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USE OF MASW FOR AN EARTH DAM CHARACTERIZATION AND SHEAR MODULUS ESTIMATION IN BELO HORIZONTE – MG, BRAZIL

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ABSTRACT. Geophysical methods have great applicability for investigations in geotechnical structures, complementing and filling information gaps associated with traditional instrumentation. The contribution of seismic methods has gained attention in recent years since the body wave velocity fields can be associated with elastic modules of geotechnical interest. In particular, S-wave velocity (Vs) correlates with the shear modulus, which significantly decreases when high levels of water saturation are present. In the present study, multichannel Rayleigh wave data was acquired through a 69 m long profile in the downstream embankment of an earth dam in Belo Horizonte – MG. Phase velocities were calculated with the MASW method and S-wave models were obtained after inversion of dispersion curves. The goal of the study was to interpret some of the main features of the dam embankment from Vs contrasts and to estimate the shear modulus variation along the profile. The Vs values ranged from 135 m/s to 750 m/s and the shear modulus ranged from 36 MPa to 1,125 MPa. Low velocity regions have been delimited and associated with possible areas of lower stiffness, while deep regions of higher velocity were associated with a transition zone between the embankment material and the saprolite foundation.

Keywords: MASW surface waves; earth dam; applied geophysics.

RESUMO. Métodos geofísicos têm grande aplicabilidade para investigações em estruturas geotécnicas, complementando e preenchendo lacunas de informação associadas à instrumentação tradicional. A contribuição dos métodos sísmicos tem ganhado atenção nos últimos anos, uma vez que os campos de velocidade das ondas de corpo podem ser associados a módulos elásticos de interesse geotécnico. Em particular, a velocidade da onda S (Vs) correlaciona-se com o módulo de cisalhamento, que diminui significativamente quando altos níveis de saturação de água estão presentes. No presente estudo, foram adquiridos dados multicanais de ondas Rayleigh ao longo de um perfil de 69 m de comprimento no talude de jusante de uma barragem de terra em Belo Horizonte – MG. As velocidades de fase foram calculadas com o método MASW e modelos de ondas S foram obtidos após inversão das curvas de dispersão. O objetivo do estudo foi interpretar algumas das principais características do aterro de jusante da barragem a partir de contrastes de Vs e estimar a variação do módulo de cisalhamento ao longo do perfil. Os valores de Vs variaram de 135 m/s a 750 m/s e o módulo de cisalhamento variou de 36 MPa a 1.125 MPa. Regiões de baixa velocidade foram delimitadas e associadas a possíveis áreas de menor rigidez, enquanto regiões profundas de mais alta velocidade foram associadas a uma zona de transição entre o material de aterro e a fundação saprolítica.

Palavras-chave: MASW ondas de superfície; barragem de terra; geofísica aplicada.

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INTRODUCTION

Dams are geotechnical structures mainly used as water reservoirs and to contain tailings from mining operations. Given the enormous damage associated with a failure event, these structures have a generally high aggregate risk (Morales-Nápoles et al., 2014; Owen et al., 2020). Several dam rupture events have been reported and described worldwide, with different levels of human fatalities and environmental impacts. Recent and deadly tailing dam failures in Brazil triggered massive considerations on the safety policies around earth dams in the country (Owen et al., 2020). For the operation of a dam to be considered safe, assessment practices should be vastly applied. Thus, the search for methodologies to obtain information about the internal conditions in the embankment of a dam is fundamental for making quick and technically correct decisions.

The conventional installation of instrumentation in a dam is invasive, offers only local sampling and the very presence of the equipment can eventually influence soil conditions (Parekh, 2016). These limitations can be overcome with the use of geophysical methods, which are minimally invasive approaches to evaluate subsurface features. Although several geophysical methods have potential applicability for investigations in hydraulically active structures (*e.g.*, dams), seismic, electrical and electromagnetic methods are the most frequently applied (Hickey et al., 2015). However, it is important to emphasize that geophysical methods do not substitute the measurements made by auscultation instruments, but provide continuous 2D or 3D indicators that, once calibrated, allow a complete and low-cost spatial assessment.

The contribution of seismic methods for dam assessments is specially of geotechnical interest, since seismic velocities of body waves can be associated with elastic modules (*e.g.*, Kim et al., 2011; Cardarelli et al., 2014; Uhlemann et al., 2016). Surface wave methods are well established solutions for S-wave velocity (Vs) estimations. The Vs values correlate with shear modulus (Sheriff & Geldart, 1995), thus being generally used as a satisfactory stiffness indicator. Park et al. (1999) developed the Multichannel Analysis of Surface Waves (MASW) to calculate phase-velocity values from multichannel records of Rayleigh waves, which can be used for inversion of a dispersion curve and computation of a Vs profile.

Water saturation in embankments of earth dams can lead to piping formation, due to internal erosion caused by water flow (Foster *et al.*, 2000; Zhang *et al.*, 2009), and loss of contact between grains, which contributes to static soil liquefaction, a frequently addressed issue around dam failure events (*e.g.*, Agurto-Detzel et al., 2016). In Brazil, many studies reported assessments of water flow in earth dams' embankments, majority relying on the use of Electrical Resistivity Tomography (*e.g.*, Camarero et al., 2019; da Rocha et al., 2019; Arcila et al., 2021). Considering that water saturation significantly decreases the shear modulus (Baechle et al., 2009), the MASW method can be a straight-forward approach for potential saturation assessment and loss of stiffness.

In the present study, the MASW method was used in an earth dam in the city of Belo Horizonte, state of Minas Gerais, Brazil. The goal was to evaluate the use of the method to interpret some main features of the dam embankment from a pseudo-2D Vs distribution model and to estimate an approximate variation of the shear modulus, a parameter of great importance in the context of the stability and monitoring of geotechnical structures.

STUDY AREA

The Santa Lúcia dam (Fig. 1) is an earth dam with an artificial reservoir, built by the damming of an urban stream in the early 1950s, in Belo Horizonte, state of Minas Gerais, Brazil. The area is geologically located in the context of the Sabará Group (Minas Supergroup, Quadrilátero Ferrífero region), characterized mainly by schists, meta-sandstones and meta-siltites (Baltazar et al., 2005). The foundation of the analyzed structure is composed of residual soil and saprolite (Perché, 2015) from the rock weathering of the Sabará Group, in which the dam is geologically contextualized..

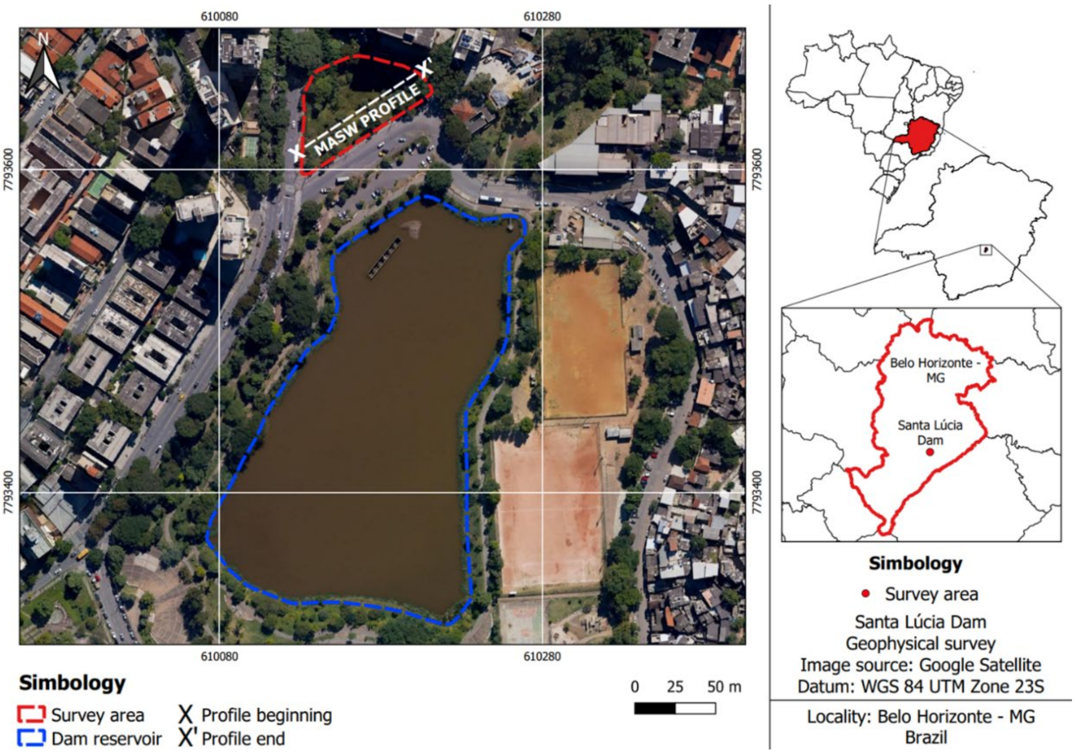

Figure 1 - Study area location in the context of the Santa Lúcia earth dam, Belo Horizonte - MG, Brazil.

This dam was built with the main objective of controlling floods in the rainy season, preventing flooding events. Its geotechnical instability could cause the non-fulfillment of its functional objective and result in irreversible damages to human life and urban infrastructure. Through Figure 2, it is possible to observe the studied dam where the geophysical survey was carried out. In the beginning of 2020, due to the heavy rains in the period, there was an overflow of the reservoir of the dam, a fact of great repercussion in the state of Minas Gerais, Brazil. In 2021, the reservoir was emptied in the same period of the year, a measure that aimed to contain this possible occurrence.

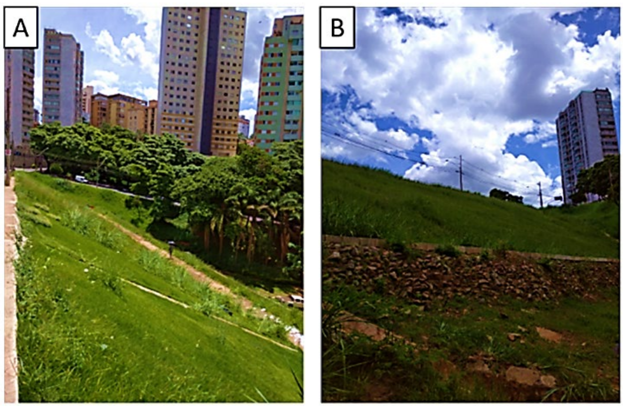

Figure 2 - Contextualization of the structure. A: Field photo of the crest region, oriented from the right abutment towards the left abutment. B: Field photo of the downstream region, oriented toward the crest and left abutment of the structure.

Table 1 presents the main geotechnical characteristics of the Santa Lúcia dam. The dam, consisting of compacted clay, has a height of 18 meters, a crest length of 115 meters, a foundation in residual soil, a spillway discharge controlled by a vertical shaft, a total volume of 189,000 m^3 and a useful reservoir volume of 76,000 m^3, with percolation through the structure controlled by the drainage system. The maximum level of operation in the structure is 900.30 meters and the maximum level of the water surface in the reservoir is 903.30 meters (Perché, 2015).

Table 1 – Main geotechnical characteristics of the Santa Lúcia dam (Perché, 2015).

Characteristics	**Description**
Dam height	18 m
Crest length	115 m
Total reservoir volume	189,000 m^3
Type of dam	Homogeneous earth dam
Type of foundation	Residual soil
Percolation	Internal drainage system
Water height in the reservoir	2.30 m
Spillway	Vertical shaft
Maximum operating level	900.3 m

MATERIALS AND METHODS

Multichannel Analysis of Surface Waves (MASW) and Shear Modulus Correlation

Park et al. (1999) proposed the MASW method to obtain profiles of the variation of Vs in depth from Rayleigh waves (ground roll) of a multichannel seismic record. Based on the dispersive behavior of Rayleigh waves, the MASW method determines the phase-velocities directly from the surface wave data of a multichannel seismic section. For each frequency, there are different modes of vibration, characterized by their own propagation velocity. The greater energy content is associated with the fundamental mode of propagation (Foti et al., 2018), and the phase velocities associated with the frequencies within this mode form a dispersion curve.

A 1D Vs profile in a layered model can be obtained from the inversion of an observed dispersion curve. A subsurface layer model consists of parameters of Vp, Vs, density, and thickness (Xia et al., 1999b; Hayashi, 2008). However, for the fundamental mode of the Rayleigh waves, Vs is considered the parameter that most influences the sensitivity of the dispersion curve (Xia et al., 1999b). The surface wave inversion problem is not linear; therefore, the nonlinear least squares technique can be applied on an initial layer model (Xia et al., 1999b; Hayashi, 2008).

The shear modulus was estimated from the following equation:

$$\mu = \rho . Vs^2 \qquad (1)$$

From (1), Vs and density (ρ) are directly proportional with the maximum shear modulus (μ). The maximum shear modulus will increase if shear velocity also increases. However, considering that the first 30 meters of the subsurface are most considered for shallow geotechnical studies, a small influence of density variation in this interval is expected (*e.g.,* 2 g/cm³ to 3 g/cm³ for most cases). Thus, simplifications regarding the choice of density value are justified, since μ has a linear dependence with ρ, while there is a quadratic dependence with Vs. The variation of Vs, therefore, can be used as a satisfactory stiffness indicator.

Data Acquisition

A single profile of seismic data was acquired in a berm, on the downstream embankment of the dam. A Geode seismograph (Geometrics) was used to record the waveforms registered by 24 units of 14 Hz vertical component geophones, positioned in a straight line and spaced every 3 m, totaling a 69 m long profile. The impact of a 10 kg sledgehammer against a metal plate was used as the seismic energy source (Fig. 3). The source positions were distributed every 3 m between pairs of geophones and five automatic stacks were used to increase the signal-to-noise ratio of the data.

Data Processing

The SeisImager/SW (Geometrics) software was used to obtain 1D Vs profiles. With the Pickwin module, seismic sections were edited, which consisted in removing noisy traces and trimming sections by 12 sequential receivers in an end-on shot configuration every 3 m and exporting each trimmed section (Fig. 4A) as a new SEG2 file. Since the 1D Vs profiles obtained by the MASW method are best representative at the middle of the trimmed receiver spread, two extra sections of six traces were also exported as an attempt to better fill the imaging gaps around the borders of the model. After the roll along trimming processes, a total of 15 waveform files were generated.

The workflow of the MASW method was executed as follow: a) each seismic trace was transformed by the Fast Fourier Transform for the frequency domain; b) each seismic section in the frequency domain was integrated in relation to the apparent phase velocities; c) the absolute value was calculated and plotted on an image of phase velocity vs frequency; d) the selection of the phase velocities was carried out as a function of the maximum amplitude in each frequency in the fundamental mode, constructing a dispersion curve (Fig. 4B).

For calculating the 1D Vs profiles using the dispersion curve inversion, the WaveEq module was used. The dispersion curves were edited

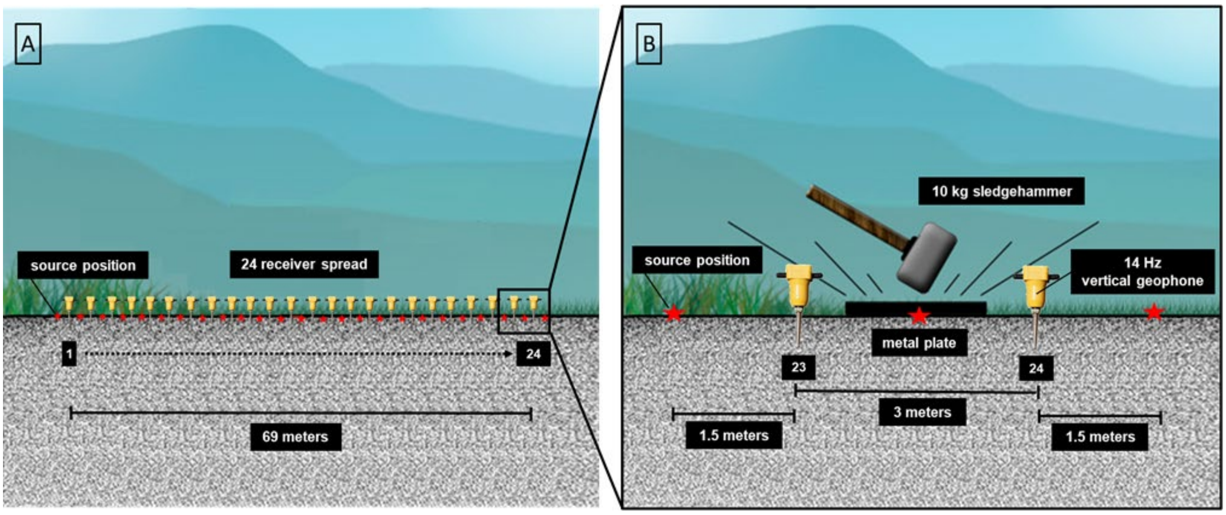

Figure 3 - Data acquisition representation with the active seismic source (10 kg sledgehammer). A: 24 geophone distribution along the 69 m long profile. B: Detailed representation of a seismic section acquisition, with five automatic stacks at a source position between a pair of geophones.

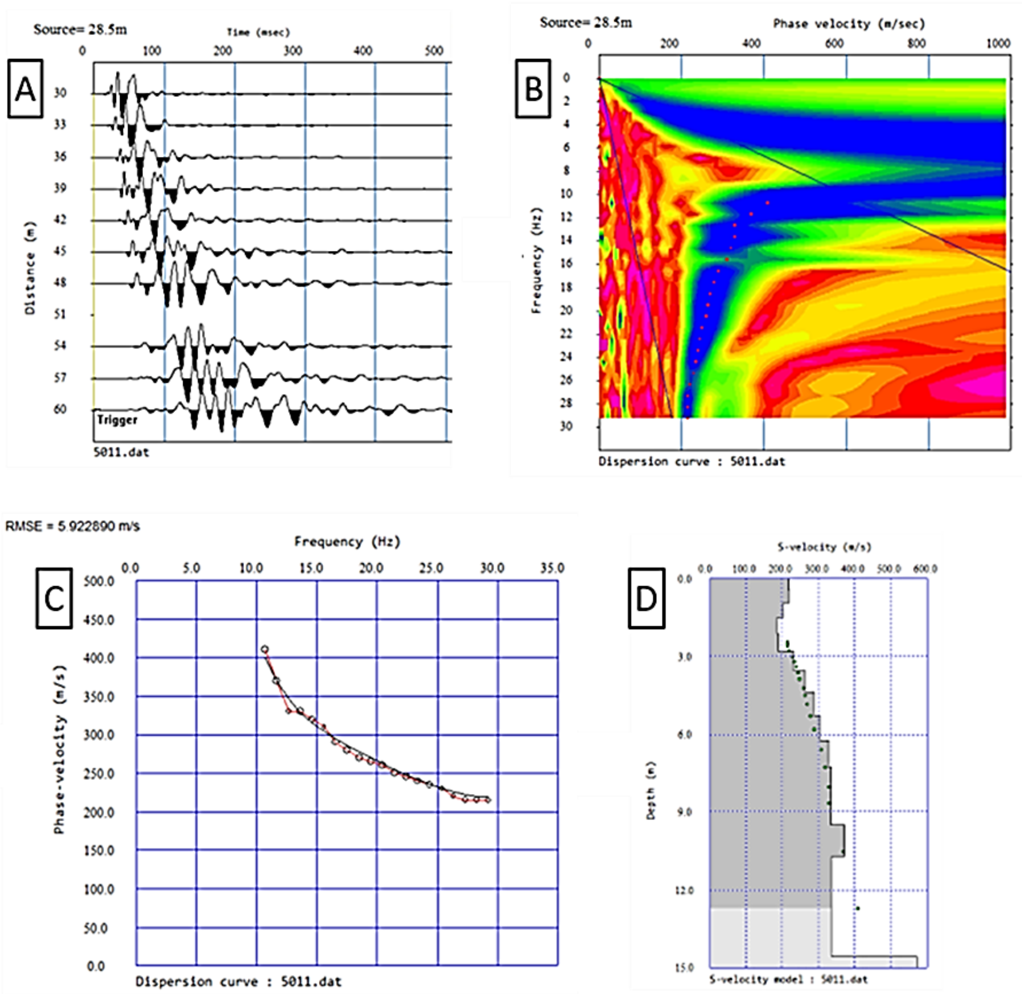

Figure 4 - Processing flow example around one of the acquired data with the MASW method. A: A trimmed seismic section. B: Image of phase-velocity picks in dispersion, marked as red dots. C: Inversion of the dispersion curve, with observed and calculated data marked as the red and black lines, respectively. D: Final 1D Vs profile, with the apparent depth from the one-third wavelength transformation of phase velocity data marked as green dots, which highlights the dark gray area.

(smoothed and the inconsistent phase-velocity picks removed) and posteriorly inverted. The data inversion followed the ensuing steps: a) an initial layered velocity model was built for a given set of parameters (Vp, Vs, density and thickness of the layer), following the 1/3 wavelength approximation for the model depth (Hayashi, 2008); and b) the velocity model was reconstructed in an iterative process, until the difference (Root Mean Square - RMS misfit error) between the calculated and observed dispersion curves was minimized (Fig. 4C), generating the final 1D Vs profile (Fig. 4D). The depth and Vs values of each layer of the final model were exported into an ASCII file.

Although 1D analyses are more commonly performed with the MASW method, pseudo-2D models can also be obtained. Following the two-dimensional analysis proposed by Xia et al., (1999a), the 15 obtained 1D Vs profiles were horizontally aligned and interpolated using the Surfer Software (Golden Software), forming a pseudo-2D velocity model. The term “pseudo-2D” is probably appropriate, since, to date, there are no well-established algorithms for 2D dispersion curve inversion, and 2D MASW results are, in essence, direct products of interpolation techniques of 1D results.

RESULTS AND DISCUSSION

Through the data processing and inversion, the pseudo-2D models of horizontal and vertical distribution of Vs and the calculated shear modulus were obtained, as shown in Figure 5A and Figure 5B, respectively. The pseudo-2D model of the calculated shear modulus was interpolated using equation (1), considering a constant density value of 2 g/cm^3, commonly associated with silty-clayed materials.

The Vs model in Figure 5A presents an irregular depth range geometry, reaching just over 20 m in depth. Conventional MASW campaigns have been reported to be not enough to achieve penetration depths deeper than 30 m (*e.g.*, Hayashi et al., 2016; Foti et al., 2018). There are some good practice guidelines regarding the investigation depth, which usually consider the receiver spread length (Foti et al., 2018). However, for data inversion, an initial model is constructed from the one-third wavelength transformation (Hayashi, 2008) in terms of an apparent depth (da), phase-velocity (c) and frequency (f), as

$$\mathrm{da} = \mathrm{c}/3\mathrm{f} \qquad (2)$$

This means that greater depths can only be obtained when a higher phase-velocity is observable at a lower frequency in dispersion imaging. The use of 4.5 Hz geophones is generally the first choice for MASW data acquisition to make phase-velocities at observable lower frequency ranges, which are related to a greater depth range. However, Park et al. (2002) found that results obtained with 10 Hz geophones were almost identical to those of 4.5 Hz geophones down to 5 Hz. Thus, the depth of investigation with the MASW method is not an exclusive matter of field parameters and instrumentation, but rather likely to be site specific and may vary even within the same acquisition profile, if the geology shows variation of velocity values.

The obtained Vs values varied from 135 m/s up to 750 m/s, presenting a considerably gradual and homogeneous behavior, with lower velocities in superficial regions and higher velocities around greater depths. The obtained velocity values are within the range of values found in other similar structures. Kim et al. (2011) applied MASW in an earth dam in South Korea and obtained Vs values from 100 m/s up to 1,480 m/s down to a depth of 30 m. Cardarelli et al. (2014) applied S-wave Seismic Refraction Tomography in an earth dam in Italy and obtained Vs values from 120 m/s up to 300 m/s down to a depth of 9 m. Hayashi et al. (2014) applied MASW in an earth dam in USA and obtained Vs values from 120 m/s up to 350 m/s down to a depth of 16 m. Netto et al. (2020) applied MASW and S-wave Seismic Refraction Tomography in an earth dam in Brazil and obtained Vs values from 150 m/s up to 700 m/s down to a depth of 16 m.

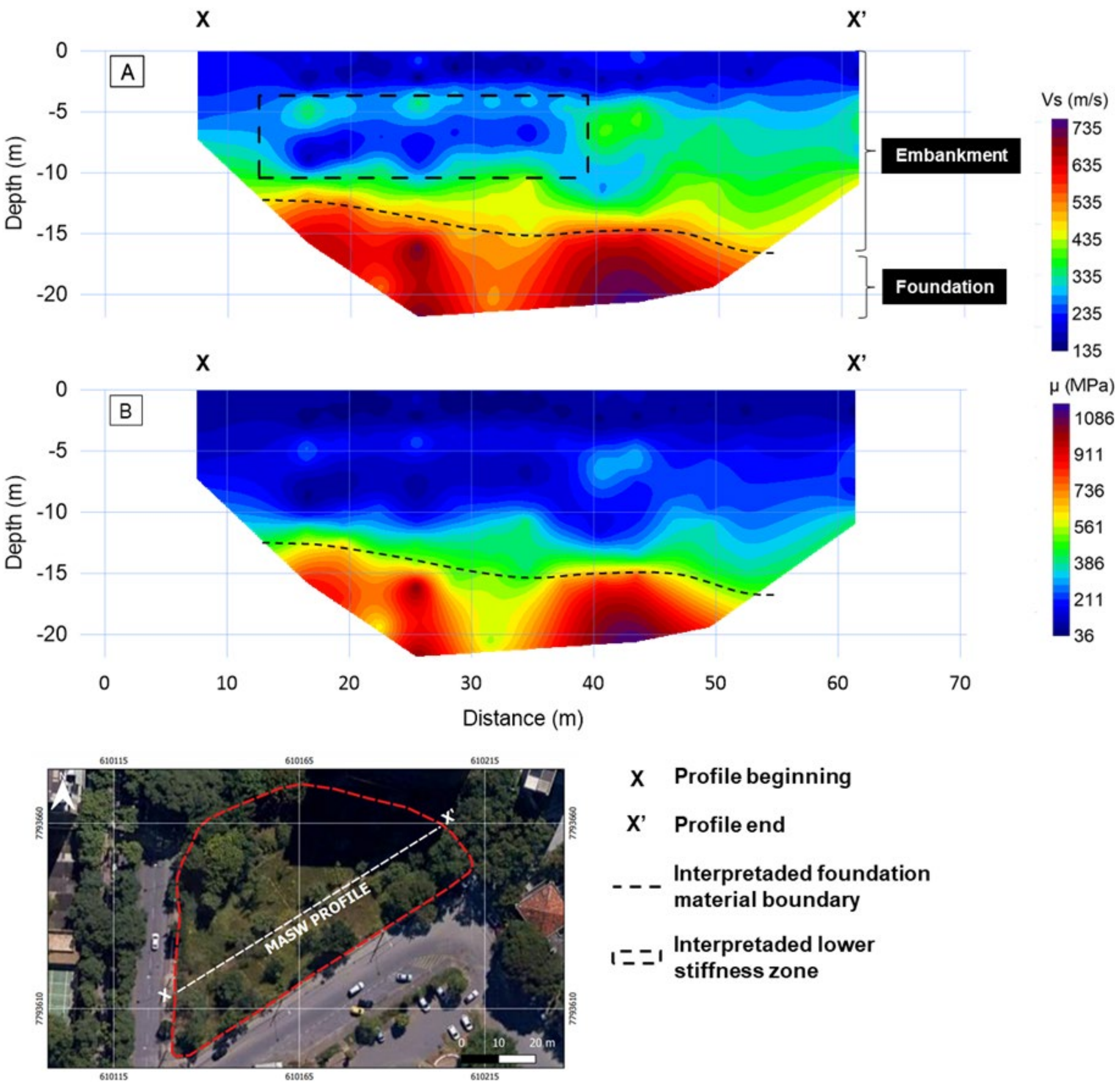

Figure 5 - 2D sections interpreted. A: 2D Vs distribution model. B: 2D shear modulus distribution model.

Two main layers were interpreted from the obtained velocity model. The first most superficial layer, down to about 15 m in depth, presents Vs from 135 m/s to approximately 450 m/s, associated with a less compacted clay soil. From 15 m downwards, the Vs values are higher, from approximately 450 m/s to 750 m/s, associated with the saprolite that forms the foundation material, marked in Figure 5A as the possible limit with the foundation ground. The μ values were obtained in the range of 36 MPa to 1,125 MPa (Fig. 5B). Following AASHTO (1996), lower μ values could be associated with silty-clayed materials from the dam embankment, while higher values could be associated with the residual soil/saprolite foundation, suggesting the classical pedological profile of alteration of the fresh rock.

Regions of possible shear weakness associated with lower velocity values were delimited in Figure 5A. Baechle et al. (2009) point that water presence decreases μ, since it affects both P and S-wave velocities. Water saturated soils usually have an increase in Vp and a decrease in Vs, if compared to a dry soil (Baechle et al., 2009; Kassab & Weller, 2015; Konstantaki et al., 2016; Foti et al., 2018). Thus, the interpreted locations may indicate materials of lower compaction, higher porosity or with higher levels of water saturation.

CONCLUSIONS

The results of the MASW method applied in an earth dam for the development of a S-wave velocity model reached just over 20 m in depth. The Vs values found ranged from 135 to 750 m/s and the shear modulus ranged from 36 MPa to 1,125 MPa, assuming an average homogeneous density distribution of 2 g/cm³. Regions of lower velocity values were delimited, associated with lower compaction or higher levels of water saturation. A superficial layer with predominance of lower velocity and shear modulus values were associated with the silty-clayed embankment material. From 15 m downwards, the higher Vs and shear modulus values were interpreted as the transition between embankment and the saprolite that forms the foundation material.

As other works reported, the MASW method is not likely to be a self-sufficient approach to image Vs variation over a few tens of meters. Passive surface wave surveys might be alternative methods to achieve greater depths, especially in noisier environments. While the S-wave velocity field provides useful information, it is a function, just like P-wave velocity, of different individual elastic soil properties. We suggest that future works involve the processing of seismic refraction data to obtain Vp models, since Vp/Vs ratio is independent of density and can assist in the stage of interpretation of the models, reducing ambiguities.

The use of the geophysical method, as well as *in situ* observations, supported the interpretations and can contribute, in the future, to a more focused monitoring of interesting areas and/or zones with structural weakness. The MASW method proved to be a straightforward solution for the characterization of internal features in geotechnical structures and factors that favor dam impacts, such as erosive process, anomalous saturation zones and unexpected flows.

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G.A.S.P.: conceptualization, geophysical interpretation, text writing and revision. **V.J.C.B.G.**: conceptualization, field acquisition, data processing and inversion, geophysical interpretation, text writing and revision. **G.W.G.:** conceptualization, field acquisition, geophysical interpretation, text writing and revision. **M.A.F.V.**: field acquisition, text revision. **I.L.S.C.C.**: figures design, text revision.

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