Seismic ground characterization by means of the

MASW method

(Multichannel Analysis of Surface Waves)

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PRESENTATION

Dr Roma obtained his Master degree in Civil Structural Engineering at the Technical U niversity of Turin (Politecnico di Torino), where he also received (in 2001) the title of Phylosophiae Doctor in Geotechnical Engineering under the supervision of Prof. Lancellotta. Dr Roma also spent one year (between 2000 and 2001) as visiting PhD student at the Georgia Institute of Technology of Atlanta (Georgia, USA) under the supervision of Prof. Rix.

Dr Roma has developped the MASW method (Multichannel Analysis of Surface Waves) during his PhD research and in the following years with passion and zealousness, as it is testified by the long list of "case histories" reported in the charter 4 of the book.

I am a Geotechnical Engineering Professor at the Technical University of Pisa (Tuscany), strongly convinced of the great importance of the geophysical methods for the geotechnical characterization od the sites, but I am not an export of Geophysics.

Nevertheless I have some certainties, in addition to the importance of the geophysical methods:

- I disagree with the use of commercial softwares without knowing the basic hypotheses, the limits and the potentialities of the software itself;
- Instead I agree with all the divulgatory actions aimed at a better comprehension of the tools which are used;
- I am convinced that surface seismic techniques are not only the most economical method for seismic classification accordino to international codes, but, as in the case of the MASW method, they also are the best compromise between cost and reliability for the dynsmic characterization of osils and rocks.

The work of Dr Roma, independently from the relevance of the innovative aspects, which I am not expected to judge, offers, by a simple manner, the basics for understanding the potentialities of the

MASW method. His work is also an example of divulgation of an advanced and innovative method such as the MASW.

Pisa, November 2006

Prof. Lo Presti Diego

Technical University of Pisa

Presentation

The interest of the scientific community and professionals toward the MASW (Multichannel Spectral Analysis of Surface Waves) method of investigation has grown up in the last 5 years. The reasons of this interest are: 1) the increased consciousness of the importance to identify the dynamic properties of soils, hence the importance of finding the shear wave velocity profile Vs by means of properly studied methods, with the aim of designing and understing the soil-structure dynamic interaction under dynamic loads (earthquake, wind, vibrations, explosions, etc..); 2) the need of a relattively simple method, which be sufficiently reliable and can overcome some of the drawbacks of altermative methods.

This book is associated to the software MASW and is intended to transmit the fundamental theoretical concepts at the basis of the MASW method to professionals, in a simple manner, together with practical suggestions on how to perform the MASW test in field, on

how to determine the experimental dispersion curve of the ground and on how to determine the shear wave velocity profile Vs, by which the equivalent shear wave velocity Vs30 and also the seismic class canbe established according to the international seismic codes like Eurocode 8.

As always happens the research day by day finds new theories and it is followed by a certain delay by the correspondent applicative and technological progress. Also in this case a possible application of the MASW method is proposed, which will probably be improved in the research centers worldwide.

The wish of the author is to make simple to use this new geotechnical and seismical method of investigation.

Torino (Italy), November 2006

Vitantonio Roma

Dedicated to Elena, Miriam and Lorenza

1. CHAPTER 1: SEISMIC CLASSIFICATION OF SOILS AND LOACL EFFECTS

1.1 Introduction

This chapter is arranged as follows.

After a brief reference to the indications provided by the new italian seismic code and by the european Eurocode 8 about the loacl seismic classification of the sites, the importance is underlined of the alternative geotechnical methods of investigations, which should be considered as complementary each others. Finally the MASW method is introduced and explained.

1.2 Seismic site classification accordino to the new italian seismic code OPCM 3274 and to the italian law DM 14/09/2005

The new italian seismic code OPCM, as well as the new italian law DM 14/09/2005 "Testo Unico sulle Costruzioni", when no other specific analyses are avilable, defines the seismic load for design on the basis of the seismic zone and the seismic class of the site where the structure is expected to be constructed. Inside the italian country 4 seismic zones have been identified until now. To each zone a value a_g of the peak ground acceleration normalised to the gravity has been assigned. The conventional values a_g of the 4 different seismic zones refer to the peak acceleration on the free surface of site of type A, that is rock or very stiff soil (**table 2.1**), where the seismic motion does not vary significantly propagatine from the bedrock to the free surface. When dealing with sites of type B, C, D E, S1, S2 the seismic motion varies passing from the bedrock to the free surface, depending on the amplitutde and the frequency content of the motion and the seismic

and geotechnical and geometrical caracteristics of the soils above the bedrock.

When a specific anlysis of the local seismic effects at the site is not available, for sites B, C, D, E the code recommends the amplification factor S, to evaluate the seismic spectral acceleration, as well as the caracteristic periods T, that define the spectral response of a simple oscillator with 5% damping. When dealing with sites of type S1 or S2 the code recommends a specific anlysis of the local seismic effects at the site.

The seismic classification of the site is conventionally performed on the basis of the averaged equivalent propagation velocity of the shear waves within the first 30m of the site:

$$V_{s30} = \frac{30}{\sum_{i}^{n} \left(\frac{h_i}{V_{si}} \right)} \qquad (1.1)$$

where Vsi and hi are the shear wave velocity and the thickness of the ith layer.

It should be observed that:

- Even if it is not explicitly said, the vertically propagating shear waves must be considered
- The velocity Vs30 is not a simple arithmetic average of the shear wave velocities Vsi of the different layers, but it is the “equivalent” velocity in terms of time within the first 30m of site.
- When the velocity Vs30 is not available, the code allows the use of the Nspt (for granular soils) or the use of the undrained shear resistance Cu (for coesive soils). This option is discouraged bu the author, since it is not appropriate. In fact the SPT test and the Cu are only indidìrectly linked to the

wave propagation caracteristics of the ground; also the use of Nspt or Cu may be difficult in several situations: when both granualr and coesive layers exist; failure of the SPT test due to the presence of blocks; value of Cu depending on deformation level and on the method of investigation.

- The seismic classification of the site cannot be performed by knowledge of only the velocity Vs30, in fact additional information are required for sites of type S1 and S2. This remebers us that the geotechnical classification of a site can be done by means of different types of geotechnical investigations, which should be considered complementary each others.

Suolo	Descrizione geotecnica	Vs_{30} (m/s)
A	Formazioni litoidi o suoli omogenei molto rigidi caratterizzati da valori di Vs30>800m/s, comprendenti eventuali strati di alterazione superficiale di spessore massimo pari a 5m	>800
B	Depositi di sabbie o ghiaie molto addensate o argille molto consistenti, con spessori di diverse decine di metri, caratterizzati da un graduale miglioramento delle proprietà meccaniche con la profondità e da valori di Vs30 compresi tra 360m/s e 800m/s	360÷800 (Nspt > 50) (Cu >250 kPa)
C	Depositi di sabbie o ghiaie mediamente addensate o argille di media consistenza, con spessori variabili da diverse decine fino a centinaia di metri, caratterizzati da valori di Vs30 compresi tra 180m/s e 360m/s	180÷360 (15 < Nspt < 50) (70 < Cu < 250 kPa)
D	Depositi di granulari da sciolti a poco addensati o coesivi da poco a mediamente consistenti, caratterizzati da valori di Vs30 < 180m/s	< 180 (Nspt < 15) (Cu < 70 kPa)
E	Profili di terreno costituiti da strati superficiali alluvionali, con valori di Vs simili a quelli dei tipi C o D e spessore compreso tra 5m e 20m, giacenti su di un substrato di materiale più rigido con Vs > 800m/s	
S1	Depositi costituiti da, o che includono, uno strato spesso almeno 10m di argille/limi di bassa consistenza, con elevato indice di plasticità (IP>40) e contenuto d'acqua, caratterizzati da valori di Vs30 < 100m/s	< 100 (10 < Cu < 20 kPa)
S2	Depositi di terreni soggetti a liquefazione, di argille sensitive, o qualsiasi altra categoria di terreno non classificabile nei tipi precedenti	

Table 2.1: Seismic classification of the ground according to the new italian code O.P.C.M. n. 3274/2003 and D.M. 14/09/2005 Testo Unico sulle costruzioni.

1.3 Seismic classification accordino to the european Eurocode 8

The seismic classification reported by the new italian codes is the same as the european Eurocode 8. In **table 2.2** the seismic types of ground are reported.

Ground type	Description of stratigraphic profile	Vs_{30} (m/s)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	>800
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360÷800 (Nspt > 50) (Cu >250 kPa)
C	Deep deposits of dense or mediumdense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180÷360 (15 < Nspt < 50) (70 < Cu < 250 kPa)
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm coesive soil.	< 180 (Nspt < 15) (Cu < 70 kPa)
E	A soil profile consisting of a surface alluvium layer with vs values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with vs > 800 m/s.	
S1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (10 < Cu < 20 kPa)
S2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S1	

Table 2.2: : Seismic classification of the ground according to Eurocode 8.

1.4 Seismic classification of the ground by means of hte MASW method

The MASW method (Multichannel Analysis of Surface Waves) is a non invasive technique (no boreholes are needed) which allows to determine the shear wave velocity profile of the ground, by measuring the wave motion on the free surface of the ground. The main contribution to the superficial wave motion is given by the Rayleigh waves, which travel at a speed, that is strictly correlated to the stiffness of the soil region where propagation occurs. In a layered half-space Rayleigh waves are dispersive, that is waves with different wavelength travel with different speeds, both phase and group velocities (Achenbach, J.D., 1999, Aki, K. and Richards, P.G., 1980). This means that the apparent phase velocità of Rayleigh waves depends on the frequency.

Dispersion phenomenon is related to the fact high frequency waves (short wavelengths) travel through superficial layers, instead low frequency waves (long wavelengths) involve deeper layers durino propagation (**figure 2.13**).

The MASW method can be distinguished into active MASW method and passive MASW method (Zywicki, D.J. 1999) or a combination of both methods can be used.

In the activa MASW method the superficial waves generated at a point on the free surface of the ground are measured along a linear array of receivers. In the passive method the receivers can be placed along a line, a circe, a square, a triangle and the ambient noise is measured.

Generally the active method allows to measure an apparent dispersion curve (or phase velocity) within the frequency range 5Hz - 70Hz,

hence it gives information about the first 30m - 50m of the ground, depending on the ground stiffness. The passive method generally allows to measure the experimental apparent dispersion curve within the range 0 Hz - 10Hz, hence it gives information about the deeper layers of ground, generally at depths greater than 50m, depending on the ground stiffness.

In the following reference will be made to only the active MASW method, which allowes to determine the seismic class of the site, because the shear wave velocità profile of only the first 30m are required.

The MASW method consists of 3 steps:(Roma, 2002): (1) the first step consists of calculating the experimental apparent dispersion curve on the basis of the wave motion measured in field, (2) the second step consists of calculating the numerical apparent dispersion curve, based on a preliminary soil profile, (3) the third and last step consists of finding the optimal shear wave velocità profile Vs, by varying the thickness h, the shear and compression wave velocities Vs and Vp (or equivalently the Poisson coefficient υ), the mass density ρ of the ground layers, until an optimal match between the experimental apparent dispersion curve and the numerical apparent disprsion curve is obtained. In the next chapters the meaning of the dispersion curves, both experimental and numerical, will be explained, as well as how they can be calculated.

The soil profile and hence the shear wave velocità profile can be found by means of a trial and error method or an authomatic procedure or with a combination of both.

Generally the nummebr of ground layers, the Poisson coefficient, the mass density are assigned and then the thicknesses and the shear wave velocities of the layers are changed.

In the trial and error procedure the user assignes different values of the Vs and the thicknesses, trying to get a satisfactory match between the experimental and the numerical dispersion curves. In the autohmatic procedure (Roma, 2002, Roma, 2001, Joh, 1998) the search of the

optimal solution is performed by means of a local or a global algorithm.

Generally when the relative error between the experimental and the numerical dispersion curves is comprised between 5% and 10% the solution is satisfactory and the soil profile can be considered valid by a design point of view.

Once the shear wave velocity profile has been found, the equivalent shear wave velocity Vs30 can be calculated and the seismic class of the ground can be determined.

The reader shoul remember what has beem previously said about the importance of additional geotechnical information when dealing with soils of type S1 or S2.

1.5 Considerations about methods alternative to MASW

The MASW method is very similar to the sismic refraction and seismic reflection methods, because they both are based on the measurement of the wave motion on the free surface of the ground.

With respect to the refraction method, the MASW method offers the advantage of overcoming some problems, for example caused by the existance of soft layers between stiffer ones, or stiff layers trapped between softer ones, or when using the P waves caused by the existance of the water table, which covers under water layers with a compression wave velocity lower than the P wave velocity into water. The MASW method allows to determine the shear wave velocità profile when dealing with strong stiffness contrast among layers. The existance of the water is modelled by assigning a Poisson coefficient comprised between 0.4 and 0.5 depending on the saturation degree.

The theoretical basis of the MASW method refer to a horizontally stratified half-space, hence in grounds with a gradient higer than 20° the MASW method needs further validation. In practice it has been observed that, if the aray of receivers is alligned with the direction of maximum gradient, then the dispersion curve is shifted. The problem

can be mitigated by allignining the receivers array perpendicularly to the direction of maximum gradient.

With respect to the other geotechnical methods used to determine shear wave velocità profile, such as cross-hole, down-hole, up-hole, SCPT, the MASW methods needs less time and money. Also the MASW method offers the advantage of providing averaged information within the whole region of ground that has been investigated, without the need of repeating the test at several points (i.e. cross-hole). Another advantage is that it is quite easy to reach the location to perform the test, as no big machines are required for the test.

On the other hand the interpretation of the MASW test requires an expert user.

2. CHAPETR 2: THEORETICAL BASIS OF MASW METHOD

2.1 Introduction

The scope of this chapter is to provide a qualitative description of the main theoretical concepts about wave propagation through elastic layered media. After a brief description of the several types of waves, wich may exist into a homogeneous, elastic, infinite medium and at the interface between two semi-infinite media, Rayleigh waves are explained, since the MASW method relay on Rayleigh waves. As it has been said in the previous chapter, the MASW method allows to determine the shear wave velocity profile Vs with depth by properly modifying the shear wave velocities and the thicknesses of the layers, until a satisfactory optimal match is obtained between the the experimental apparent dispersion curve (or apparent phase velocity) measured in field and the numerical apparent dispersion curve (or apparent phase velocità). For this purpose it will be explained what the experimental and numerical dispersion curves are and how they can be determined.

2.2 Infinite homogeneous medium

Into an infinite homogeneous medium two types of waves can propagate: compression waves P, also called primae, and distorsional waves S, alse called secundae. The speed of propagation of these waves depends on the elastic properties of the medium.

Compression waves P travel at a speed c_p equal to:

$$c_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \qquad (2.1)$$

where μ=G , (2.2)

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)} \qquad (2.3)$$

are the Lamè's elastic constant of the medium, G is the shear stiffness, E is the Young's modulus, ν is the Poissin's coefficient, ρ is the mass density,

and mass particles of the medium oscillate in the same direction of wave propagation.

Shear waves S travel at a speed c_s equal to:

$$c_s = \sqrt{\frac{\mu}{\rho}} \qquad (2.4)$$

and mass particles of the medium oscillate along a direction which is perpendicular to the direction of wave propagation.

2.3 Shape of the wave front

Until now we have seen that into an infinite homogenous medium two types of wave can propagate: compression waves P and distorsional waves S. We have not yet specified the shape of the wave front. First of all we need to define the concepì of wave front. To a wave perturbation we can associate an amplitute and a phase. The phase is correlated to the periodicity of the wave motion in time and in space, the amplitude is correlated to the energy transferred by the wave. The wave front may refer to the phase or to the amplitude and it separates the region of the time-space which has already experienced the effects of the perturbation from the region of the time-space which is still at rest. Several shapes of wave front exist in nature, the simplest ones are the plane shape, the spheric and the cylindrical.

The plane wave propagate with plane wave fronts, where the wave amplitude remain the same, without geometrical attenuation. An example consists of the sound wave which travels into a corridor completely confined by the lateral walls, the floor and the ceiling.

In spheric waves total energy propagates away from the origin source with spheric wave fronts, hence energy density decreases as a factor of $1/r^2$ as a function of the distance r from the source. Several examples of spheric waves exist in nature, such as the the light form a spheric source or the sound generated by an explosion in the sky. Cylindrical waves propagate with cylindrical wave fronts and geometric attenuation of energy occurs with a factor of 1/r.

A common example is the perturbation which travels on the free surface of a lake after the fall of a stone.

2.4 Stationary and progressive waves

Another important distinction among several types of waves is represented by stationary or progressive waves. Stationary waves are characterised by stationary points (said nodes) which have null phase. The nodes appear always the same in time and space, wthout any change. Progressive waves propagate through the matter with travelling nodes.

For example consider the displacement caused by a plane wave, which propagates at a phase speed c along the direction of the propagation vector $\hat{p}$. It can be written as:

$$\underline{u}(\underline{x},t) = f(\underline{x}\cdot\hat{p} - ct)\hat{d} \qquad (2.5)$$

where $\underline{x}$ is the position vector, t is time and $\hat{d}$ is a versor which indicates the direction of the particle oscillation.

Wave fronts of the phase are expressed by the following equation :

$$\underline{x}\cdot\hat{p} - c\cdot t = \text{costante} \qquad (2.6)$$

they propagate at a phase velocità c remaining perpendicular to the direction of the propagation vector $\hat{p}$.

2.5 Waves at the interface of two media and Stoneley waves

In the following we will deal with steady-state plane waves if not differently specified and it will be shown what happens when an incident wave encounters a plane interface between two half-spaces with different mechanical properties (**figure 2.1**). The first half-space is beneath the interface and its properties are λ, μ, and ρ, the second half-space is above the interface and its properties are indicated by the index B.

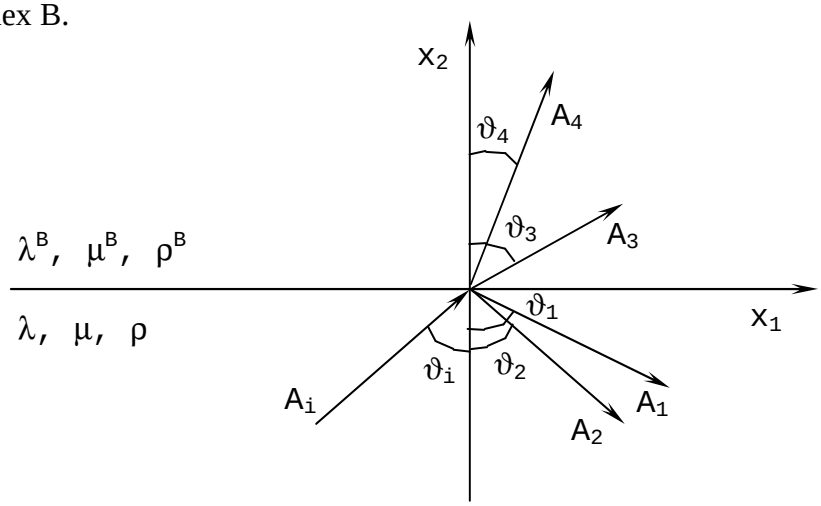


Figure 2.1: Incident wave Ai, reflected A1, A2 and transmitted A3, A4 in-plane waves at a plane interface between two different half-spaces.

Consider an incident stationary plane wave of amplitude A_i which reaches the plane interface.

If the two media have an elastic behaviour, then horizontally polarised incident waves SH will cause only SH refracted and reflected waves; if the incident wave belongs to the vertical plane (P or SV waves), then refracted and reflected waves will belong to the vertical plane

too. Let us consider the in-plane motion, so that only P and SV waves are concerned. In general an incident P or SV wave coming from the first half-space generates both P and SV reflected waves in the same half-space and P and SV transmitted waves in the second half-space (mode conversion phenomenon). Under particular conditions waves propagating along the interface can be generated, that, when no one of the two half-spaces is air, are called Stoneley waves. In all cases the principle of causality must be respected, so that all the waves produced by the incident wave at the interface must propagate away from the interface (Achenbach, 1999). For any further details reference is made to (Roma, 2001, Achenbach, 1999, Ewing et al., 1957).

2.6 Rayleigh waves into an infinite homogeneous half-space

When one of the two half-spaces separated by an interface, say the upper one, is air it can be assumed that there are not transmitted waves and in general only reflected waves exist. It can be proven that for a homogeneous half-space, besides the body P and S waves as just seen in an unbounded region, a new kind of wave exists, called Rayleigh wave from Lord Rayleigh who first investigated it. The Rayleigh wave is the result of the interaction of P and S waves under the following particular conditions:

1. the wave motion associated with the Rayleigh waves rapidly attenuates with depth
2. no stresses exists at the free interface

The speed of propagation of the Rayligh wave on the free surface of the homogeneous half-space is slightly lower than the speed c_s of the shear waves S (between $0.862 \cdot c_s$ and $0.955 \cdot c_s$) and it depends on the Poisson coefficient υ (Achenbach, 1999):

$$c_R = \frac{0.862 + 1.14\nu}{1+\nu} \cdot c_S \qquad (2.7)$$

Into a homogeneous half-space the phase velocity of Rayleigh wave does not depend on frequency or wave number k, hence dispersion does not happen.

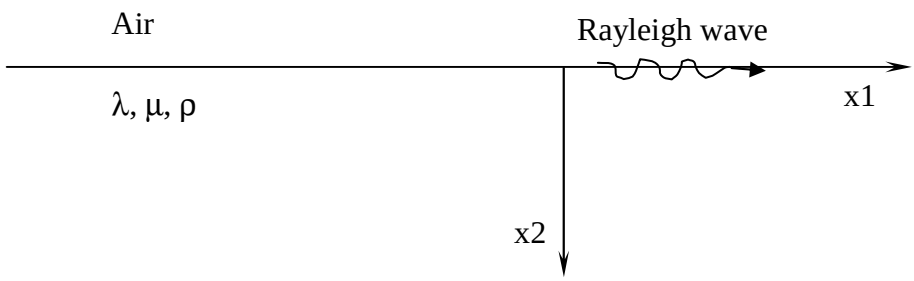


Figure 2.2: Rayleigh waves in a homogeneous half-space.

We can observe from **figura 2.3** that the horizontal and the vertical components are 90° out of phase, so that during the propagation they generate an ellipse. The major axe of the ellipse is parallel to the free surface down to a depth of about 0.2λ (λ is the wavelength), where the horizontal displacement changes its sign and the orientation of the axes and the sense of going around of the ellipse are reversed. It can also be realized how the displacements drop down with increasing depth, so that the motion, due to Rayleigh wave, is confined in the upper side of the half-space, inside a length of about 1.5 wavelengths λ (**figura 2.4**).

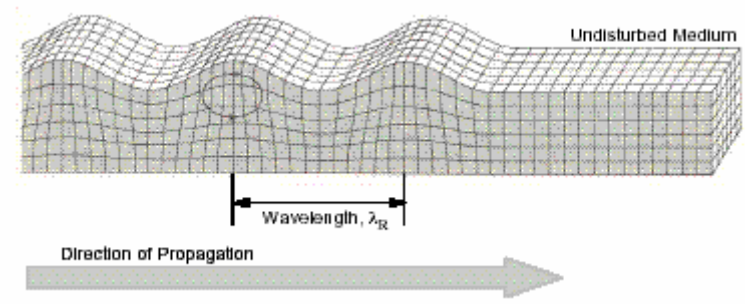


Figure 2.3: Rayleigh disturbance on the free surface of a homogeneous half-space (Bolt, B.A., 1976).

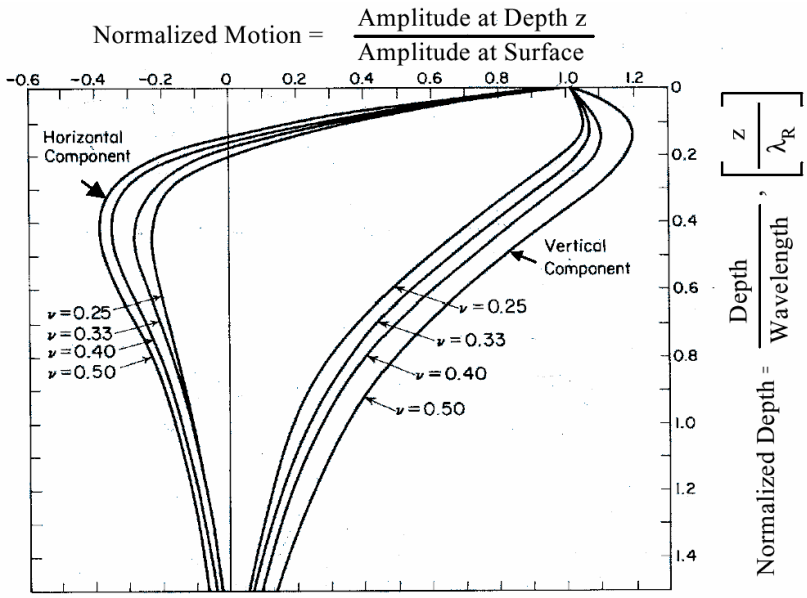


Figure 2.4: Variation of horizontal and vertical normalized components of displacements induced by Rayleigh waves with normalized depth in a homogeneous isotropic, elastic half-space (Richart et al.,1970).

2.7 Onde in un semispazio infinito stratificato

In the previous sections we have seen which types of waves can propagate into an unbounded region, i.e. P, SV, SH waves and in a homogeneous half-space, i.e. P, SV, SH and Rayleigh waves . We have also studied what happens at an interface between two half-spaces with different characteristics: mode conversion, Stoneley waves. We know that when a P or S wave encounters an interface, several kinds of waves can be generated, depending upon the properties of the two half-spaces. In a general situation part of the energy carried by the incident wave is reflected back and the remaining part passes through the interface, sometimes another part travels in the vicinity of the interface, that behaves like a store of energy. Anyway when a layered half-spaced is considered, with n infinitely horizontal, homogeneous, linear elastic layers overlying an infinite half-space, it can be imagined how complicate it becomes to account for all the possible waves (**figure 2.5**).

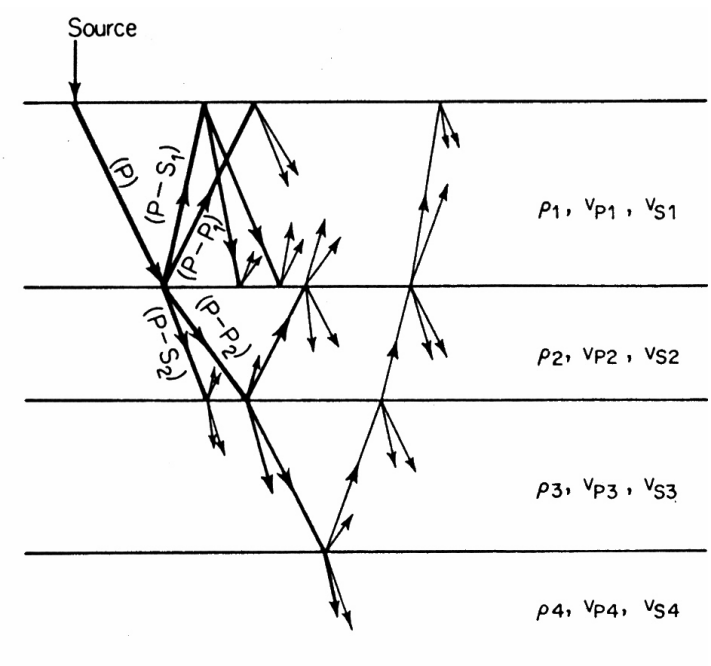


Figure 2.5: Multiple interaction among incident, reflected and transmitted waves in a layered half-space: mode conversion phenomenon (from Richart et al.,1970).

What happens is an interaction among all the incident, reflected and transmitted waves inside each i-th layer, that combine together canceling or reinforcing each other, giving raise to destructive or constructive interference.

In order to explain this concept, look at the fig.1.6

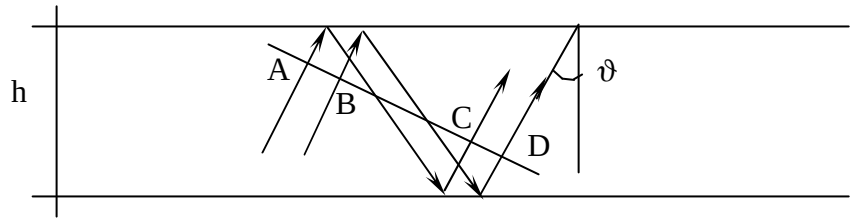


Figure 2.6: Constructive interference of reflected rays in a wave-guide (Tolstoy, 1973, Ewing et al, 1957).

If we consider a plane wave reflected back and forth inside a layer, after n reflections any pair of neighboring elements of a wave-front will remain in phase, that is:

Path A to C = path B to D = $n\lambda$

in which λ is the wavelength of the wave.

Rigorously speaking the equations of motion must be written for each i-th layer using the mechanical properties of the layer. Also the continuity of displacements and stresses at the interfaces must be imposed. For each layer 4 independent constants have been adopted: shear wave velocity VSi, thickness hi, Poisson's ratio νi and mass density ρi (**figure 2.7**). The radiation condition is also assumed (that is the perturbation disappears at infinite depth), in addition to the stress-free condition on the free surface (if no external loads are applied) and the boundary-initial conditions (that need to be specified for each situation).

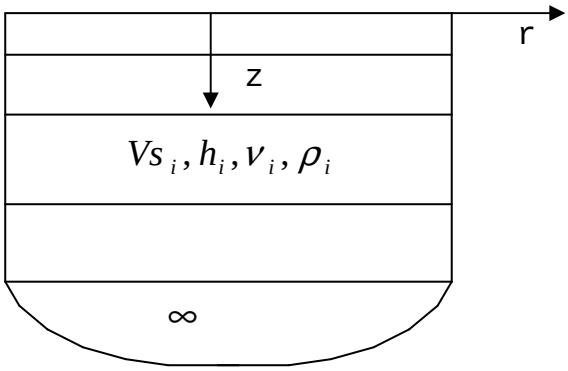


Figure 2.7: Model of the layered half-space

2.7.1 Love waves

Before going on with the analysis of the Rayleigh waves and the other types of surface waves in the vertical plane, Love waves deserve to be mentioned. Love waves are horizontally polarized waves that propagate near the free surface of a layered half-space (**figure 2.8**).

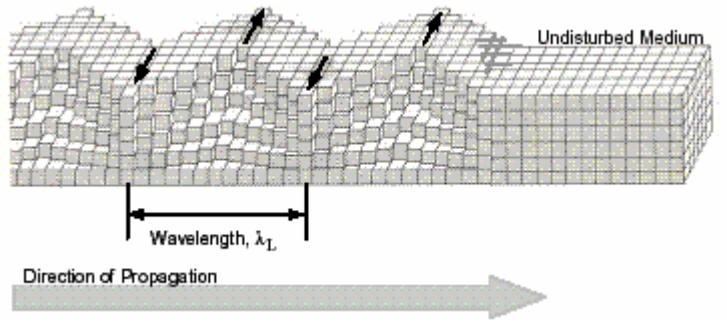


Figure 2.8: Love wave on the top of a layered half-space (Bolt, 1976).

In fact it can be proved that this type of wave cannot exist in an infinite homogeneous half-space (Aki and Richards, 1980, Pujol, 2002), and at least one layer is necessary for their existence. The reason is that Love waves are the result of the constructive interference among incident and multiple reflected SH waves. It is interesting to notice that, under the hypothesis of linear elasticity in an isotropic medium, an incident SH wave generates only reflected and transmitted SH waves and mode conversion does not occur, for the equation of motion for horizontal displacement is uncoupled. This aspect could be properly used in soil characterization, since during the experiments, only horizontally polarized motion should be measured, if a perfect horizontal source is employed. Even if it will not be shown herein, it is reminded that Love waves are dispersive, that is the phase velocity depends on the frequency associated to the wave.

2.7.2 Head waves

Head waves are also referred as “refraction arrivals” or “Lateral waves” and the “seismic refraction” method for determining the thickness and the body velocities of a layered half-space are based on these types of waves. When an incident wave impacts an interface between two layers with different velocities at the total internal reflection angle δ (**figure 2.9**), a disturbance is generated, that travels along the interface with the velocity $v_2 > v_1$ of the lower layer.

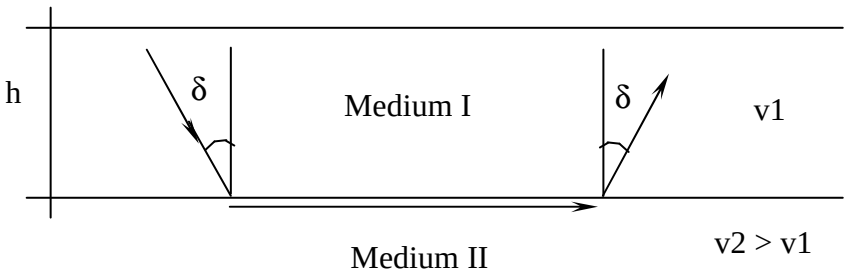


Figure 2.9: Head wave generated at an interface

On the interface the disturbance produces a new wave, that arises from the interface at the same angle δ and has got an amplitude proportional to the amplitude of the incident wave (Brekhovoskikh, 1960).

2.8 Rayleigh waves and modal curves in a layerd half-space

The MASW method is based on measurement and analysis of Rayleigh waves in a layered half-space.

The existence of Rayleigh waves in a layered half-space has been studied in the past years by means of several methods. The the most common methods are the *propagator matrix methods* (Kennett, 1983, Aki and Richards, 1980) and the *method of reflection and transmission coefficients* (Kennet, 1974, Aki and Richards, 1980). The *transfer matrix methods* (Thomson, 1950, Haskell, 1953) and the dynamic stiffness matrix method (Kausel and Roesset, 1981) belong to the first class of methods. In the *transfer matrix method*, without loss of generality, a plane time harmonic perturbation is assumed as solution for the equations of motion in the vertical plane that are written for each layer. Successively by imposing the continuity of the velocities and the stresses at the interface between the n-th layer and the (n-1)-th layer, enables one to write a recursive formula that correlates stresses and displacements in one layer. The matrix that allows for such a correspondence is the transfer matrix of the layer. The quantities of the first layer and of the half-space can be related, by means of the continuity of displacements and stresses at the interfaces. If the amplitude of the perturbation is made exponentially decay to zero at infinite depth (radiation condition) and the stresses at the free surface of the layered half-space are set equal to zero, a system of equations is obtained. In order to have non trivial solutions, the determinant of the matrix of the coefficients of this system, the so called global transfer matrix, must vanish. In this way the Rayleigh secular function (2.8) is originated. The Rayleigh secular function is an implicit relationship among the geometrical-mechanical properties of the layered half-space and the frequency f and the wave number k of the possible perturbations, that we want to find into the system under the above specified conditions:

$$R(Vs_i, h_i, \nu_i, \rho_i, k, f) = 0 \qquad i = 1 \div n+1 \qquad (2.8)$$

The wave number k is by definition related to the wavelength $\lambda=2\pi/k$ in analogy to the angular frequency ω, which is related to the period $T=2\pi/\omega$.

The *stiffness matrix method* is conceptually the same as the transfer matrix method, but it offers the advantages given by the use of the tools of the structural analysis.

By using the transfer matrix of the generic i-th layer, the equilibrium of the force acting on the i-th layer is assured and the stiffness matrix of the layer is defined as the link between the forces and the displacements at the two interfaces of the i-th layer. Then, using the rules of the structural analysis, the stiffness matrices of all the layers and the half-space are combined together at the nodal interfaces, to get the dynamic equilibrium of the whole system:

$$\overline{F} = [S] \cdot \overline{X} \qquad (2.9)$$

in which $\overline{F}$ and $\overline{X}$ represent the external loads and the displacements at the interfaces of the layers. Even in this method in-plane time-harmonic solution has been assumed, so that the stiffness matrix S includes both inertial and elastic contributions expressed in terms of the geometrical and mechanical properties of the system V_{Si}, h_i, ν_i, ρ_i ($i=1\div n+1$) and of the circular frequency ω and the wave number *k*.

Since Rayleigh modes are the free vibrations of the layered half-space, the external loads vector is set equal to zero:

$$\overline{F} = 0 \qquad (2.10)$$

and the resulting homogeneous eigenvalue problem is considered:

$$0 = [S] \cdot \overline{X} \tag{2.11}$$

In order to look for non trivial solutions, the determinant of the stiffness matrix S must vanish:

$$\det[S] = 0 \tag{2.12}$$

In this way the Rayleigh geometrical dispersion relation (2.8) is again reached in implicit form. From dispersion relation (2.8) modal curves can be obtained.

Now we will focus on the roots of the Rayleigh dispersion relation (2.8), also called period equation of Rayleigh. Generally the roots are searched by numerical techniques, fixing a value of frequency f_0 and looking for the wave numbers that satisfy (2.8). The Rayleigh dispersion relation is a multi-valued function, so for a fixed frequency several wave numbers may exist that solve (2.8). Each solution is an eigenvalue and physically represents a simple wave, called Rayleigh mode, that can propagate in the system under all the conditions that have been previously specified. For a fixed circular frequency ω_0 the first mode corresponds to the greatest wave number k_1 and it is the fundamental Rayleigh mode. The other wave numbers define the higher Rayleigh modes and are characterized by smaller wave numbers. For a better comprehension of these concepts an example (case A) will be introduced.

Consider the system whose characteristics are reported in the **table 2.1** below:

Layer	Thickness h(m)	Vp (m/s)	Vs (m/s)	Mass density (Kg/m^3)
1	5	600	350	1800
2	10	700	400	1800
Half-space	∞	800	450	1800

Table 2.1: Characteristics of the system for Case A

If we plot the Rayleigh dispersion relation in the frequency- wave number domain (**figure 2.10**), we observe that for very low frequencies at least one root or wave number k exists.

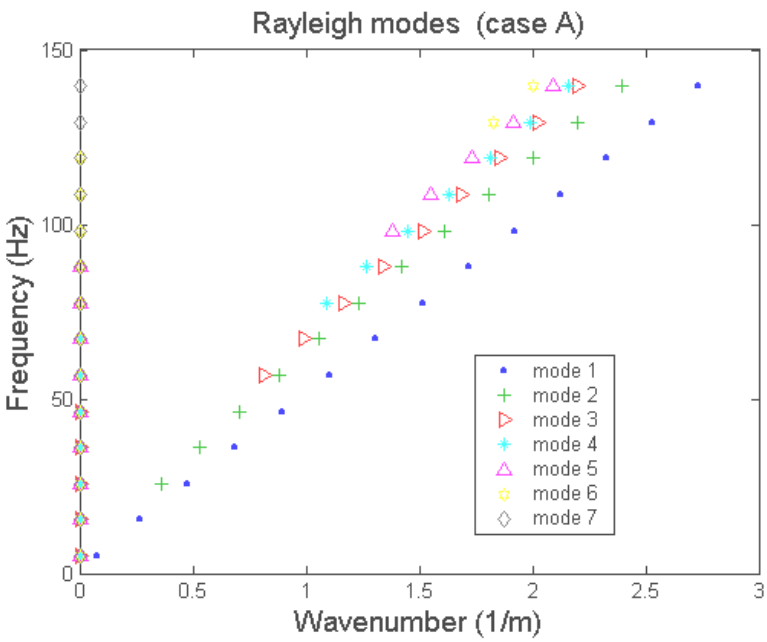


Figure 2.10: Dispersion Relation and Rayleigh modes for Case A.

It corresponds to the first or fundamental mode and in fig.1.10 is represented by blue dots.

For frequencies greater than about 25 Hz a second root is found, that is the second mode (green plus) and so on for the other higher modes. It is evident that each higher mode appears above a certain frequency called *cut-off frequency*. The cut-off frequency increases as the mode number increases too and the mode cannot propagate below this critical frequency, since it does not carry energy at all. It is important to underline that we have introduced the concept of Rayleigh modes as the roots of the dispersion relation (2.8), so instead of fixing a value

of frequency and looking for the wave numbers that satisfy (2.8), we can also hold a fixed wave number and search all the frequencies that solve (2.8).

This idea is easy to understand if in the **figure 2.10** we enter with a particular wave number, say k=1/m and intersect the first three modal curves, to which three different frequencies correspond. It should be noted that the 7-th mode has got a cut-off frequency of about 150 Hz, hence it is not visible on the graph.

For each mode we can define modal quantities, that refer to phase velocity, group velocity, displacement and energy. If we imagine to keep constant a value of frequency f_0, each mode is individuated by its wave number and the modal phase velocity becomes:

$$c_j = \frac{\omega_0}{k_j} = \frac{2\pi f_0}{k_j} \tag{2.13}$$

Another quantity needs to be introduced, that is the group velocity defined as:

$$\frac{\partial \omega}{\partial k} = c + k\frac{\partial c}{\partial k} \tag{2.14}$$

For a fixed value of frequency the group velocity is:

$$U_j = \frac{\partial \omega_0}{\partial k_j} \tag{2.15}$$

Looking at the **figure 2.11** the geometrical meaning of both phase and group velocities is presented. At a point P on a generic j-th modal curve the phase velocity is the tangent of the angle δ, instead the group velocity is the tangent of the angle β made by the tangent to the modal curve in P and the horizontal line.

The physical meaning of these two velocities is: the phase velocity describes how fast the surface of constant phase, associated to the perturbation, is moving. The group velocity has got a cinematic and an energetic definitions, so it may represent either the speed of a group of waves travelling together or the velocity of the energy carried by the disturbance.

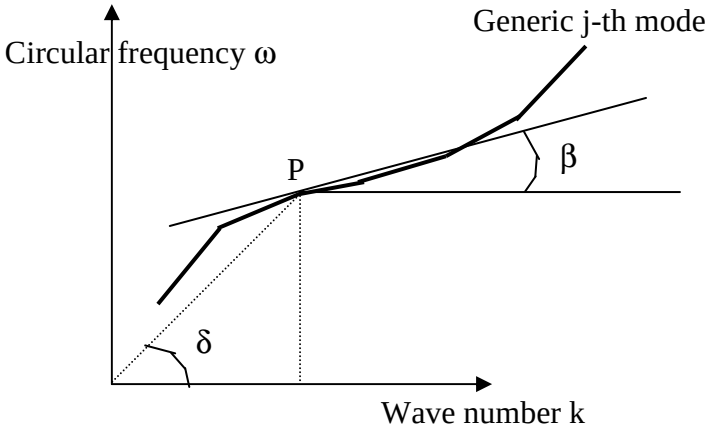


Figure 2.11: Geometric explanation of phase and group velocities in the frequency-wave number domain.

Now that the significance of phase velocity has been clarified, it is possible to show the Rayleigh dispersion relation for the same case A in the phase velocity-frequency domain (**Figure 2.12**):

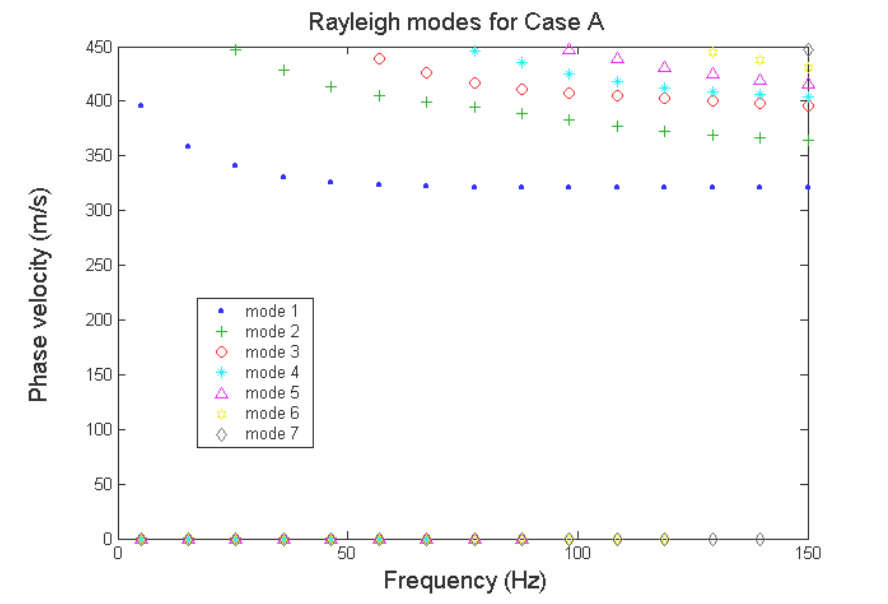


Figure 2.12: Rayleigh modes for case A.

In this representation some interesting aspects can be underlined. First of all for a given frequency each mode is characterized by its own velocity and this is why we talk of dispersion. Actually the dispersion of waves is always present in a system when waves of different wavelengths travel with different speeds. So if the phase velocity is a non constant function of the frequency, then dispersion exists and, as a consequence, group and phase velocities are different.

In f**igure 2.12** the cut-off frequencies for the higher modes are again visible. It can also be observed that, at the cut-off frequency, all the modes have got a phase velocity equal to the shear wave velocity of the half-space $V_{S\infty}$=450 m/s. The reason is that at the cut-off frequency the generic j-th mode has got its greatest wavelength λ_{max} according to the relationship between spatial and temporal scales:

$$c = \lambda \cdot f \tag{2.16}$$

For the second mode of the case A the maximum wavelength is:

$$\lambda_{\max} = \frac{c}{f_{cut-off}} \cong \frac{450 m/s}{25.7 Hz} = 17.5 m \tag{2.17}$$

Since Rayleigh waves travel on the surface inside a belt of about 1÷2 wavelengths, the disturbance with a great wavelength is mainly travelling through the deepest layer. On the other hand for very high frequencies the wavelength is so small, that it is as if the disturbance does not feel the presence of the deeper layers and travels

through the surface layer with the same phase velocity that it would have in a homogeneous half-space with the same characteristics of the first layer. In fact as the frequency increases to infinity, all the modal phase velocities tend to the value given by (2.18), where $c_S = V_{S1} = 350 m/s$ and $\nu = 0.24$:

$$c = \frac{0.862 + 1.14 \cdot 0.24}{1 + 0.24} \cdot 350 m/s = 320 m/s \qquad (2.18)$$

The **figure 2.13** well illustrates the physical insight behind these observations:

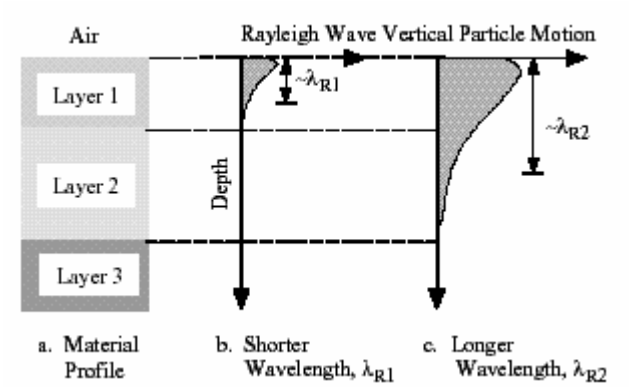


Figure 2.13: Depth sampled by Rayleigh waves with different wavelengths (Stokoe II and Santamarina, 2000)

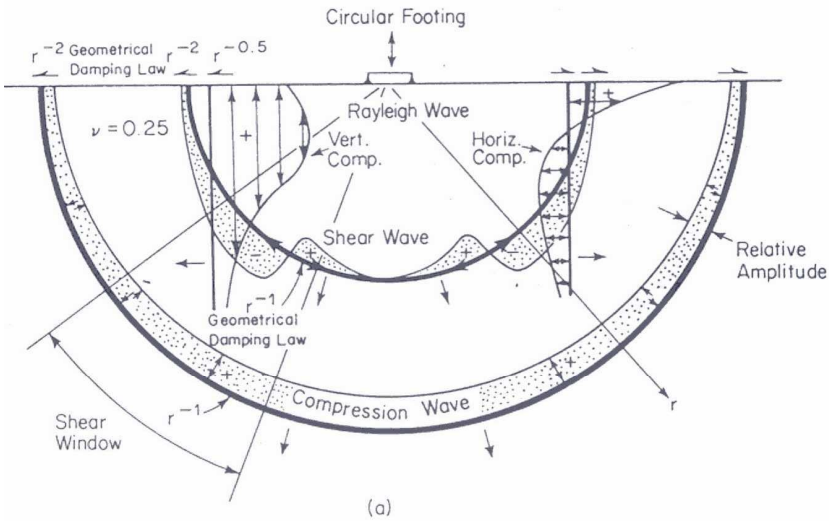
Waves with different wavelengths give information on the medium by sampling its characteristics at different depths. Of course a medium-size wavelength, that involves all the layers, informs about averaged properties. This feature constitutes the basis for soil characterization in practice.

Information obtained on the shear wave velocity profile are to be intended as avaraged values along the receivers array used for the MASW test in field.

2.9 Apparent dispersion curve of Rayleigh waves in a layered half-space

When a point source is applied on the free surface of a layered half-space different types of waves are generated: P, SV, Rayleigh and head waves, if the source is vertical. If the source ha a horizontal component, then SH and Love waves are generated too.

In the proposed MASW method only Rayleighu waves are considered and the effects of P and S waves are neglected. Even if P and S waves are generated by a point source (**figura 2.14**), the contribution of Rayleigh waves is predominant for two reasons. The first reason is that Rayleigh waves transfer about 67% of the total energy realesed by the the source. The second reason is that P and S waves propagate with spheric wavefronts, instead Rayleigh waves propagate with cylindrical wavefronts, hence geometrical attenuation is greater in P and S waves with respect to Rayleigh waves.



Wave Type	Per Cent of Total Energy
Rayleigh	67
Shear	26
Compression	7

Figure 2.14: Waves generated by a vertical time harmonic load on a circular footing on the free surface of a homogeneous half-space(a) and energy distribution among them(b) for a Poisson ratio ν=0.25.(Richart et al., 1970).

2.9.1 Experimental apparent dispersion curve

In previous sections the existence of higher modes of Rayleigh waves and modal curves in a layered half-space has been explained, independently from the existence of a source at the free surface of the site.

Durino the experimental MASW test in the field the surface waves are measured in the time-space, that is the traces at the several recivers.

The measured perturbation generated by a point source on the free surface contains all the modes of Rayleigh waves (P and S waves attenuate after few meters from the source), which are not separeted, but they still constitute a whole train waves. In order to measure separated modes (dispersion phenomenon) in practice at least 100m are needed, depending on soil dynamic characteristics.

When the wave motion is transformed from time-space domain to the frequency-wave number domain, or equivalently in the frequency-phase velocità domain, and the dispersion relation or dispersion curve is represented, then it can be observed that it is not possible, or at least it is not so easy, to identify the experimental modes. In fact usually only an apparent or effective experimental dispersion curve can be discerned.

In **figure 2.15** an example is shown of the experimental velocity spectrum in the frequency-wave number domain (Roma, 2001).

It can be observed that together with the apparent dispersion curve other points exist, which represent a sort of noise to be eliminated in the analysis.

In **figure 2.16** the experimental dispersion curve has been isolated. This process of extraction of the experimental apparent dispersion curve is easier in the frequency-phase velocità domain, where it is easier to identify the noise (**figures 2.17** and **2.18**).

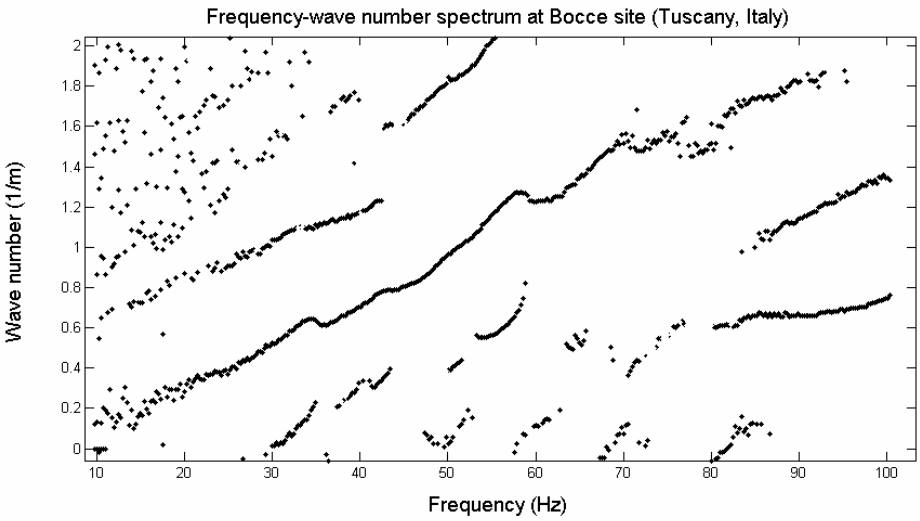


Figure 2.15: Frequency-wave number spectrum of the global field (all relative picks of the spectrum) of vertical velocities on the free surface (Roma, 2001).

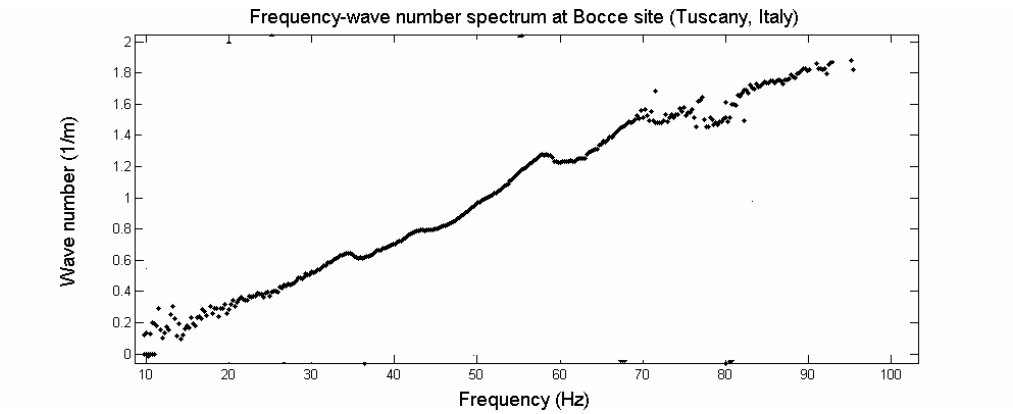


Figure 2.16: Experimental Rayleigh apparent dispersion relation at Bocce site (Tuscany, Italy) after a cleaning process (Roma, 2001).

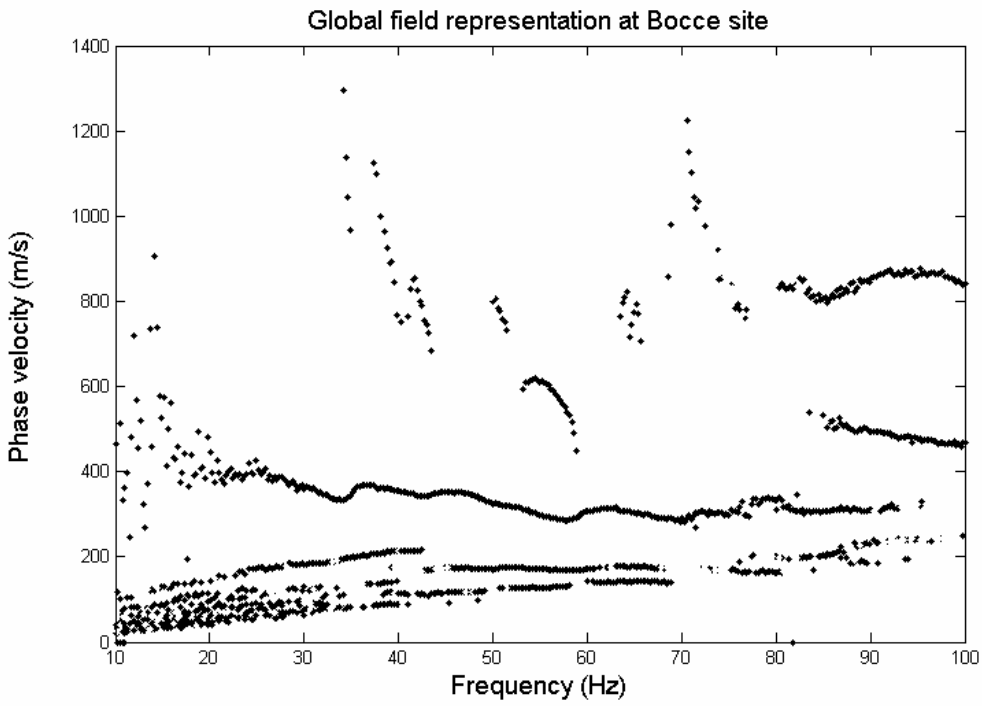


Figure 2.17: Representation of the global field (all relative picks of the spectrum) in the frequency-phase velocity plane (Roma, 2001).

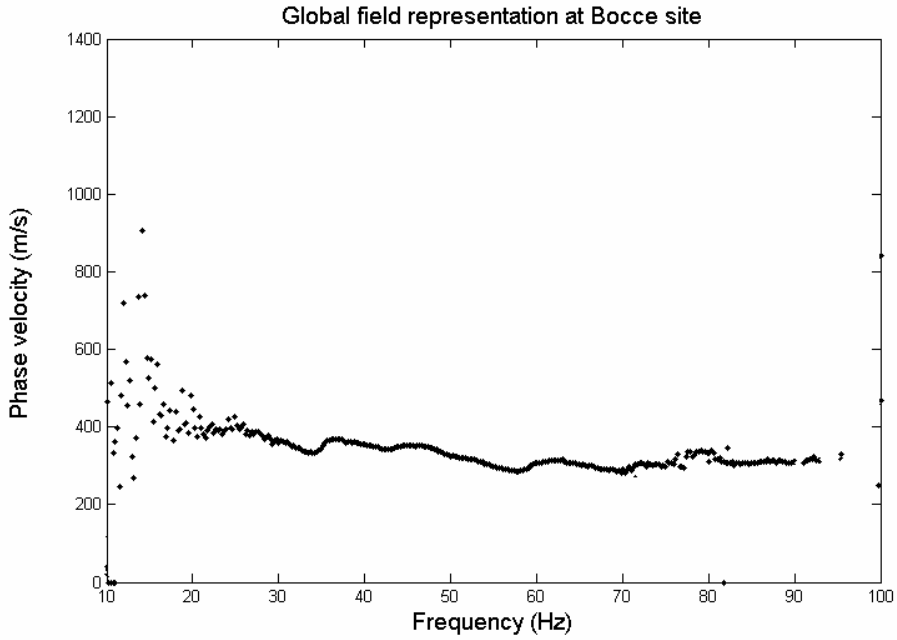


Figure 2.18: Final experimental apparent or effective dispersion curve at Bocce site in terms of phase velocity (Roma, 2001)

The apparent or effective dispersion curve which is obtained from the in field traces is the result of the interaction among all the mods of Rayleigh and the array of receivers. The array of receivers may influence the value of the apparent phase velocità (or apparent dispersion curve) at certain frequencies.

Independently from the interference caused by the receivers array, the apparent dispersion curve is anyway the result of the superposition of all the modes of Rayleigh (fundamental and higher modes). Depending on the geometric (thicknesses) and dynamic (Vs, Vp, mass density) of the ground layers, any modes of Rayleigh are predominant within any frequency ranges with respect to the other modes. Generally when the stiffness gradually increases with depth, the fundamental mode of Rayleigh is predominant at all the frequencies. Nevertheless there are any profiles, with stiff layers trapped between

softer layers or with soft layers trapped between stiffer layers or with rapidly varying stiffness profile, where higher modes of Rayleigh become predominant at certain frequencies. It may happen that there any frequencies of transitino, where more modes have the same anergy importance (**figura 2.20**). In these cases the apparent dispersion curve does not coincide with one particolar mode, but it is the result of the superposition of all the modes (Roma, 2001).

In order to comprehend this concept, consider the example reported in **table 2.2.**

Consider for example the system illustrated in the table 2.2:

Layer	**Thickness h(m)**	**Vp (m/s)**	**Vs (m/s)**	**Mass density (Kg/m^3)**
1	5	750	500	1800
2	10	600	400	1800
3	10	750	500	1800
Half-space	∞	900	600	1800

Table 2.2: Inversely dispersive site from Lai, 1998: Case 3.

For this system the Rayleigh modes and the theoretical apparent dispersion curve are plotted in the phase velocity-frequency domain in **figure 2.19**. The spatial array consists of 24 sensors with a sampling Δx=1.5m. As it can be seen, the apparent dispersion curve jumps from the first mode to the higher modes as the frequency increases. The explanation can be found looking at the normalized spectrum of the modal displacements in **figure 2.20**.

The transition of predominance from the ith mode to the jth mode occurs in a range of frequencies, where the energy of the ith mode drops down and the energy of the jth mode grows up. The reason why such a transition exists from one mode to another is not completely understood yet. It seems as if the frequencies of transition of predominance from the ith mode to the jth mode coincides with the zones where the curvature of the dispersion curve is stationary in the phase velocity-frequency representation, as just evidenced by some authors (Gucunski and Woods, 1991).

The energy of the ith mode decreases at about the same frequency at which its group velocity becomes definitely lower than the group velocity of the new predominant j^{th} mode, without hope of overcoming it again at higher frequencies. This happens if the ith mode will never become predominant again at higher frequencies. In the meantime the energy of the new predominant j^{th} mode grows up. It seems as if the predominant mode be characterized by the fact that it will reach the maximum flux of energy, before losing its predominance. Remember that the group velocity represents the velocity at which the energy associated to the wave travels. The main energy is carried by the mode that will carry it at the maximum speed. Anyway in the opinion of the Author the Rayleigh dispersion relation contains all the information, that is necessary to predict how the influence of the several modes varies in the f-k representation. For the example Lai Case3 the transition from the 1st mode to the 2nd mode happens between 40Hz and 50Hz and from the 2nd mode to the 3rd mode between 70Hz and 80Hz.

The experimental apparent dispersion curve in **figure 2.18** is obtained from the picks of the f-k (frequency-wave number) spectrum (**figura 2.15**), which is obtained by a 2D Fourier transformation applied to the time-space traces. At each assigned frequency the wave number is searched where the spectrum has a maximum. The apparent phase velocity c associated to those frequency and wave number can be calculated as:

$$c_{apparente}(\omega) = \frac{2\pi f}{k_{\max}} \tag{2.19}$$

The maxima of the f-k spectrum give the dispersion relation, since the dispersion relation of Rayleigh waves is the denominator of the f-k spectral displacements. The Rayleigh modes are the zeros of the dispersion relation, which becomes zero for those couples of frequency and wave number which represent a Rayleigh mode. Hence when the dispersion relation is zero, the spectral displacements become infinite in theory, but in reality material attenuation causes finite displacements. Any further detail can be found in (Roma, 2001).

I massimi dello spettro individuano la curva di dispersione perché la relazione di dispersione delle onde di Rayleigh compare al denominatore dell'espressione spettrale degli spostamenti.

If all the relative maxima of the f-k spectrum are also considered, for each assigned frequency two or more apparent dispersion curves may be found, which in general would not coincide with the theoretical modes of Rayleigh, but they would rather be the result of the interaction between higher modes and receivers array (**figure 2.17**).

The use of two or more apparent dispersion curves could be an additional constraint for the solution of the inversion process to find the optimal shear wave velocity profile.

2.9.2 Numerical apparent dispersion curve: Roma's method

The numerical apparent dispersion curve (**figure 2.19**) can be determined in the same manner used to obtained the experimental apparent dispersion curve, except the way in which the f-k spectrum is calculated.

In the experimental method the traces in time-space are available and a 2D Fourier transformation is applied to obtain the f-k spectrum. In the numerical method it would be too computationally expensive to use synthetic traces in time-space obtained by applying a point source

on the free surface of the layered half-space. Another problem would be to define the frequency and wave number content of the source.

So the new method proposed by Roma (Roma, 2000 and Roma, 2001) consists of applying 1D Fourier Transform to the Green or Transfer function of the system (i.e. the layered half-space) along the space domain, in order to obtain the same f-k spectrum.

The Green function of the layered half-space is known in analytic form(Aki, K. and Richards, P.G., 1980) in the frequency-space domain:

$$u_{\beta}(r,z,\omega) = \sum_{j=1}^{M} \left[A_{\beta}(r,z,\omega) \right]_j \cdot e^{i\left(-k_j \cdot r + \varphi_{\beta}\right)} \tag{2.20}$$

$$\left[A_{\beta}(r,z,\omega)\right]_j = \begin{bmatrix} A_r(r,z,\omega) \\ A_y(r,z,\omega) \end{bmatrix}_j = \frac{r_2(z_S,k_j,\omega)}{4v_j \cdot U_j \cdot I_j \cdot \sqrt{2\pi r \cdot k_j}} \cdot \begin{bmatrix} r_1(z,k_j,\omega) \\ r_2(z,k_j,\omega) \end{bmatrix} \tag{2.21}$$

$$I_j(z,k_j,\omega) = \frac{1}{2}\int_0^{\infty} \rho(z)\left[r_1^2(z,k_j,\omega) + r_2^2(z,k_j,\omega)\right]dz \tag{2.22}$$

where β=y or β=r indicates the vertical or the horizontal wave motion component, j indicates the j-th mode of Rayleigh, M is the total number of considered Rayleigh modes, k_j is the wave number of the j-th mode at a given frequency ω, z_s is the source depth, φ_β is the phase shift equal to $\pm\pi/4$ depending of the wave component β, A_j is the amplitude of the modal displacement of the j-th mode, v_j and U_j are the modal phase and group velocities, I_j is the first energetic integral and r_1, r_2 are the displacements and stress autovectors.

By applying a 1D Fourier transformation along the spatial coordinate to the Green function (2.20) of the layered half-space, the wave motion is transformed from the frequency-space to the frequency-

wave number domain. From the f-k spectrum the same procedure used in the experimental method can be followed, that is at each assigned frequency the wave number is searched where the f-k spectrum reaches the absolute maximum.

The fact that the numerical dispersion curve, to be compared then with the experimental dispersion curve, can be obtained directly from the Green function of the layered half-space is not obvious, in fact it was not used before (Roma, 2001), and in this method there are not assumptions on the frequency and wave number content of the point source. The mathematical demonstration of the validity of the method can be found in (Roma, 2001), even if there is numerical evidence of the rightness of the method, which has been applied to several numerical cases (Roma et al, 2002).

If the source would not be a point source with respect to the array of receivers, then the dispersion curve would be significantly influenced by the frequency and wave number content of the source. In this case the numerical simulation of the in field MASW test would require the specification of the frequency and the wave number (or equivalently the time-space) content of the source.

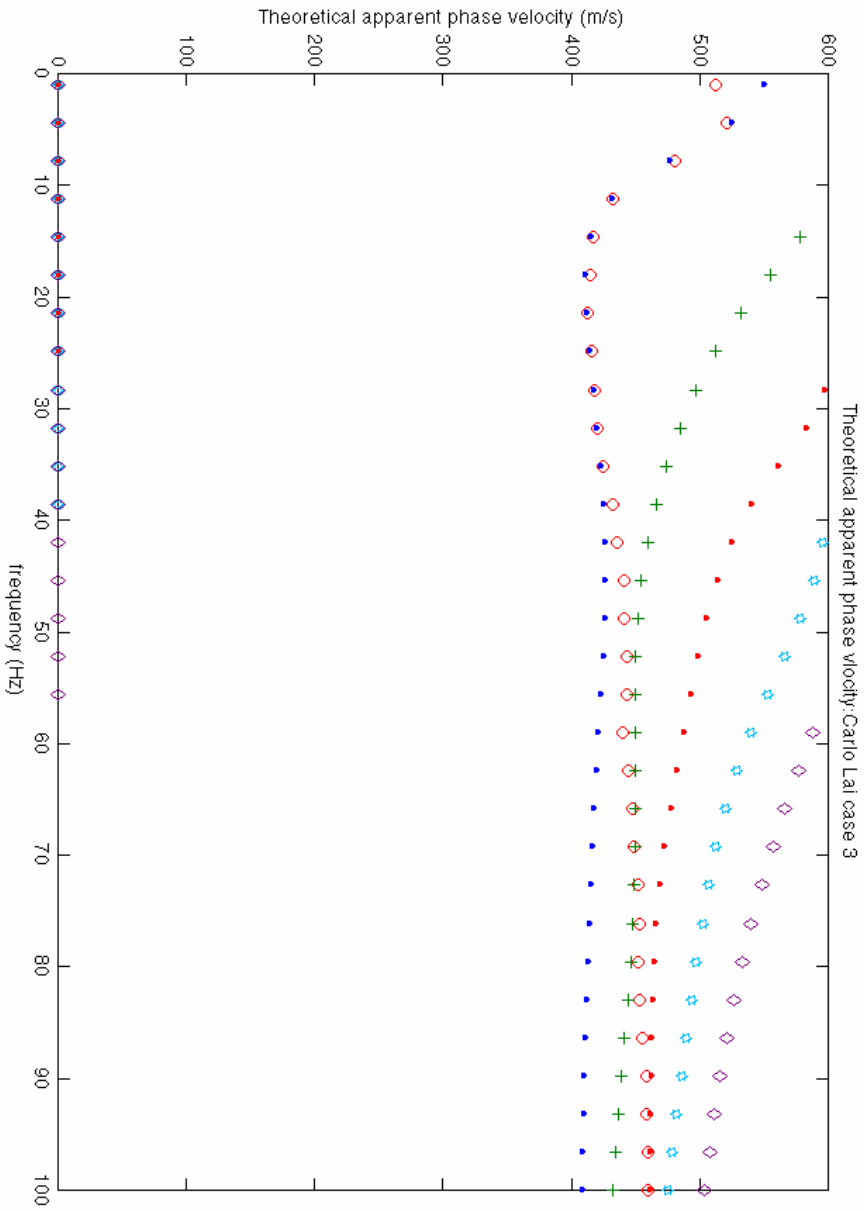


Figure 2.19: Rayleigh modes and theoretical apparent dispersion curve (red circles) for Lai Case3.

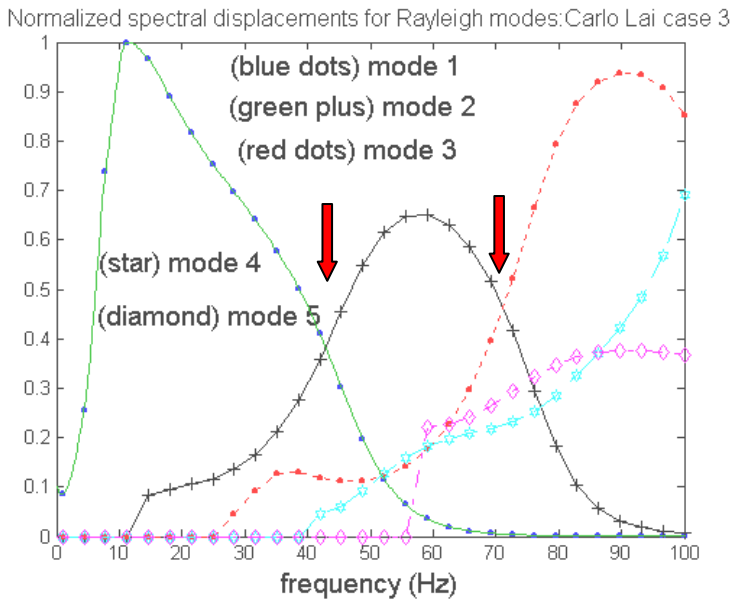


Figure 2.20: Relative importance of Rayleigh modes and natural frequencies.

2.9.3 Numerical effective dispersion curve: Lai-Rix method

As an alternative and equivalent method to determine the numerical apparent or effective dispersion curve the method by Lai and Rix can be adopted (Lai, 1998). If the wave train generated by a point source is considered as a whole perturbation, where dispersion phenomenon has not yet occured due to the small distance covered by the receivers array and hence all modes of Rayleigh travel still together, then a unique wave front can be considered for the phase of the whole wave train. This unique wave front of the apparent phase can be searched as the locus of point of constant phase in time:

$$\left[\omega t - \Psi_{\beta}(r,z,\omega)\right] = \text{costante} \tag{2.23}$$

where

$$\Psi_{\beta}(r,z,\omega) = \tan^{-1}\left\{\frac{f(r,z,\omega)}{g(r,z,\omega)}\right\} \tag{2.24}$$

$$f(r,z,\omega) = \sqrt{r}\cdot\sum_{i}^{M}\left[\mathrm{A}_{\beta}(r,z,\omega)\right]_{i}\cdot\sin\left[rk_{i}+\varphi_{\beta})\right] \tag{2.25}$$

$$g(r,z,\omega) = \sqrt{r}\cdot\sum_{j}^{M}\left[\mathrm{A}_{\beta}(r,z,\omega)\right]_{j}\cdot\cos\left[rk_{j}+\varphi_{\beta})\right] \tag{2.26}$$

By differentiating the phase (2.23) with respect to time, we obtain:

$$\omega - \frac{\partial\Psi_{\beta}}{\partial r}\frac{dr}{dt} + \frac{\partial\Psi_{\beta}}{\partial z}\frac{dz}{dt} + \frac{\partial\Psi_{\beta}}{\partial\omega}\frac{d\omega}{dt} = 0 \tag{2.27}$$

The fequency of excitation is keeped constant with time, the propagation of the modes of Rayleigh occurs only in the radial direction, hence from (2.27) it can be written that:

$$\frac{dr}{dt} = c_{apparent}(r,z,\omega) = -\frac{\omega}{\dfrac{\partial\Psi_{\beta}}{\partial r}} \tag{2.28}$$

After any analytical manipulations:

$$c_{apparent}(r,\omega) = -\frac{\omega}{\dfrac{g\cdot f' - fg'}{g^{2}+f^{2}}} \tag{2.29}$$

where

$$f'(r,z,\omega) = \sqrt{r}\cdot\sum_{i}^{M}\left[\mathrm{A}_{\beta}(r,z,\omega)\right]_{i}\cdot k_{i}\cos\left[rk_{i}+\varphi_{\beta})\right] \tag{2.30}$$

$$g'(r,z,\omega) = -\sqrt{r} \cdot \sum_{j}^{M} \left[\mathrm{A}_{\beta}(r,z,\omega) \right]_j \cdot k_j \sin\left[r k_j + \varphi_{\beta}) \right] \qquad (2.31)$$

The apparent or effective phase velocity, expressed by the (2.29), by means of (2.30) and (2.31), is represented in a different form with respect to the expression of Lai (Lai, 1998), but it can be proved that the two expressions are equivalent. The apparent or effective phase velocity (2.29) depends on the spatial coordinate r, hence the avaraged apparent phase velocity along the receiver array can be calculated as:

$$c_{apparent}(\omega) = \frac{\sum_{receivers} c_{apparente}(r,\omega)}{N_{receivers}} \qquad (2.32)$$

It can be demonstrated that under few conditions about the regularity of the dispersion curve, the apparent and the effective dispersion curves obtained with Roma's and Lai's methods are equivalent at all. Except for any profiles with strong stiffness contrasts with depth at only at certain frequencies, the apparent and the effective dispersion curves obtained with Roma's and Lai's methods perfectly coincide, as it is possible to numerically verify by means of the software MASW.

2.9.4 Relative error between experimental and numerical dispersion curve

In order to evaluate the reliability of the shear wave velocity Vs profile which has been found with the inversion process, it is necessary to define a criterion to estimate the match between the experimental and the numerical dispersion curves. A relative error between the experimental and the numerical dispersion curves can be defined as:

$$error = \sum_{j} \left(\frac{\left| c_{experimental}(j) - c_{numerical}(j) \right|}{c_{experimental}(j)} \right) \qquad (2.33)$$

where the summation includes all the frequencies j where the apparent phase velocity has been calculated.

The smaller is the relative error defined by (2.33), the closer are the experimental and the numerical apparent dispersion curves, the greater is the reliability of the final shear wave velocity profile.

2.9.5 Layers with strong stiffness contrast

In the method implemented by the software MASW, during the search of the shear wave velocity profile, two conditions can be opted by the user: strong stiffness contrast between two consecutive layers are allowed or not.

It has been defined a criterion to establish whether a strong stiffness contrast exists between consecutive layers. This is the case when the i-th layer is softer or stiffer than the (i-1)th and (i+1)th layers, according to the following conditions on the shear wave velocity:

case of rigid i-th layer

$$\begin{aligned} 1.7 \cdot Vs_{(i-1)} &\leq Vs_{(i)} \\ 1.7 \cdot Vs_{(i+1)} &\leq Vs_{(i)} \end{aligned} \qquad (2.34)$$

case of soft i-th layer

$$\begin{aligned} Vs_{(i-1)} &\geq 1.7 \cdot Vs_{(i)} \\ Vs_{(i+1)} &\geq 1.7 \cdot Vs_{(i)} \end{aligned} \qquad (2.35)$$

When a strong stiffness contrast exists between two consecutive layers and the user has decided not to allow it, the shear wave velocity Vs(i) of the i-th layer is substituted by the median value of the shear wave velocities of the (i-1)th and (i+1)th layers:

$$Vs_{(i)} = \frac{\left(Vs_{(i-1)} + Vs_{(i+1)}\right)}{2} \qquad (2.36)$$

2.9.6 Degree of uncertainty of the final Vs profile

The shear wave velocity profile obtained by the MASW method is affected by a certain degree of uncertainty, which depends on the following aspects:

- Uncertainty e_{exp} associated to the experimental measures
- Propagation of the uncertainty in the model of numerical simulation
- Relative error or distance $e_{relative}$ between the experimental and the numerical dispersion curves

The uncertainty associated to the experimental measures e_{exp} is generally defined by a range of variation of the phase experimental velocity at each frequency j:

$$e_{\exp} = \frac{\left| c_{(\exp)\max} - c_{(\exp)\min} \right|}{c_{(\exp)median}} \qquad (2.37)$$

The relative error $e_{relative}$ between the experimental and the numerical dispersion curves has been already defined by (2.33).

The most difficult aspect to estimate is the propagatin of the uncertainty through the numerical simulation of the model, which correlates the phase velocity c to the shear wave velocity profile Vs. This difficulty is due to the fact that the correlation between the apparent phase velocity and the shear wave velocity profile Vs is strongly non linear and also it is not known in analytical form.

In order to overcome this difficulty the following simplified assumption has been adopted to correlate the apparent phase velocity and the shear wave velocity profile Vs:

$$Vs = 1{,}1 \cdot c \qquad (2.38)$$

where the values of Vs is assigned at a depth z, which is correlated to the wavelength:

$$z = \frac{\lambda}{(1{,}5 \div 2{,}0)} \tag{2.39}$$

the wavelength is also related to the frequency f and to the phase velocity c:

$$c = \lambda \cdot f \tag{2.40}$$

Equations (2.33), (2.37), (2.38), (2.39), (2.40) define the relative error associated to the shear wave velocity Vs at the depth z from the ground level, by means of the relative error known at each frequency as:

$$e_{(Vs)} = e_{\exp} + e_{relative} \tag{2.41}$$

In fact by assuming a simplified linear relation between the disprsion curve and the shear wave velocity profile, the relative error e(Vs) at each frequency can be calculated as the sum of the experimental relative error and of the distance between the experimental and the numerical dispersion curves. This approximation can be considered reliable, since it is applied nearby each frequency.

From equation (2.41) the relaitve error e(Vs) at the generic depth z can be calculated, thanks to equations (2.39) and (2.40).

3. CHAPTER 3 : IN FIELD MASW TEST

3.1 Introduction

This chapter suggests a standard test for the active MASW, some practical suggestions are given in common situations. Also the minimum equipment is described to perform the in field the active MASW test.

3.2 Minimum equipment to perform active MASW test in field

To perform the active MASW test in field you need the following instrumentations:

- Multichannel acquirer with at least 12 channels.
- Receivers geophones (4,5 Hz) or accelerometers. It is suggested to use at least 12 receivers, preferebly 24. The cables should cover a distance of at least 100m.
- Impulsive source: hand hammer of weigth 5kg-10kg with rabber or steel plate of size 15cm x 15cm to place on the ground for beating with the hammer. If they are available you can use alternative sources, like vibrodines or big mass to lift and leave on the ground (**figure 3.16**). In the case you use the software made by the author, if you energize the ground with a controlled source you need to calculate the experimental dispersion curve by your own and give it as an input to the software. The current version of the software does not allow to calculate the experimental dispersion curve using harmonic or controlled source.
- A taped line to locate the receivers.

3.3 Spatial array of receivers for active MASW test

The MASW test provides the monodimensional Vs profile, by assuming an average value of Vs along the array of receivers.

The total length of the array of receivers depends on both the vailable total number of receivers and the available space in field.

Usually you can locate the receivers with a constant span between 0.5m and 3.0m.

For a given number of available receivers a span of 3.0m allows a longer array of receivers and a better resolution of the experimental dispersion curve in the wave number axis k. Nevertheless the Nyquest wave number becomes low and the dispersion curve for wave numbers greater than the Nyquest wave number is not reliable.

Vice versa a small span for the receivers is suitable for small space in field, implies a great Nyquest wave number, but gives a poor resolution of the dispersion curve along the wave number axis k.

The Nyquest wave number is equal to

$$k_{Nyquest} = \frac{\pi}{\Delta x_{\min}} \tag{3.1}$$

where Δx_{min} is the smallest span between two consecutive receivers. The resolution of the experimental dispersion curve along the wave number axis k is:

$$\Delta k = \frac{2\pi}{N \cdot \Delta x} \tag{3.2}$$

where N is the total number of receivers of the array.

It is suggested to adopt a span of 1.5m, so if you use 12 receivers you can cover a total length of 18m. If you need evalute the Vs profile for a longer distance you can repeat the MASW test moving the array of 12 receivers.

You can locate the source at a distance Δx equal to the receiver span.

The MASW test offers the advantage of considerably mitigate the influence of body P and S waves in the near field.

It is a good rule to make the test 3 times with the source near the first receiver and then to repeat the test 3 times with the source at the last receiver.

Is has been observed that when the layers are inclined more than 15°-20° the experimental dispersion curves obtained moving the source from the first to the last receiver are different. Usually it is not necessaru to average the field misurements of the 3 tests, since it is sufficient to choose the best experimental curve by view.

It is generally suggested to perform the test along 2 orthogonal directions, in order to determine the 1D Vs profile in the 2 orthogonal directions.

When layers are inclined more than 15°-20° it is suggested to perform alternative field test sto verify the reliability of the MASW test. It is also suggested to locate the array of receivers in the direction of maximum slope.

3.4 Temporal configuration of the active MASW test in field

It is suggested to measure the field motion generated by a hammer shot by using a temporal interval of about $\Delta t=2\cdot10^{-3}$ s and a total time of acquisition equal to about 4s (approximately 2048 temporal samples). You can start the acquisition by hand or by means of an automatic trigger immediately after the hammer shot. The above suggested temporal parameters of acquisition give a Nyquest frequency of:

$$f_{Nyquest} = \frac{1}{2\Delta t} = 250\text{Hz} \qquad (3.3)$$

where Δt is the time sampling.

The resolution in time of the experimental dispersion curve is equal to:

$$\Delta f = \frac{1}{M \cdot \Delta t} = 0{,}244\text{Hz} \qquad (3.4)$$

where M=2048 is the number of time samples.

The following figures show the array of receivers, the measured traces, the f-k spectrum, the experimental dispersion curve before and after selection of the significant points to be used for the sequent inversion process.

Figure 3.1: tipycal array of receivers for the active MASW test in field.

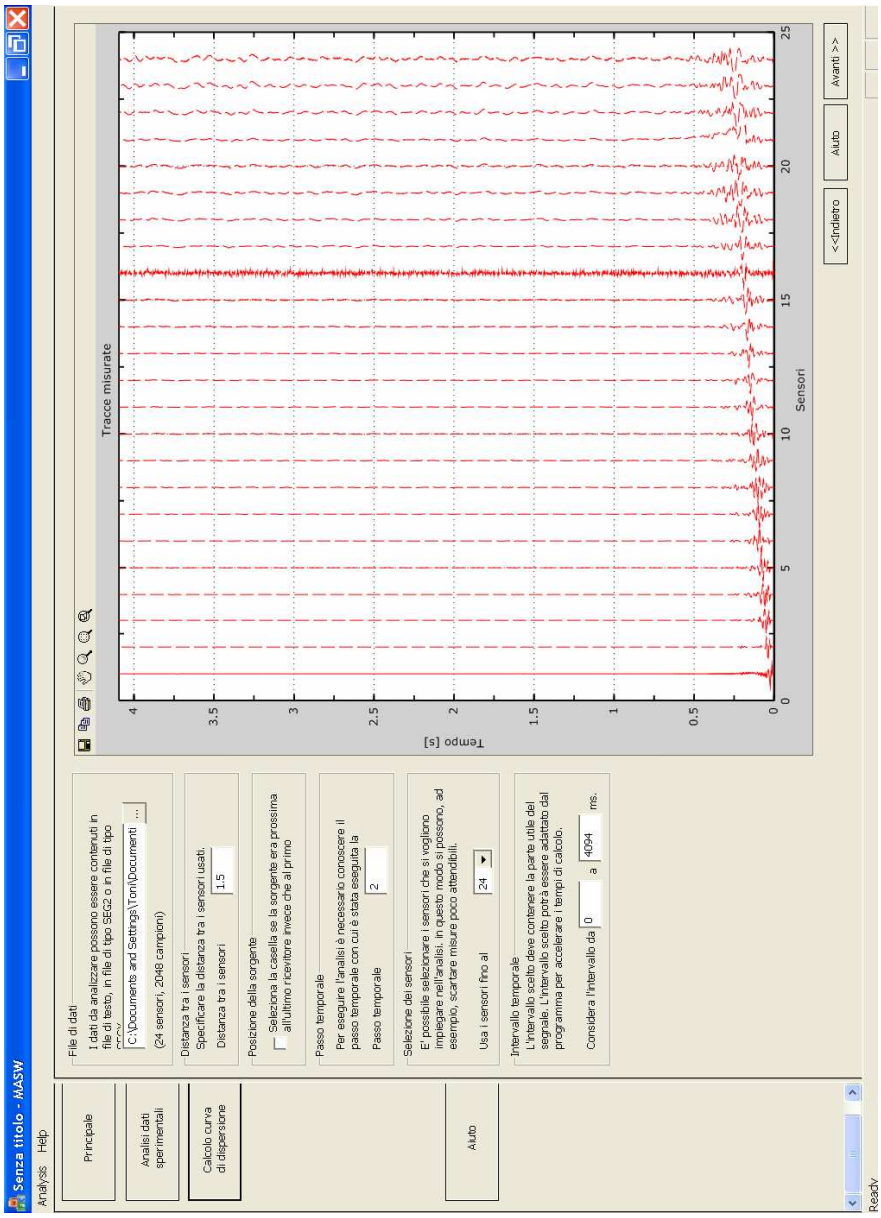


Figure 3.2: traces measured with 24 geophones (Δx=1.5m, Δt=2ms)

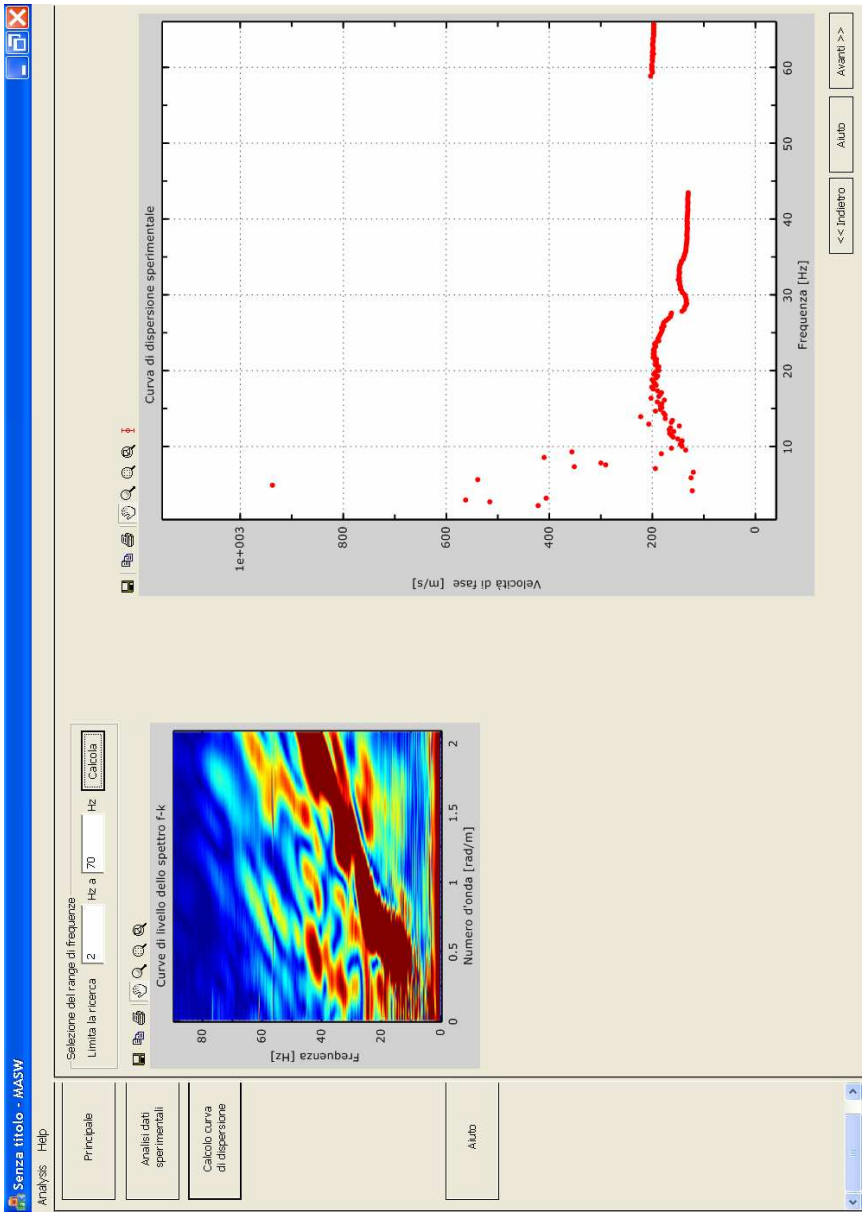


Figure 3.3: f-k spectrum of measured velocities and experimental disprsion curve.

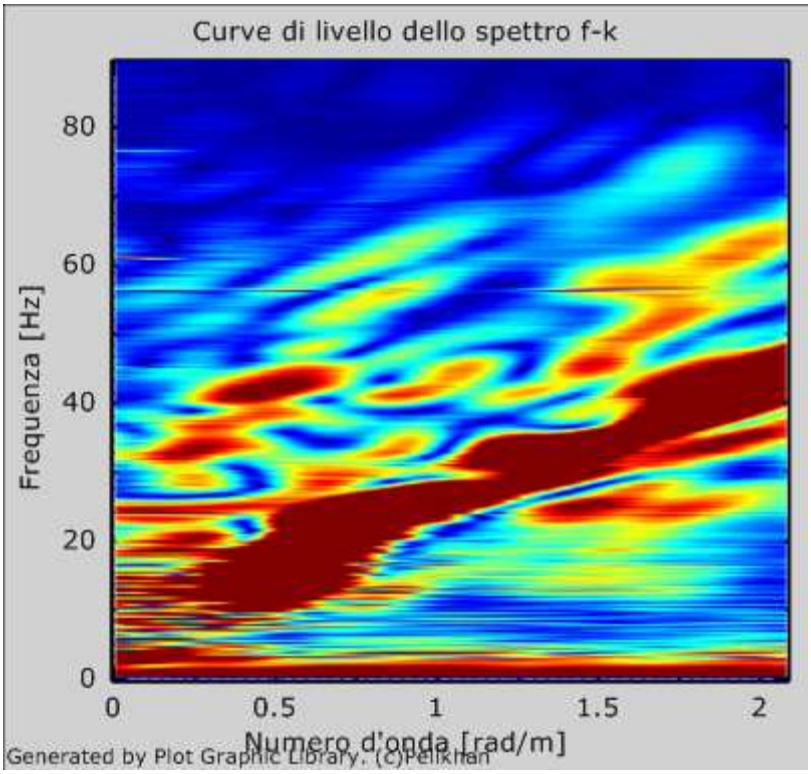


Figure 3.4: f-k spectrum of measured velocities.

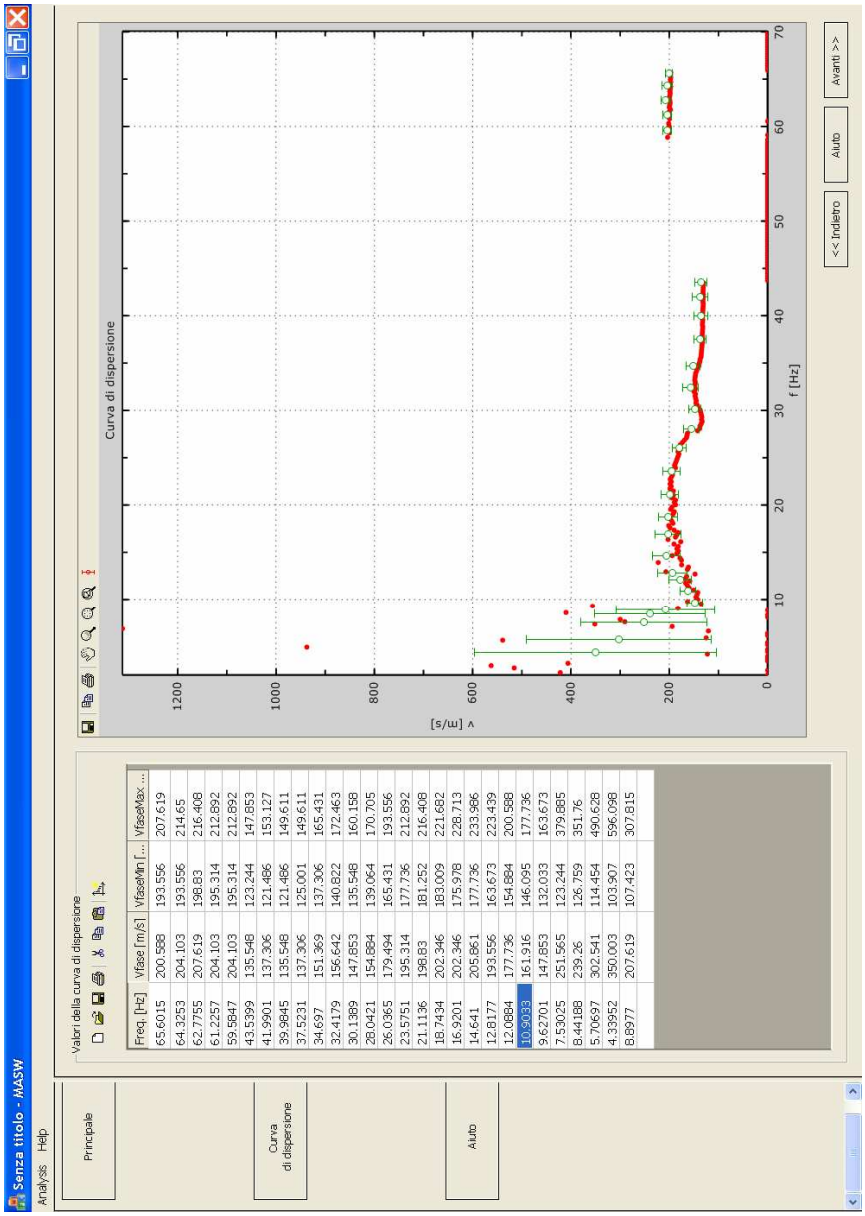


Figure 3.5: selection of the significant points of the experimental dispersion curve to be used in the inversion process to find the Vs profile.

3.5 Format of input files

In the current version of the software you can open the files of the field traces in the formats txt, xls and SEG2. It is also possible to input the experimental dispersion curve calculated by you by other methods and import it from an xls or putting the data directly in the proper table (**figure 3.5**).

3.6 Selection of the experimental dispersion curve

One of the most difficult aspect of the interpretation of the MASW test is the selection of the experimental dispersion curve to use to determine the Vs profile.

Given the f-k spectrum (**figure 3.2**) you need to define a frequency range where to compute the experimental dispersion curve.

Generally if you are not interested in the dynamic characteristics of a rigid surficial pavementation, then you can use a frequency range of 2Hz - 80Hz. Anyway by observing the position of the main peaks of the f-k spectrum (red zones) you can visually determine the significant part and frequency range of the f-k spectrum.

In the case of the **figure 3.4** the red zone of the main peaks of the spectrum is comprised between about 10Hz and about 50Hz. It is suggested to slightly extend the frequency range, for example considering a frequency range of 2Hz-70Hz, so that you can

estrapolate the measured data at low frequencies, which contain information about deeper layers of the ground.

After calculation of the experimental dispersion curve in the defined frequency range, you need to select a limited but significant points of the experimental dispersion curve. It is suggested to limit the maximum number of points to 25-30 (**figure 3.5**).

This choice since by taking over 30 points computational time increases considerably, without improving the final results.

It is recommended to select the points of the experimental dispersion curve in order to have more points at low frequencies where the slope of the dispersion curve is greater than at high frequencies. An exception is represented by inversely dispersvive sites, wher dispersion curve grows up at high frequencies.

At each experimental point, i.e. at each frequency, you can associate an uncertainty range of the average phase velocity. This information is used by the software to give an estimate of the uncertainty of the final Vs profile.

It may happen that the trend of the experimental dispersion curve calculated from the f-k spectrum be discontinous and irregular. It may depend on several causes, like quality of the measured data, ambient noise, other types of waves, irregular stiffness profile. In the case of **figure 3.5** the experimental dispersion curve is not available in the frequency range 45Hz - 60 Hz. In similar cases you can consider the experimental dispersion curve only where it is available.

Generally you try to define the experimental dispersion curve into the most extended frequency range, trying to estrapolate the trend of the dispersion curve towards the low frequencies, when experimental data do not allow a clear identification of the dispersion curve at low frequencies (between 5 Hz and 20 Hz). This aspect can be faced by extrapolation of data, by assigning a proper uncertainty to the data, or by using a different type of source, i.e. a greater weight left from a certain height or a controlled source.

For most of the sites the experimental dispersion curve has an apparent phase velocity which grows up moving towards low frequencies in the frequency range 0 Hz - 30 Hz. The trend can be easily induced by the few dispersed data or by the trend of the dispersion curve at greater frequencies.

Soon a new version of the software will be available for analysis of ambient noise to get experimental information at very low frequencies 0 Hz - 15 Hz (passive MASW method).

If you observe the experimental dispersion curve of pavimented sites at very high frequencies 50 Hz - 1000 Hz, then you can observe a growing trend of the dispersion curve with frequency. Nevertheless this is not the interest of the software MASW, which is intended to work at frequencies lower than 100Hz.

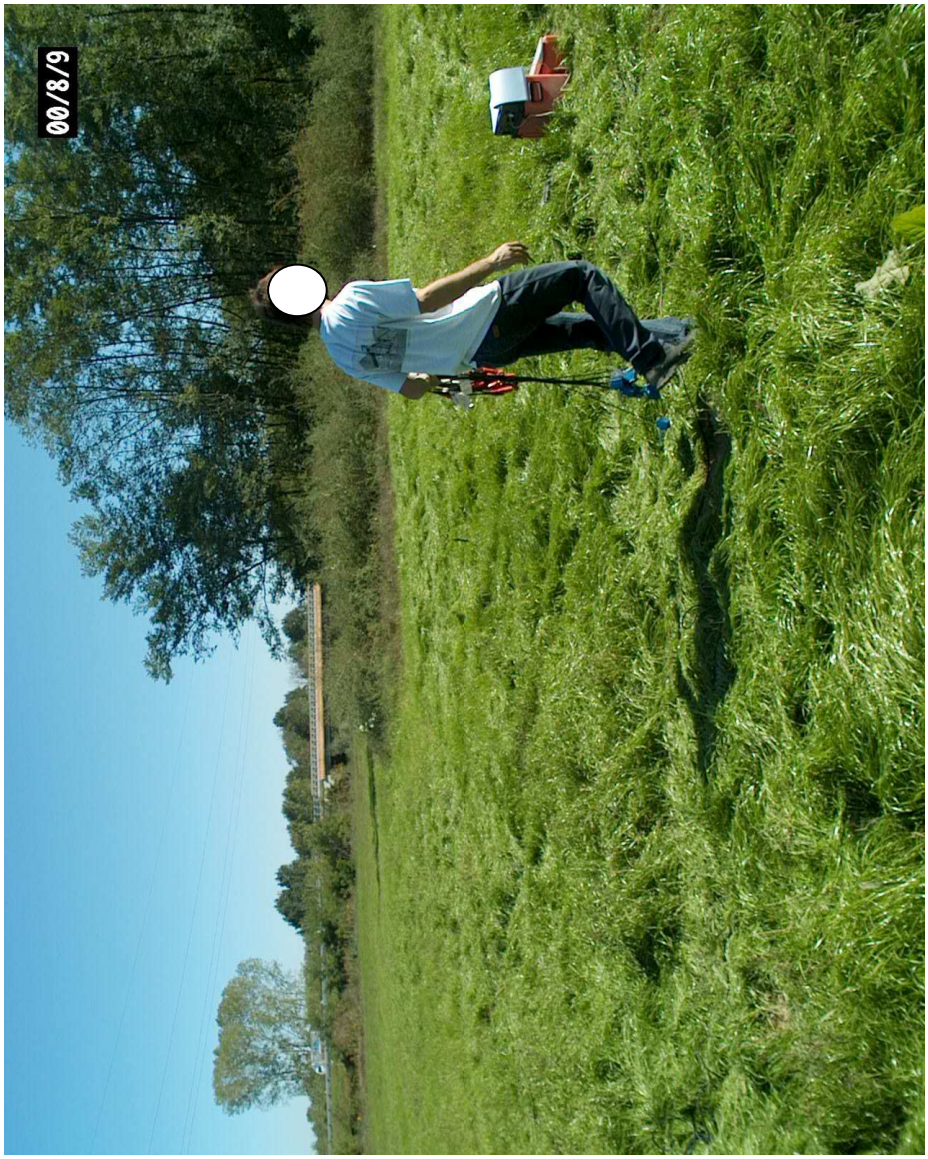


Figure 3.6: MASW test into a field with grass. You need to remove the grass to fix the geophones to the ground.

Figure 3.7: hand hammer with steel plate.

Figure 3.8: active MASW test in urban ambient, with road traffic.

Figure 3.9: hand hammer with steel plate.

Figure 3.10: MASW test with accelerometers.

Figure 3.11: hand hammer with steel plate.

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Figure 3.12: hand hammer with steel plate.

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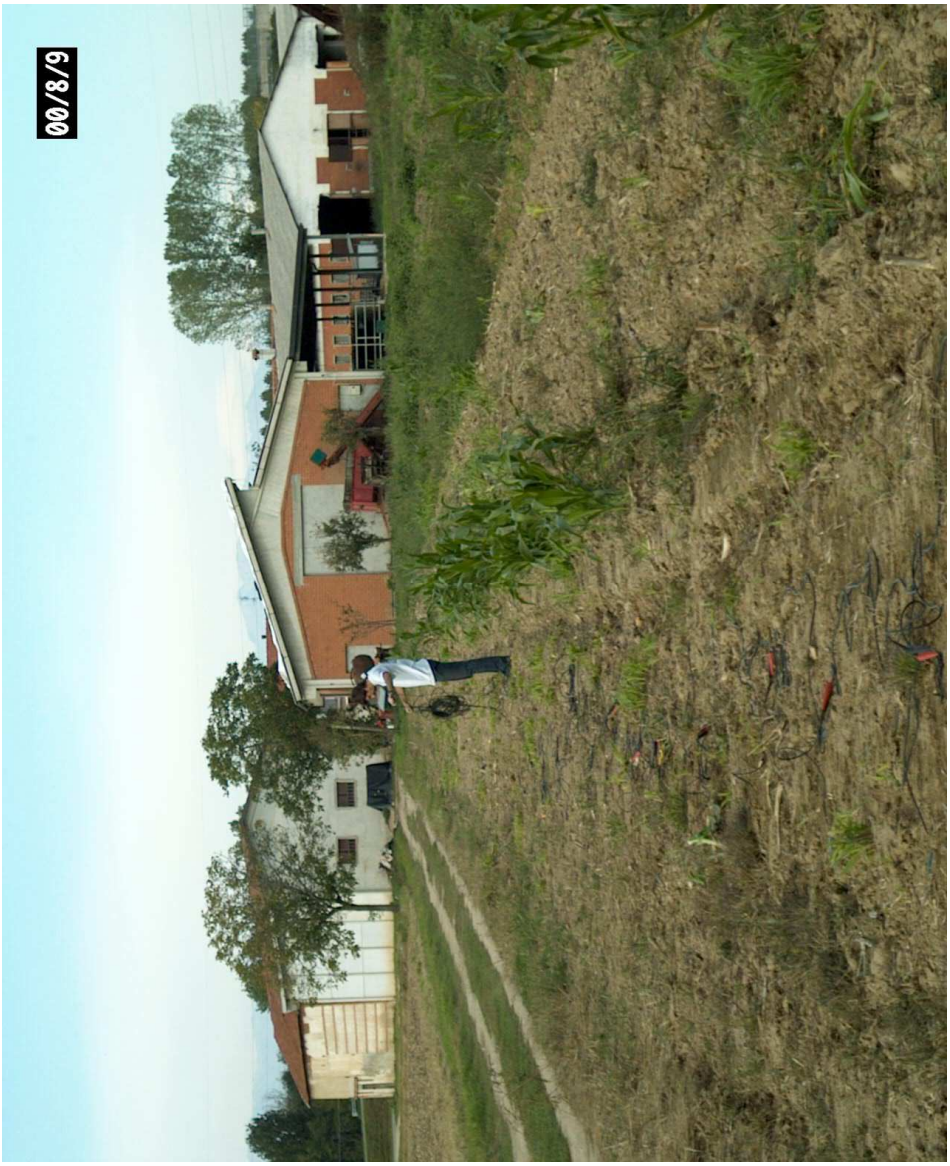


Figure 3.13: spatial array for the MASW test.

Figure 3.14: spatial array for the MASW test.

Figure 3.15: spatial array for the MASW test.

Figure 3.16: source made by great weight left from 3m height.

Figure 3.17: spatial array for the MASW test.

Figure 3.18: hand hammer with steel plate.

Figure 3.19: spatial array for the MASW test.

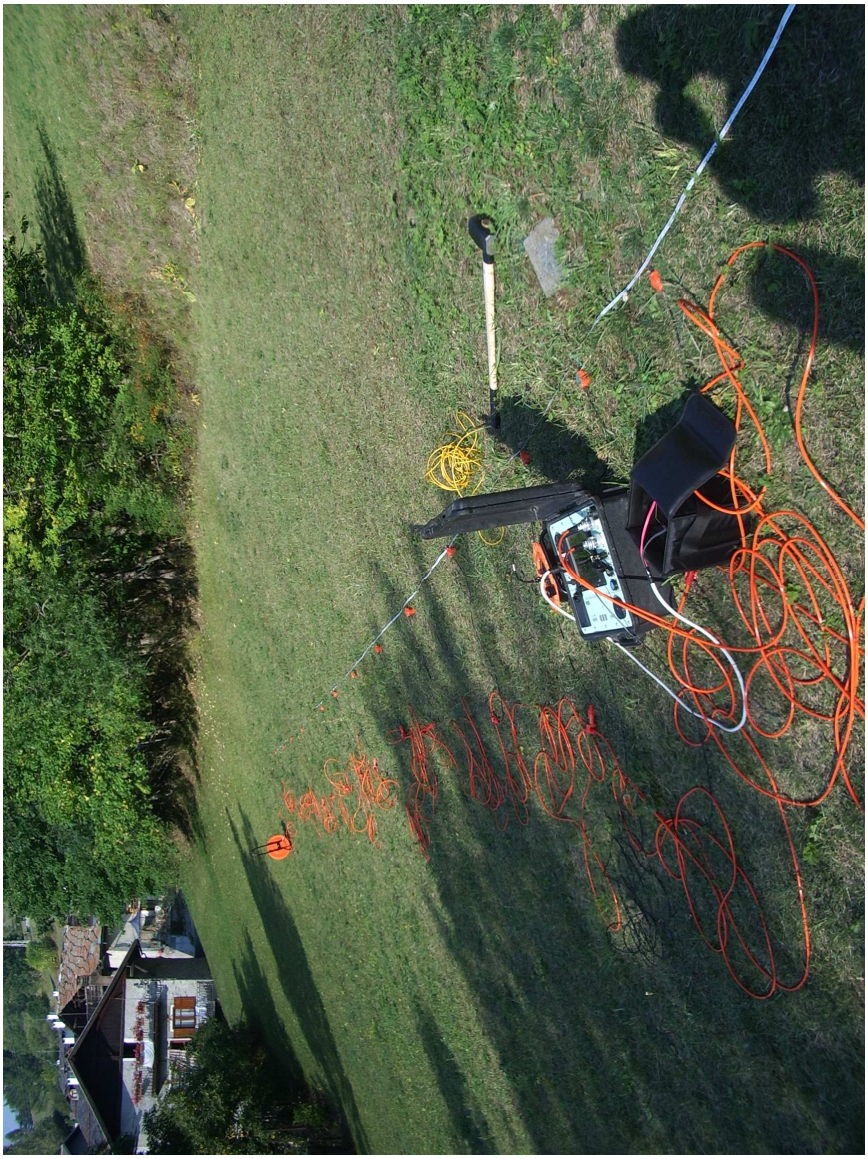


Figure 3.20: active MASW test along a contour line of a slope.

4. CHAPTER 4 : NUMERICAL EXAMPLES AND CASE HISTORIES

4.1 Introduction

This charter presents some numerical examples and case histories, which can help you to find the shear wave velocities profile Vs and hence the seismic class of the site by means of the MASW method. The numerical examples comprehend the most common types of Vs profiles, hence they may represnt a valid guide to infer the Vs profile by looking at the experimental dispersion curve measured in field.

4.2 Practical suggestions and observations

Some suggestions and observations follow on how to identify the shear wave velocities profile Vs and the stiffness profile Gs of the ground.

1) At first calculate the numerical dispersion curve using the Vs profile suggested by the software for default, to verify the match with the experimental dispersion curve.

2) if you run the automatic search:

when dealing with normally dispersive sites use only the first or fundamental mode of Rayleigh, when dealing with inversely dispersive sites use at least 10 modes, use few layers, say 6 layers to reduce time of computation; use 10-30 iterations, generally 15 iterations assure a good result. At the end of the automatic search try to improve the obtained result, by modifing by hand the Vs profile, for example adding new layers, adding other modes of Rayleigh if at high frequencies the apparent numerical curve coincides with the higher available mode used in the automatic search.

3) When dealing with sites which have a stiffness profile irregular with depth, i.e. with strong stiffness contrasts, the number of layers may influence the relative error between the experimental and the numerical dispersion curves, hence the final Vs profile. By increasing the number of layers (for example 9 layers) computational time durino the automatic search increases. Generally with more than 6 layers the user can describe very well the Vs profile in the first 30 m of the site.

4) Usually a relative error between the experimental and the numerical dispersion curves which is less than 10% means that a satisfactory and valid result has been obtained by a practical point of view. If the relative error is comprised between 10% and 20%, it is suggested to modify the shear wave velocity Vs of any layers to try to reduce the error. The relative error is an objective indicator of the match between the experimental and the numericaldispersion curve, in spite of that, in presence of more several profiles with the same error, the user can decide the optimal Vs profile by a visive comparison of the different matches or on the basis of a priori information available for the site.

5) Due to the mathematical ill-posedeness of the inversion process, the final Vs profile found by the automatic search may depend on the initial guess. Generally it is suggested to run the automatic search starting from 2 or 3 different initial guesses (for example form the Vs profile given by default by the software or from a profile with a constant value of Vs for all the layers and equal to a value of the experimental phase velocity along which is equal to an intermediate value within the frequency range), trying to fix the shear wave velocity Vs of

both the superficial layer and the half-space. When dealing with 2-3 final Vs profiles the user can choice the one that gives the best match between the experimental and the numerical dispersion curve. This choice may be influenced by a priori information available on the site (i.e. geotechnical nature of the soils, position of the water table, presence of known geologic formations, existence of a rigid pavement, presence of a rigid bedrock at a known depth). In absence of theese kind of information the relative error represents a usefull tool for judgement to choice the most probable Vs profile.

6) When dealing with uncommon profiles it may occur that the search of the modes of Rayleigh fail, due to the presence of complex root of the dispersion relation (2.8) or to the existance of leaky modes. This may happen for example when the half-space is definitely softer (with a lower shear wave velocityVs) than the upper layers. In this case it is suggested to increase the maximum depth of the geotechnical model down to a rigid layer with a high value of shear wave velocity Vs. An example is given by a site with a superficial pavement. In theese cases a message appears as in **Figure 4.1** ; clik OK and modify the Vs profile, by adding layers at greater depth with a Vs equal or greater than the Vs of the superficial pavement.

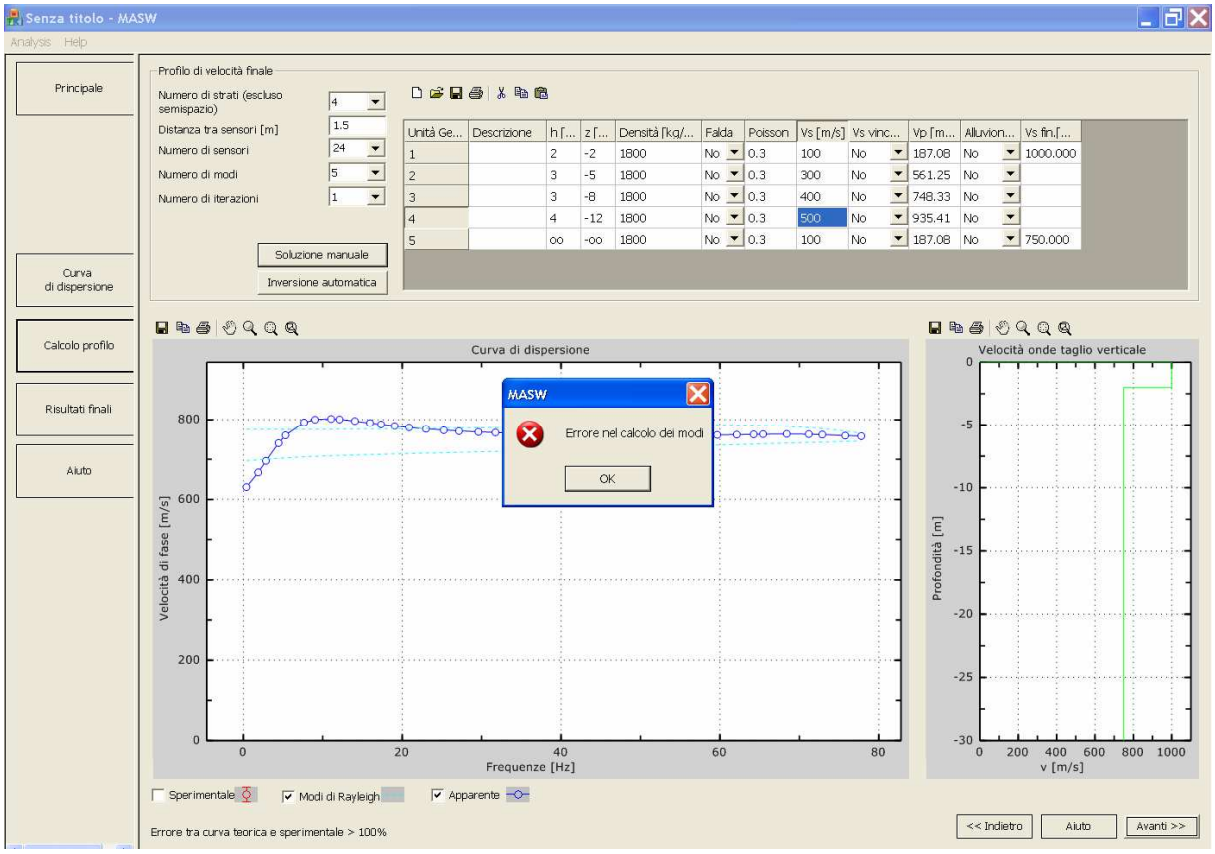


Figure 4.1: modes of Rayleigh not found when dealing with a very soft half-space (Vs=100m/s)

7) From visual inspection of the experimental dispersion curve it is possibile to gain at least 2 useful data for the inversion process. The shear wave velocity Vs of the superficial layer and the shear wave velocity Vs of the half-space. At high frequencies (> 50Hz) the experimental dispersion curve tends to the Rayleigh phase velocity of a homogeneous half-space with the same Vs velocità of the superficial layer, i.e. to about 0.9 Vs of the superficial layer.

At low frequencies (< 5Hz-10Hz) the experimental dispersion curve tends to the Rayleigh phase velocity of the half-space at the base of the model. If the experimental dispersion curve is only available at frequencies of 15Hz-20Hz, it is possibile anyway to infer the shear wave velocity Vs of the half-space. If the half-space at the base of the model is a stiff layer, then the experimental phase velocity grows up at low frequencies, otherwise if the half-space is soft, then the experimental phase velocity decreases at low frequencies.

Some examples of typical sites follow. For theese sites the nuemrical dispersion curve has been calculated. Knowledge of the shape of the dispersion curve for typical known sites can help find the Vs profile when dealing with the experimental dispersion curve of unknown sites.

4.3 Example 1: stiff layer on the free surface of the site

This example shows the shape of the apparent dispersion curve of a site with a vey stiff layer on the free surface. The thickness of the stiff surficial layer is equal to 2m and the shear wave velocity to Vs=800m/s. This example may represents the case of a strongly overconsolidated clay layer or a compacted sandy layer (for axample earth dams or embankment of roadways).

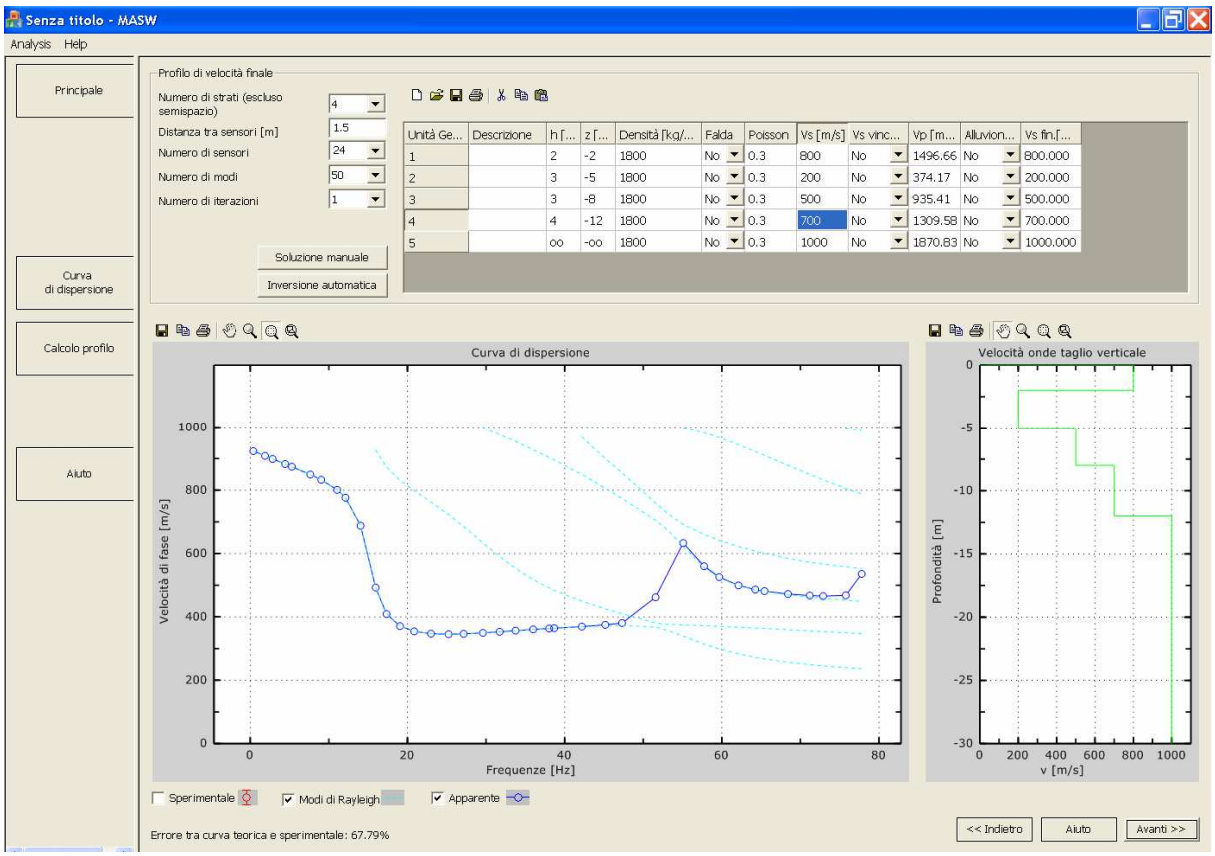


Figure 4.2: stiff superficial layer

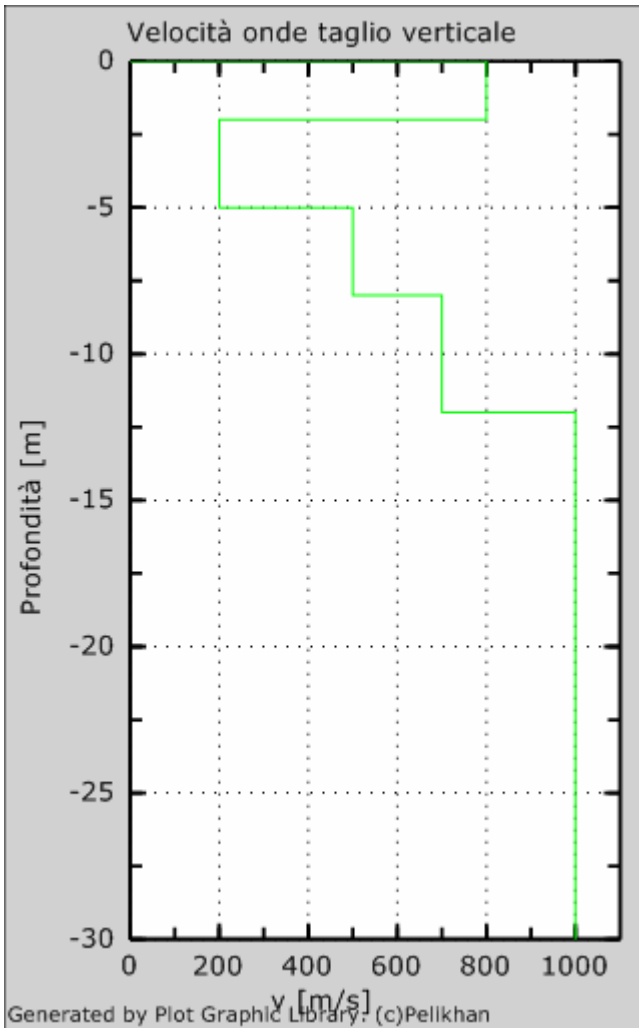


Figure 4.3: Vs profile

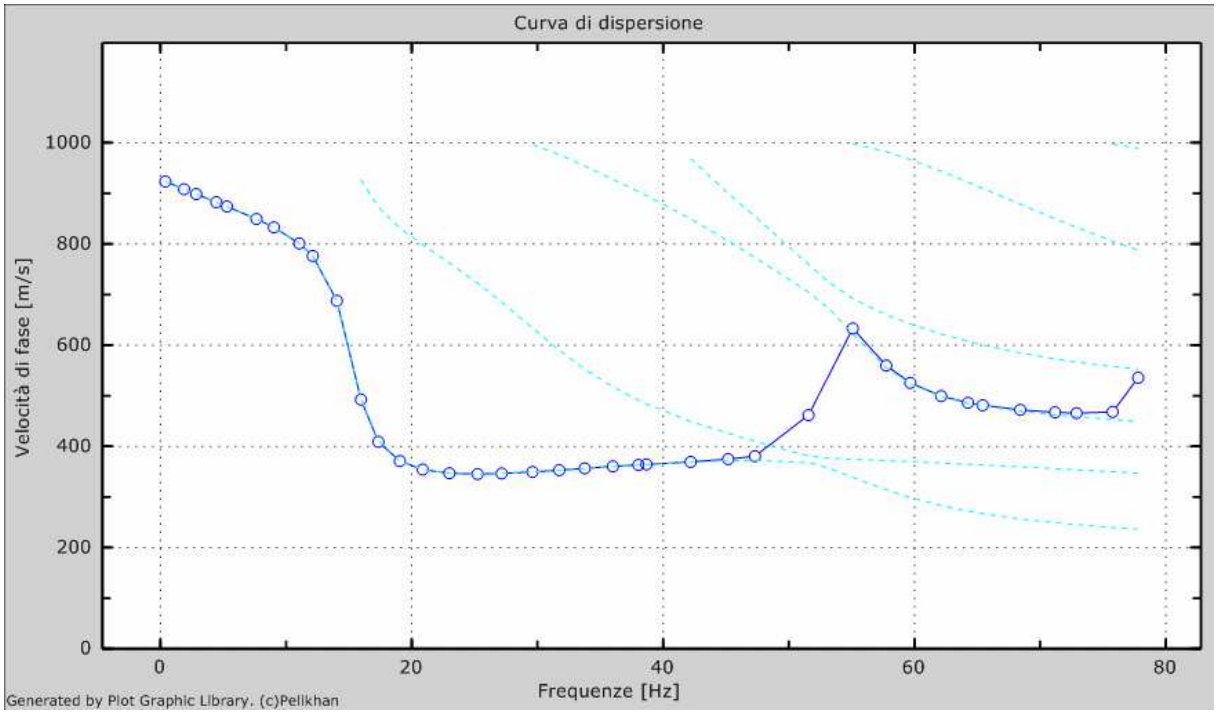


Figure 4.4: numerical apparent dispersion curve and modes of Rayleigh

The apparent dispersion curve coincides with the fundamental mode of Rayleigh until 50Hz, then it is comprised between the 2th mode and the 3rd mode, then between 55Hz and 75Hz coincides with the 3rd mode, then at higher frequencies moves toward higher modes of Rayleigh.

4.4 Example 2: stiff intermediate layer

This example shows the shape of the apparent dispersion curve of a site with a vey stiff layer at an intermediate depth. The behavior of the dispersion curve is similar to the case of the stiff superficial layer. When the apparent dispersion curve does not coincide with the fundamental mode of Rayleigh at all the frequencies, but it moves towards the higher modes of Rayilegh at higher frequencies, it means that the shear wave velocity profile does not increase monotonically with depth. In general it is not true the contrary, that is a Vs profile which increases monotonically with depth may generate an apparent dispersion curve which moves towards higher modes of Rayleigh at certain frequencies. The example 3 testify this case.

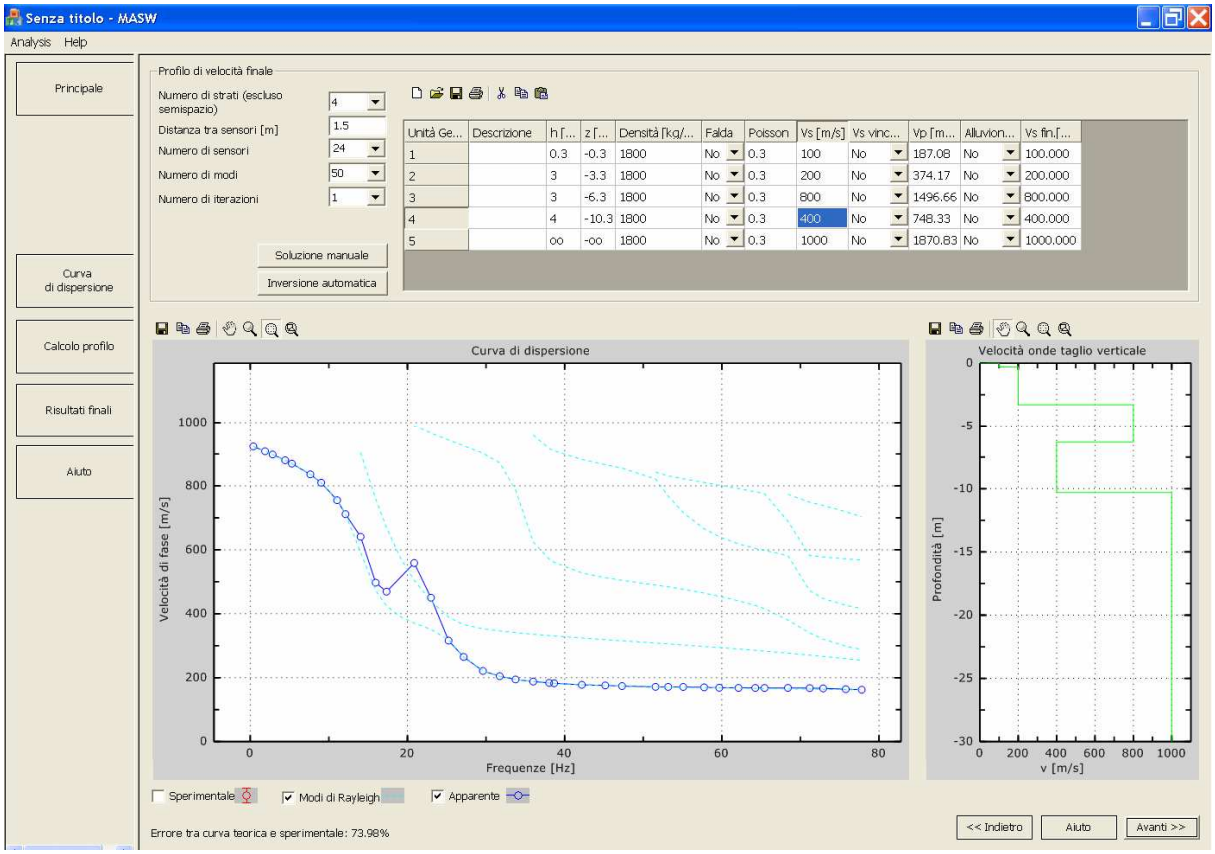


Figure 4.5: intermediate stiff layer.

4.5 Example 3: stiff half-space at the base

Generally the existence of a stiff half-space at the base of the model guarantees that there are not anomalies in searching the modes of Rayleigh or in the behavior of the apparent dispersion curve.

The following Vs profile presents a monotonically growing Vs with depth; nevertheless the site is inversely dispersive, since the apparent dispersion curve jumps from the fundamental mode to the 2nd mode of Rayleigh at about 10Hz-17Hz.

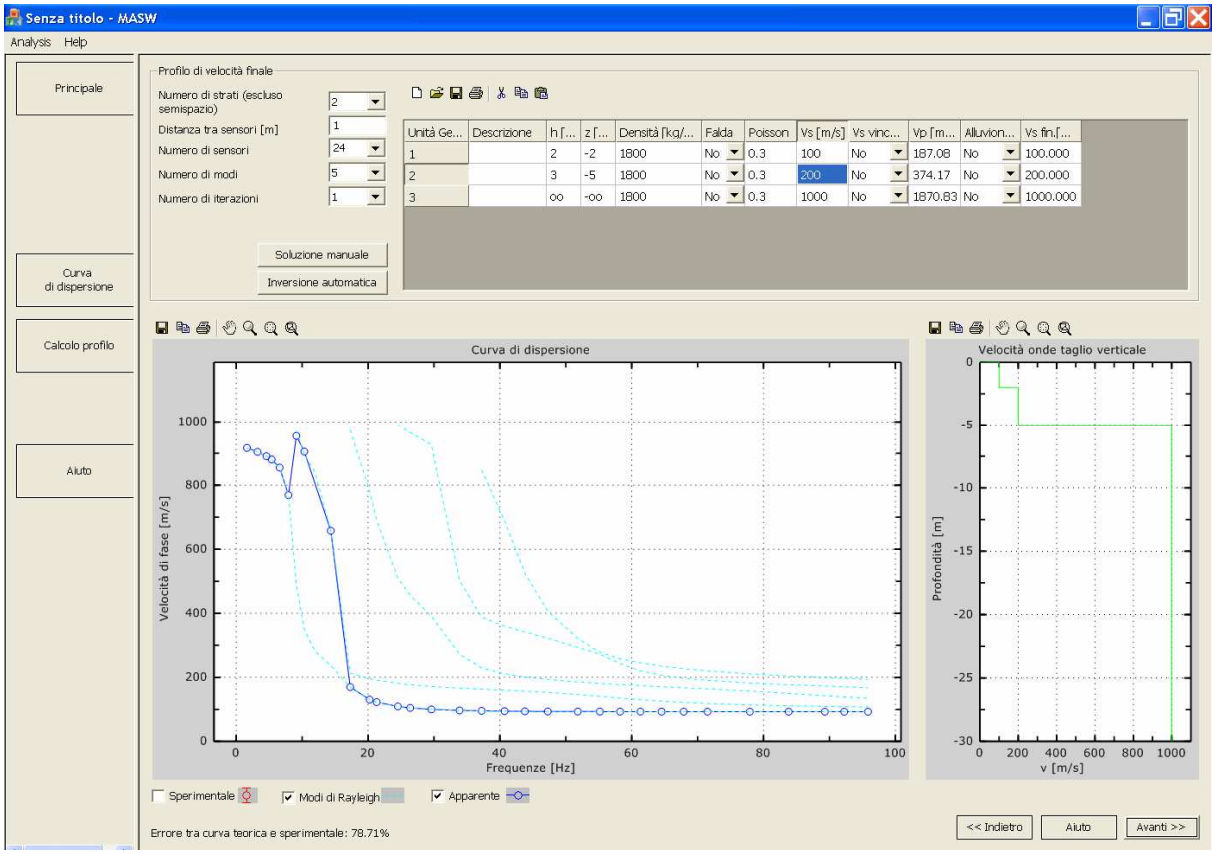


Figure 4.6: very stiff half-space.

4.6 Example 5: intermediate soft layer

This case is similar to that of the example 2. If the Vs of the soft layer is very low compared with the other layers, then the apparent dispersion curve may appear really irregular over the entire frequency range (see **figure 4.7**). In theese circumstances it may become really difficult to infer the Vs profile by simply looking at the shape of the apparent dispersion curve. Nevertheless this type of shape indicates the existence of one or more soft layers in the Vs profile.

In **figure 4.8** it is shown the more reliable case of a soft intermediate layer, but the stiffness contrast with the other layers is moderate. In theese sites the apparent dispersion curve assumes a quite regular and continous behavior over the frequency range: the apparent dispersion curve moves from the fundamental mode to higher modes of Rayleigh as frequency increases. It is quite easy to recognise theese types of sites, with a soft intermediate layer.

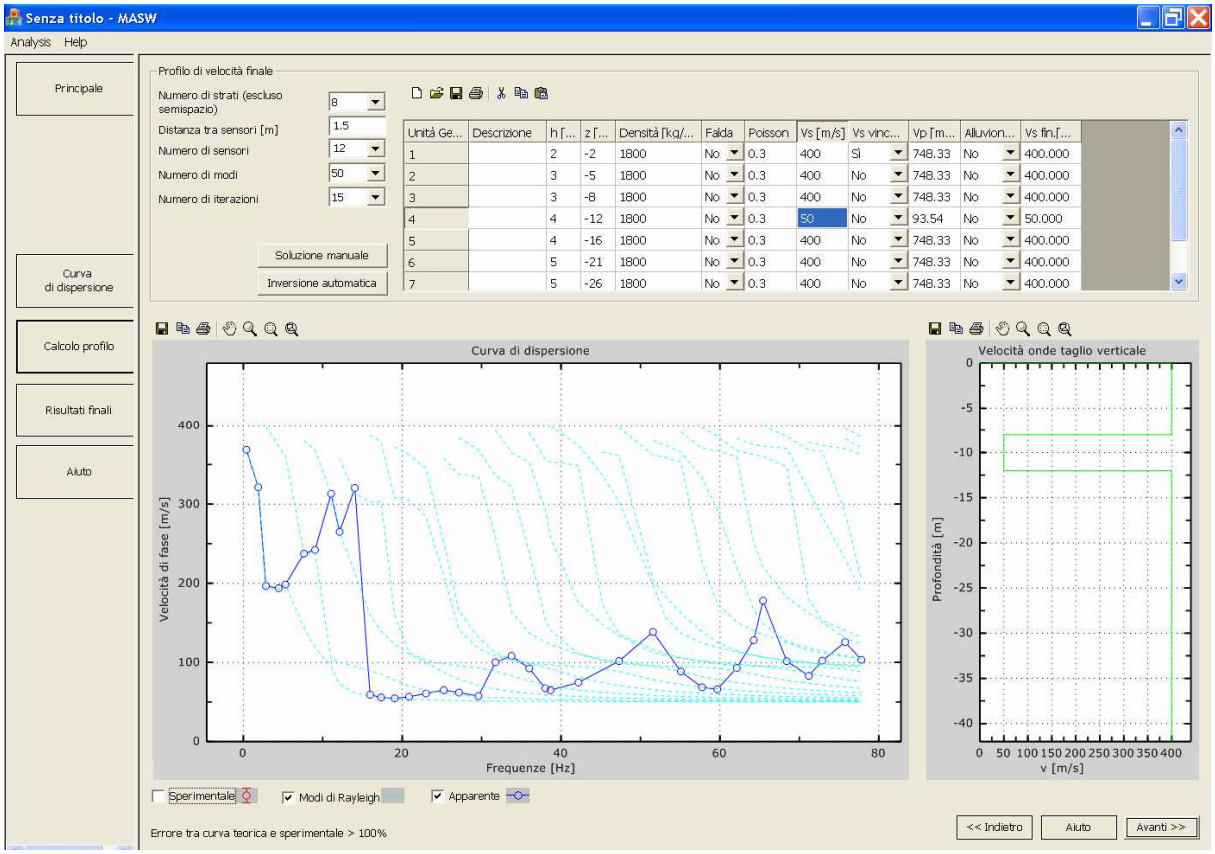


Figure 4.7: very soft intermediate layer.

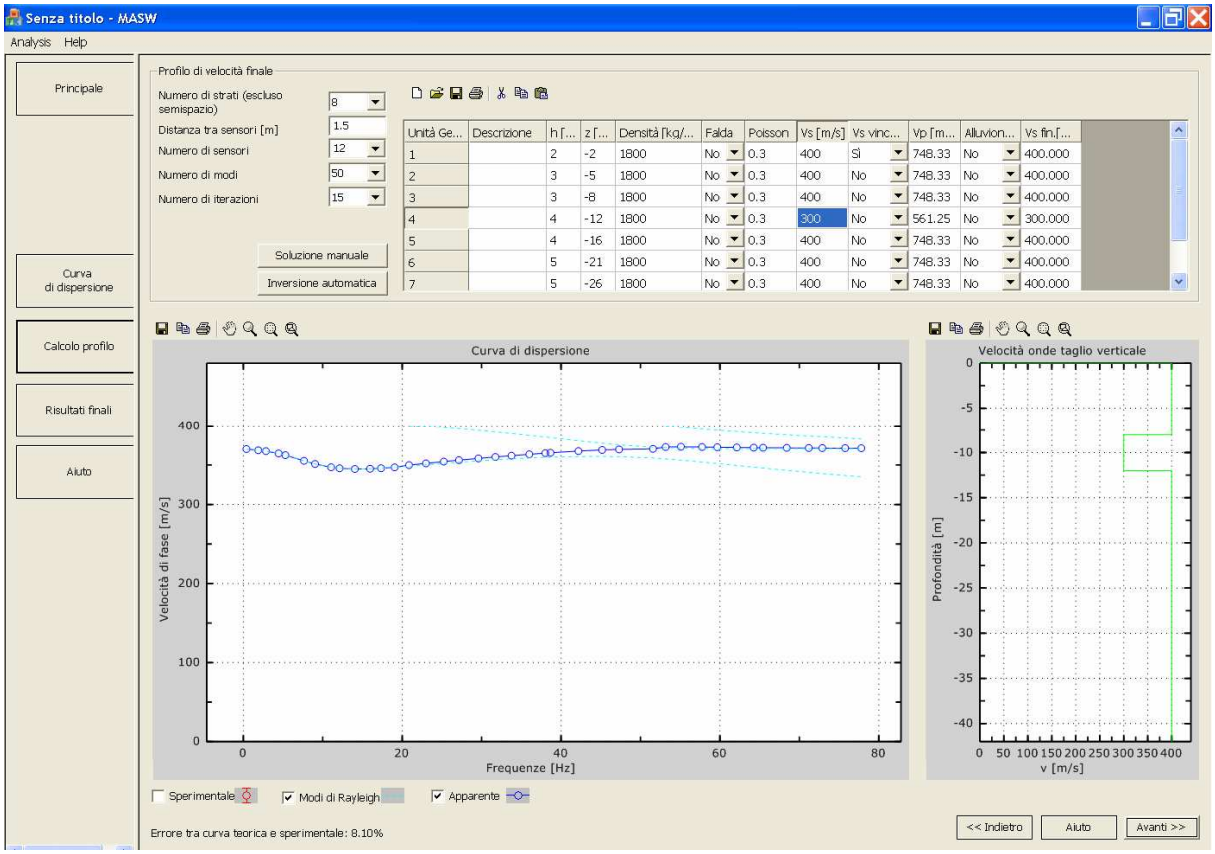


Figure 4.8: moderately soft intermediate layer.

4.7 Example 6: soft half-space

This is the most critical case, since the absence of a stiff half-space represents a condition of existence of the modes of Rayleigh into a layered half-space over all the frequencies. In fact when layer stiffer than the half-space exist, the so called leaky modes arise, which are coupling modes between the upper stiff layers and the soft half-space. Theese leaky modes attenuate rapidly with distance from the source and they determine the transmission of energy from the upper stiff layers to the soft half-space below. Leaky modes represent the complex roots of the dispersion relation: the imaginary part determines the hysteric attenuation durino propagation, the real part determines the phase velocity, which is greater than the Vs velocity of the half-space. In addition to the leaky modes, symmetric and anti-symmetric Lamb modes arise, which are typical of isolated plates with 2 opposite free surfaces. Several situations can be discerned:

- One case occurs when there is only one very stiff superficial layer over a soft half-space (Vs_half-space < 70% Vs_layer). In this case there are problems to find leaky and Rayleigh modes (see **figure 4.9**). It is suggested to increase the number of layers to reach depth where the half-space has a shear wave velocity Vs of the superficial layer.
- Another case similar to the previous one consists of a moderately stiff superficial layer over the half-space (Vs_half-space > 70% Vs_layer). In this situation there not problems to finde the modes of propagation (**figures 4.10, 4.11, 4.12**).

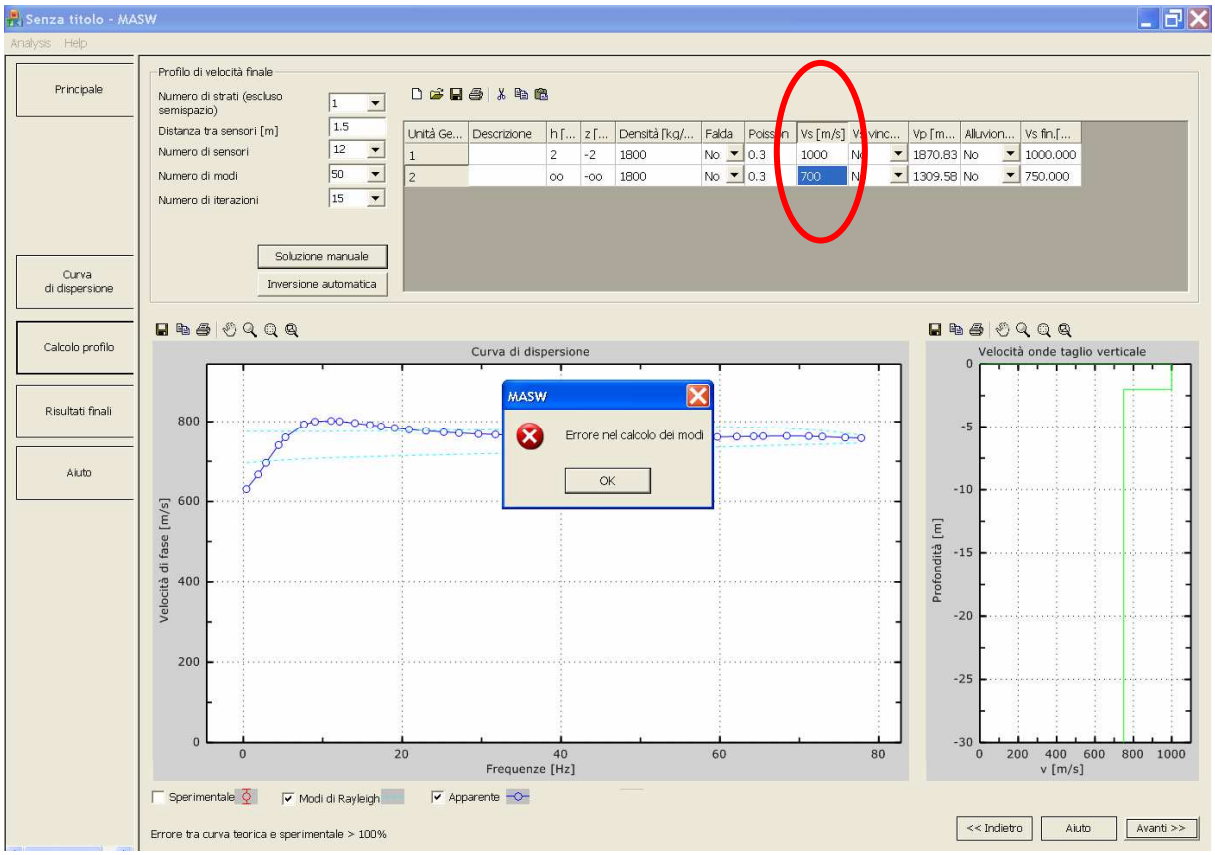


Figure 4.9: very stiff superficial layer over the half-space: failure to find the modes of propagation (see the Vs profile into the table of the figure, not the graph).

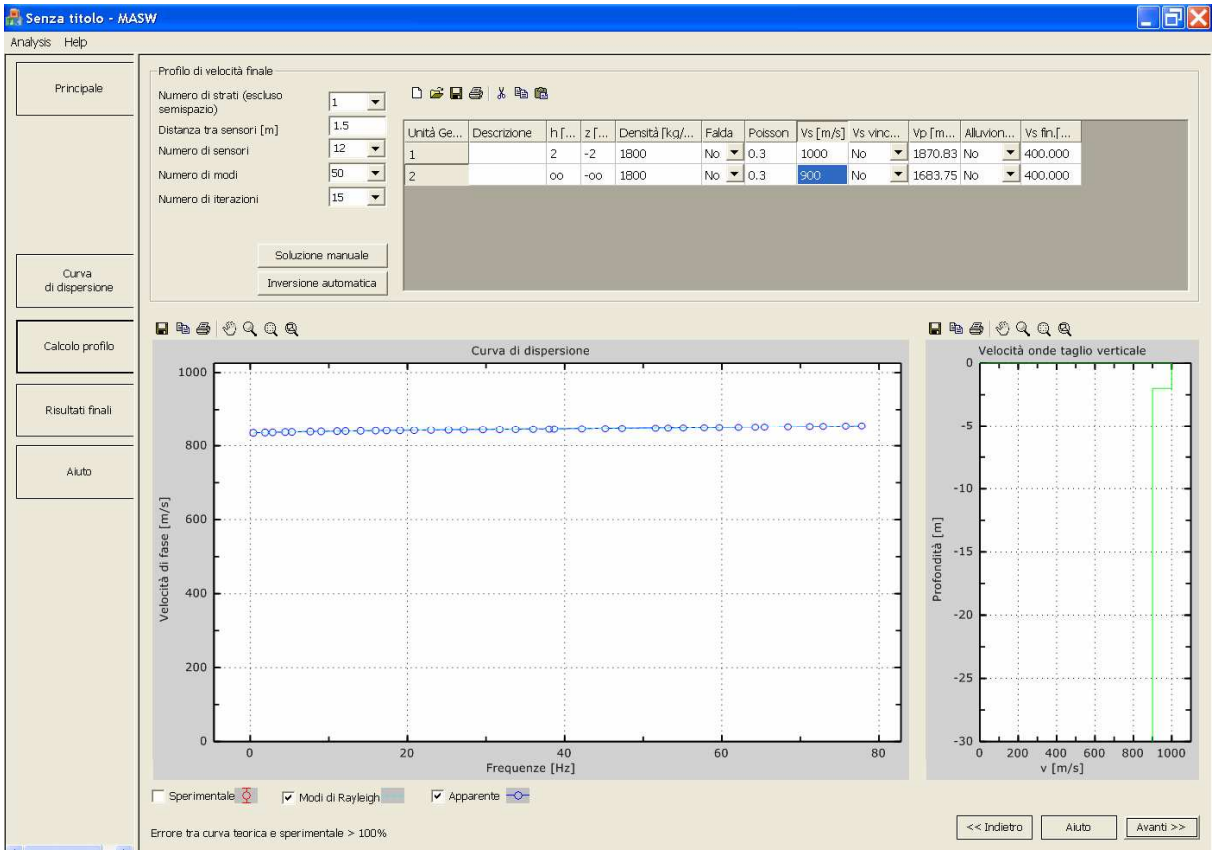


Figure 4.10: moderate stiff superficial layer over the half-space.

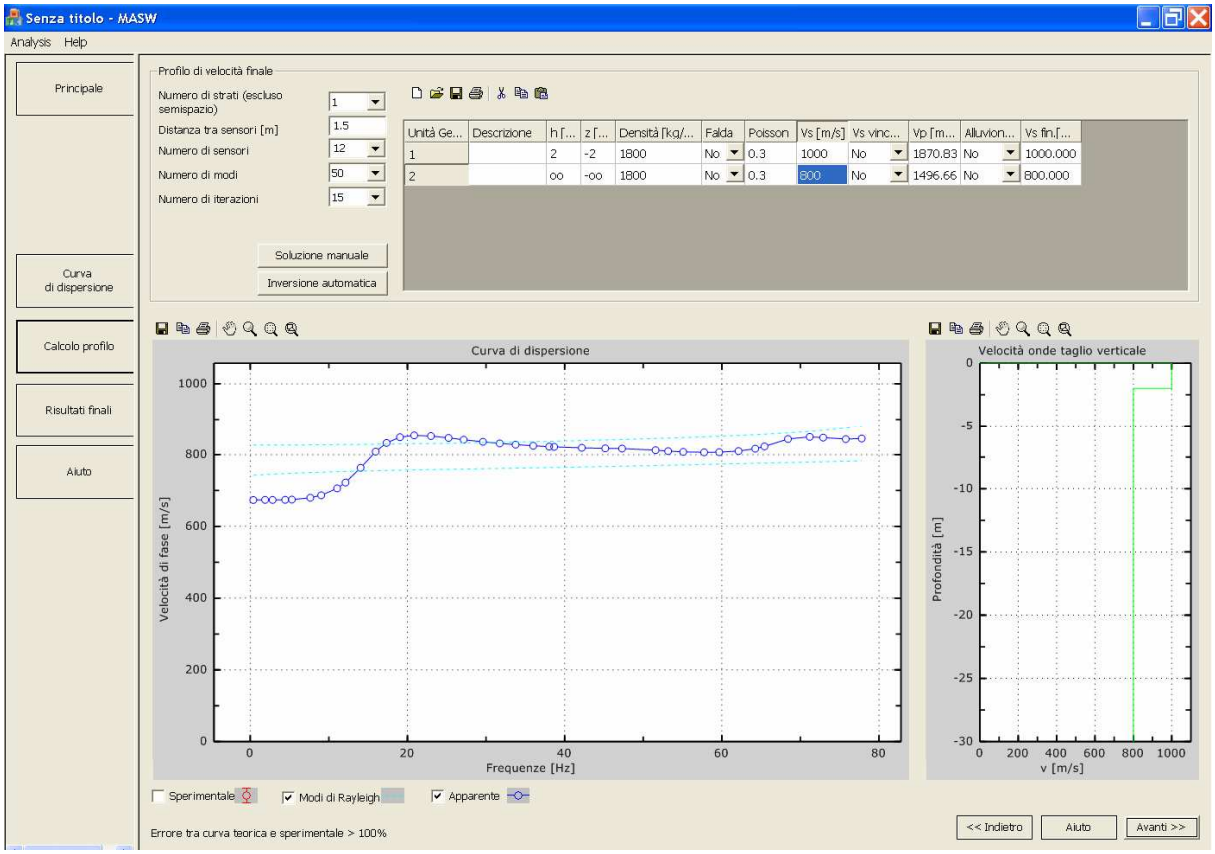


Figure 4.11: moderate stiff superficial layer over the half-space.

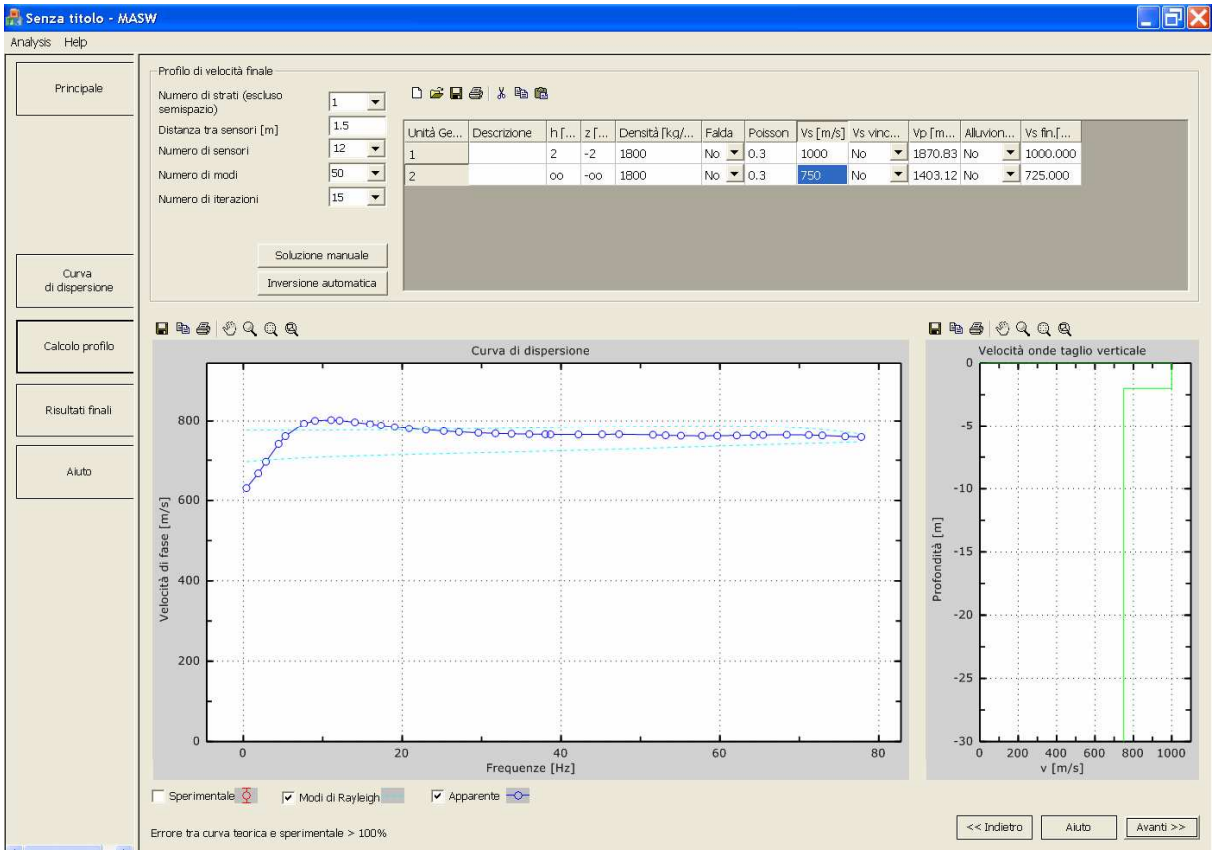


Figure 4.12: moderate stiff superficial layer over the half-space.

- Another case consists of more than one layer over a soft half-space. Even in these conditions may exist problems in finding the modes of propagation or the apparent dispersion curve may show an irregular, oscillating trend (**figures 4.13, 4.15, 4.16**).

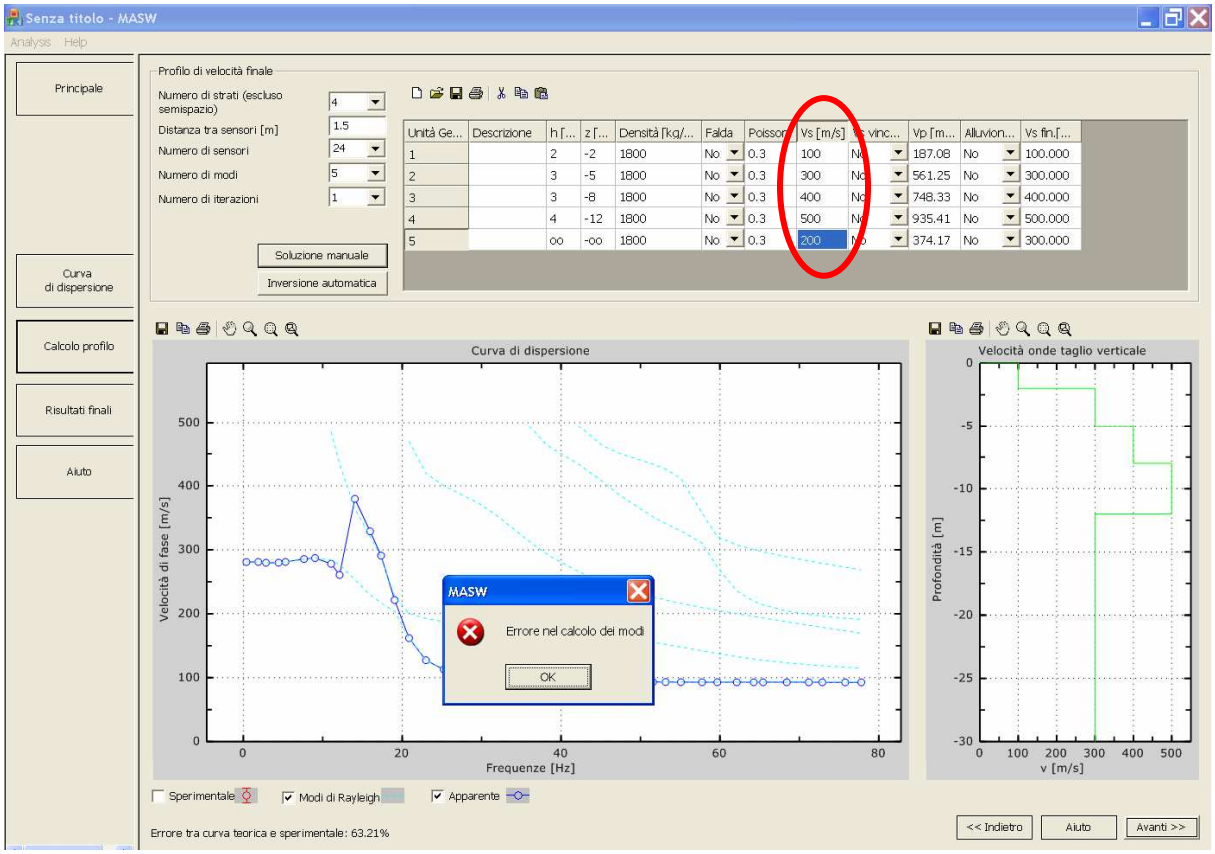


Figure 4.13: stiff layers over a too soft half-space (see the Vs profile into the table of the figure, not the graph).

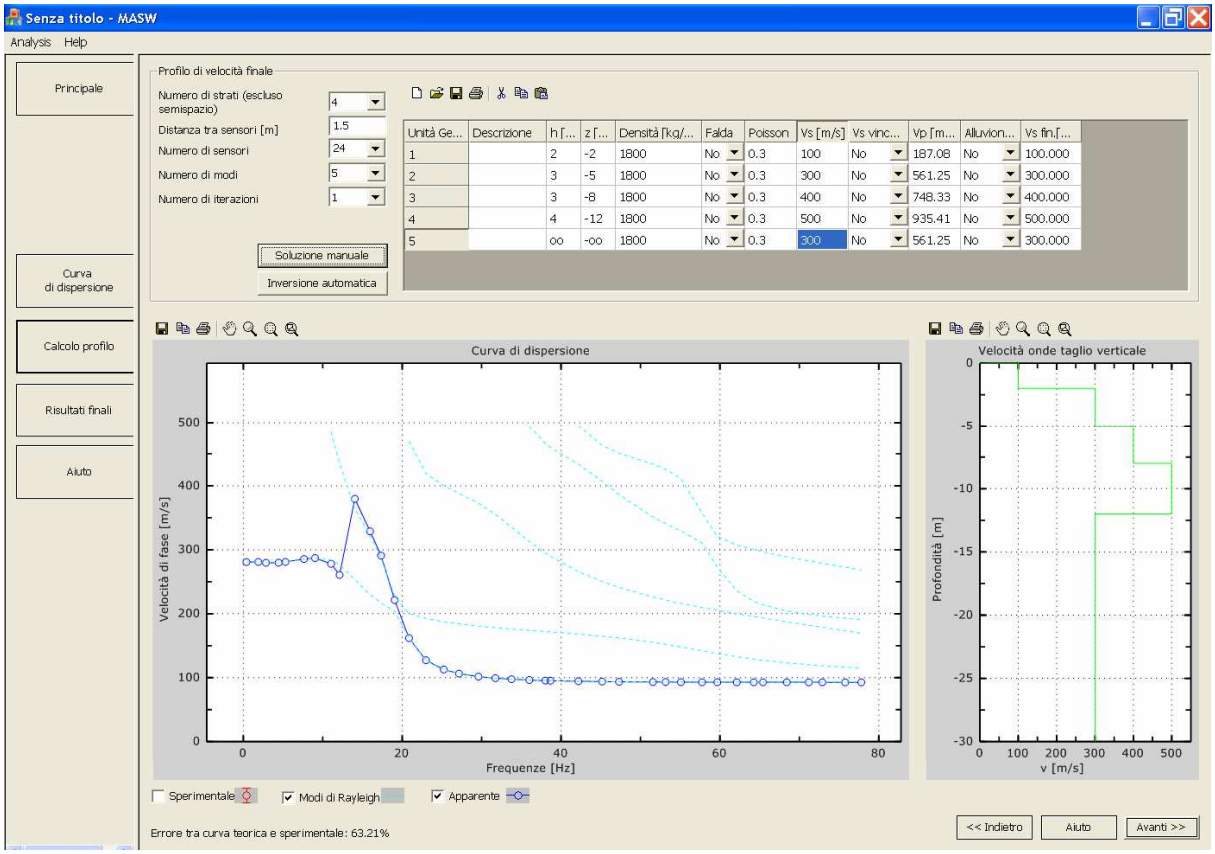


Figure 4.14: stiff layer over a moderately soft half-space.

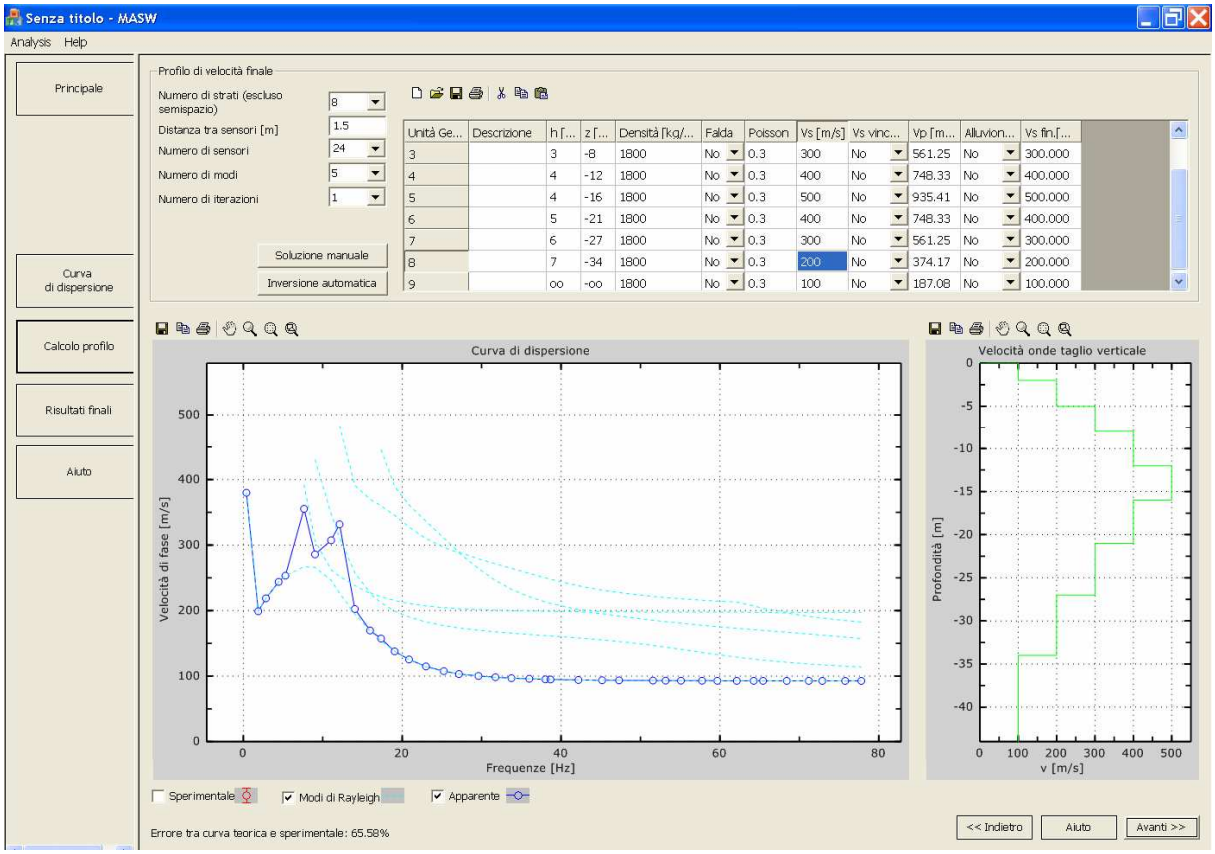


Figure 4.15: stiff layers over a soft half-space: oscillating dispersion curve.

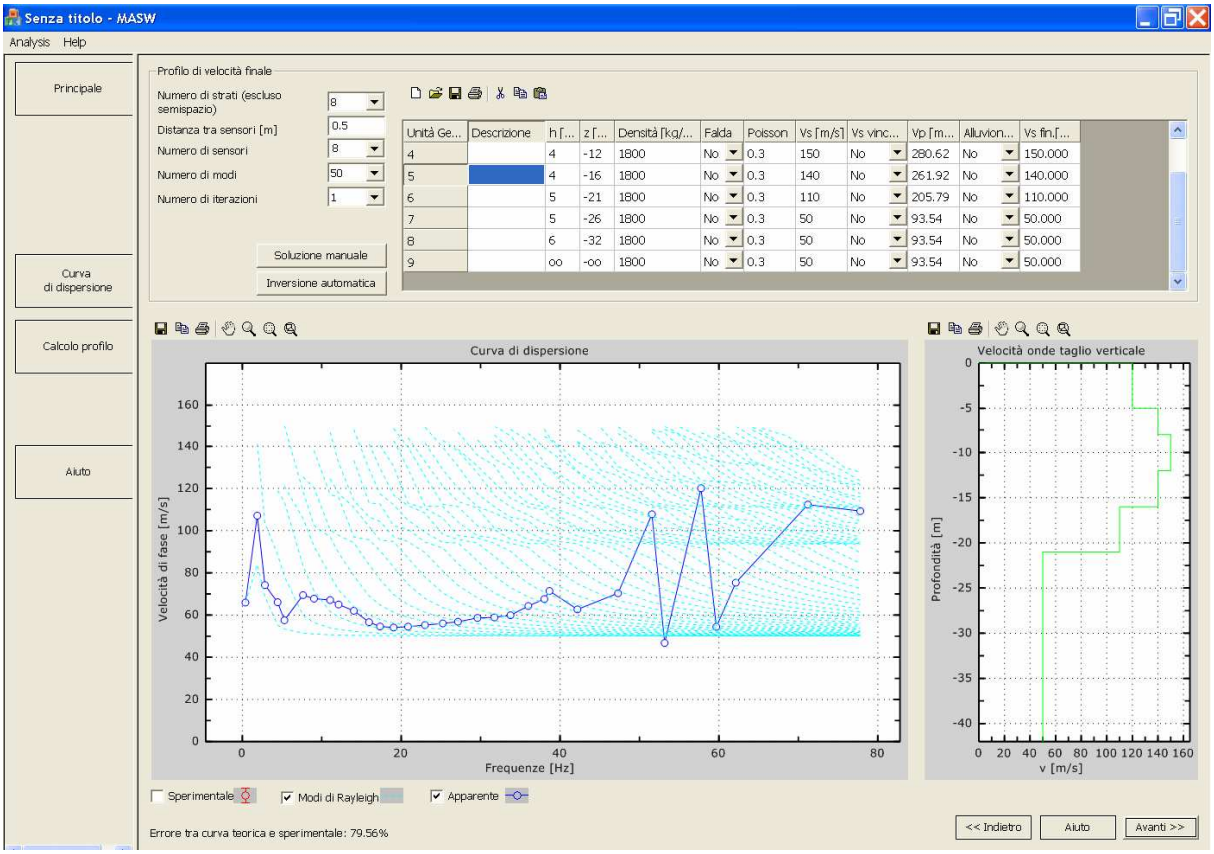


Figure 4.16: stiff layers over a soft half-space: oscillating dispersion curve.

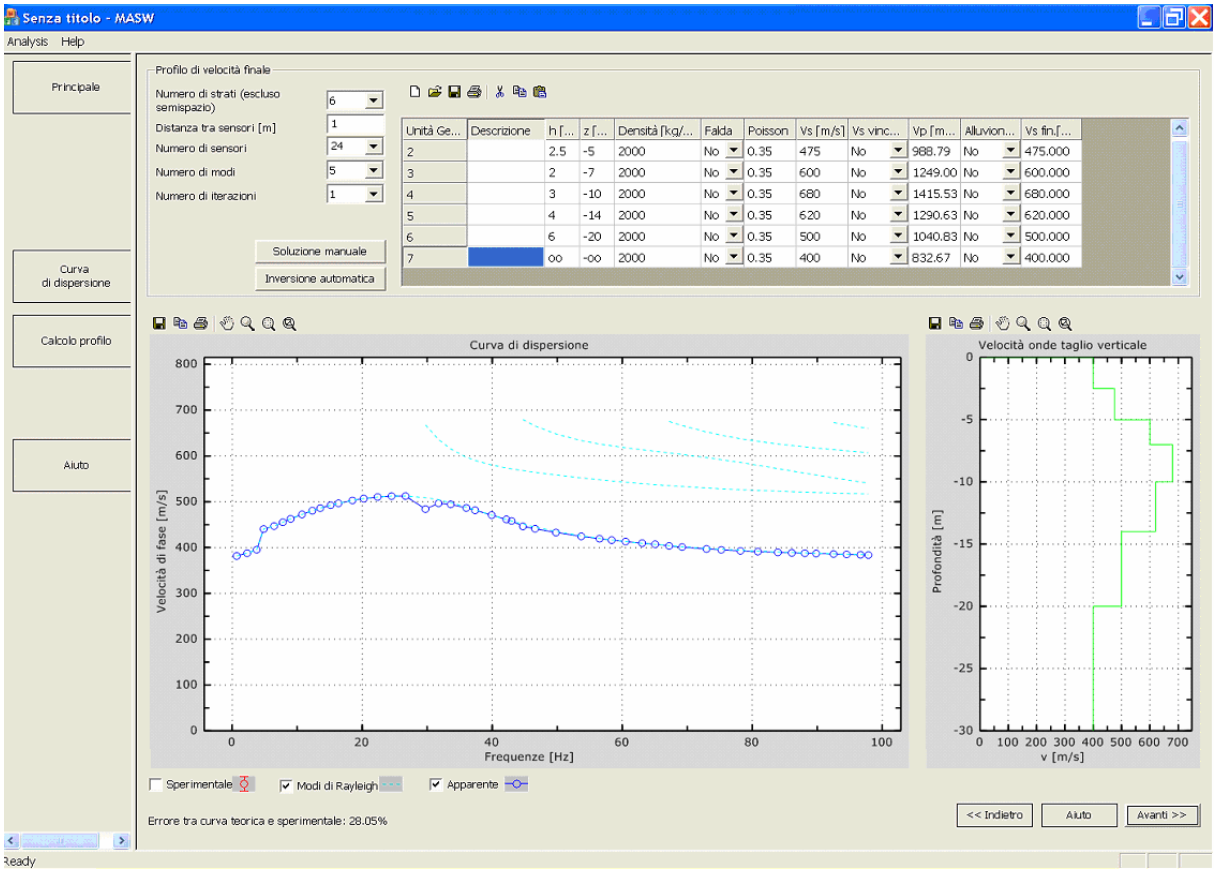


Figura 4.17: stiff layers over a soft half-space: example in figure 15 by O' Neill "Full wave form reflectivity for inversion of surface wave dispersion in shallow site investigations".

4.8 Example 7: rigid superficial pavement

This example presents the apparent dispersion curve of a site with a stiff superficial layer, which has Vs=800m/s and thickness h=0.3m and could represents a pavement. The stiffness of the site gradually increaeses with depth with a halfspace at the base which is stiffer than the superficial pavement. The presence of a stiff half-space guarantees the existence of the Rayleigh modes of propagation over all the frequencies.

Generally in sites like that shown in **figure 4.18** the apparent dispersion curve moves from the fundamental mode of Rayleigh towards the 2nd mode within the frequency range 10Hz – 30Hz; at frequencies higher than 30Hz the apparent dispersion curve coincides with the fundamental mode, then at very hgigh frequencies the apparent dispersion curve jumps towards higehr modes of Rayleigh. When dealing with pavemented sites the experimental data could show the fundamental symmetric and anti-symmetric Lamb modes. The anti-symmetric Lamb mode already exists and is visible at low frequencies; it can be easely recognised, since it coincides with a phase velocity which grows with frequency.

It may happen that the experimental dispersion curve be not visibile at low frequencies, less than 5Hz – 10Hz and hence the jump form the fundamental to the 2nd mode is not visibile. In this case the experimental dispersion curve seems to coincide with only the fundamental mode and this would be a mistake. The knowledge that there is the superficial pavement helps infer the correct shape of the dispersion curve and hence help find the correct Vs profile.

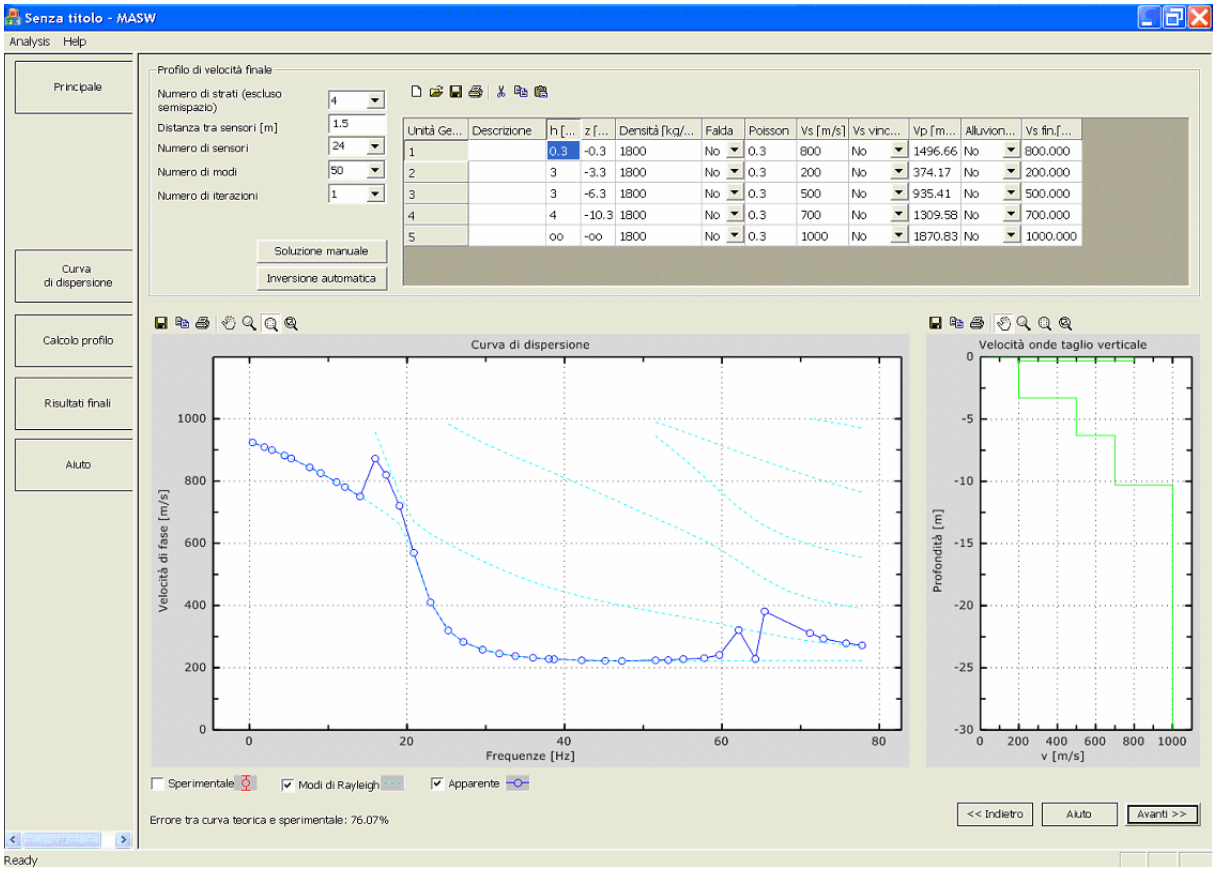


Figure 4.18: site with thin superficial stiff pavement (h=0.3m) and stiff halfspace.

4.9 Example 8: homogeneous layered halfspace

This case is not common, as it requires a constant stiffness of the soil down to 30m; nevertheless it is reported for completeness.The apparent dispersion curve is constant with frequency, since this site is not dispersive and only the fundamental mode exists (**figure 4.19**). It should be observed that a layered half-space with layers with the same velocities behaves like a homogeneous halfspace.

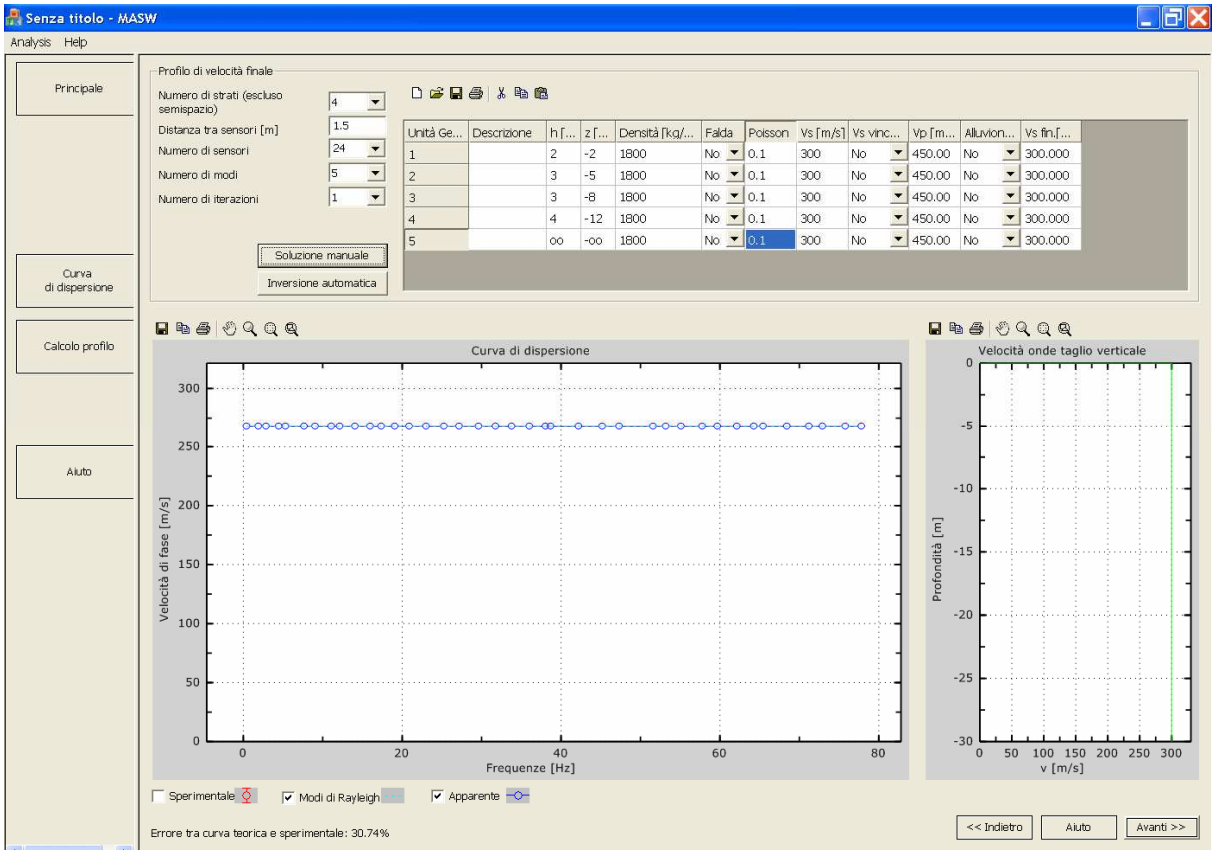


Figure 4.19: site with constant Vs profile (homogeneous half-space).

4.10 Example 9: influence of water table

The presence of water can be considered by adopting a Poisson's coefficient equal to about 0.5. In the software the value of 0.48 is adopted if water is present. The user can modify the Poisson's coefficient by turning off the option that indicates existence of the water.

Generally the water influences the apparent dispersion curve, nevertheless the influence of water is very low compared to the influence of the shear wave velocities Vs of the layers.

Consider the homogeneous site in **figure 4.20**, obtained adding the water to some layers of the site in **figure 4.19**. The apparent dispersion curve changes slightly, since the water causes a greater phase velocity. It may happen that the water influence much more the apparent dispersion curve with respect to the shown example.

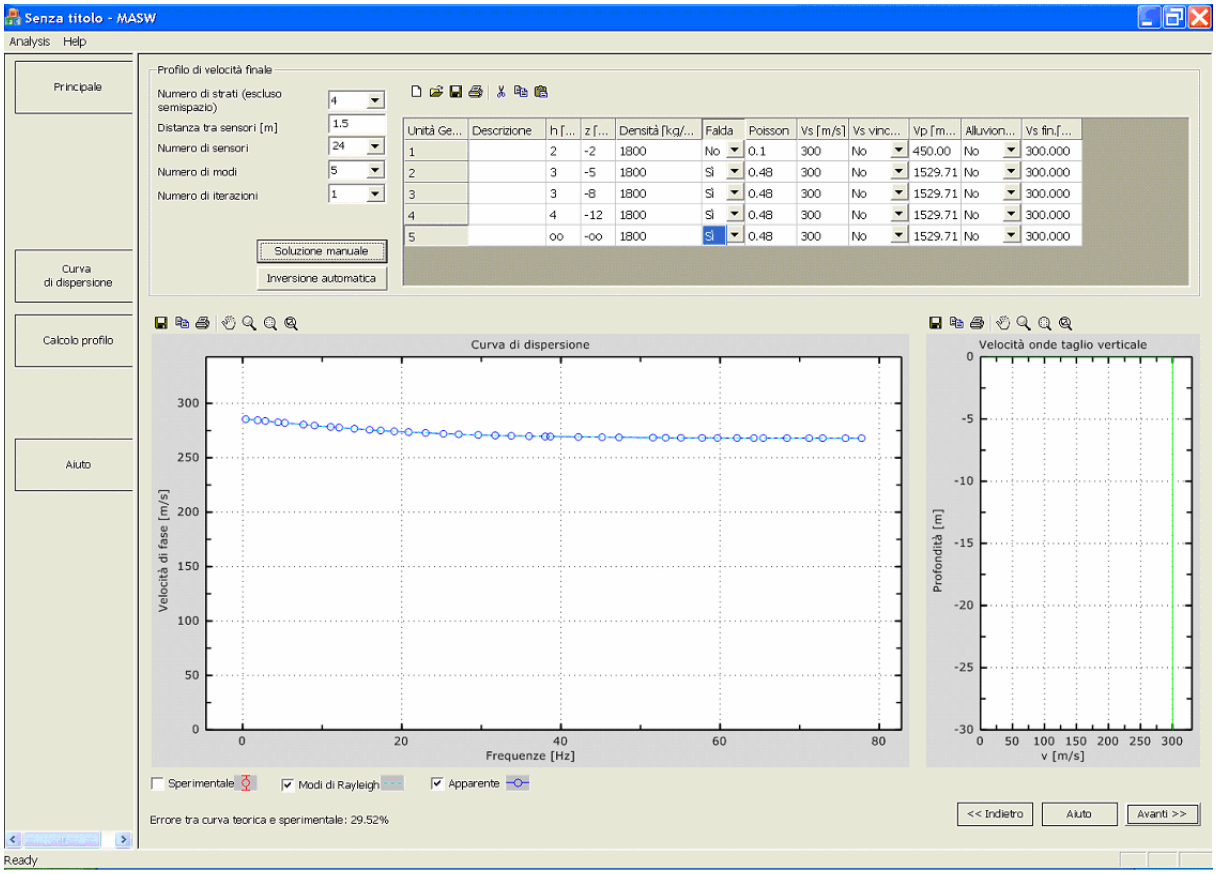


Figure 4.20: same homogeneous site as in figure 4.19, but now the water exists in some layers.

4.11 Example 10: influence of the number of modes of Rayleigh

The number of modes of Rayleigh may influence the apparent dispersion curve, especially at high frequencies when dealing with inversely dispersive sites, when the contribution of the excluded higher modes is significant (see **figures 4.21 and 4.22**).

This situation is evident when the apparent dispersion curve reaches the highest available mode of Rayleigh and there are not other higher modes where the apparent dispersion curve can move. When dealing with sites with strong stiffness contrasts, at frequencies lower than 80Hz it is a good rule to use between 5 and 10 modes with the automatic search and at least 20 modes with the trial and error search. If there are very soft or very stiff intermediate layers at very high frequencies more than 20 modes of Rayleigh could be necessari. When dealing with moderate stiffness contrasts or when the stiffness gradually and monotonically increases with depth, the the fundamental and the 2nd modes of Rayleigh are sufficient. At the end of the automatic search of the optimal Vs profile it is suggested to runa gain the manual search, after increasing the number of available modes of Rayleigh.

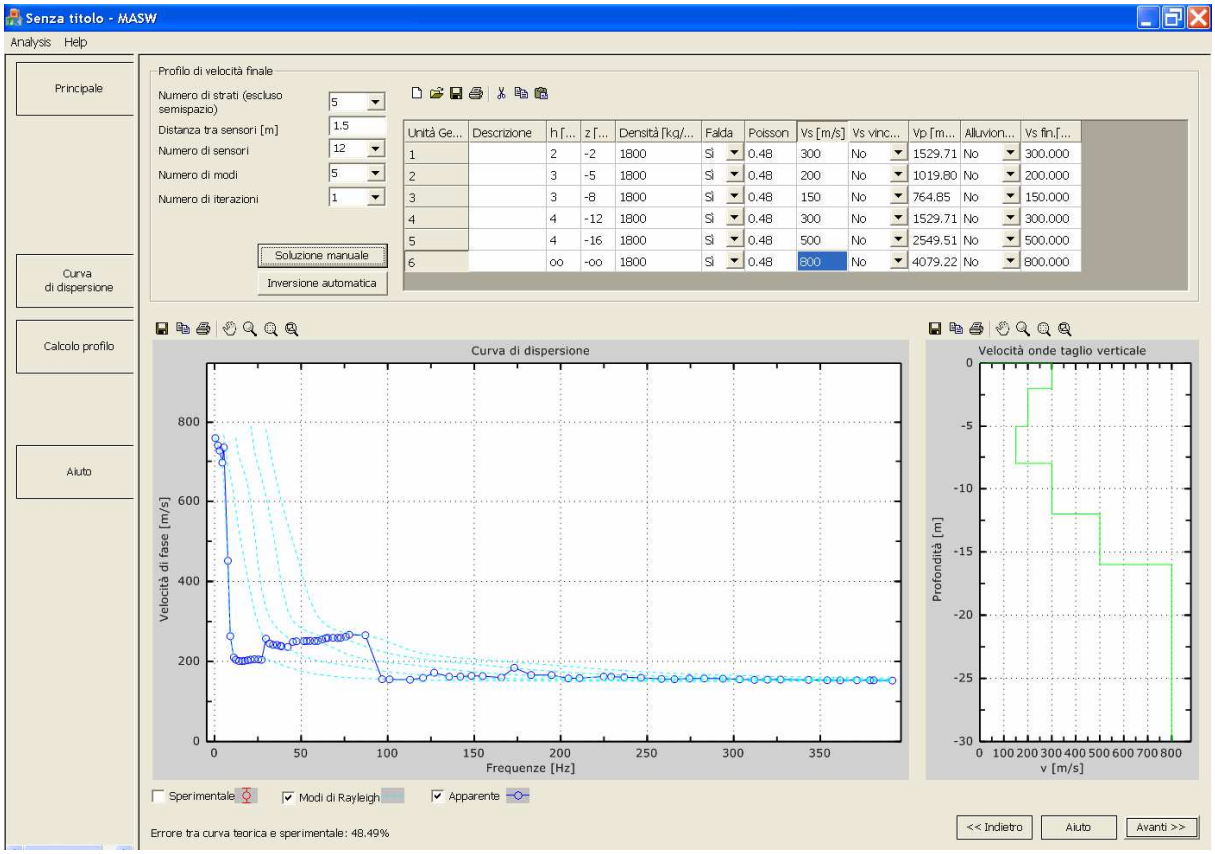


Figure 4.21: apparent dispersion curve at high frequencies with only 5 modes of Rayleigh.

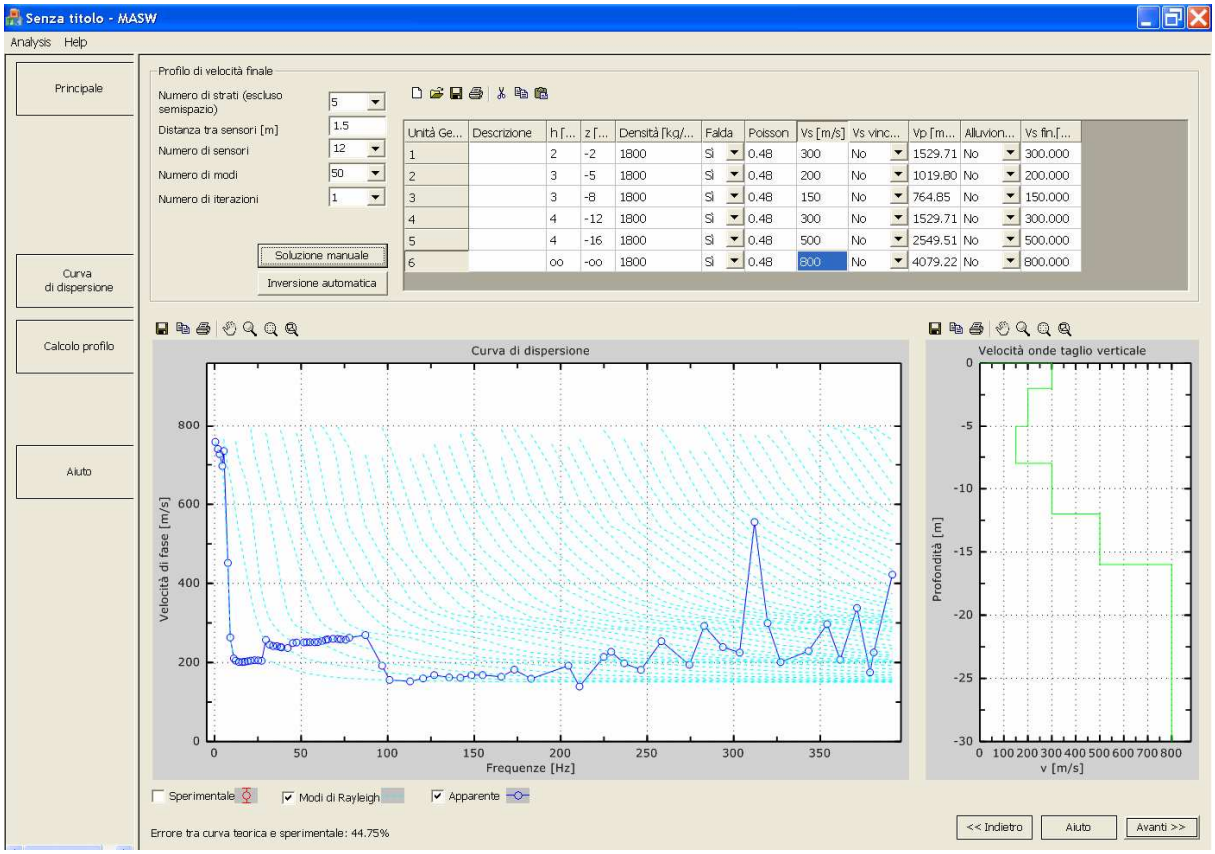


Figure 4.22: oscillatine apparent dispersion curve at high frequencies with 50 modes of Rayleigh.

4.12 Example 11: influence of the receivers array

The spatial configuration of the receivers, i.e. the span between two consecutive receivers when the spani s constant, may influence the shape of the dispersion curve at certain frequencies. For this reason in the numerical simulation it is suggested to use an array which is the same used in the field test. In the **figures 4.23** and **4.24** are shown the apparent dispersion curves using the same Vs profile and the same number of receivers (24), but using two different spans.

In **figure 4.23** the spani s equal to 1.5m, in **figure 4.24** the spani s equal to 5.0m. The reader can observe a diveristy of the two dispersion curves at around 20Hz.

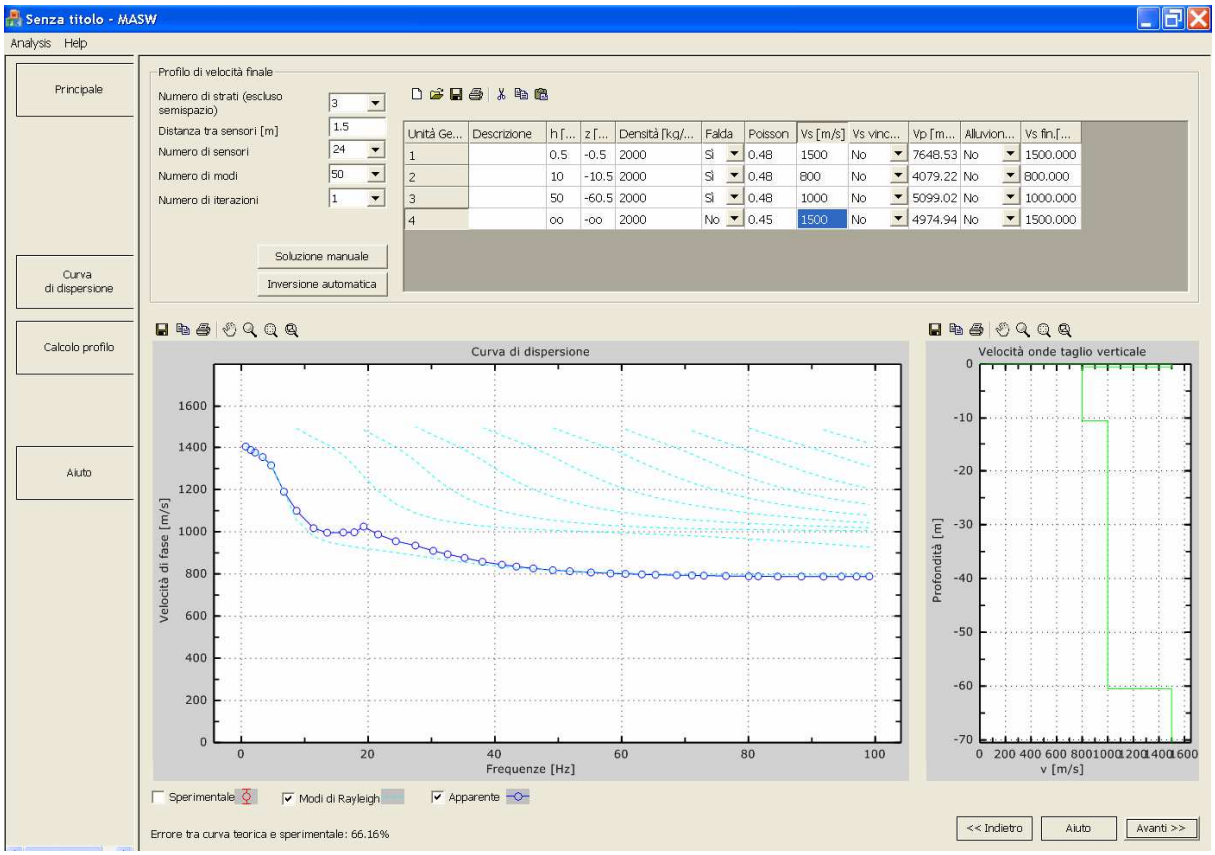


Figure 4.23: apparent dispersion curve with 24 receivers and a span of 1.5m

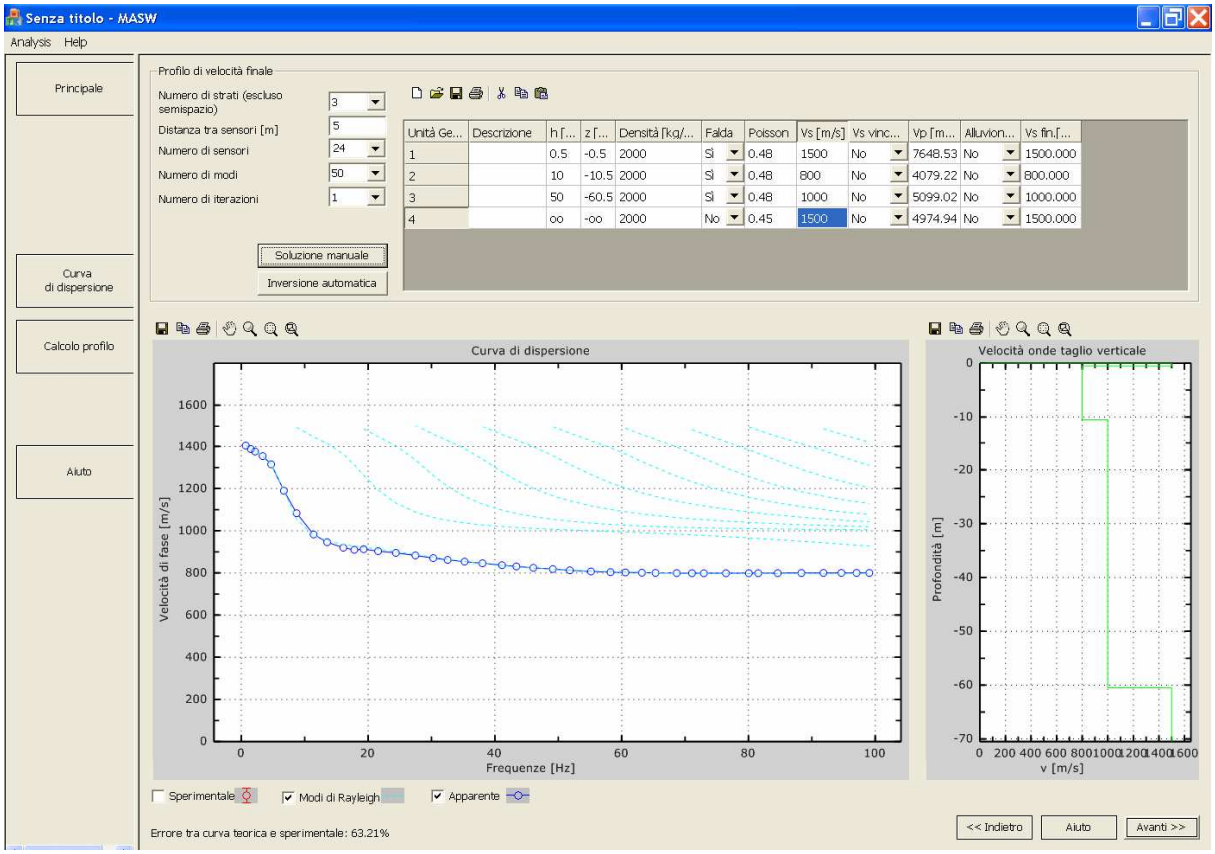


Figure 4.24: apparent dispersion curve with 24 receivers and a span of 5.0m.

4.13 Example 12: behavior at high frequencies

When dealing with some sites with strong stiffness contrasts and layers of thickness less than 5m, it may happen that the apparent dispersion curve appear strongly irregular or oscillating at high frequencies, generally higher than 70Hz-80Hz (**figure 4.22**). It is suggested to limit the analyses below 80Hz, since the information given by the apparent dispersion curve at frequencies higher than 80Hz concern the upper 1m-2m of the ground. The proposed method and software are expected to determine the seismic class of the site, not the Vs velocità of the pavement or the first 1m-2m of the ground.

Some case histories follow, where the Vs profile and the seismic class have been determined by means of the MASW method.

4.14 Example 13: site near FIAT factory in Tuirn

The investigated site is located in a zone of turin, where there are layers of gravel and sand, with a level of cementation which grows up with depth. Any layers of sandy silts may exist. The water table is at a depth of about 15m from ground level.

The active MASW test has been executed both on a rigid pavement with thickness of 20-30 cm and on the ground near the pavement.

The parameter of the test are:

receivers span = 1.5m

time sampling = 2ms

total length of the receivers array = 36m

source: hand hammer of 5kg.

We analyse first the MASW test on the ground free from pavement.

In **Figure 4.25** the measured wave motion is plotted. In figura **Figure 4.26** the fk spectrum and the experimental dispersion curve in the frequency range 2Hz-70Hz are plotted.

In **Figure 4.27** the significant points of the experimental dispersion curve have been selected for the successive steps. The source has furnished useful information within the frequency range 20Hz - 70Hz. This situation implies a greater uncertainty on the shear wave velocità Vs of the deeper layers of the profile.

In **Figure 4.28** a trial initial geotechnical profile has been assigned. The Vs velocities have been assigned by default by the software, considerino 8 layers. The receivers spani s equal to 1.5m and 5 modes of Rayleigh have been adopted. The trial and error (or manual) search associated to the initial Vs profile has generated a numerical apparent dispersion curve, which

is quite distant from the experimental dispersion curve, in fact the relative error between the 2 curves is equal to about 43%.

In the next manual attempt the Vs profile has been modified, by increasing the Vs of the deep layers to increase the phase velocity at low frequencies (**Figure 4.29**). Also the thicknesses of the layers can be changed, i.e. the thickness of the upper layers is reduced, instead the thickness of the deeper layers is increased. The Vs=275.7m/s of the superficial layer is fixed, before running the automatic search with a maximum of 5 iterations. At the end of 5 iterations the Vs profile in **Figure 4.29** is obtained. Even if the relative error is quite low, equal to 7%, the Vs profile is anomalous, because of a very stiff intermediate layer with thickness of 2m at a depth of about 6m from the ground level. This situation seem to be strange and not justified by complementary geotechnical information. So another manual search is performed, after some modifications, until the final Vs profile with an error of 6% is obtained (**Figure 4.30**).

The site with the found Vs profile has an equivalent shear wave velocity of Vs30=626m/s within the first 30m, hence the site belongs to the seismic class B (**Figure 4.31**).

Even if probably other similar Vs profiles exist, which give a good match between the experimental and the numerical dispersion curves, the variation of the Vs of theese different profiles does not cause a significant change of the Vs30, hence the seismic class remain the same. The obtained Vs profile is valid for design porpouses.

From this first case history the reader can understand that determination of the Vs profile of the site can not be exclusively meden by the automatic search, but it is the result of an iterative process, where automatic and manual searches alternate under the judgement of the user. During this process the experience of the user and the a priori available information on the site play a main rule.

As second case we consider the MASW test on the pavemented ground.

It can be observed that the presence of the rigid thin pavement does not influence the shape of the disperison curve at frequencies below 60Hz-70Hz, in fact up to 60Hz-70Hz the numerical dispersion curve obtained considerino a rigid pavement with Vs=800m/s and thickness of 20cm is quite the same that is obtained with the same site without the rigid pavement (see **Figures 4.30, 4.32**).

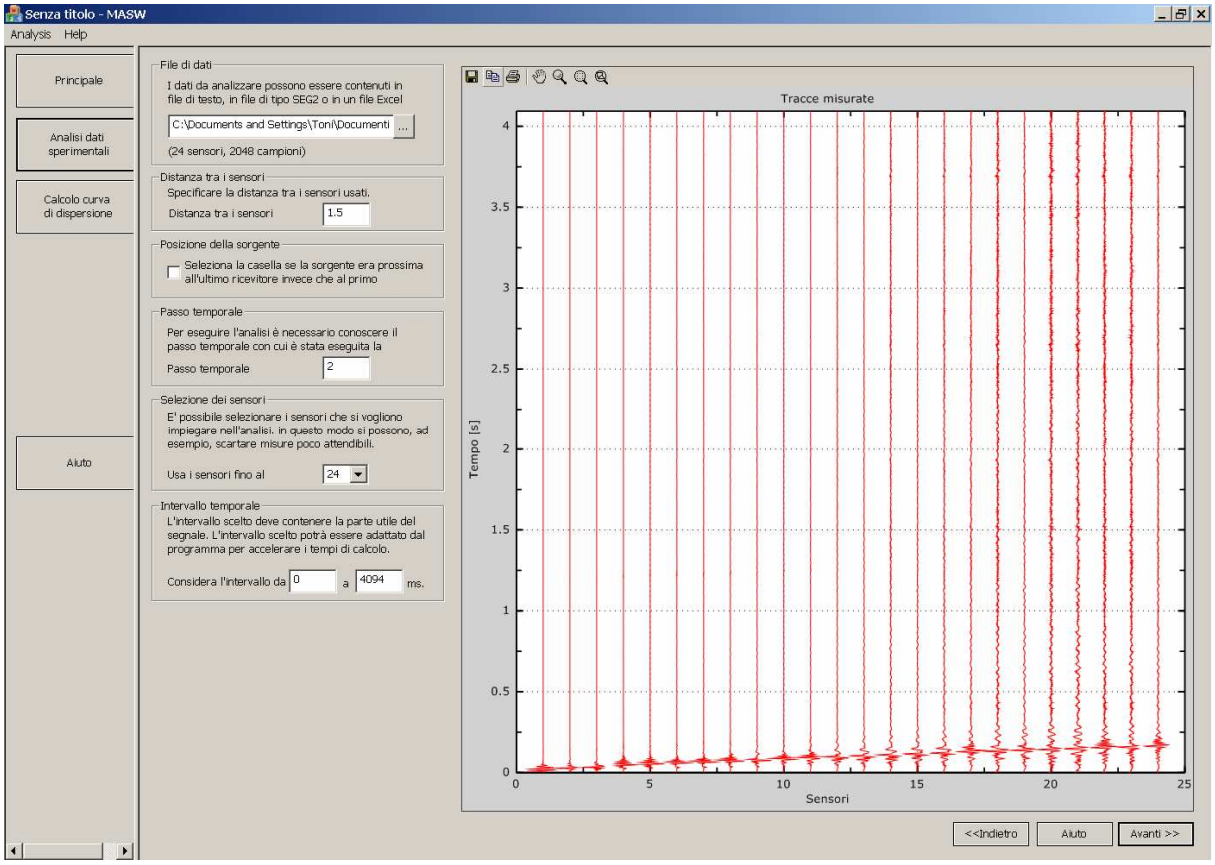


Figure 4.25: traces of the wave motion measured with 24 vertical geophones.

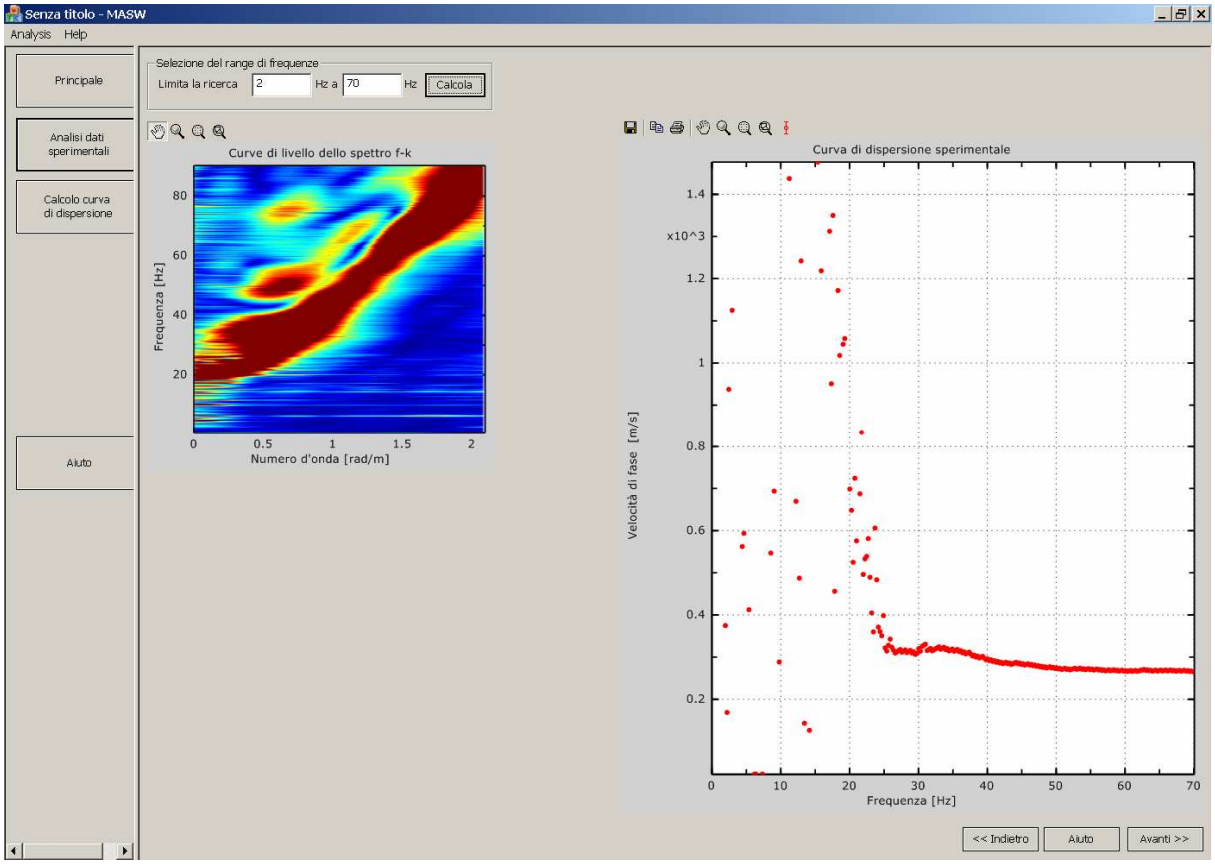


Figure 4.26: f-k spectrum and experimental dispersion curve.

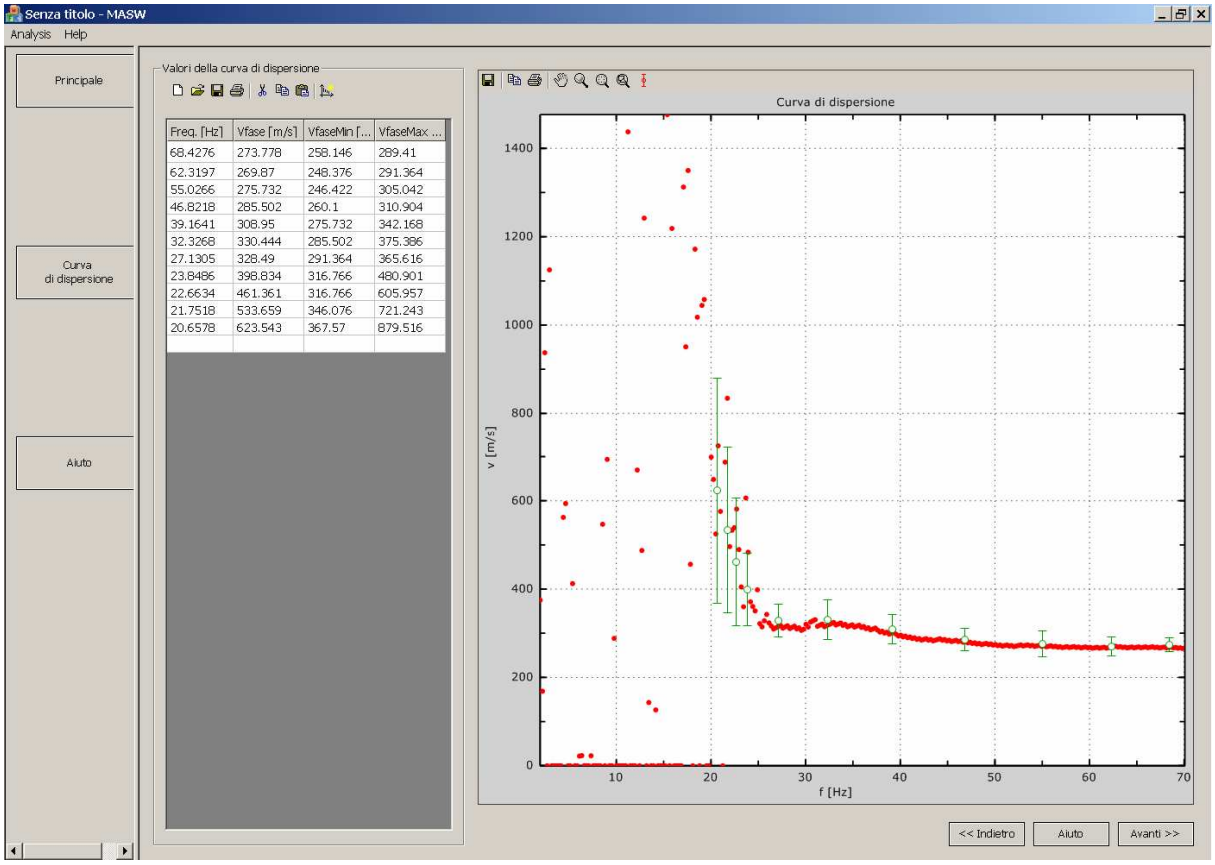


Figure 4.27: selection of a limited but significant number of points from the experimental dispersion curve.

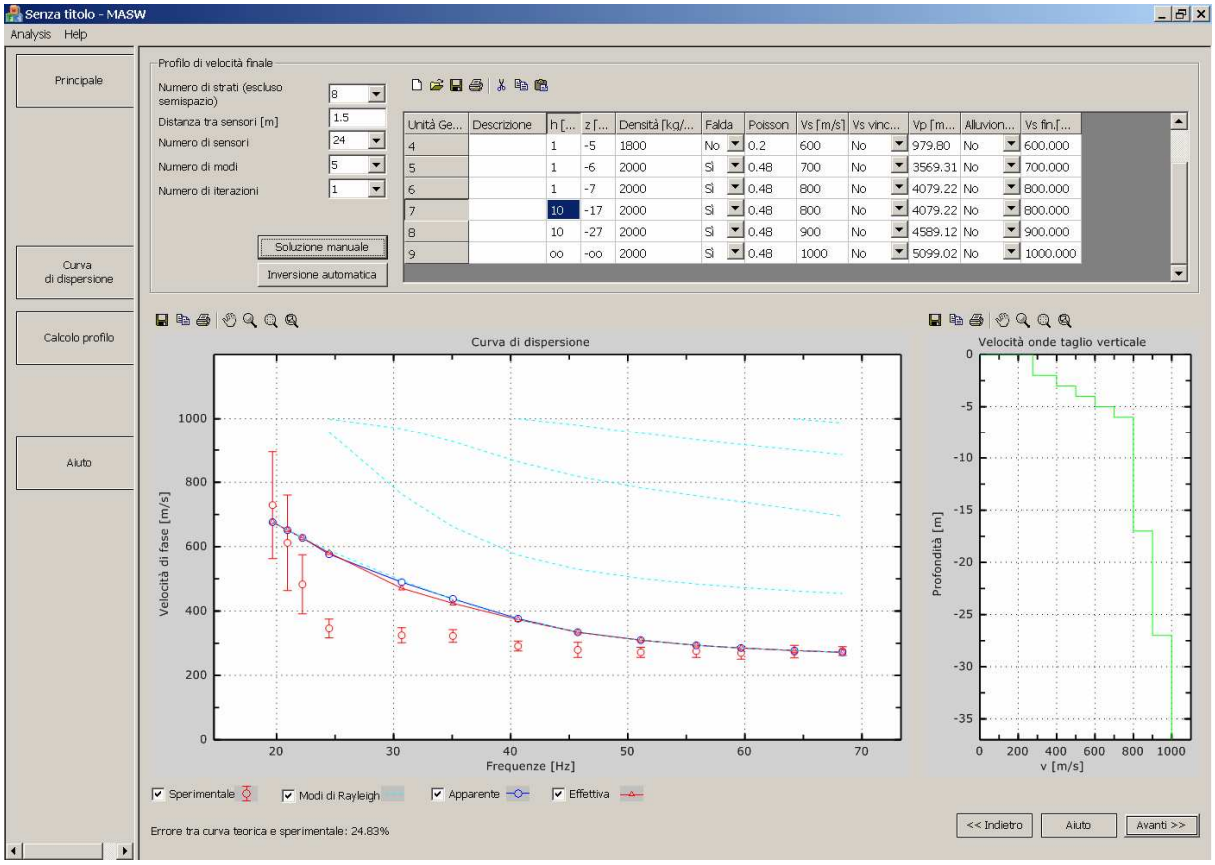


Figure 4.28: first attempts to find the Vs profile by manual search.

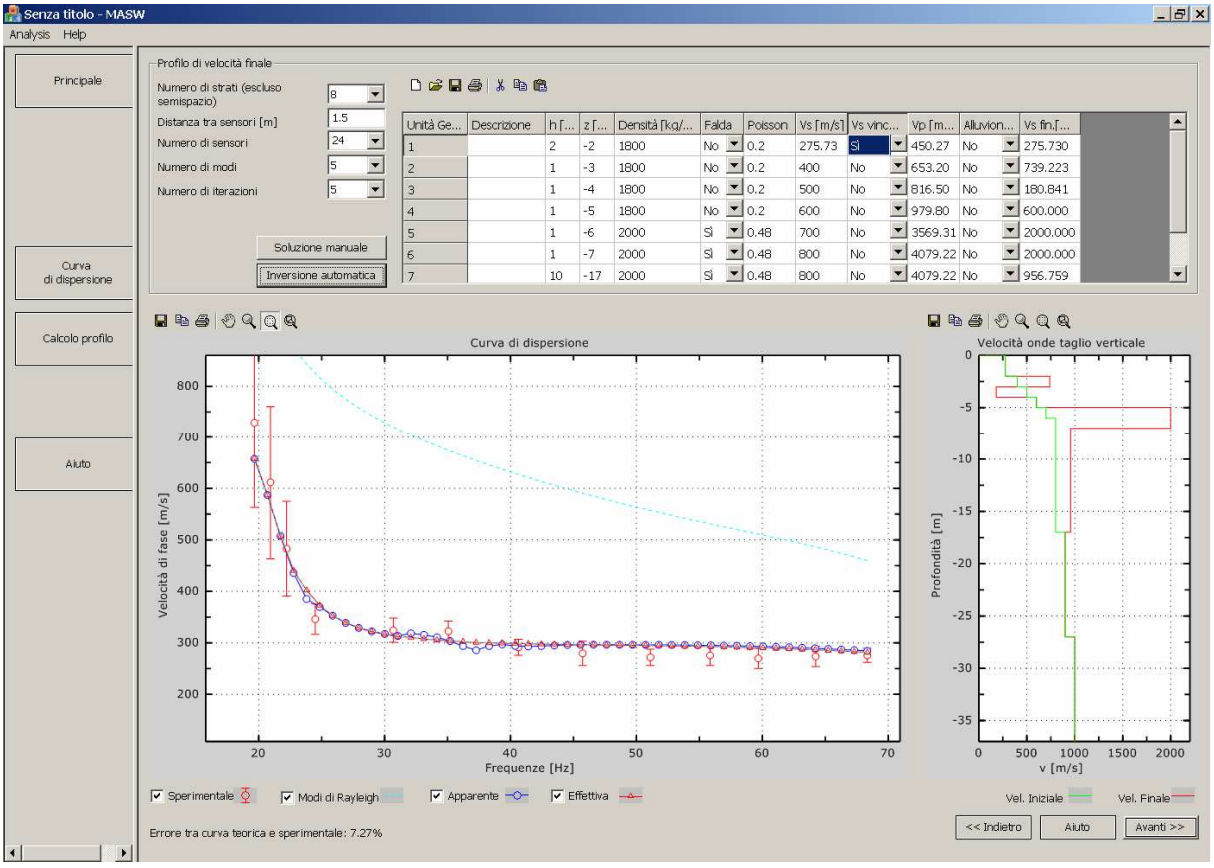


Figure 4.29: Vs profile obtained by means of the automatic search. A strange intermediate stiff layer appears at a depth of about 6m from the ground level.

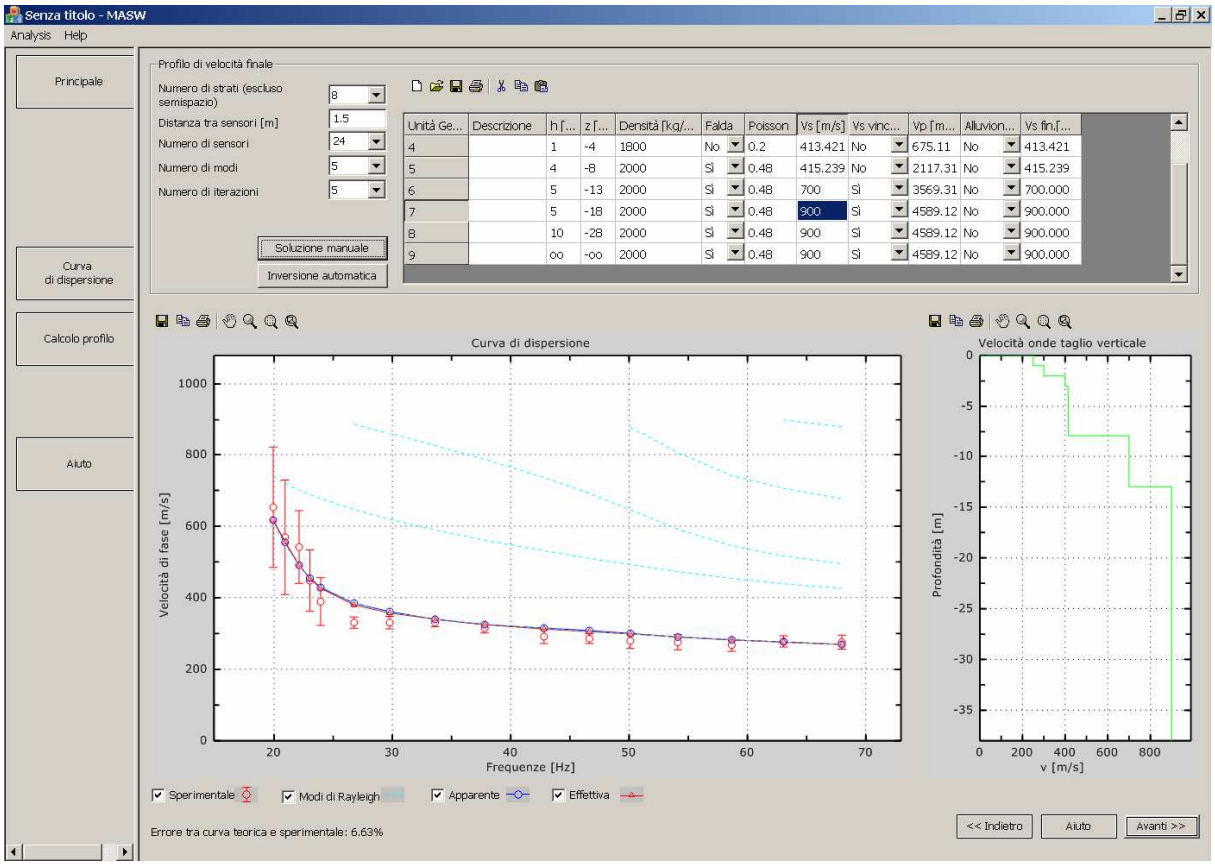


Figure 4.30: Optimal Vs profile, obtained by changing manually the Vs profile given by the previous automatic search.

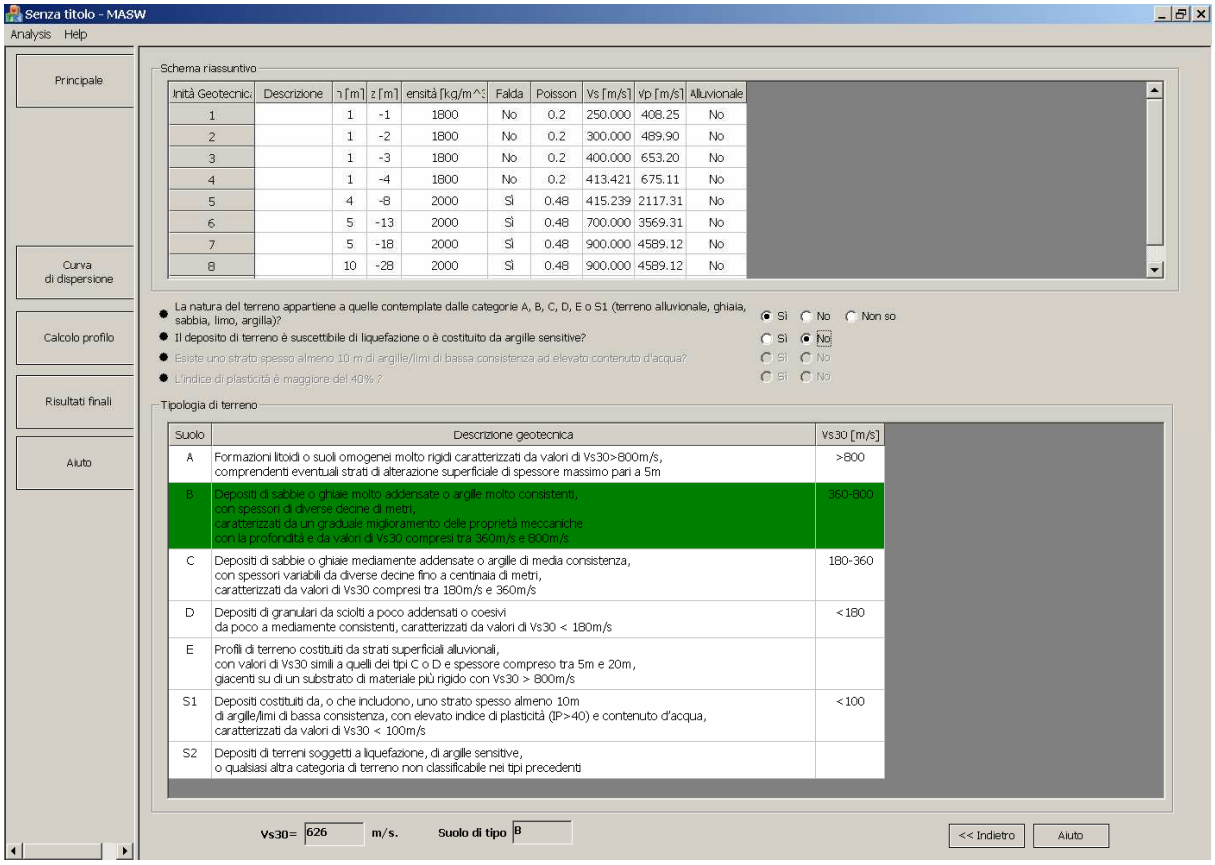


Figure 4.31: seismic class B for the analysed site.

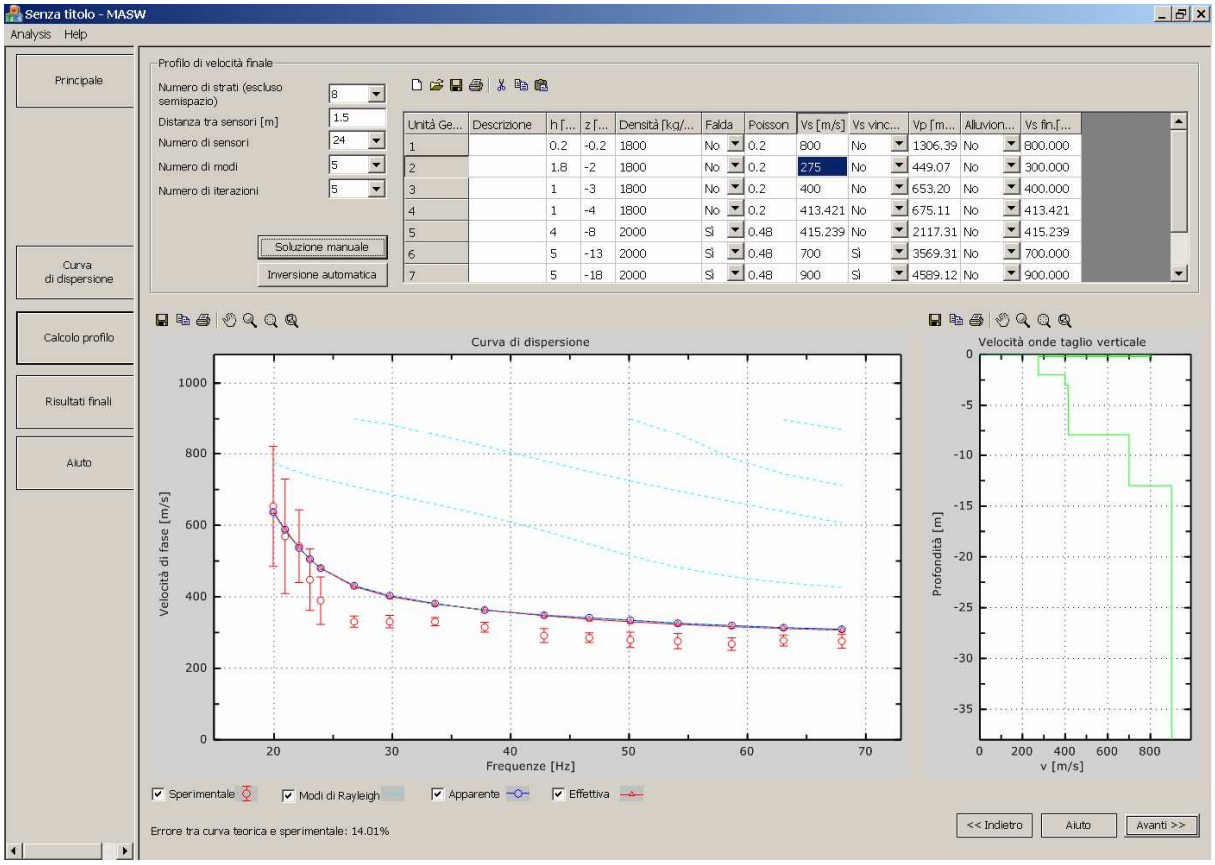


Figure 4.32: numerical dispersion curve within the frequency range 20Hz-70Hz, when a rigid superficial pavement exists.

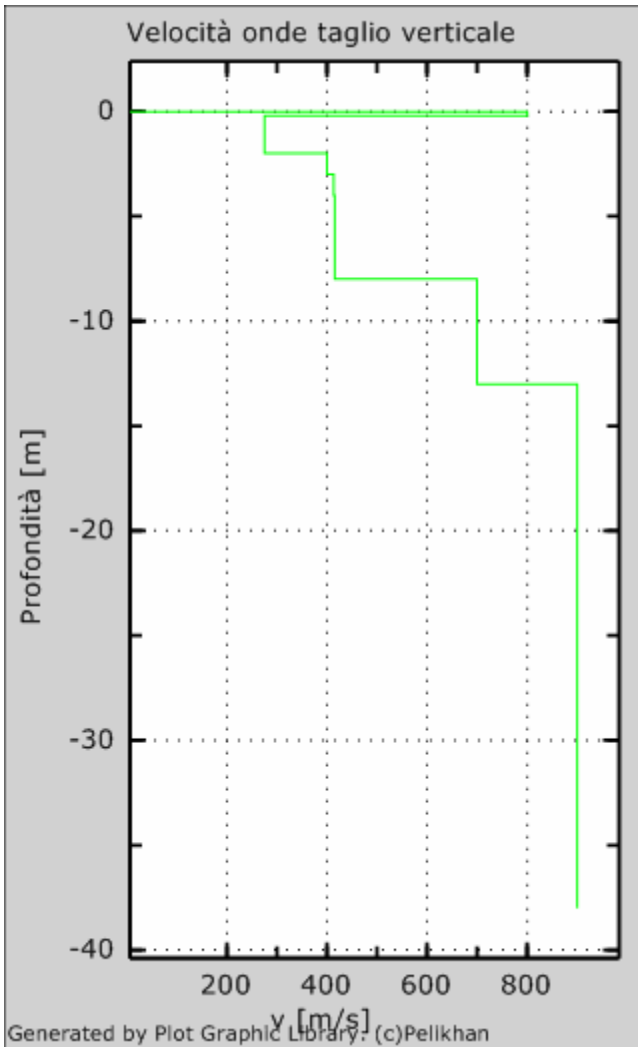


Figure 4.33: Vs profile with thin (20cm) rigid superficial pavement.

Consider the MASW test performed on the rigid pavement.

The experimental dispersion curve of the pavemented ground differs from that of the not pavemented ground only at frequencies higher than 50Hz-70Hz (**Figures 4.26 e 4.34**). At frequencies higher than 50Hz-70Hz the experimental dispersion curve increases its phase velocity due to the presence of the rigid pavement on the surface. In this case the Vs profile of the ground below the superficial pavement can be found by limiting the inversion process to frequencies below 50Hz-70Hz.

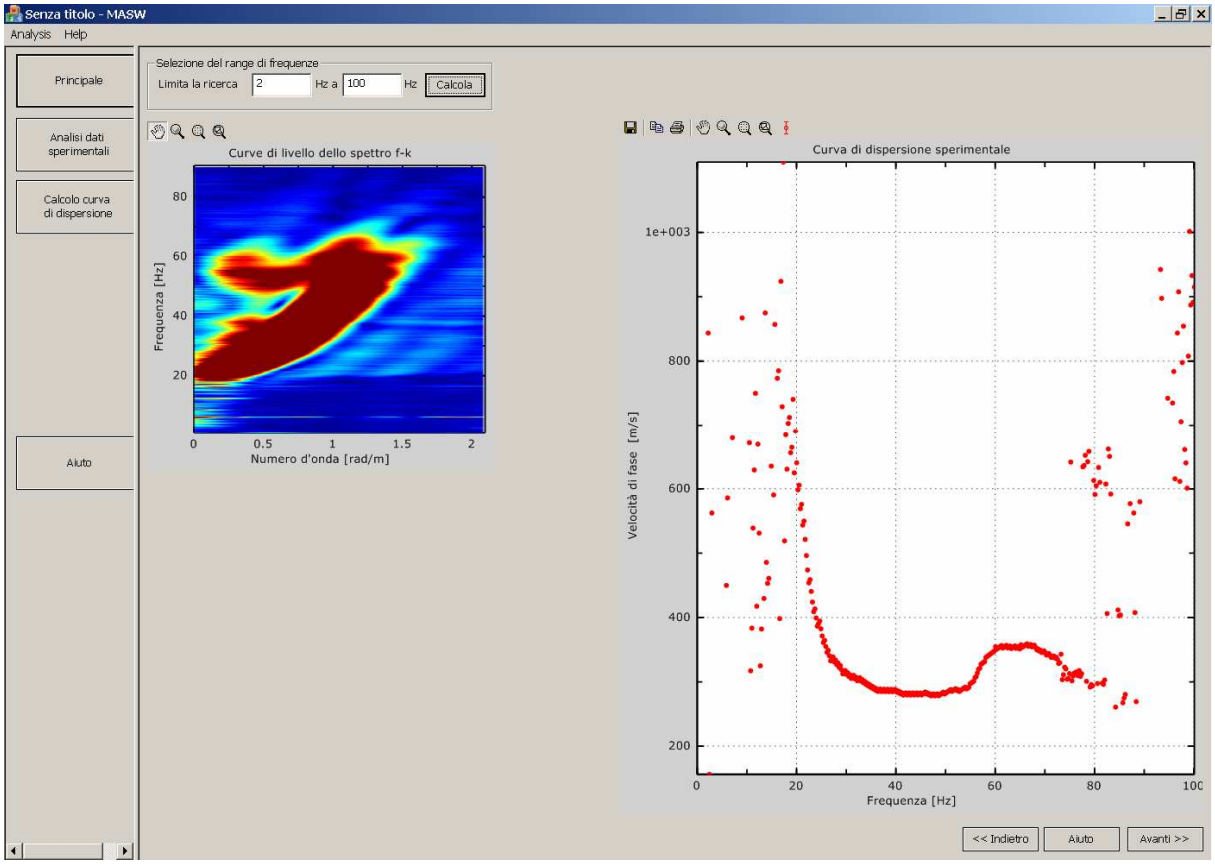


Figure 4.34: f-k spectrum and experimental dispersion curve with a superficial stiff pavement.

4.15 Example 14: Wind Power Plant at Gello (Pontedera, Pisa, Tuscany)

This site has been well investigated during a series of geotechnical investigations for the project of wind power plant made of 4 wind towers 100 m high.

The site is located in the industrial zone of Gello (Pisa, Tuscany). The area belongs to the seismic class number 2, according to the new italian seismic code OPCM of 2003 (or equivalently the Eurocodes) and the site is flat.

On the basis of the geological information and the results of the geotechnical investigations the soils of the area are recent alluvial soils of the Arno river.

The geotechnical units that have been found down to a depth of 30m form ground level are:

1. Geotechnical unit 1: thickness of about 1m form the ground level, vegetal soil
2. Geotechnical unit 2: down to about 20m from g.l., sandy-clayey silts
3. Geotechnical unit 3: from about 20m down to 35m, silty sands and sandy silts

The 2 boreholes S1 and S2 indicate slight different interfaces among the 3 geotechnical units.

The 2 piezometers in S1 and S2 indicate the existence of water under pression at about 10m form g.l.

Table 4.1: Geotechnical model

Geotechnical unit	**description**	**z (m)**	**γ (kN/m^3)**	**ϕ' (°)**	**c' (kPa)**
1	Vegetal soil	0-1	18	-	-
2	sandy-clayey silts	1-20	17-19 (18)	22-26 (24)	0-20 (10)
3	silty sands and sandy silts	20-30	17-20 (18)	23-27 (25)	0-10 (5)
3	silty sands and sandy silts	30-40	17-20 (18)	23-27 (25)	0-10 (5)

where:

values comprised into parentheses indicate average values

γ= natural volumetric weight of the soil

ϕ' = shear resistence angle

c' = effective cohesion

Figure 4.35: spatial array for the MASW test at Gello.

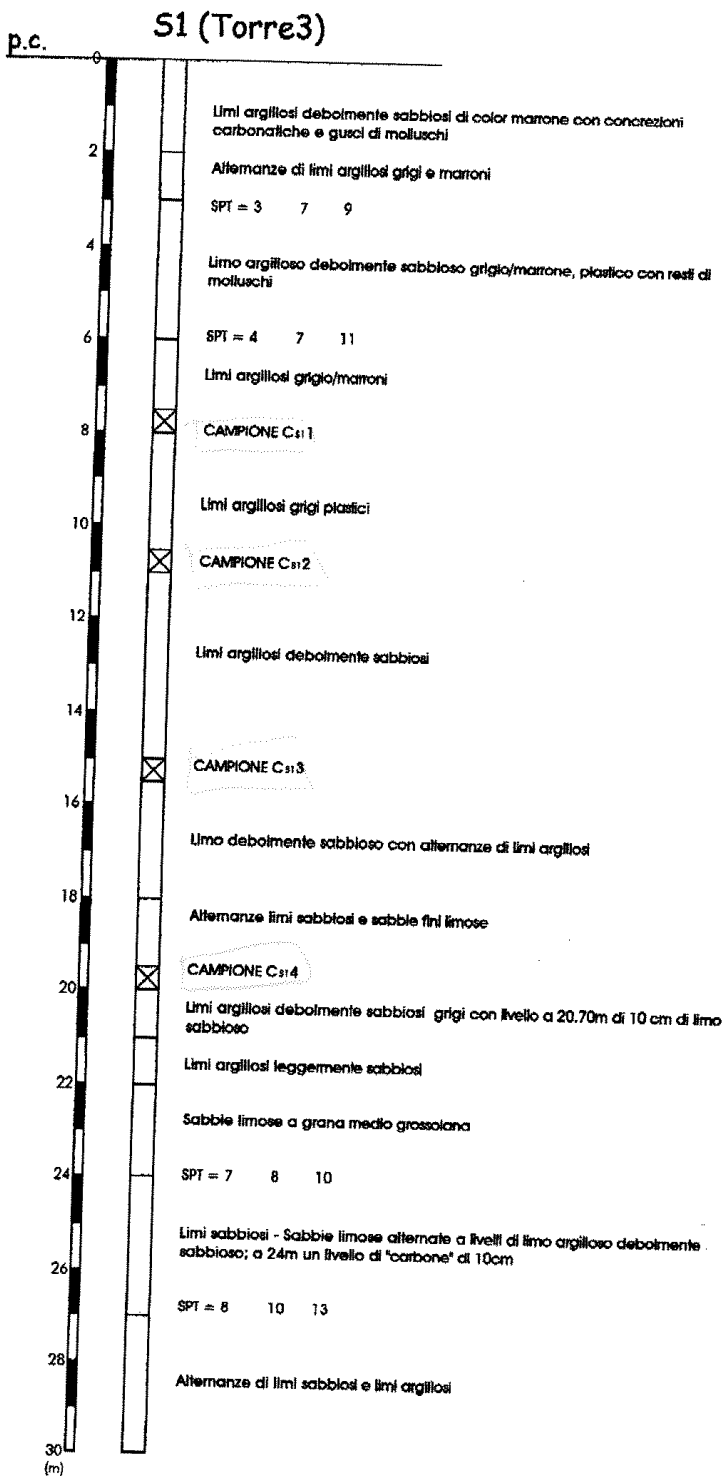


Figure 4.36: ground stratigraphy at Gello.

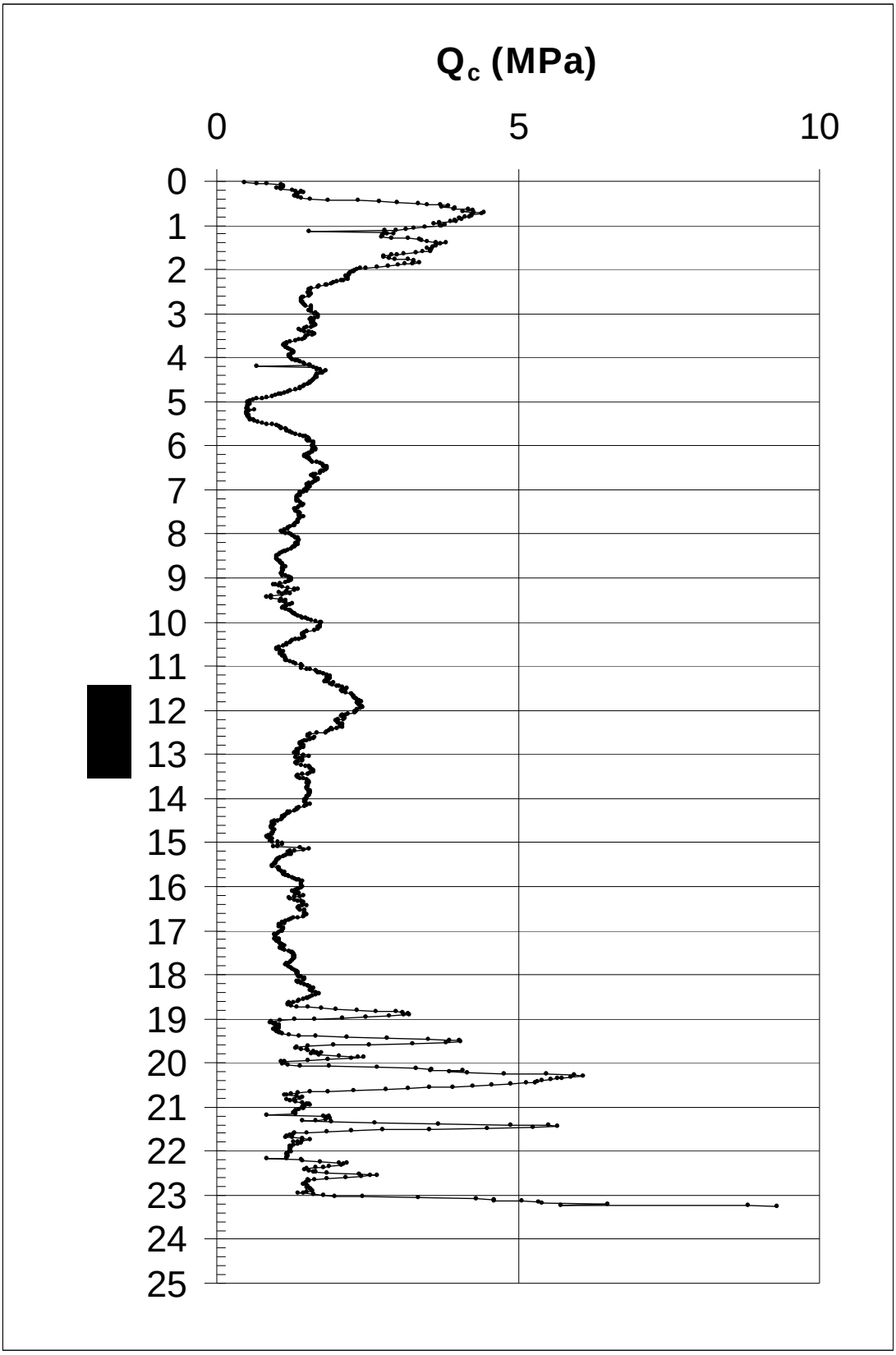


Figure 4.37: penetration resistence at tip durino a SCPTU test at Gello.

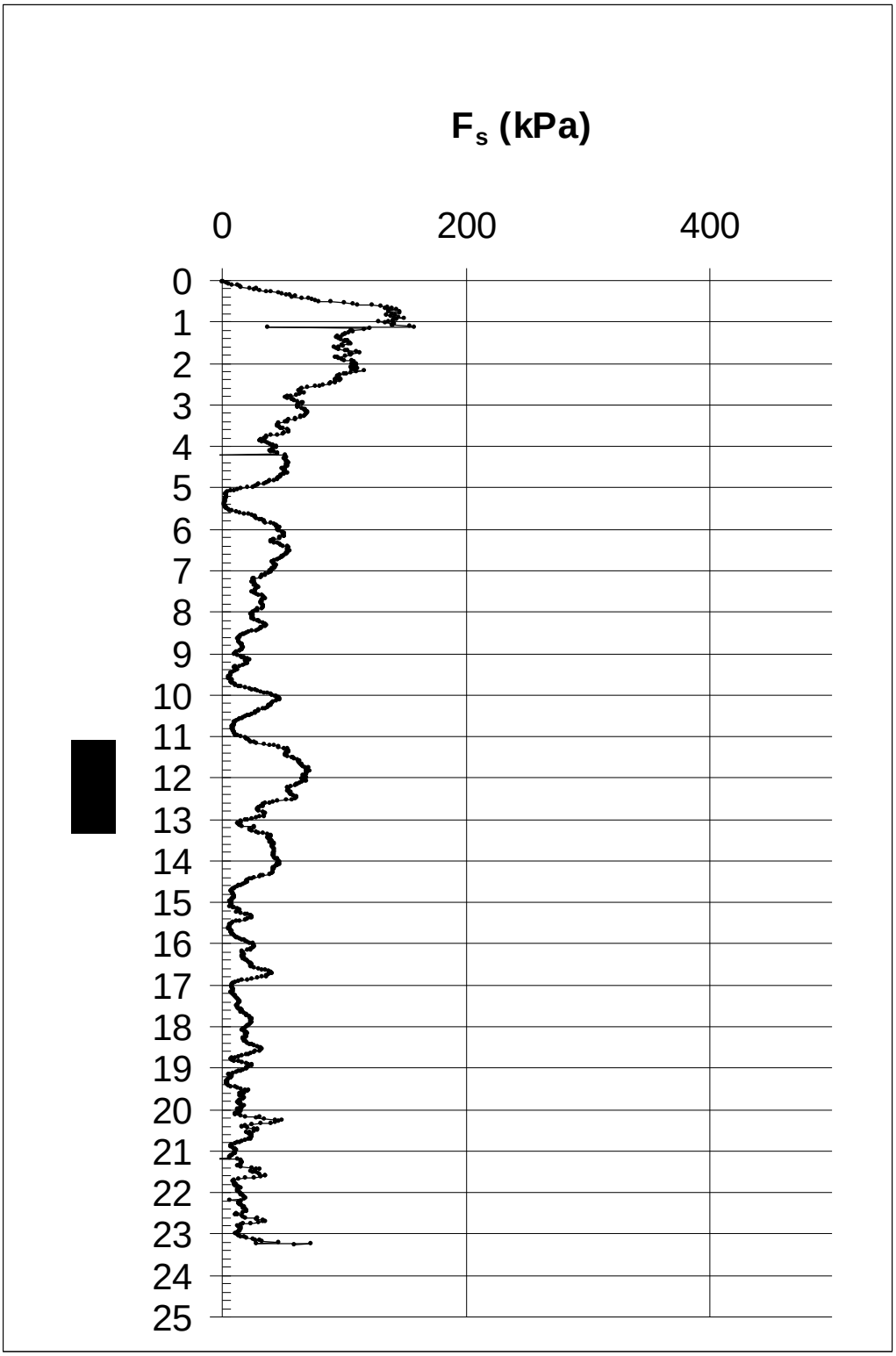


Figure 4.38: lateral resistence to penetration durino a SCPTU test at Gello.

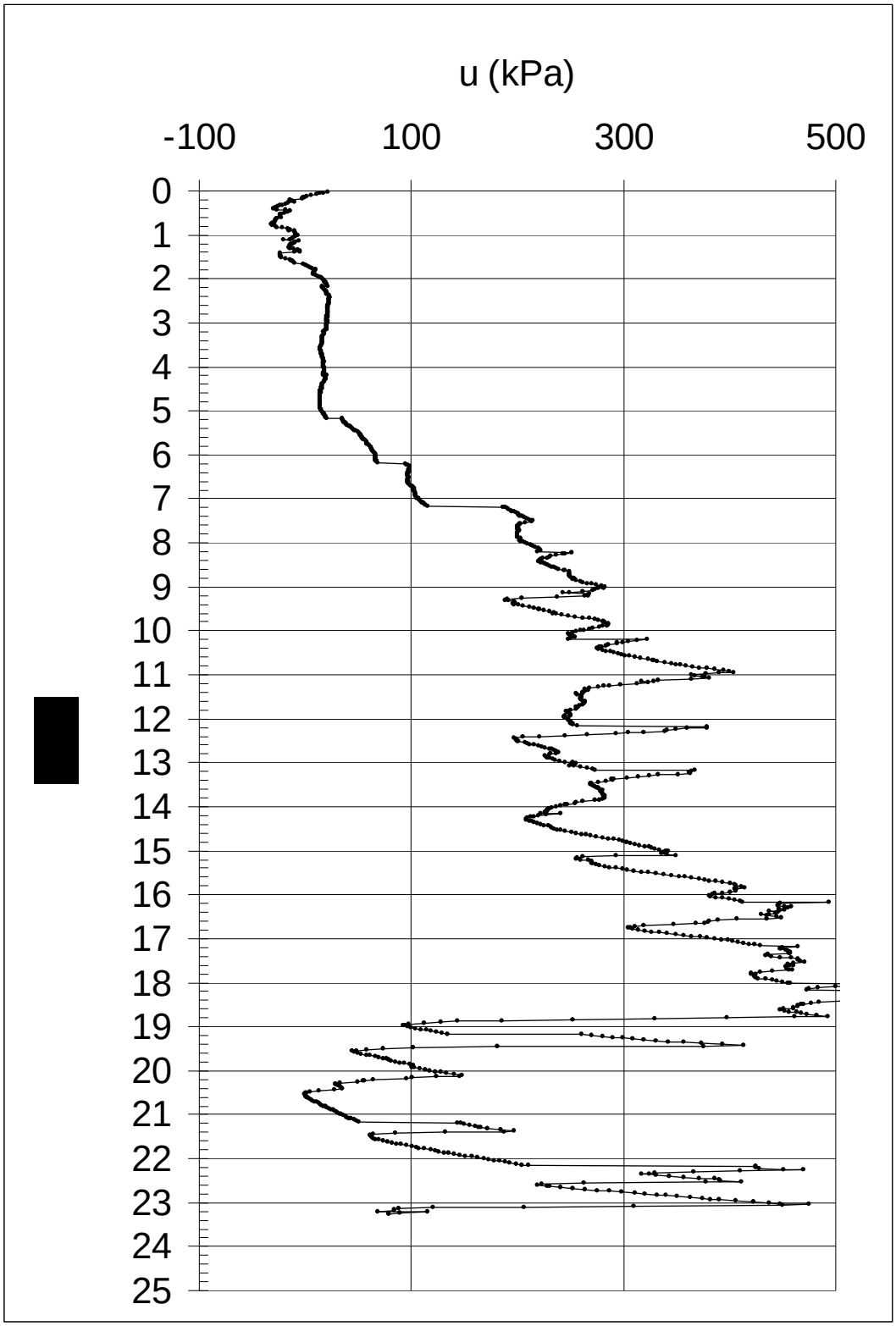


Figure 4.39: water overpressure durino a SCPTU test at Gello.

Durino the MASW test in field the source was located near the last receiver (**Figure 4.40**), hence you need to switch the source location by clicking the proper box (**Figure 4.41**).

The f-k spectrum and the experimental dispersion curve in the frequency range 2Hz-70Hz are shown in **Figure 4.41**. During the selection of the significant points of the experimental dispersion curve, points at frequencies higher than 50Hz can be excluded, since zero or negative values of the phase velocity do not have any physical sense (**Figure 4.42**).

The discontinuità of the experimental dispersion curve between 25Hz and 40Hz means that a strong stiffness contrast exists in the upper part of the Vs profile of the ground.

By running the Vs model which is assigned by default the thoretical dispersion curve (apparent or effective) shows as in **Figure 4.44**.

After any trial and error attempts the Vs model in **Figure 4.45** has been obtained. The equivalent verticval shear wave velocity of the site is Vs30=228 m/s, hence the site belongs to the seismic class C.

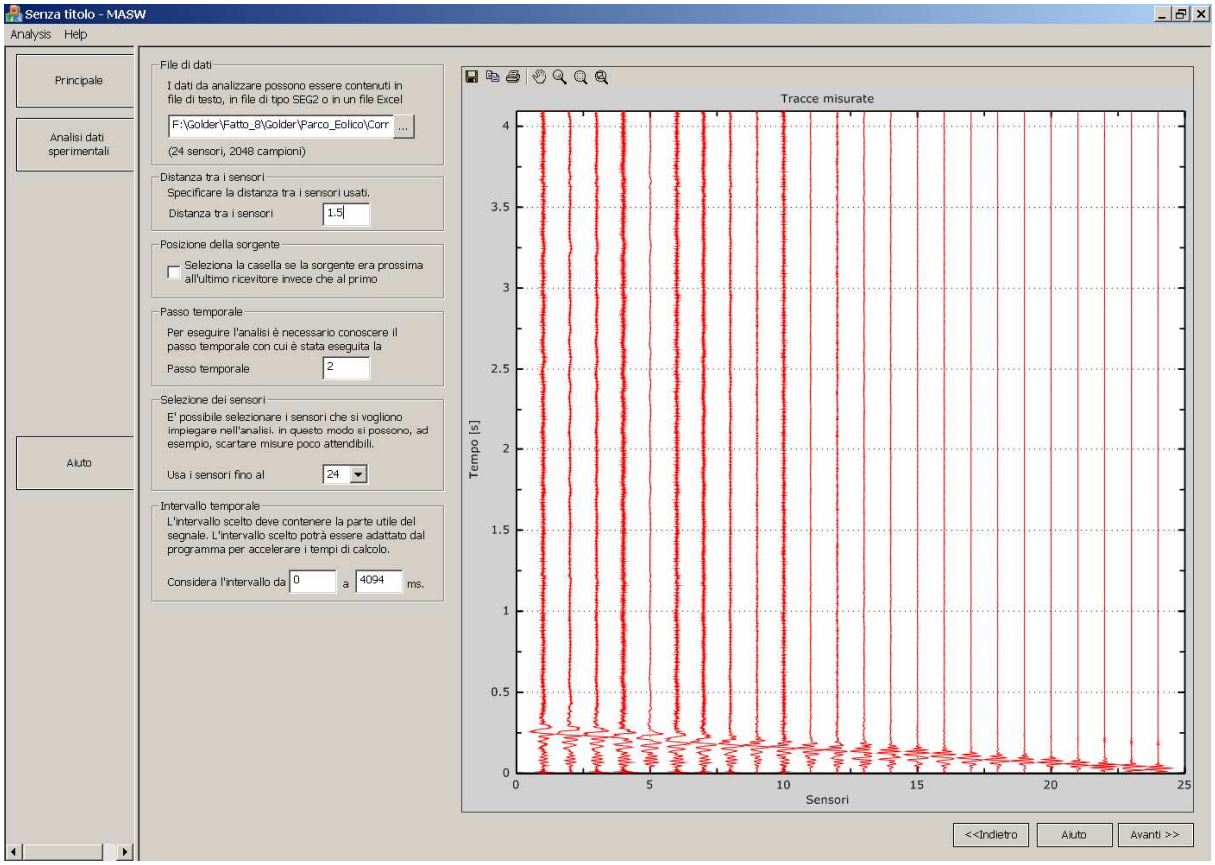


Figure 4.40: traces with source on the right.

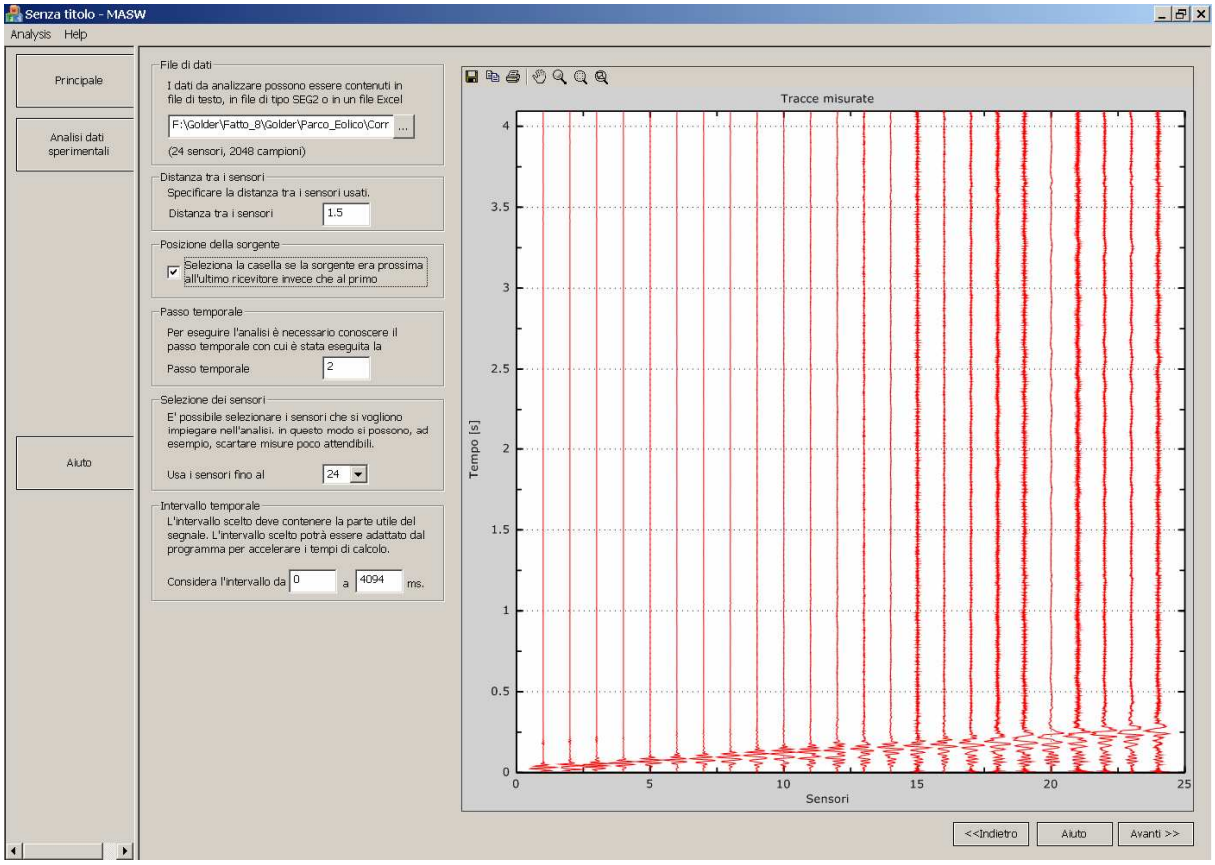


Figure 4.41: traces with the source on the left.

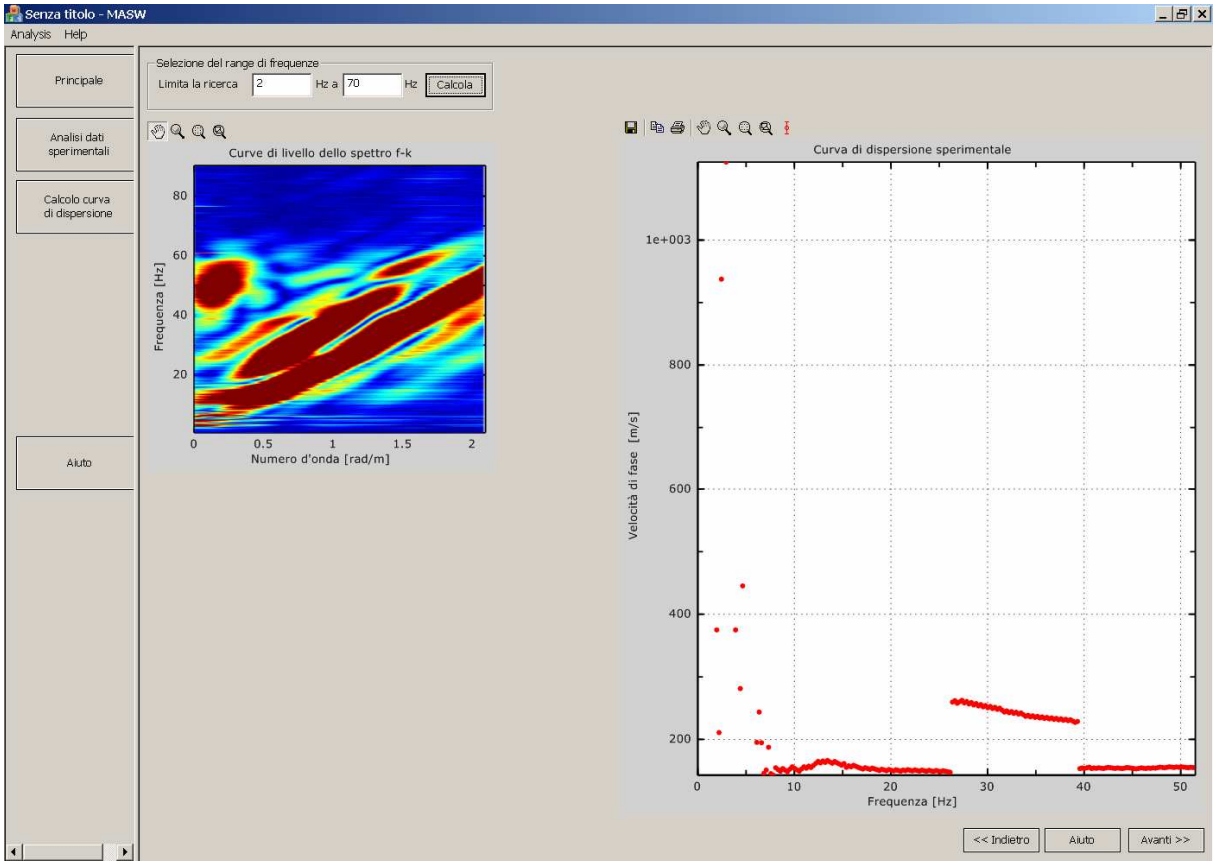


Figure 4.42: f-k spectrum and experimental dispersion curve.

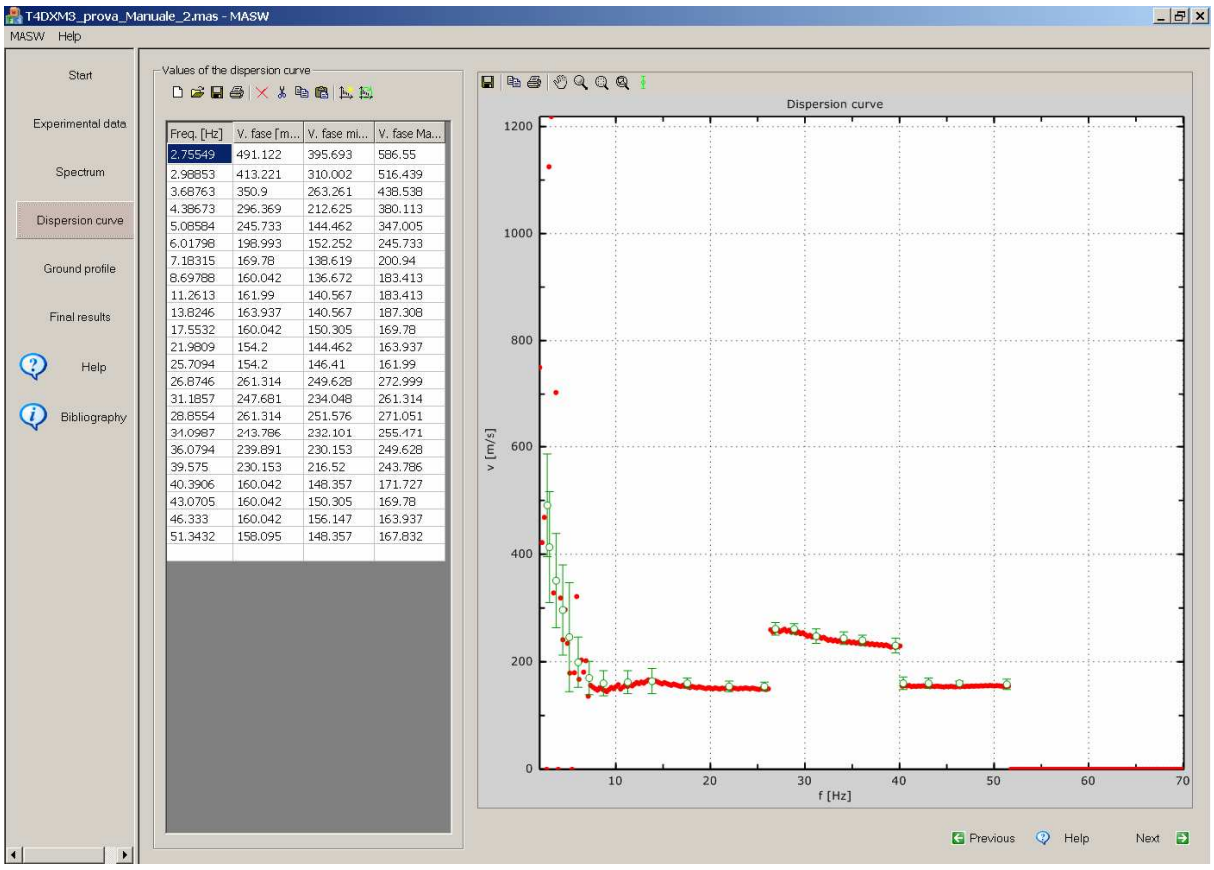


Figure 4.43: selection of significant points of the experimental dispersion curve.

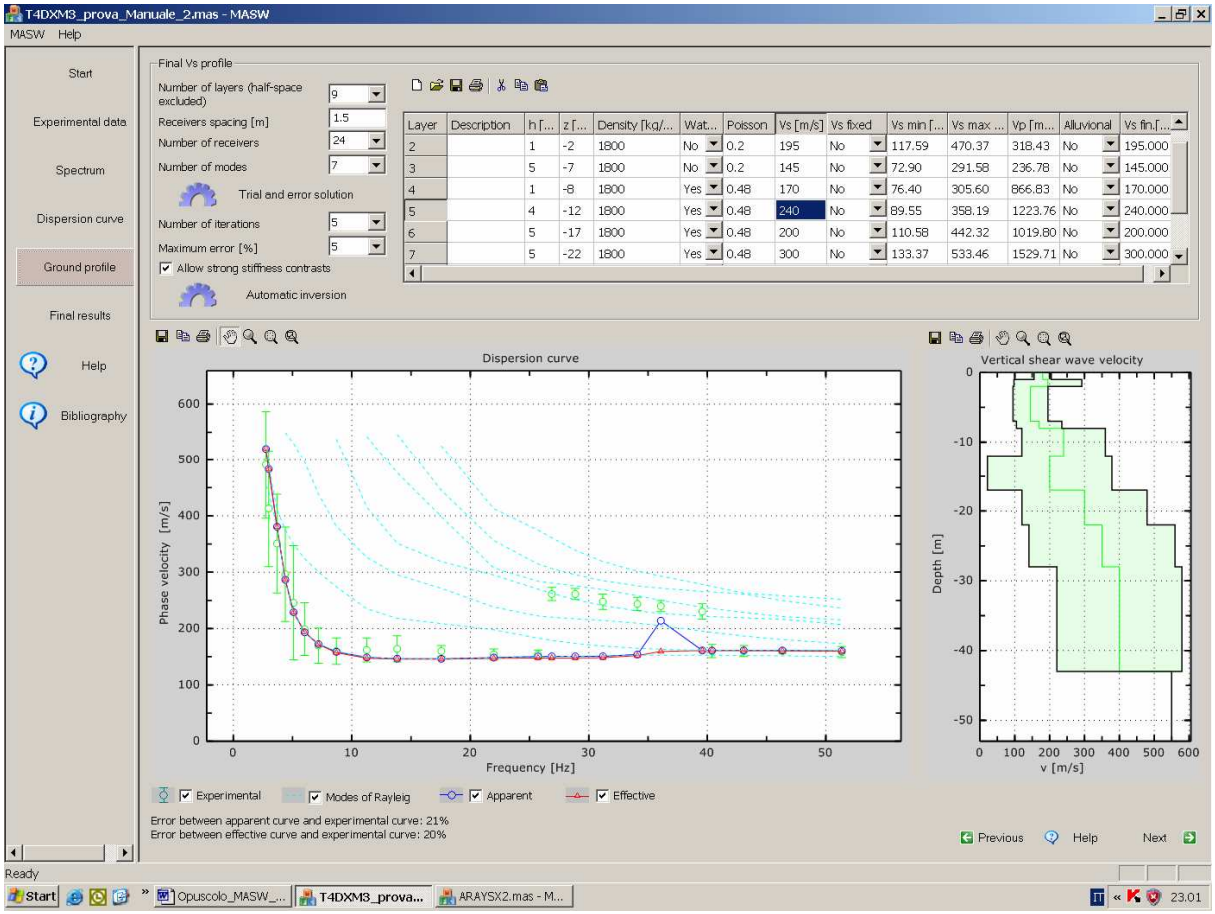
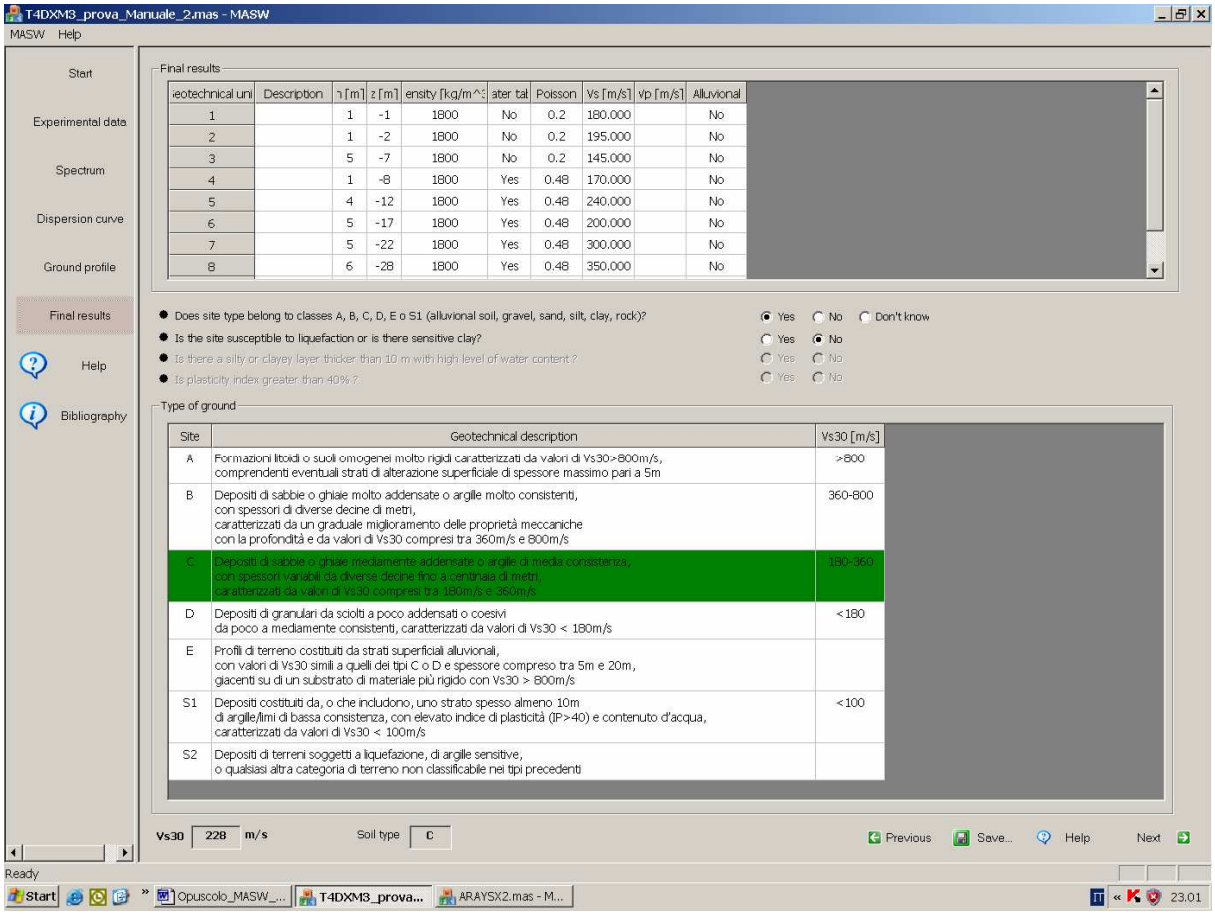


Figure 4.44: final Vs profile.



ieotechnical uni	Description	ɔ [m]	z [m]	ensity [kg/m^3	ater tal	Poisson	Vs [m/s]	vp [m/s]	Alluvional
1		1	-1	1800	No	0.2	180.000		No
2		1	-2	1800	No	0.2	195.000		No
3		5	-7	1800	No	0.2	145.000		No
4		1	-8	1800	Yes	0.48	170.000		No
5		4	-12	1800	Yes	0.48	240.000		No
6		5	-17	1800	Yes	0.48	200.000		No
7		5	-22	1800	Yes	0.48	300.000		No
8		6	-28	1800	Yes	0.48	350.000		No

Site	Geotechnical description	Vs30 [m/s]
A	Formazioni litoidi o suoli omogenei molto rigidi caratterizzati da valori di Vs30>800m/s, comprendenti eventuali strati di alterazione superficiale di spessore massimo pari a 5m	>800
B	Depositi di sabbie o ghiaie molto addensate o argille molto consistenti, con spessori di diverse decine di metri, caratterizzati da un graduale miglioramento delle proprietà meccaniche con la profondità e da valori di Vs30 compresi tra 360m/s e 800m/s	360-800
C	Depositi di sabbie o ghiaie mediamente addensate o argille di media consistenza, con spessori variabili da diverse decine fino a centinaia di metri, caratterizzati da valori di Vs30 compresi tra 180m/s e 360m/s	180-360
D	Depositi di granulari da sciolti a poco addensati o coesivi da poco a mediamente consistenti, caratterizzati da valori di Vs30 < 180m/s	<180
E	Profili di terreno costituiti da strati superficiali alluvionali, con valori di Vs30 simili a quelli dei tipi C o D e spessore compreso tra 5m e 20m, giacenti su di un substrato di materiale più rigido con Vs30 > 800m/s	
S1	Depositi costituiti da, o che includono, uno strato spesso almeno 10m di argille/limi di bassa consistenza, con elevato indice di plasticità (IP>40) e contenuto d'acqua, caratterizzati da valori di Vs30 < 100m/s	<100
S2	Depositi di terreni soggetti a liquefazione, di argille sensitive, o qualsiasi altra categoria di terreno non classificabile nei tipi precedenti	

Figure 4.45: seismic soil classification based on theVs30.

4.16 Example 15: Underground park in Mollieres (Cesana, Torino, Piemonte)

The site is located in Mollieres (Piemonte) and the project concerns an underground park. The site belongs to the seismic class 3 and the free surface is plane and inclined with a slope of about 15°. The stratigraphy consists of:

- Geotechnical unit 1: thickness of about 50cm, reported loose soil
- Geotechnical unit 2: thickness of about 1m, vegetal soil
- Geotechnical soil 3:thickness between 5m and 10m, morenic deposits of gravel and cobbles into sandy, silty and clayey matrix
- Geotechnical unit 4: rock base of calcescisti graffitici.

There is not water table at the site.

It is quite easy to calcolate the f-k spectrum and the experimental dispersion curve from the traces measured in field durino the MASW test. In this case the available frequency range is between 10Hz-15Hz and 70Hz. At high frequencies, between 50Hz and 70Hz the experimental dispersion curve slightly oscillates; in the inversion processa n average value has been adopted,

By running the trial and error search starting from the Vs model assigned by default the theoretical dispersion curve is shown in **Figure 4.50**. In order to increase the phase velocità of the dispersion curve at low frequencies, the shear wave velocità of the deep rock layer must be increased.

After any trial and error attempts the final Vs profile shown in **Figure 4.52** has been obtained. The equivalent verticval shear wave velocity of the site is Vs30=759 m/s, hence the site belongs to the seismic class B (**Figure 4.53**).

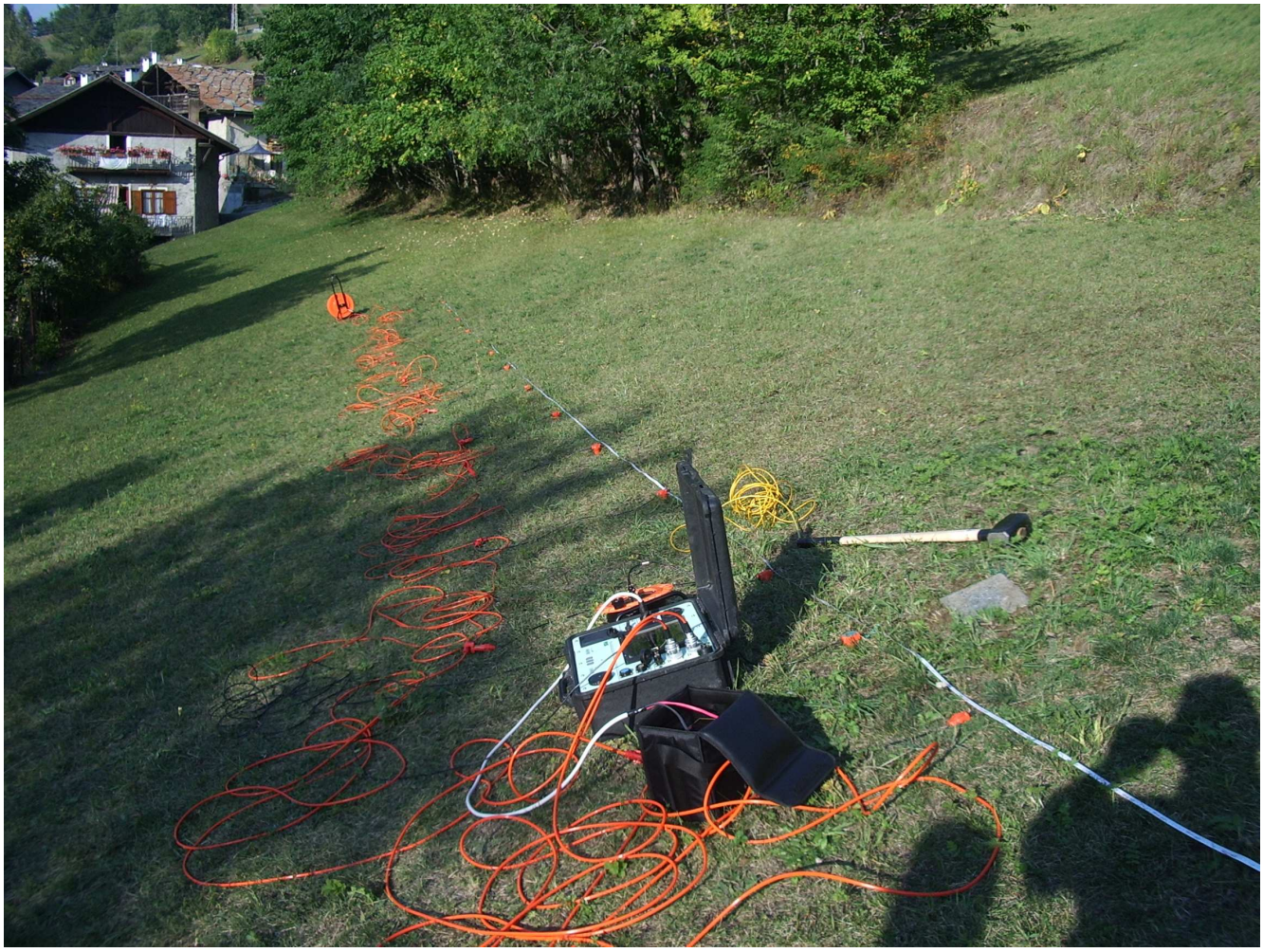


Figure 4.46: in field MASW test along a contour line of a slightly inclined slope in Mollieres.

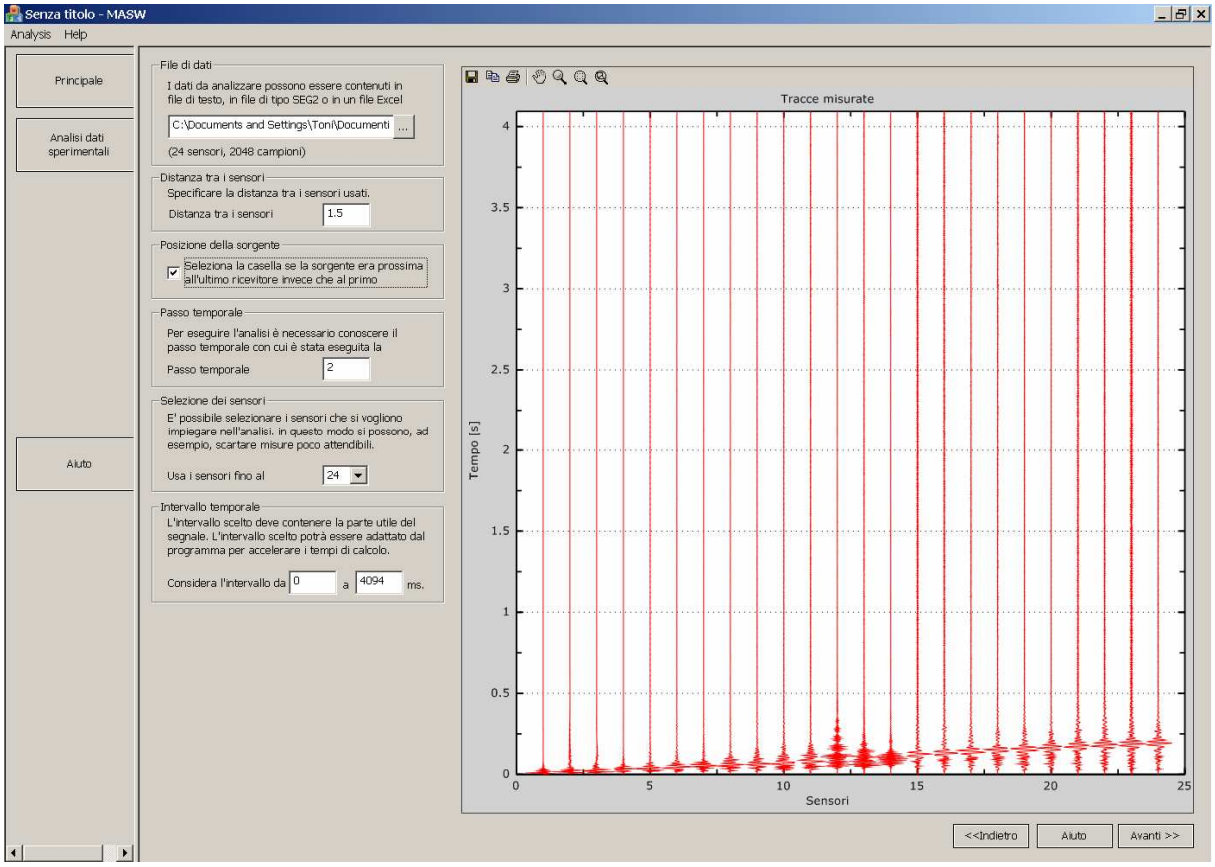


Figure 4.47: traces with source on the left side.

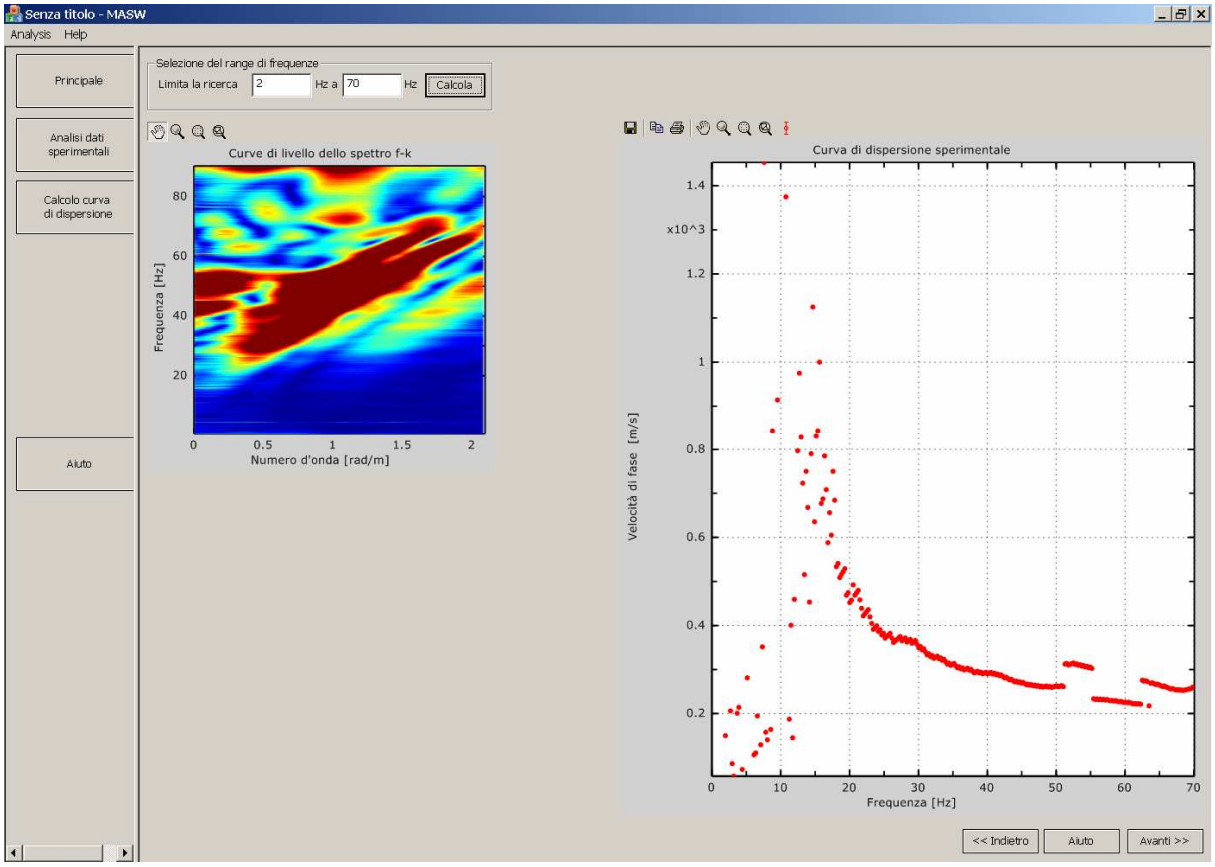


Figure 4.48: f-k spectrum and experimental dispersion curve.

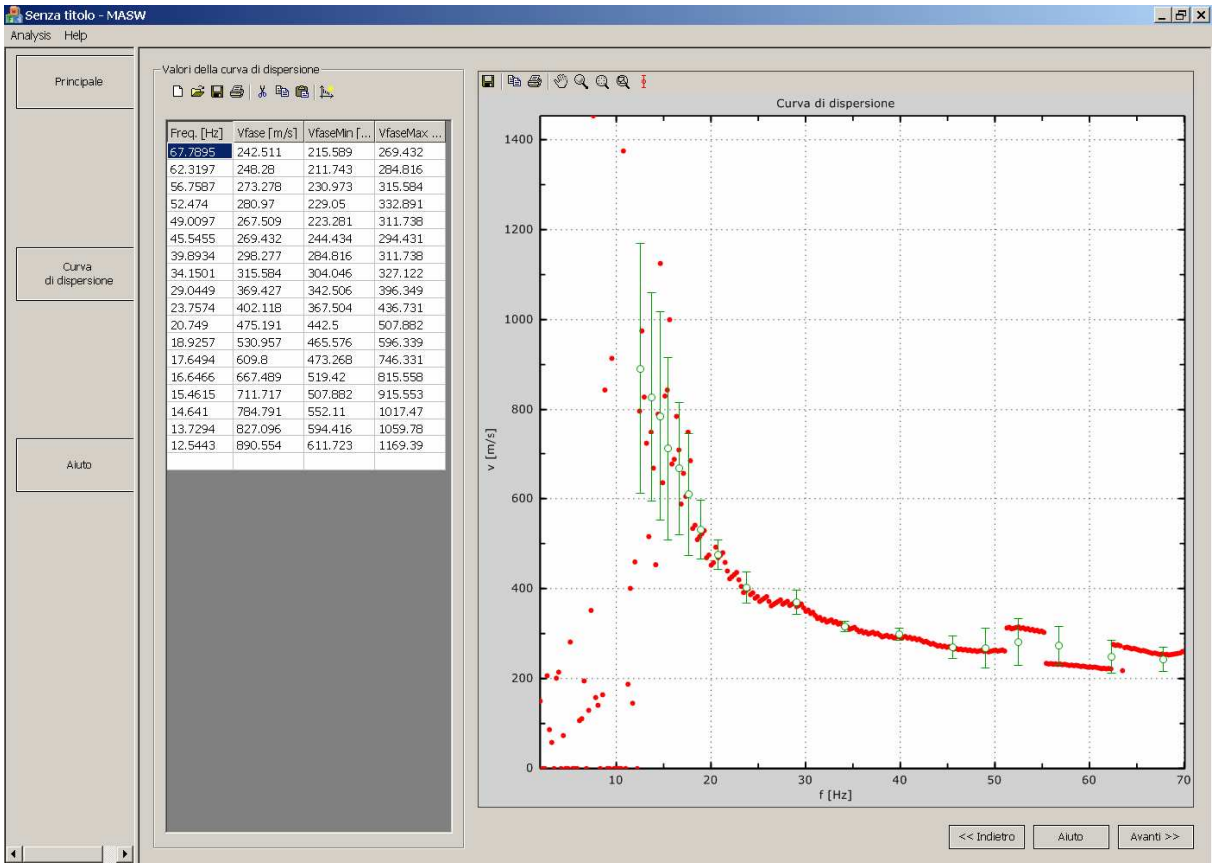


Figure 4.49: selection of significant points of the experimental dispersion curve.

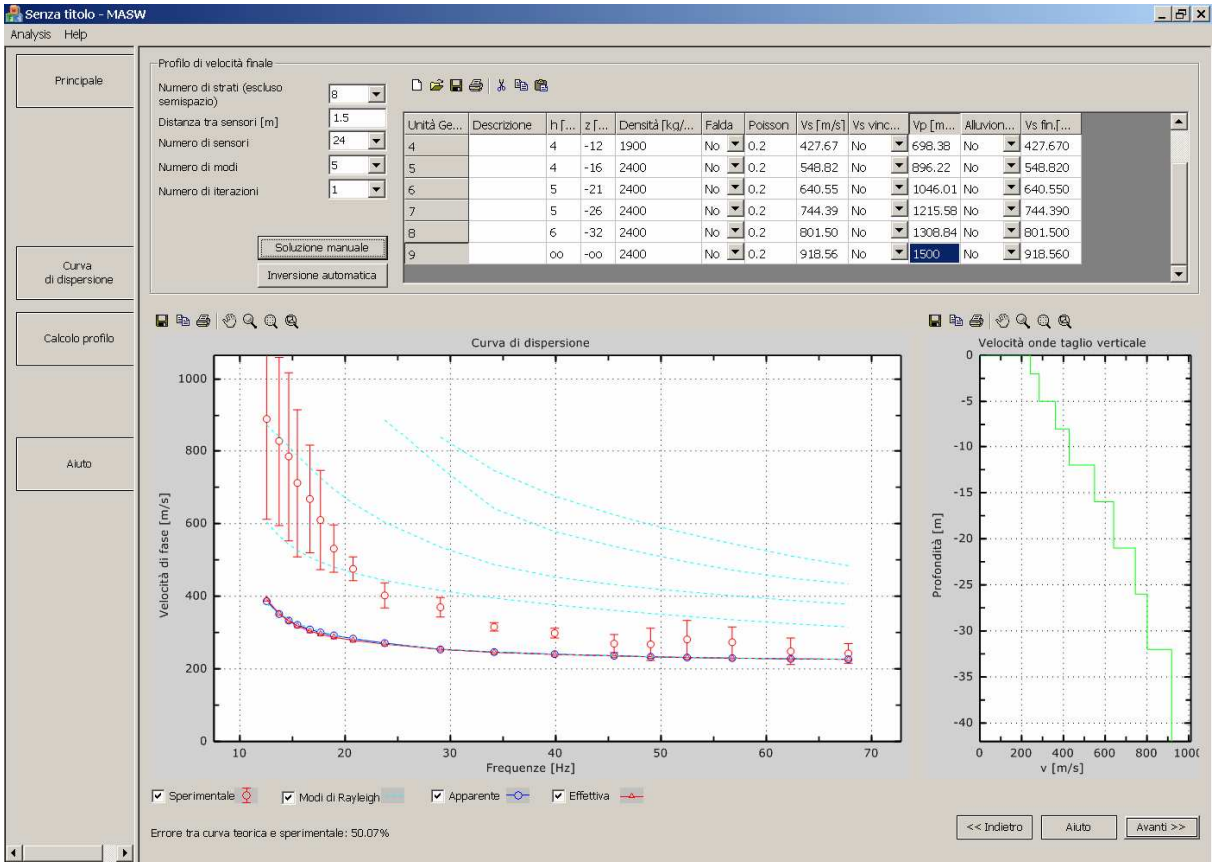


Figure 4.50: results obtained with the default Vs model.

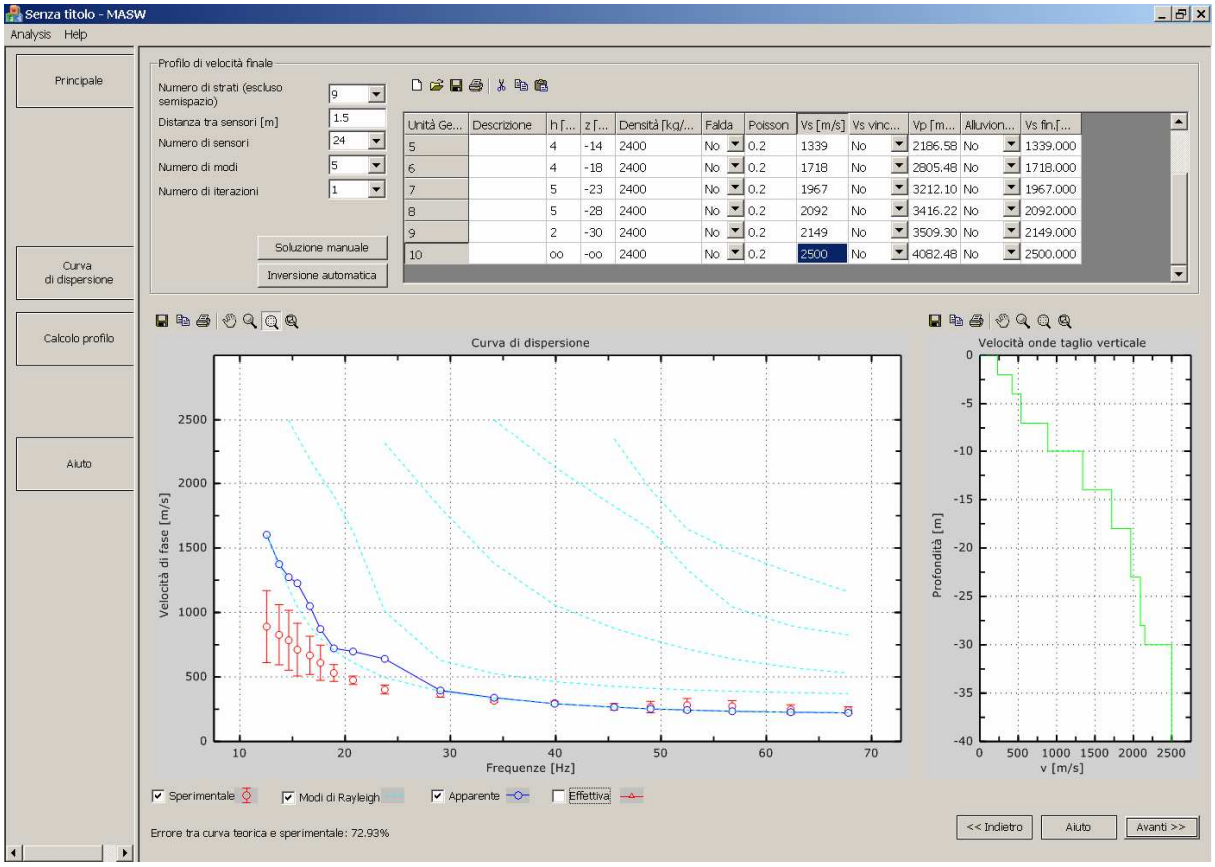


Figure 4.51: typical result after few trial and error attempts.

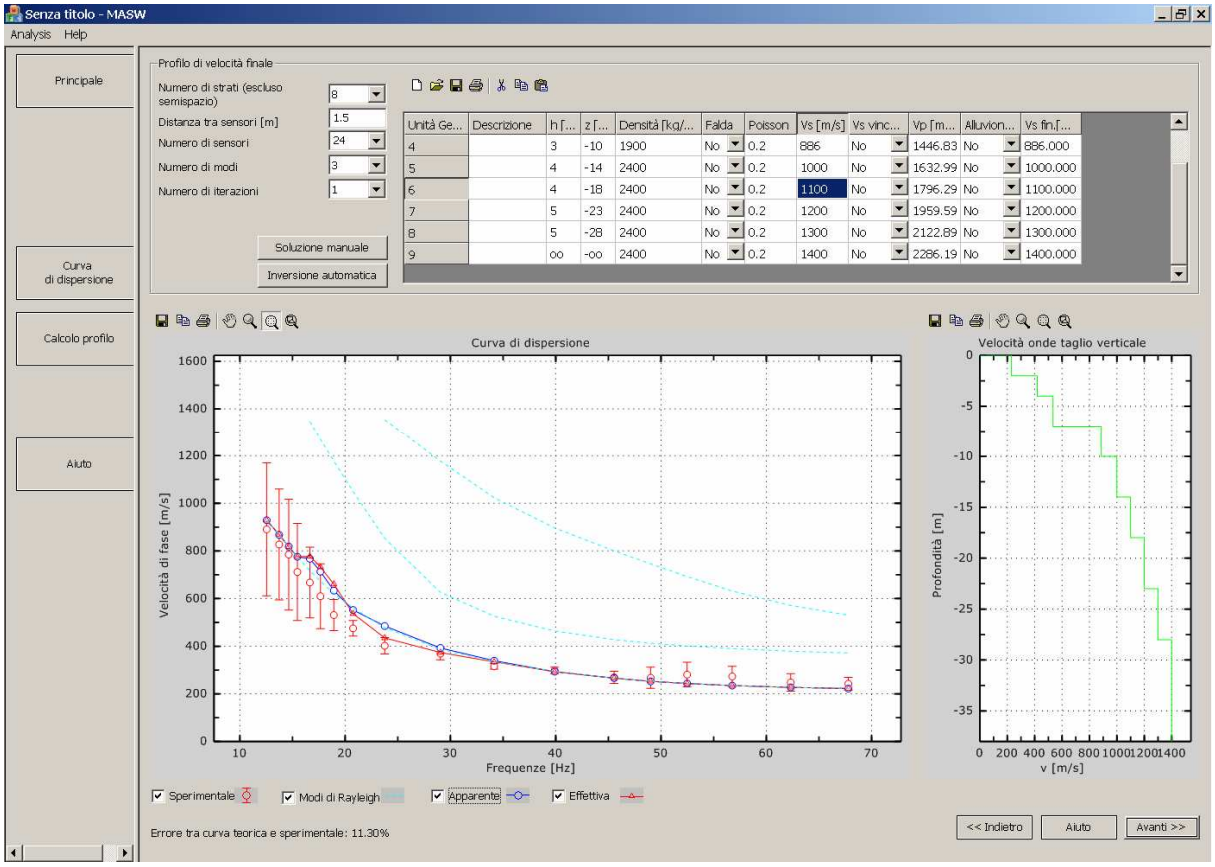


Figure 4.52: final optimal Vs profile.

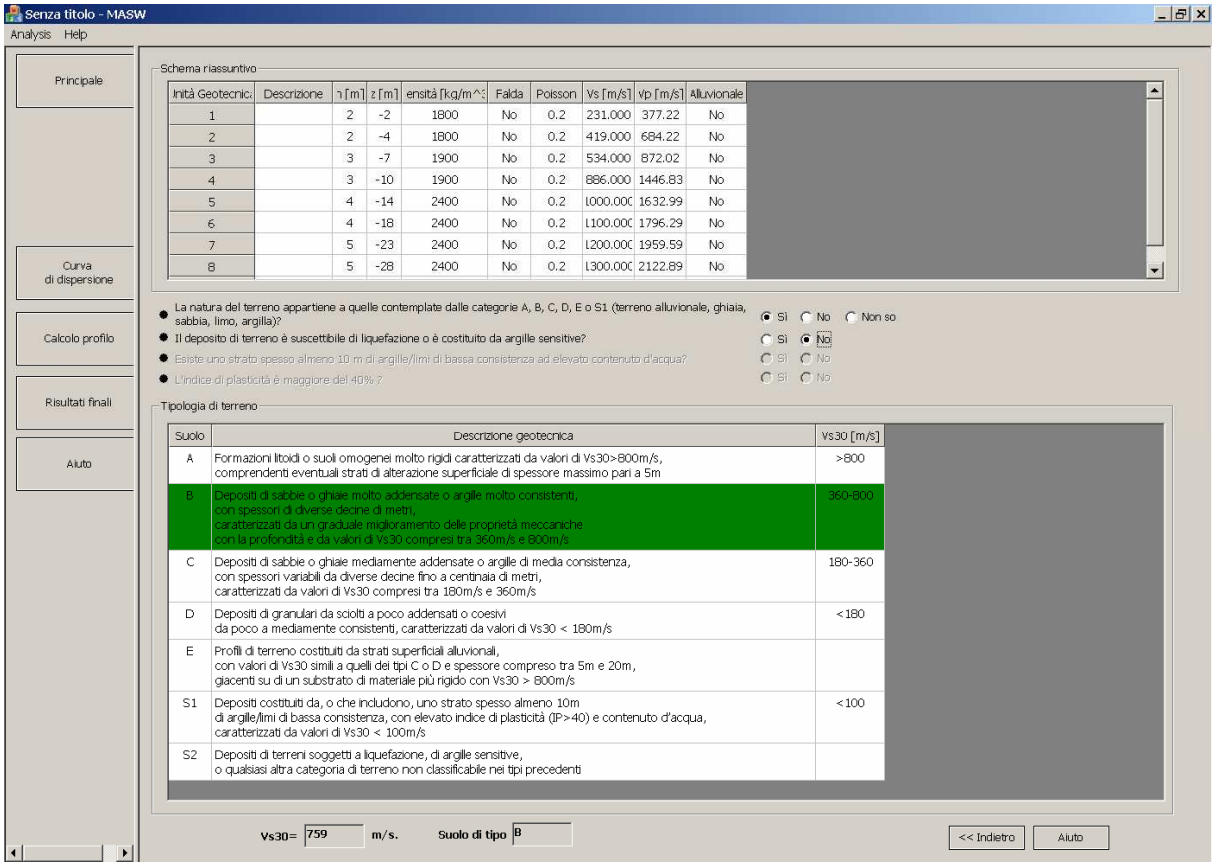


Figure 4.53: seismic soil classification based on theVs30.

4.17 Example 16: industrial plant in Settimo (high speed railway between Milan and Turin)

The site is located aside the high speed railway between Torino and Milano, near an industrial plant near Settimo Torinese. The ground stratigraphy consists of alternate dense layers of sands and gravels. The water table is at about 4m under the ground level.

Figure 4.54: MASW test near an industrial plant using 14 accelerometers.

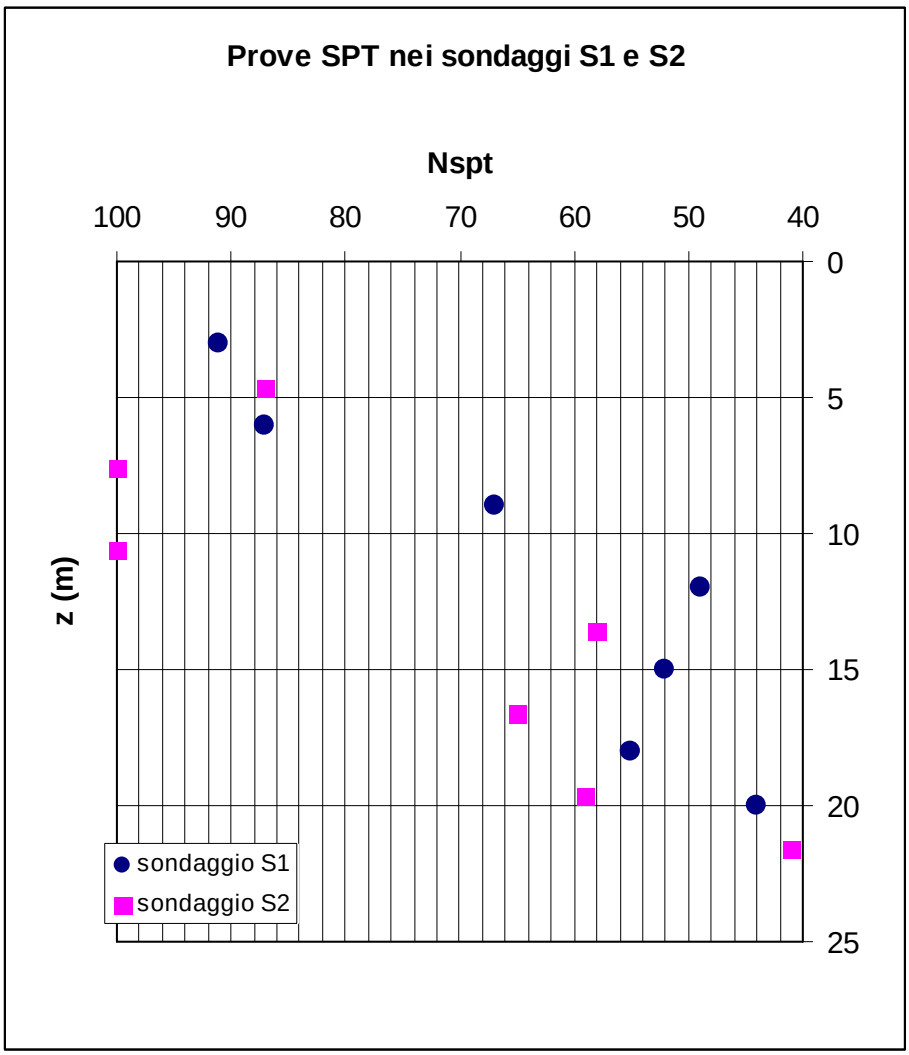


Figure 4.55: SPT results in the boreholes S1 e S2

In this example the analysis of the measured traces is omitted and the experimental dispersion curve is directly provided (**figure 4.56**). Data acquisition has been performed using 14 accelerometers with a receiver interspace equal to 2m and a time sampling of 2ms.

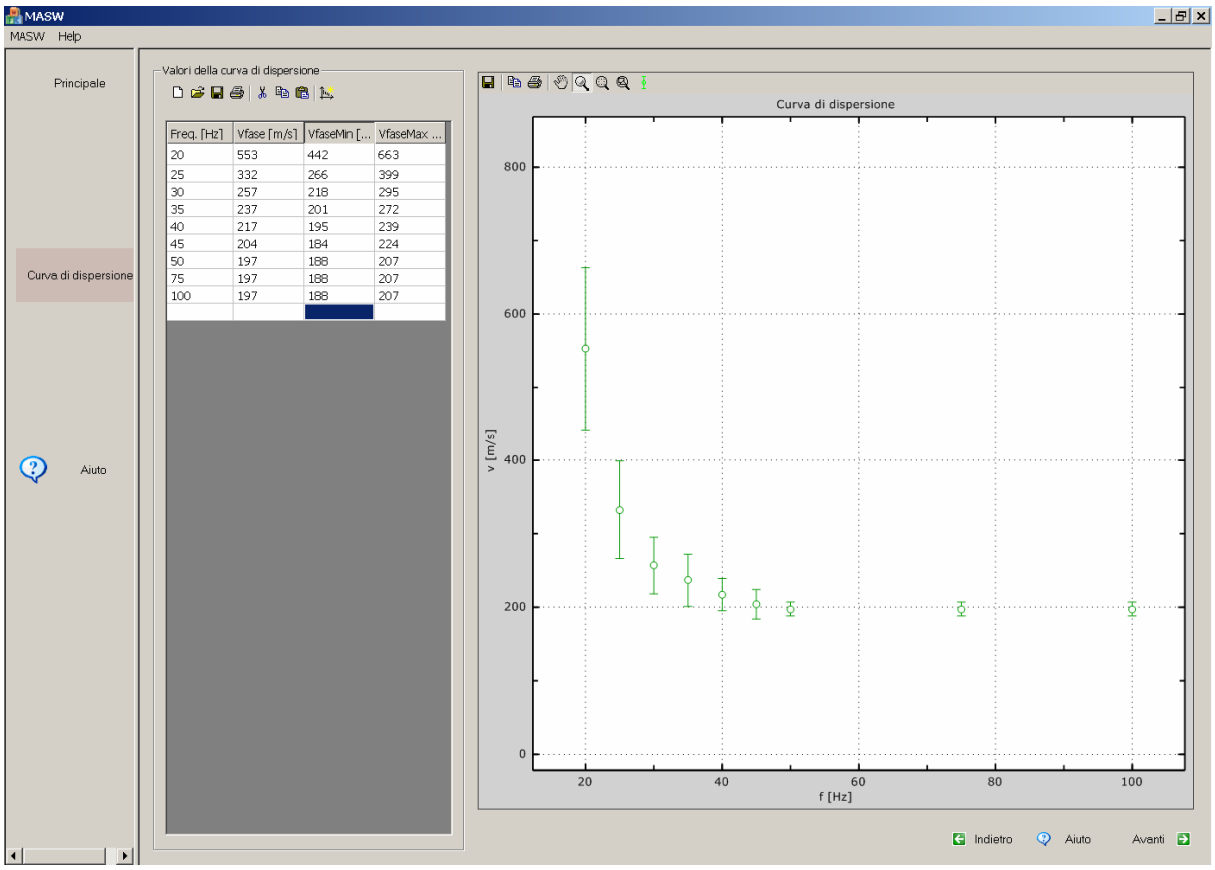


Figure 4.56: experimental dispersion curve at Settimo Torinese.

By default the software gives a first Vs profile based on the available experimental dispersion curve. Poisson coefficient and mass density of the layers are set equal to 0.2 and 1800kg/m^3 respectively. Before running the trial and error search of the Vs profile the mass density and the Poisson coefficient are modified to 1900 kg/m^3 and to 0.48 (only for layers under water).

The experimental apparent dispersion curve monotonically decreases with frequency (normally dispersive profile) and no strong stiffness contrasts are expected in the Vs profile, hebce only the fundamental mode of Rayleigh waves is used for the inversion process.

After the first attempt the numerical apparent dispersion curve is quite distant from the experimental dispersion curve (the relative error is 43%) especially at low frequencies (**figure 4.57**). To increase the apparent phase velocity at low frequencies we need to increase the shear wave velocità Vs of the deep layers of the profile.

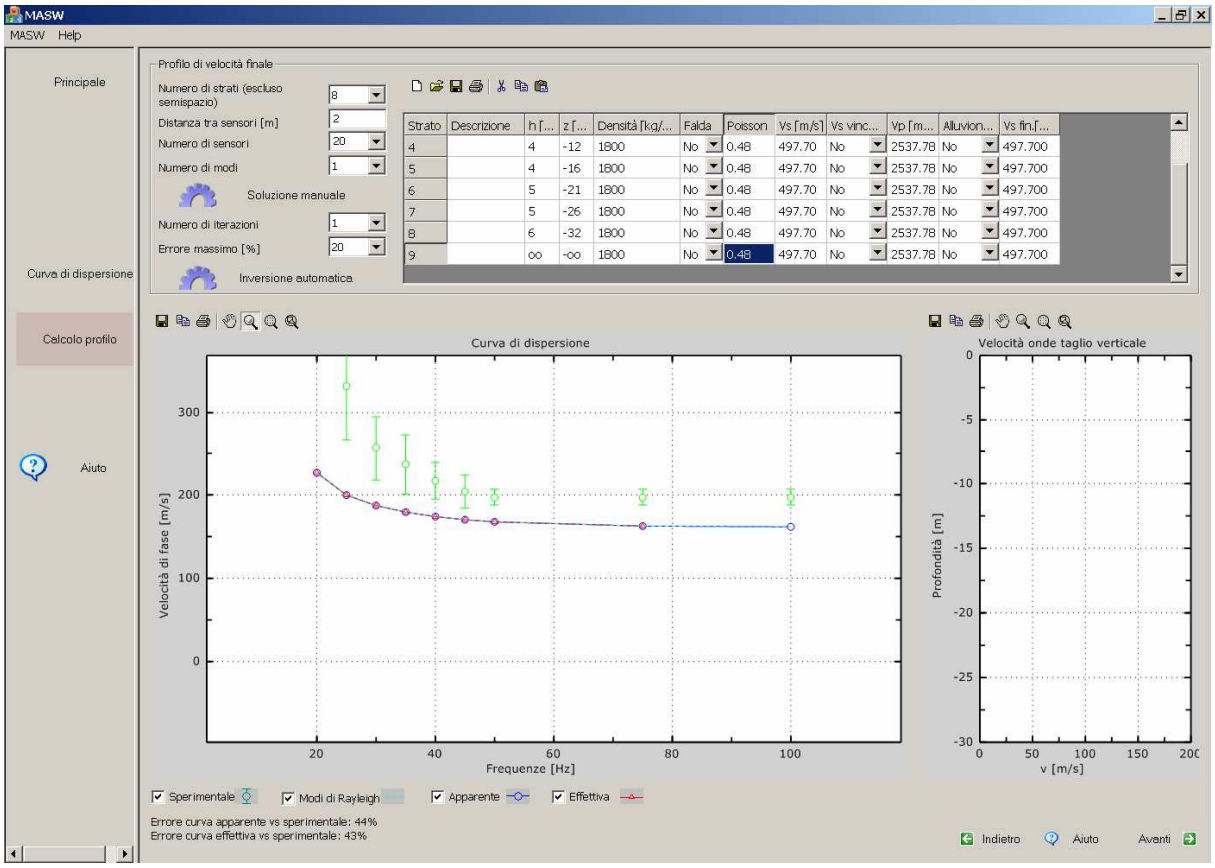


Figure 4.57: results obtained with the Vs profile assigned by default.

After few attempts with the trial and error metod, by increasing the number of surficial layers, an optimal Vs profile is reached, with a relative error of 6% between the experimental dispersion curve and the numerical dispersion curve (**figures 4.58, 4.59**). The final Vs profile aloows to determine the seismic class of the site, that is B with Vs30=627m/s (**Figure 4.60**).

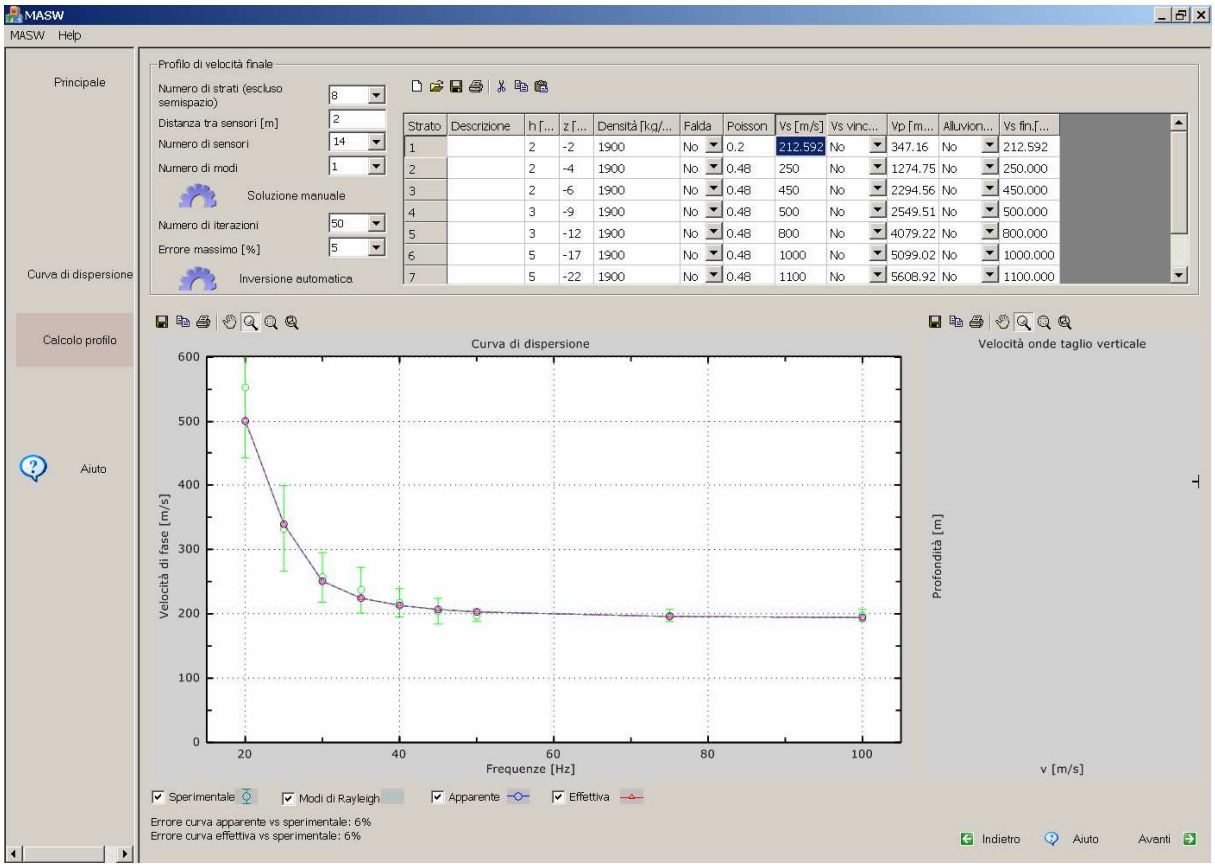


Figure 4.58: results of the final optimal Vs profile.

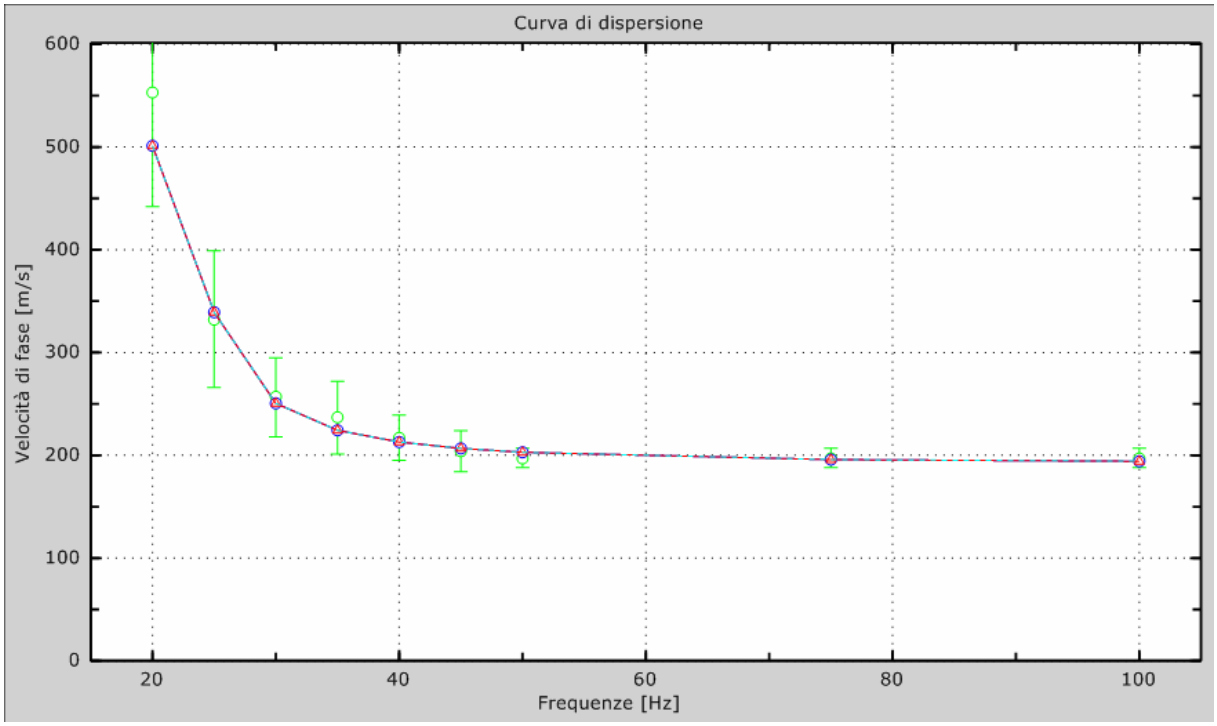


Figure 4.59: optimal match between experimental and numerical dispersion curves**.**

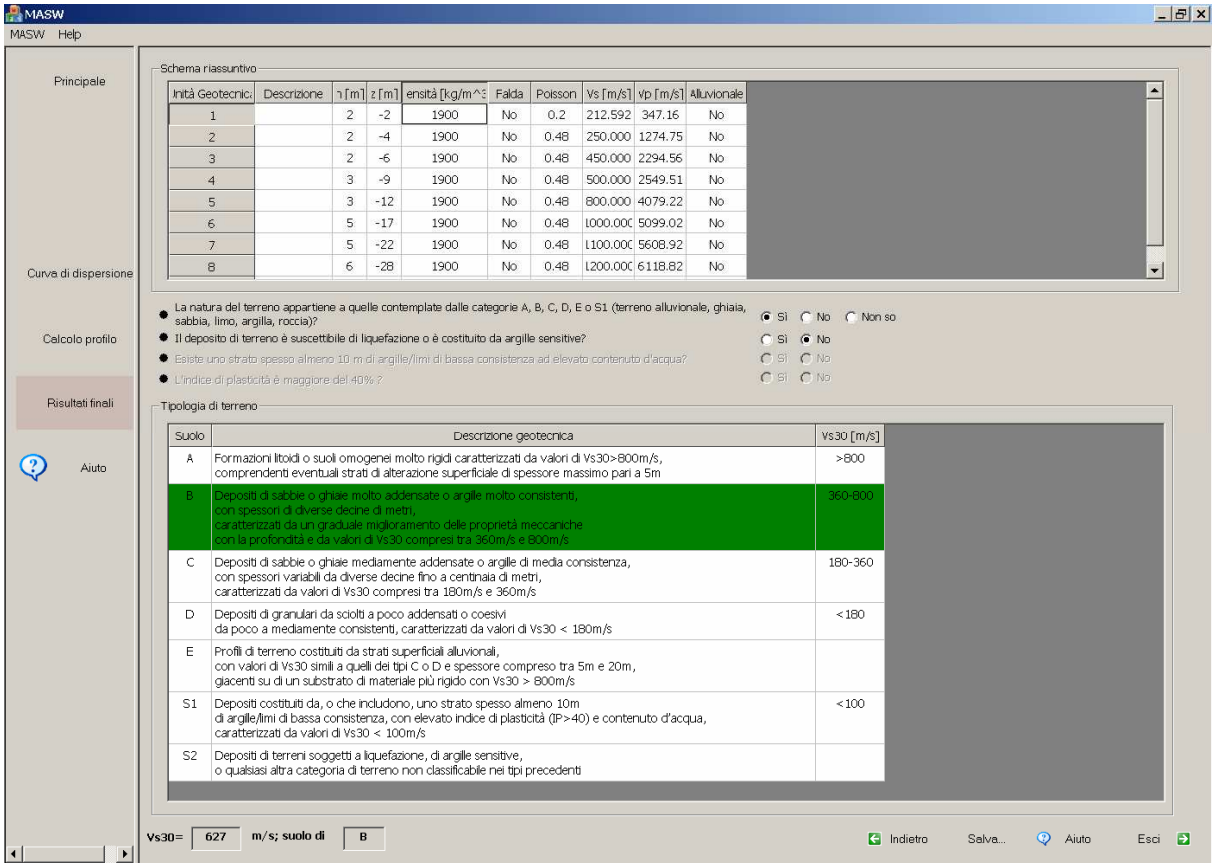


Figure 4.60: site of class B with Vs30=627m/s.

4.18 Example 17: Telecom headquarters in Torino

The site is located in Torino (Italy) in Cso Inghilterra street at the corner with Cavalli street, near the building of the Telecom headquarters. The stratigraphy consists of dense layers of sand and gravel with a degree of cementation which gradually increases with depth. The water table is at about 20m under the ground level.

Figure 4.61: MASW test in urban environment, with high traffic noise.

Parameters of acquisition during test:

span of geophones = 2.5m

time sampling = 2ms

lentgh of array = 32.5m

source: 5kg hammer.

By visual inspection of the measured traces (**figure 4.62**) it can be observed that the signal to noise ratio is low from receiver number 7 to number 14. For this reason only the first 6 receivers have been used for the analysis. In **figure 4.63** both the f-k spectrum and the experimental apparent dispersion curve are shown; **figure 4.64** shows the selection of the significant points of the experimental dispersion curve to be used for the inversion process.

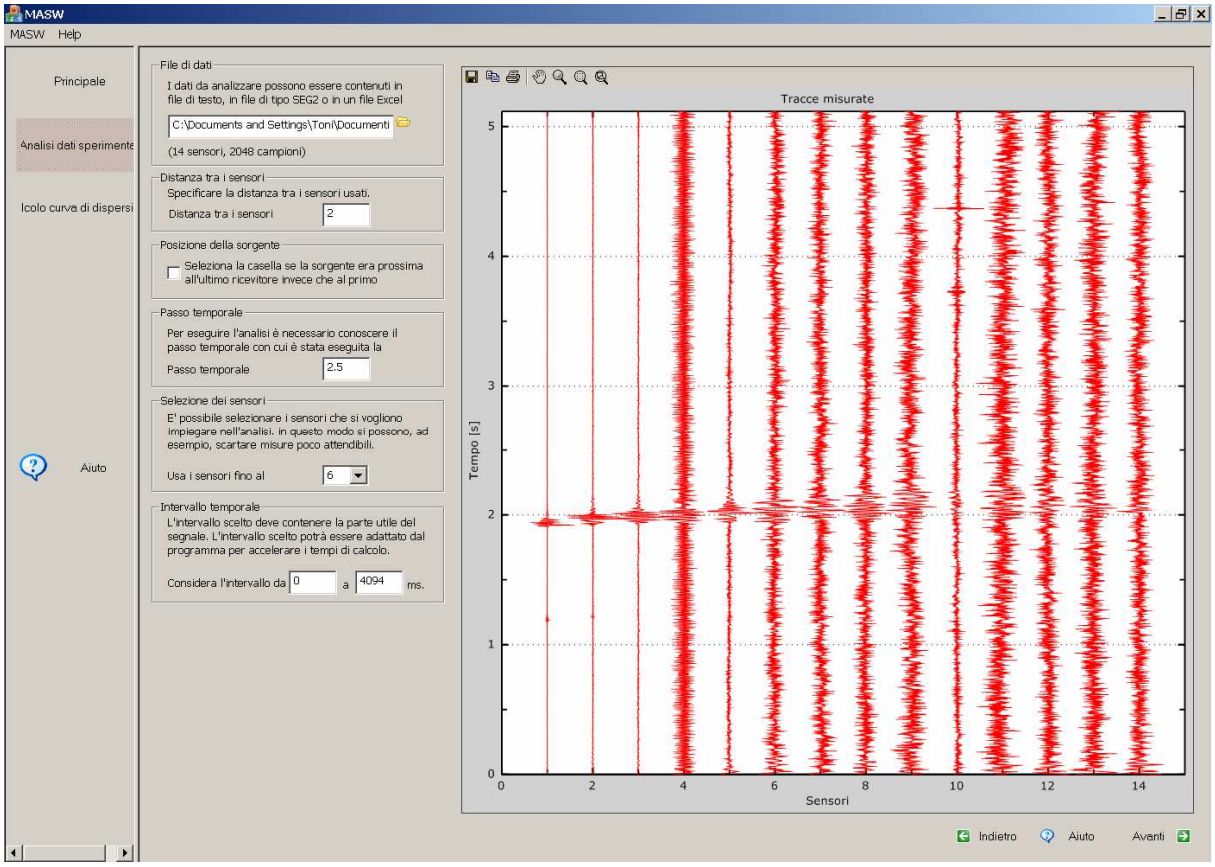


Figure 4.62: measure traces near the building of Telecom headquarters in Torino.

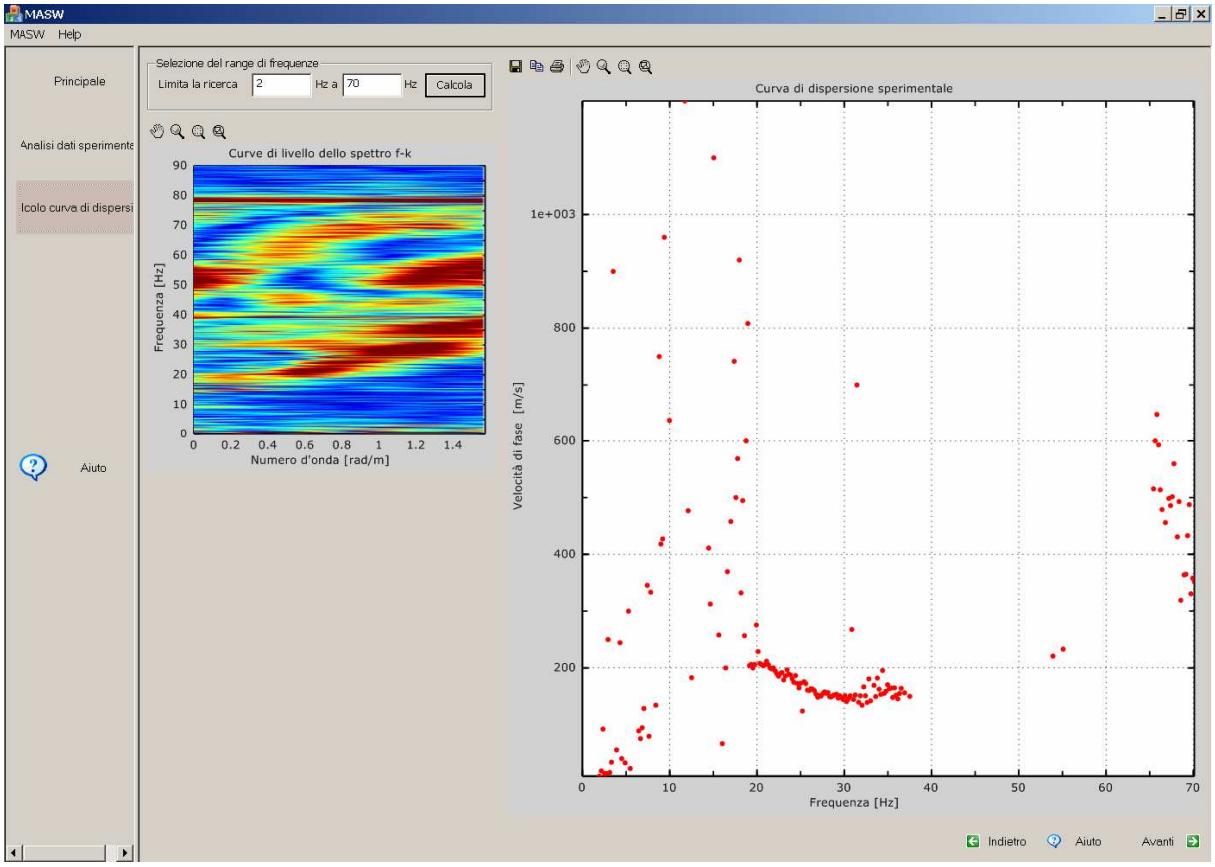


Figure 4.63: f-k spectrum and experimental dispersion curve near the building of Telecom headquarters in Torino.

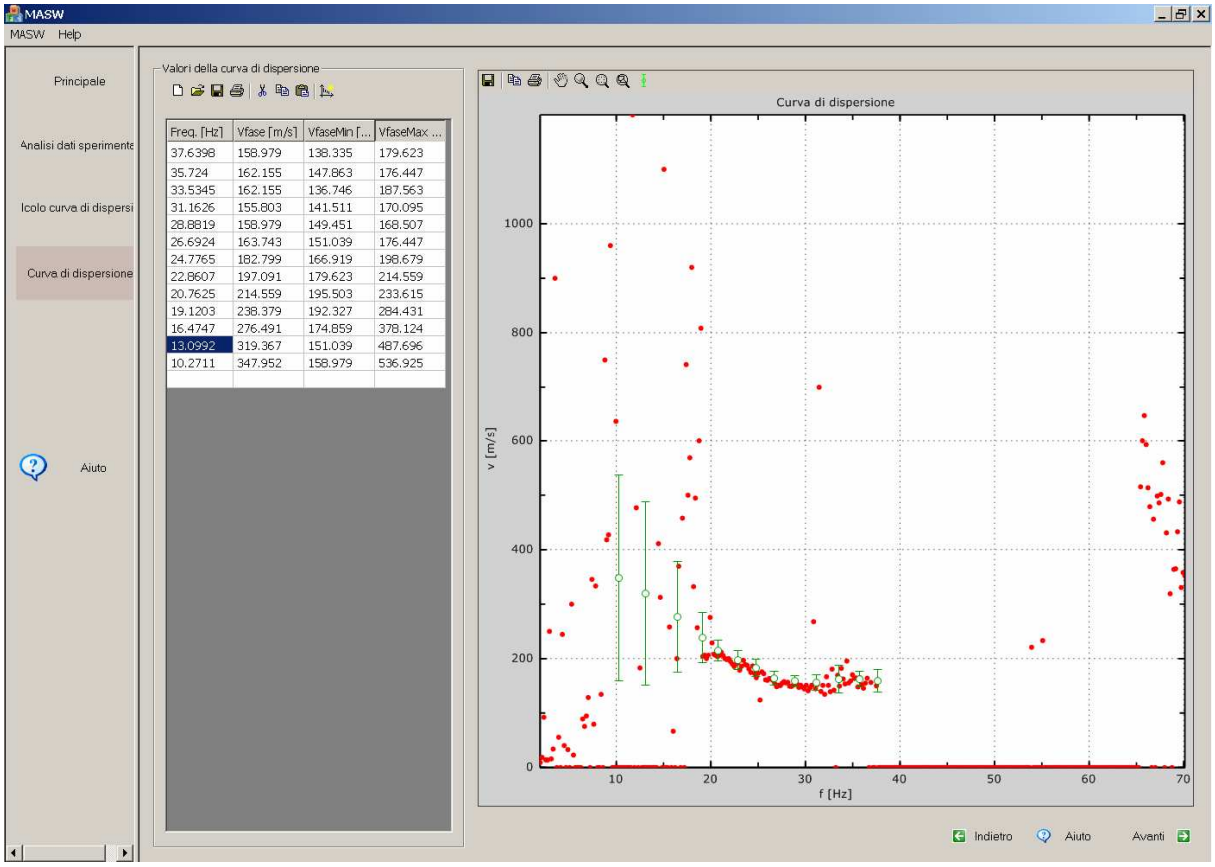


Figure 4.64: selection of significant points of the experimental dispersion curve.

By fixing the shear wave velocity of the half-space to a value of Vs=950m/s, by reducing the number of layers to 6, the automatic search with only the fundamental mode of Rayleigh waves gives a Vs profile, to which cooresponds a numerical dispersion curve with a relative error of 10% (**figure 4.65**). The correspondent Vs30=424m/s, hence the site belongs to the seismic class B.

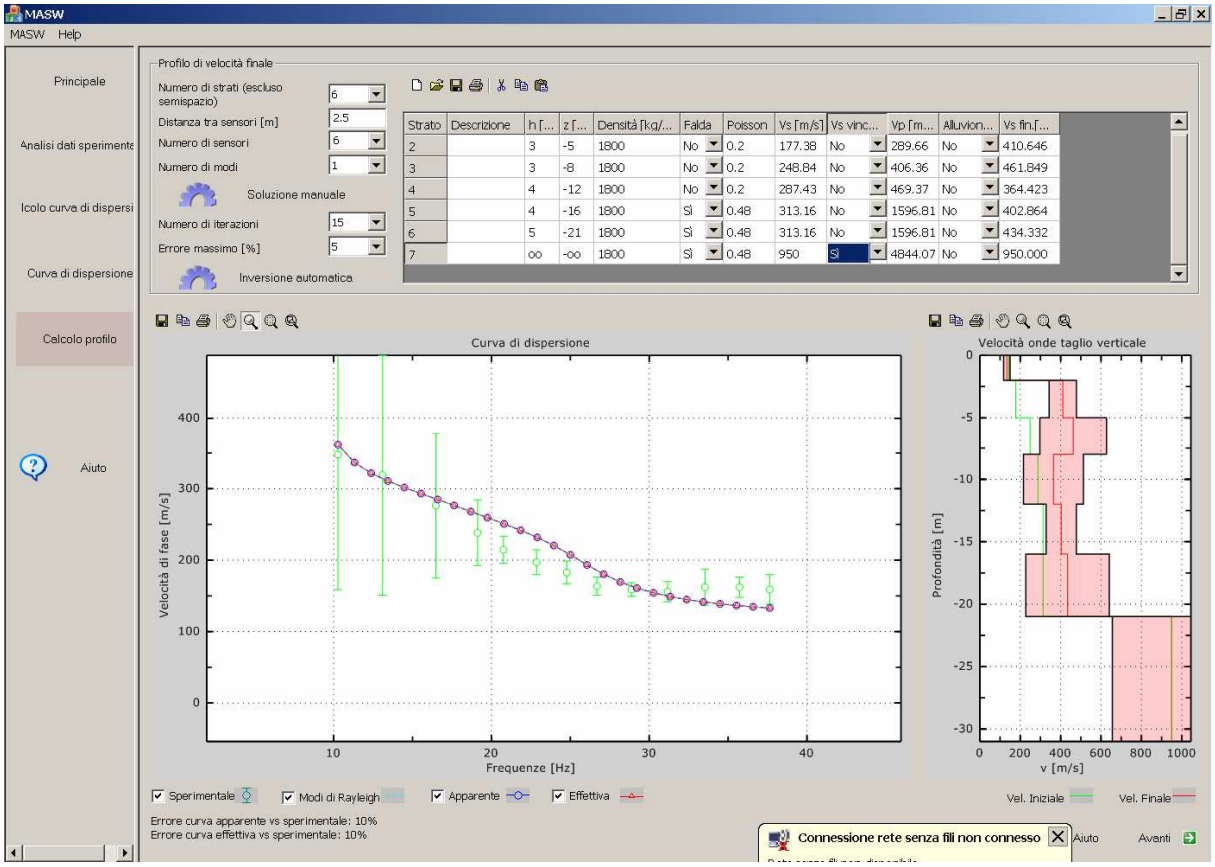


Figure 4.65: results of the automatic search.

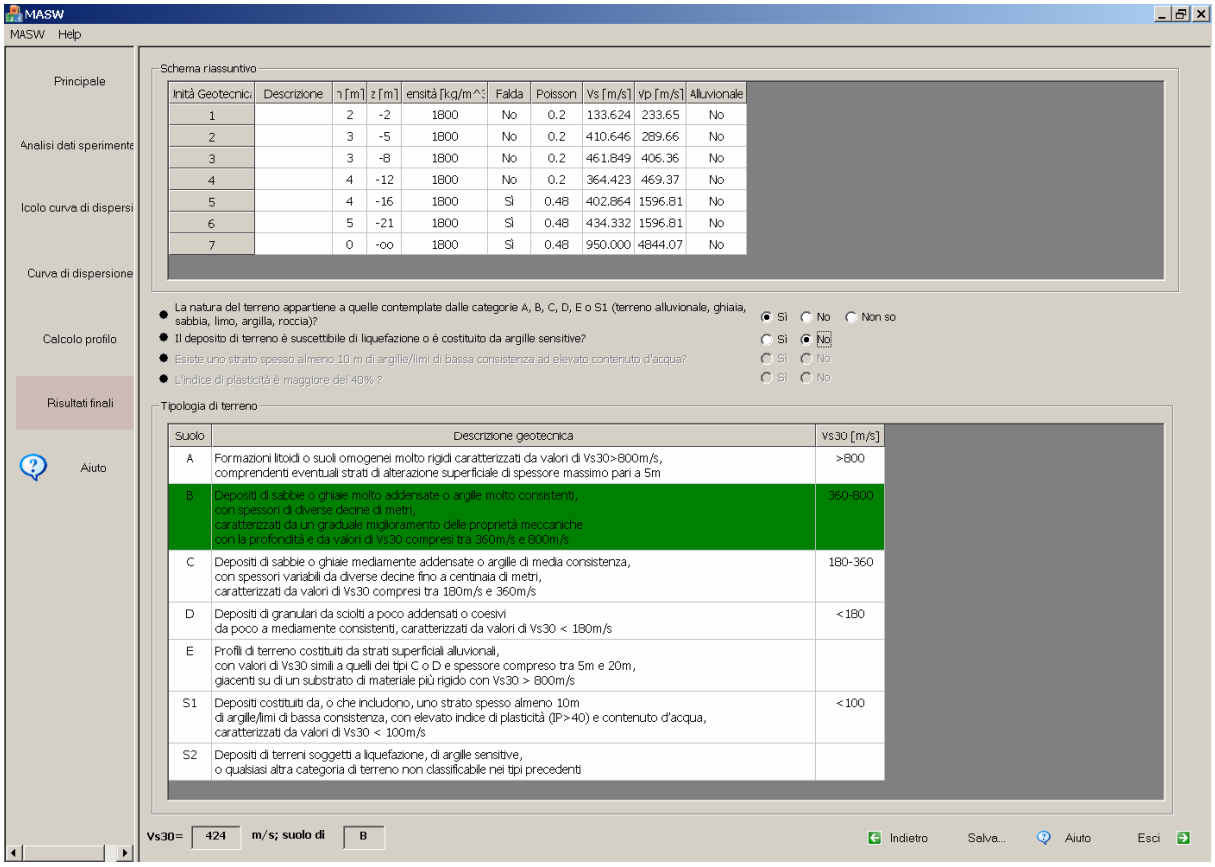


Figure 4.66: seismic classification of the site.

4.19 Example 18: Leaning Tower of Pisa

The MASW test in Miracles square near the leaning tower of Pisa has been performed in May 2001, durino a geotechnical investigation of the Technical University of Turin (Politecnico). Information on the traces and the experimental test can be found in (Roma V. 2001, PhD Thesis).

Parameters of acquisition during test:

span of geophones = 2.5m

time sampling = 2ms

lentgh of array = 32.5m

source: electromechanic shaker with harmonic excitation.

With respect to the hammer, the electromechanic shaker with controlled harmonic excitation offers the advantage of exciting the ground at frequencies lower than 10Hz (**figure 4.67**). Nevertheless the hammer is much less expensive with respect to the electromechanic shaker.

The stratigraphy consists of alternate layers of sands, silty sands and clays under the surficial layer of compacted fill of thickness of 3m. The upper water table is at about 3m under the ground level. To consider the water the Poisson coefficient has been set equal to 0.48.

By properly modifying the thicknesses and the shear wave velocities of the layers, the final optimal Vs profile has been obtained, with a relative error between the numerical and the experimental dispersion curves equal to 3% (**figura 4.68**).

The equivalent shear wave velocity within the first 30m of ground is Vs30= 206m/s, hence the seismic class of the site is C.

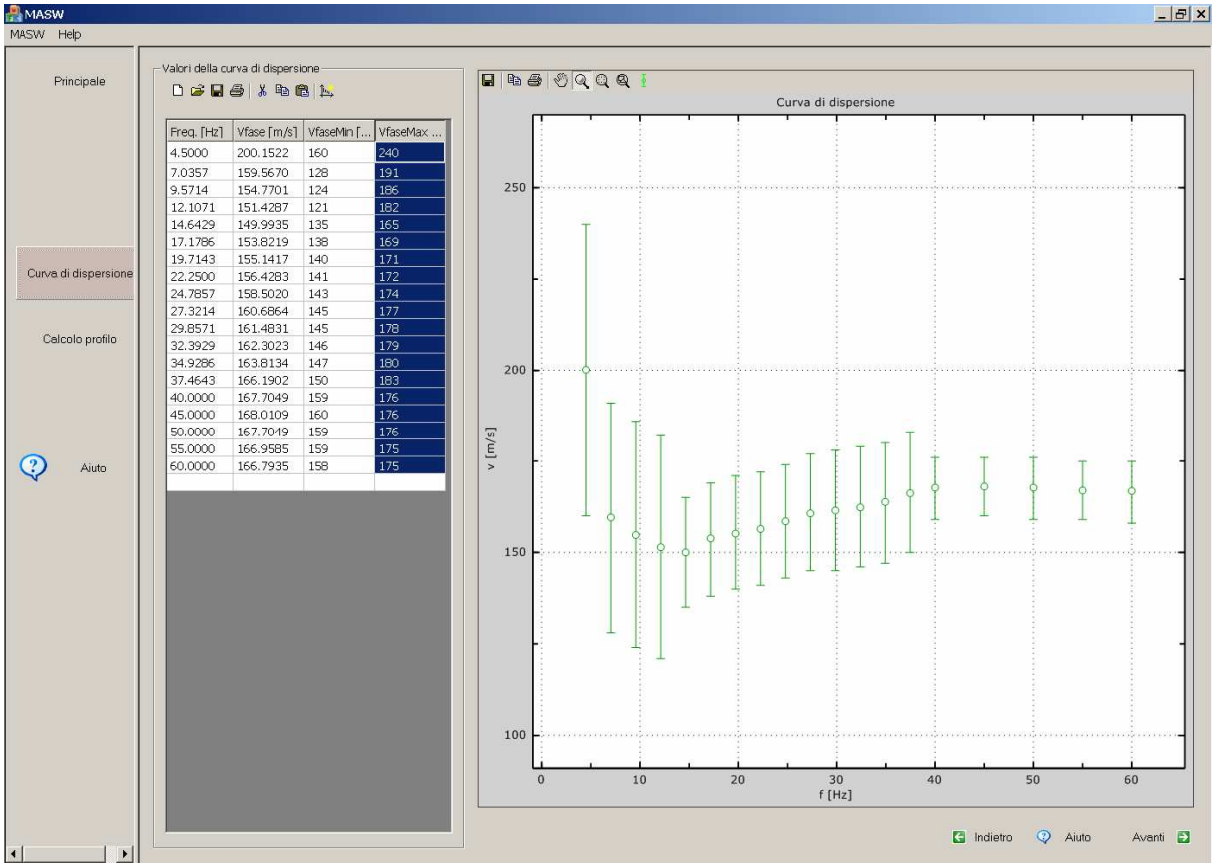


Figure 4.67: experimental dispersion curve at the leaning tower of Pisa.

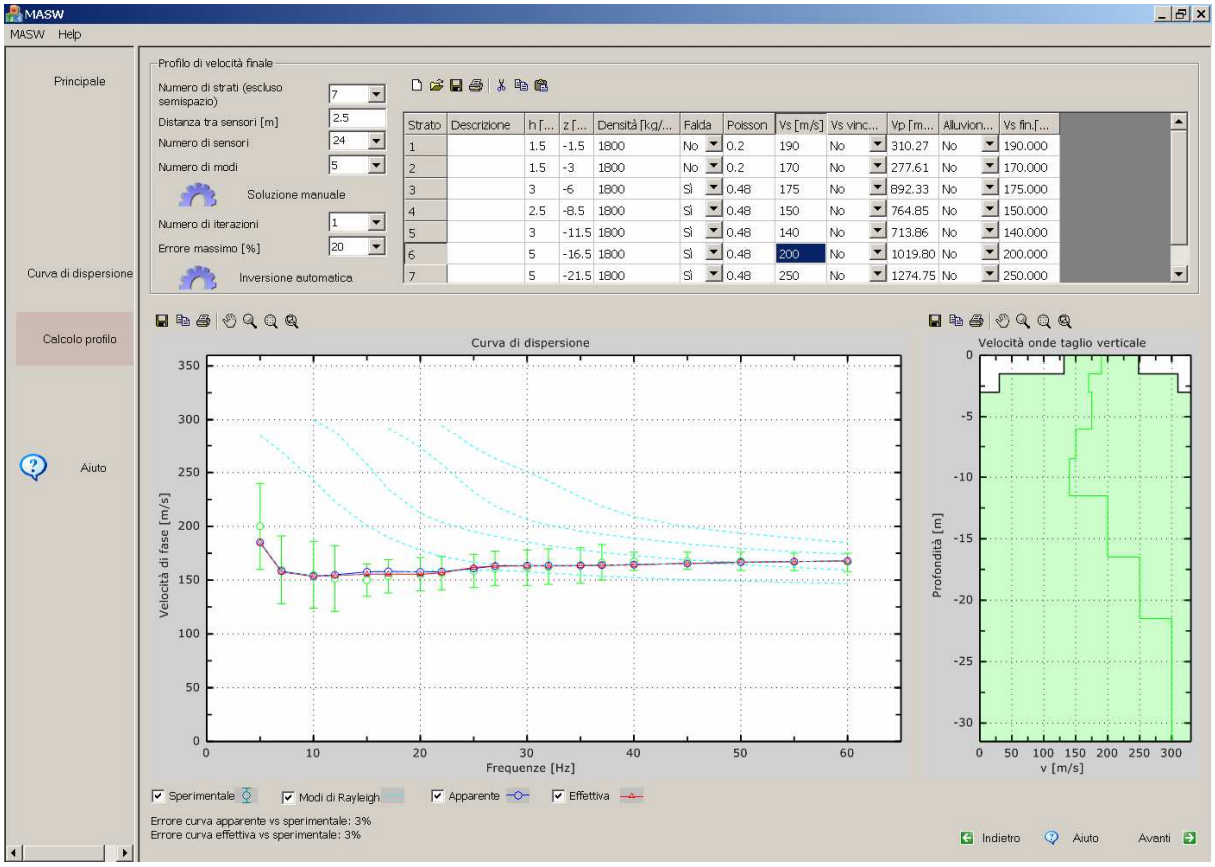


Figure 4.68: final optimal Vs profile at the leaning tower of Pisa (trial and error search).

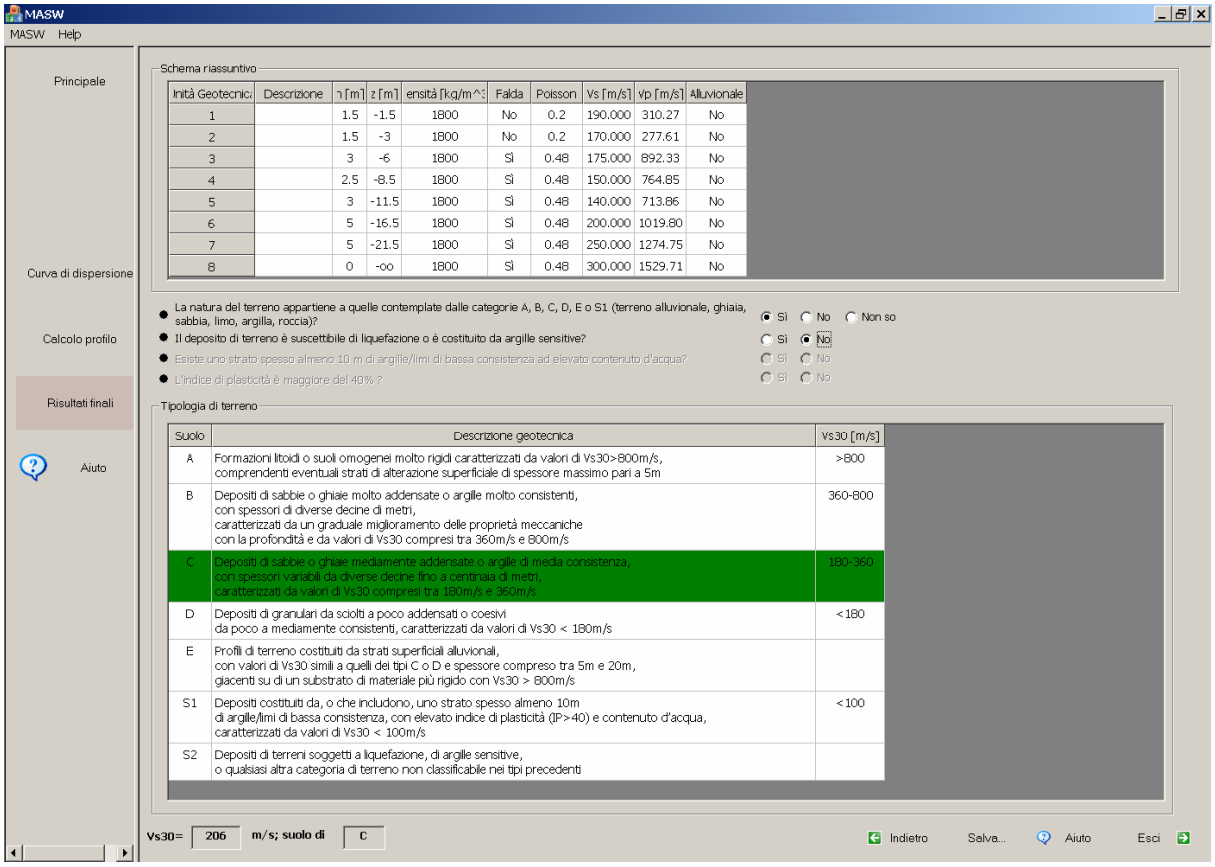


Figure 4.69: seismic class of the ground at under the leaning tower of Pisa (trial and error search).

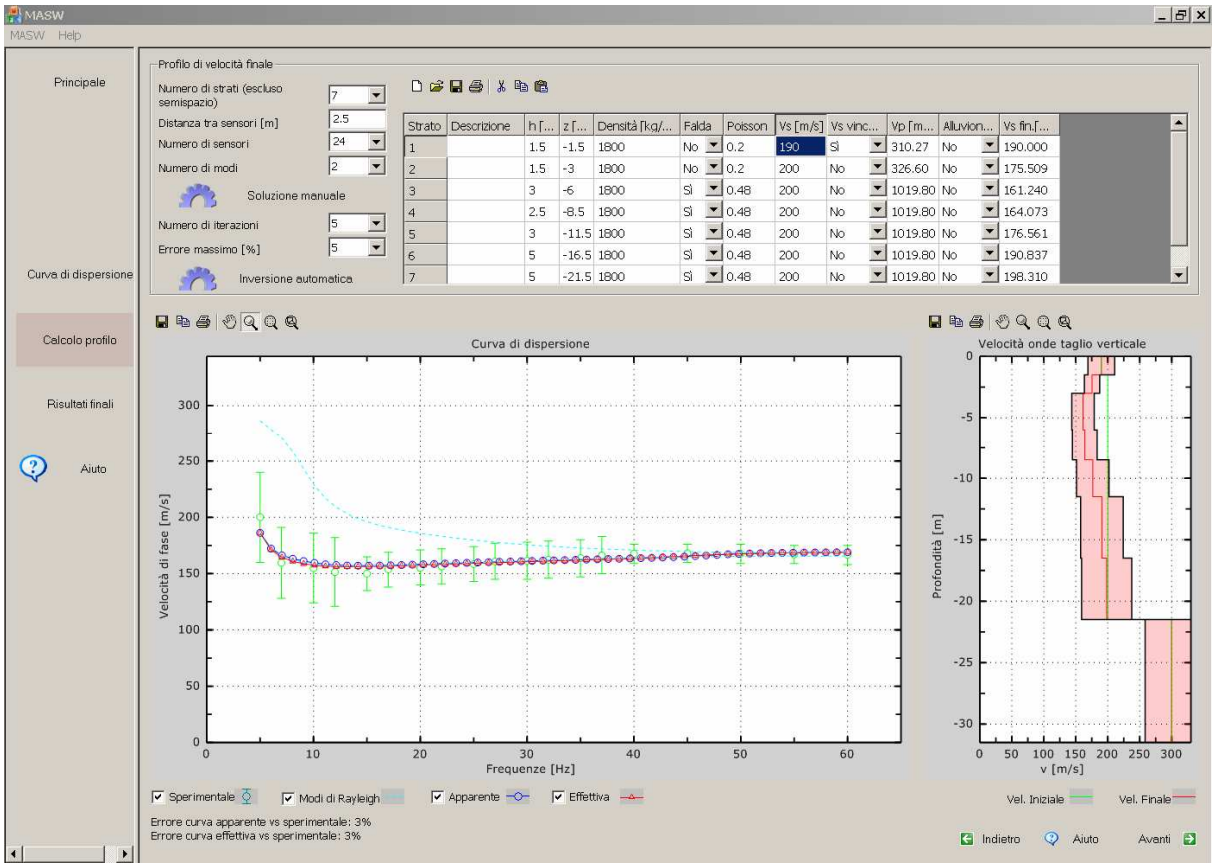


Figure 4.70: final optimal Vs profile at the leaning tower of Pisa (automatic search).

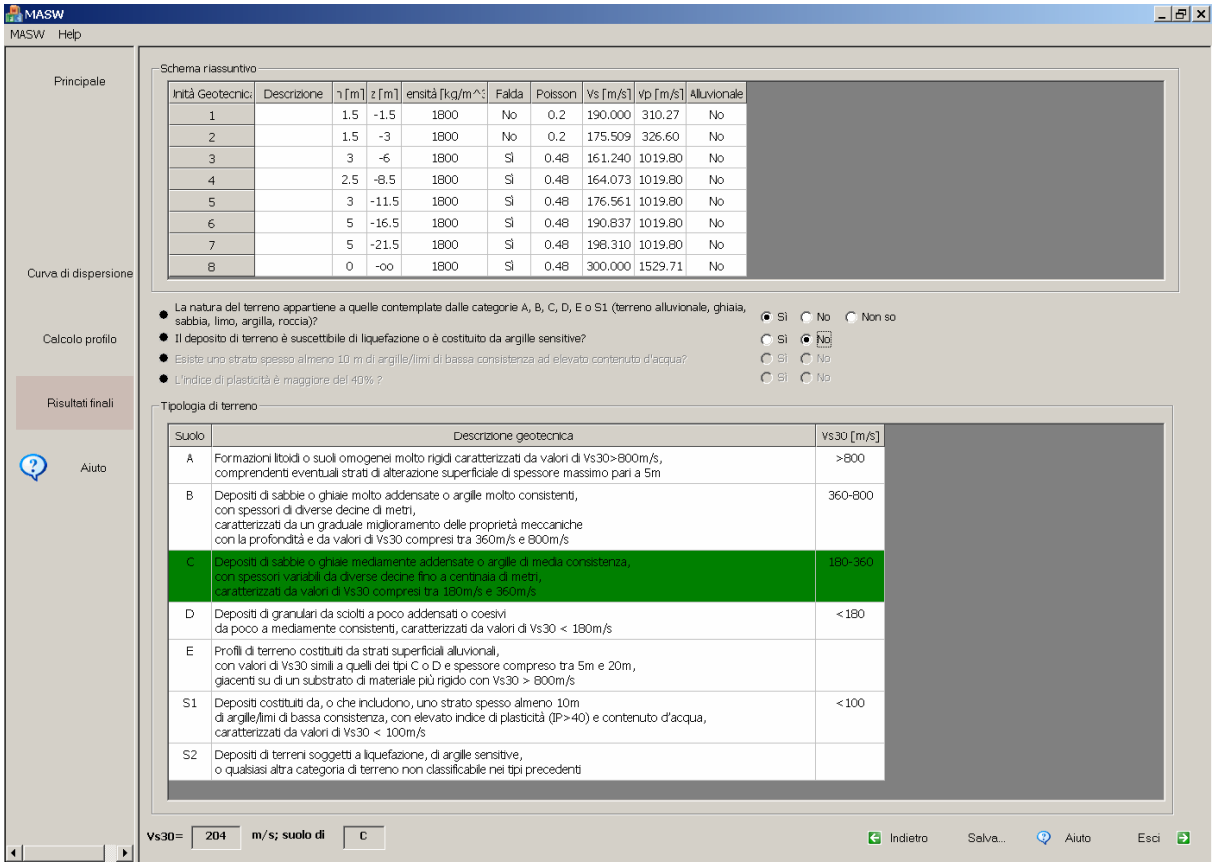


Figura 4.71: seismic class of the ground at under the leaning tower of Pisa (automatic search).

4.20 Example 19: Villadossola (Verbania)

The MASW tests have been performed in 3 different sites located in the industrial area of Villadossola (Piemonte) and its stratigraphy consists of alternate layers of gravel, sand and cobbles. The water table is at about 14m under the ground level (**figures 4.72, 4.73**).

Parameters of acquisition durino MASW test:

number of receivers = 12

span of geophones = 1.5m

time sampling = 2ms

total time of acquisition = 4s.

source: 5kg hammer.

In the following figures the experimental dispersion curves obtained at the 3 sites are shown.

For the sites 1 and 3 at frequencies higher than 70Hz the experimental dispersion curve tends toward growing velocities, that indicates that a stiff surficial layer exists.

Figure 4.72: MASW test at site 1 in Villadossola.

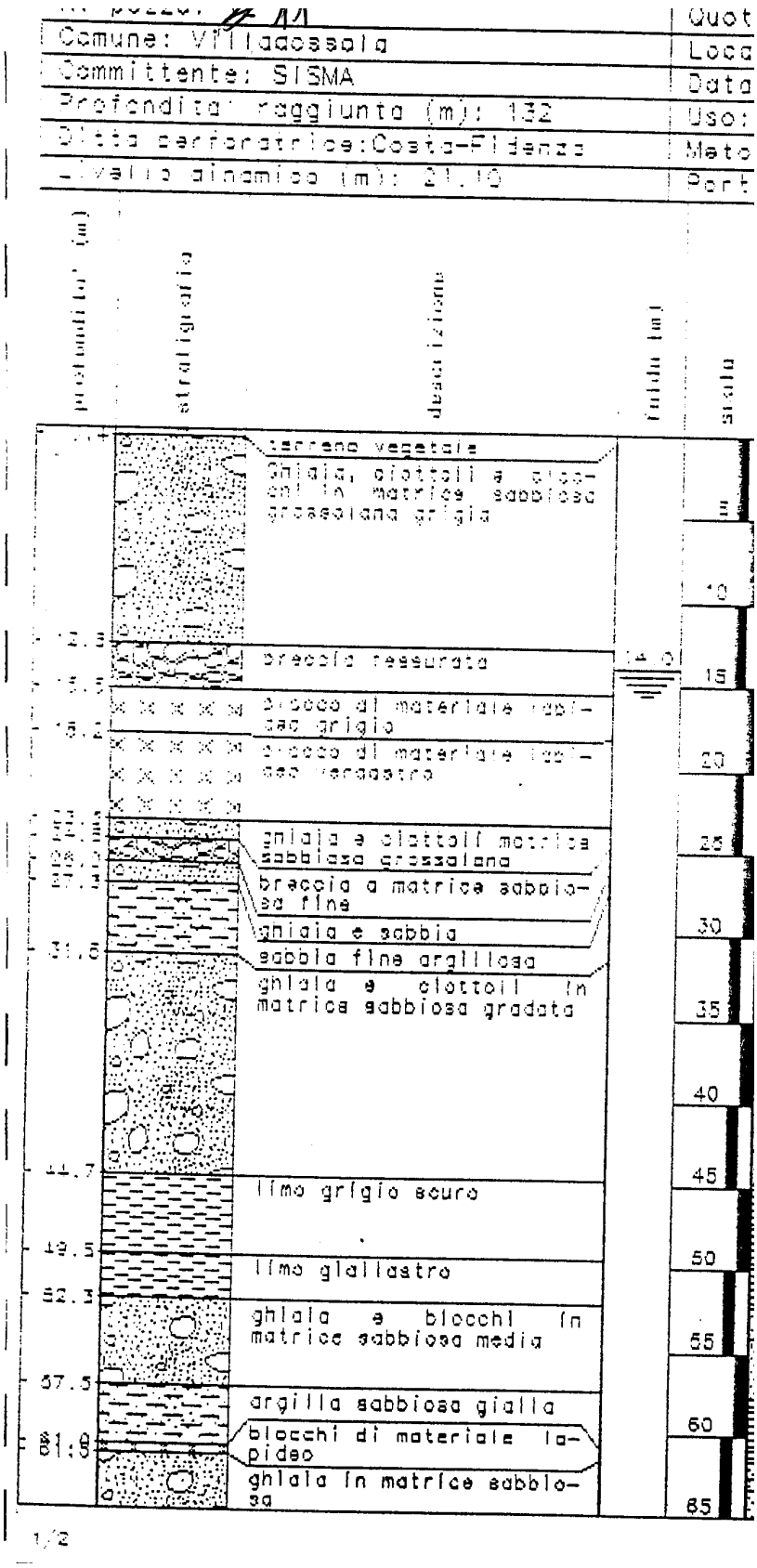


Figure 4.73: stratigraphy in Villadossola.

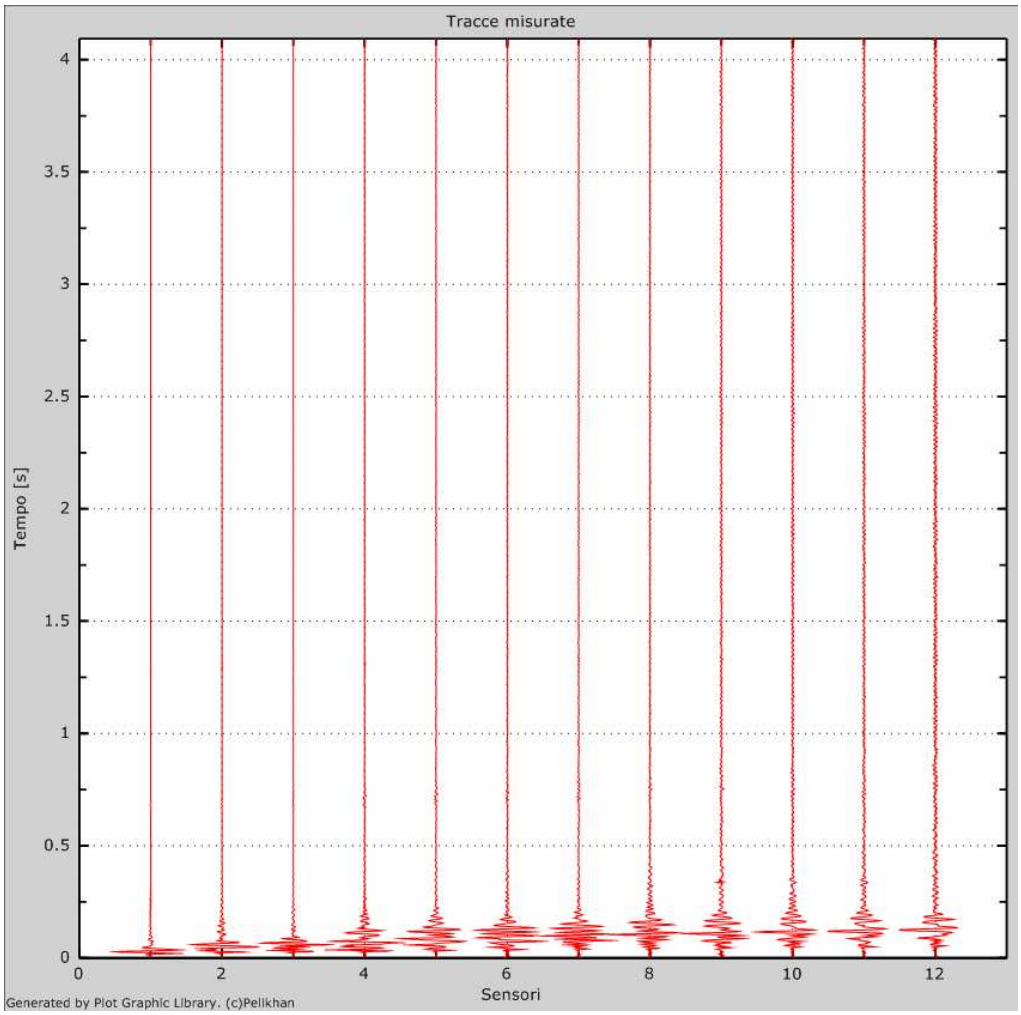


Figure 4.74: measured traces in field..

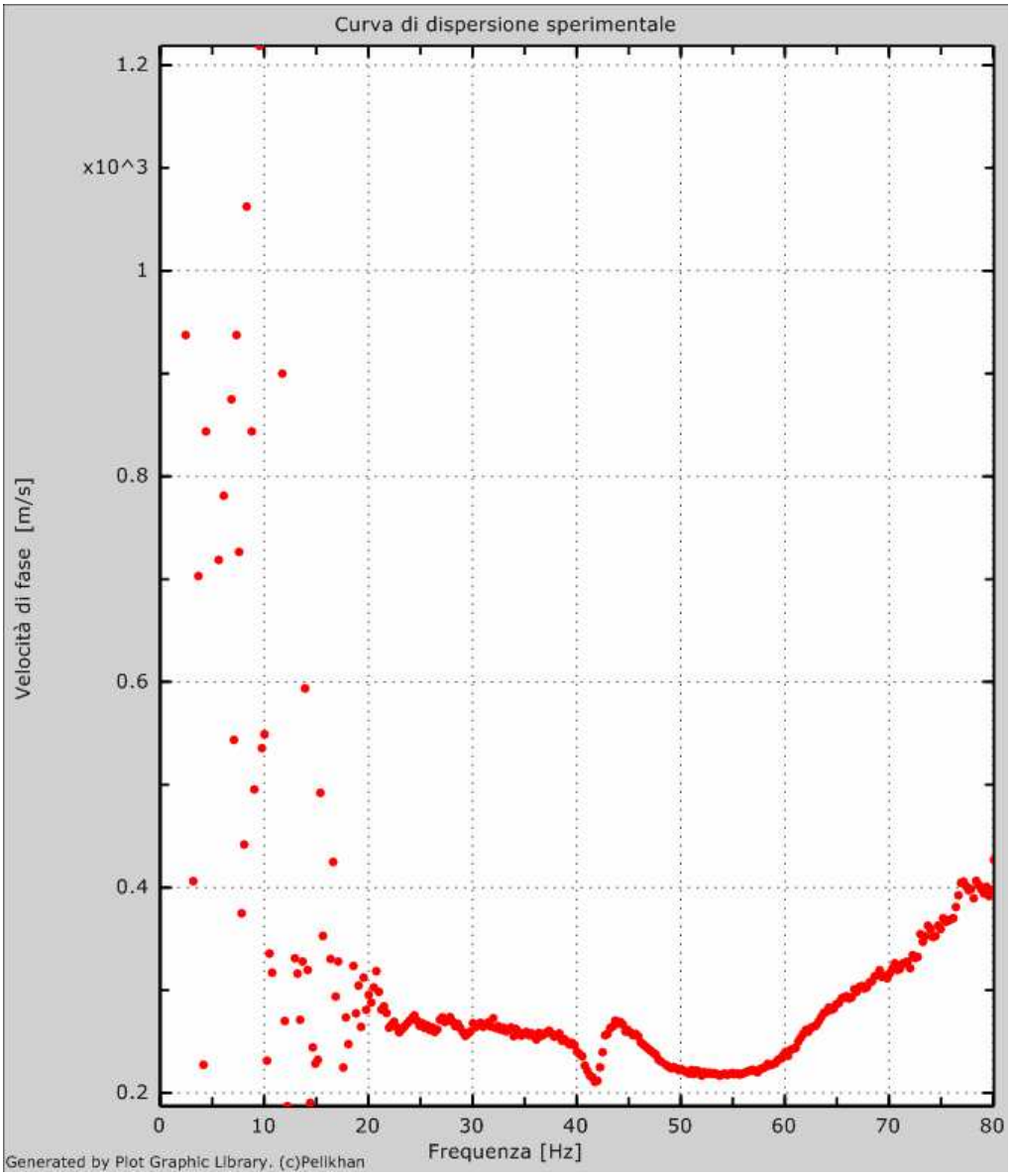


Figure 4.75: experimental dispersion curve at site 1 in Villadossola.

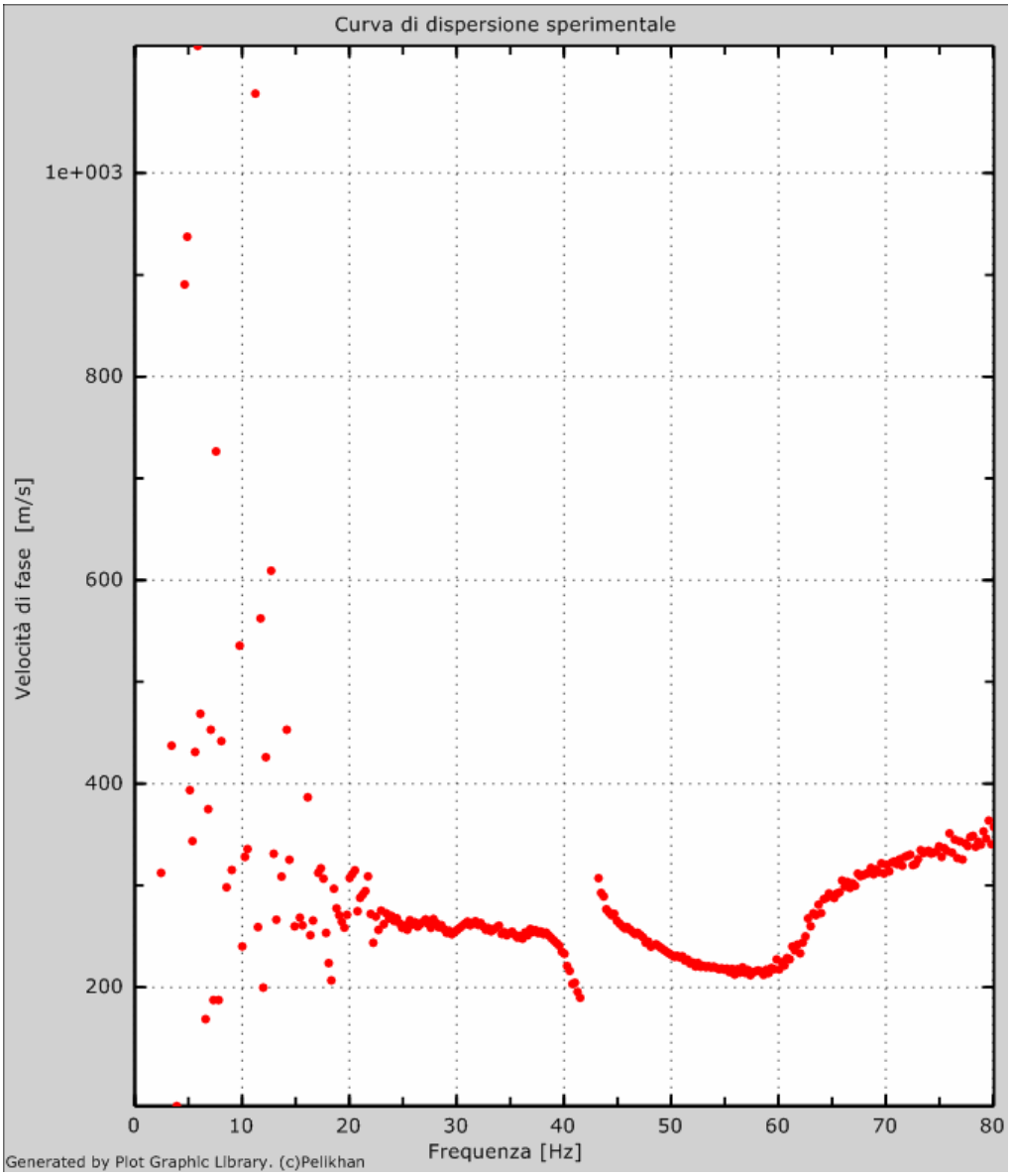


Figure 4.76: experimental dispersion curve at site 1 in Villadossola.

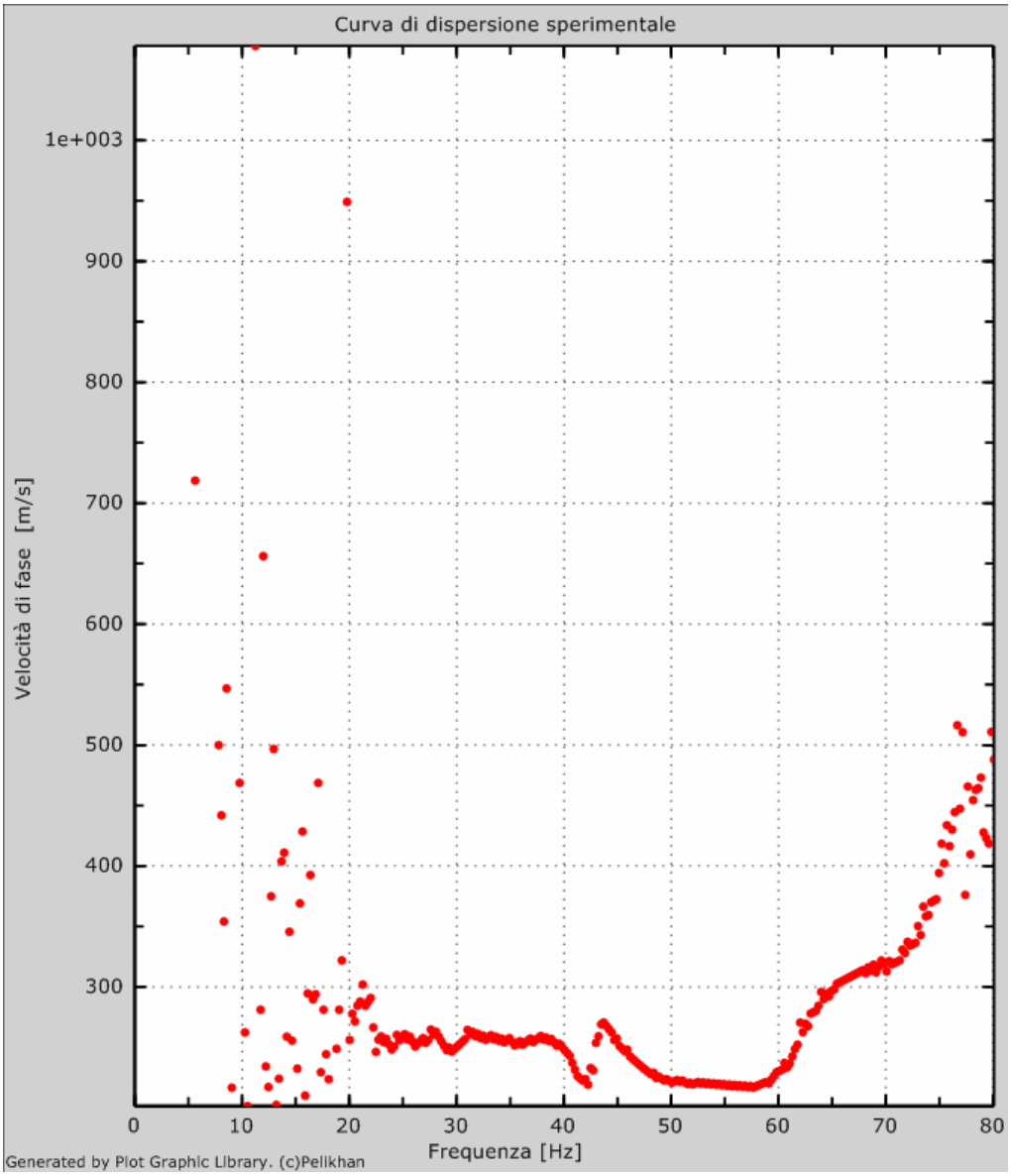


Figure 4.77: experimental dispersion curve at site 1 in Villadossola.

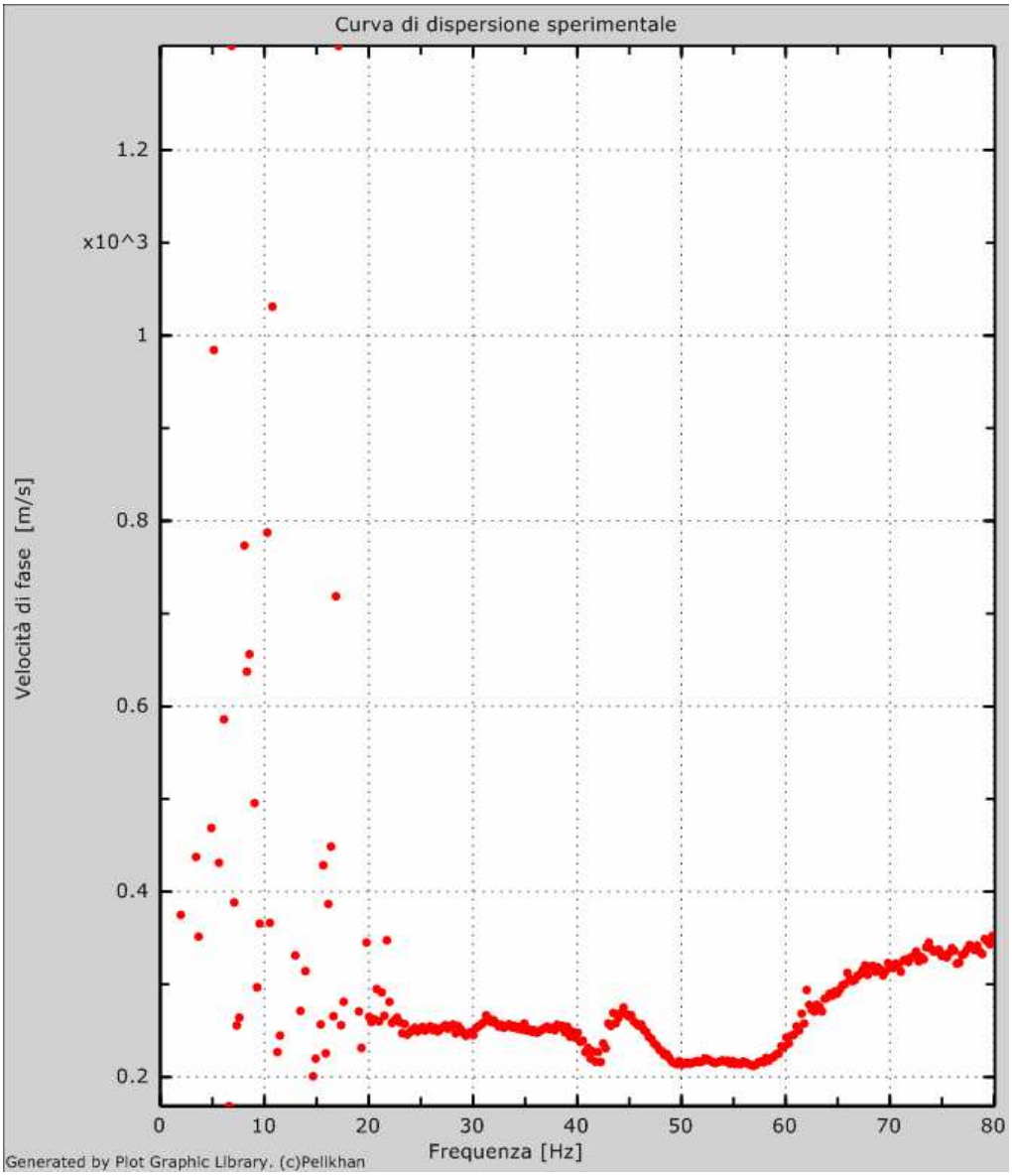


Figure 4.78: experimental dispersion curve at site 1 in Villadossola.

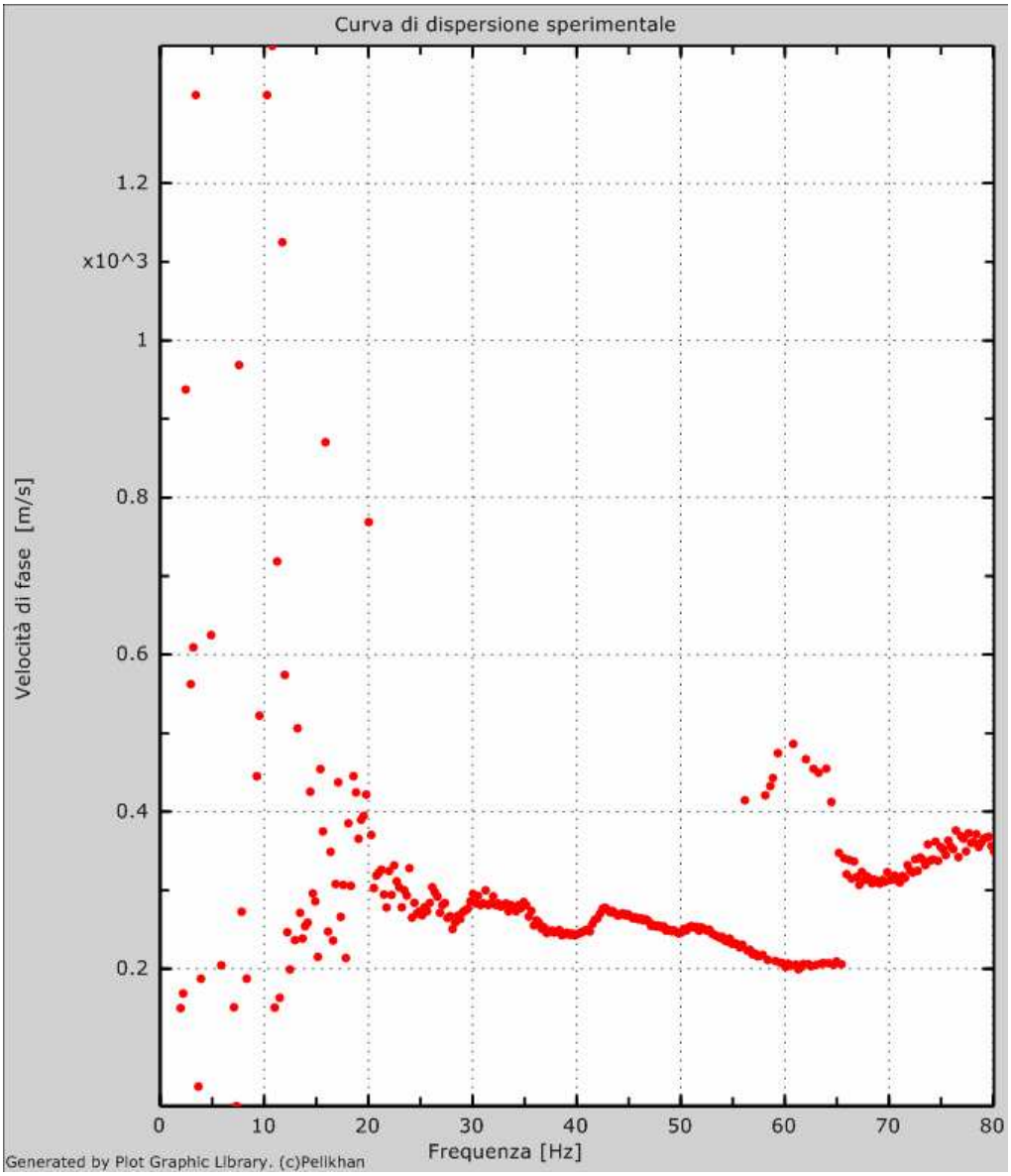


Figure 4.79: experimental dispersion curve at site 1 in Villadossola.

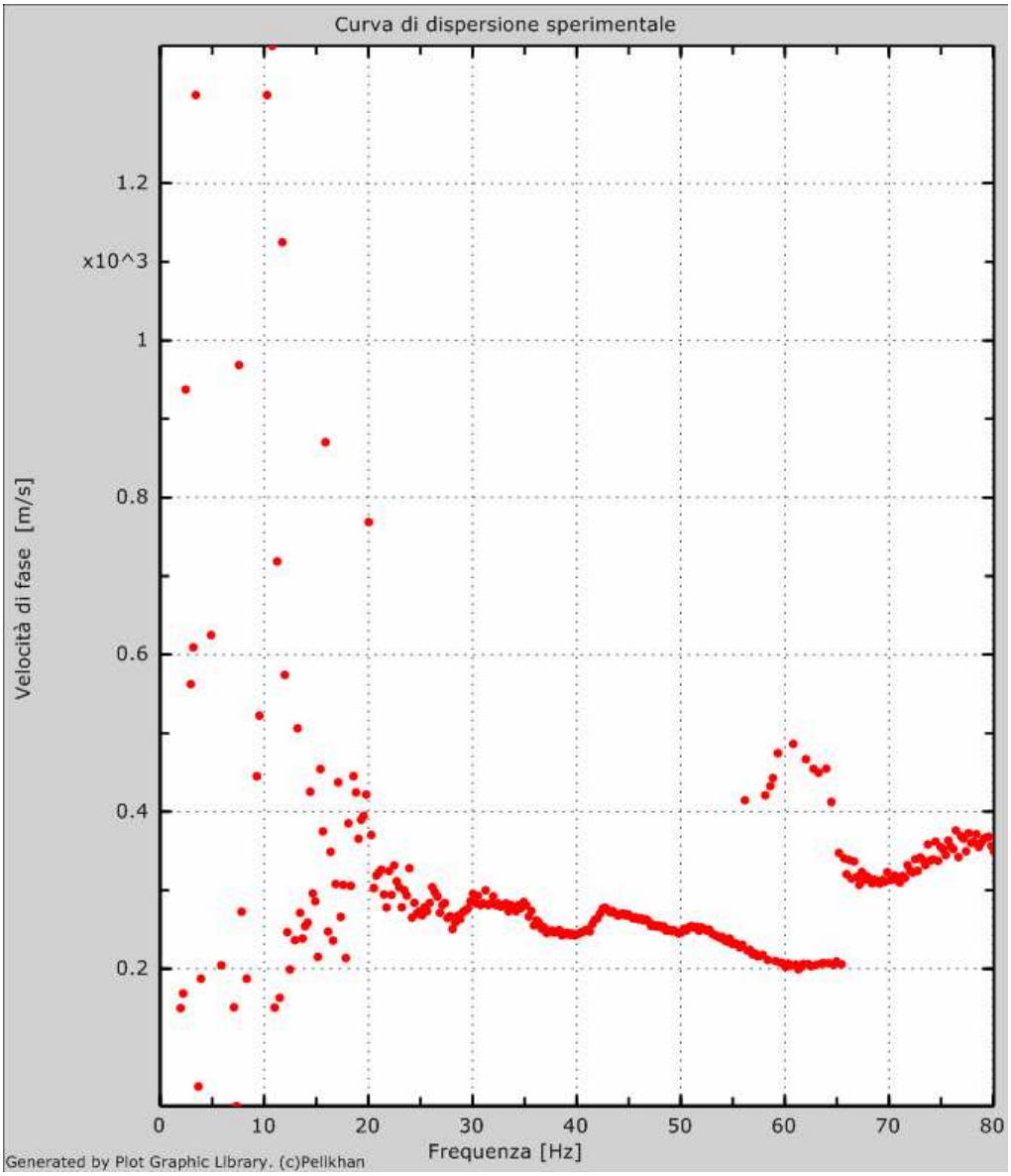


Figure 4.80: experimental dispersion curve at site 1 in Villadossola.

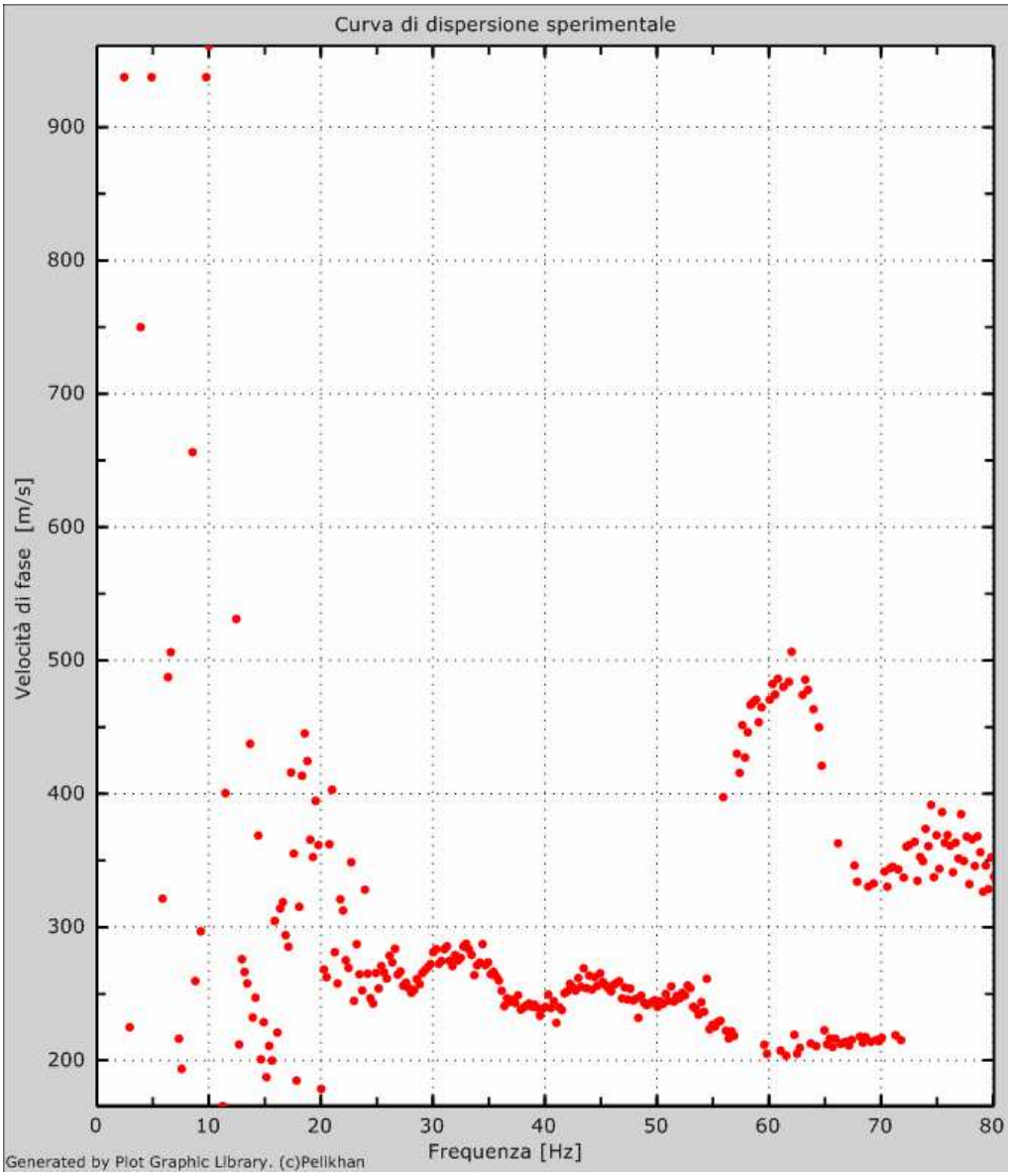


Figure 4.81: experimental dispersion curve at site 1 in Villadossola.

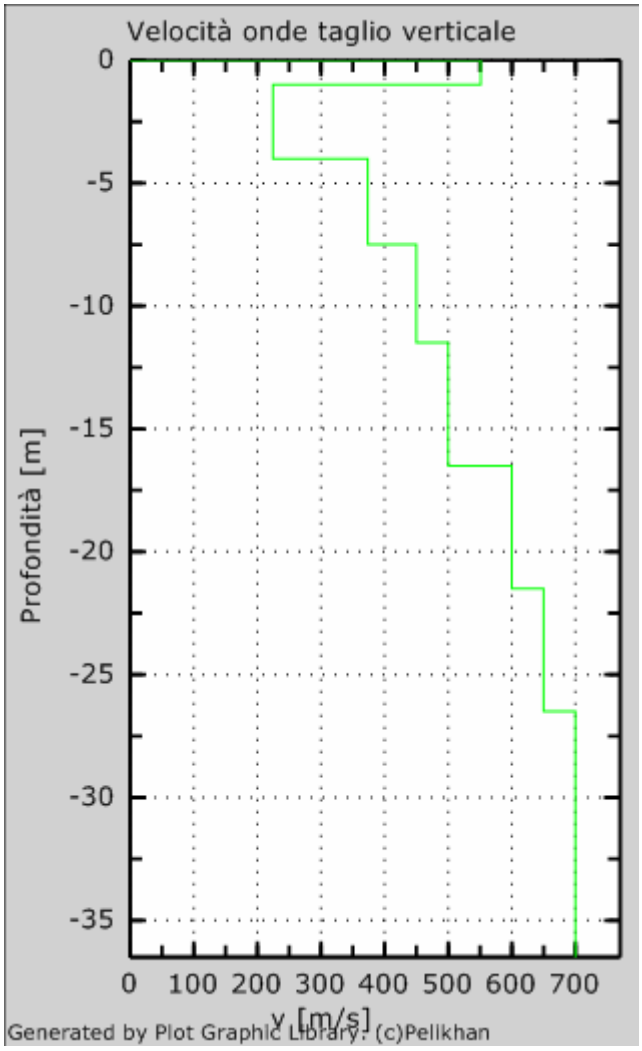


Figure 4.82: : Final Vs prfile at site 1.

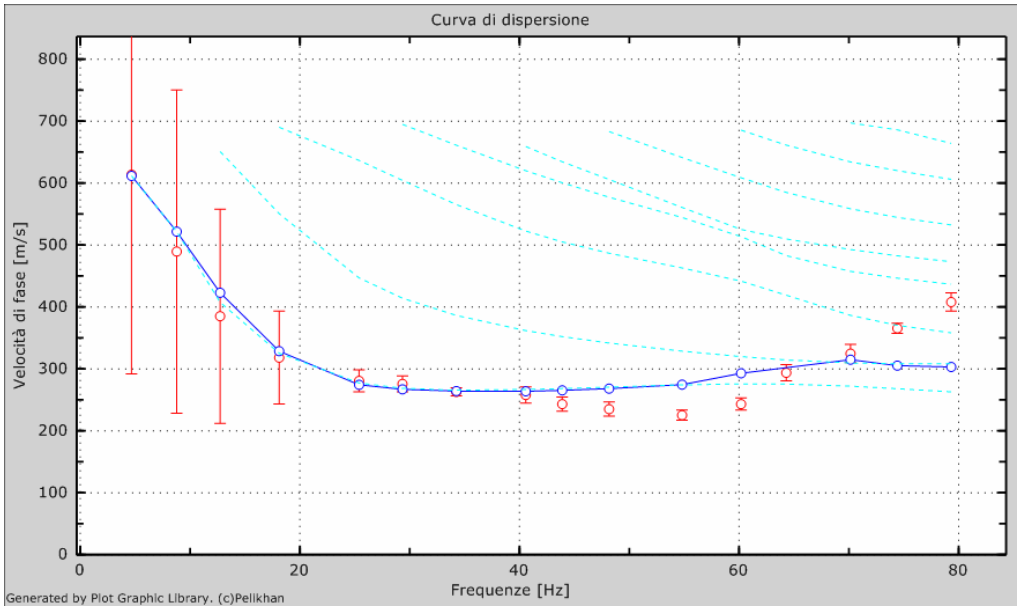


Figure 4.83: comparison between experimental (red circles) and numerical (solid line with blue circles) dispersion curves at site 1.

The equivalent shear wave velocity within the first 30m is Vs30 = 465 m/s, hence the seismic class is B.

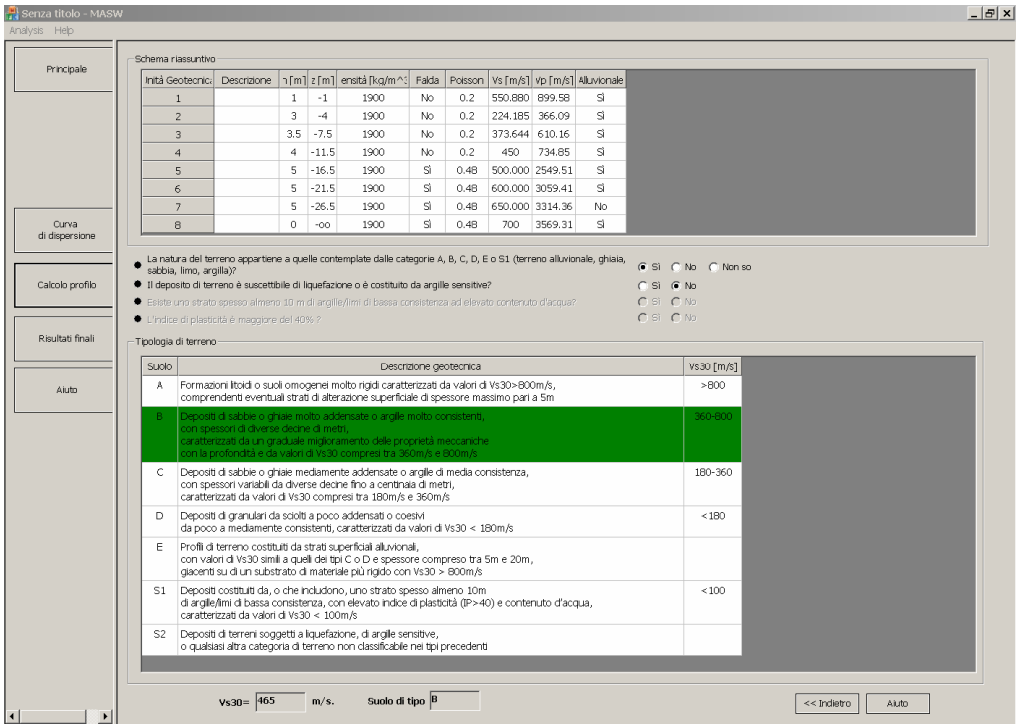


Figure 4.84: seismic classification of the site 1.

Figure 4.85: site 2 in Villadossola

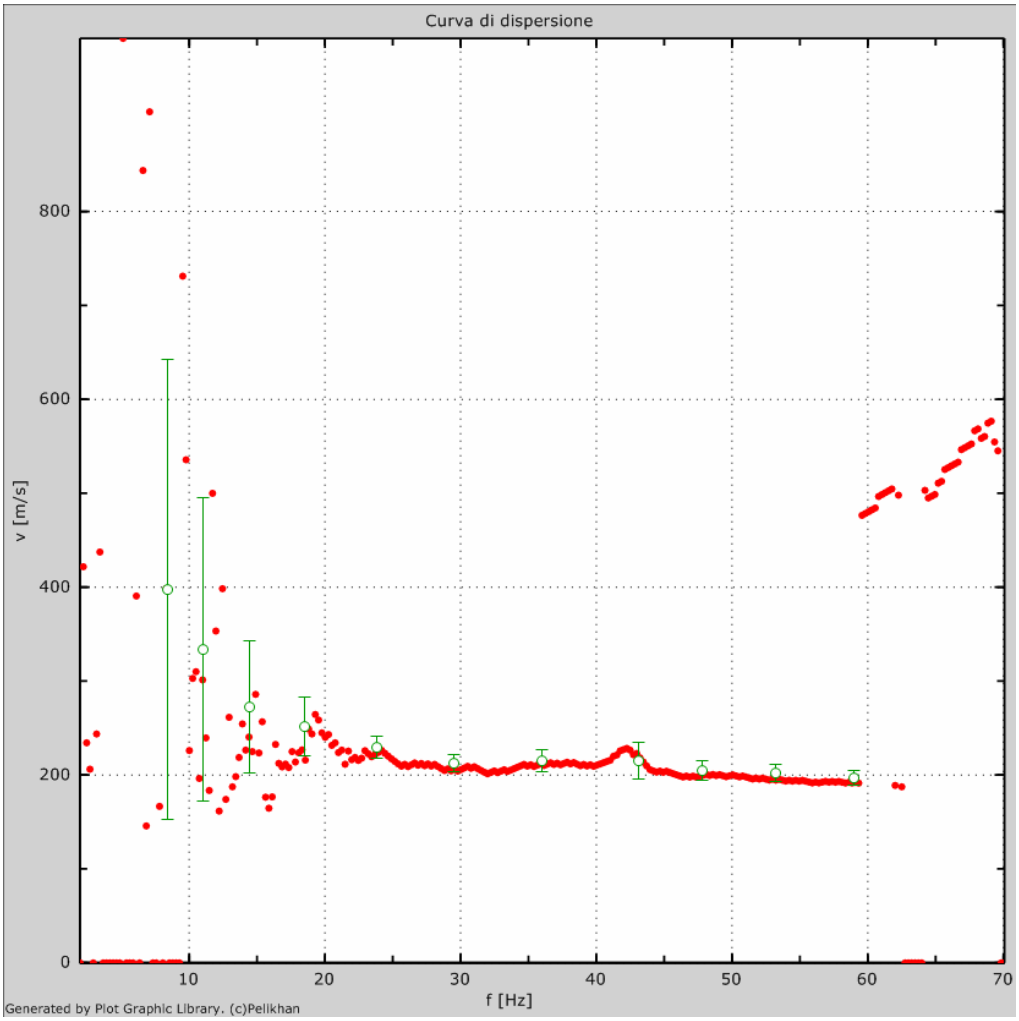


Figure 4.86: Experimental dispersion curve (red points) and selected points (green circles) for site 2.

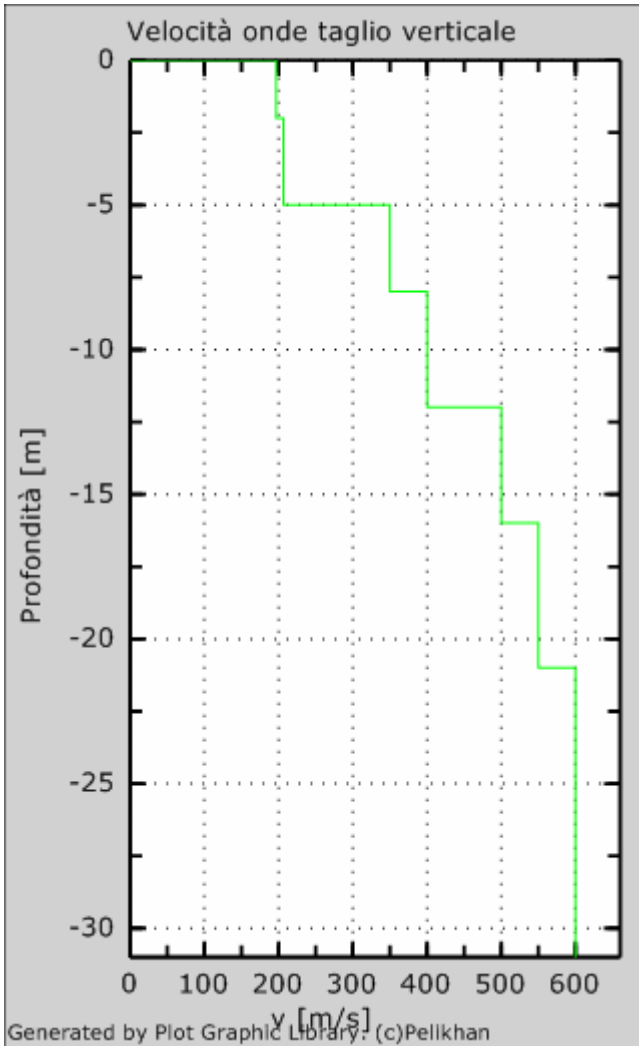


Figure 4.87: : final Vs profile at site 2.

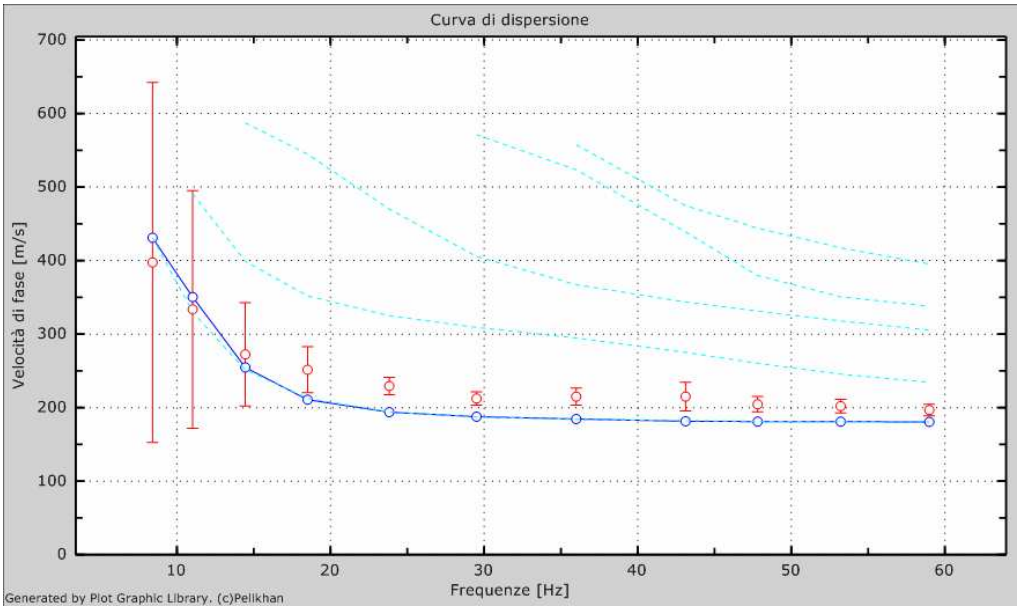


Figure 4.88: comparison between experimental (red circles) and numerical (solid line with blue circles) dispersion curves at site 2.

The equivalent shear wave velocity within the first 30m is Vs30 = 398 m/s, hence the seismic class is B.

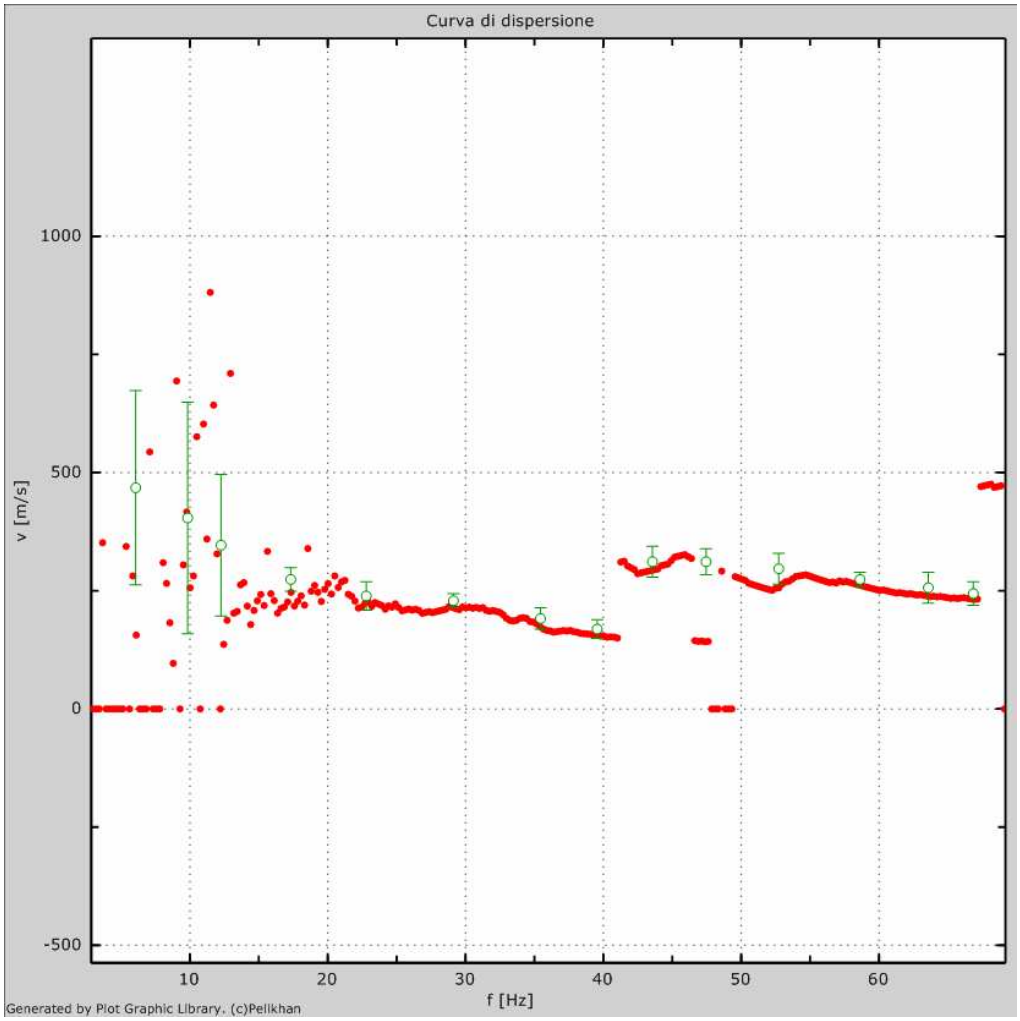


Figure 4.89: Experimental dispersion curve (red points) and selected points (green circles) for site 3.

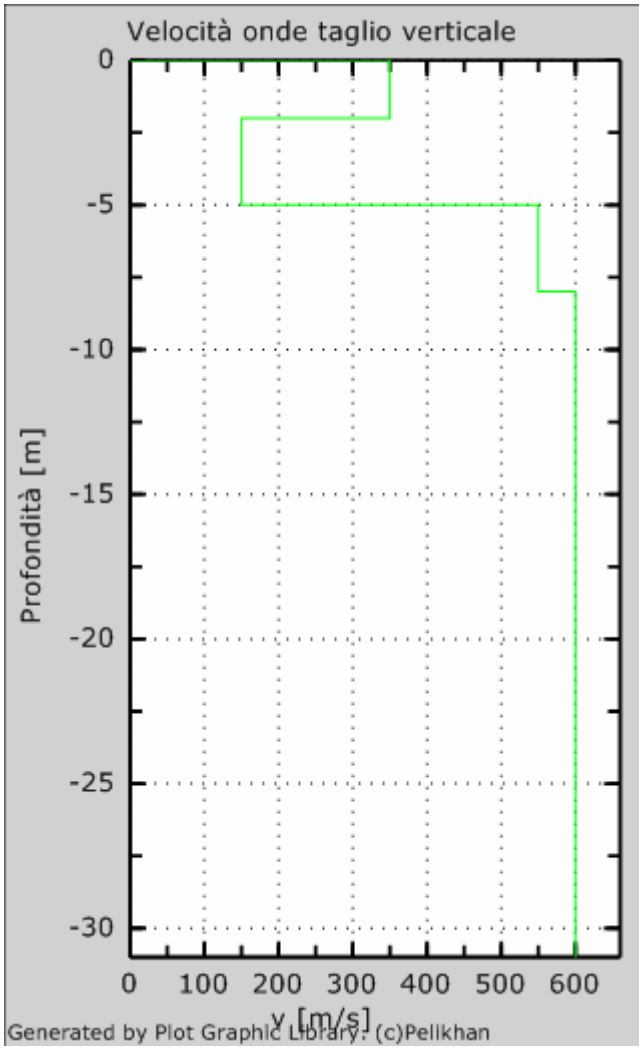


Figure 4.90: : final Vs profile at site 3.

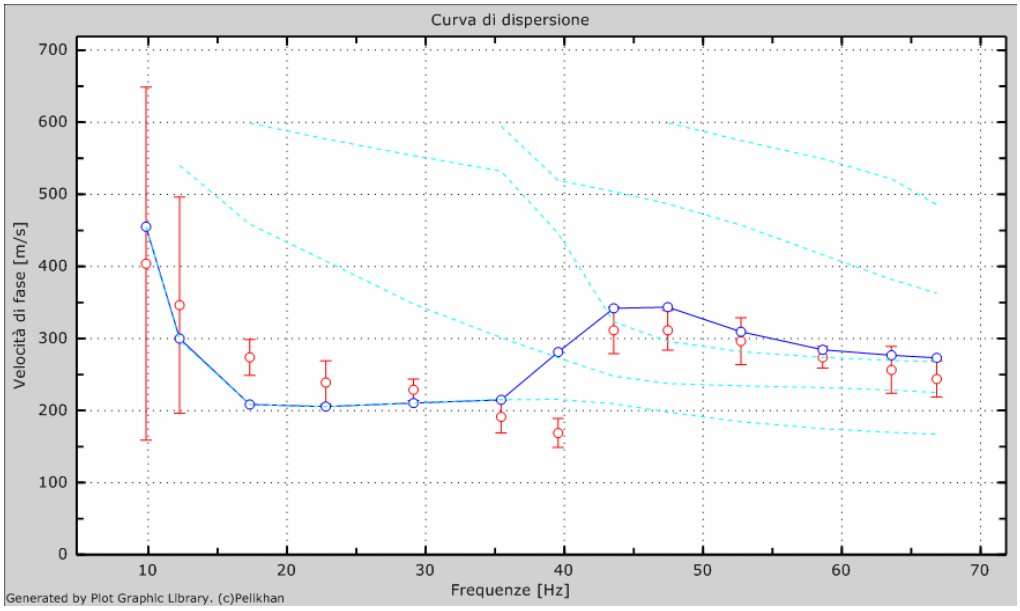


Figure 4.91: comparison between experimental (red circles) and numerical (solid line with blue circles) dispersion curves at site 3.

The equivalent shear wave velocity within the first 30m is Vs30 = 442 m/s, hence the seismic class is B.

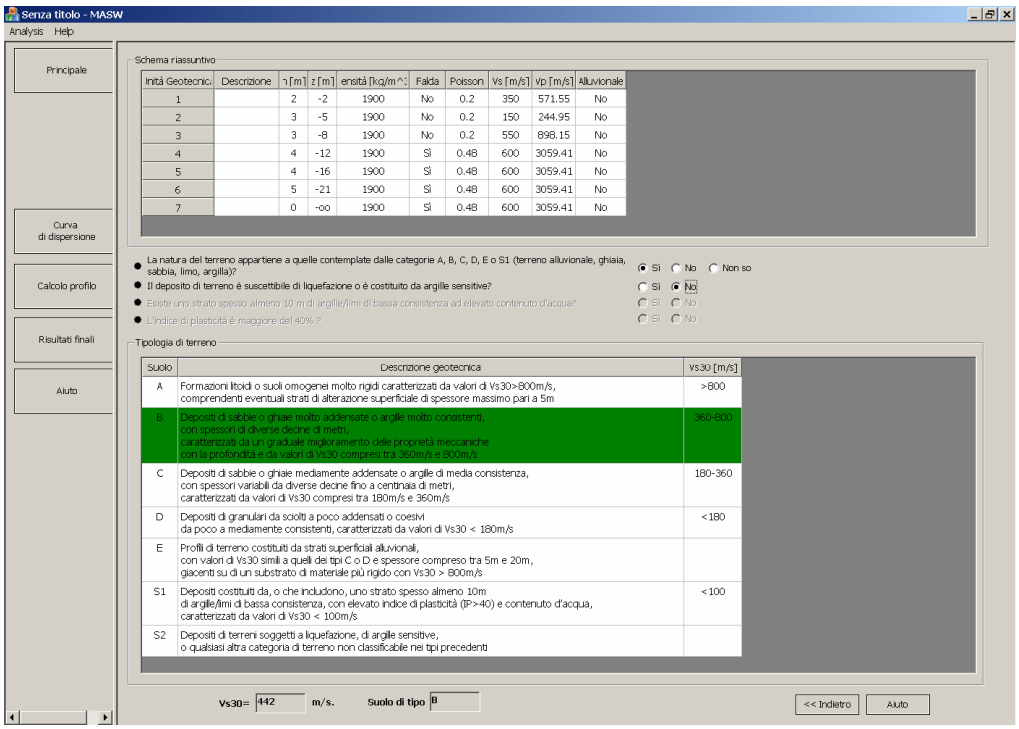


Figure 4.92: seismic classification of the site 3.

4.21 Example 20: Volvera (Torino)

The site is located near Volvera (Torino, Italy) and it is comprised between the two streams Rio Torto and Rio Chisola.

On the basis of the geological information and the laboratori and in situ geotechnical investigations two main geotechnical units can be discerned:

- Geotechnical unit 1 made of sandy silts and clayey silts;
- Geotechnical unit 2 made of sandy gravel and gravelly sand.

The geotechnical parameters of the two units are reported in **table 4.2**.

Table 4.2: parameters of the geotechnical units.

Geotechnical unit	γ	c’	Φ'	E’	Cu
	(kN/m^3)	(kPa)	(°)	(MPa)	(kPa)
Vegetal surficial ground	17	0	26	4-5	-
Sandy silts	19	0	32	10-25	35
Clayey silts	18	0	28	10-15	50
Sandy gravels and gravelly sands	20	0	36	> 50	-

Parameters of acquisition durino MASW test:

number of receivers = 24

span of geophones = 2.0m

time sampling = 2ms

total time of acquisition = 4s.

source: 5kg hammer.

Figure 4.93: Voliera site.

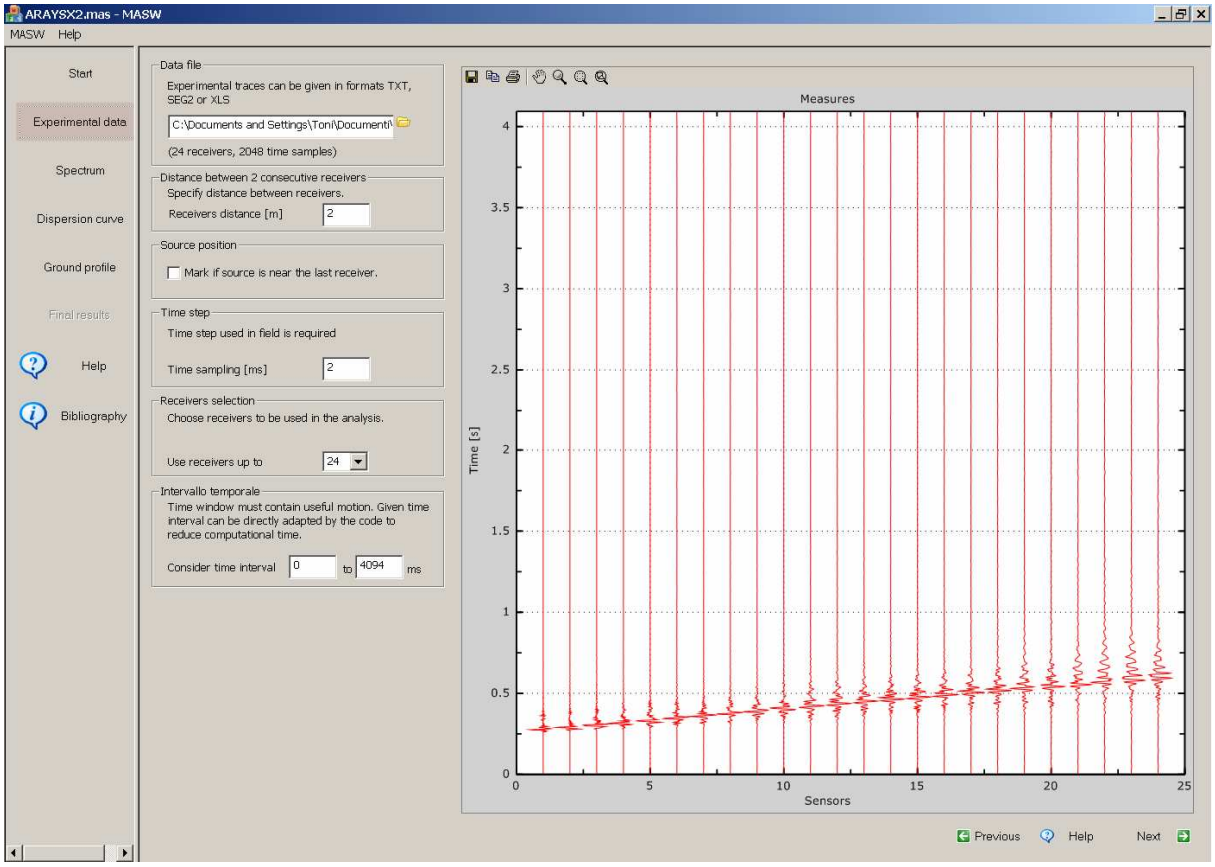


Figure 4.94: measured traces at Volvera.

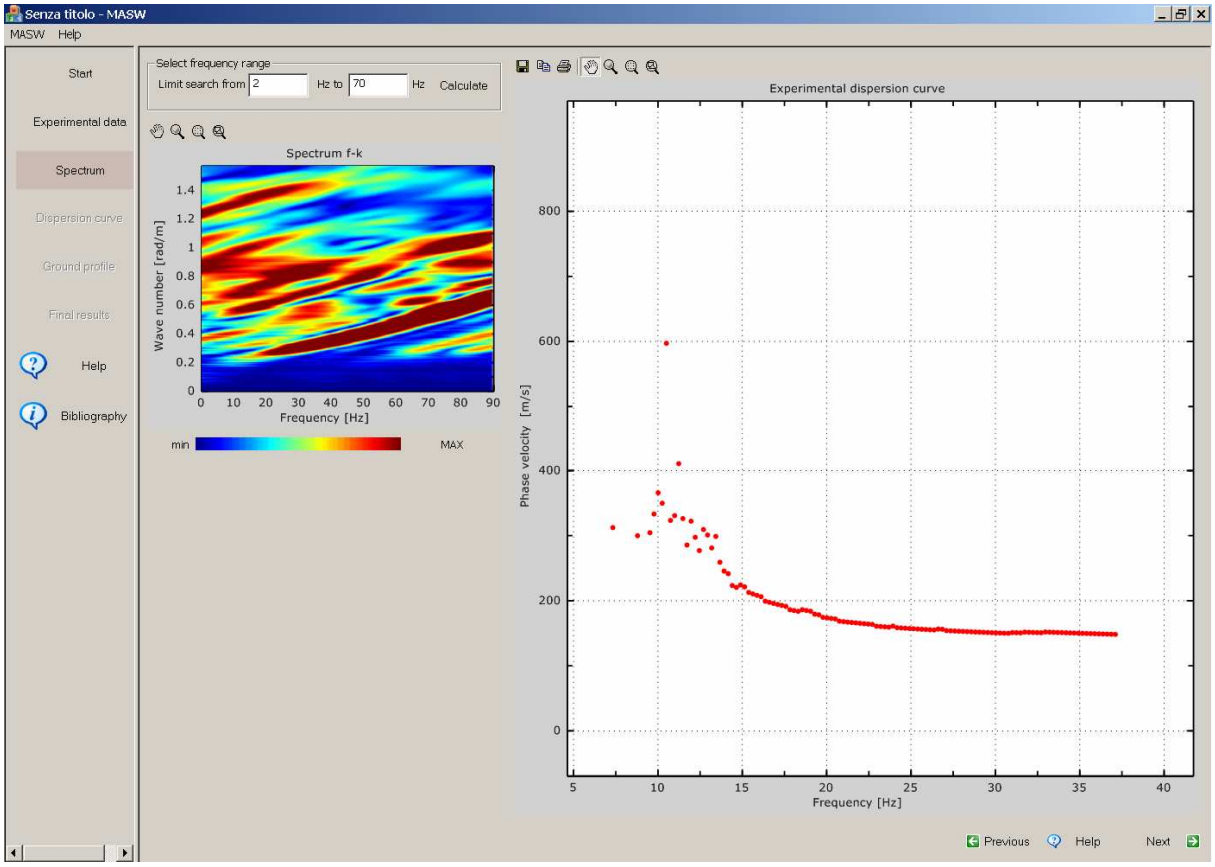


Figure 4.95: f-k spectrum and experimental dispersion curve at Volvera.

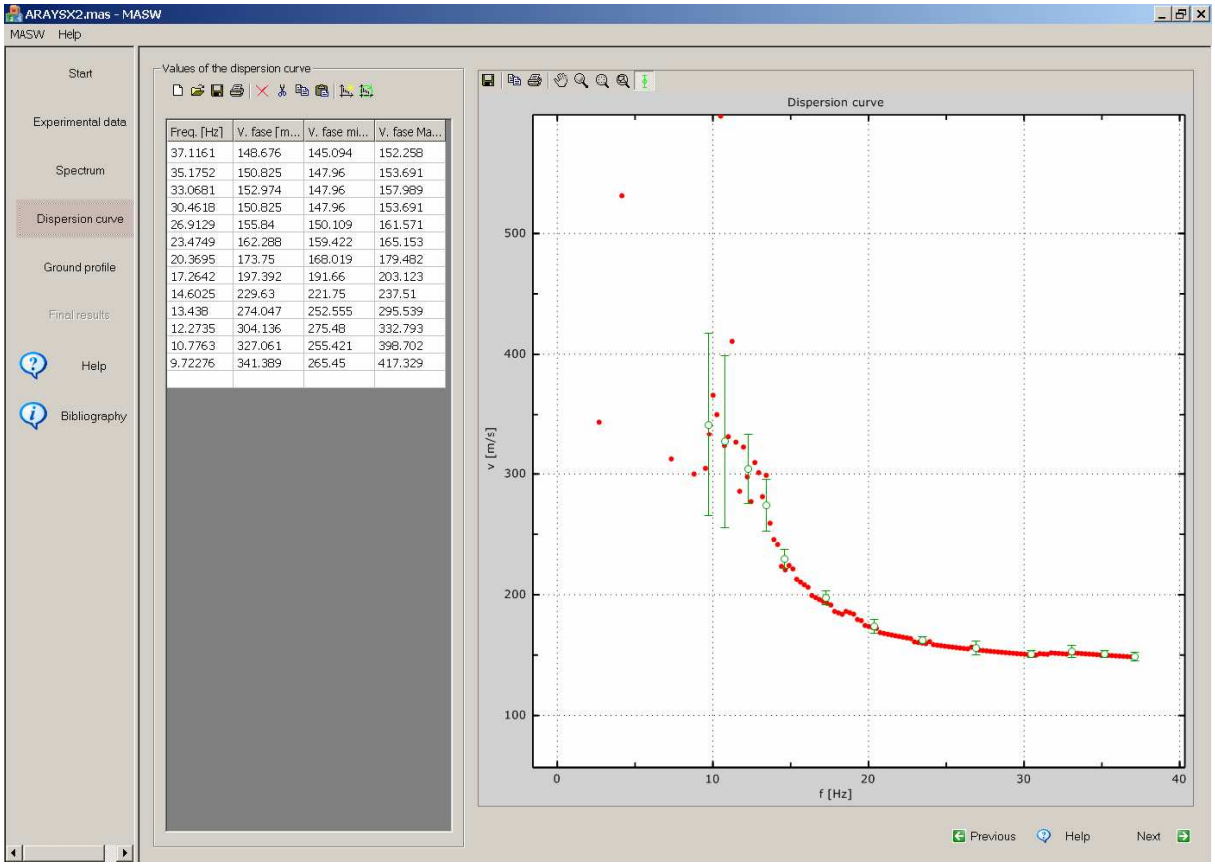


Figure 4.96: Selection of significant points of the experimental dispersion curve to be used for the inversion process.

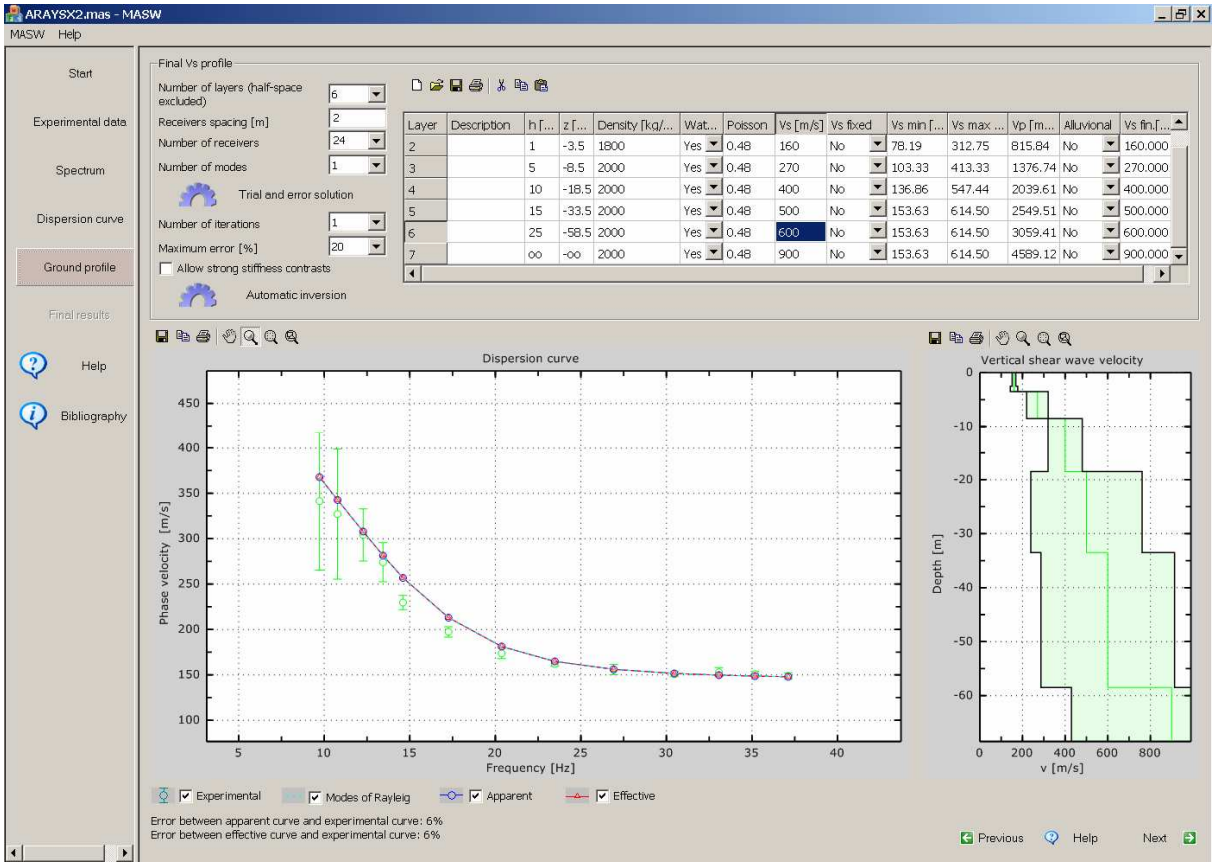
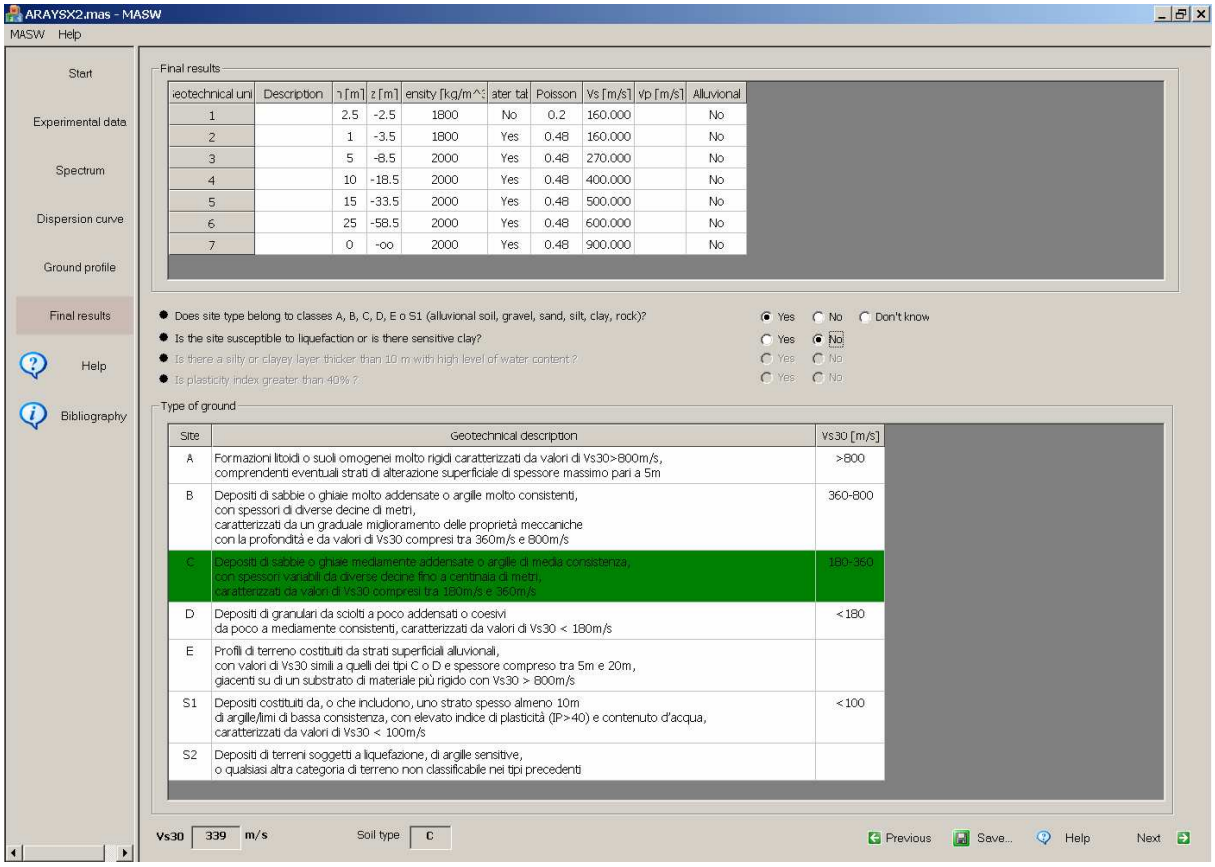


Figure 4.97: final optimal Vs profile.



eotechnical uni	Description	h [m]	z [m]	ensity [kg/m^3	ater tal	Poisson	Vs [m/s]	Vp [m/s]	Alluvional
1		2.5	-2.5	1800	No	0.2	160.000		No
2		1	-3.5	1800	Yes	0.48	160.000		No
3		5	-8.5	2000	Yes	0.48	270.000		No
4		10	-18.5	2000	Yes	0.48	400.000		No
5		15	-33.5	2000	Yes	0.48	500.000		No
6		25	-58.5	2000	Yes	0.48	600.000		No
7		0	-oo	2000	Yes	0.48	900.000		No

Site	Geotechnical description	Vs30 [m/s]
A	Formazioni litoidi o suoli omogenei molto rigidi caratterizzati da valori di Vs30>800m/s, comprendenti eventuali strati di alterazione superficiale di spessore massimo pari a 5m	>800
B	Depositi di sabbie o ghiaie molto addensate o argille molto consistenti, con spessori di diverse decine di metri, caratterizzati da un graduale miglioramento delle proprietà meccaniche con la profondità e da valori di Vs30 compresi tra 360m/s e 800m/s	360-800
C	Depositi di sabbie o ghiaie mediamente addensate o argille di media consistenza, con spessori variabili da diverse decine fino a centinaia di metri, caratterizzati da valori di Vs30 compresi tra 180m/s e 360m/s	180-360
D	Depositi di granulari da sciolti a poco addensati o coesivi da poco a mediamente consistenti, caratterizzati da valori di Vs30 < 180m/s	<180
E	Profili di terreno costituiti da strati superficiali alluvionali, con valori di Vs30 simili a quelli dei tipi C o D e spessore compreso tra 5m e 20m, giacenti su di un substrato di materiale più rigido con Vs30 > 800m/s	
S1	Depositi costituiti da, o che includono, uno strato spesso almeno 10m di argille/limi di bassa consistenza, con elevato indice di plasticità (IP>40) e contenuto d'acqua, caratterizzati da valori di Vs30 < 100m/s	<100
S2	Depositi di terreni soggetti a liquefazione, di argille sensitive, o qualsiasi altra categoria di terreno non classificabile nei tipi precedenti	

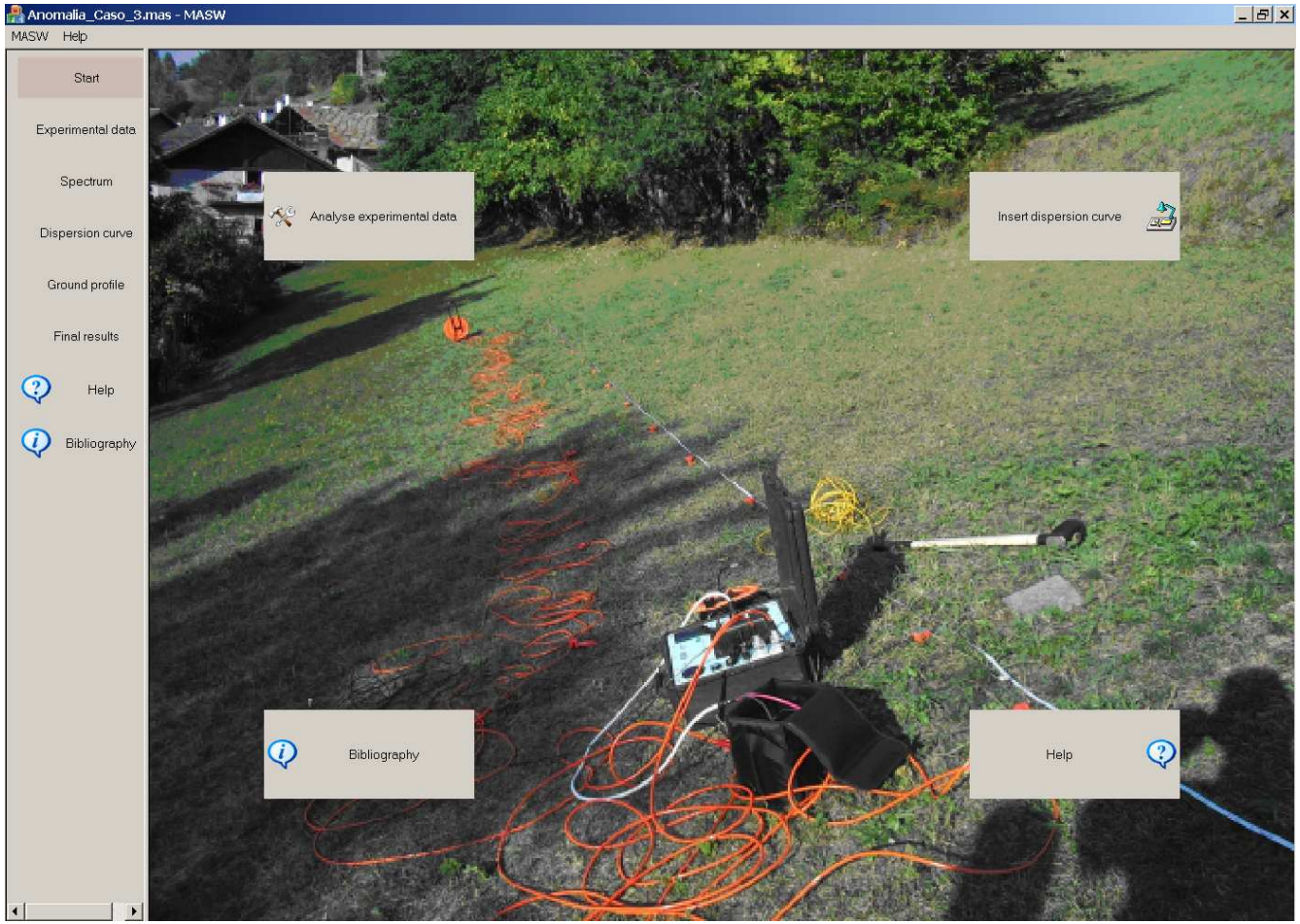
Figure 4.98: seismic classification of the site at Volvera.

The equivalent shear wave velocity within the first 30m is Vs30 = 339 m/s, hence the seismic class is C.

5. CHAPTER 5 : TUTORIAL FOR THE SOFTWARE MASW

5.1 MAIN WINDOW

Figure 5.1: start or main window



In **Figure 5.1** is shown the start window of the software; it is divided into 2 parts.

On the left you can:

move to other previous windows:

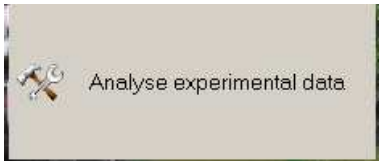
Start	at start you can see only the main window. In the following you can see both the previous and the next windows
Experimental data	this button allows to visualize the window of the measured traces and the acquisition parameters of the in sito test: number of receivers, span between 2 receivers, time sampling, total time of acquisition, position of the source.
Spectrum	this button allows to visualize the window of the f-k spectrum, where you can calcolate the experimental dispersion curve of Rayleigh waves.
Dispersion curve	this button allows to visualize the window of the experimental dispersion curve, where you need to select a limited number of significant points to be used for the inversion process to calcolate the Vs profile
Ground profile	this button allows to visualize the window where you determine the Vs profile of the site
Final results	this button allows to visualize the final window where you determine the type of site based on the Vs profile and the Vs30, according to the Eurocode 8 and the new italian seismic code OPCM 3274

or

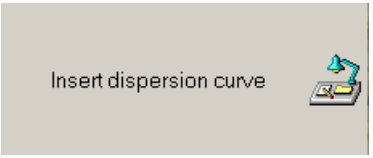
Help	call this tutorial for istructions

see the available bibliography

On the right of the main window you can:

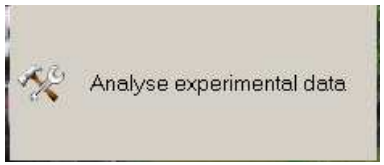


Choose whether to analyse the measured traces to get the experimental dispersion curve



or to input directly the experimental dispersion curve determined by you elseway

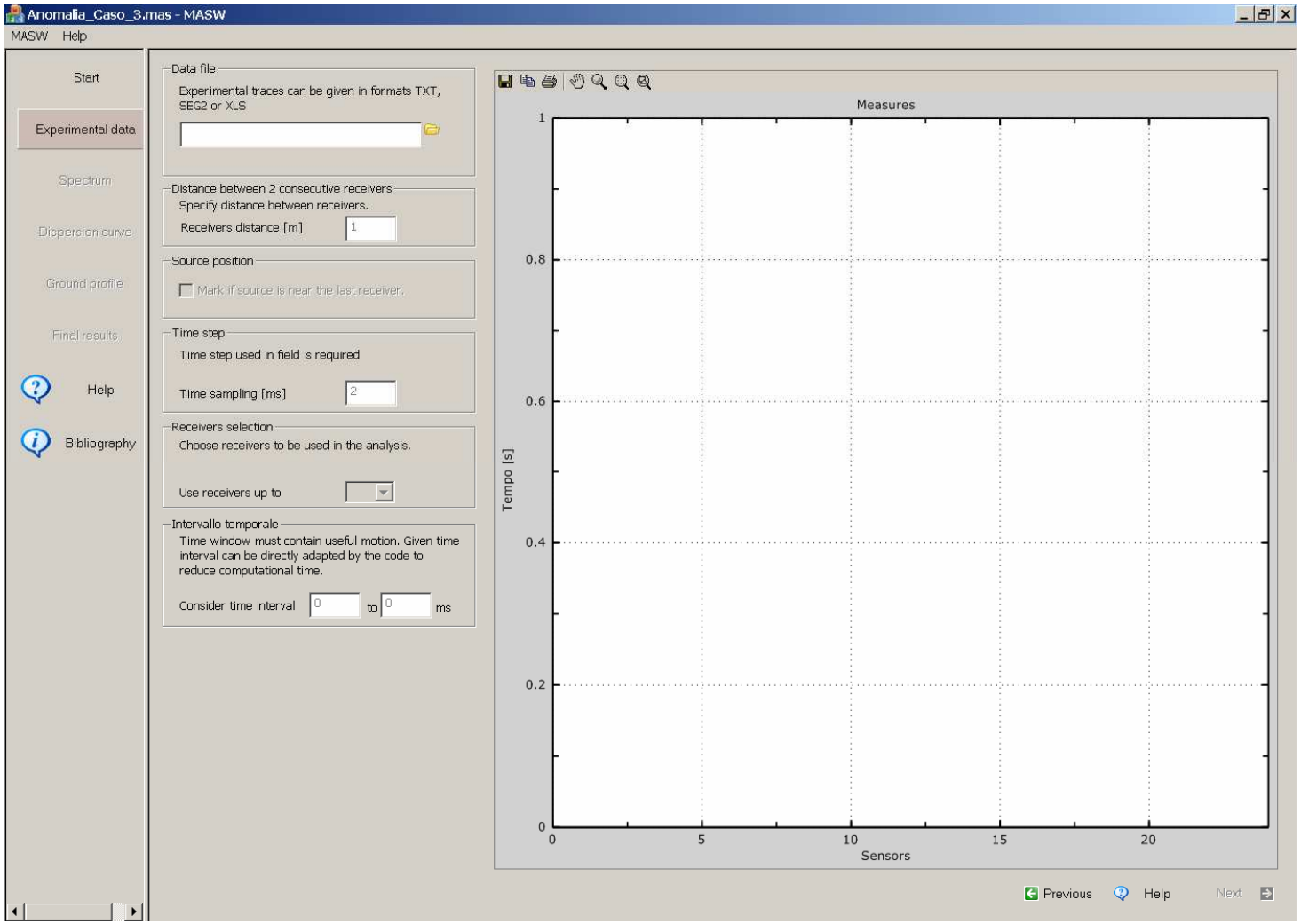
If you choose the option

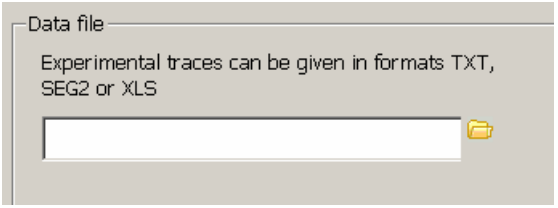


Then the window Analysis of experimental data will appear as in **Figure 5.2**

5.2 WINDOW OF ANALYSIS OF EXPERIMENTAL DATA

Figure 5.2: window Analysis of experimental data





Measured traces must be gathered in format files .txt, xls, SEG2.

By clicking the button the window in **Figure 5.3 appears**, It allows to open the file of the measured traces in field.

The traces measured in field with source placet on the left side of the array of receivers, i.e. near the receiver number 1, look as in **Figure 5.4**. If the source is placet near the last receiver, then the traces appear as in **Figure 5.5**. In this case you need to riverse the traces by clicking on the icon below:

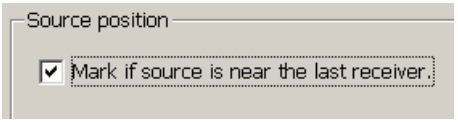


Figure 5.3: window to open the measured traces

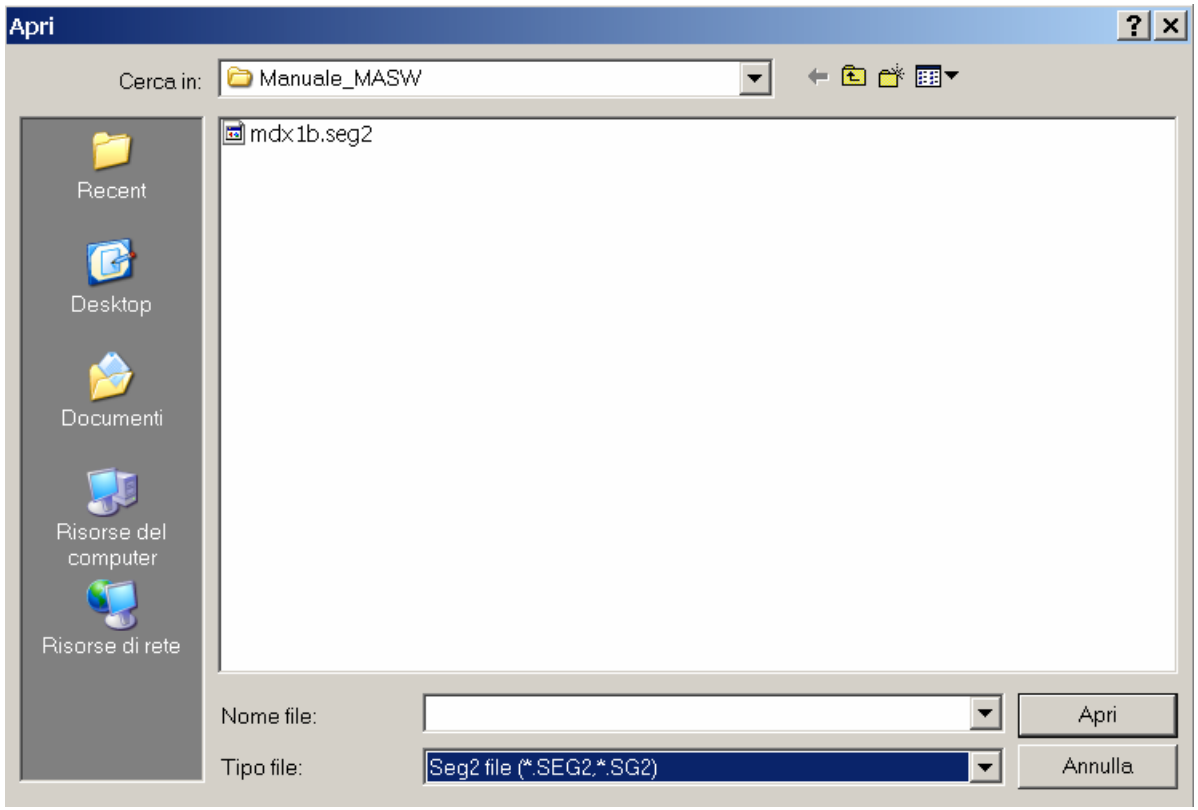


Figure 5.4: window Analysis of experimental data schermata (source near the first receiver)

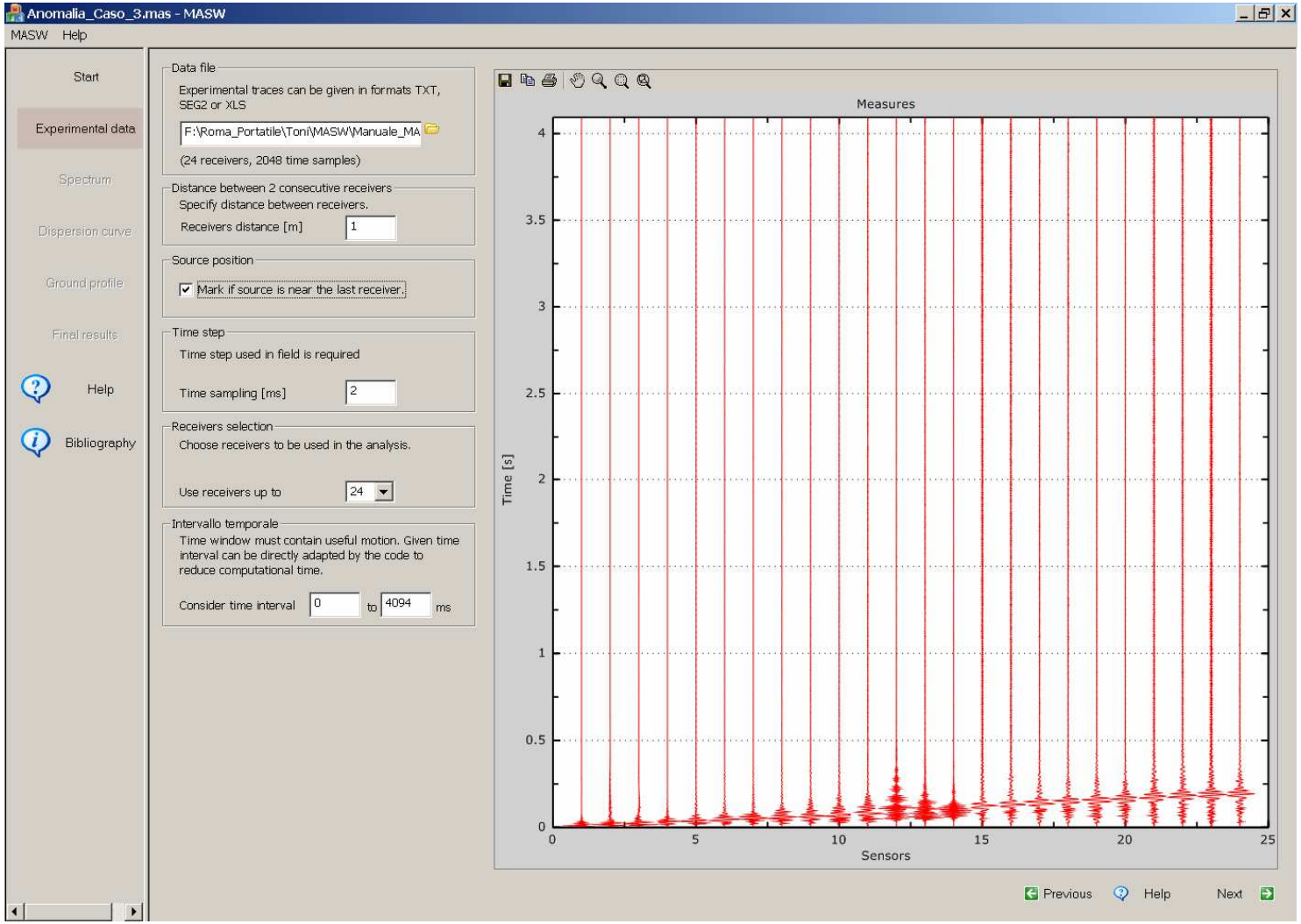
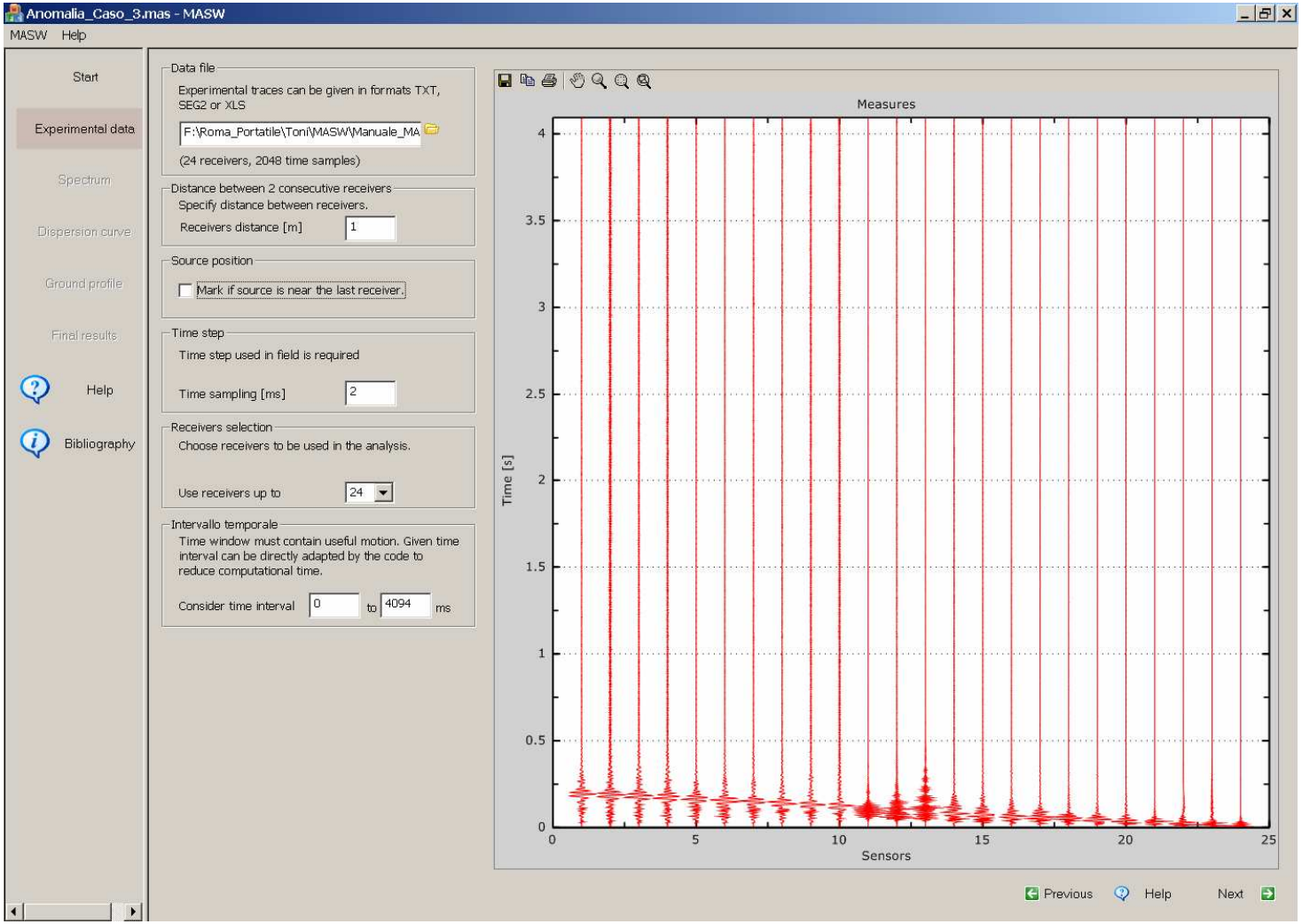
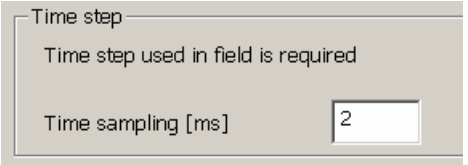


Figure 5.5: window Analysis of experimental data schermata (source near the last receiver)

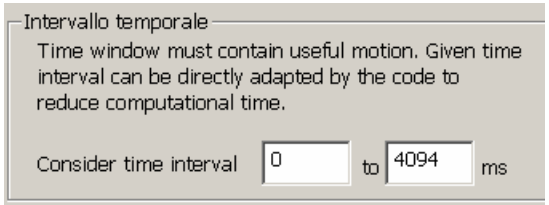


After visualitazion of the measured traces of th in field motion the software requires some information about the spatial array of the in field MASW test.



Specify the span between 2 consecutive receivers. It is suggested to use a constant span among receivers and also between the first receiver and the point source, since the numerical simulation of the MASW test is based on a Fourier transform, which assumes a constant span among receivers and the point source. The choice of the span among receivers influences the range of the available wave numbers k and hence the region of the f-k spectrum which is available. The choice of the span also depends on the total number of available receivers, on the total distance of the ground to be investigated, on the available space in field. Usually it is suggested to use a span among receivers between 0.5m and 3.0m, preferibly 1.5m.

Also the time sampling of the field motion influences the portino of the f-k spectrum which is available. It is recommended to use a time sampling equal to $2 \cdot 10^{-3}$ s.



It may happen that the field motion measured at any receiver be disturbed by noise or other causes or simply it was not turned on during the field test. In theese cases you can discard that unreliable receiver and use the receivers which precede that perticular receiver. Nevertheless the presence of unreliable motion at a couple of receivers does not significantly influence the results of the analysis.

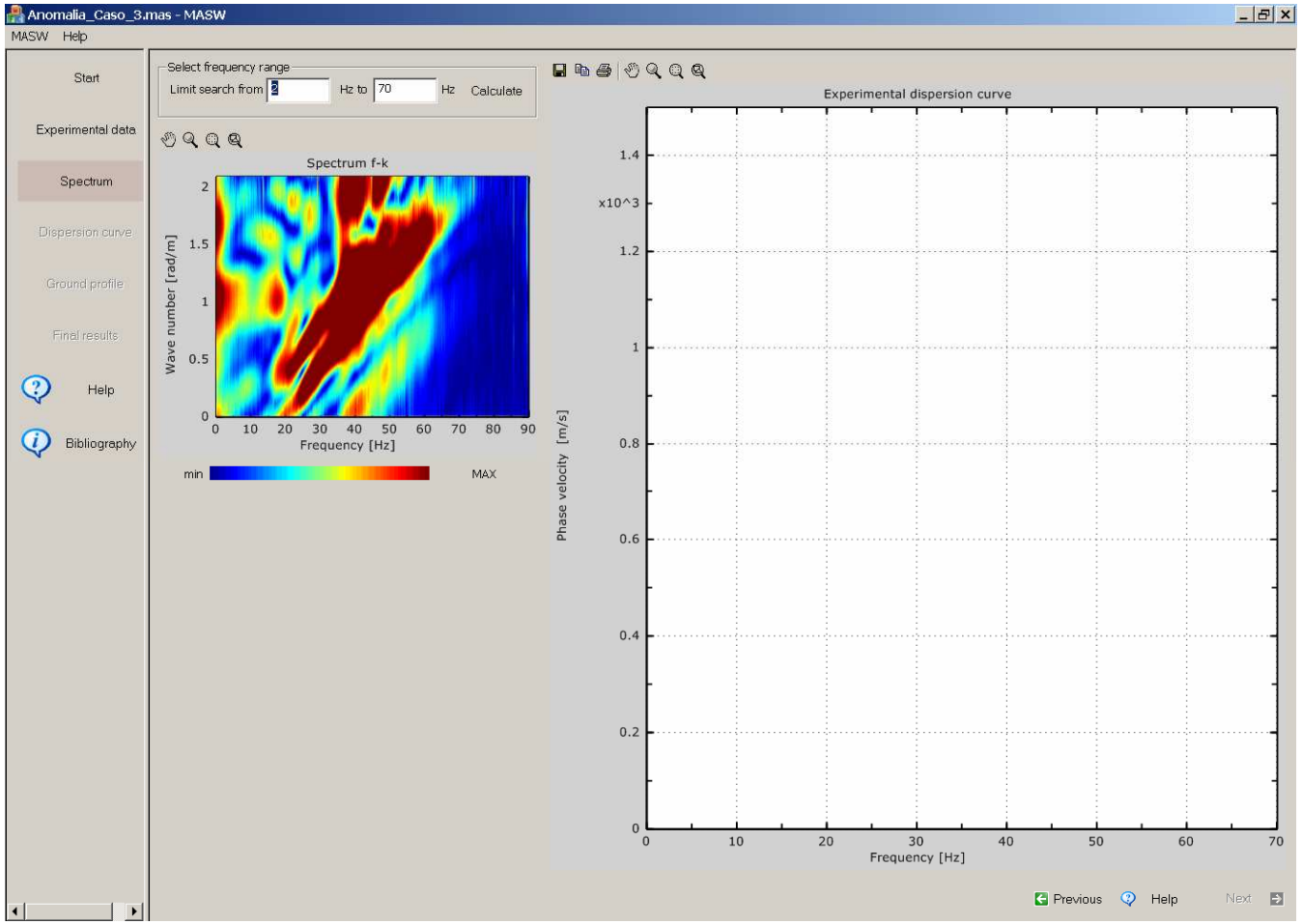
Durino the field test it is suggested to use a total acquisition time of about 4 s. In the analysis the software uses a temporal range between 0 ms and 4094 ms, to improve the frequency resolution of the f-k spectrum.

In the lower right part of the windows there are buttons to change window, to go backward (PREVIOUS) or forward (NEXT) or to call the on line help (HELP).

After inserting the required information on the in fiel MASW test, push the Next button to go ahead. The new window DETERMINATION OF THE EXPERIMENTAL DISPERSION CURVE apeears as reported in **Figura 5.6**.

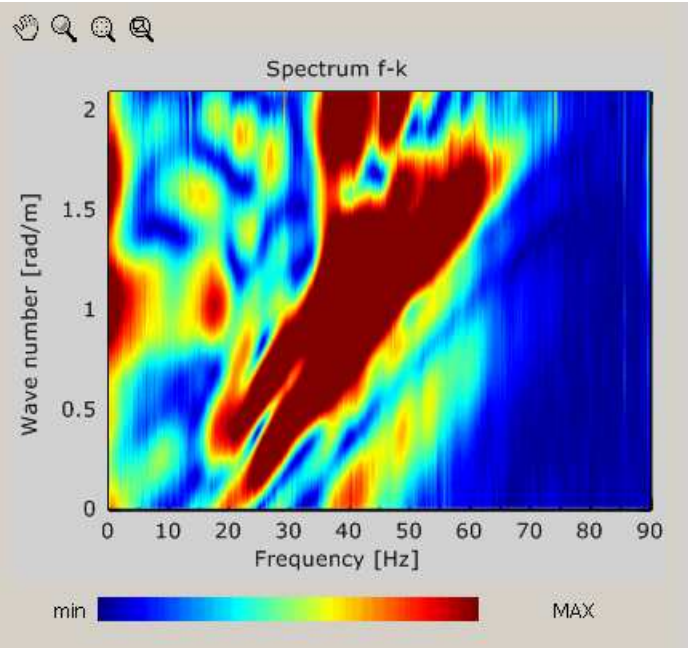
5.3 WINDOW DETERMINATION OF THE EXPERIMENTAL DISPERSION CURVE

Figure 5.6: window schermata DETERMINATION OF THE EXPERIMENTAL DISPERSION CURVE by means of the f-k spectrum and experimental dispersion curve in the domain frequency-phase velocity.



On the left side of the window are plotted the contour lines of the f-k spectrum of the ground duirng travelling of Rayleigh waves (**Figure 5.7**).

Figure 5.7: contour lines of the f-k spectrum of the ground

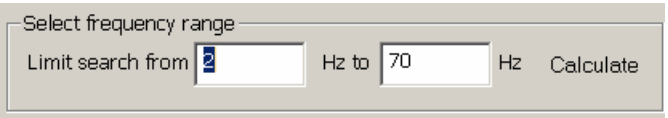


The red regions of the f-k spectrum indicate the crests of the spectrum, the blue regions represent the hills of the spectrum. The crests of the f-k spectrum determine the dispersion relation or dispersion curve of the ground for travelling Rayleigh waves.

Above the f-k spectrum graph there some buttons to manage the graph itself.

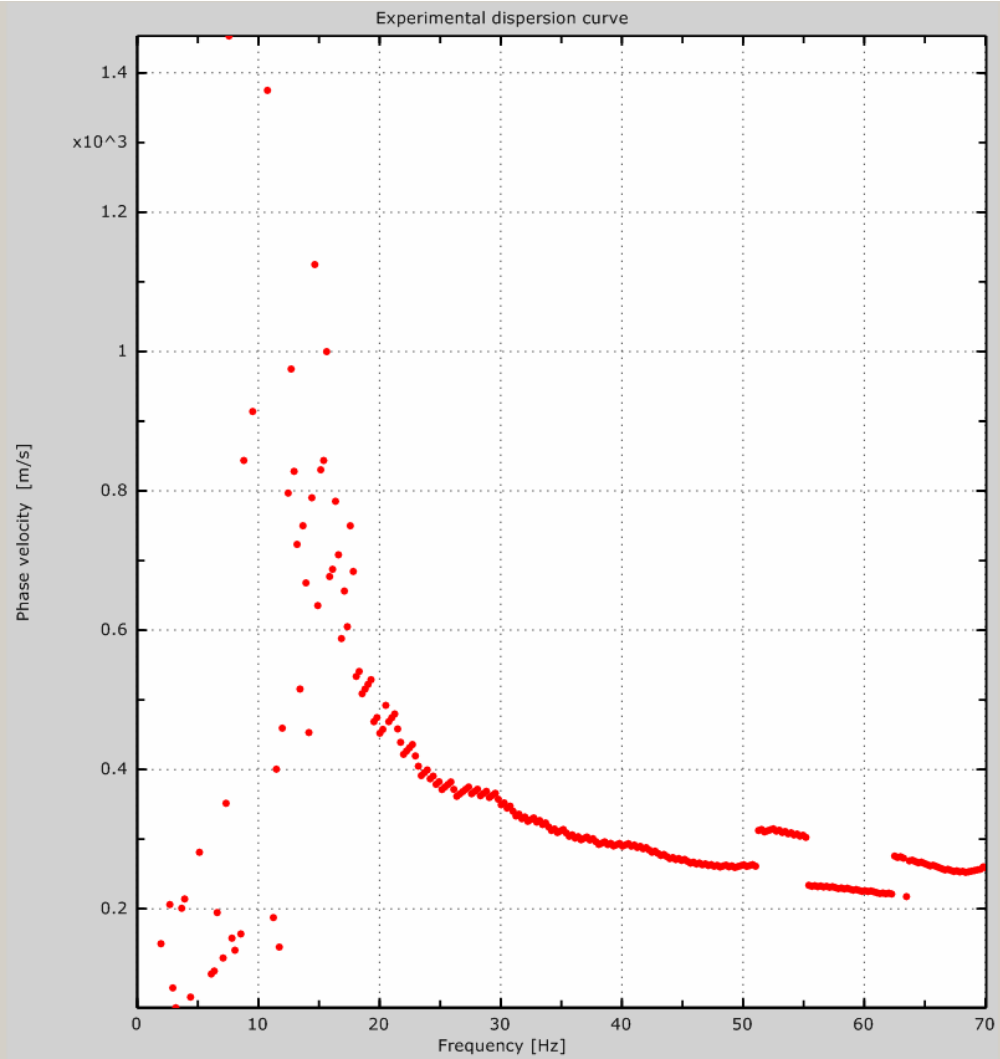
The next step consists of defining the frequency range where to calcolate the experimental dispersion curve.

Generally for usual grounds the frequency range of interest is comprised between 2 Hz and 70 Hz, which are the default values. You can also assign a different frequency range (anyway comprised between 0 Hz and the Nyquest frequency automatically calculated by the software on the basis of the time sampling) by looking at the crests of the f-k spectrum, where the main energy is located. In the case shown in **Figura 5.7** there is a continous crest between 15 Hz and 65 Hz. Anyway the frequency range between 2 Hz and 70 Hz includes the range 15 Hz - 65 Hz.

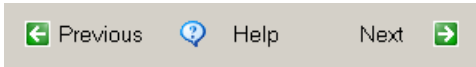


After definition of the frequency range click on the button CALCULATE and after some seconds the experimental dispersion curve will appear as in **Figura 5.8**.

Figure 5.8: experimental dispersion curve bifore selection of significant points.



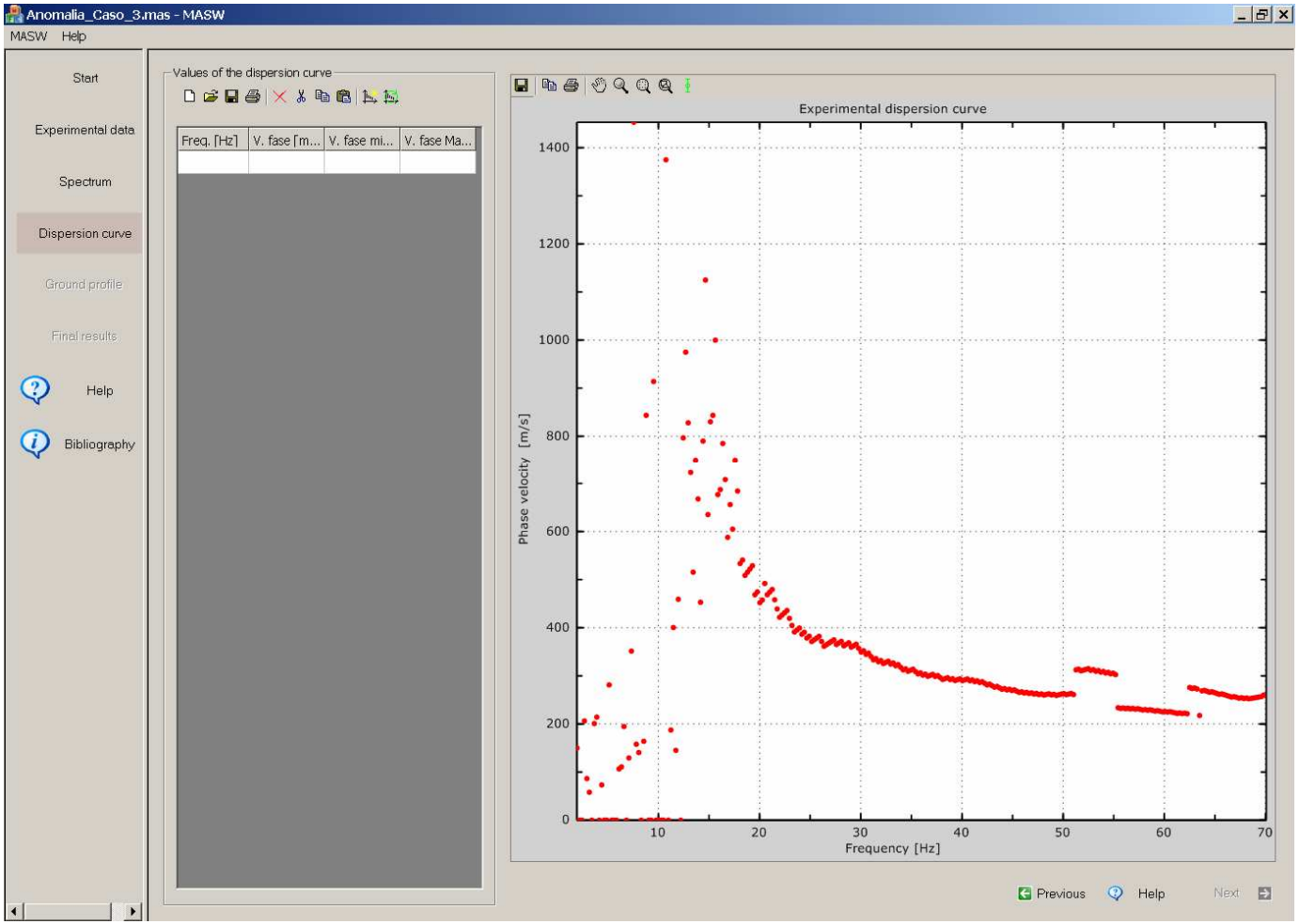
Go ahead pushing the button NEXT



The window in **Figura 5.10** will appear, where you are required to select a limited but significant number of points from the experimental dispersion curve to be used for the successive inverions process to determine the shear wave velocità profile Vs and finally the seismic type of site.

5.4 WINDOW SELECTION OF THE EXPERIMENTAL DISPERSION CURVE

FigurE 5.9: experimental dispersion curve bifore selection of significant points.



In the graph of the experimental dispersion curve bifore selection of significant points in **Figure 5.9** the mein crest of the f-k spectrum are plotted at each frequency. You can notice that:

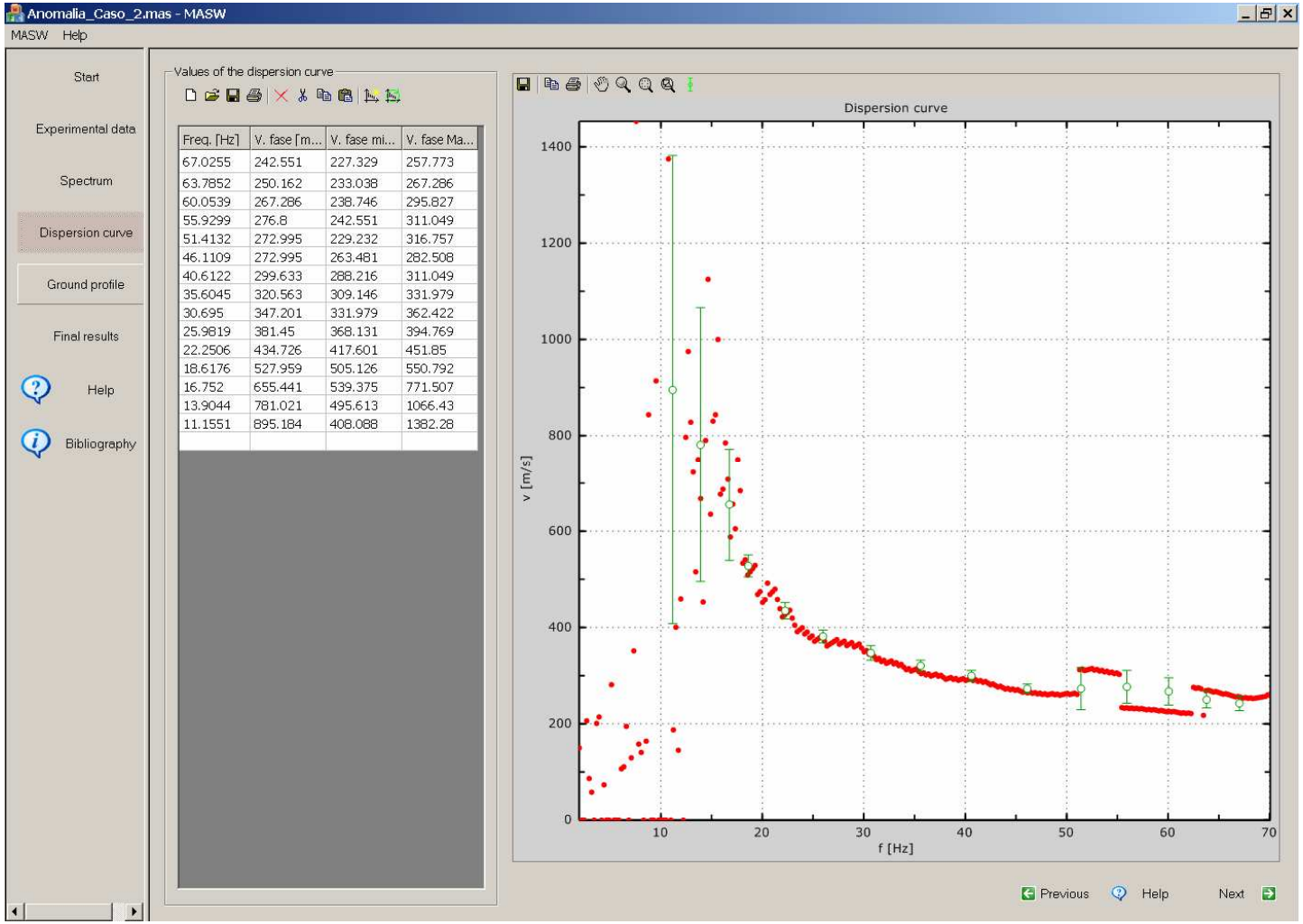
- In the frequency rabge between 20 Hz and 45 Hz the trend of the experimental dispersion curve is well-defined, with a low spread of the points at intermediate frequencies, with respect to high frequencies.
- At low frequencies (<10 Hz) the trend of the experimental dispersion curve is quite spreaded, due to a greater uncertainty of the data.
- At high frequencies (> 50 Hz) there are some discontinuities, probably due to the presence of an alternation of thin soft and rigid layers in the upper part of the ground.

Click the button above the graph of the experimental dispersion curve to select the significant points of the experimental dispersion curve into the graph. You must assign a mean values as well as a lowe and a upper limit of the phase velocty at each frequency. All the information of the selected points are reported on the table on the left side of the window, where you can eliminate any point if you want.

If you click the button the software will automatically make a choice of the significant points, which you can confirm or change.

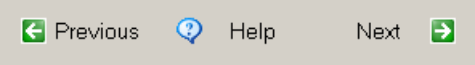
The window will be like in **Figure 5.10**:

Figure 5.10: experimental dispersion curve after selection of limited points.



There are the buttons to save, copy, print, move, zoom, select the points of the experimental dispersion curve.

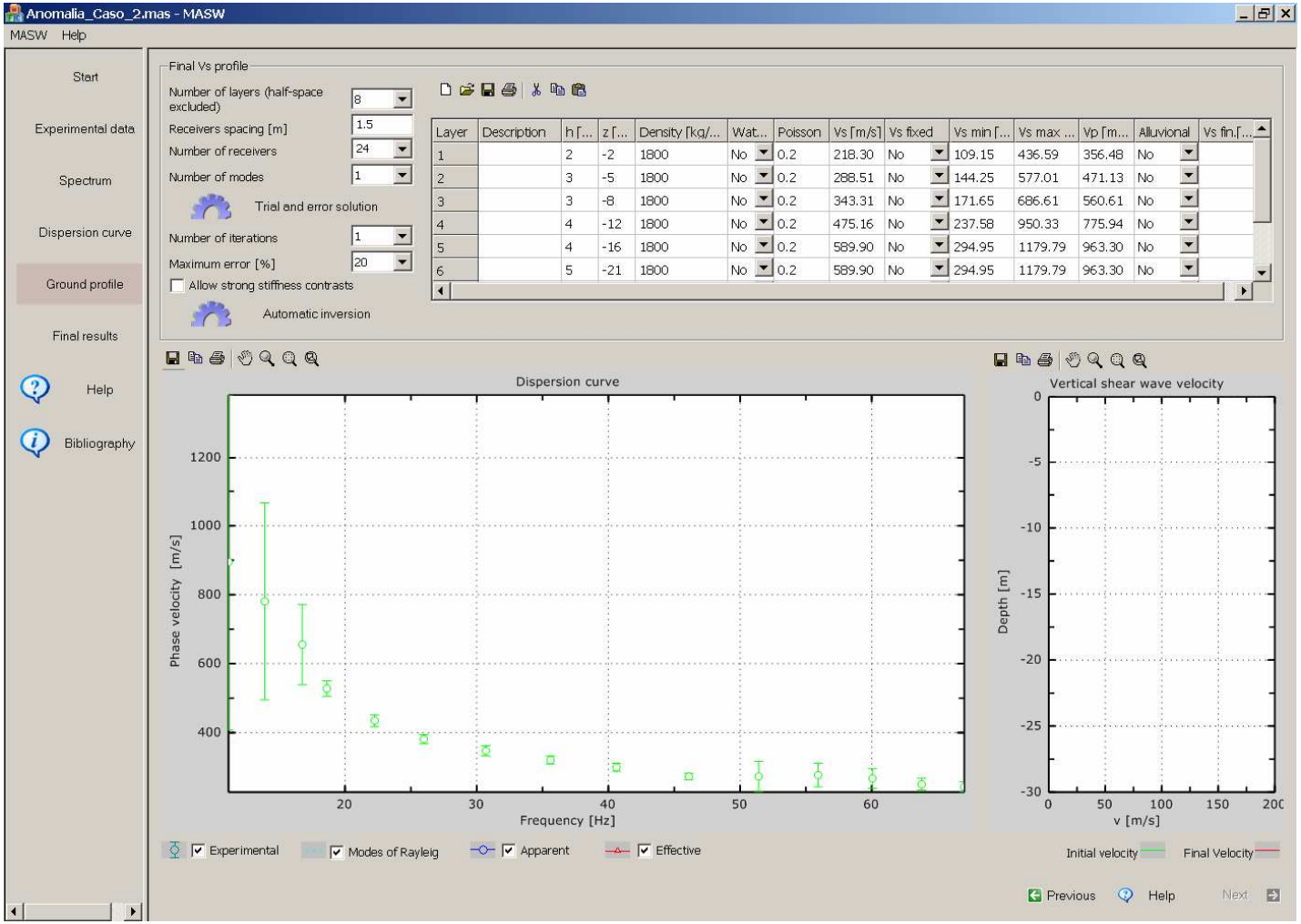
After selection of the points of the experimental dispersion curve go to the successive window DETERMINATION OF THE Vs PROFILE (**Figure 5.11**)



Click the button NEXT below on the right.

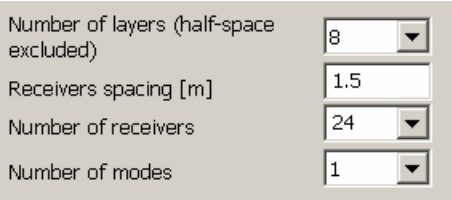
5.5 WINDOW DETERMINATION OF THE Vs PROFILE

Figure 5.11: window determination of the Vs profile



In this window you determine the shear wave velocities and the thicknesses of the layers of the ground.

You are required to introduce some information concerning:



- number of lauers (between 1 and 8, excluded the half-space at the bottom of the gorund); usually 5-7 layers are sufficient to model several types of ground. If you want to reach a very good resolution of Vs profile, then you can use more then 7 layers, up to 8 layers plus the half-space
- the span among receibers used for the in field MASW test
- the total number of receivers
- the total number of Rayleigh modes you want ot use. For normally dispersive grounds the fundamental mode (mode number 1) is sufficient, otherwise for inversely dispersive grounds you need to use 3-5 modes. When dealing with inversely dispersive sites with strong stiffness contrasts, i.e. in presence of a pavimentation, you may need to use up to 10-20 modes of Rayleigh. The software allows to use up to 50 modes of Rayleigh.

After definition of the number of layers you are required to define a trial ground profile, by assignining the thickness h, the mass density, the existence or not of the water table into each layer, the Posson's coefficient (equal to 0.48 for layers under water table), shear wave velocities Vs with lower and upper limits of variation (only for automatic search), existance of any alluvium layer. You can also fix the Vs velocity of any layer durino automatic search.

Figure 5.12: input table of the geotechnical-seismic model of the site

Layer	Description	h [...	z [...	Density [kg/...	Wat...	Poisson	Vs [m/s]	Vs fixed	Vs min [...	Vs max ...	Vp [m...	Alluvional	Vs fin.[...
1	argilla	2	-2	1800	No	0.2	218.30	No	109.15	436.59	356.48	No	
2	limo	3	-5	1800	No	0.2	288.51	No	144.25	577.01	471.13	No	
3	sabbia	3	-8	1800	No	0.2	343.31	No	171.65	686.61	560.61	No	
4	sabbia	4	-12	1800	No	0.2	475.16	No	237.58	950.33	775.94	No	
5	ghiaia	4	-16	1800	No	0.2	589.90	No	294.95	1179.79	963.30	No	
6	ghiaia	5	-21	1800	No	0.2	589.90	No	294.95	1179.79	963.30	No	

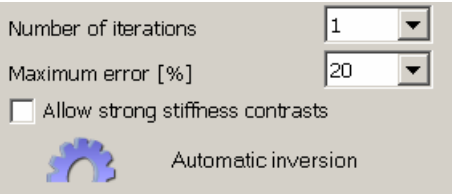
The software assign by default thicknesses, velocities Vs and the other parameters for the trial start model. You can modify the choices of the software.

Usually the most important parameter to search is the shear wave velocity Vs, since the thicknesses and the other parameters can be inferred or determined by other geotechnical methods. Also the shear wave velocity Vs is the parameter that mostly influences the seismic behavior ot the site and hence the Rayleigh dispersion curve. For theese reasons the author has chosen to allow the search of the shear wave velocità Vs rather than the search of the thicknesses h.

You can procede to the search of the Vs profile by a trial and error way or by the automatic search, by clicking the buttons below:

click this button for trial and error search

or



click this button fora n automatic search.

in the case of automatic search you need to define:

- the maximum number of allowed iterations (comprised between 1 and 50)
- the relative error (expressed in percentaige), between the experimental and the numerical dispersion curve, below which the optimal Vs profile has been reached
- whether or not the strong contrasts of stiffness between layers are allowed durino search. The definition of strong contrasts of stiffness is reported in the book at paragraph 2.9.5.

In the automatic search the software also stops the search if the realitve error at the current iteration is greater than the error at the previous iteration.

In the trial and error search you can modify by hand the thichknesses h, the velocities Vs, the densities and the Poisson's coefficients based on your experience or based on your a priori information about the ground.

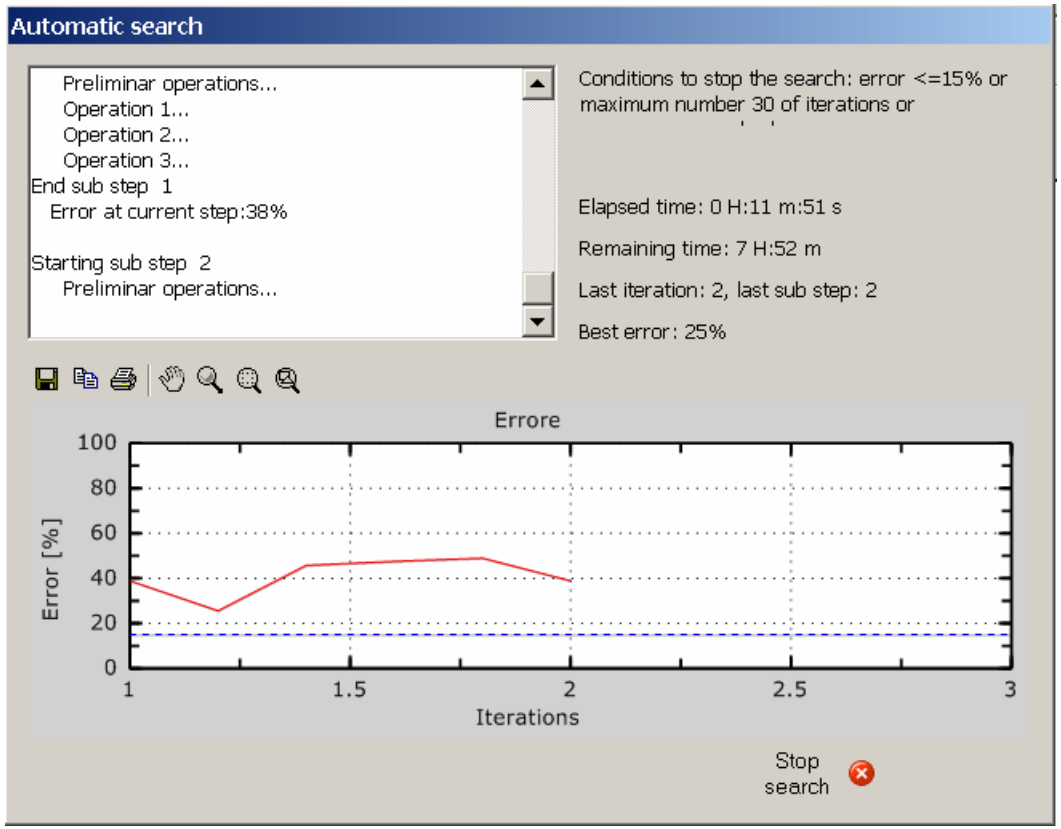
You can compare the match between the experimental and the numerical dispersion curves by means of the relative error or simply by view.

When a satisfactory match is reached between the experimental and the numerical dispersion curves (usually with a relative error less than 10%-15%), then you can say that the Vs profile has been found and you can procede to determine the seismic ground classification.

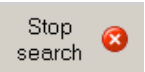
The greater is the number of iterations the greater is the chance to find an optimal Vs profile, which corresponds to a numerical dispersion curve closed to the experimental dispersion curve, wuth a low relative error. Commonly 15 iterations are sufficient to the pur pose.

It is underlined that the ill-posedness of the mathematical problem, at the same conditions (thicknesses, densities, water table position, Poisson's coefficients) the final Vs profile found by the automatic search may depend on the starting trial profile. If you start the automatic search form different trial Vs profiles (at least 3), then you can compare the different results and choose the best match. By the experience of the author, when dealing with normally dispersive sites, in most cases the different Vs profiles are quite similar and determine the same seismic class of ground. Sites with strong stiffness contrasts among layers represent an exception. It is always suggested to improve by hand the match between the experimental and the mnumerical dispersion curves obtained after the automatic search, by slightly modifing the thickness and/or the velocity of any layer.

During the automatic search a window appears to inform you about the steps of the search.



You can stop the automatic search at any time, by clicking the button STOP SEARCH:



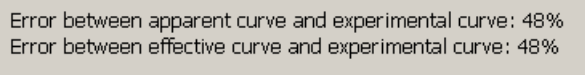
The automatic search stops when on of the following conditions is reached:

1. the relative error between the experimental and the numerical dispersion curves is less than the threshold setted by you

2. the maximum allowed number of iterations assigned by you has been reached
3. the relative error at the current iteration is greater than the error reached at the previous iteration. This criterion derives from the fact that the search algorithm is expected to converge to the best solution at each iteration.

By running the trial and error or the automatic search the software calculates the modes of Raleigh and the apparent numerical dispersion curve associated to the given Vs profile; then both the numerical and the experimental dispersion curve are plotted together as well as the modes of Rayleigh and the relative error is displyed below the figure.

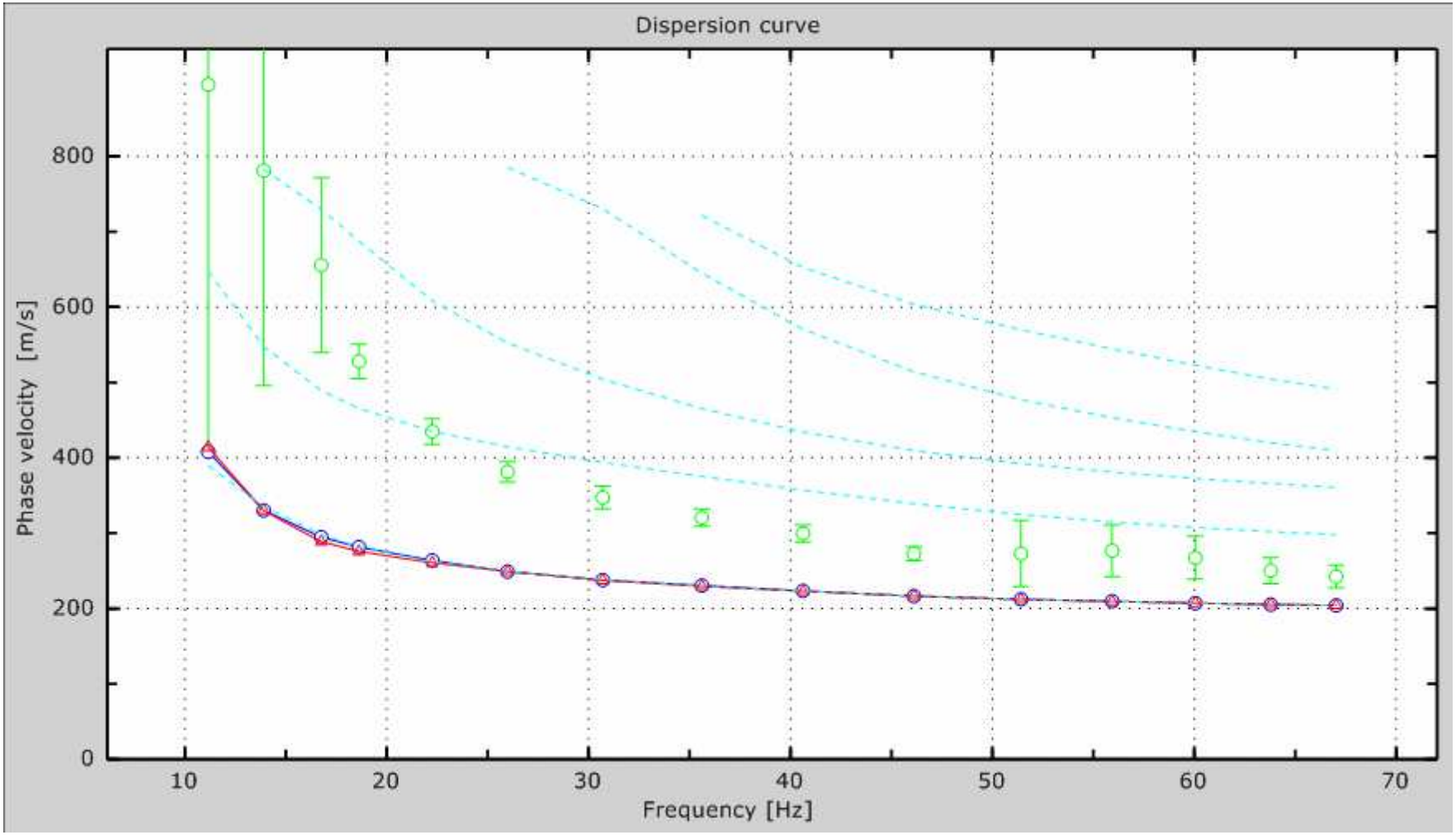
It is underlined that the relative error between the numerical and the experimental curves is calculated with reference to the numerical apparent dispersion curve calculated using the method proposed by Roma (paragraph 2.9.2), and with reference to the numerical effective dispersion curve proposed by Lai and Rix (paragraph 2.9.3).



by clicking into the boxes below

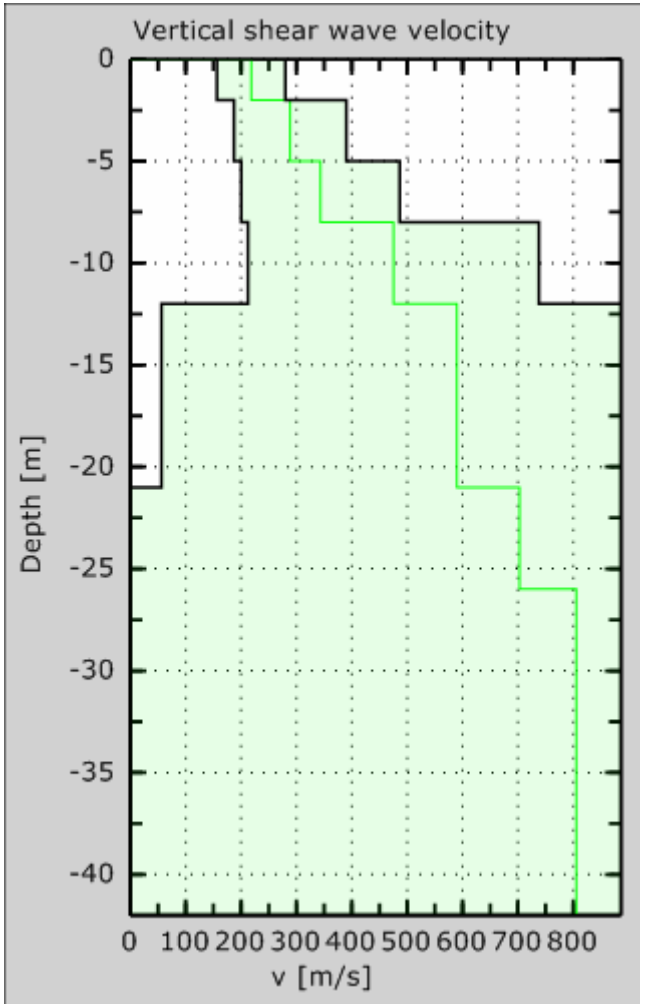
you can plot independently the experimental dispersion curve, the numerical apparent and effective dispersion curves, the modes of Rayleigh.

Figure 5.13: experimental, numerical apparent, numerical effective dispersion curve, modes of Rayleigh



Initial and final Vs profiles are plotted on the right side of the window and reporte in the table above.

Figure 5.14: shear wave velocities profile Vs.



Together with the Vs profile also the uncertainty is plotted by means of a green shadowed zone around the Vs profile.

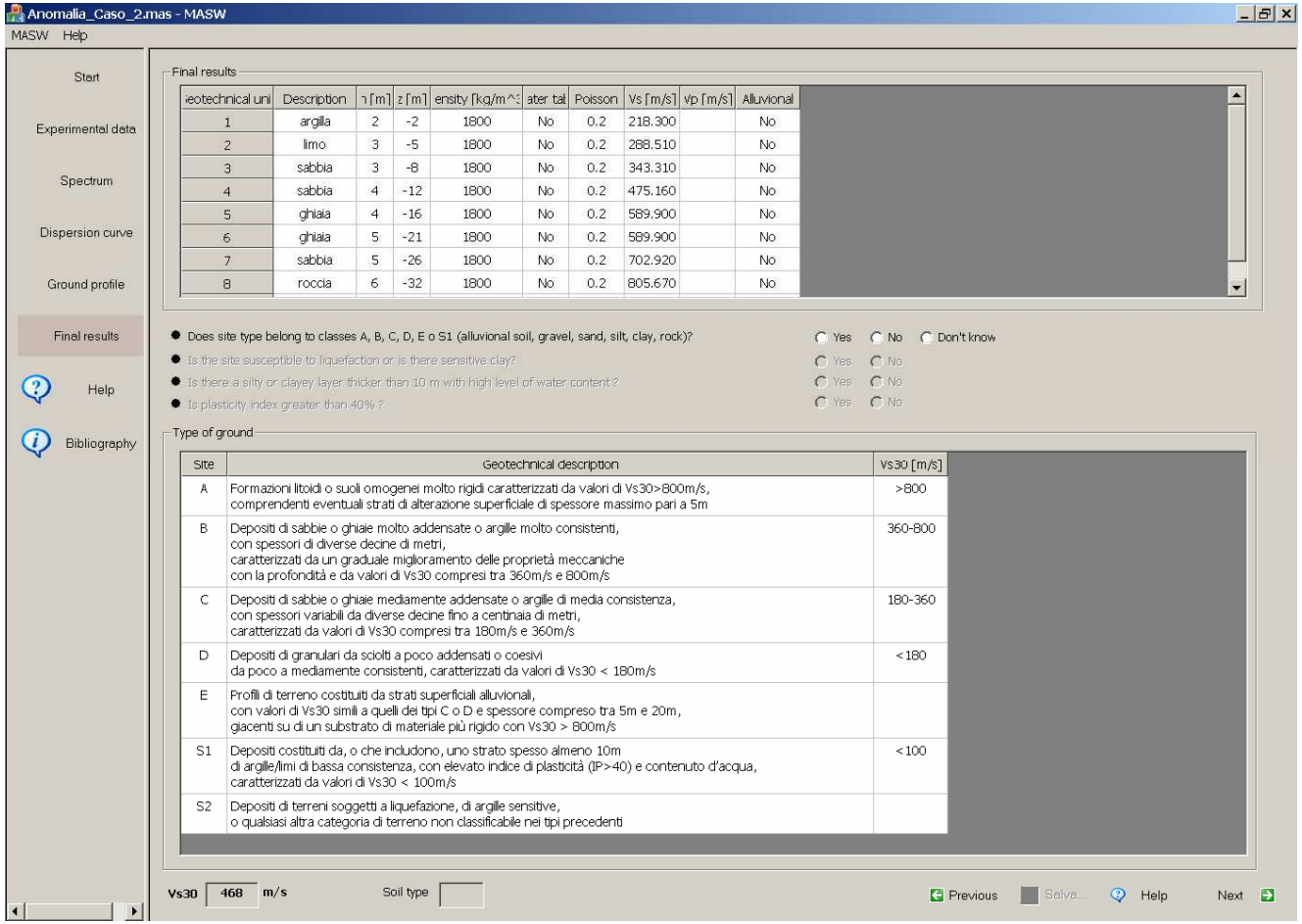
Both the table and the figures cab be copied or plotted using the proper buttons in the window.

After determination of the Vs profile you can go to the final window FINAL RESULTS, by clicking the button NEXT in the rigth low corner of the window.

5.6 WINDOW FINAL RESULTS

The window FINAL RESULTS appears as in **Figure 5.15,** it proposes the table of the final profile of the ground found at the previous window.

Figure 5.15: window FINAL RESULTS



eotechnical uni	Description	ɔ [m]	z [m]	ensity [kg/m^3	ater tal	Poisson	Vs [m/s]	vp [m/s]	Alluvional
1	argilla	2	-2	1800	No	0.2	218.300		No
2	limo	3	-5	1800	No	0.2	288.510		No
3	sabbia	3	-8	1800	No	0.2	343.310		No
4	sabbia	4	-12	1800	No	0.2	475.160		No
5	ghiaia	4	-16	1800	No	0.2	589.900		No
6	ghiaia	5	-21	1800	No	0.2	589.900		No
7	sabbia	5	-26	1800	No	0.2	702.920		No
8	roccia	6	-32	1800	No	0.2	805.670		No

Site	Geotechnical description	Vs30 [m/s]
A	Formazioni litoidi o suoli omogenei molto rigidi caratterizzati da valori di Vs30>800m/s, comprendenti eventuali strati di alterazione superficiale di spessore massimo pari a 5m	>800
B	Depositi di sabbie o ghiaie molto addensate o argille molto consistenti, con spessori di diverse decine di metri, caratterizzati da un graduale miglioramento delle proprietà meccaniche con la profondità e da valori di Vs30 compresi tra 360m/s e 800m/s	360-800
C	Depositi di sabbie o ghiaie mediamente addensate o argille di media consistenza, con spessori variabili da diverse decine fino a centinaia di metri, caratterizzati da valori di Vs30 compresi tra 180m/s e 360m/s	180-360
D	Depositi di granulari da sciolti a poco addensati o coesivi da poco a mediamente consistenti, caratterizzati da valori di Vs30 < 180m/s	<180
E	Profili di terreno costituiti da strati superficiali alluvionali, con valori di Vs30 simili a quelli dei tipi C o D e spessore compreso tra 5m e 20m, giacenti su di un substrato di materiale più rigido con Vs30 > 800m/s	
S1	Depositi costituiti da, o che includono, uno strato spesso almeno 10m di argille/limi di bassa consistenza, con elevato indice di plasticità (IP>40) e contenuto d'acqua, caratterizzati da valori di Vs30 < 100m/s	<100
S2	Depositi di terreni soggetti a liquefazione, di argille sensitive, o qualsiasi altra categoria di terreno non classificabile nei tipi precedenti	

In this window some informations are required about the geotechnical nature of the site, in order to classify the site by a seismical point of view.

The needed information are:

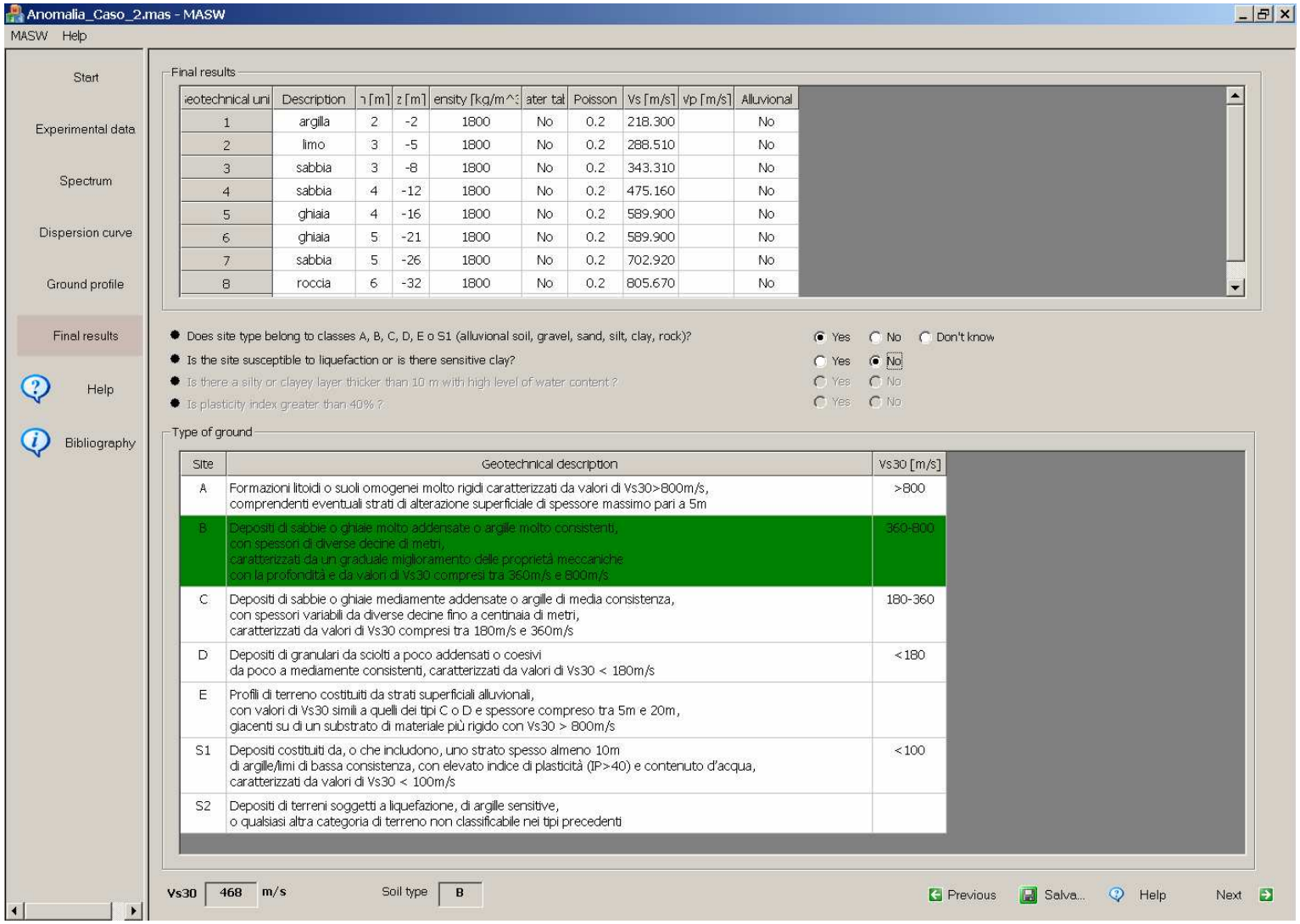
- the geotechnical nature of the ground
- the ground stability, i.e. whether the ground is susceptible to liquefaction or the ground contains any layer of sensitive clay
- presence of low consistent clay or silt with high plasticità index and water content
- Plasticità index IP

The above reported information are the same required by the Eurocode 7 and 8 and by the new italian seismic code OPCM 3274 (2003) in order to define the seismic class of the site, according to the table reported in **Figure 5.15**.

On the basis of the shear wave velocities profile Vs the software calculates the equivalent shear wave velocity Vs30 in the first 30m of the site. By adding the geotechnical information above reported the software determines the seismic calss of the ground according to the Eurocodes 7 and 8 and to the new italian seismic regulation OPCM 3274 del 2003.

The seismic class of the site allows to determine the seismic actions on the structures prescribed by the seismic codes..

Figure 5.16: window FINAL RESULTS



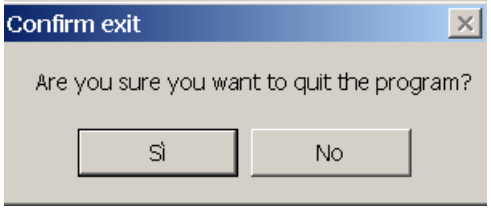
eotechnical uni	Description	ɔ [m]	z [m]	ensity [kg/m^3	ater tal	Poisson	Vs [m/s]	vp [m/s]	Alluvional
1	argilla	2	-2	1800	No	0.2	218.300		No
2	limo	3	-5	1800	No	0.2	288.510		No
3	sabbia	3	-8	1800	No	0.2	343.310		No
4	sabbia	4	-12	1800	No	0.2	475.160		No
5	ghiaia	4	-16	1800	No	0.2	589.900		No
6	ghiaia	5	-21	1800	No	0.2	589.900		No
7	sabbia	5	-26	1800	No	0.2	702.920		No
8	roccia	6	-32	1800	No	0.2	805.670		No

Site	Geotechnical description	Vs30 [m/s]
A	Formazioni litoidi o suoli omogenei molto rigidi caratterizzati da valori di Vs30>800m/s, comprendenti eventuali strati di alterazione superficiale di spessore massimo pari a 5m	>800
B	Depositi di sabbie o ghiaie molto addensate o argille molto consistenti, con spessori di diverse decine di metri, caratterizzati da un graduale miglioramento delle proprietà meccaniche con la profondità e da valori di Vs30 compresi tra 360m/s e 800m/s	360-800
C	Depositi di sabbie o ghiaie mediamente addensate o argille di media consistenza, con spessori variabili da diverse decine fino a centinaia di metri, caratterizzati da valori di Vs30 compresi tra 180m/s e 360m/s	180-360
D	Depositi di granulari da sciolti a poco addensati o coesivi da poco a mediamente consistenti, caratterizzati da valori di Vs30 < 180m/s	<180
E	Profili di terreno costituiti da strati superficiali alluvionali, con valori di Vs30 simili a quelli dei tipi C o D e spessore compreso tra 5m e 20m, giacenti su di un substrato di materiale più rigido con Vs30 > 800m/s	
S1	Depositi costituiti da, o che includono, uno strato spesso almeno 10m di argille/limi di bassa consistenza, con elevato indice di plasticità (IP>40) e contenuto d'acqua, caratterizzati da valori di Vs30 < 100m/s	<100
S2	Depositi di terreni soggetti a liquefazione, di argille sensitive, o qualsiasi altra categoria di terreno non classificabile nei tipi precedenti	

Based on the Vs profile the software calculates the equivalent shear wave velocità Vs30 in the first 30m of the ground and hence the seismic class of the ground.

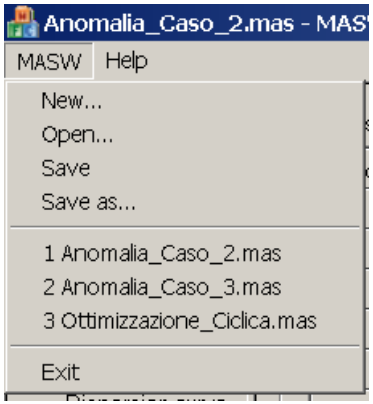
By clicking the button SAVE the software generates a txt file as report where the significant steps of the analysis are reported.

By clicking the button NEXT the software asks a confirmation about exiting.



At every step of the analysis, i.e. at each window you can save the job by cliking the button MASW on the left up corner of the window.

It is suggested to frequently save the job.



You can also come back to the previous windows by using the buttons located on the left side of the window.

6. FINAL CONSIDERATIONS

Even if I have tried to give a simple tool with the aim of divulgate the use of the MASW method, there are some intrinsic difficulties in the use of the MASW method.

The most critical aspects of the proposed MASW method are the choice of the experimental dispersion curve, to be used in the successive steps, and the determination of the final stiffness profile (or equivalently the final shear wave velocities profile Vs), which generates an optimal match between the numerical and the experimental dispersion curves

About the choice of the experimental dispersion curve I have given useful and practical suggestions, also showing how the experimental dispersion curve has been determined in several case histories.

The determination of the final stiffness or Vs profiles is the result of an optimal compromise among a priori information about the site, trial and error search and automatic search. Even if when dealing with normally dispersive sites, with stiffness profiles regular with depth, the automatic search finds a quite valid solution, it is always suggested to modify by hand the Vs profile. By means of this exercise the reader or the user will gain knowledge, experience and sensibility that you will be able to use when dealing with inversely dispersive sites, where not always the automatic search gives a valid solution.

On the basis of the observations made in the Charter 4, which reports the numerical examples and the case histories, the readers have understood that the MASW method requires anyway experience for execution, interpretation and final determination of the seismic class of the ground.

I also know that the proposed method and software refer to the current state of knowledge and that scientific research always procedes. Hence it is not excluded, on the contrary it is auspicated, that the method proposed in this book will be overcomed by the introduction of new techniques or improvements. The proposed software, described in charter 5, allows to separate the experimental part and the inversion process of the MASW method. In this way the user can introduce the experimental dispersion curve calculated by a different manner, for example obtained by the passive MASW method based on ambient noise, or by the active MASW method based on a controlled harmonic source. It is hower underlined that the numerical dispersion curve is calculated by assuming a linear array of receivers, hence it is preferable to adopt the same linear configuration of the receivers in the field test.

Inevitably any errors may be still present in the software, evevn if numerous tests have been peforned. Only with the help of the users will be possibile to consider all the possibile cases and hence eliminate all the errors. I will appreciate the users who will indicate any problems or errors or anomalies whcih they will find using the software.

It is suggested to save the job at each step before procedine, so that it will be easy to find and repair any errors in the software.

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