Love wave analysis for the dynamic characterisation of sites

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ABSTRACT Love waves are surface waves whose dispersive properties can be used to characterise the near surface, for instance for seismic site response assessment. The approach can be very similar to the surface wave method with Rayleigh waves. The general features of the Love Wave Method are described, and the comparison with Rayleigh wave testing is provided. The Love Wave Method can be applied on purposely acquired data, or it can be used to analyse the Love waves in shear wave reflection and refraction data. Some examples are shown to discuss the robustness of the methods, and to show the benefit of a full wave approach in shallow seismic characterisation techniques in order to increase the information extracted from seismograms and the reliability of the results.

1. Introduction

In seismic and geotechnical engineering the dynamic characterisation of the subsoil is of a primary importance: the system to be characterised is a complex natural system whose response to a certain solicitation has to be predicted. The simulation of this response requires first a schematisation of the system and its parameterisation, and then the characterisation, i.e. the determination of the model parameters. The techniques used for the characterisation should then test if the assumed model fits the site under study, estimate the model parameters, and estimate their uncertainty: this depends of course on the physical parameter that is considered.

The shear wave velocity V_S is a parameter of great interest for the analysis of site effects in earthquake engineering but also in static problems at the shallow scale. The determination of the distribution of the stiffness modulus G_0 in the subsoil can be obtained with seismic techniques: seismic waves are generated or simply observed, the characteristics of the propagation are determined, and finally they are used to make inference about the subsoil. The propagation to be analysed should of course depend on the G_0 distribution: the shear wave propagation has traditionally been used, and the SH refraction and reflection have become the most used techniques for such a shallow and high resolution characterisation.

A very interesting alternative for the evaluation of the V_S is the use of surface waves: their propagation indeed mainly depends on the shear modulus. There is a wide variety of surface waves, depending on the source type and position and on the soil property distribution, which have been used for the characterisation: Rayleigh, Love and Lamb waves at a horizontal free surface [for instance Park *et al*. (1999), Mari (1984), Rydén *et al*. (2003), respectively], Scholte waves at the surface under a water layer (Shtievelman, 1999), Stoneley wave in boreholes (Glangeaud *et al*., 1999).

They are all interfacial waves, with a reduced geometric spreading with respect to body waves, they have a limited penetration beyond the surface, they are dispersive, they have a frequency response and resonance, they have modes: what allows them to be used for the characterisation is that their propagation velocity depends mainly on the shear parameters of the materials, and their analysis is made easier by the fact that they are often dominant events in seismic records with source and receivers at the surface.

Even if surface waves have traditionally been considered in seismic exploration as coherent noise, masking the useful signals, nowadays the characterisation techniques based on the analysis of surface waves are widely diffused. Recent and current research work is improving the reliability and robustness of these methods: multistation (McMechan and Yedlin, 1981), multimode (Gabriels *et al*., 1987), velocity and attenuation (Lai, 1998), control of the model (Strobbia and Foti, 2002), uncertainty estimation, joint acquisition with other techniques (Foti *et al*., 2003), joint inversion (Hering *et al*., 1995; Misiek *et al*., 1995), passive measurements with arbitrarily shaped arrays (Okada, 2003) and so on. In these works, pratically only the Rayleigh waves have been considered, but the methods developed are actually more general, and with some additional care in the acquisition of Love waves, they can easily be used for the characterisation.

Their main limit, compared to Rayleigh waves, consists of the risk of not having Love waves at a site: this suggests a joint acquisition with SH refraction and reflection data, which is an interesting approach for an efficient shear-wave prospecting. A strong motivation for analysing of Love waves can be to increase the information that is extracted from the records: when Love waves are present, it is important not to simply throw them away.

In this paper, the general features of the Love Wave Method (LWM) are first described considering the modelling, the acquisition, the processing and the inversion of surface wave data. Then the peculiarity of Love waves and the main differences to Rayleigh waves are stressed, some examples (both successful and not) are shown.

2. General aspects of the LWMs

Surface waves propagate parallel to the free surface and do not spread energy into the body: their penetration is limited in depth, and hence their propagation is influenced by the properties of a limited portion of the medium depending on the wavelength, and hence depending on the frequency. The dependence of the velocity on frequency, called geometric dispersion, is the principle on which Surface Wave Methods (SWMs) are based: the properties of different layers are identified analysing the propagation of different frequencies. The vertical variation of the shear velocity is the usual target, but also lateral heterogeneity can be investigated: for example, Love wave dispersion has been analysed for the static correction of the shear wave profile (Mari, 1984), but also to detect the lateral variation in unconsolidated near surface sediments at the seabed (Winsborrow *et al*., 2003).

In general, the SWM consists of three steps: acquisition, processing and inversion. Fig. 1 shows these steps of a real example where the Love wave dispersion is used to estimate the soil profile down to 15 metres. The acquisition consists in gathering raw seismic data containing surface waves in an adequately wide frequency band, the processing consists of estimating the characteristics of the propagation (velocity vs. frequency) from raw data, the inversion estimates the soil model parameters from the surface wave propagation characteristics. The last step can be solved through different approaches, that are all based on a forward modelling algorithm that simulates the propagation, given a known soil model.

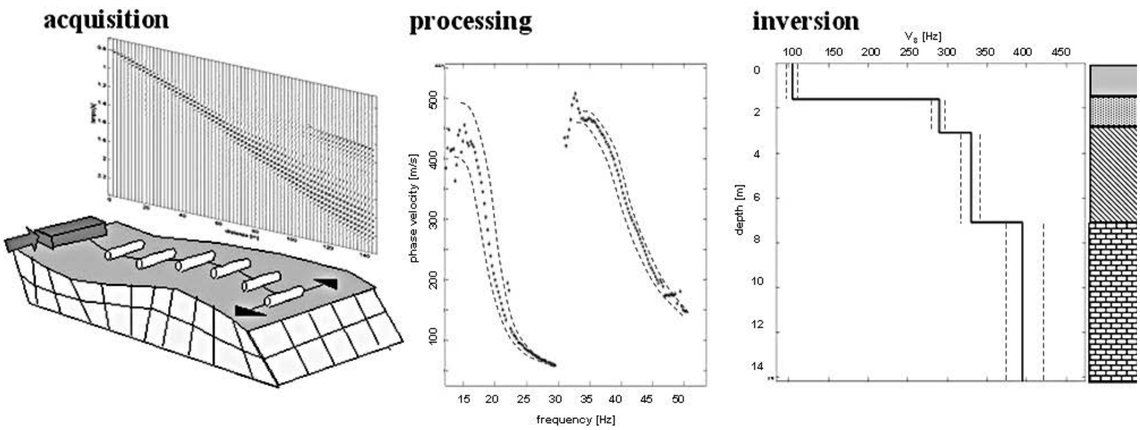


Fig. 1 - The three steps of the LWM over a real data set.

This approach is quite general (Socco and Strobbia, 2004), and applies to different kinds of surface waves: the features of the different steps have to be designed according to the target and the kind of wave that is used.

3. Modelling

The modelling should reproduce, synthetically, the result of the experimental testing procedure, that is the characteristic of the propagation that is used to make the inference about the subsoil: to achieve this task all the parameters influencing the experimental result have to be taken into account within the modelling.

Assuming a linear elastic or a linear viscoelastic material, the solution can be found in layered media, for instance with the propagator matrix approach (Gilbert and Backus, 1966). The distortional and compressional potentials can be written in each layer, then the continuity at the layer interfaces is imposed, and the single layer matrices are multiplied to obtain a global matrix equation where the boundary conditions (stress free surface and zero action at infinity) can be imposed. An eigenvalue problem is obtained: a non trivial solution exists only for special values of the wavenumber at each frequency; i.e. only special velocities exist at each frequency (Aki and Richards, 2003). The main difference between Love and Rayleigh waves is that for the former only SH displacement potential is needed, while for the latter P and SV potential are used: Love wave displacement is indeed pure shear perpendicular to the direction of propagation.

The modal curves (Fig. 2a) are the kinematic condition of the eigenvalues, hence the possible velocities at each frequency: after computing the modal curves, the eigenfunctions are computed (stress and displacement with depth, Fig. 2b), and Green's function is introduced for the source used. The energy distribution along the modal curves, for a record gathered at the free surface, can hence be computed. This is an essential point of the modelling, useful to define the sensitivity to certain target and the investigation depth, and to analyse the several aspects of the propagation

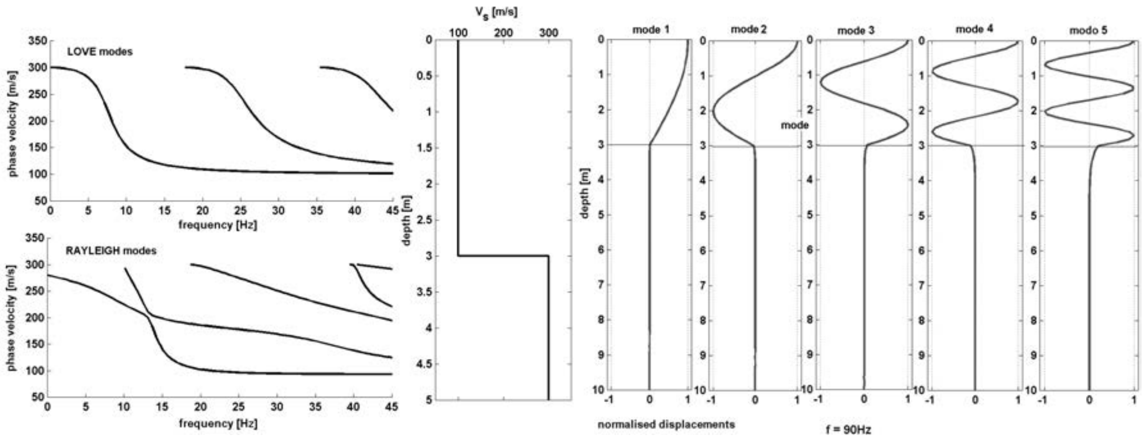


Fig. 2 - For a simple 2 layer model the modal curves of both Rayleigh and Love waves are computed (left) and the displacements with depth at a single frequency for the first 5 Love modes (right).

besides the velocity. The knowledge of the distribution of the stress and displacement vs. depth, frequency and mode, and the effects at the free surface, are necessary to identify the possible resonance of a shallow layer, the high pass-filter performed by certain sites, the possibility of dominance of higher modes. A complete modelling can even allow us to interpret the absence of information as useful information: when, for instance, energy is limited in a frequency band, this is probably due to a strong impedance contrast.

In the frequency-phase, velocity plane, the kinematic description of the propagation consists simply of the modal curve: the energy can however be concentrated on a single mode, often the first, and in a narrow frequency range. An experimental example, in the f-k domain, is depicted later in Fig. 6.

The most interesting aspect is that Love waves can be explained through the constructive interference between multiple reflections, and this can happen under special stratigraphic conditions: Love waves can exist only in certain cases, and velocity inversion on a first layer is critical.

Of great importance is the effect of the observation layout: in theory, the propagating energy should be located exactly on modes, and the ideal f-k spectrum should have spikes on the wavenumbers. In a real observation this is not possible because of the energy spreading due to the finite length of the array (Foti *et al*., 2002): especially with Rayleigh waves, the energy spread by different modes can be superimposed and create fictitious maxima in the spectrum not corresponding to actual modal curves. The mode superposition resulting in an apparent dispersion curve is one of the main difficulties in Rayleigh wave data interpretation, while this effect is less critical with Love waves.

4. Acquisition

Acquiring surface waves means gathering, in space and time, the maximum of information about the surface waves propagation: the identification of surface waves and the estimate of their properties is possible, for example, in full wave form seismic active records.

In active methods, a source and a linear array are deployed on the ground: even if two receivers are sufficient to compute the velocity, a higher number of receivers can be proven to reduce the uncertainty of the estimate. A multi-station acquisition is more stable and robust, it allows us to identify the presence of several modes, to filter data in order to enhance the surface wave contribution, to check the presence of lateral variations and near field effects.

The high quality of the information is another important issue: surface waves often appear as dominating events in seismic records, but the evaluation of the signal-to-noise ratio (S/N) is not straightforward in the time domain, because of the possible resonance of the site: a high S/N has to be obtained in the whole frequency range of interest, and this can be evaluated with a spectral statistical analysis of data. In general, to avoid the attenuation and the phase distortion of geophones below their natural frequency, low-frequency geophones should be used.

The particle displacement of the Rayleigh wave has a strong vertical component at the free surface, and hence the acquisition of Rayleigh waves is straightforward with common seismic equipment with vertical source and receivers. On the other hand, the Love wave displacement is horizontal and parallel to the direction of propagation: the source has to produce a horizontal component, and the receivers should record the horizontal cross-line displacement. The acquisition has hence to be performed with the same care used in SH wave refraction or reflection acquisition (Deidda and Balia, 2001): the polarity of the source is reversed and data are subtracted to enhance the S component and attenuate the P component. An efficient alternative is the use of special receivers that perform the synchronous by stacking electrically [Swyphones receivers (Sambuelli *et al.*, 2001)].

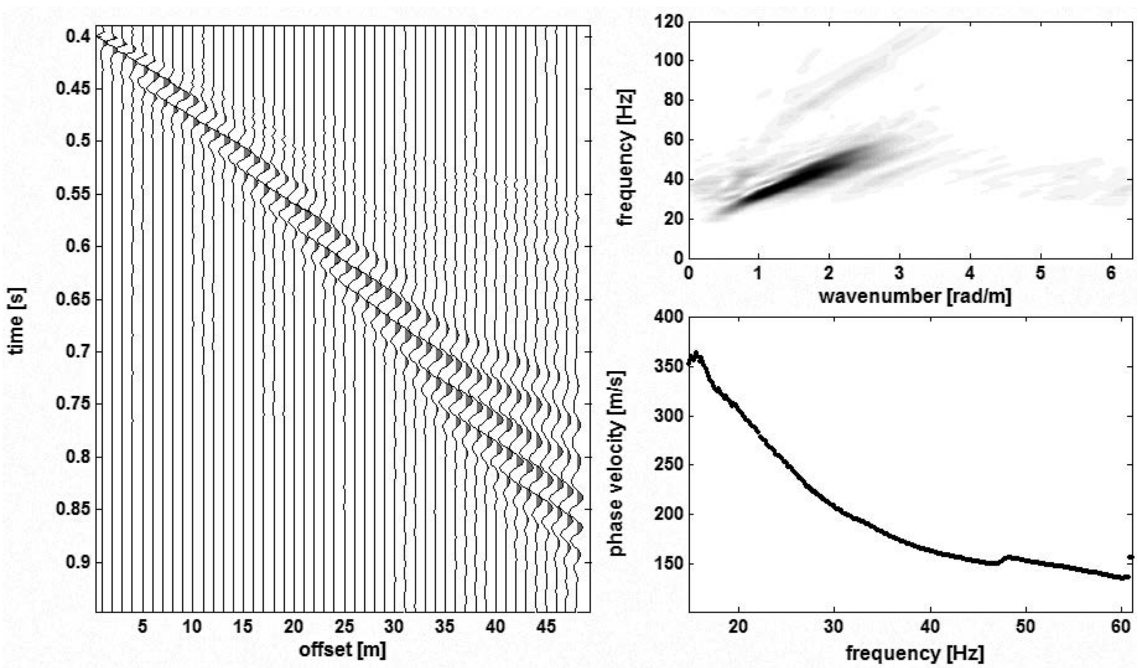


Fig. 3 - Example of processing of Love waves: the seismogram, the f-k spectrum, and the dispersion curve.

The layout array used influences the minimum and the maximum wavelength: the latter is not a strict limit, but the amplification of the uncertainty depending on the wavelength over array length ratio suggests the use of long arrays, which are nevertheless more sensible to lateral variations. The investigation depth is, however, more influenced by the local site conditions, the characteristics of the materials and the thickness of the layers. A typical configuration for surface wave testing can be 24 channels 2-3 m spaced, that allows the use of portable light sources and gives a good investigation depth.

An aspect of the acquisition which is very important to increase the robustness of the characterisation is the joint acquisition with refraction or reflection data. The synergies between surface waves and refraction have been discussed for the Rayleigh-P case by Foti *et al*. (2003), and very similar considerations can be made about the Love-SH case: body waves can give warning for surface wave lateral variations and localize sharp boundaries, surface waves overcome some limitations of the refraction, for instance the hidden layer problem.

The SH reflection can also be similarly integrated successfully, and the techniques work well especially in absence of Love waves, as shown later in the last example.

5. Processing

The processing of dispersive waves can be faced through different approaches: since the aim is estimating the propagation properties as a function of the frequency, the spectral analysis is the common step in different processing techniques. Several techniques allows the processing of multistation data, both the extension of the 2-receiver approach (MFA or the CPS phase) and the classic array processing techniques, such as the wavefield transforms. The latter (frequency-wavenumber f-k, frequency-slowness f-p) are robust and fast techniques, that profitably use the redundancy of the information.

The f-k is simply a way of transforming the data, acquired in the space-time domain, into the frequency-wavenumber domain where the modal curves are easily defined as lines. This approach is equivalent to other transforms, and has been proven to be effective in the processing of surface waves, and in particular, is necessary when multiple modes are present (Nolet and Panza, 1976; McMechan and Yedlin, 1981; Gabriels *et al*., 1987). A high-resolution 2D Transform is applied to the seismogram and the energy density as a function of frequency and wavenumber is obtained: then the maxima of the spectrum gives the kinematic properties of the present seismic events, and surface waves are easily recognised as dominant event. An automatic search of maxima at each frequency of the spectrum gives the wavenumbers which are easily converted into phase velocities as $v = 2\pi f / k$ (Fig. 3). This gives a global estimate of the phase velocity obtained averaging the information of all receivers: the redundancy of the information guarantees a stability and robustness of the estimate, which is slightly influenced by near-field effects and single uncertainty in the measuring system.

The main problem of this approach is the absence of a controlled weighting of the information and the distortion due to lateral variations: the quality of the data is space and frequency dependent, and some traces can simply deteriorate the information, and lateral variations are not recognised but only averaged. A possible solution is the use of a local estimate of the propagation properties, for instance with the algorithm proposed by Strobbia and Foti (2002, 2004).

The equation of the surface wave propagation is written in terms of modal contributions as

$$s(\omega,x) = \sum_m A_m(\omega,x)e^{\,i(\omega t-k_m(\omega)x)}$$

where x is the source to receiver distance, ω is the circular frequency, $k_m(\omega)$ and $A_m(\omega,x)$ are, respectively, the wavenumber and the amplitude associated to the m^{th} mode (Aki and Richards, 2003). For each single mode the amplitude and the phase as a function of the offset can be uncoupled: the phase is linear and the amplitude, after correcting the geometric spreading, is exponentially decaying. Experimental data, can be used for an inversion process that estimates the wavenumber and the attenuation coefficient. Focusing on the wavenumber, the approach consists of transforming a series of seismograms and computing the statistical distribution of amplitude and phase as a function of f and x. The phase is estimated with a statistical approach, providing an estimate of its probability density function at each frequency, for each offset: then, these data are used in a weighted inversion with a linear model that gives the wavenumber with its distribution (Fig. 4). This procedure allows a test of the assumed 1D soil model: if a statistical test (for instance an χ^2 test) rejects the hypothesis of linearity of the phase vs. offset curve, some external effect is probably present, as near field of lateral variations. This approach moreover, allows a direct estimate of the uncertainty of the dispersion curve.

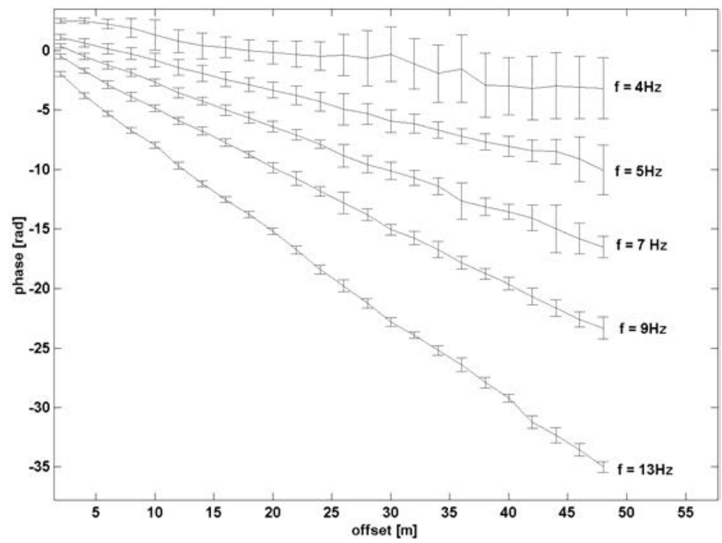
It is useful to stress that the uncertainty depends on the frequency and on the offset: the weighting of the information can hence be effective in reducing the final uncertainty of the wavenumber, because low quality data are rejected or less considered. Another interesting aspect to be considered is the amplification of the uncertainty on the phase velocity, especially at low values of the wavenumber (Fig. 4b). The information about the deep layers can hence be affected by a large uncertainty: the higher modes can help in reducing this uncertainty, because their wavenumber is larger at the same velocity. The reliability of the technique depends on the reduction but also on the assessment of the uncertainty: the portions of the results affected by large errors, as the deep part of the model that will be estimated using the low frequencies in Fig. 4b, will have of course a lower reliability.

6. Inversion

The inversion is the final step of the test: the characteristics of the propagation of the surface waves (velocity and amplitude vs. frequency) obtained are transformed into the soil model. This is done by means of an inverse problem in which the measured data are compared to simulated data: the objective function to be minimised is usually defined, according to the least-square approach, as RMS residuals for a continuous branch of the dispersion curve.

The optimisation can be performed with different approaches of both the local and the global search. The different strategies of inversion have, however, some common aspects to be discussed. It can be said that the most important aspect of the inversion are the selection of data to be inverted, the parameterisation of the model, and forward modelling: the relations between the model space and the data space are indeed of primary importance in directing the choices and evaluating the reliability of the result.

The problem of surface-wave inversion is clearly mix-determined: all the wavelengths affect a)



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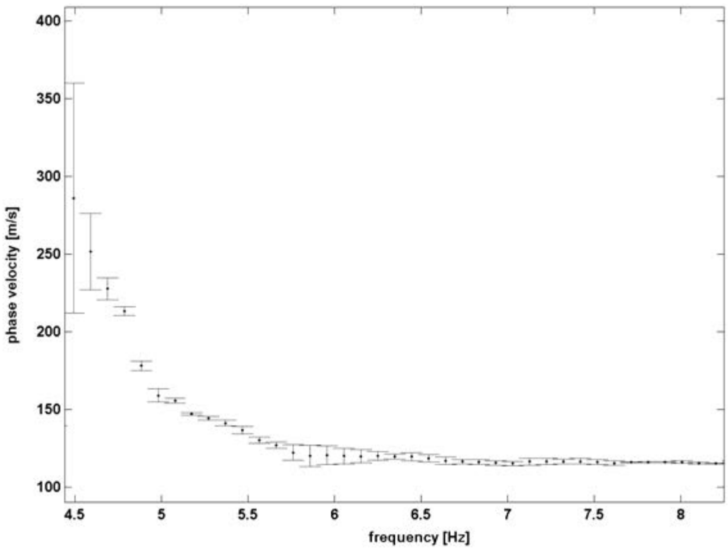


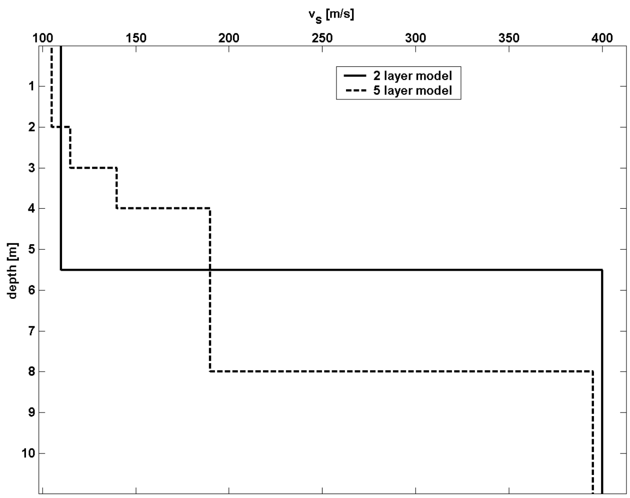
Fig. 4 - The experimental unwrapped phases at different frequencies as a function of the offset (a) are used for a weighted estimate of the wavenumbers. A linearity test is performed, then the phase velocity can be computed (b).

the shallow layers, while only the long wavelength reaches the deep layers, and the sensitivity decreases with the depth. The sampling of the data space is added to this physical aspect: extreme points can be present, and the sampling can be extremely coarser in some portions with respect to others. The partial derivative of the wavelength with respect to the frequency f can be written as v/f^2: at low frequency the sampling becomes coarser, also because of the increase of the velocity v. As mentioned before, these points may also be affected by large uncertainties. To face this situation great care has to be put into the parameterisation of the model: the maximum depth and the number of resolvable layers have to be chosen according to the experimental data.

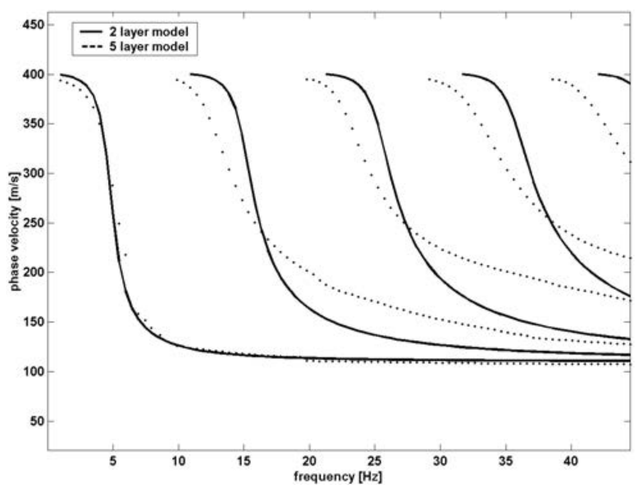
Considering the number of layers that are used, a minimum parameterisation has, in general, to be preferred for the parsimony principle, or "Occam's razor" (Menke, 1989). It is, in fact, always possible to increase the number of layers without increasing the misfit: in other words, the over-parameterisation can produce equivalence. A possible approach can be the optimisation with a model with an increasing number of layers: the process is stopped when the misfit is small compared to the uncertainty of the data. In the example shown in Fig. 5, two models are compared by considering their dispersion characteristics: a simple 2-layer model and a 5-layer model cannot be recognised for their first mode.

It can be said that for the first mode the two models are equivalent: it can be considered a lack of information of the first mode or an over-parameterisation of the 5-layer schematisation.

If higher modes are detected, as often happens with Love waves, it is important to consider the information that they carry: in the case of Fig. 5 the number of layers can be increased if higher modes are considered, and less equivalence is present in the data.



a)



b)

Fig. 5 - Two simple models (a) and their modal curves (b). In the inversion of the first mode the two models can be considered equivalent, while not for higher modes.

The SVD analysis of the data kernel matrix can help in recognising over-parameterisation: if we consider the eigenvectors associated to the greater singular values, they can be interpreted as linear combination of the layer velocities, and it can be observed that the information regards averages of several layers. So, a first inversion can be run with many layers, and the result is simplified after the SVD analysis of the data kernel matrix, considering the local linearisation of the problem (Strobbia, 2003).

The investigation depth should be carefully evaluated before inversion, considering the maximum reliable wavelength and evaluating the decrease of the sensitivity with depth: the inversion will indeed invent the velocities beneath the actual investigation depth, and will highly amplify the uncertainties of the model parameter where the information is poor (Jackson, 1972). If the uncertainties are properly evaluated, the result will clearly declare the investigation depth: the confidence interval of portions of the model that are too deep will simply be unacceptable.

One of the problems of the inversion, when Rayleigh waves are considered, is the modal superposition: this aspect is usually less critical with Love waves. However, it is important to check the importance of higher modes, and to use a multimode modelling.

The analysis of the uncertainty of the final model (as the velocity uncertainty in Fig. 1) is the crucial point in the assessment of the reliability of the technique for different applications. For high resolution application in geotechnical engineering the geometrical characterisation of the formation can be needed: the results of these indirect techniques can be usefully integrated with the borehole seismic test, and can spatially extend their punctual results if the information about the depth of the interesting target is not lost in the blur of the uncertainties. When the shear velocity of the shallow structures is the main target, the effectiveness of these techniques is easily assessed considering the uncertainty of the velocity as acceptable: this happens in general, when a site classification is made considering the shear wave velocity averaged on a certain depth.

7. Comparison between Rayleigh and Love waves

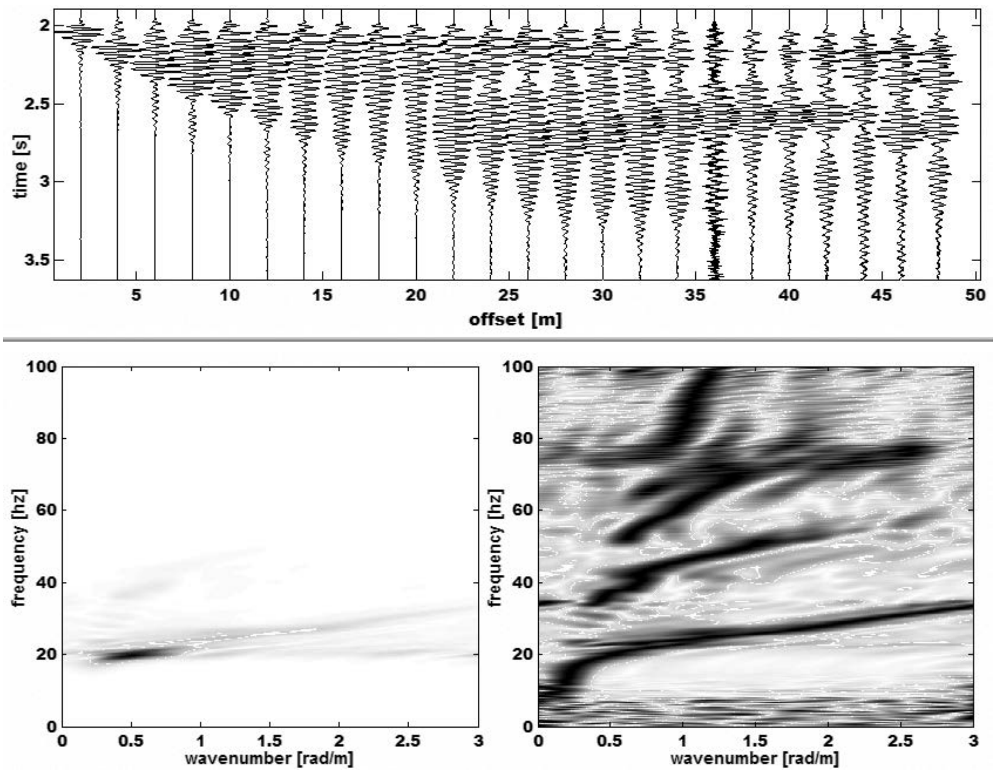
One of the main advantages of the Rayleigh Wave Method is its robustness: the high energy of Rayleigh waves in all stratigraphic situations makes this technique particularly versatile. The same cannot be said about Love waves, which do not always exist: it is, hence, possible to have a site without Love waves in the interesting frequency range.

Another important difference is in the simplicity of the acquisition: Rayleigh waves are acquired with an easy conventional approach, with vertical source and vertical receivers: by contrast, Love waves require horizontal receivers and horizontally polarized sources. The energy which is put into the ground with a horizontal source is usually lower than with a vertical one, and hence the S/N ratio can be lower.

Love wave data can be a by-product of an SH reflection acquisition: high resolution SH reflection is a powerful technique allowing the identification of sharp variations and estimating a 2D shear velocity model. Love wave analysis can increase the reliability of the reflection processing, and can help, especially at shallow depth, in increasing the reliability and the resolution: a better velocity model in the uppermost layers allows a better processing and depth conversion of the seismic section. Similar synergies can exist with SH refraction, and the analysis of Love waves can increase the information extracted by seismograms.

Love waves are in general less problematic for the presence of higher modes, while in Rayleigh-wave testing the proper identification of modes can be a serious problem: moreover, there is the added complication of wave conversion between P and S, and the curves are more complex (Glangeaud *et al.*, 1999). In the end, with shear sources less coherent noise events are present in data.

The case shown in Figs. 6 and 7 refers to a site with a shallow deposit on a shallow bedrock, with a strong impedance constrast: Love waves and Rayleigh waves have been acquired with the



a)

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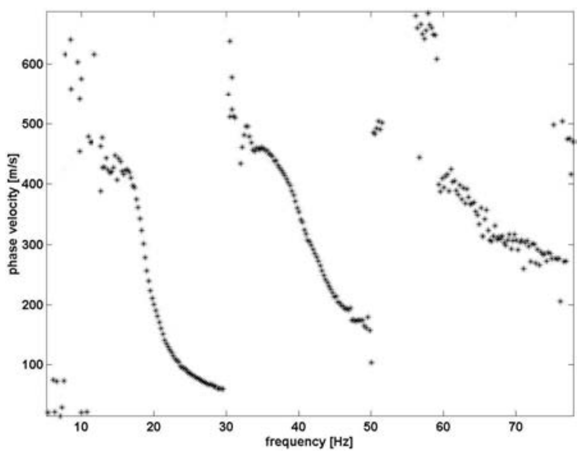
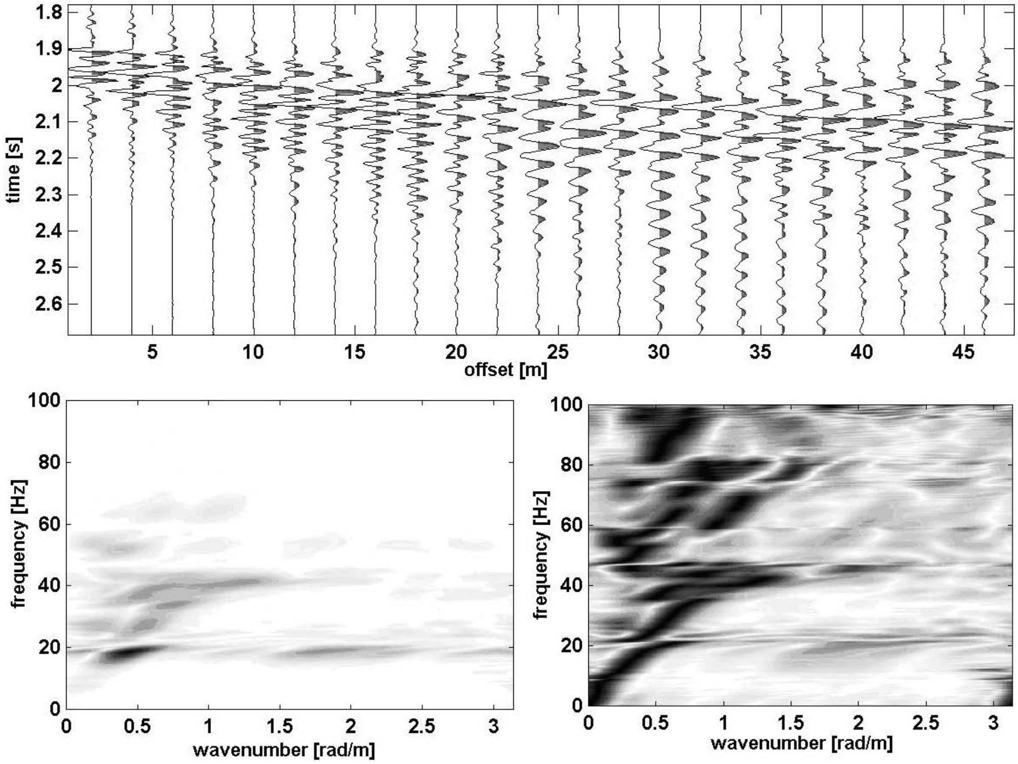


Fig. 6 - Love wave data at a site with a sharp velocity contrast.

a)



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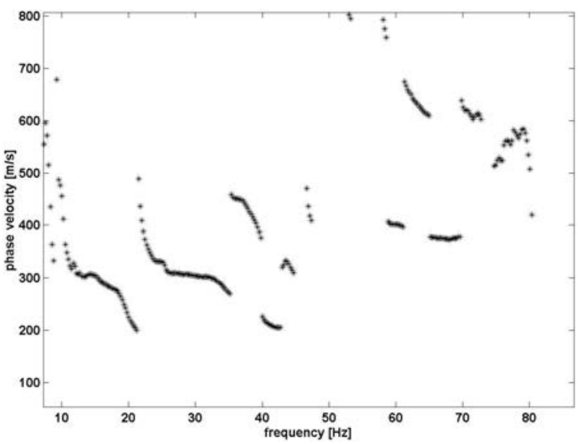


Fig. 7 - Rayleigh wave data at the same site of Fig. 6.

same array layout. Energy of Love waves is mainly trapped in a shallow very soft layer, but the evidence of the bedrock is identified in the data. Most of the energy is associated to the first mode main frequency of the first layer (19 Hz). The higher velocities are associated to low energy and are therefore hardly detected (Fig. 6). The seismogram, the f-k spectrum, and the frequency normalised f-k spectrum are shown in Fig. 6a: the dispersion curve is shown in Fig. 6b.

The presence of a higher velocity bedrock in Rayleigh wave data is more evident (Fig. 7): however modes are more interfering, and the interpretation can be mode difficult.

8. Terceira example

The first example that is presented shows a case where the first Rayleigh mode is identified with difficulty, whereas the information obtained from the Love waves can be usefully integrated.

The site, that suffered strong damage for the earthquake of Jaunary 1, 1980, is located in Sao Sebastiao, Terceira Island of the Azores archipelago. The village is located in a volcanic caldera, with a basaltic bedrock and some lateral pyroclastic cones: a geophysical campaign was performed, acquiring mainly surface wave and refraction data, and the presence of very low velocity sediments was detected in some portions of the area. The case is discussed here to show the possible synergies between Love and Rayleigh wave testing: more details can be found in Lopes (2004).

The acquisition was performed with a Ras24 seismograph: a sledgehammer on metal plate and vertical geophone was used for the Rayleigh wave acquisition, while a sledgehammer, laterally striking a sleeper, and horizontal receivers (Swyphones prototypes) was used for the Love wave acquisition. The two seismograms and the f-k spectra are shown in Fig. 8, together with the two dispersion curves.

The first mode of Rayleigh suffers a strong attenuation, and looses more than 1.3 dB/m: the higher mode, that is clearly visible both in the t-x and f-k domains is less attenuated because of

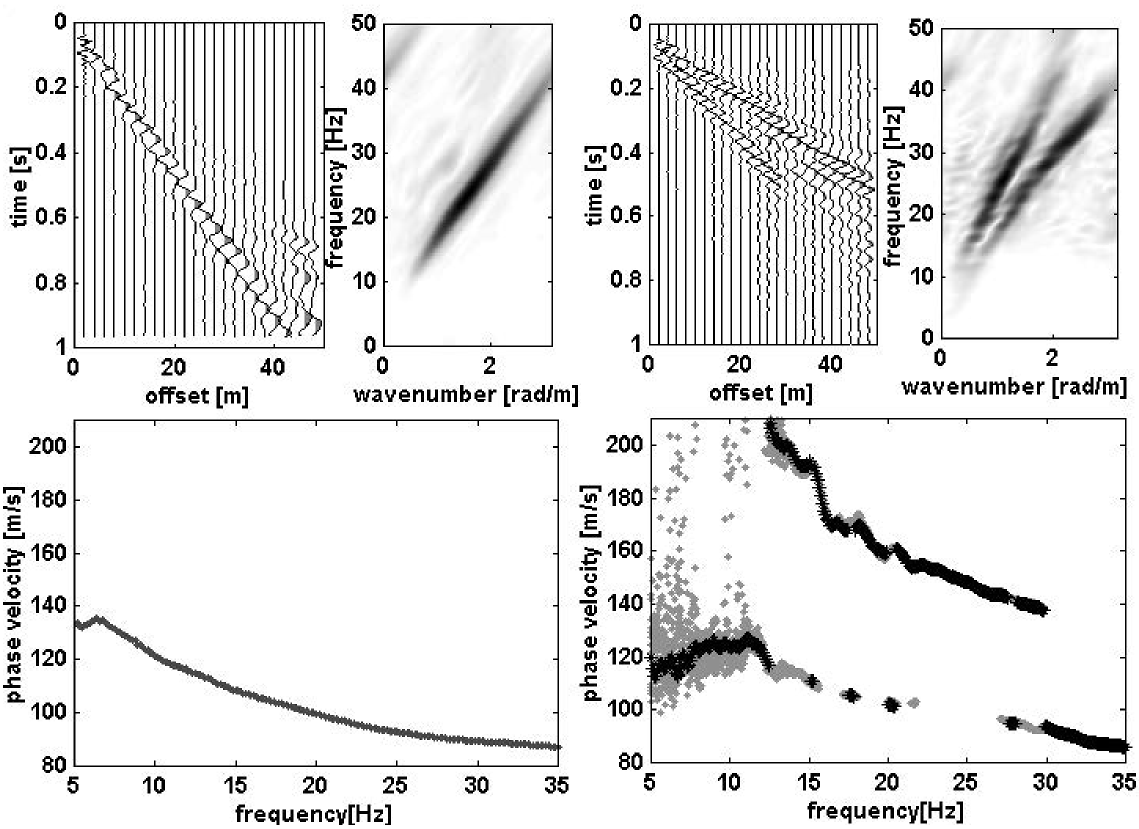


Fig. 8 - Comparison of Rayleigh and Love waves at the Terceira site.

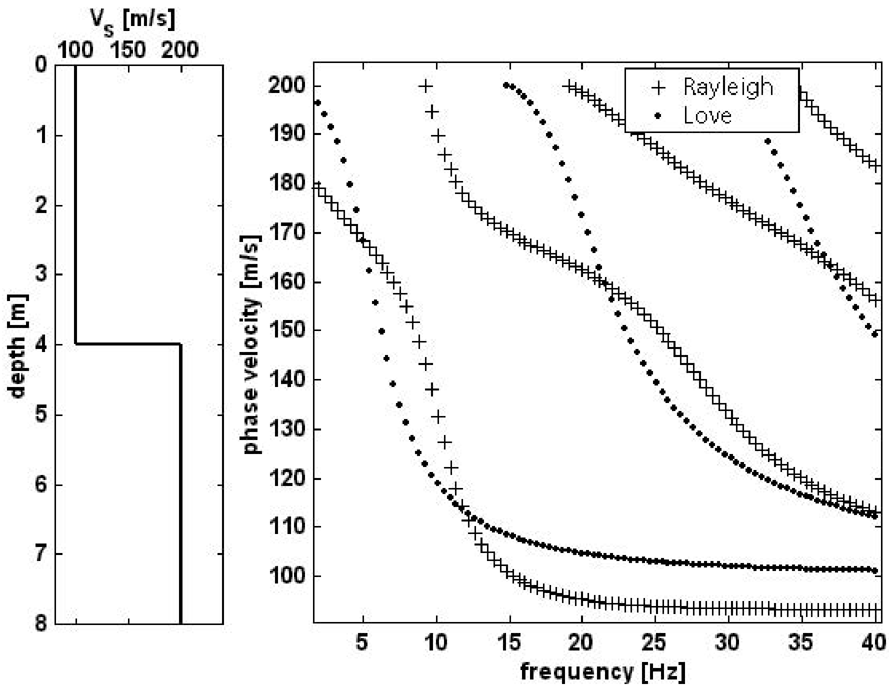


Fig. 9 - Comparison of Rayleigh and Love dispersion without anisotropy: synthetic data.

the higher wavenumbers. The Love wave's first mode is better defined and confirms the velocity of the first Rayleigh mode.

The joint interpretation of Love and Rayleigh waves can estimate the anisotropy of the material: the shear solicitation of the two kinds of waves are actually perpendicular. In an ideal isotropic situation their velocities are different even in the frequency ranges where they solicit the same layer (Fig. 9).

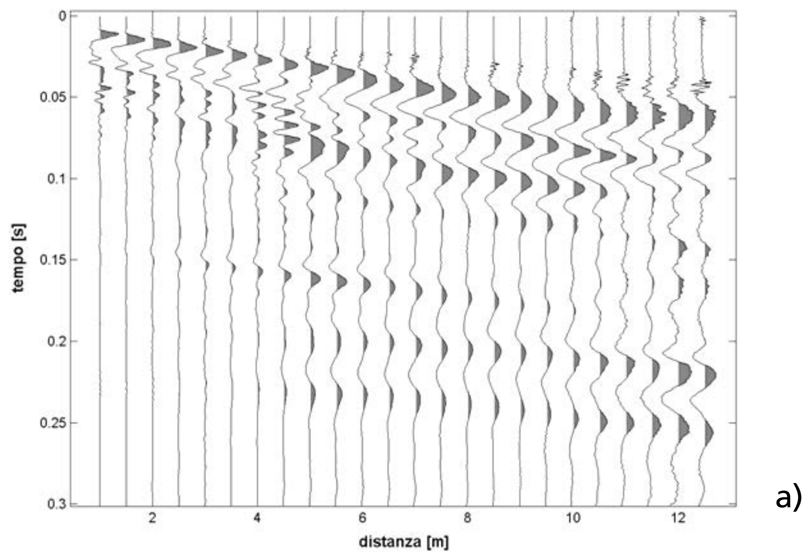
9. Santa Iria example

This example wants to show that sometimes things go wrong with Love waves.

The site is located close to the Tagus river near Lisbon, in Portugal: the geological setting is represented by Miocene bedrock covered by thick Quaternary terraces and soft alluvial deposits, with loose sand and high plasticity silt with seashells. The geotechnical characterisation of the site is described by Lopes *et al*. (2005), who also discuss and compare the results of Rayleigh wave testing.

The site is particularly interesting for the geophysical characterisation: the determination of the shear velocity is needed also because of the presence of a very shallow water table. The P-wave refraction is almost completely blinded by the water table, as can be observed in Fig. 10b, where the refracted P-wave is the first event at 1550 m/s.

Different measurements were performed, with vertical and horizontal receivers. The acquisition of the horizontal component was performed with horizontal receivers and a polarized horizontal source: a shot gather is shown in Fig. 10a. Direct SH waves and a strong reflection are evident in the record even without AGC, while no dispersive Love waves are present: this is probably due to the presence of a shallow dry overconsolidated crust. A seismogram of the vertical component with vertical source is shown in Fig. 10b and highlights the presence of strong Rayleigh waves.



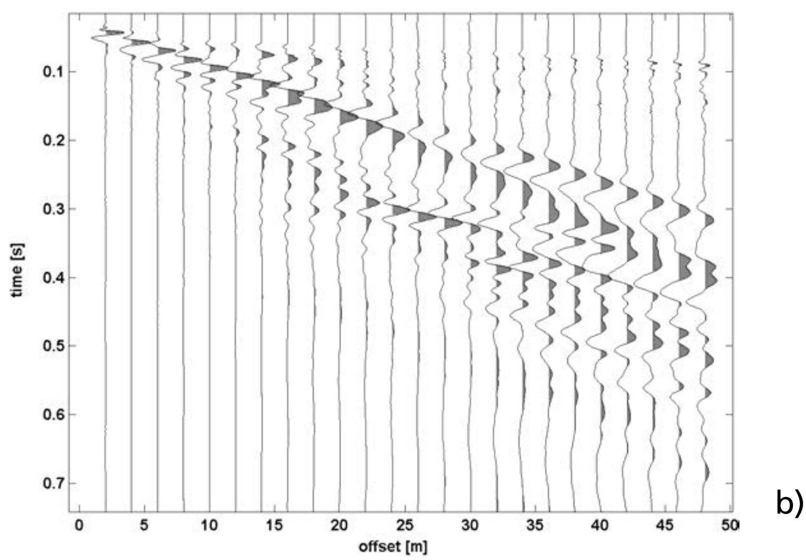
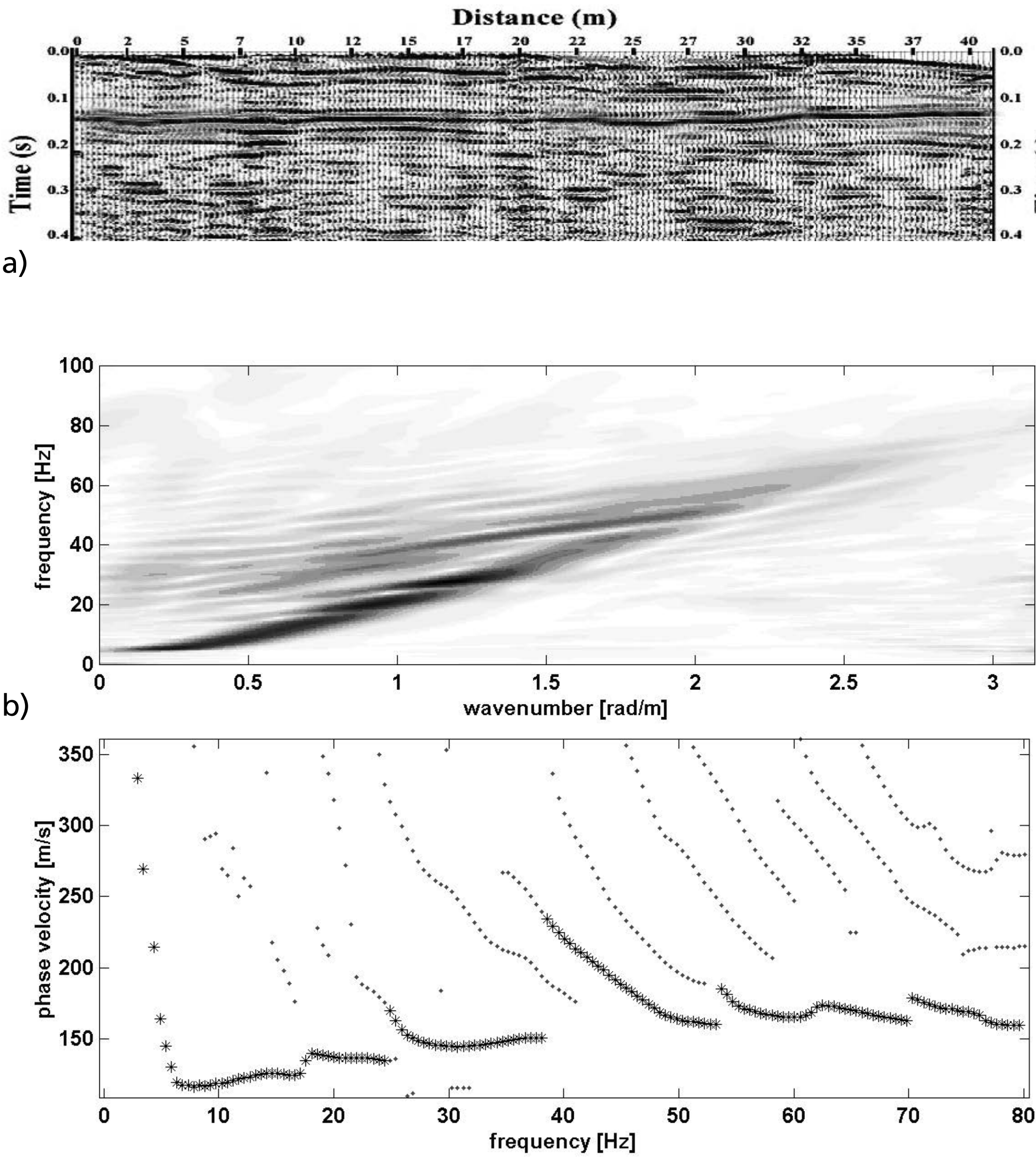


Fig. 10 - Comparison of Rayleigh and Love seismogram at the Santa Iria site.

Sometimes things go wrong, but when a technique fails sometimes another technique can succeed; an SH reflection section has been acquired and interpreted (Fig. 11, courtesy of G.P. Deidda), and the Rayleigh wave data can be interpreted and are in good agreement with the existing geotechnical data. The reason of the absence of Love waves is the shallow velocity inversion, which is evident in the dispersion of Rayleigh wave: the velocity increases, increasing the frequency.



a)

b)

Fig. 11 - SH reflection time section (a) and dispersion of Rayleigh waves (b).

10. Conclusions

Love waves can be used for site characterisation to determine the shear wave velocity profiles: the technique, similar to the Rayleigh Wave Method, however needs a different acquisition. Rayleigh waves always exist, while Love waves do not: the Love Wave Method is hence less robust, but great interest lies in the synergies with shear wave refraction and reflection.

The risk of not having Love waves in data purposly acquired is mitigated by the possibility of a full waveform analysis of shear seismograms: and the Love wave analysis can also be a by-product of the shear wave acquisition.

In favourable conditions, the Love waves analysis can be a stand-alone tool for the characterisation of the near surface layers, of great utility for seismic site response analysis. In other situations, the technique can be useful for refraction and reflection.

In case of a multi-component acquisition, the joint analysis of Rayleigh and Love waves can increase the reliability of the result, and also estimate the anisotropy of the subsoil.

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