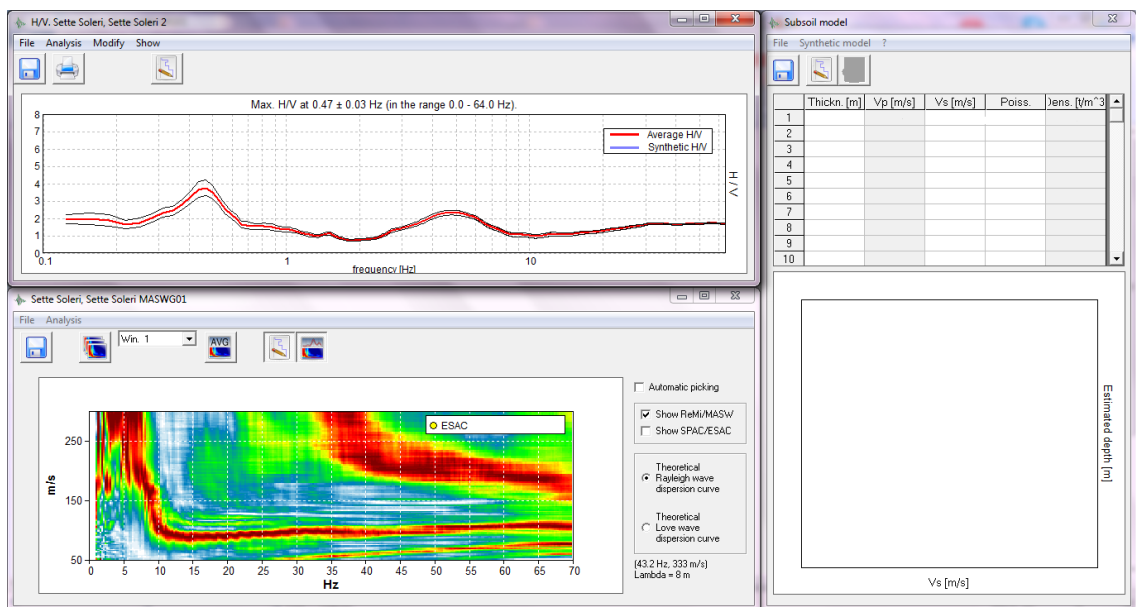
Joint fit of H/V and dispersion curves with *Griffa*

TUTORIAL VIDEO 02

Timing [mm:ss]	
00:00	In this video we will see how to perform a joint model of H/V and dispersion curves (Rayleigh waves, vertical component).
00:18	<p>Let us start from the surface wave dispersion curve obtained from the array survey, as shown below. As explained in the tutorial video #01, it is important to preliminary assess the maximum and minimum depths of investigation reached by the survey. In this example we see that the maximum wavelength λ is about 33 m, which corresponds to a depth of investigation certainly lower than 15 m.</p> <div style="display: flex; align-items: flex-start;">  <div style="border: 1px solid black; padding: 10px; margin-left: 20px; width: 200px;"> <p>Maximum depth of investigation $< \lambda_{\max}/2$, (where $\lambda_{\max} = 200\text{m/s} / 6\text{ Hz} = 33\text{ m}$)</p> </div> </div> 
00:45	<p>Let us now open the H/V curve recorded at the same site. Let us click on this icon  from the dispersion curve window to open the subsoil model on the right.</p> <p>Let us then click on this other icon  from the dispersion curve window to plot the H/V curve over the dispersion curve.</p> <p><i>Griffa</i> asks the user to select the single station analysis (H/V) of interest from the database. Click <i>Ok</i> to recall the database and select the database line of interest, which will be highlighted in blue.</p>
01:00	<p>Let us now select <i>View > View all the analysis of the selected file</i> from the menu or click the icon . This will open a window displaying the list of analyses present in the database for the selected recording. Select the analysis of interest and click <i>Ok</i>.</p>



The H/V curve will now be displayed on the top left of the screen, the dispersion curve on the bottom left and the table to enter the subsoil model on the right.

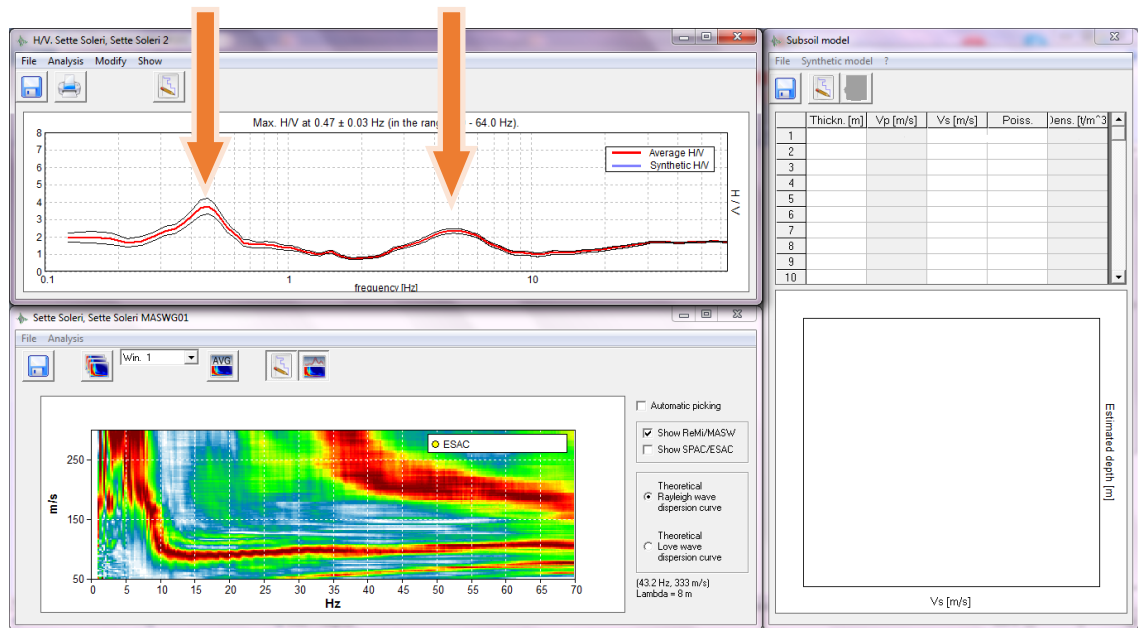


01:45

Let us now consider the H/V curve: here we have to identify the relevant peaks of stratigraphic origin that we wish to reproduce with the modeling tool. In the present example, these are at 5 and at about 0.5 Hz (red arrows in figure below). The first peak is clearly related to a shallow feature of the subsoil (within 5-10 m depth) while the second peak is related to a deep feature of the subsoil (impedance contrast at depth larger than 100 m).

(2) H/V peak due to the resonance of more than 100m thick covers overlying the local seismic bedrock.

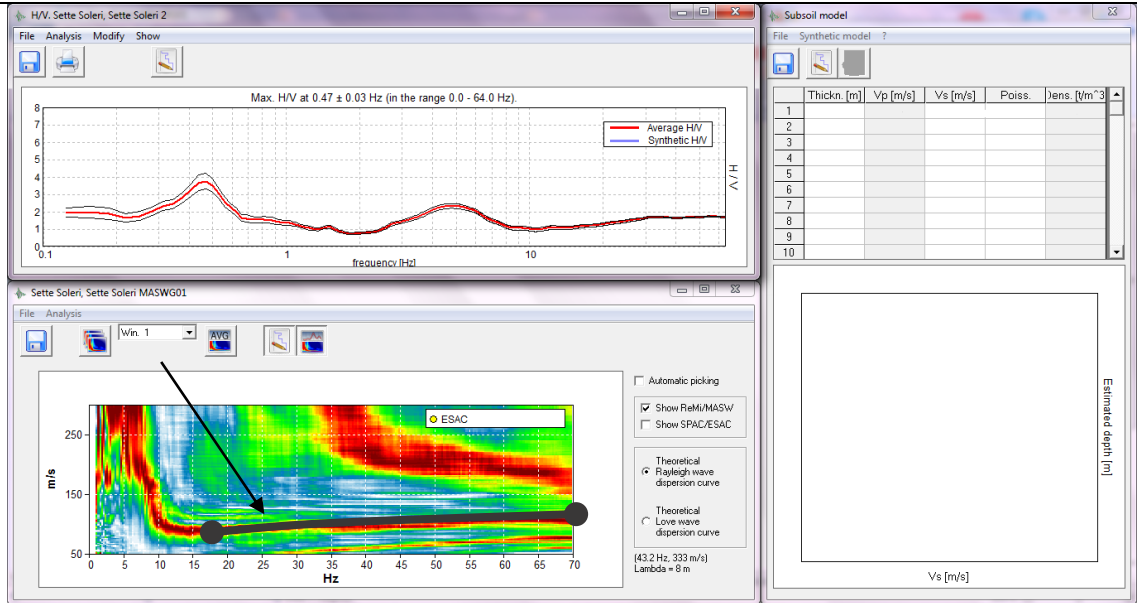
(1) H/V peak originated by the resonance of a soft layer overlying a stiff reflector within 10 m depth (as it will be clearer from the model).



02:35

Let us now start with the modeling. We observe something peculiar in this dispersion curve, i.e. the velocity values slightly decreasing from high to mid frequencies. The question is whether this feature is related to a velocity inversion in the subsoil (stiffer soil overlying a softer soil) or whether this is due to a coalescence of higher and fundamental modes.

Is this feature a velocity inversion (stiffer layer overlying a softer layer) or a coalescence of modes?

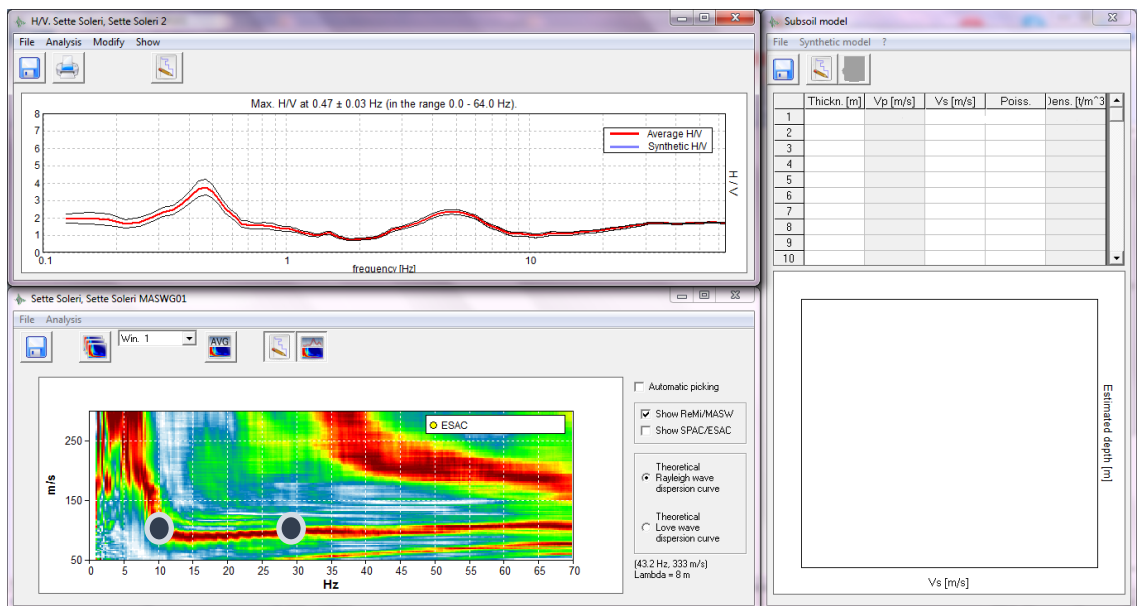


In this case the H/V curve helps us because we know that significant velocity inversions are marked by persistent H/V ratios < 1 (for decades of frequency, e.g. Castellaro and Mulargia, *Pure Appl. Geophys.*, 2009). This pattern is not evident in the H/V curve, therefore we will interpret the dispersion curve as a coalescence of modes.

25

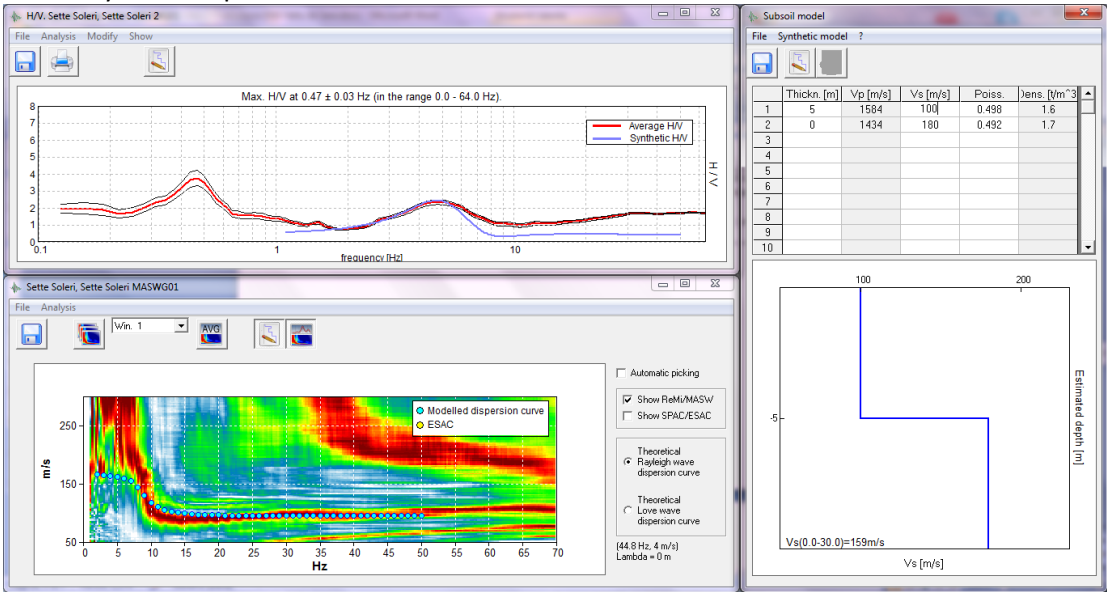
04:00

The dispersion curve from 9 to 30 Hz is here interpreted as the fundamental mode while above 30 Hz it is here interpreted as a higher mode. Let us focus on the part below 30 Hz. At 30 Hz we find a wavelength $\lambda = V / f \approx 3$ m and the associated depth is approximately 1.5 m. At 10 Hz the associated depth is approximately 5 m ($\lambda = 10$ m). At the depth comprised between 1.5 and 5 m, the Rayleigh wave velocity is therefore 100 m/s (and the S-wave velocity is 10-15% higher).



04:40

At frequencies below 10 Hz (i.e. depth > 5 m), the Rayleigh wave phase velocity increases from

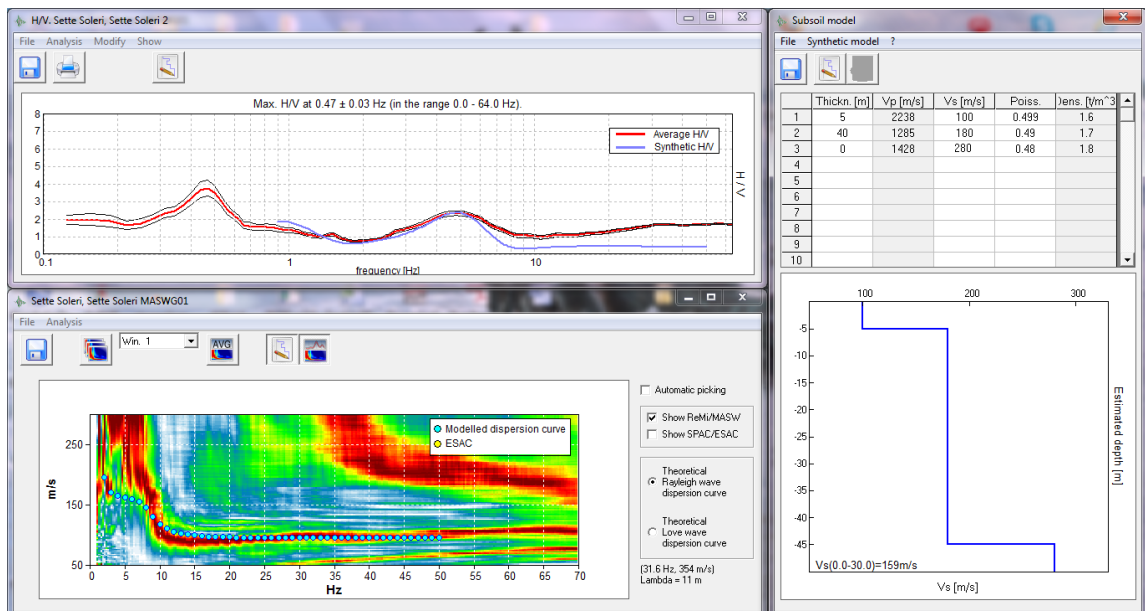
	<p>100 to 180 m/s. We start filling the model table with the following values:</p> <ul style="list-style-type: none">• Layer 1. Thickness: 5 m, velocity: 100 m/s• Layer 2. Velocity = 180 m/s <p>The survey under study was recorded in an island of the Venice lagoon where sediments are water saturated. This implies that we must use very high Poisson's ratios to ensure that the P-wave velocity V_P is about 1400 m/s, which is its typical velocity of propagation in water.</p>																																																							
05:45	<p>Let us now produce the theoretical H/V and dispersion curves by clicking the  button from the model window (right panel). The theoretical curves reproduce reasonably well the experimental curves. The H/V peak at 5 Hz is therefore related to the impedance contrast set in the model at 5 m depth, which is related to an over-consolidated clayey palaeosoil locally known as <i>caranto</i>.</p> <p>This is only the first part of the model.</p> <div></div> <table><tr><th>Thickn. [m]</th><th>V_P [m/s]</th><th>V_S [m/s]</th><th>Poiss.</th><th>Dens. [t/m³]</th></tr><tr><td>1</td><td>5</td><td>1584</td><td>100</td><td>1.6</td></tr><tr><td>2</td><td>0</td><td>1434</td><td>180</td><td>0.492</td></tr><tr><td>3</td><td></td><td></td><td></td><td></td></tr><tr><td>4</td><td></td><td></td><td></td><td></td></tr><tr><td>5</td><td></td><td></td><td></td><td></td></tr><tr><td>6</td><td></td><td></td><td></td><td></td></tr><tr><td>7</td><td></td><td></td><td></td><td></td></tr><tr><td>8</td><td></td><td></td><td></td><td></td></tr><tr><td>9</td><td></td><td></td><td></td><td></td></tr><tr><td>10</td><td></td><td></td><td></td><td></td></tr></table>	Thickn. [m]	V_P [m/s]	V_S [m/s]	Poiss.	Dens. [t/m ³]	1	5	1584	100	1.6	2	0	1434	180	0.492	3					4					5					6					7					8					9					10				
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06:35	<p>As already noted, the array survey reached only 15 m depth. The remaining H/V peaks are related to stratigraphic features at depths much larger than 15 m. To reach those depths we can rely on the H/V curve alone and this is now possible, as a first approximation, since the H/V curve has been constrained in the high frequency part by the joint fit with the array curve.</p> <p><i>Do not forget that no H/V curve can be fit if no constraint on shallow V_S or thickness of the resonating layer is provided, because there would exist infinite possible solutions.</i></p>																																																							
07:15	<p>To reproduce the low H/V peak at 1 Hz we start from the resonance equation where the resonance frequency $f = V_S / (4H)$, from which the thickness of the resonating layer $H = V_S / (4f)$. This simple formula strictly applies to the case of a single resonating layer overlying the bedrock (which is not the case in the present example), however we use it as first approximation.</p> <p>V_S is the 'average' V_S of the layers overlying the stiff layer that produce the resonance observed at 1 Hz. Here the average V_S is approximately 180 m/s which, divided by 4 and divided by 1 Hz, gives $H = 45$ m. The approximate thickness of the whole layer resonating at 1 Hz is 45 m. Since we have already introduced a 5 m thick layer in our model, we add a second layer with thickness $45 - 5 = 40$ m.</p> <p>We input again a high Poisson ration to obtain a V_P velocity of about 1400 m/s, typical of water</p>																																																							

saturated sediments.

09:05



We run the model by clicking the button  in the model window (right panel). In order to understand the effect of the V_s of the third layer on the 1 Hz H/V peak, let us use a random V_s value, e.g. 320 m/s. We see that this value is too large because it produces an overamplified peak compared to the experimental curve. This means that we have to lower the impedance contrast and by using $V_s = 280$ m/s we get a reasonably good fit.



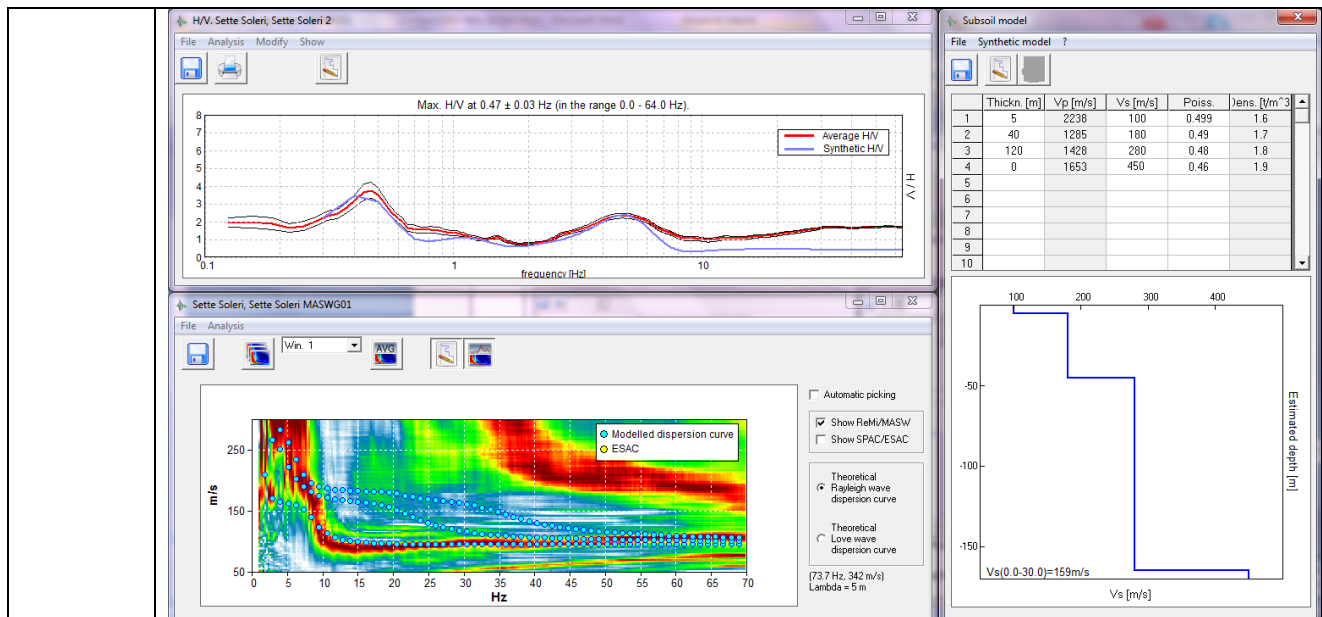
27

10:00

As a last step, let us attempt to model the H/V peak at 0.5 Hz. As we did before, we use the resonance frequency equation as first approximation guide. The average V_s of the covers is around 250 m/s and their thickness is approximately $250 \text{ m/s} / (4 \times 0.5 \text{ Hz}) = 160 \text{ m}$. To this number we must subtract the previously input 45 m, which results in a third layer thickness of 120 m.



Let us run the model by clicking the button  in the model window (right panel). The peak at 0.5 Hz is reproduced at the correct frequency. The addition of layers to the model can slightly modify the theoretical curve in the upper part. Some minor changes can be introduced at this stage to refine the match between the theoretical and the experimental curves.

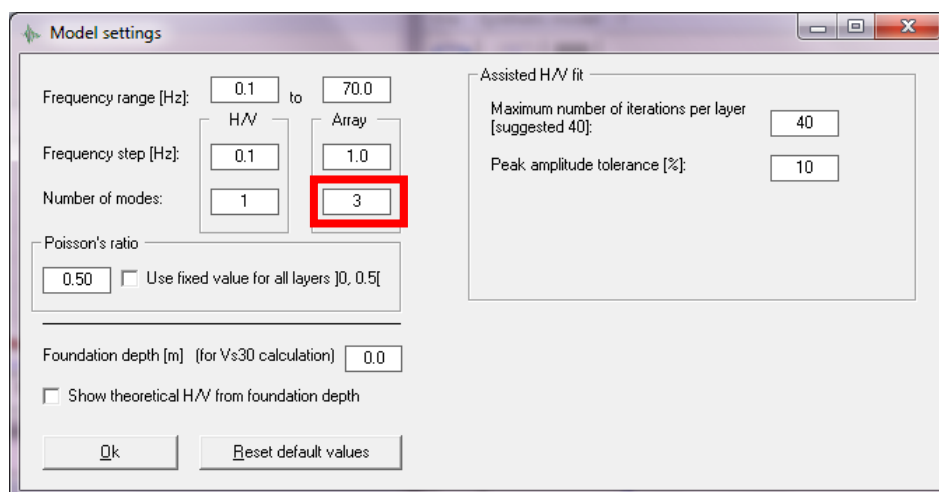


11:35

The proposed model reproduces reasonably well both the dispersion and the H/V curve.

- We note that to reproduce a H/V curve with N peaks, N+1 layer are sufficient, with the only exception of velocity inversions.
- We also note that the model reproduces the fundamental mode below 6 and between 9 and 30 Hz while the branches of the dispersion curve between 6 and 9 Hz and above 30 Hz are higher modes.

To view the theoretical higher modes, click *Synthetic model* > *Settings* from the model panel and set the desired number of modes, as shown below.



28