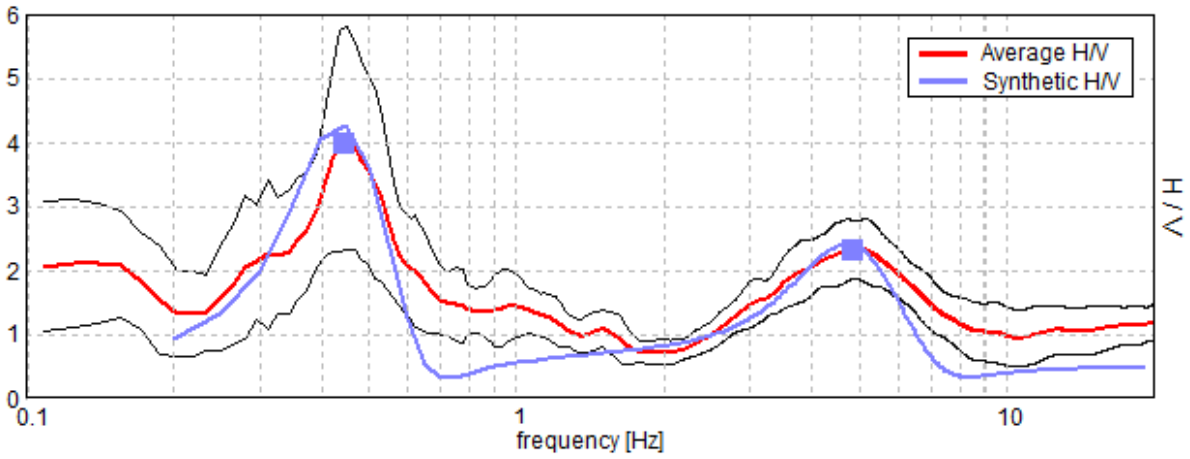
# INTRODUCTION TO THE H/V MODELING ROUTINE FOR STRATIGRAPHIC PURPOSES IN *Grilla*




Ver. 3.0
August 2012

**Micromed s.p.a.**
Via Giotto 2, 31021 Mogliano Veneto, Treviso - Italy
Tel: +39-041-593 7000 - Fax: +39-041-593 7011
Business Registry of Treviso Registration Number TV03906850262
VAT number IT03906850262

QUALITY SYSTEM CERTIFIED - UNI EN ISO9001 - UNI CEI EN. ISO13485

# Contents

Contents ..... 2
Introduction ..... 3
First of all: ..... 4
1) is the H/V measurement clear enough? ..... 4
2) choice of the parameters in the analysis of the experimental H/V curves ..... 4
3) cleaning of the experimental H/V curves ..... 4
4) choice of the peaks to fit ..... 5
Input parameters ..... 5
Other parameters ..... 7
How to use the model in practice ..... 7
CASE 1: FORWARD MODELING ..... 9
CASE 2: AUTOMATIC FIT ..... 15
Other parameters ..... 16
Limitations ..... 17
Final recommendations ..... 18
Examples ..... 19
CASE 2 ..... 19
CASE 3 ..... 20
Bibliography ..... 21

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 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

The code which generates synthetic H/V curves implemented in *Grilla* is based on the simulation of the surface-wave (Rayleigh e Love) field in plane-parallel multi-layered systems, according to the theory described in Aki and Richards (1964) and Ben-Menahem and Singh (1981).

The code can process models with:

1) any number of layers (limited to 50 entries in the *Grilla* input table),
2) any frequency interval within [0, 100]Hz,
3) any number of modes (fundamental and higher).



However, for the H/V modelling we recommend to visualize the fundamental mode only. This is different from the surface wave-based array methods, where higher modes are often dominant and can be informative (Castellaro and Mulargia, 2009a).

To start the H/V modelling routine, click ANALYSIS >> SURFACE WAVE MODELLING in the H/V window shown in Figure 1 or click the red-framed button in the same figure.

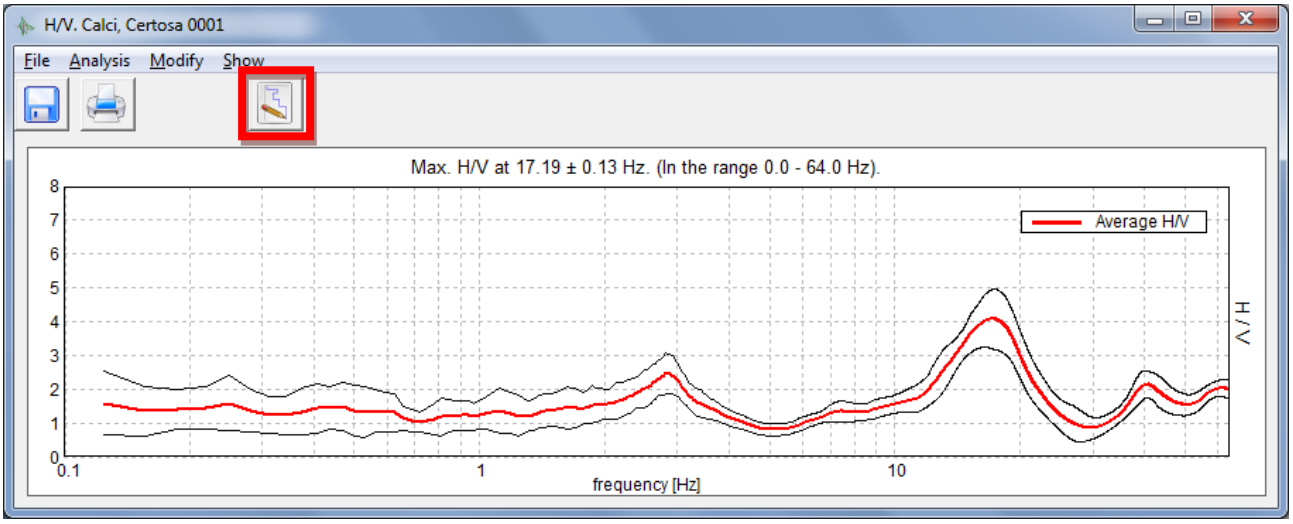



**Figure 1. Button (red square) to start the H/V modelling routine.**

# First of all:

## 1) is the H/V measurement clear enough?

Please refer to "The short TROMINO® How To" and the TROMINO® user's manual. Here we simply remind that it is important, whenever possible, to take the H/V recording directly on natural soil and *not* on asphalt, pavements or stiff artificial coverings. The latter can in fact induce velocity inversions capable to hide layers with even strong impedance contrasts in the first few tens meters (Castellaro and Mulargia, 2009b).



## 2) choice of the parameters in the analysis of the experimental H/V curves

Since the parameter choice for the H/V analysis may affect both the frequency and the amplitude of the H/V peaks, it is recommended:

a) not to use larger smoothing than 10% the central frequency,

b) not to use window length shorter than 20 s for frequencies of interest above 1 Hz and window length of 40-60 s for frequencies of interest between 0.1 and 1 Hz.

## 3) cleaning of the experimental H/V curves

Before attempting a H/V modelling be sure that transient disturbances have been accurately removed, in order not to include in the modelling peaks which are only apparent. An example of H/V curve which must not be modelled before an accurate cleaning is given in Figure 2: a large confidence interval can be observed below 1 Hz (black curves around the average H/V curve in red), which introduces an apparent peak at 0.3-0.5 Hz. After the cleaning performed by means of the apposite routine of *Grilla* (see *H/V time stability* in the *Grilla* user's manual), the H/V curve shown in Figure 3 is obtained, and this can be analyzed.

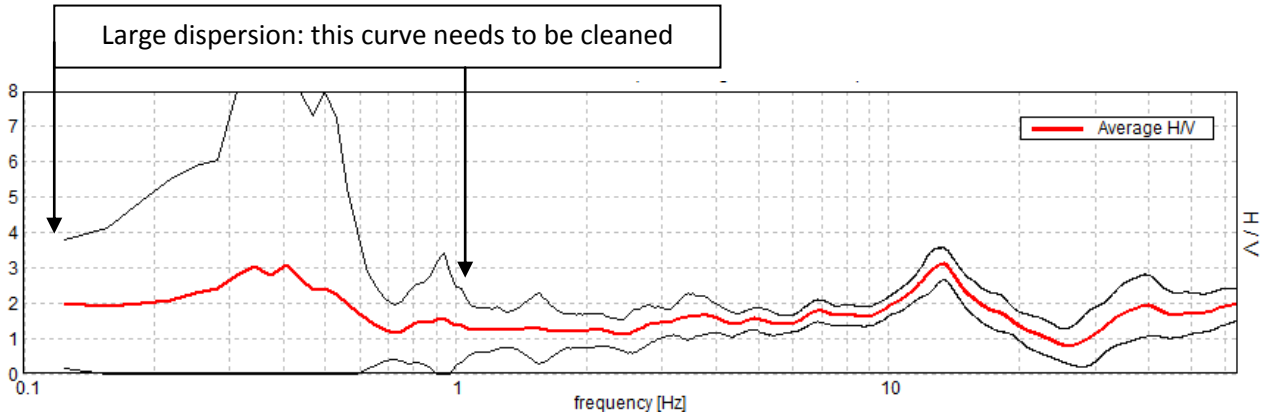



**Figure 2. Example of H/V curve which needs to be cleaned. Note the large data dispersion around the average values at frequencies below 4 Hz (black lines represent the 95% confidence interval, red line represent the average H/V). The H/V after cleaning is shown in Figure 3.**

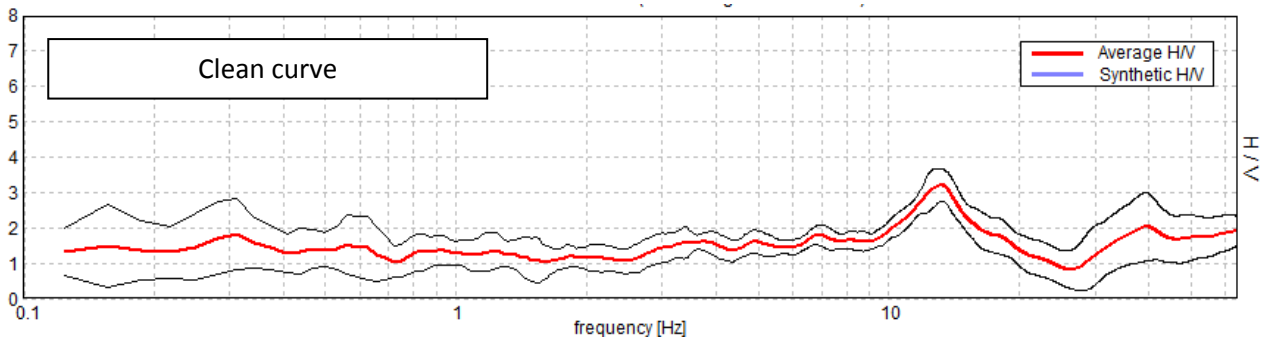





Figure 3. Example of clean H/V curve. Note the narrow confidence interval (black lines).

## 4) choice of the peaks to fit

The basic principle of the modern scientific method is the Occam's Razor principle, which states *Entia non sunt multiplicanda praeter necessitate* (entities must not be multiplied beyond necessity). This means that among the many (or infinite) models that can equally reproduce the experimental data, the simplest model (i.e. the one with less parameters) should be used.

Transferring this to H/V curves, it implies that to fit one H/V peak, only 2 layers are needed (the resonating layer and its 'bedrock') and further layers should not be added.

The well known equation $\lambda = V/f$, wavelength = velocity / frequency helps us figuring out the size of the seismic reflectors needed to give some signal of their existence at each frequency. It also helps us focusing the attention on the main features of the H/V curve (i.e. the clear peaks[1] only) and to neglect the minor wiggles that can represent higher modes etc.

## Input parameters

The code for surface waves modelling implemented in *Grilla* requires the following input parameters for each layer:

1) thickness of the layer in [m] *[thickness, NOT depth!]*,
2) $V_P$, P-wave velocity in [m/s] *[input not requested to the user. It is calculated automatically, see below]*,
3) $V_S$, S-wave velocity in [m/s],
4) density in $10^3$ kg/m$^3$.

The last layer of the model is assumed to have an infinite thickness. This must be indicated with 0 thickness (yellow cell in Table 1).

The $V_P$ column cannot be filled manually. This is compiled automatically on the basis of the $V_S$ and Poisson's ratio values inserted by the user.

[1] To distinguish stratigraphic from anthropic peaks please refer to the "The Short TROMINO® How To".

| | Thickness [m] | $V_P$ [m/s] | $V_S$ [m/s] | $\nu$ Poisson's ratio | Density [$10^3$ kg/m$^3$] |
|---|---|---|---|---|---|
| **1** | 10 | | 220 | 0.4 | 1.7 |
| **2** | 30 | | 300 | 0.4 | 1.8 |
| **3** | 0 | | 450 | 0.4 | 2.0 |

**Table 1. Example of input table. Note the 0 thickness (which actually means ∞) of the last layer and the empty $V_P$ column which will be filled automatically.**



$V_P$ and density do not play a relevant role in any surface wave-based technique. This implies that the theoretical H/V shape is primarily affected by the $V_S$ profile only. It follows that:

**ANY SURFACE WAVE-BASED MODEL DO *NOT* PROVIDE $V_P$ AND DENSITY PROFILES**

Given their minor importance, the $V_P$ and density columns in the input table (Table 1) have a grey background.

Typically, densities in the range 1.6-2.2 $10^3$ kg/m$^3$ and $V_P$ depending on $V_S$ according to the Poisson's ratio

$$\nu = (V_p^2-2V_s^2) / [2(V_p^2-V_s^2)]$$

will be used. In natural materials, being $V_P > V_S$, the Poisson's ratio is included in the ]0, 0.5[ interval and in the shallow subsoils it varies between 0.38 and 0.49.
The Poisson's ratio estimated through geophysical prospections in the field is usually much larger than the same modulus calculated at the sample scale in the laboratory. The sample size involved in the geophysical prospection is much larger and at this scale the sample is usually layered, fractured etc. This lowers seismic wave velocities and their ratios considerably in the field, compared to the 'ideal' sample of the laboratory.
If no independent measurements of the Poisson's ratio are available, the values reported in Table 2 can be used as a reference.
Note that in soft soils (i.e. soils that would present $V_P < \approx 1450$ m/s in dry conditions) under the water table, the P wave transmits through the fluid phase with a velocity $V_P \approx 1450$ m/s. The Poisson's ratio must therefore be chosen in order to get $V_P \approx 1450$ m/s from the $V_S$ velocity estimated for that site/layer.

| Material | Typical $\nu$ |
|---|---|
| Hard rock | 0.35 |
| Soft rock | 0.38 |
| Sand-gravel | 0.4-0.42 |
| Clay | 0.45-0.48 |
| Soft soils ($V_P < \approx 1450$ m/s in dry conditions) under water | $\nu$ to be chosen so that $V_P \approx 1450$ m/s |

**Table 2. Typical Poisson's ratio values.**

## Other parameters

Use the SYNTHETIC MODEL >> SETTINGS menu in the *Subsoil Model* window (right in Figure 5) to enter the parameter settings window (Figure 4).

Here you can set:



**FREQUENCY RANGE [Hz]:** the lower (0 Hz) and upper (half sampling rate) frequency limit for the synthetic H/V curve.

**FREQUENCY STEP [Hz]:** frequency step for the synthetic H/V calculation. 0.1 Hz means that the curve will be calculated at, e.g., 1.5, 1.6, 1.7, 1.8 etc. Hz. 0.1 Hz is an adequate step to model the curve down to 0.2 Hz.

**NUMBER OF MODES:** number of modes to compute. One is recommended for the H/V.

**POISSON'S RATIO:** Poisson's ratio ]0, 0.5[. By marking the box the same value will be used for each layer.

**FOUNDATION DEPTH:** allows to calculate the H/V curve at a depth different from the free surface (0 m). The Vs30 value will also be computed starting from this depth (Figure 10).

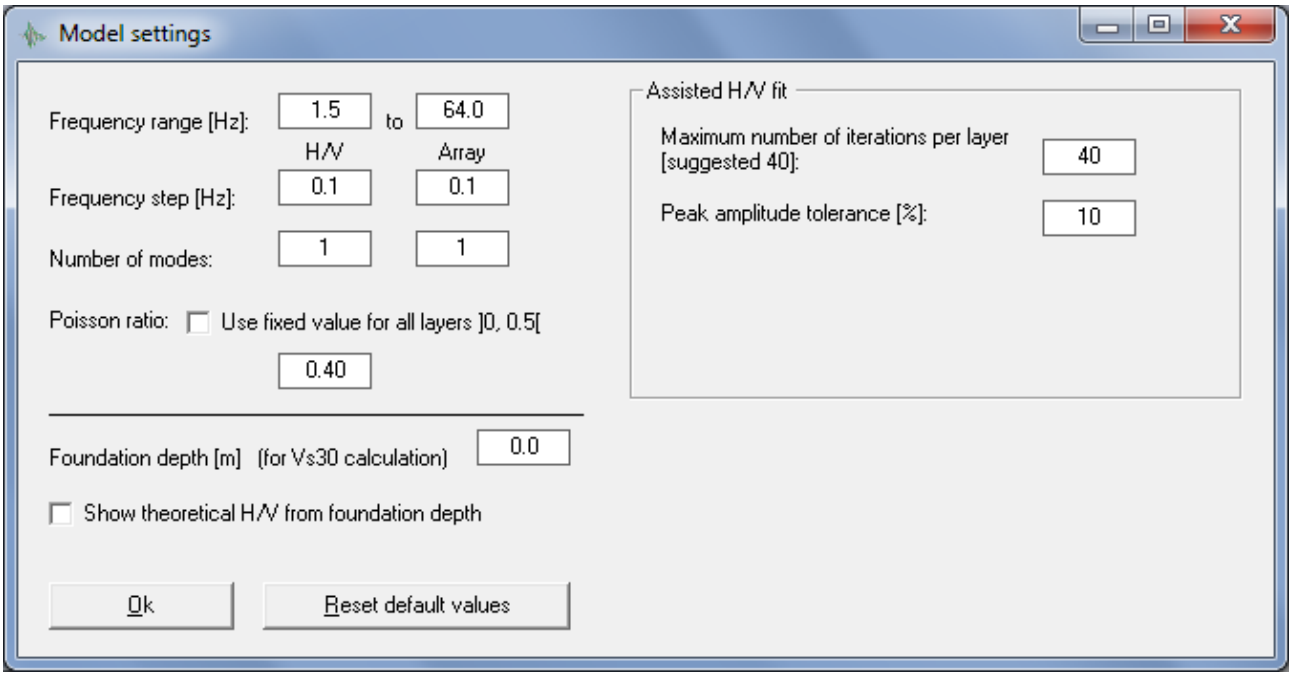



Figure 4. Parameter settings window for the H/V modeling routine.

## How to use the model in practice

Even in the most simple case of a single layer of thickness H overlying the bedrock, from the resonance equation $f_0 = V_S / (4H)$ it is easy to realize that a H/V curve – which provides $f_0$ only – leaves the equation underdetermined. To estimates $V_S$, it is mandatory to know H or viceversa.

The same holds in the multi-layered cases, where the surface wave field modeling is necessary: a constraint is needed to estimate a $V_S$ profile. Such a constraint can be:

1) the depth of a reflector (known from the stratigraphy and which can be recognized in the H/V curve), or
2) the average $V_s$ in the first layer, known from independent techniques (such as the usage of the trigger cable in TROMINO® ENGY).



Since the depth of the first layer (item 1 above) is usually known in the geotechnical practice from penetration tests, drillings, pits, outcrops etc., we will discuss only case 1) above.

> **No $V_S$ profile can be obtained from a H/V curve without any constraint. With no constraint, infinite solutions are possible.**

Even in presence of a constraint, there exist some limitations that will be discussed later. However, this kind of modelling, correctly applied, can be considered a sufficient estimator of the $V_S$ profile for routine seismic site classifications.

# CASE 1: FORWARD MODELING

Now we see how to model a H/V when the constraint is the depth of a seismic reflector (usually a stiff layer), that determines the resonance of the overlying layers at the frequency f.

The case discussed in the next pages can be found in the *Grilla* CD, in the EXAMPLE folder (Case 1).



### STEP 1: IDENTIFY THE PEAKS OF STRATIGRAPHIC ORIGIN

The H/V peaks of stratigraphic origin are characterized by a local minimum in the vertical spectral component (see "The Short TROMINO® How To"). In the case of Figure 5, these appear at 2.8 and 17 Hz.

| Always start fitting a H/V curve from right to left, from high to low frequency, from shallow to deep soil. |
|---|

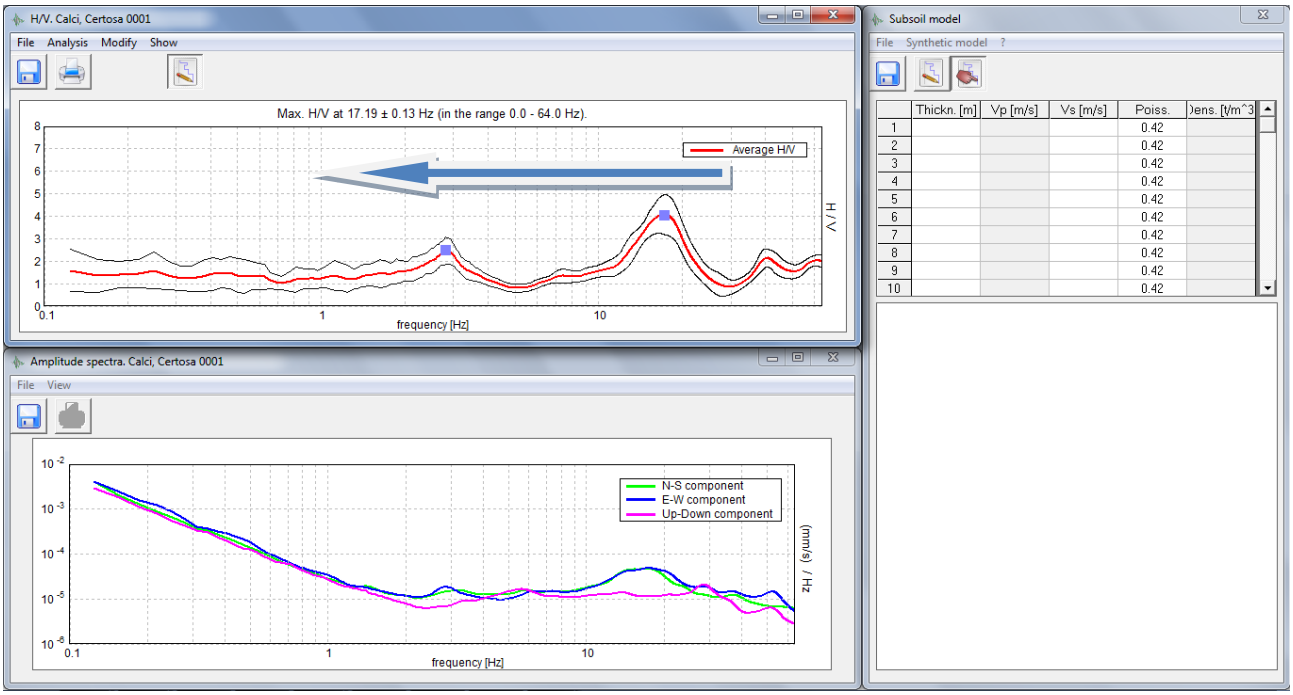



Figure 5.

### STEP 2: CHARACTERIZE LAYER 1

The H/V peak corresponding to the shallowest stiff layer is the one at 17 Hz. This peak indicates the resonance of 2 m silt overlying gravels (data known from a shallow drilling). Even though the resonance equation cannot be used in the multilayer cases, it can still be used as a first approximation. In this case the $V_S$ of the resonating layer (silt) is $V_S \approx 4\ H\ f \approx 4 \times 17\ Hz \times 2\ m \approx 130\ m/s$. We can therefore fill the first line (layer 1) of the model as shown in Figure 7.

Now, since the amplitude of the H/V peak is proportional to the impedance contrast between layer 1 and 2, $V_S$ of layer 2 will be determined by fitting the peak amplitude. We can proceed with a trial-and-error approach: should the $V_S$ of layer 2 be too low, a synthetic H/V curve (blue) underestimating the amplitude of the experimental (red) one will be found, and vice versa.

As an alternative approach, we can use Figure 6 (follow the blue dashed lines for the 17 Hz peak), where the expected H/V peak amplitude is shown as a function of the impedance contrast (here meant simply as the $V_S$ ratio between the two layers generating the resonance) and of the Poisson's ratio. In the case of study the H/V peak at 17 Hz has an amplitude equal to 5, the Poisson's ratio is 0.42 and the suggested impedance contrast between layer 1 and 2 is 2.4. The $V_S$ value proposed for layer 2 is therefore approximately 130 m/s x 2.4 = 310 m/s. This value is reported in the model table (Figure 7).



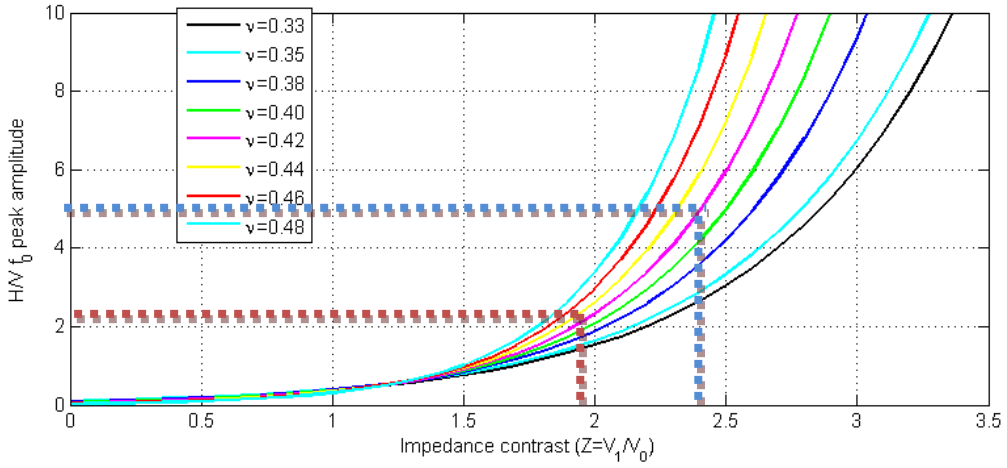



**Figure 6. First approximation relation between the H/V peak amplitude and the impedance contrast (here simply meant as the $V_S$ ratio between two layers) as a function of the Poisson's ratio for Rayleigh waves. The blue dashed lines refer to the impedance contrast between layer 1 and 2 in the case under examination. The brown dashed lines refer to the impedance contrast between layer 2 and layer 3.**

To run the code and get the synthetic model, click the red framed button shown in Figure 7.

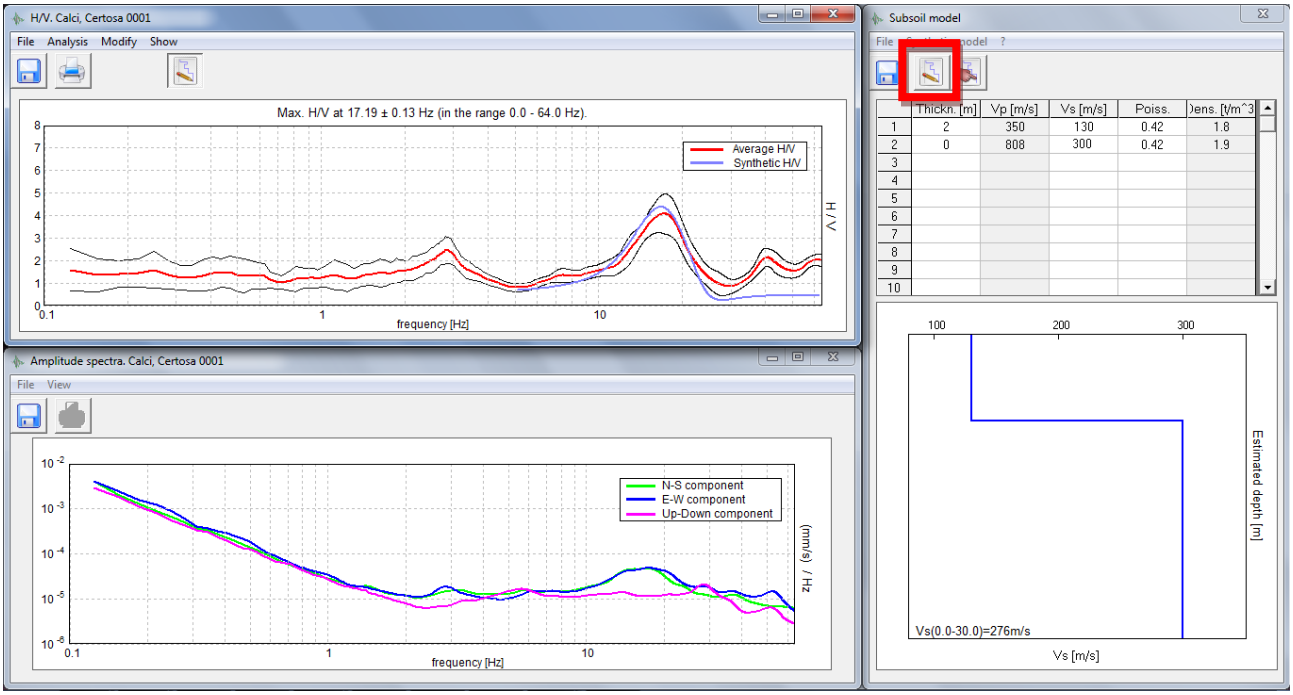



**Figure 7. Experimental (red) and synthetic (blue) H/V curve for the subsoil model shown on the right.**

**STEP 3: CHARACTERIZATION OF LAYER 2**

We now have to define the thickness of layer 2 in order to explain the second resonance peak at 3 Hz. At this point we know that the subsoil presents a 2 m layer with $V_S \approx 130$ m/s, followed by a layer with $V_S \approx 300$ m/s. From the resonance equation (Figure 8) it follows that the 3 Hz peak should be related to a stiff layer at about 20-30 m depth. The first 2 m silt has little influence on the average $V_S$ of the whole layer giving resonance at 3 Hz and the latter will be close to 300 m/s of layer 2. An approximate estimate of the depth of the reflector causing the resonance at 3 Hz is therefore H ≈ 300 m/s / (4 x 3 Hz) ≈ 25 m. To get the thickness of layer 2 we just subtract layer 1 from H: 25 m – 2 m = 23 m. We can insert this value in the model table (Figure 9).



As before, $V_S$ of layer 3 can now be determined through a trial and error procedure until the amplitude of the synthetic and the experimental curve fits or by following the brown dashed lines in Figure 6. The latter suggest an impedance contrast 1.9 between layer 2 and 3, that is a $V_S$ of layer 3 equal to 300 m/s x 1.8 = 540 m/s. The subsoil model of Figure 9 is filled with this new value and the final synthetic curve fits well the experimental one.

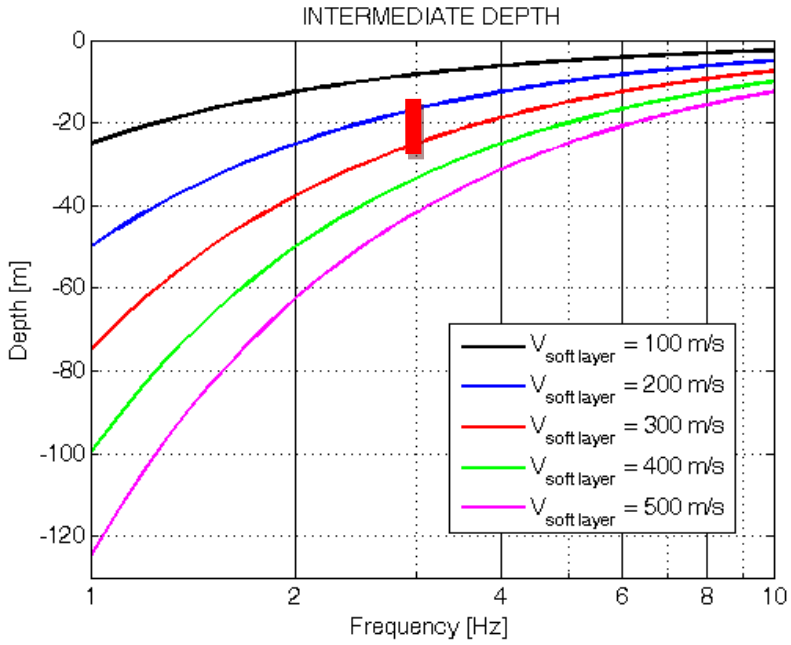



**Figure 8. Relation between the thickness of the resonating layer and the resonance frequency as a function of the average $V_S$ of the resonating layer.**

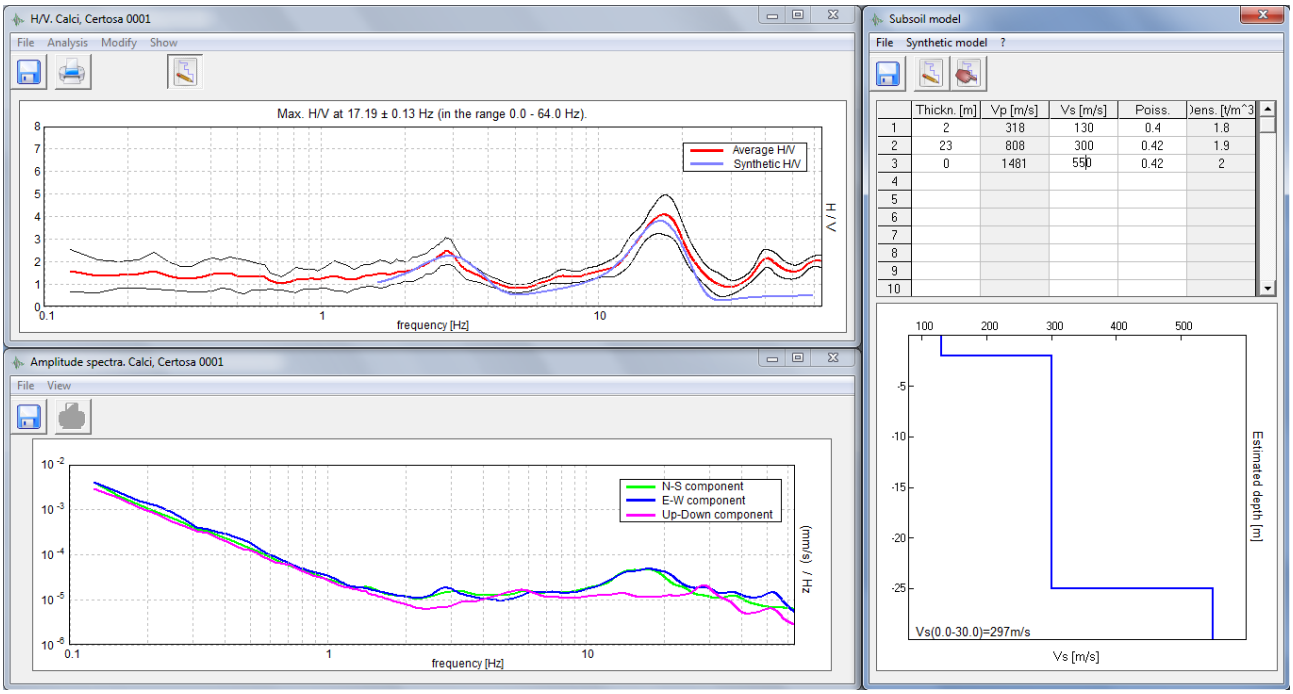



Figure 9. Experimental (red) and synthetic (blue) curve for the subsoil model on the right.

To view the synthetic H/V curves calculated from a level different from the ground level, select SYNTHETIC MODEL >> MODEL SETTINGS in the *Subsoil model* window and type the desired depth in red framed area shown in Figure 10.

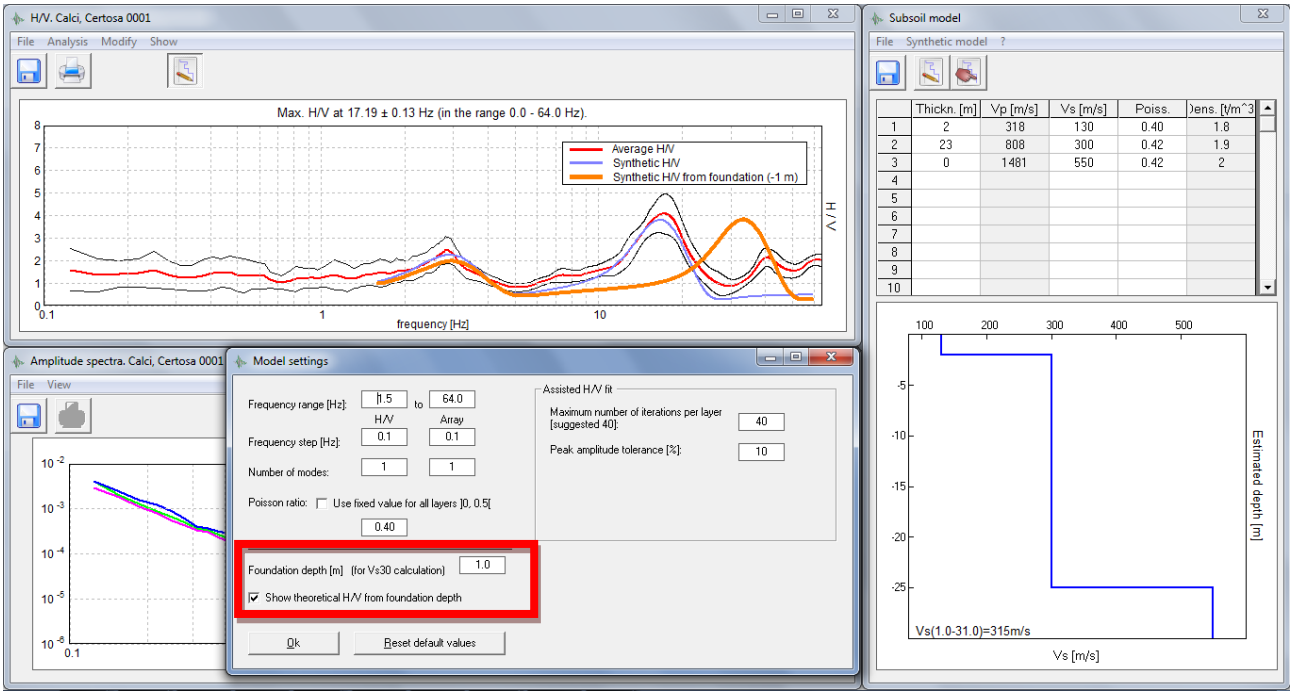



Figure 10. Experimental H/V curve (red), synthetic curve calculated from the ground level (blue) and from 1 m below the ground level (orange) for the subsoil model on the right.

**RÉSUMÉ**

Let us now summarize the path followed to compile the subsoil model in the previous pages.

1) In the field we measure the resonance frequencies f(i)
2) To translate an H/V curve into a $V_S$ profile, a constraint is mandatory (typically the layer 1 thickness H(1))



| | **f** | **$V_S$** | **THICKNESS** |
|---|---|---|---|
| **Layer 1** | f(1) | | H(1) |
| **Layer 2** | f(2) | | |
| **Layer 3** | f(3) | | |
| **…** | | | |
| **Layer n** | f(n) | | |

3) This allows to get a first approximation of $V_S(1)$ through the resonance equation, even though this does not strictly apply to multilayered systems (which is the reason why we are running this modeling routine)

| | **f** | **$V_S$** | **THICKNESS** |
|---|---|---|---|
| **Layer 1** | f(1) | $V_S(1)$ | H(1) |
| **Layer 2** | f(2) | | |
| **Layer 3** | f(3) | | |
| **…** | | | |
| **Layer n** | f(n) | | |

4) We now have all the elements to estimate $V_S(2)$ from the amplitude of the resonance peak at f(1), through a trial-and-error approach or by exploiting Figure 8

| | **f** | **$V_S$** | **THICKNESS** |
|---|---|---|---|
| **Layer 1** | f(1) | $V_S(1)$ | H(1) |
| **Layer 2** | f(2) | $V_S(2)$ | |
| **Layer 3** | f(3) | | |
| **…** | | | |
| **Layer n** | f(n) | | |

5) Now we can hypothesize H(2) on the basis of considerations as in Figure 8

| | **f** | **$V_S$** | **THICKNESS** |
|---|---|---|---|
| **Layer 1** | f(1) | $V_S(1)$ | H(1) |
| **Layer 2** | f(2) | $V_S(2)$ | H(2) |
| **Layer 3** | f(3) | | |
| **…** | | | |
| **Layer n** | f(n) | | |

6) And determine $V_S(3)$ by fitting the amplitude of the peak at f(2), through a trial-and-error procedure or by exploiting Figure 8

| | **f** | **$V_S$** | **THICKNESS** |
|---|---|---|---|
| **Layer 1** | f(1) | $V_S(1)$ | H(1) |
| **Layer 2** | f(2) | $V_S(2)$ | H(2) |
| **Layer 3** | f(3) | $V_S(3)$ | |
| **…** | | | |
| **Layer n** | f(n) | | |



The procedure goes on in this way for all the layers. However, remind that

| To fit a number N of H/V peaks, only N+1 layers are needed |
|---|

The only exception is the case of velocity inversions in the subsoil (Castellaro and Mulargia, 2009b). According to the Occam's Razor principle and the scientific method,

| Among the infinite models capable to explain the same experimental features, the one with the lowest number of parameters (layers in this case) has to be preferred |
|---|

A 2-3 layer model is usually more than adequate to reproduce the H/V curves above 1 Hz.

## CASE 2: AUTOMATIC FIT

The H/V curves can also be modelled in an automatic way. To this aim, select SYNTHETIC MODEL >> ASSISTED FIT in the *Subsoil Model* window or click the red framed button shown in Figure 11.

Now select the H/V peaks to fit by picking them on the H/V window: they will be indicated by a blue square. In case of error the selection can be cleared by clicking the red framed button in Figure 11 and a new selection can be performed by clicking again the same button.



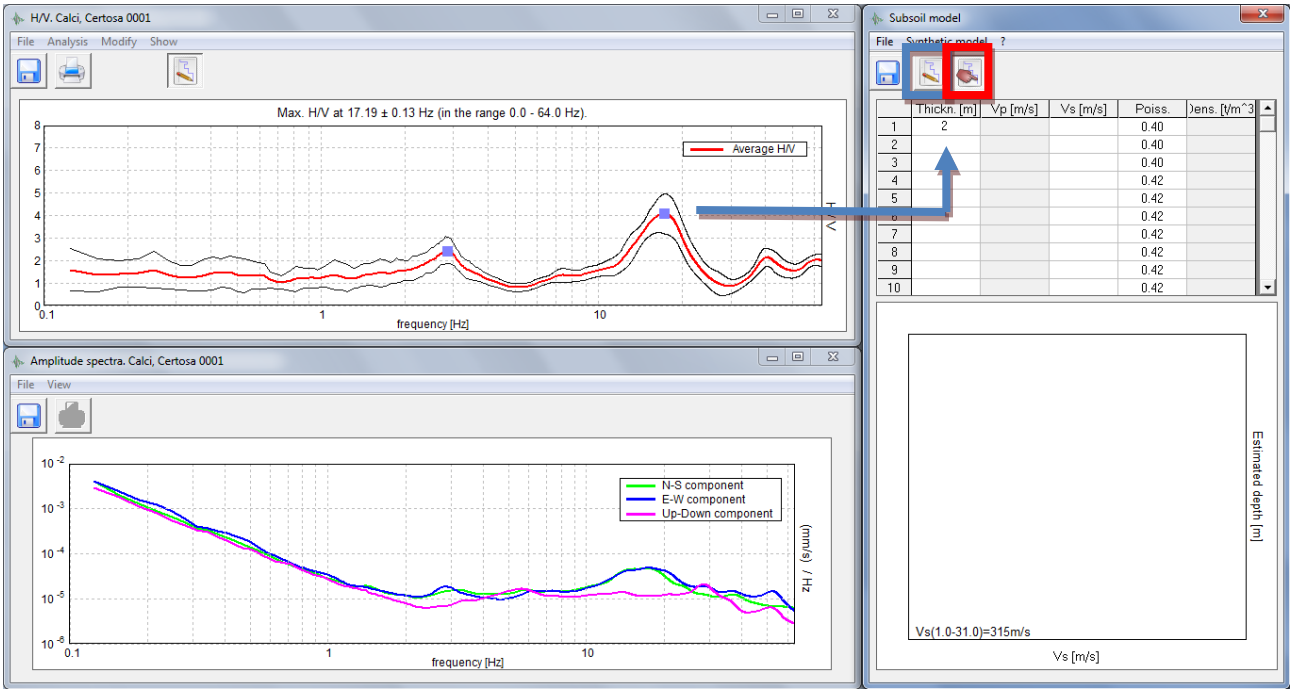



**Figure 11. To enter the H/V automatic fit routine, click the red framed button. To run the automatic fit, click the blue framed button after selecting the peaks to model (blue squares on the top left panel).**

| To run the automatic modeling routine a constraint is mandatory as described on p. 7. Failing to do so, results in infinite solutions |
|---|

The only acceptable constraint is the thickness H(1) of layer 1, that is of the layer resonating at the frequency identified by the rightmost H/V peak (Figure 11, blue arrow).

To run the model, select SYNTHETIC MODEL >> RUN in the *Subsoil Model* window or click the blue framed button in Figure 11. A window showing the progress of the modelling will appear and, at the end, the model proposed for the site (Figure 12).

Note that even if the synthetic model proposes values like 633 m/s (e.g. for layer 3), these cannot be considered significant from an experimental point of view, where the typical uncertainty in the $V_S$ estimate is about 20%. The scientific annotation imposes to write 6.3 $10^2$ m/s, instead.

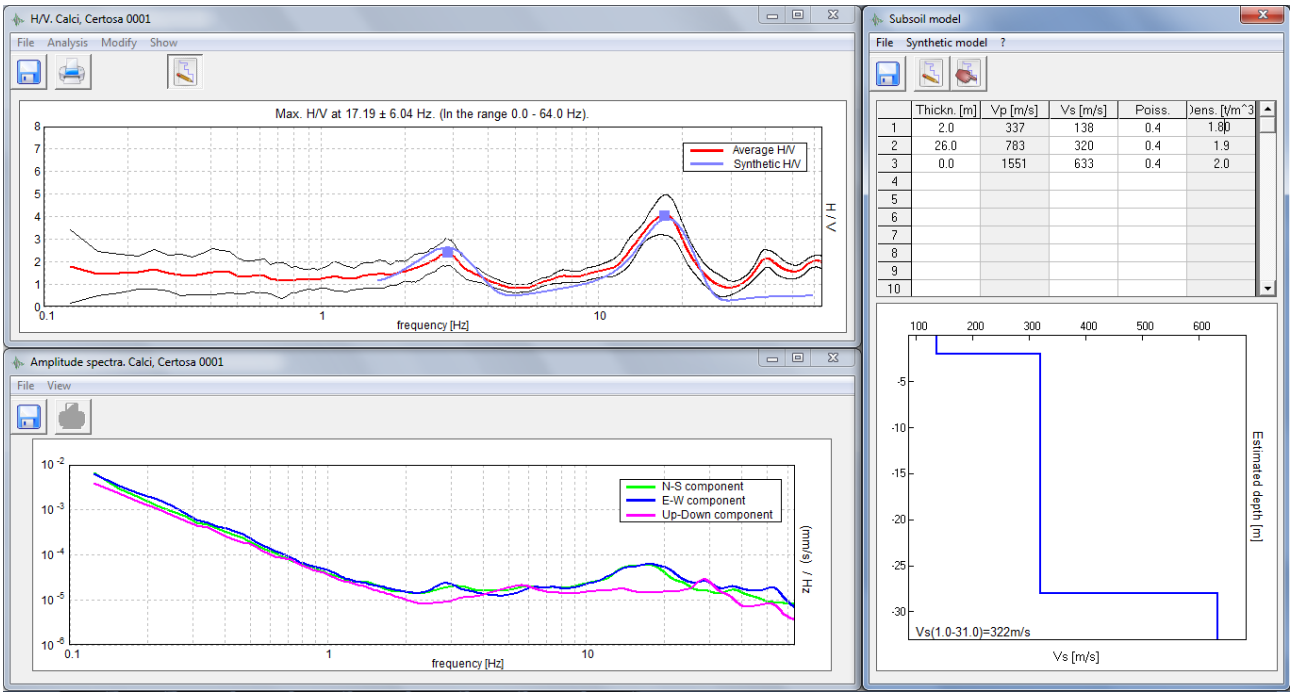



**Figure 12. Synthetic H/V curve (blue) produced by the automatic modelling routine of *Grilla*.**

**IMPORTANT WARNINGS:**

- ➔ If N peaks are selected for modeling, the automatic fit will always propose N+1 layers only (Occam's Razor principle).
- ➔ The automatic fit algorithm does not propose velocity inversions for mathematical reasons (contact support@tromino.it for questions). When a velocity inversion is suspected, the problem has to be addressed with the manual procedure.
- ➔ Do not try to fit more than 3-4 peaks. The automatic modeling follows the same rules of the manual modeling and fitting more than 4 peaks in the [0.1, 30]Hz usually makes little sense.
- ➔ Peaks very close in frequency could not be reproduced satisfactorily by the automatic modelling procedure.

## Other parameters

Further parameters relative to the automatic fit routine can be set by selecting SYNTHETIC MODEL >> MODEL SETTINGS in the *Subsoil model* window.

**MAXIMUM NUMBER OF ITERATIONS PER LAYER:** maximum number of iterations allowed to find an appropriate synthetic model for each layer (40 is the recommended number).

**PEAK AMPLITUDE TOLERANCE [%]:** accepted misfit (in percentage) between the experimental H/V peak amplitude and the synthetic one.

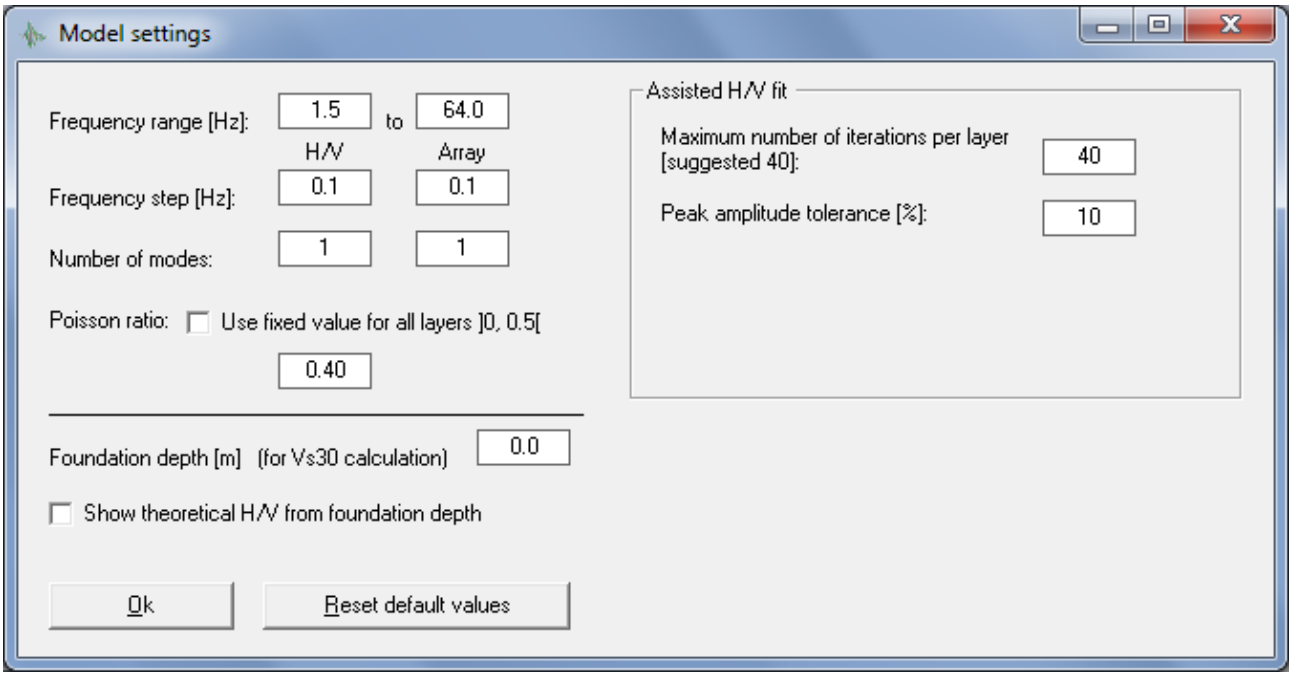





Figure 13. Parameter settings window for the automatic H/V modelling routine (right).

## Limitations

i) The modelling code introduced in *Grilla* is based on the assumption of plane-parallel layers. The comparison between H/V curves acquired at nearby sites can effectively show whether this assumption is satisfied or not.

ii) A quasi-equipartition of the wavefield between Rayleigh and Love waves is presently implemented in the code. This ratio could be varied, although it is difficult to be known *a priori*.

iii) One of the most critical part of the code implemented is the search for solutions of some sets of equations. It follows that the model can get 'unstable' for some $Vs_1$ / $Vs_2$ ratios (where 1 and 2 denote layer 1 and 2). This possibility is implicit in the nature of these models and, should it occur, the problem can be solved by adding a layer with $Vs_1 < V_S < Vs_2$.

iv) The velocity inversions, which are identified by a H/V ratio below 1 for a *wide* range of frequencies[2], due to the depression of the horizontal spectral components below the vertical one, are not easy to model since this is the case which suffers more from numerical instabilities. In presence of velocity inversions the user is forced to use low negative velocity gradients, e.g. a $V_S$ decrease from 400 m/s to 370 m/s. It will be more difficult to model an abrupt decrease from 400 m/s to, for instance, 200 m/s without any intermediate layer.

v) Since the H/V curve amplitude of broadband instruments below 1 Hz can be affected by meteorological and oceanic microtremor sources (due to instrumental tilt), the modelling code implemented in *Grilla* should be used with care below this frequency.

[2] A *narrow* H/V minimum at $2f_0$, where $f_0$ is the resonance frequency, is due to the ellipticity of the Rayleigh wave and not to a velocity inversion.

## 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 geophysics it is common to handle under-determined systems, with more unknowns than equations. These systems have an infinite number of solutions and this means that a same experimental curve can be fitted by an infinite number of models. In order to eliminate this ambiguity further constrains need to be introduced. In the single-station H/V case the constrain typically comes from the knowledge of the depth of a layer (from a penetration test, a drilling, a pit or an outcrop), the marker of which can be identified in the H/V curve or from the independent knowledge of $V_S$ in the first layer (e.g. by using the trigger cable of TROMINO® ENGY).

iii. The H/V curve modelling is a process which can take some time to beginners: be patient.

iv. Since the H/V curve amplitude recorded with broadband instruments below 1 Hz can be affected by the meteorological and oceanic microtremor sources (as an effect of the instrumental tilt), the modelling code implemented in *Grilla* should be used with care below this frequency.

v. As for other seismic modelling techniques, the simplifying assumptions underlying the models cause the $V_S$ estimate to suffer from an error which is normally of 20%.

vi. In no case surface-wave based models can provide $V_P$ and density profiles.

# Examples

The trace files of the following examples can be found in the *Grilla* CD. CASE 1 is the example fully discussed in the previous pages.



## CASE 2

Figure 14 illustrates the H/V curve recorded at a site characterized by 5 m silty sands overlying breccia. The contact with the calacareous bedrock is known to be located at about 30-40 m.

The resonance of the 5 m silty sands is well signaled by the H/V peak at 10 Hz, while the resonance of the covers overlying the bedrock cannot be clearly distinguished (it is possibly at 3-4 Hz, where the vertical spectral component still shows a local minimum) due to the poor impedance contrast between the breccias and the bedrock.

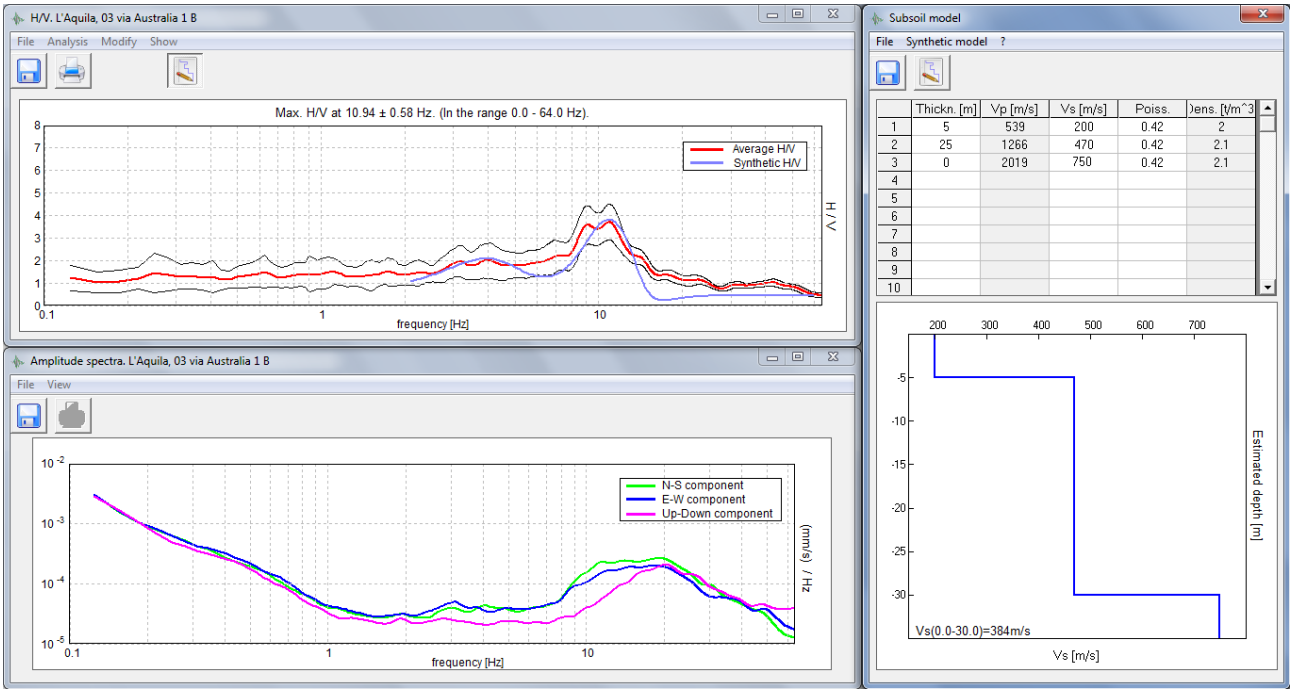



**Figure 14.**

## CASE 3

Figure 15 illustrates the case of a H/V curve recorded at a site characterized by 1 m natural soil, followed by silts down to 13 m depth, followed by gravels. The seismic bedrock is deeper than 100 m.

Three main H/V peaks appear: 40 Hz (natural soil-silt), 5 Hz (silt-gravel), 0.9 Hz (gravel-bedrock).



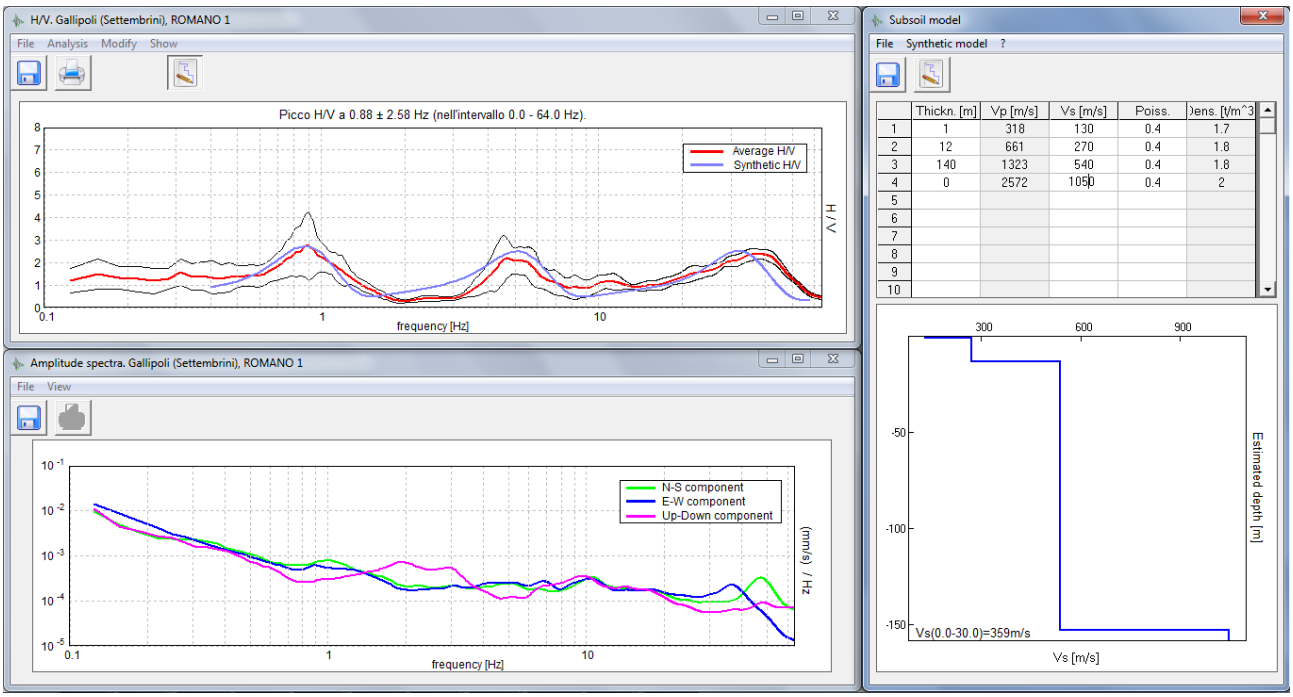



Figure 15.

# Bibliography

Aki K. and Richards P., 1964. *Quantitative Seismology*, University Science Books, Sausalito.

Ben-Menahem A. and Singh S.J., 1981. *Seismic Waves and Sources*, Springer-Verlag, New York.

Castellaro S. and Mulargia F., 2009a. Vs30 estimates using constrained H/V measurements, *Bull. Seism. Soc. Am.*, 99, 761-773.

Castellaro S. and Mulargia F., 2009b. The effect of velocity inversions on H/V, *Pure Appl. Geophys.*, 166, 567-592.