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Deeper V_s profile constraining the dispersion curve with the ellipticity curve: A case study in Lower Tagus Valley, Portugal

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ABSTRACT

Shear wave velocity profile and bedrock depth are key parameters for seismic site response estimation and a reliable tool to evaluate liquefaction potential in soil deposits. They can be determined using in-situ geotechnical tests such as the seismic Cross-Hole (CH), seismic Cone Penetration Test (SCPT), seismic Dilatometer Test (SDMT), or through geophysical surface wave methods. The main advantages of surface wave methods are their non-invasive nature and the ability to characterize the shear wave velocity of the soil at a larger scale. However, the investigation depth in general is less than 20 m. Using the Rayleigh ellipticity curve to constrain the dispersion curve from active and/or passive measurements, deeper Vs-profile is obtained.

In this study, the V_s profile of the soil at a site located over Lower Tagus alluvial Valley was obtained using different surface wave methods. For this purpose, ambient vibration measurements using a single three-component seismic station were made, to complement active and passive linear measurements. The Rayleigh wave ellipticity curve was computed from the single station recordings using the RayDec method and dispersion curves were estimated with the array recordings processed using *f-k* based methods: MASW, ReMi and conventional f-k method for non-linear array data. A joint inversion procedure was applied to the data and the results were compared with V_s profiles obtained from direct measurements with Cross-Hole and SDMT tests. The results show that considering the passive ellipticity curve in the joint inversion process with the dispersion curve, it is possible to obtain deeper and less scattered V_s profiles.

1. Introduction

Surface wave methods are nowadays a competitive solution for the identification of shear-wave velocity profiles of the soil [6]. These methods are used to characterize dynamic properties of the soil. For example, the HVSR method [23,24] is used to assess the fundamental frequency of soil deposits, while the MASW (Multichannel Analysis of Surface Waves) is used to obtain the shear wave velocity profile at a large scale [19] in a non-invasive way once they do not imply the execution of boreholes. These methods use records of vibrations measured at the surface, generated by a controlled source (active) or by ambient vibration sources (passive). The resolution of the results and investigation depths depend on several parameters, such as the test setup, equipment, sources and correlation between the recorded events. Active measurements provide in general information at higher frequencies and thus about the shallow layers, while passive measurements are rich in low-frequencies, reaching deeper horizons.

There are different types of array methods that can be used to determine the dispersion curve and those are mainly divided into two groups: i) frequency-wavenumber (f-k) based methods [18,4] and ii) spatial autocorrelation based methods [1,2,9]. The MASW method [25,7] is an f-k based method, mainly known as a linear active method. One of its main advantages, when compared to refraction methods, is that it allows identifying low velocity zones (LVZ), i.e. profiles with velocity inversions in depth.

The ReMi (Refraction Microtremor) method [22] is a passive linear method that also identifies the dispersion curve in the f-k domain. It is convenient in practical terms because it can use the same array used for active measurements (MASW). However, once it is used with a linear array, it is assumed in the formulation that ambient vibration sources are isotopically distributed at all azimuths. When waves arrive obliquely to the array, the estimated apparent velocity is higher than the velocity of the medium. Non-linear arrays overcome this limitation, as they ensure a good azimuthal coverage for all arrival directions, with a

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large aperture to provide a good resolution and a small inter-station distance for good aliasing capabilities can be used [32]. These data can be processed using conventional f-k methods [17,18], high-resolution f-k method [4] or using spatial autocorrelation methods [1,2].

The main issue of surface wave methods is a consequence of its non-invasive nature and is known as the non-uniqueness problem of the solution [8]. The inversion of the seismic data gives a set of velocity models that are compatible with the experimental data.

To exclude profiles that are not compatible with the site, the current practice consists in assessing the profiles that are compatible with available geological-geotechnical data. Furthermore, the inversion of different seismic data types, that provide additional information about the soil structure, helps to increase the accuracy of the results [20,26,28].

In this paper, the Rayleigh wave ellipticity curve identified from passive single-station measurements is used in association with the dispersion curve computed from active and/or passive measurements, through a joint inversion process. By adding information from the ellipticity curve, the number of velocity models that are compatible with all the experimental data is smaller, as the uncertainty of the results. Furthermore, by combining active and passive data, which are rich at high and low frequency range respectively, deeper profiles are obtained.

The Rayleigh wave ellipticity curve is the ratio between the horizontal and vertical component of motion, as a function of frequency. Since the ellipticity curve is tightly linked to soil structure, it can be used to determine the shear wave velocity profile of the soil, for example through a joint inversion with array seismic data [13,15,5]. The inversion of this curve alone provides a Vs profile with large uncertainty.

The experimental ellipticity curve was determined from three-component single-station measurements of ambient vibration using a method based on the Random Decrement Technique, known as RayDec method [13]. This method identifies Rayleigh waves by summing a large number of specially tuned signal windows and the effect of Rayleigh waves is highlighted by taking into account the high correlation between the horizontal and vertical components, after applying a 90° phase shift.

The aim of this work is to evaluate the accuracy of the joint inversion of Rayleigh wave dispersion and ellipticity curves for the identification of the shear wave velocity profile of the soil at a site located in the left margin of Lower Tagus Valley (LTV). The results obtained through the surface seismic methods were compared with shear wave velocity profiles obtained with the Seismic Dilatometer test (SDMT) and the Cross-Hole (CH) test for validation purposes. The inversion of the seismic data can be classified as blind, as the available geological and geotechnical data was not used to constrain the inversion process.

The shear wave velocity profile was obtained by jointly inverting different Rayleigh wave data, namely:

i) Dispersion curve obtained from active linear measurements;
ii) Dispersion curve obtained from passive linear and circular measurements;
iii) Rayleigh wave ellipticity curve computed from passive three-component single-station measurements.

In addition, the HVSR method was used to identify the fundamental frequency of the soil deposit and thus evaluate the continuity of soil layering along the study area, condition that is necessary for the application of the array seismic methods.

It is shown that the joint inversion of the single-station data and the active array provides a reliable velocity profile that is deeper, compatible with other available geotechnical test results. In this case, the passive single-station seismic data, easily obtained and used to compute the Rayleigh wave ellipticity curve, provided rich information in the low frequency range that allowed to increase the investigation depth and reduce the uncertainty of the shear wave velocity profile. Although passive circular array measurements provide rich information at lower frequencies, it did not allow accurately identifying the position of the interface between soil and bedrock. In this case, the single-station measurement, used to compute the ellipticity curve, was important to constrain bedrock depth.

2. Location and geological setting

Under the activities of the EU H2020 LIQUEFACT project ("Assessment and mitigation of liquefaction potential across Europe: a holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters"), a comprehensive ground characterisation was done in the Lower Tagus Valley region, located in the densely populated and developed region of the Metropolitan Area of Lisbon, at central-western mainland Portugal (Fig. 1).

The stratigraphic section across the Tagus delta-estuarine plain shown in Fig. 2 describes the sedimentary infilling of a Late Pleistocene valley, incised into the Tertiary substratum [29]. The late Quaternary unlithified sediments are resting here mainly on Miocene deposits.

The continental deposits (see Fig. 2) are formed by coarse sand, gravelly sand and gravel, poor in fine grained inter-granular matrix, with coarser pebbly lags, organized into metre scale fining upward cycles. The unit top is probably sharp and undulate in shape and it is likely to record primary depositional morphologies.

These continental deposits are globally fining upward, being dominated by silt and argillaceous silts, with clay and fine sand intercalation. Fig. 3 shows Vs generally fluctuating between 250 and 400 m/s.

The marginal marine and prodelta deposits (see Fig. 2) are formed by large volumes of clay, silty clay, and loams, with mollusc bioclasts. The lower 5–6 m record a fining upward evolution, from sand to clay, resulting from true marine environments. Vs values are around 150–200 m/s (Fig. 3).

The tidal bar and channel deposits (see Fig. 2) consist of medium to coarse-grained sand with disturbed clay laminae in a coarsening-upward sequence. Vs fluctuate between 150 m/s and 250 m/s, with average values near 200 m/s (Fig. 3).

The tidal flat and marsh deposits (see Fig. 2) consist of silty clay, loam, clay, silts, with subordinated intercalation of fine grained sand, corresponding to spill over episodes. They rest on the delta-estuarine sands and are limited on the top by the topographic surface. This unit accumulated since the medieval times and was terminated by the modern land reclamation works. The unit can reach a thickness of 10 m, but it is normally just a few metres thick. The Vs profile shows the lowermost values of Vs recorded in the area, often well below 150 m/s (Fig. 3).

Noise measurements were performed along the A10 cross section that crosses the central basin of the LTV (Fig. 2). These measurements were processed to compute HVSR curves [21]. The coupling of the Vs measurements with the HVSR curves supported preliminary considerations on the study area:

- lower frequency peaks, around 0.9–1.1 Hz, are detectable in the central basin. Those peaks may refer to the impedance contrast between the Miocene and the upper deposits, at an average depth of 50–60 m below the ground;
- higher frequency peaks, around 1.5–3.0 Hz, may be highlighted in the central basin. Those peaks may detect a shallow impedance contrast;
- higher frequency peaks, around 1.5–3.5 Hz, are visible on both borders of the basin. Those peaks may refer to the impedance contrast between the non-fractured Miocene and the upper fractured Miocene at an average depth of 7–35 m below the ground.