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Seismic Geotechnical Site Characterization by MASW-REMI Method: Importance of Higher Modes of Rayleigh Waves

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SUMMARY

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 this article the potentialities of a new algorithm (www.masw.it, Roma 2001) that calculates the apparent dispersion curve using all higher modes are shown into an application to a real case.

Introduction

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 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 higher modes from the field data in the geotechnical scale. It is well known that the apparent experimental in field 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. 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.

Seismic Site Classification by means of the MASW and REMI methods

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) (Achenbach, J.D., 1999, 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 the 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 in field apparent phase velocity (or dispersion curve) within the frequency range 5Hz -15Hz. Hence the passive method can generally provide information about deeper layers, below 50m, depending on the stiffness of the site.

In the following both the active and the passive MASW methods will be explained. As passive method the ReMi procedure (Refraction Microtremors) will be used, 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 2), (2) in the second step the numerical-theoretical apparent phase velocity (or dispersion curve) is calculated (Figure 5), (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).

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.

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 which are required by the international codes to evaluate the Vs30.

Importance of Higher Modes of Rayleigh Waves and Apparent Dispersion Curve

From the field data it is generally 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 (**Figure 1**). The experimental in field apparent dispersion curve obtained from the wave motion measured in field is the result of the interaction among all the several modes of Rayleigh. Depending on the geometric (thicknesses) and mechanical (Vs, Vp, ρ) of the ground layers, some modes of Rayleigh 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 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 (**Figure 2**), or more generally with a strong stiffness contrast between two consecutive layers, where higher modes of Rayleigh 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 the same energy. Under these conditions the apparent dispersion curve does not coincide with any mode of Rayleigh, since the apparent dispersion curve is the combination of all the predominant modes.

The theoretical apparent dispersion curve determined by Roma's procedure (Roma V. 1999) is calculated in the same manner followed in determining the experimental in field dispersion curve. The Roma's procedure allows to consider the contribution of both the fundamental mode and 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.

Application to a real case

The site is located in Rieti (Italy), where both the MASW and REMI methods were executed. In the upper side there is stiff conglomerate, overlying software ground layers of sand, gravel, silt. The parameters of the active MASW and REMI tests are:

Geophones interspace = MASW 2.0m REMI 5.0m; Source type = MASW 8kg hammer REMI ambient noise; Delta time of acquisition = MASW 2.0ms REMI 2.0ms; Source location = MASW 2.0m from first geophone; Total time of acquisition = MASW 4 s REMI 32s; Number of geophones = 24.

The data have been processed by means of the software MASW (**www.masw.it**). The software MASW is able to calculate the apparent numerical dispersion curve considering the superposition of the fundamental and higher modes of Rayleigh Waves.

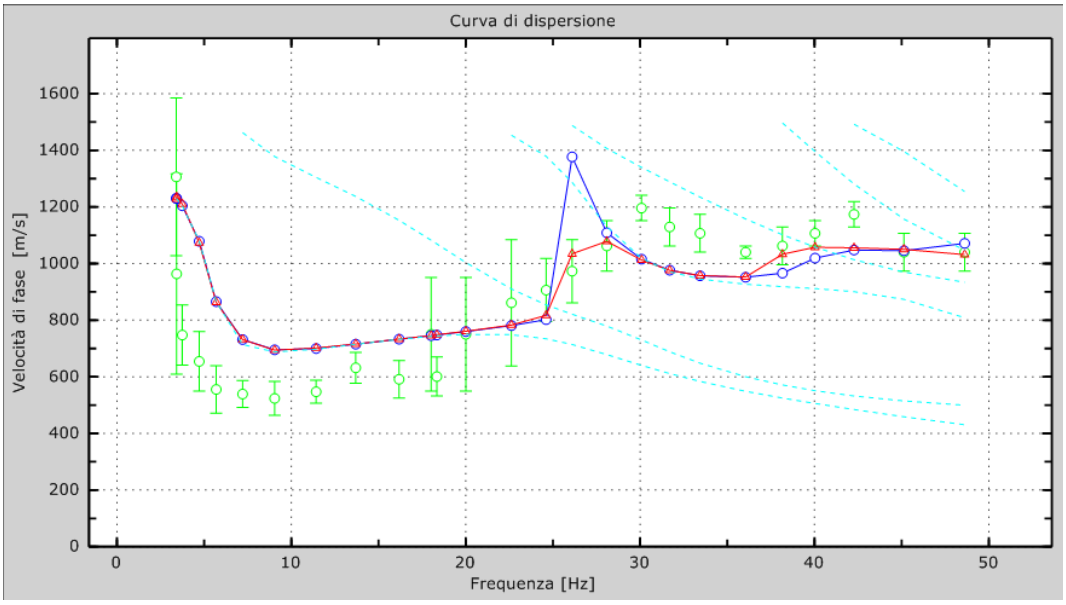

Figure 1 *x axis (frequency), y axis (phase velocity): fundamental and higher modes of Rayleigh waves (blue dotes lines) and apparent dispersion curve: field experimental (green circle) and numerical: blue circles (Roma's method) and red triangles (Lai and Rix method).*

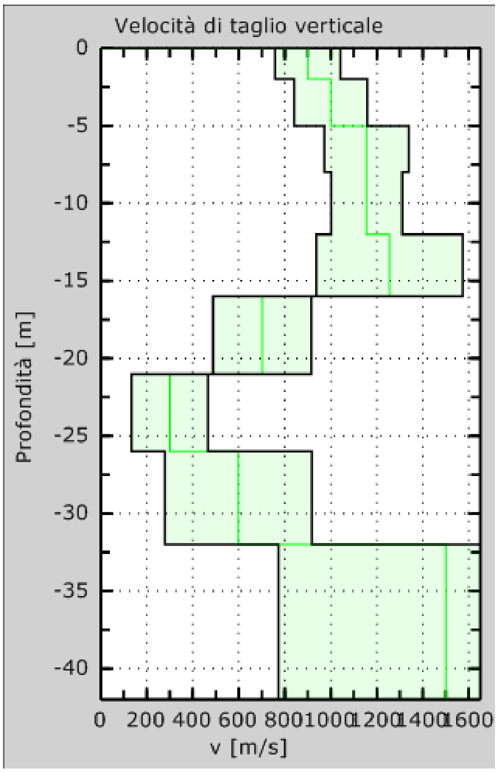

Figure 2 *shear wave velocity Profile Vs (green line) x axis (Vs), y axis (depth) with uncertainty of the results (shadow zone) due to both dispersed data and matching of the experimental and numerical apparent dispersion curve.*

Description of the field equipment

The seismograph used for the data measurements works with a 24 bits A/D converter, the vertical geophones have an intrinsic natural frequency of 4.5Hz.

Conclusions

The MASW-REMI is a powerful method for site seismic characterization. The combination of the active MASW and the passive REMI allows to determine the apparent or effective experimental dispersion curve over a broad range of frequencies, included the low frequencies which contain information about deeper layers of the ground. In general cases the MASW-REMI method is reliable only if the apparent or effective dispersion curve is used. The apparent dispersion curve is a combination of both the fundamental mode and higher modes of Rayleigh waves. If only the fundamental mode or separated higher modes are used the method is not reliable in most of the sites. It is well known that the identification of higher modes by the professional is affected by great uncertainty and that mis-identification of the mode number implies a final incorrect Vs profile. Hence all the algorithms that consider the higher modes, but perform the inversion of the Vs profile considering the higher modes separately from each others, are likely to generate not reliable results.

The proposed algorithm overcomes the great difficulty of identifying a priori the higher modes from the experimental measured f-k spectrum. The algorithm in fact performs the inversion of the Vs profile, by considering the apparent or effective dispersion curve, which is already the superposition of all the higher modes. This procedure is analytically rigorous and also avoids subjectivity in selecting a priori the higher modes.

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