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The use of Rayleigh wave ellipticity for deeper V_s profile identification—a case study in Lisbon city

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ABSTRACT: The shear wave velocity (V_s) profile of the soil and bedrock depth can be determined using surface wave methods. These are non-invasive and can be used to determine small-strain stiffness profiles. Their main drawbacks are associated to the non-uniqueness problem of the solution and increasing uncertainty with depth. The combination of different seismic data, active and passive tests, helps to reduce the uncertainty of the results and increase the investigation depth. In this study the V_s profile of the soil of a site located in a densely urban area of Lisbon, confined by the subway tunnel and an underground car park, was identified using different surface wave data, through the joint inversion of the experimental Rayleigh wave ellipticity curve and active-source dispersion curve. The consideration of the ellipticity curves in the analysis allowed to reduce the uncertainty of the results, increase the investigation depth and helped to avoid mode misidentification.

1 INTRODUCTION

The characterization of the mechanical properties of the soil can be made through laboratory tests or in situ tests. Current in situ tests, such as SPT tests (Standard Penetration tests) and CPT tests (Cone Penetration tests), provide information associated to a point in depth. Mechanical properties are mainly estimated based on empirical correlations and thus the reliability of the results depends on the suitability of those correlations. In these tests, small strain stiffness is not characterized due to the perturbations induced to the soil during the execution of the tests.

Laboratory tests can be used to accurately determine soil properties and study complex stress paths. However those results are associated to a small sample which may not be representative of the site and depend on sample quality. Small strain stiffness can be determined using appropriate equipment, using laboratory tests that are sensitive to very low deformations such as resonant column tests or cyclic torsional loading tests (Santos 1999).

Surface wave methods provide information at a larger scale and are able to determine the shear wave velocity soil profile and thus small-strain shear modulus, based on the dispersive characteristics of surface waves. These methods do not imply the execution of boreholes and only use recordings of vibrations performed at the surface using several sensors. The accuracy of the results depends on many factors, such as soil variation along the acquisition array, soil properties, setup of the array, properties of the used equipment and source type and distribution. Active measurements are in general used to estimate the shear wave velocity of the soil layers near the surface and passive tests provide information associated to deeper layers. The main shortcoming of these methods is the non-uniqueness of the solution. Shear wave velocity values are obtained through the inversion of dispersion curves, however many velocity profiles are compatible with the acquired seismic data. By combining different seismic data it is possible to reduce the number of compatible velocity profiles and thus improve the reliability of the results. The combination of active and passive tests allows to obtain velocity profiles that are well resolved near the surface and increase the investigation depth.

The MASW (Multichannel Analysis of Surface Waves) is a surface wave method that uses active linear array acquisitions for the estimation of the shear wave velocity profile of the soil through the inversion of Rayleigh wave dispersion curves (Park et al. 1999; Foti 2000; Gabriels et al. 1987; Lopes 2005) e ReMi (Refraction Microtremor Array). Since active source is used, shallow layers are well resolved. For a better constrain of deeper layers, passive test results may be considered in the inversion process, such as Rayleigh wave dispersion curves, SPAC curves or dispersion curves obtained through ReMi method (Louie 2001).

The fundamental frequency of the soil layer can be determined using the HVSR method (Horizontal-to-Vertical Spectral Ratio) (Nakamura 1989, 2000). This technique uses ambient vibration three-component single-station measurements performed at the surface. According to the author of the technique, the peak frequency is a good estimate of the fundamental frequency of the soil layer. It has been successfully applied in many site effect studies (Field 1996, Guéguen et al. 2006, Lombardo et al. 2001). Its reliability depends on the impedance contrast between soil and bedrock, showing better results for higher contrasts (Konno & Ohmachi 1998).

The HVSR curve can be used in association with other seismic data for the estimation of the shear wave velocity profile of the soil, for example, inversion of the dispersion curve and HVSR peak frequency. The inversion of HVSR curve alone is not recommended once there is a big trade-off between thickness and velocity values of the layers. As a consequence, there are numerous profiles that present similar HVSR curves. Furthermore, modelling HVSR curves is challenging because these curves are affected by source type and distribution and modelling HVSR curves implies the assumption of determined wavefield composition that may not be compatible with the recorded signal.

As an alternative, the Rayleigh wave ellipticity curve can be jointly inverted with Rayleigh wave dispersion curves (Fäh et al. 2009, Hobiger et al. 2009, Hobiger 2012). By this means, active seismic linear data can be used in association with passive single-station data for the estimation of the velocity values of shallow and deeper layers. Passive Rayleigh wave ellipticity curves can be used as an alternative to passive non-linear methods (ex.: SPAC) when those are not possible to implement, for example, due to space limitations which is a common issue while performing seismic tests in densely urban areas.

In this study, the shear wave velocity profile of a site located in a densely urban area, between underground structures and with high noise level. The fundamental frequency of the site, at several points, was determined using the HVSR method. The V_s profile was estimated through the joint inversion of Rayleigh wave dispersion and ellipticity curves. The latter was computed using the RayDec method, developed by Hobiger (2011). Results showed that the addition of the passive single-station recording, which is very simple to obtain, allowed to reduce the uncertainty of the results, increase the investigation depth and helped to avoid mode misidentification.

2 GEOLOGICAL SETTING AND DATA ACQUISITION

In this study different surface wave methods were applied to active linear and passive single-station recordings for the estimation of the shear wave velocity profile of a site located in the city of Lisbon.

The area is located in Saldanha, Lisbon, next to Fontes Pereira de Melo Avenue. The area is here referred as corresponding to confined conditions once it is located between the subway tunnel and an underground car park.

A schematic location of the study area and single-station and linear array acquisitions is presented in Figure 1. It includes the location of boreholes where SPT tests were performed. The materials identified in those boreholes are presented in Figure 2, as well as the SPT results extrapolated to 30cm penetration depth, in order to emphasize the stiffness contrast between layers.

Figure 1. Schematic location of ambient vibration single-station recordings (yellow dots), boreholes (red dots) and acquisition lines.

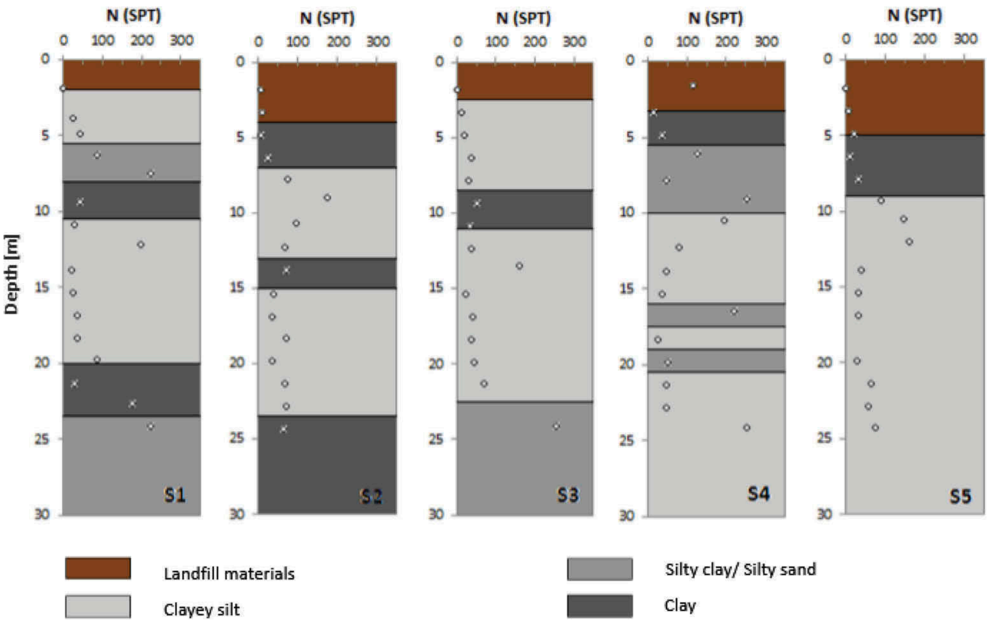

Figure 2. SPT test results and materials identified in boreholes S1-S5.

According to the borehole data, the lithology of the site is composed by heterogeneous landfill materials (N(SPT) between 4 to 27 blows) with 2 to 5m thickness, over a Miocene unit known as “Argila dos Prazeres”, mainly composed by levels of stiff clay and silt (more than 24 blows).

Higher N(SPT) values are in general associated to levels of marl and/or limestone. Stiffer materials were identified bellow 7m depth, including a reduction of stiffness around 15-18m depth where organic materials were detected.

Two types of seismic data were acquired: active linear array measurements (SWM1) and ambient vibration single-station recordings (points 1, 2, 3, 4, 5 and 6) (Fig. 1).

Active source linear array measurements were made using a 24bits seismograph (RAS-24, SEISTRONIX), connected to vertical geophones with 4.5Hz (GEOSPACE). The data was retrieved from 24 geophone linear spread with 1.5 m spacing. The active source distance from the first geophone was defined as 1.5 m and the recorded signal was generated using a 10kg sledge hammer. Several signals were recorded with a sample frequency of 1000Hz and 2s of duration. In total, a minimum of 20 signals were recorded, 10 for forward shot and 10 for backward shot in order to allow posterior stacking of the signal.

The ambient noise single station measurements were made using a recorder unit MR2002-CE (SYSCOM) and an external three-component velocity sensor (MS2003+, SYSCOM) that presents the same characteristics for the three components and a flat response between 1 and 350Hz. Time series were recorded during 35 to 40min, with a sample frequency of 400Hz and under favorable weather conditions, i.e., weak wind and no rain. The data was detrended, baseline corrected and bandpass filtered between 0.5Hz and 200Hz in order to avoid excessive distortion of the signal and aliasing, respectively.

3 METHODOLOGY

In this study, the HVSR and the RayDec methods were applied to single-station measurements and used to compute the experimental HVSR curves and Rayleigh wave ellipticity curves, respectively. The shear wave velocity profile was obtained through the joint inversion of the ellipticity curve and dispersion curve. The latter was obtained by applying the MASW method to active source linear array recordings.

3.1 *HVSR method*

The HVSR curves were computed using the freeware program GEOPSY (www.geopsy.com). The average curves were calculated considering time windows with 30s that were not associated to transient sources. The number and length of the time windows were defined in order to obtain representative results, i.e., including minimum number of cycles depending on the frequency of interest. The reliability of the results was evaluated according to the recommendations defined on the scope of SESAME European project, which include stability criteria and definition of the peak.

3.2 *RayDec method*

The experimental Rayleigh wave curves were computed using the RayDec method (Hobiger 2011). The average curve was calculated considering 5min length time windows (total length of the recorded signals varied between 30 to 40 min), corresponding to the geometric mean of all ellipticity curves associated to each part of the signal. The computation of the referred curves has two free parameters. The length of the buffered signal (Δ) and the width of the frequency filter (df) were defined as a function of frequency, corresponding respectively to 10/f and to 0.2f (Hobiger 2011).

3.3 *Identification of the velocity profile*

The active source dispersion curves were identified using the Linear F-K tool box available in GEOPSY program. The signals associated to the same source location were filtered and stacked before the calculation of the f-V spectra. The dispersion curves of forward and backward shots were compared in order to analyze the variation of soil properties along the acquisition lines. The joint inversion of Rayleigh wave dispersion and ellipticity curves was made using Dinver (GEOPSY). In this program, the inversion procedure is made by using the Conditional Neighbourhood algorithm (Wathelet 2008).

The model was defined with three layers over half-space, with V_s varying between 100-800m/s for soil layers and between 100-1500m/s for half-space. The V_p values were linked to V_s values through the Poisson ratio, defined between 0.2 and 0.5. The density was set up as constant, corresponding to 1800kg/m^3. An equal misfit weight was initially considered during the joint inversion of Rayleigh wave ellipticity and dispersion curves.

4 RESULTS

The HVSR curves calculated using the ambient vibration recordings made at points 1 to 6 (Fig. 1) are presented in Figure 3.

The HVSR curves obtained at points located within the study area (1, 2, 3 and 6) present a well-defined and stable peak frequency. Those curves respect the criteria indicated in SESAME guidelines, indicating that the identified HVSR peak frequencies correspond to the fundamental frequency of the soil bellow those points. The identified peak frequencies and standard deviation, associated to each measurement point, are indicated in Figure 3.

The peak frequency values are very similar, varying between 3.1 and 3.4Hz, as well as the maximum amplitude (between 3.5 and 4.5) suggesting that the variation in soil stratigraphy in the area is not very significant. This is an important factor while applying array methods once in the inversion process it is assumed the hypothesis of horizontal stratification along the acquisition line.

The obtained peak frequencies are relatively high, which is in accordance with the available borehole data and N(SPT) results presented in Figure 2, where stiff materials were identified.

The HVSR curves obtained next to the underground structures, namely the underground car park (Point 5) and subway tunnel (Point 4) present a relatively flat shape, which is in general obtained while performing recordings over bedrock. In this case, this may be associated to complex wave propagation patterns next to those structures, generating vibrations with similar vertical and horizontal amplitudes. Once in these cases the peak frequency is not stable and defined, no frequency values are presented.

The Rayleigh wave ellipticity computed using measurements made at Point 6, located at the middle of acquisition line SWM1, is presented in Figure 4. Its shape follows the shape of the HVSR calculated using the same recordings, but presenting lower amplitude. The difference in terms of amplitude between the HVSR curve and the Rayleigh wave ellipticity curve is associated to the effect of other wave types, including body waves and Love waves.

The Rayleigh wave dispersion curve estimated using stacked signals associated to forward and backward shots are presented in Figure 4, as corresponding to SWM1 - Source SW and SWM1 - Source SE. Both curves are relatively similar indicating that no significant variation is expected in soil stratigraphy along the acquisition line.

The dispersion curves seem regular and present increasing velocity with decreasing frequency. However, a small discontinuity was identified in the V-f spectra, were curves were picked, between 25-35Hz. As an attempt to verify if the entire curves presented in Figure 4 corresponded to fundamental mode, those were inverted, alone. The results, not here presented, were not compatible with the materials and variation of soil strength with depth suggested in the N(SPT) results. The velocity profiles presented a high velocity contrast near the surface (depth lower than 10m) and high velocities values bellow that depth. Those profiles were also not compatible with the HVSR peak frequency identified at Point 6. This suggest that, at least the part of the curve identified at frequencies lower than 25Hz may correspond to a higher mode and not to the fundamental mode.

For inversion purposes, only the dispersion curve defined for frequencies higher than 30Hz was considered, as well as the left (between 1.4 and 2.4Hz) and right (between 4.3 and 5.0Hz) sides of the Rayleigh wave ellipticity curve. The difference between the results obtained using the dispersion curve associated to Source NW and Source SE, within the referred frequency range, were not significant. Therefore, only the results obtained through the joint inversion of

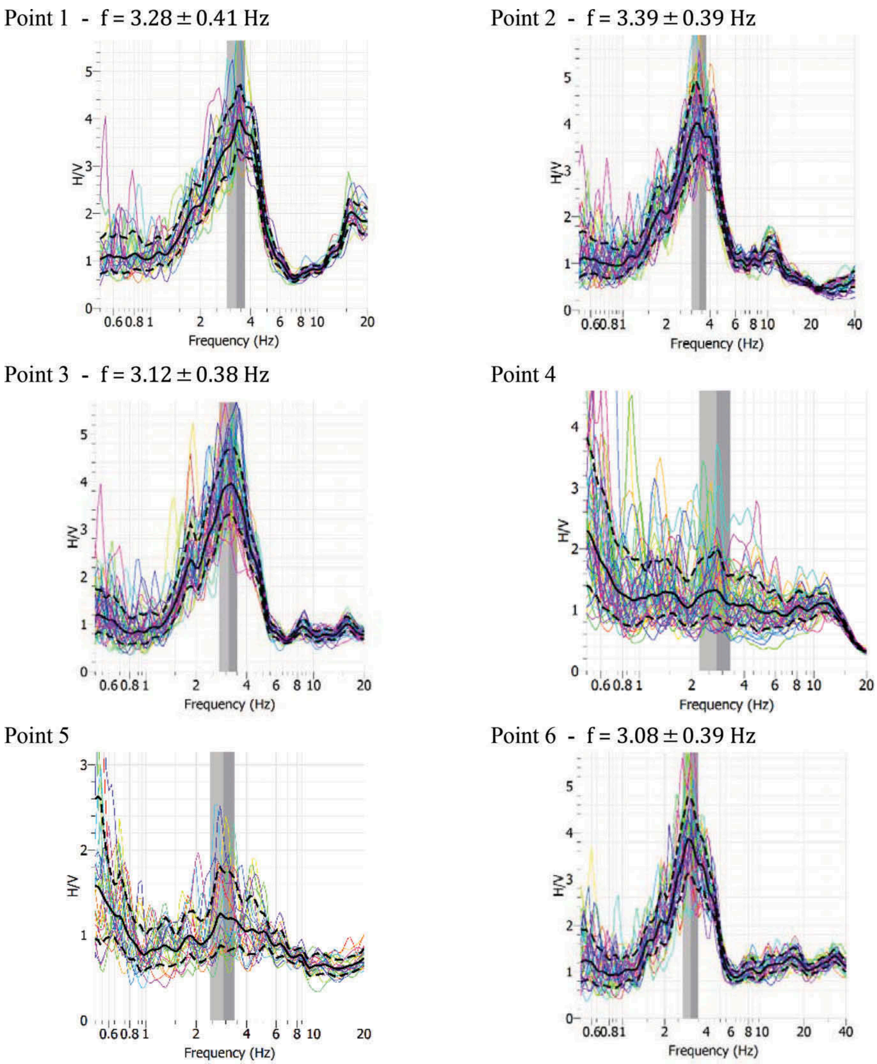

Figure 3. HVSR curves computed using ambient vibration single-station recordings and peak frequencies.

the dispersion curve SWM1 – Source SE, defined for frequencies higher than 30Hz, and the left and right sides of the ellipticity curves are presented (Fig. 5).

The shear wave velocity model associated to the lowest misfit is presented in Figure 5, as well as shear wave velocity values calculated based on the N(SPT) -V_s correlations developed by Ohta & Goto (1978), for all soil types, and developed by Pitilakis et al. (1999), for clays. For this purpose, the N(SPT) values obtained in boreholes S3, S4 and S5, whose location is presented in Figure 1, were used.

The shear wave velocity profiles obtained through the joint inversion process were relatively well constrained at deeper layers. This was not achieved while inverting the active-source fundamental mode dispersion curve alone. The velocity values are within the expected values for the materials identified in the boreholes.

The comparison between the velocity model obtained with seismic tests and the velocity values calculated based on the N(SPT) results is merely qualitative. In general, velocity values obtained using different correlations can present a wide variation. In this case, only the results obtained with Ohta and Goto (1978) and Pitilakis et al. (1999) are presented, since those were

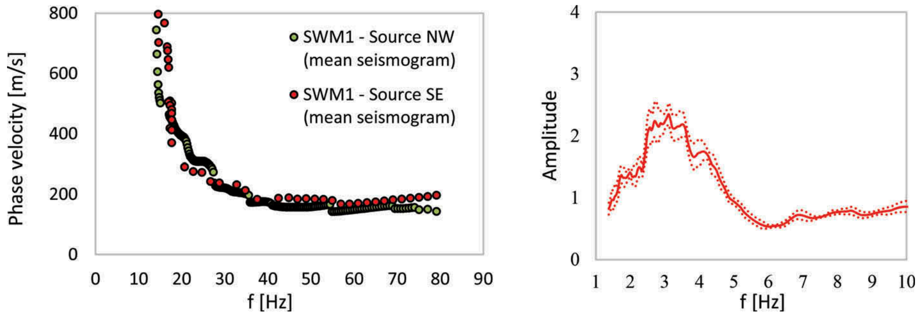

Figure 4. Rayleigh wave dispersion and ellipticity curve (Point 6).

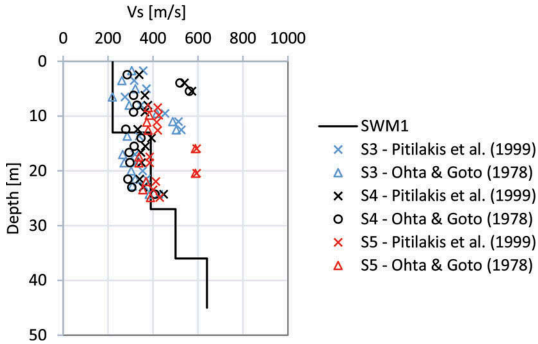

Figure 5. Shear wave velocity profile (minimum misfit) obtained through the joint inversion process (black line) and V_s values estimated using N(SPT)-V_s correlations from Ohta & Goto (1978) and Pitilakis et al. (1999).

the ones that presented a better match with the V_s model obtained through the seismic test. Below 10m depth, the results obtained based on N(SPT) -V_s correlations and the results estimated with the seismic tests are fairly compatible, however a significant difference can be identified at shallow layers. The difference between the results might be associated to the variability of these layers along the acquisition line.

The local variations in soil strength, qualitatively identified in SPT test, especially in boreholes S4 and S5, are not represented in the V_s profile obtained through the joint inversion process. Most of those stiff materials were not verified at the same depth in all boreholes. In general, those correspond to local variations that are not continuous over the acquisition line. Once V_s profiles obtained through seismic tests may represent soil properties along the acquisition line, non-continuous local variations are not identified.

5 CONCLUSIONS

In this study, the shear wave velocity of a site located in a urban area under confined conditions, i.e., between underground structures, was identified using surface wave methods, namely through the joint inversion of the active-source Rayleigh wave dispersion curve and passive Rayleigh wave ellipticity curve. In this case, the space available for the implementation of the arrays was limited due to the occupation of the car park where acquisition line SWM1 was placed.

The existence of prior geological information, the borehole data, was advantageous because it allowed to identify incompatibilities between the velocity models obtained with the inversion of the dispersion curve alone. Those incompatibilities were verified due to the misidentification of the fundamental mode, in the first stage. However, the analysis of the compatibility between those velocity models and the HVSR curves or the Rayleigh wave curve would also indicate that issue.

The experimental Rayleigh wave ellipticity curves were in this study used as a toll to avoid the incorrect identification of the fundamental mode. Its consideration in the joint inversion process also provided a better constrain of the deeper layers, increasing the investigation depth and helped to reduce the uncertainty of the results.

Local variations in soil stiffness were not represented in the velocity models obtained through the joint inversion of the dispersion and ellipticity curves. Those variations were identified at thin layers and were not continuous along the study area. The obtained velocity models are representative of the soil profile along the acquisition line and in general, those values are compatible with the identified materials.

Good results can be obtained through the joint inversion of active and passive source dispersion curves. However, the implementation of wide arrays is not always possible, especially in dense urban areas. The advantage of considering the Rayleigh wave ellipticity curve, is that it only implies the execution of a single-station measurement which is very easy to make.

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