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ESTIMATION OF SHEAR-WAVE VELOCITY-DEPTH MODELS USING LOVE SURFACE WAVES RECORDS: A COMPARISON WITH OTHER SEISMIC METHODS

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Abstract

Within the methods focused on geotechnical characterization of soils for Civil Engineering applications, geophysical methods have excelled in measuring shear waves due to its effectiveness and low cost compared to traditional invasive methods. Among the geophysical methods, propagation and recording of seismic waves have been the key to measure parameters such as compressional and shear-wave velocities, which are strongly related with the major geotechnical parameters of interest. Because Love and Rayleigh waves provide a large percentage (~70%) of the seismic energy, one of the most widely used techniques is based on dispersion curves modeling of surface waves. The phase velocity of these waves depends mainly on the shear-wave velocity and allows to compute the average Vs30 parameter.

This work aims at developing a complete methodology based on Love surface waves analysis to determine one dimensional structures of shear-wave velocity versus depth, and to compare this method with the modeling of refracted SH body waves, and other procedures based on the analysis of Rayleigh surface waves typically used in geotechnical studies, such as MASW and ReMi methods.

The Love waves are formed by constructive interference of SH body waves propagating below the earth surface, and their phase velocity depends on frequency, but not on the propagation velocity of the compressional P-wave. This feature represents an advantage in the use of Love instead of Rayleigh waves, decreasing the number of variables required for the modeling of dispersion curves in order to get shear wave velocity-depth models.

The application of the Love Surface Wave Method (LSWM) is carried out on seismic SH wave data, acquired using a horizontal source as well as the transversal horizontal component of geophones. Overall, the dispersion curves modeling shows strong sensitivity to the variation of the properties of the medium at high frequencies, indicating good resolution at shallow depths and a decreasing sensitivity and resolution at higher depths, especially in the absence of low frequencies in the records.

The comparative analysis between the LSWM and the other seismic methods shows that, at least down to 25 m deep, all the resulting shear wave velocity models are concordant, with a decreasing correlation between them at greater depths probably due to lack of data in frequencies below of 5 Hz and the loss of resolution due to the decreasing sensitivity of dispersion curves at deeper layers.

Keywords: Love waves, Dispersion curves, Geotechnical parameters

1. Introduction

The geotechnical features of soils have become valuable information for civil engineering and construction works. This is particularly important in a country like Chile, where the periodic occurrence of large earthquakes has required the development of methodologies aimed at reducing their damage and consequences. Within this context, over the past decades geophysical methods have contributed significantly and proved to be effective and cheaper than invasive methods typically used for subsurface characterization [1].

Important geotechnical parameters are related to the velocities of elastic waves propagating through the ground. In particular, the shear modulus (or modulus of rigidity μ) has a direct relationship with the shear wave velocity (V_s or β). Velocity determination has become a valuable task in geotechnical and engineering studies of the subsurface, making geophysical exploration methods associated with seismic wave propagation the most widely used techniques in the last decades for the estimation of shear wave velocity structure versus depth. In this context, the use of surface waves has recently taken great relevance because they constitute a large percentage (60-90%) of the energy contained in the seismic records. In recent decades, many methodologies and field configurations have been developed to obtain V_s profiles from surface waves records [1, 2].

Among the surface waves methods currently used for the estimation of shear wave velocity structures versus depth, are the MASW (Multichannel Analysis of Surface Waves, [1]) and ReMi (Refraction Microtremor, [3]) methods. The common feature of these methods is that they are mainly based on the spectral analysis of Rayleigh surface waves, which are measured in the field using tipically the vertical component of the seismic receivers. In the MASW and ReMi methods, the source of surface waves, is however different. While the MASW method uses an active source (hammer or explosives), the ReMi method uses a passive one, capturing the environment noise related to vehicle or airplane traffic, machines, seawaves, etc.

Other less conventional way of obtaining a shear wave velocity versus depth profiles is applying the refraction method using SH waves, that is, using an horizontal active source and the horizontal component of geophones perpendicular to the seismic line. The same records can be used to perform spectral analysis of Love surface waves. The advantage of using either of these methods over MASW or ReMi is that their data modeling is independent of the compressional P-wave velocity, which is a parameter that needs to be estimated independently to be provided to the MASW and ReMi processing.

This work aims at studying the Love surface wave method and compare it with the seismic refraction of SH waves method and other methods as MASW and ReMi.

2. Methodology

Surface waves propagate parallel to the surface of the earth at and under the free surface. Because these waves propagate horizontally, the amplitude decay with distance from the source is less than for body waves, whose propagation is volumetric in all directions. About 70% of the total energy in seismic records seismic energy comes from surface waves [4].

Because surface waves are dispersive, their propagation velocity (phase velocity) depends on the wave frequency [5]. This feature is commonly observed as dispersion curves (e.g. Fig. 1), which can be theoretically calculated from a velocity model and experimentally measured from surface wave data [4, 6].

Love surface waves are formed by SH body waves trapped in the shallow layers near the ground. Similarly, Rayleigh surface waves are composed of suitable combination of P and SV waves, whose components are coupled and also trapped in the shallow layers. Unlike P-SV waves, SH waves do not interact either with P or SV waves.

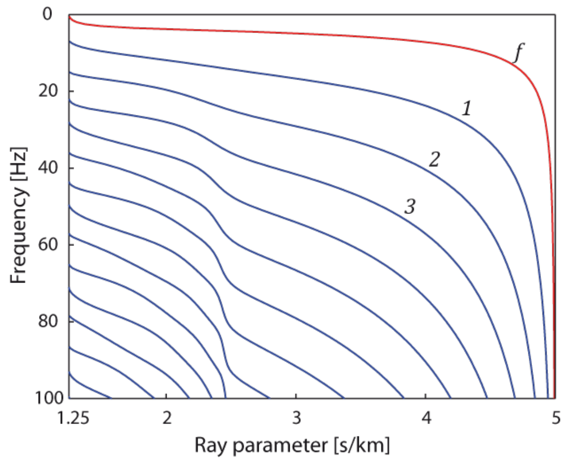

Fig. 1 – Example of dispersion curves of Love waves for a velocity model composed of two layers over an infinite half-space. The red line shows the fundamental mode curve, while the blue lines correspond to the higher dispersion curves modes.

This study develops a methodology for the estimation of shear wave velocity models in depth by applying a spectral analysis of Love surface waves [6] and compare it with the seismic refraction of SH waves method and other methods as MASW and ReMi.

Surface waves methods consist basically of three stages: data acquisition, spectral analysis of dispersion curves and data modeling.

2.1 Data acquisition

The acquisition of SH/Love waves data is similar to the typical acquisition for seismic reflection and refraction methods, but in the SH/Love case a horizontal source and horizontal receivers are used instead of vertical source and receivers used in P-waves velocity studies. Horizontal source is based on hammer blows applied on a wooden beam placed on the ground. During this stage, the beam is struck repeatedly at both ends to increase the signal-to-noise ratio and produce reversed polarities of the SH arrivals that make them easy to recognize. An increase on spatial resolution can be achieved by increasing the amount of receivers and decreasing the distance between them.

A set of seismic data was acquired in Laguna Caren, Santiago (Pudahuel), Chile (Fig. 2a). The seismic data set includes active vertical source measurements for MASW, passive source records for ReMi and active horizontal source data for the SH refraction and LSWM methods. Data were acquired on two seismic lines (L1 and L2) of 24 geophones (4.5 Hz) every 5 m (Fig. 2b). The sampling interval was 0.5 ms for the active source experiments and 4 ms for the passive measurements, with a time length of 3 or 60 s respectively.

2.2 Spectral analysis of dispersion curves

The spectral analysis of surface waves is carried out by the transformation of seismic (x,t) domain records into the frequency-ray parameter (f, p) domain. This process involves the application of a Tau-p transform [7] over the (x,t) records followed by a Fourier transformation in time domain. The outcome of this procedure is frequency-ray parameter (or slowness) domain seismograms, whose amplitude peaks correspond to the dispersion curves required for the modeling process.

The application of this process in LSWM is performed using a software developed during the thesis work described in [6], which allows the visualization and digitalization of dispersion curves. For active MASW and ReMi methods a Geopsy software (freely available at www.geopsy.org) was used.

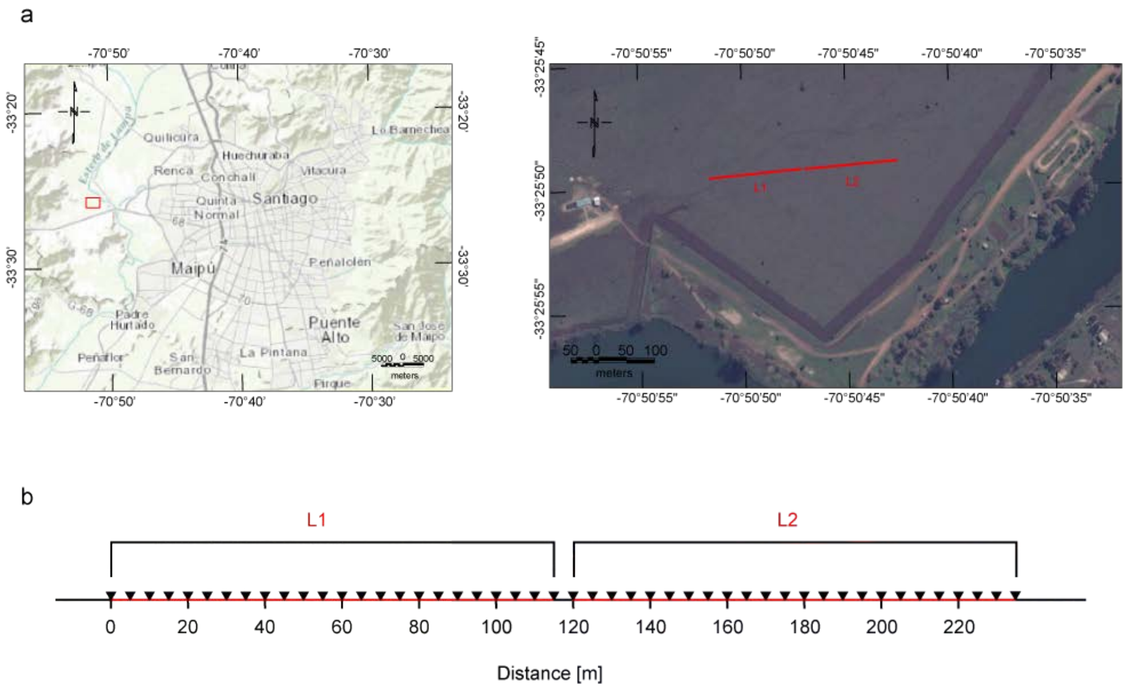

Fig. 2 – Data acquisition in Laguna Caren. In (a), the red box to the left shows the study area presented in the figure on the right, where the position of the seismic lines L1 and L2 is presented as red lines. In (b) the geometry of data acquisition is shown, where the position of receivers (geophones) is observed as black filled triangles.

2.3 Data modeling

The modeling assumes a homogeneous layered velocity model from which theoretical dispersion curves are computed. The observed dispersion curves are adjusted by theoretical ones, allowing the determination of a shear wave velocity model versus depth.

The application of this process in LSWM is made running a software described in [6], which allows the forward modeling of Love dispersion curves by an interactive adjustment. For MASW and ReMi methods a Geopsy module called Dinver was used.

3. Results and discussion

Following the methodology described in the section 2, the LSWM was applied and the results were compared with those obtained by seismic SH refraction method and other techniques based on spectral analysis of Rayleigh surface waves (active MASW and ReMi).

3.1 LSWM results

Fig. 3 shows the spectral analysis of Love surface waves applied on the data set acquired in Laguna Caren, observed in the frequency-ray parameter (f, p) domain. It's possible to identify the fundamental mode dispersion curve in a frequency range between 2 and 15 Hz. In other seismic experiments carried out in the Chile Central Valley [6], was in general difficult to obtain data for frequencies below 10 Hz. In this particular data set, however, lower frequencies are reached allowing definition of deeper layers. At higher frequencies, higher modes dispersion curves are observed, but they are not considered in this study to simplify the comparative analysis.

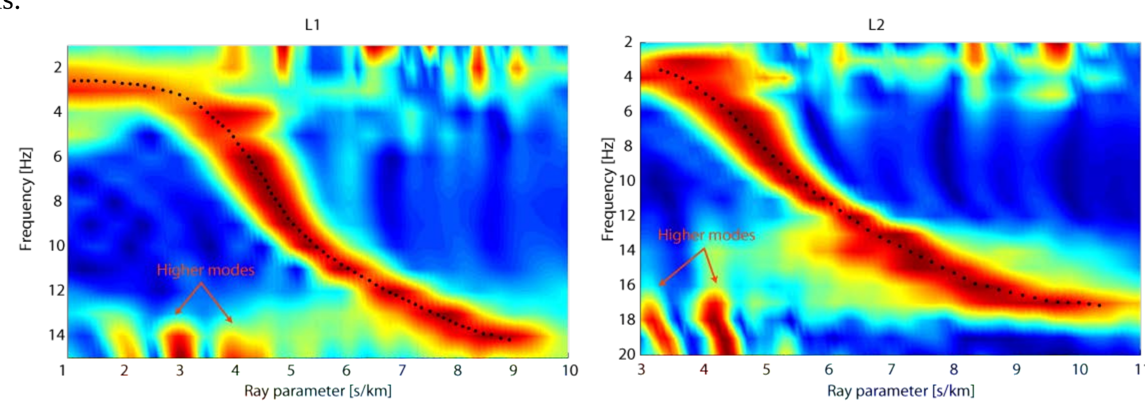

Fig. 3 - Spectral analysis of Love waves for L1 and L2. The black dots represent the interpreted and digitized fundamental dispersion curve mode. The position of the seismic source was at x = 120 m and x = 240 m for lines L1 and L2, respectively.

Fig. 4 presents the shear wave velocity models and the corresponding dispersion curves compared with the observed dispersion curves points for L1 and L2 lines. The L1 velocity model indicates increasing velocities with a penetration depth of at least 40 m. A shallow structure of 3 low velocity layers (56.5 m/s, 185 m/s, 260 m/s) in a total thickness of 26 m is followed by significant velocity jump to 800 m/s down to a depth of ~40 m. The L2 model, on the other hand, shows a similar trend, with 55 m/s velocity at the surface layer reaching 280 m/s at a depth of ~25 m, where also a significant velocity change to 800 m/s is observed.

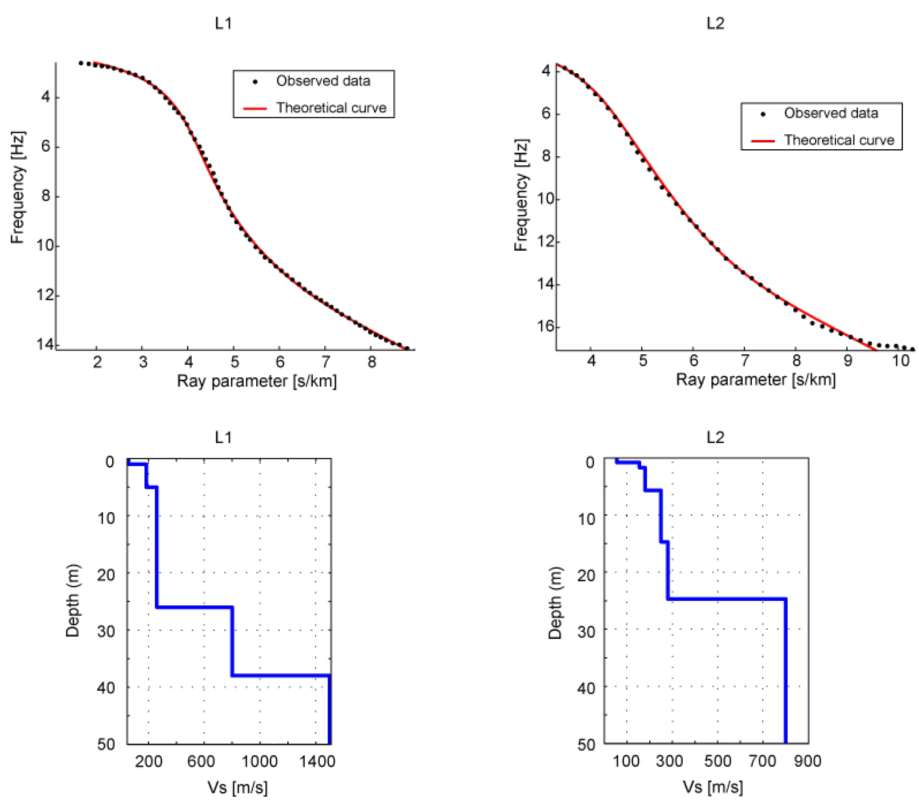

Fig. 4 - Data modeling for LSWM. The figure below shows the resulting V_s models from the adjustment between the observed (black dots) and theoretical (red line) curves shown in the figure above.

The dispersion curves sensitivity is not uniform for all frequency values [7], being more sensitive to the shallow layers properties (higher frequencies), losing sensitivity and resolution at deeper layers.

3.2 Comparison between LSWM and other seismic methods

3.2.1 SH refraction method

The estimation of a shear wave velocity model can be done in a straightforward way by applying the refraction method to SH waves. In this method, the first arrival travel times of SH body waves are identified on seismic records produced by a horizontal source and acquired by transversal seismic receivers. Fig. 5 shows the recorded seismic data, where first arrival travel times of SH waves and the Love surface waves train are clearly observed.

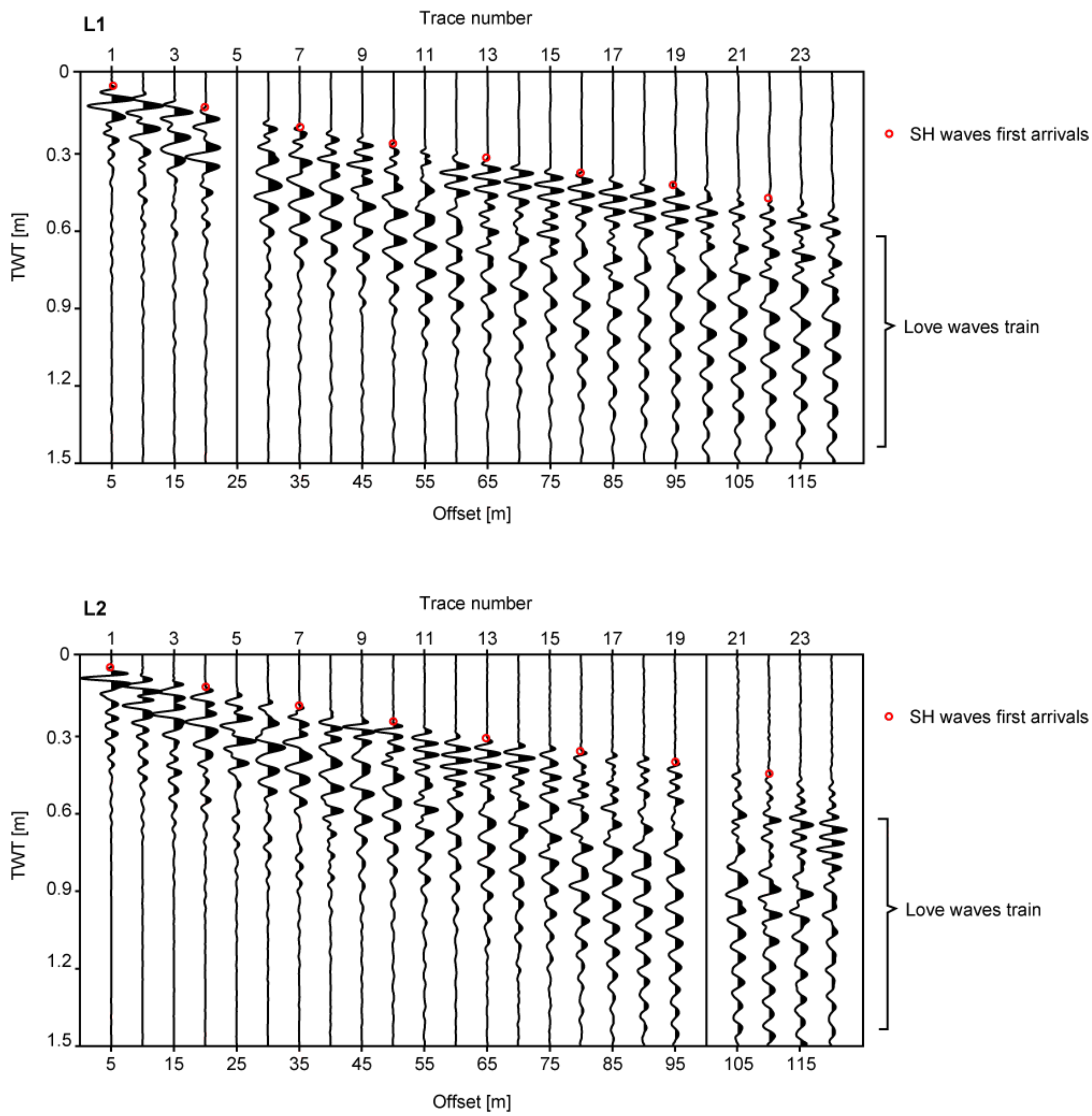

Fig. 5 - SH records used in SH refraction and LSWM methods. At the top it is possible to identify the first arrival travel times of SH body waves (e.g. red circles), while in the lower portion the Love surface wave train is observed. The position of the seismic source was at x = 120 m and x = 240 m for lines L1 and L2, respectively.

Fig. 6 presents the first arrival travel times modeling and the resulting shear wave velocity profile. The LSWM velocity model is also shown for comparison. Both LSWM and SH refraction models show consistent results for L1 to at least a depth of 25 m. The refraction method cannot penetrate beyond ~30 m in depth and is not able to see the major velocity jump showed in the LSWM model. Similarly, L2 shows an increasing velocity with depth model which agrees with the LSWM model down to about ~25 m. As in L1, the refraction method is not able to see the major velocity change evidenced by the LSWM model.

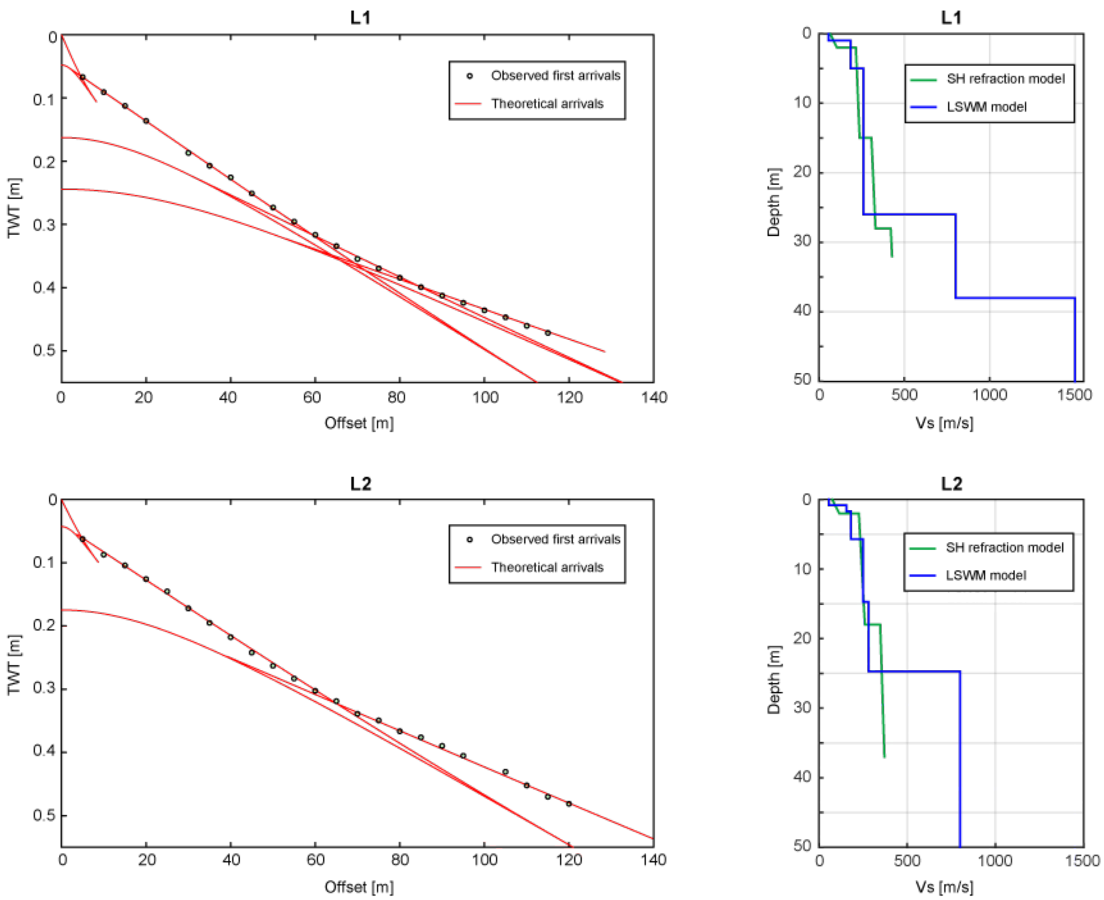

Fig. 6 – SH waves first arrivals modeling. The figures on the left show the adjustment between the theoretical (red line) and observed arrivals (black circles). The figures on the right show the resulting models (green line) and the LSWM model for comparison.

3.2.2 Rayleigh surface waves methods

Active MASW and passive ReMi methods have been widely used in geotechnical characterization to, for example, determine the Vs30 parameter. Both methods are focused on the estimation of one dimensional S wave velocity profiles vs depth by dispersion curves modeling. The main difference between Rayleigh waves methods and the LSWM is that the former depend theoretically on both the S-wave velocity (Vs) and the P-wave velocity (Vp), while Love waves do not depend on Vp. Even when the propagation properties of Rayleigh waves are more sensitive to Vs than Vp, there is one more parameter that affects the robustness and quality of the results as compared to the Love surface waves method.

Fig. 7 shows the spectral analysis of dispersion curves for the MASW and ReMi methods for L1 and L2. Dispersion curves agree in a frequency range between 4 and 12 Hz for both seismic profiles and methods. No major differences are observed between both seismic lines. In both cases, a curve appearing below the fundamental mode in the MASW is observed at a slowness of 3 s/km and 12 Hz frequency. This curve could represent a higher mode dispersion curve, which is however not seen in the ReMi method, probably due to the lack of required energy to excite the surface waves higher modes.

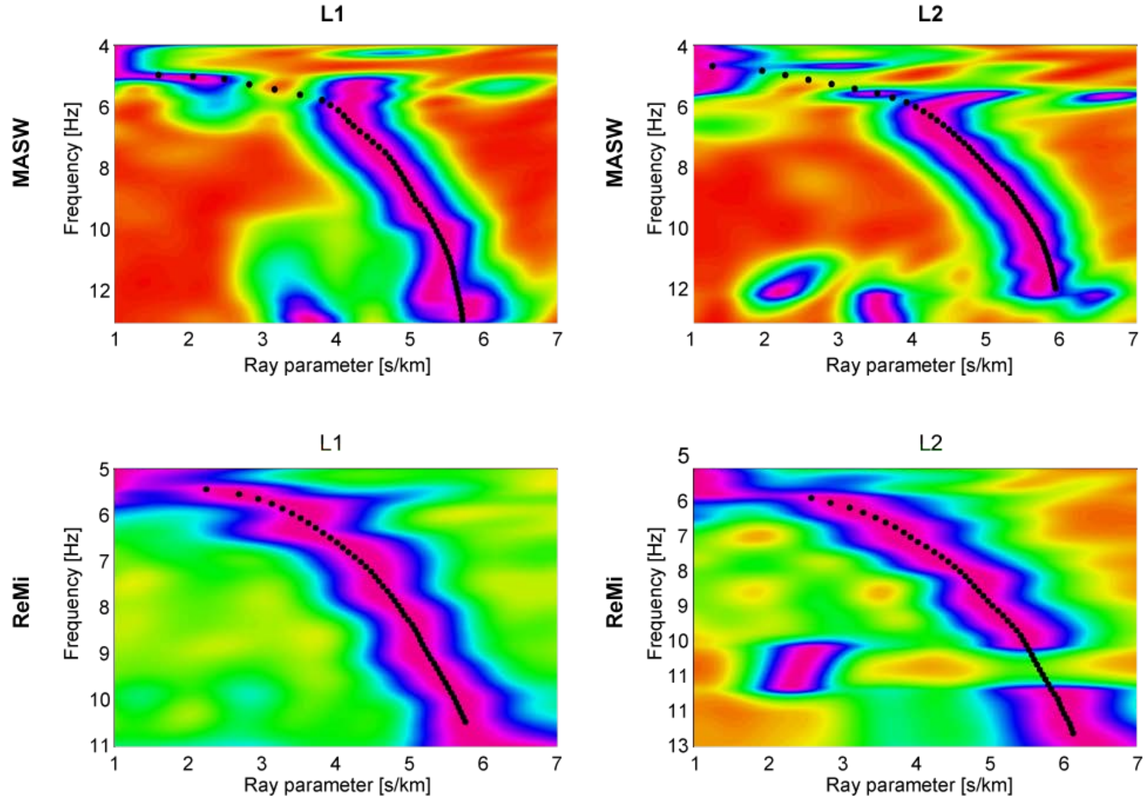

Fig. 7 - Spectral analysis of Rayleigh waves for L1 and L2. The black dots represent the interpreted and digitized fundamental dispersion curve mode. The position of the seismic source for the active experiment was at x = -2.5 m and x = 117.5 m for lines L1 and L2, respectively.

Even when higher frequencies from MASW and lower frequencies from ReMi were expected, the dispersion curves (Fig. 7) indicate that both active and passive records contain energy in a similar frequency range. This could be explained considering that the frequency content of the signal does not depend only on the frequency content of the seismic source, but also on other important parameters as the seismic structure, the line geometry, the frequency response of geophones, etc.

Fig. 8 shows the shear wave velocity models and the corresponding dispersion curves compared with the observed dispersion curves points for L1 and L2 lines. Consistent results are observed down to ~25 m deep, with a shallow low velocity structure between 50 and 150 m/s. Velocities between 280 and 390 m/s are observed down to depths of ~30 m, where a major velocity increase is observed up to 800-1500 m/s. At greater depths than ~25 m the results differ probably due to the decreasing sensitivity of the dispersion curves at lower frequencies (deeper layers).

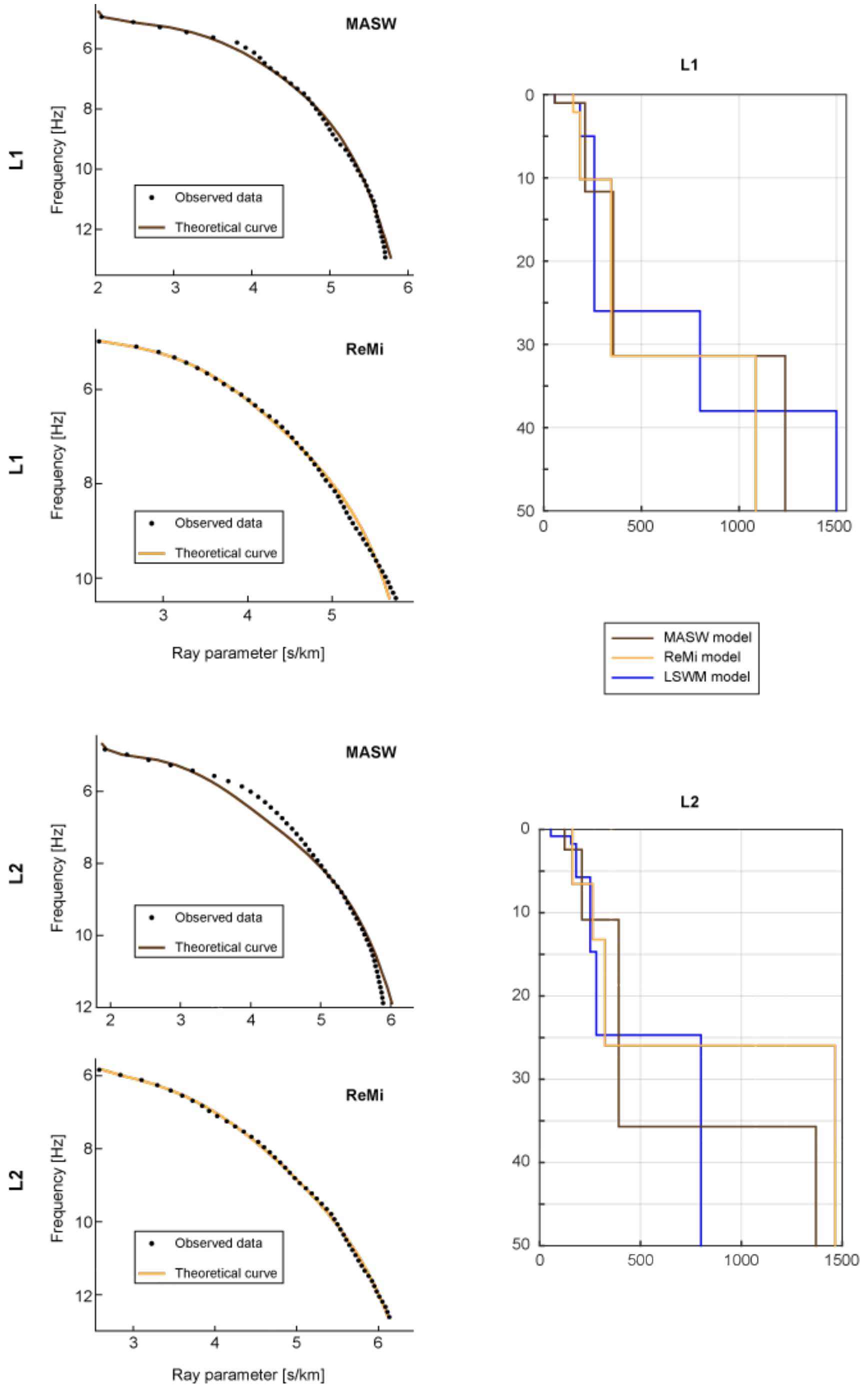

Fig. 8 - Data modeling for MASW and ReMi methods. The figures on the right shows the resulting V_s models from the adjustment between the observed (black dots) and theoretical (brown and yellow lines for MASW and ReMi, respectively) curves shown in the figures on the left. The LSWM model is also showed for comparison.

3.3 Discussion

The comparative analysis of the seismic methods shows in general concordant velocity models. Similar S-wave velocities are observed down to ~25 m. The models tend to differ at greater depths, where a significant velocity jump is observed. The only technique that did not recognize the velocity change was the refraction method SH waves, probably due to lack of penetration, or not enough source-receiver offset.

Because their processing do not depend on P-wave velocity, the LSWM and SH refraction methods are considered as the most suitable methods for the estimation of one dimensional shear wave velocity structures versus depth.

A practical exercise is to compare the V_{s30} parameter estimated for each of the resulting V_s models. Table 1 shows the value of this geotechnical parameter for all V_s models of the two acquired data sets. The V_{s30} values are very similar, between 231 and 278 m/s, corresponding to a soil that can be classified as a D-type soil, of moderately dense or firm ground [8].

Table 1 –V_{s30} parameter calculated from all the estimated V_s models.

	Surface waves methods						**Body waves methods**	
	LSWM		MASW		ReMi		SH refraction	
	L1	L2	L1	L2	L1	L2	L1	L2
V_{s30} (m/s)	231	248	247	252	256	278	236	248

While a different frequency range (10-40 Hz) was expected for the active measurements (as seen in [6]), the dispersion curves show that both active and passive records contain energy in a similar lower frequency range (4-14 Hz). In future works it is strongly recommended to study the role of the velocity structure and different field configuration parameters on the frequency content of the surface waves seismic records.

4. Conclusions

The developed methodology based on spectral analysis of Love surface waves and dispersion curves modeling appears as a good alternative to estimate one dimensional shear wave velocity structure versus depth. Among other issues, this can be used to obtain geotechnical parameters such as V_{s30}, of great relevance in geotechnical and engineering studies for the application of standard regulations about the seismic design of structures.

The main difference between MASW and ReMi methods and the LSWM is that the former depend theoretically on both the S-wave velocity (V_s) and the P-wave velocity (V_p), while Love waves do not depend on V_p. Even when the propagation properties of Rayleigh waves are more sensitive to V_s than V_p, there is one more parameter that affects the robustness and quality of the results as compared to the Love surface waves method.

The comparative analysis between the LSWM and the other seismic methods showed that at least down to a depth of ~25 m, all the resulting Vs models are consistent, with a decreasing correlation between them at greater depths probably due to lack of data in frequencies below 5 Hz and the loss of resolution due to the decreasing sensitivity of dispersion curves at greater depths.

The LSWM and the refraction of SH waves methods stand out over the MASW and ReMi methods as their data processing and dispersion curves modeling is simpler. It is important also to note that the LSWM and the SH refraction method make use of the same data, but use a different portion of the records; while the LSWM use the Love surface wave train for the spectral analysis, the refraction of SH waves method is based on first arrival travel times modeling. In both cases the resulting models are consistent, although the LSWM showed further penetration.

Altough unexpected, the spectral analysis of surface waves showed that the frequency range where dispersion curves can be identified was about the same for both active and passive experiments. This feature may be the result of local velocity structure characteristics or the used field configuration. It is important to study the frequency range nature observed in the records, which depends mainly on the velocity structure and the field configuration. A good understanding of the frequency nature on seismic records could extend the frequency range at both ends, high and low frequencies, allowing better constrained models in both shallow and deeper layers respectively.

5. Acknowledgments

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