MASW-REMI method for Seismic Geotechnical Site Characterization: Importance of Higher Modes of Rayleigh Waves

Vitantonio Roma, PhD, Roma e Associati (Italy), www.masw.it e-mail: roma.vitantonio@libero.it
Dr Costanzo Tononi, DOLANG, www. dolang.it, e-mail: info@dolang.it

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Abstract

The interest of both the scientific community and the professionals towards the MASW method (Multichannel Spectral Analysis of Surface Waves) has been increasing for the last years.

In the '90 several researchers have realized that, when dealing with inversely dispersive sites, the MASW method based only on the fundamental mode can really cause erroneous Vs profiles, hence an erroneous seismic site characterization. When dealing with inversely dispersive sites (i.e. sites where stiffness discontinuities exist, soft layers trapped between stiffer layers or viceversa stiff layers trapped between softer layers) higher modes of Rayleigh waves must be combined together with the fundamental mode to calculate the effective or apparent dispersion curve (Lai 1998, Roma 2001-2002-2006), in order to achieve a reliable Vs profile and a reliable seismic site characterization. It is not sufficient to calculate the numerical higher modes and use them separately for the inversion process, because it is practically impossible to distinguish the experimental higher modes from the field data in the geotechnical scale. It is well known that the apparent experimental dispersion curve that is determined from the field data is the result of a superposition of the several higher modes.

In order to obtain a reliable Vs profile and hence a reliable site soil characterization not only the fundamental mode, but also the higher modes of Rayleigh have be combined when calculating the apparent numerical dispersion curve. Consider that it is not sufficient to calculate the higher modes of Rayleigh, because it is necessary to combine the higher modes with the fundamental mode to calculate the numerical apparent dispersion curve, as it is measured in field. This is due to the fact that from field data it is not possible to distinguish and define the higher modes without a large uncertainty. In this article the potentialities of a new algorithm (www.masw.it, Roma 2001) that calculates the apparent dispersion curve using both the fundamental mode and all higher modes are shown into an application to a real case.

Introduction

The MASW method is a non-invasive investigation technique (there is no need of boreholes), which allows to determine the vertical shear wave velocity Vs by measuring the propagation of the surface waves at several sensors (accelerometers or geophones) on the free surface of the site. The main contribution to the surface waves is given by the Rayleigh waves, which travel through the upper part of the site at a speed, which is correlated to the stiffness of the ground. In a layered soil Rayleigh waves are dispersive, that is Rayleigh waves with different wave length travel with a different speed (both phase and group velocities) (Aki, K. and Richards, P.G., 1980). Dispersion means that the apparent or effective phase (or group) velocity depends on the propagating frequency. This circumstance implies that high frequency waves with relatively short wave lengths contain information about the upper part of the site, instead low frequency waves with longer wave lengths provide information about both superficial and deeper layers of the site. The MASW method can be applied as the active method or the passive method (Zywicki, D.J. 1999) or a combination of both active and passive. In the active method the surface waves are generated by a source located at a point on the free surface and then the wave motion is measured along a linear array of sensors. In the passive method the sensors can be located in arrays of different geometric shape: linear, circular, triangle, square, L shape, and the source is represented by the environmental noise, whose direction is not known a priori. The active method generally allows to determine an experimental apparent phase velocity (or dispersion curve) within the frequency range 5Hz -70Hz. Hence the active method can give information concerning the first 30m-35m, depending on the stiffness of the site. The passive method generally allows to define an experimental apparent phase velocity (or dispersion curve) within the frequency range 5Hz - 15Hz. Hence the passive method can generally provide information about deeper layers, even below 50m, depending on the stiffness of the site. As passive method the ReMi procedure (Refraction Microtremors) will be explained, since the results provided by the passive

MASW and ReMi are equivalent. The MASW method consists of three steps (Roma, 2002): (1) in the first step the experimental apparent phase velocity (or dispersion curve) is determined (Figure 1), (2) in the second step the numerical-theoretical apparent phase velocity (or dispersion curve) is calculated (Figure 5, 6), (3) in the last step the vertical shear wave velocity profile Vs is determined, by properly modifying the thickness h, the shear Vs and compressional Vp wave velocities (or in alternative to Vp it is possible to modify the Poisson's parameter υ), the mass density ρ of all the layers considered in the site model, until the optimal match between the experimental and the theoretical dispersion curves is achieved (Figure 5, 6). During step 3 the site model and hence the shear wave velocity profile can be determined by means of a trial and error or an automatic procedures, or a combination of both. Usually the number of layers, the Poisson's parameter υ and the mass density ρ are assigned and successively the thickness and the shear wave velocity of the layers are modified. After the shear wave velocity profile has been determined, then the equivalent Vs30 can be calculated and hence the seismic class of the site can be established. It is meaningful to acquire any additional information about the geotechnical nature of the site, so that the existence of the special sites of type S1 and S2 can be recognized

Apparent Dispersion Curve of Rayleigh Waves

The measurement of the surface waves along the sensors on the free surface of the ground gives the wave motion in the time-space domain. The perturbation generated by the point source contains all the several Rayleigh modes (Sv and P waves attenuate after few meters from the point source), which form a whole wave train and cannot be discerned nearby the point source. The dispersion of the Rayleigh modes can be completely observed only at an adequate distance from the point source (this distance is greater than about 100m in practice).

For this reason in the geotechnical scale (less than 100m) all the modes of Rayleigh waves (both fundamental and higher modes) are combined together into the wave motion. In order to obtain a reliable Vs profile and hence a reliable site soil characterization, not only the fundamental mode, but also the higher modes of Rayleigh waves have to be combined when calculating the apparent numerical dispersion curve.

Experimental in field Apparent Dispersion Curve

When the wave field is transformed from the time-space domain into the frequency-wave number or equivalently into the frequency-phase velocity domain, in order to show the dispersion relation equation (2), then it is observed that it is not possible to distinguish among the several Rayleigh modes as it is predicted by theory. Instead of the several Rayleigh modes, generally, only a unique apparent, also said effective, dispersion curve is observable (Figures 1). The experimental apparent dispersion curve obtained from the wave motion measured in field is the result of the interaction among all the several modes of Rayleigh waves, both the fundamental and the higher modes, also included the geometric array of sensors used for the measurement. In fact the geometric configuration of the sensors may influence the value of the apparent dispersion curve at certain frequencies (Roma V. 2001, Roma V. et al. 2002).
Depending on the geometric (thicknesses) and mechanical (Vs, Vp, ρ) properties of the ground layers, some modes of Rayleigh waves can appear as predominant with respect to the other modes at certain frequencies. Usually when the stiffness of the layers increases gradually with depth, then the first or fundamental mode of Rayleigh waves becomes predominant at every frequency. Nevertheless several stratigraphies exist with stiff layers trapped between softer layers, or viceversa with soft layers trapped between stiffer layers, or more generally with a strong stiffness contrast between two consecutive layers, where higher modes of Rayleigh waves become predominant at certain frequencies. It may occur that at any frequencies there is not predominance of a unique mode, but two or more modes have about the same energy. Under these conditions the apparent dispersion curve does not coincide with any mode of Rayleigh waves, since the apparent dispersion curve is the combination of all the predominant modes.

Theoretical-Numerical Apparent Dispersion Curve

The theoretical apparent or effective dispersion curve can be calculated once the modes of Rayleigh waves have been determined (Figure 5). To reach this purpose the Roma's method has been implemented (Roma V. 2001, Roma V. 2007).
The theoretical apparent dispersion curve determined by Roma's procedure is calculated in the same manner followed in determining the experimental dispersion curve. The only diversity concerns the way in which the spectrum (f-k) of the wave field is obtained. The experimental (f-k) spectrum is obtained by a 2D Fourier transform of the time-space wave field, instead the numerical (f-k) spectrum is obtained by only 1D Fourier transform, applied to the Green's function of the layered half-space. The Roma's procedure allows to consider the contribution of all higher modes for estimating the apparent dispersion curve. The contribution of all higher modes becomes relevant for inversely dispersive sites, where softer layers are trapped between stiffer layers or where stiffer layers are trapped between softer layers.

The REMI Method

The ReMi (Refraction Microtremors) method has been developed by Louie (Louie, 2001). It consists of three steps, the same as the MASW method: the first step concerns the determination of the experimental dispersion curve of Rayleigh waves; the second step coincides with the calculation of the numerical apparent dispersion curve and the third step consists of inverting the apparent dispersion curve in order to find the vertical shear wave profile of the site. In the ReMi method the experimental dispersion curve is obtained passing from the (t-x) domain gathered on site to the (p-f) domain by means of a p-tau transformation, or slantstack and a successive Fourier transform.

The active MASW method performed by means of a hammer allows to obtain information within the frequency range 10Hz-100Hz, hence it generally provides information within the first 30m of the site. If instead a more powerful source is used (i.e. a truck or a heavy shaker) lower frequencies than 10Hz and hence higher depths than 30m can be reached. Anyway the ReMi (Refraction Microtremors) method allows to obtain information within the frequency range 1Hz-15Hz, depending on the available environmental noise, hence it can give information about layers deeper than 30m, potentially down to 100m, as it is stated by Louie (2001). In this regard the ReMi method is equivalent to the linear array passive MASW. By combining the information gained with the active MASW and the ReMi methods it is possible to cover the whole frequency range of interest in the seismic site characterization 1Hz-100Hz, reaching depths greater than the 30m, even if only 30m are required by the international codes to evaluate the Vs30.

Application To a real case

The site is located in Villadossola (Piedmont, Italy), where only the MASW method was executed. The site is characterized by an alternation of sand, gravel, silt and coubbles layers.

The parameters of the active MASW tests are:

- Geophones interspace = 1.5m
- Source type = 8kg hammer
- Delta time of acquisition = 2.0ms (sampling freq = 500 Hz)
- Source location = 1.5m from first geophone
- Total time of acquisition = 4 s
- Number of geophones = 24

The data have been processed by means of the software MASW (www.masw.it). The software MASW at moment is the only one available software that is able to calculate the apparent numerical dispersion curve considering the superposition of the fundamental and higher modes of Rayleigh Waves, without the need of defining a priori the higher modes of Rayleigh Waves from field measurements.

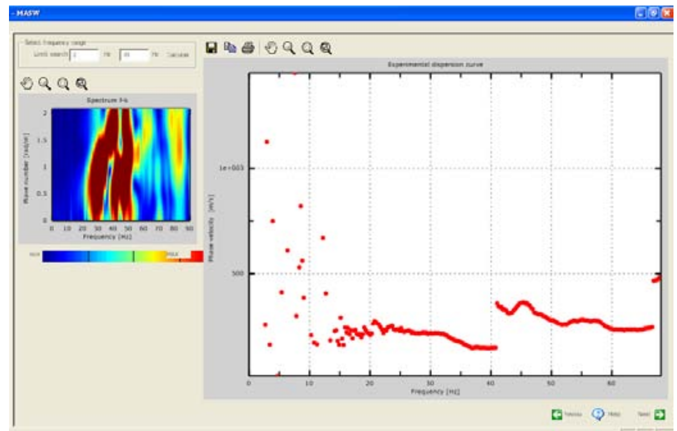

Figure 1: f-k spectrum and (v-f) exp dispersion curve.

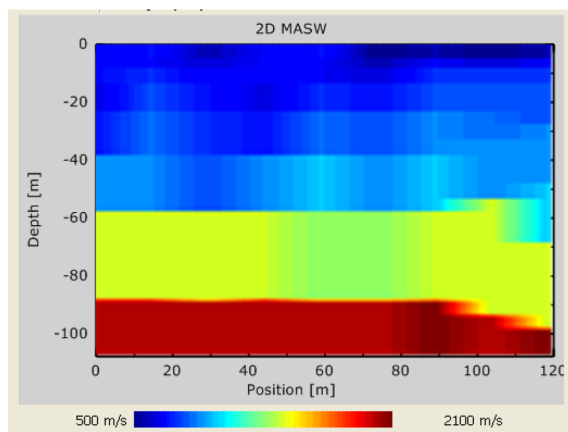

Figure 2: 2D MASW-REMI Vs profile.

In Figure 1 the f-k spectrum and the field apparent dispersion curve in the (v-f) plane are shown. Also an example of a 2D MASW-REMI Vs profile is reported. In Figure 3 and 4 a correct multi-modal apparent (v-f) field dispersion curve picking and an incorrect only fundamental mode (v-f) field dispersion curve picking are shown. If only the fundamental mode is used a not reliable Vs profile is determined (Figure 8). Only if the multi-modal apparent numerical dispersion curve is used, then a reliable Vs profile is determined (Figure 7).

According to the true multi-modal apparent Vs profile the Vs30 is equal to 442 m/s and following the Eurocode 8 the site is classified as type B.

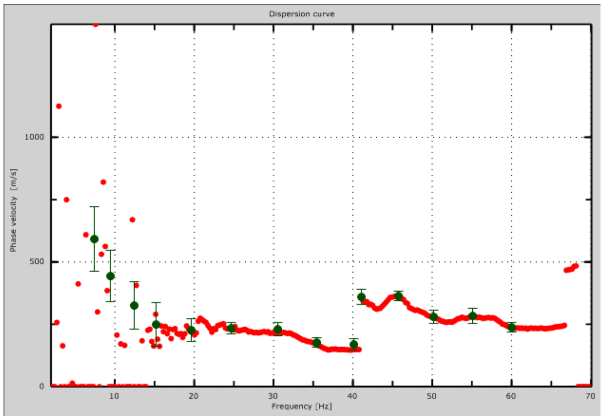

Figure 3: picking multi-modal apparent (v-f) field dispersion curve.

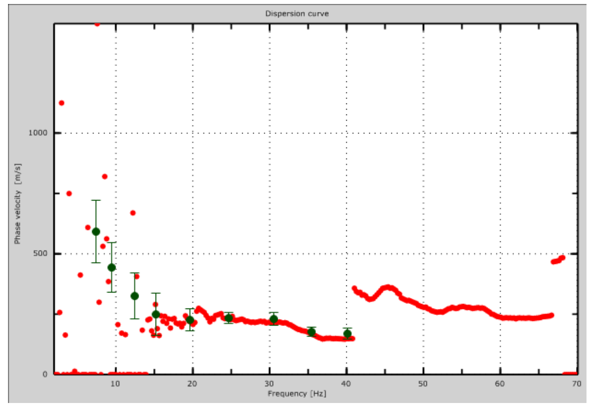

Figure 4: picking only fundamental mode (v-f) field dispersion curve.

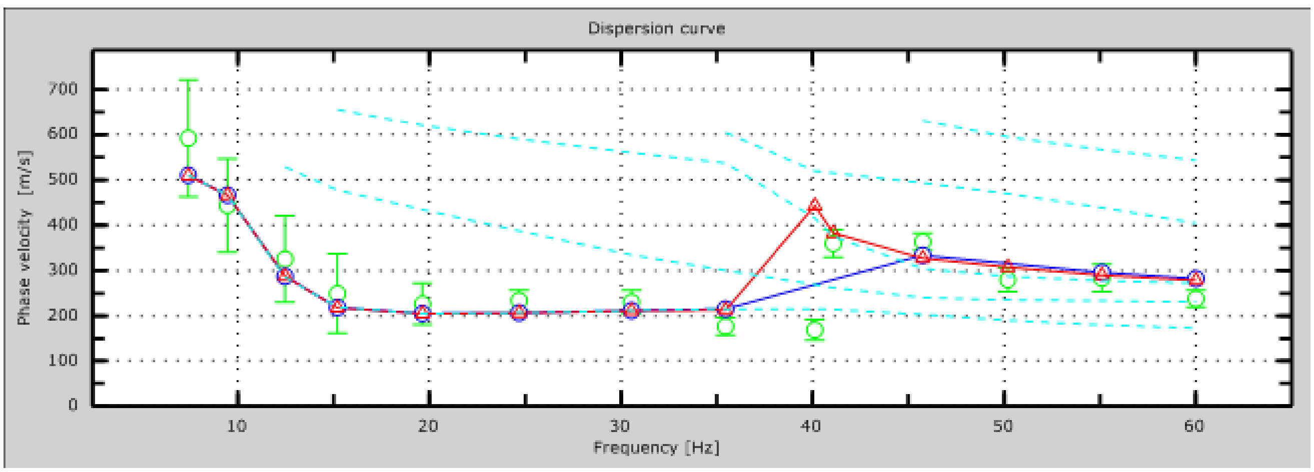

Figure 5: multi-modal apparent inversion.

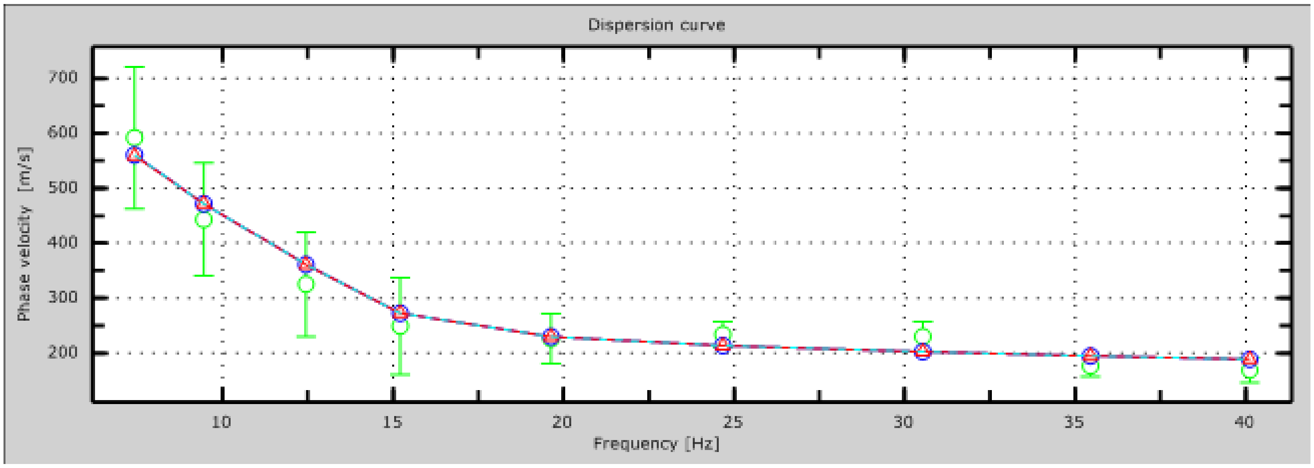

Figure 6: only fundamental mode inversion

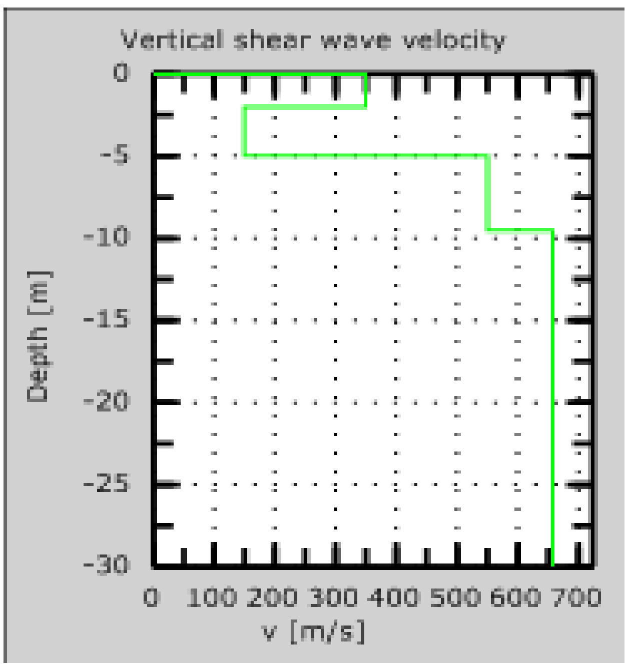

Figure 7: correct Vs profile from multi-modal apparent inversion.

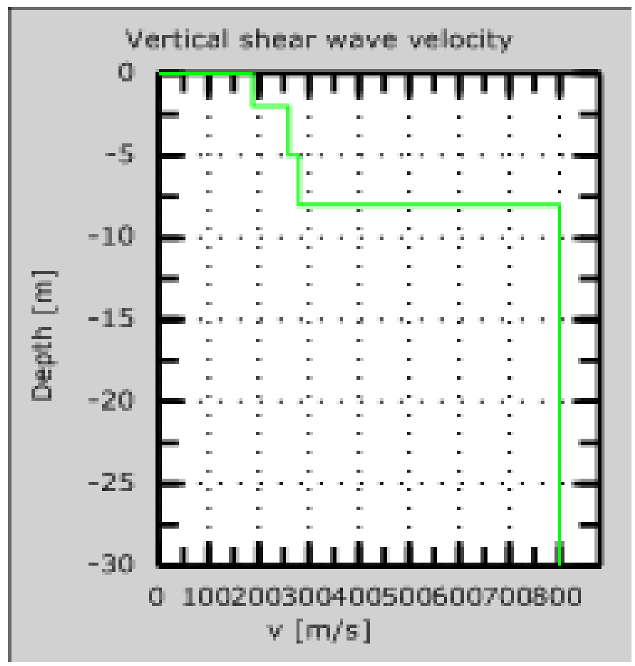

Figure 8: incorrect Vs profile from only fundamental mode inversion.

Conclusions

When dealing with inversely dispersive sites, where strong stiffness contrasts exist or softer layers are trapped between stiffer layers, higher modes of Rayleigh become important. Since it is not possible to correctly pick the higher modes from field data, the inversion process has to be performed by means of the apparent or effective dispersion curve, that is the superposition of the fundamental and higher modes of Rayleigh waves.

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