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ANALYSIS OF SEISMIC REFRACTION AND SURFACE WAVE DATA FOR THE EVALUATION OF LAYERS AND SATURATION OF SOLID WASTE FROM A LANDFILL IN BRASÍLIA, BRAZIL

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ABSTRACT. The present work discusses the characterization of landfilled solid waste and saturated zones considering the response of P and S-wave velocities (Vp and Vs), Poisson ratio (υ), Young's modulus (E) and shear modulus (G_0), obtained from velocity models in an area located in the former Jockey Clube Controlled Landfill. The obtained Vp values ranged from 231 to 1,160 m/s, while Vs values range from 124 to 449 m/s. The calculated υ ranged from 0.11 to 0.4, while G_0 and E ranged from 15 to 319 kPa and from 42 to 901 kPa, respectively. The values of G_0 and E indicate that the landfilled material is poorly competent. The combined interpretation of Vp, Vs and elastic parameters allowed the definition of three main layers in the surveyed area and their respective distance from soil surface, defined as: 1) Civil construction residual material, of around 10 meters thick; 2) A solid waste layer, of around 18 meters thick, marked as a lower Vs and higher υ interval, possibly associated with saturated material; and 3) the estimated natural landfill terrain, below the depth of 28 meters, composed by the oxisol.

Keywords: multichannel analysis of surface waves; elastic properties; wave velocities; SRT; seismic refraction tomography.

INTRODUCTION

In irregular landfills, the solid waste disposal is done directly on the soil surface. In such uncontrolled landfill, there is no drainage system for the leachate generated from the composition of organic waste. The irregular solid waste disposal can lead to disastrous consequences, such as flooding, air pollution, and impacts on public health, such as an increase in cases of diarrhea and related diseases, as well as dengue epidemics (Hoornweg and Bhada-Tata, 2012; Paixão Filho and Miguel, 2017). In Brazil, it is estimated that 40.9% of solid waste collected is improperly disposed of in open-air landfills (Alfaia et al., 2017). Such practices have been gradually replaced due to the recognition of the environmental and human health damage they cause, and to the increasing inspection by the regulatory agencies.

As they are uncontrolled landfills, little is known about the mechanical characteristics of discarded materials and the vertical and horizontal limits of the waste layers. Furthermore, due to the lack of waterproofing of the geological substrate, the flow inside the waste mass is one of the main concerns of the technical staff in landfills. Direct measurement of mechanical properties of residues generally takes place at discrete points and over a small volume of material. These sampling limitations can be overcome with the use of seismic methods, an alternative solution for landfill investigations.

Seismic methods, such as crosshole, downhole, refraction, and surface wave analysis, are indirect and non-invasive tools for the geotechnical characterization of landfills (De Iaco et al., 2003; Matasovic et al., 2006; Zekkos et al., 2011; Abreu et al., 2016; Anbazhagan et al., 2016; Gaël et al., 2017; Aranda et al., 2019; Sharma et al., 2021). Seismic refraction tomography (SRT; White, 1989) and multichannel analysis of surface waves (MASW; Park et al., 1999) are methods that provide velocity models of the compressive and shear waves (Vp and Vs, respectively).

P–waves are very sensitive to the pore-fluid content in the landfill waste. On the other hand, S-waves are low sensitive to the presence of fluid, but more sensitive to rigidity variations in the near-surface soils and landfill materials. From the velocity values of these waves and the density, it is possible to calculate the dynamic shear and Young's modulus and the Poisson ratio. In addition, the Poisson ratio can provide information on the flow of leachate within the waste mass by identifying wetlands in subsurface, since a change in pore-fluid saturation causes a change in the effective pressure, which in turn affects Vp and Vs (Konstantaki et al., 2016).

Carpenter et al. (2013) used P and S-wave velocity models generated by SRT to calculate the Poisson ratio distribution in a landfill. Konstantaki et al. (2015), using seismic reflection and MASW, calculated values of the unit weight of subsurface waste by empirical relationships from the obtained Vs and presented a density model for a heterogeneous landfill (Abreu et al., 2013). Abreu et al. (2016) analyzed the elastic response of residues using the crosshole and MASW methods, generating and analyzing profiles of Vp, Vs and Poisson ratio. Konstantaki et al. (2016) identified saturation zones along the waste mass by interpreting Vp, Vs and the ratio between them (Vp/Vs).

The mechanical properties of municipal solid waste directly influence Vp and Vs, and can vary from landfill to landfill according to the different compositions of the deposited waste (Zekkos et al., 2006). Furthermore, the percentage of moisture and organic material, which make up about 51.4% of the Brazilian Municipal solid waste (Alfaia et al., 2017), influences, in the long term, the mechanical properties of waste, as they affect the biodegradation processes (Castelli et al., 2013). In this sense, the present work aims to evaluate the integrated use of SRT and MASW in the characterization of the different layers of a local profile at the Jockey Clube Controlled Landfill and to calculate the elastic properties of geotechnical interest from relations based on Vp and Vs.

STUDY AREA

The study area is the Jockey Clube Controlled Landfill (JCCL), located in Brasília-DF, more specifically in Cidade da Estrutural (Figure 1). With just less than 2 km² in area, the JCCL is one of the largest disposal units in Latin America and currently operates only as a waste receiving unit. The beginning of waste disposal took place in the 1960s with little or no control over the nature of the waste disposed (Campos, 2018). It is believed that the waste at the site is mainly from domestic origin and is covered by a layer of construction waste that varies in thickness and composition. Below the landfill, it occurs oxisols with depths greater than 25 meters (Cavalcanti et al., 2014; Guedes et al., 2020). Figure 2 presents a simplified model of the arrangement of the landfill layers developed from resistivity sections presented in Guedes et al. (2020) and the simplified profile extracted from the drillhole recently carried out on site.

The geological framework is composed by the rocks of the Paranoá Group, of Meso/Neoproterozoic age, more specifically the Ribeirão do Torto Fm. This unit is composed of greenish-gray slates. In this set, two penetrative foliations are observed that represent the slate cleavages and configure the character of the friable and brittle rock (Campos et al., 2013).

The predominant topography in the study region is flat to gently undulating with percent of slope below 10 and elevations above 1,100 m. Within the study area, the natural topography has been extensively modified since the beginning of the JCCL's operations. Currently, the site has been modified in such a way that the center of the embankment is a topographical high informally known as “Bolo de Noiva”.

MATERIALS AND METHODS

Data acquisition

We acquired the seismic data along a linear profile in the western portion of the JCCL. A total of 48 vertical 14 Hz geophones were distributed in a straight line and fixed on the surface with a spacing of 3 meters between them, forming a profile of 141 m in length. Five shot gathers were recorded during the field campaign, four with offset seismic source configuration (positions -15 m,

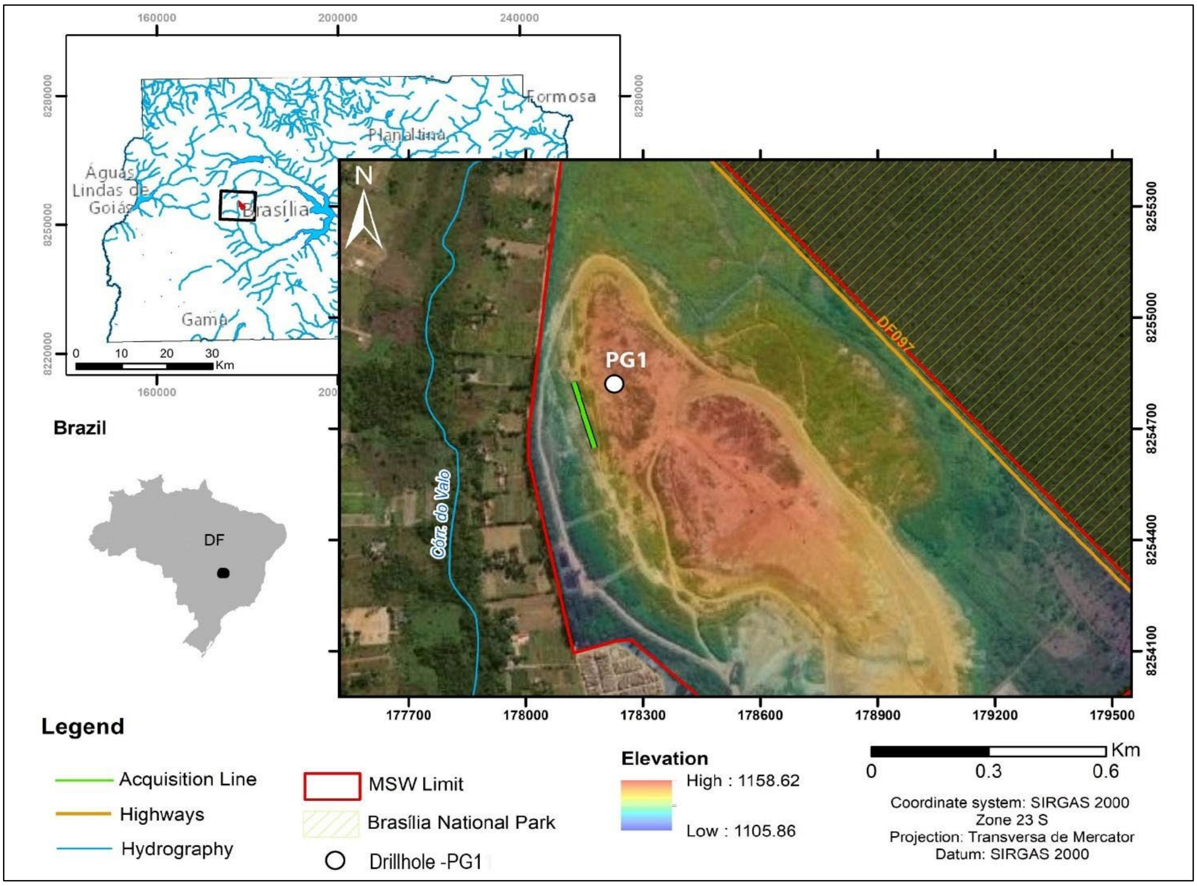

Figure 1: Location map of the seismic line acquisition (green line) and drillhole named PG1 (white dot).

-1 m, 142 m and 156 m) and one as onset (middle of the geophone spread, at 70.5 m), as presented in Figure 2A.

A drillhole from 2020 (PG1) was used as approximate information on the composition of the dumped materials. The hole is closer to the center of the JCCL, about 100 meters away from the seismic line (Figure 2B). The drillhole is composed of Civil Construction Waste (CCW) from the top to 18 meters deep, waste layer from 18 to 42 meters (34 to 10 meters in Figure 2C), and oxisols from 42 to 52 meters (Figure 2C). The bedrock was not identified in this drillhole. The thickness of the landfill in the center is greater than in its extremities (Guedes et al., 2020). As a result of the seismic acquisition, we expect the identification of the waste layer to be smaller than 24 m.

The seismic acquisition was configured using the Seismodule Controller Software - SCS (Geometrics). A general summary of the configuration used, and photographic record of the acquisition is presented in Table 1 and Figure 3, respectively.

We first acquired data using a 8 kg sledgehammer as the seismic energy source using 15 channels, as a test. Due to scattering and attenuation effects of the propagating waves in the medium (Herbst et al., 1998; Milsom, 2003; Yordkayhun and Suwan, 2012; Toney et al., 2019), the obtained data presented poor signal-to-noise ratio levels, and it was not possible to properly observe the arrivals of direct and refracted waves, especially at higher offset distances, which would significantly reduce the relevance of the velocity model (Figure 4A). We replaced the sledgehammer impacts with a 66 kg weight drop system at a height of 3 meters. The data quality of the seismograms improved significantly (Figure 4B).

Table 1: Parameters and materials used in seismic acquisition.

Acquisition parameters	Materials and values
Recording system	Geode (Geometrics)
Source type	66 kg weight drop
Shot positions	-1, -15, 70.5, 142 and 156 m
Receiver type	14 Hz vertical geophones
Receiver spacing	3 m
Profile length	141 m
Sampling interval	0.128 ms
Recording time length	1,500 ms
Automatic stacks	7

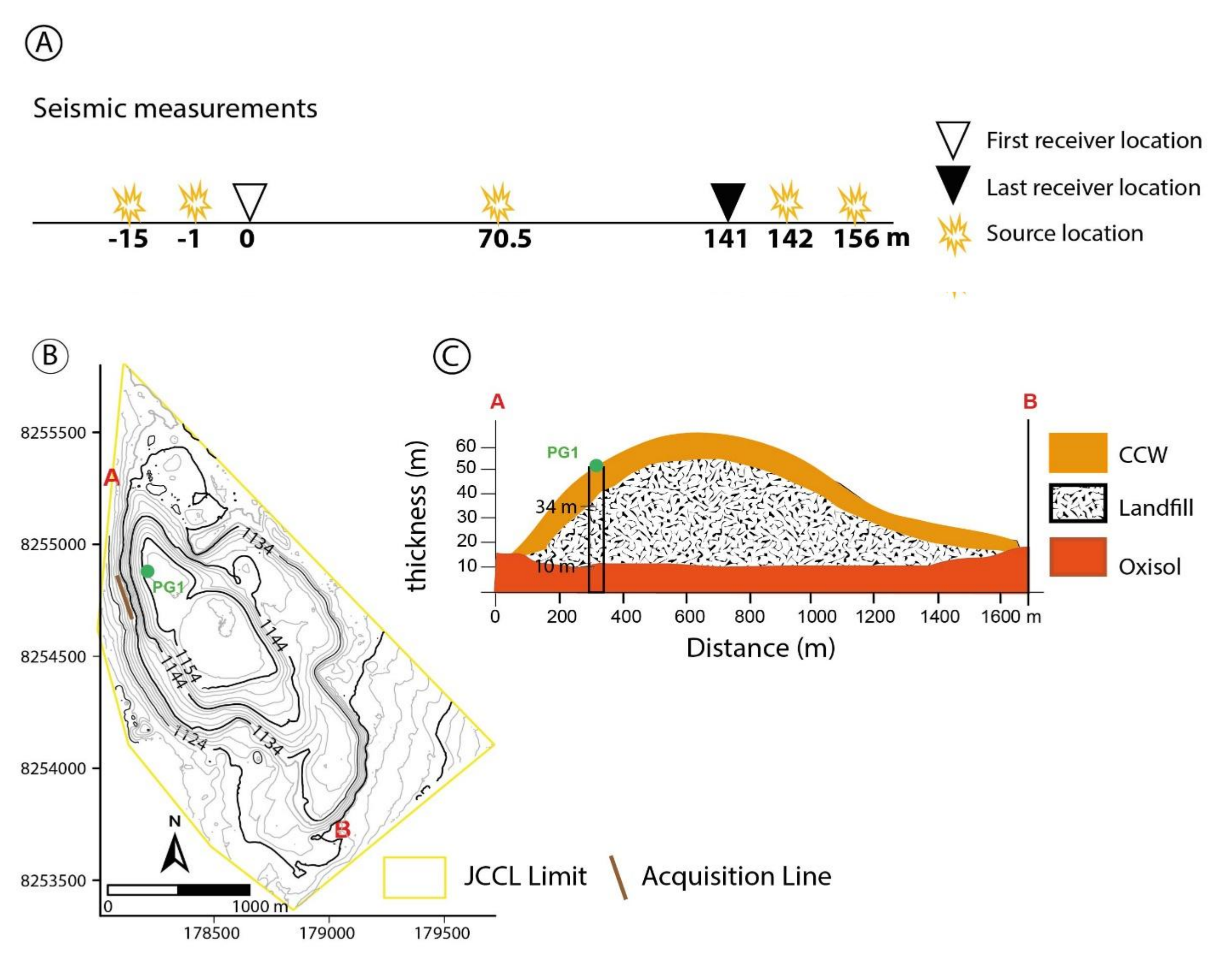

Figure 2: A) Location of the source positions. B) Plan view of the JCCL with the location of the representative section of the landfill layers. B) Simplified model of the disposition of the different materials that make up the JCCL, summarized in three main layers: civil construction waste, solid waste and natural surface (oxisol).

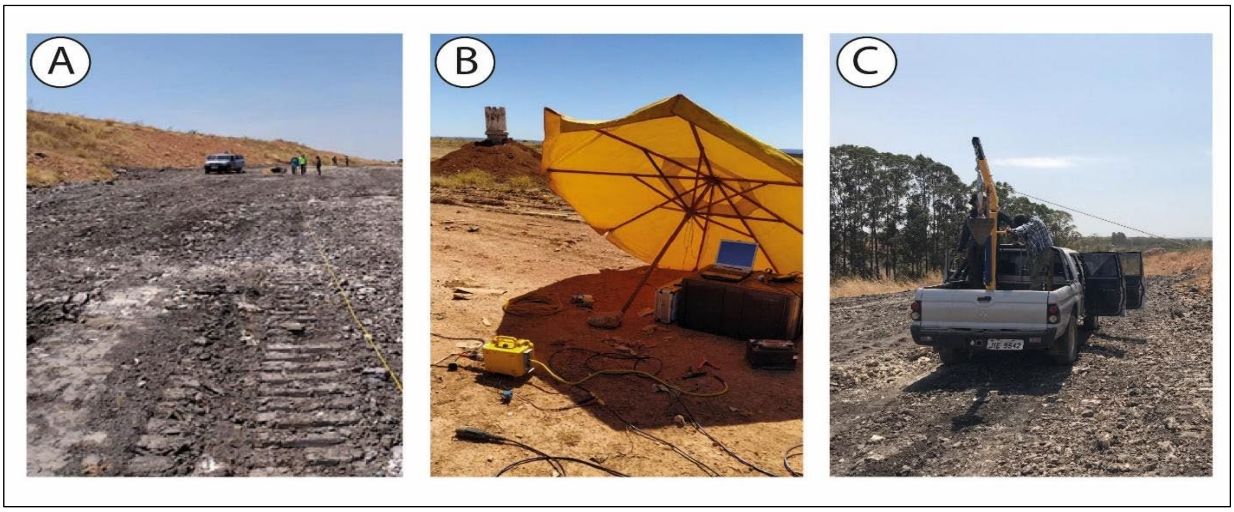

Figure 3: Photos of the seismic acquisition. A) Positioning of geophones in a straight line; B) Base station of the data acquisition controller computer; C) Preparation before the drop of the weight for seismic recording at shooting position 5.

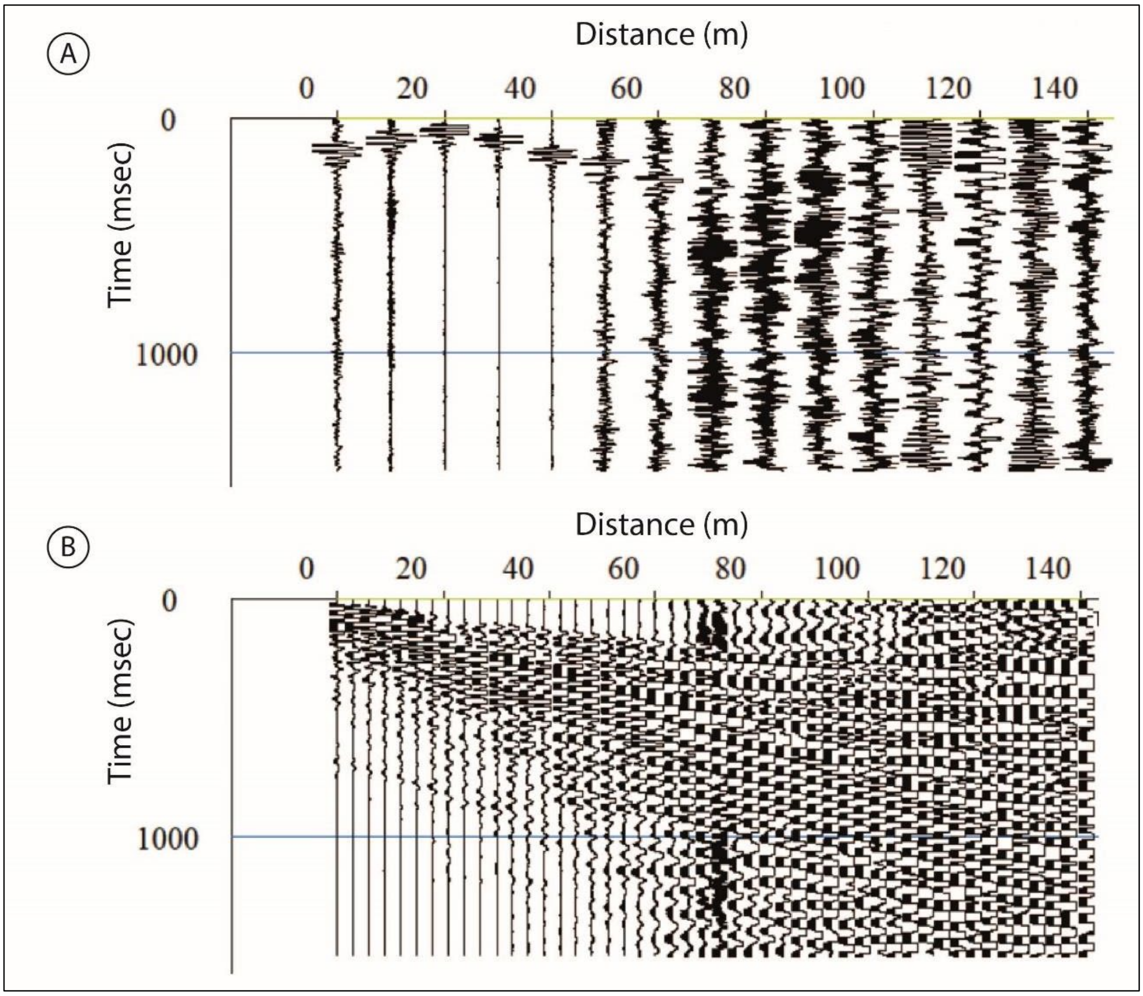

Figure 4: Comparison between example seismograms obtained with A) impacts of a 8 kg sledgehammer at position 19 m; and B) drops of a 66 kg weight at position -1 m.

An example of a first break picking for SRT is shown in Figure 5A. As for MASW, we used the ground-roll data registered in the seismogram obtained at the source position of 142 m, as presented in Figure 5B.

MASW

The MASW method (Park and Miller., 1997; Park et al., 1999) was used to obtain the Vs profile of the investigated site from the Rayleigh wave recording. The processing was performed using the seismic shot gather obtained at the source position of -15 m. We used the Surface Wave Analysis software (SeisImager/SW, Geometrics, 2009), in which the following steps were performed (Figure 6): a) transform each seismic trace from the time domain to the frequency domain through Fast Fourier Transform; b) calculate phase velocities with the phase-shit and stack method (Park et al., 1999; Hayashi, 2008); c) plot the absolute phase velocities as an image of phase velocity *vs* frequency; d) extract the fundamental dispersion curve from the dispersion image; e) construct a 1D layered initial model and invert the experimental dispersion curve by a nonlinear least squares algorithm to calculate the 1D profile of Vs in depth.

Seismic Refraction Tomography

The seismic refraction method was used to obtain the 2D Vs section of the investigated site from the inversion of the picked first arrivals from the seismograms. The processing was performed using the Pickwin and Plotrefa modules (SeisImager/2D software, Geometrics), which consisted of the following steps (Figure 7): a) Filtering the seismogram between 16 Hz and 85 Hz (no phase distortions were observable); b) Picking of P-wave first arrivals in each individual trace to build the traveltimes curves; c) Constructing the initial velocity

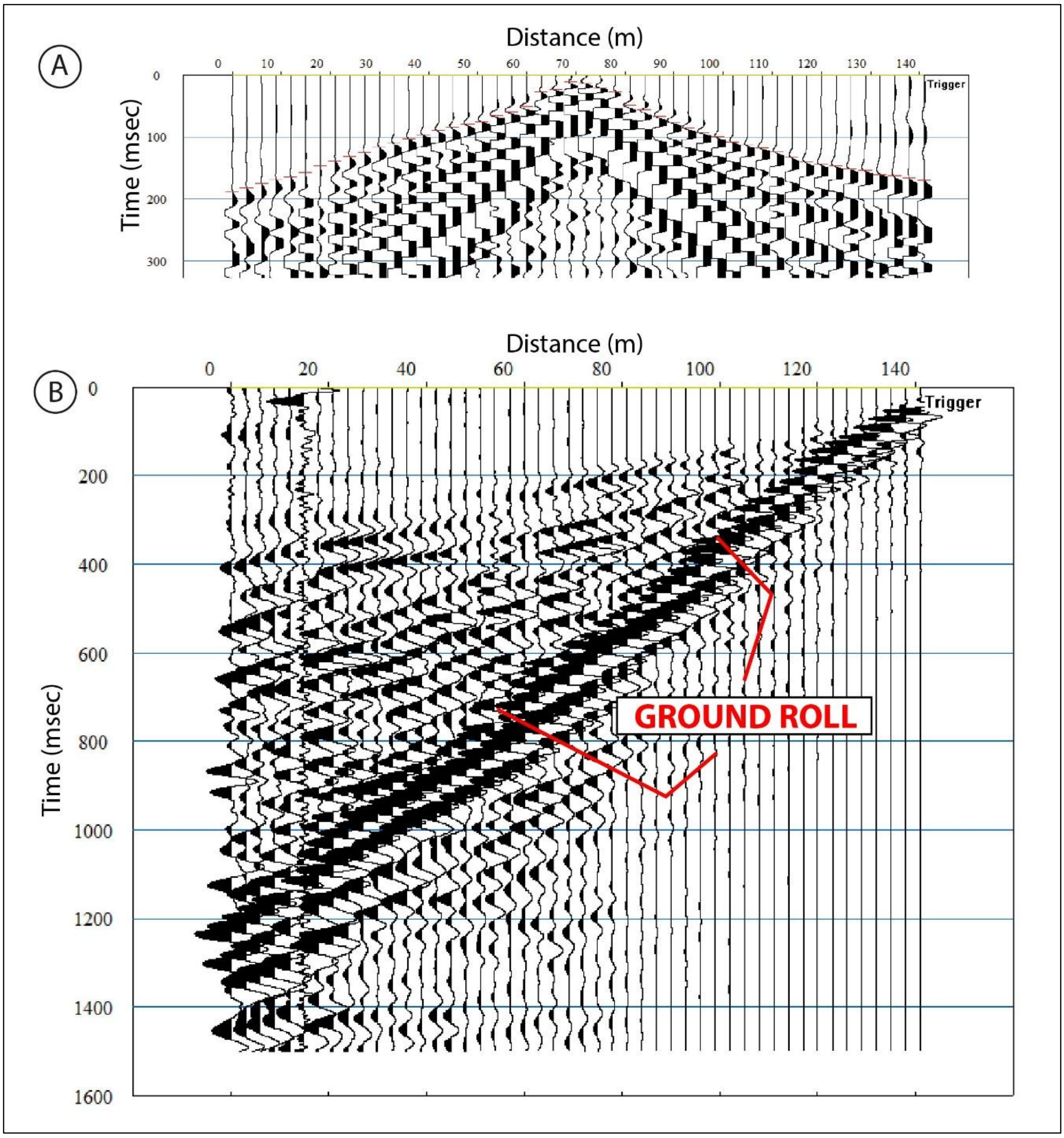

Figure 5: A) First break picking for SRT on the seismogram obtained at shot position 70.5 m. B) Seismogram used for MASW, obtained at source position 142 m.

model, followed by iterative shortest path ray tracing routine (Moser, 1991) and reconstructing the velocity model after each interaction with a nonlinear least squares inversion based on SIRT algorithm (Simultaneous Iterative Reconstruction Technique) (e.g., Hayashi and Takahashi, 2001). The total number of iterations was defined based on detecting when the model obtained with the next iteration would show no significant decrease of the error between the calculated and observed traveltimes. Thus, the final model of Vp was set to be obtained after 10 iterations.

Elastic properties

From the values of Vp, Vs and the estimated density (ρ), the dynamic elastic parameters Young's modulus (E), Poisson ratio (υ) and shear modulus (G_0) can be estimated. G_0 is a quantity commonly analyzed in geotechnical contexts, as it indicates the tendency of shear deformation, therefore being associated with the stiffness of a material (Mavko et al., 2010; Clayton, 2011). According to the theory of elasticity (Sheriff and Geldart, 1995), G_0 is defined as the ratio between shear stress and strain for homogeneous and isotropic solids

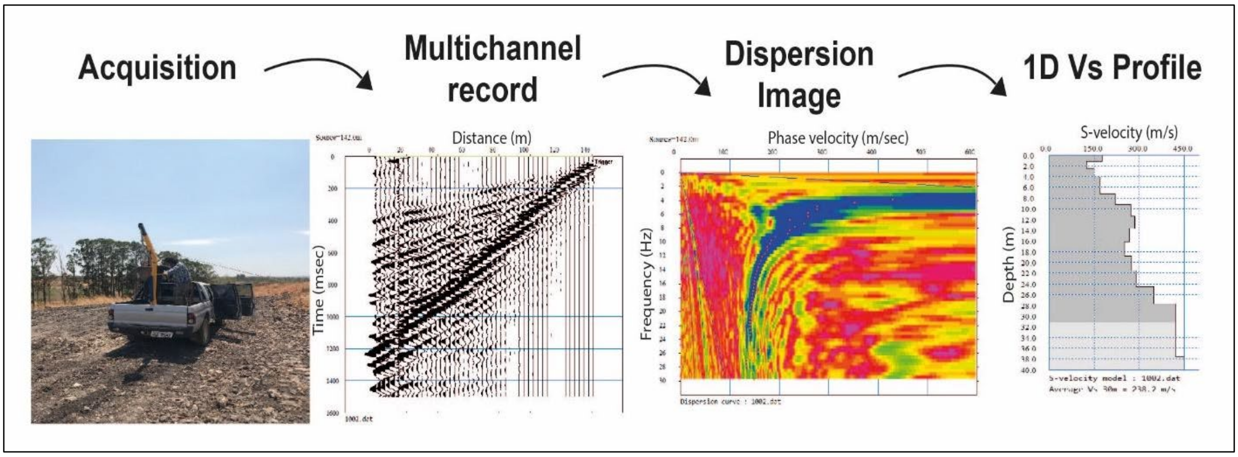

Figure 6: Synthesis of the MASW acquisition and processing steps to obtain the shear wave vertical profile (Vs). First, recording of seismic waves in a multichannel system. After, the impact using the weight drop. Then, obtaining the dispersion image through a transformation of each trace from the time domain to the frequency domain. Finally, the extraction of the dispersion curve so that the vertical velocity profile Vs is obtained in the inversion process.

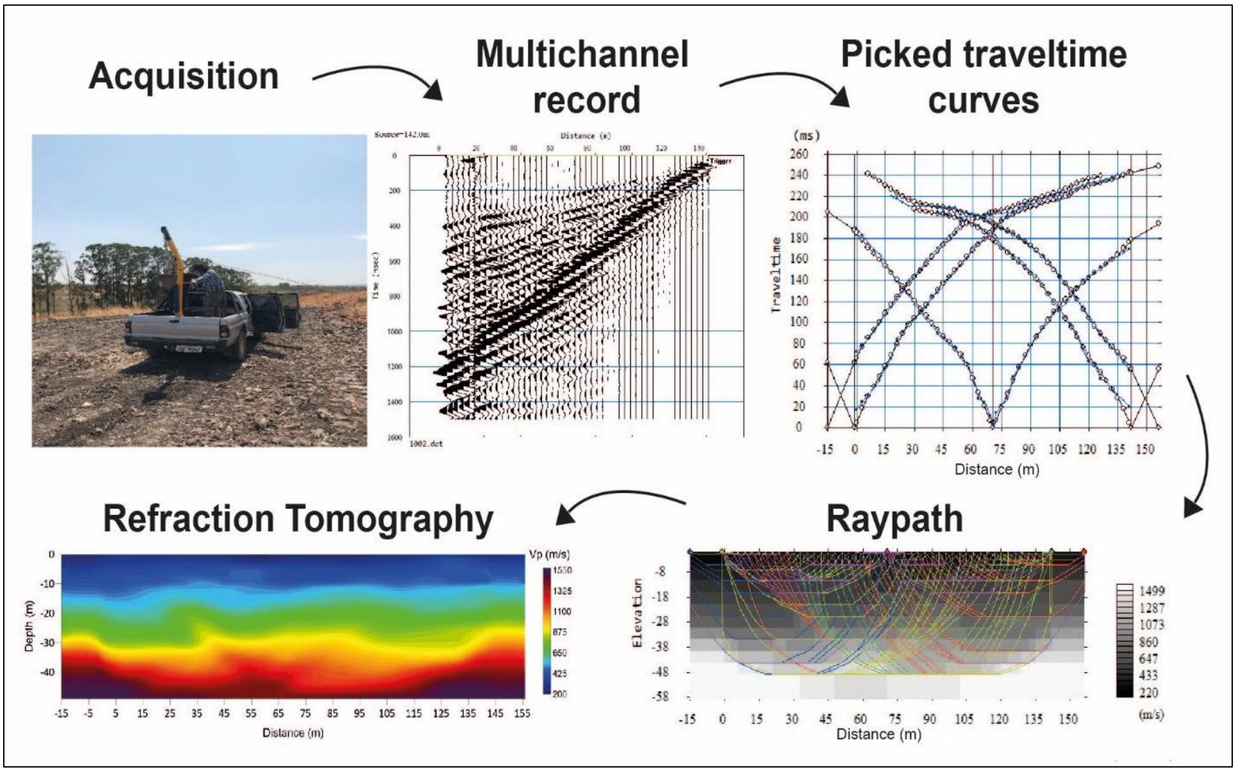

Figure 7: Synthesis of the main steps of acquisition and processing of refraction tomography to obtain the 2D Vp section. First, seismic waves recording in a multichannel system. Then, first arrivals demarcations for each trace within the seismograms. Finally, theoretical traveltimes and ray path computation from ray tracing for the last iteration and the final Vp result after 10 iterations.

Equation 1 yields G_0 from the wave velocity and the density, as:

$$G_0 = \rho V_s^2 \qquad (1)$$

Therefore, if the parameters ρ and Vs are estimated independently, G_0 can be approximated. However, considering that the first 30 meters of soil are most considered for shallow geotechnical studies, it is expected a small influence of the ρ variation in this interval (about 2 to 3 g/cm^3, for most cases). Thus, simplifications regarding the choice of density value are justified, since G_0 has a linear dependence with ρ, and a quadratic dependence with Vs. The variation of Vs, therefore, can be used as a satisfactory indicator of stiffness.

Although knowing Vp and Vs is useful, they are functions of up to three individual soil properties, being potentially ambiguous indicators of lithology if analyzed individually (Berge and Bertete-Aguirre, 2000; Kearey et al., 2009). The Poisson ratio, however, is independent of density and may be a more diagnostic geotechnical stratigraphy (Kearey et al., 2009; Alam and Jaiswal, 2017), which can be obtained in terms of the seismic velocities, as:

$$\upsilon = \frac{(V_p/V_s)^2 - 2}{2(V_p/V_s)^2 - 2} \qquad (2)$$

Young's modulus (E) is the resistance to deformation along the stress axis, depending on the density (ρ) in terms of Vs. It is also reported as an indicator of satisfactory stiffness and can be obtained from the relation:

$$E = 2{V_s}^2\rho(1 + \upsilon) \qquad (3)$$

To quantify the density parameter (ρ), an empirical relationship between Vs and the unit of weight of solid waste (γ_{waste}) was used (Choudhury and Savoikar, 2009), based on more than 30 independent measurements in landfills:

$$V_s = \frac{1}{0.0174 - 0.000978\,\gamma_{waste}} \qquad (4)$$

The density can be calculated as:

$$\rho = \frac{\gamma_{waste}}{g} \qquad (5)$$

Where g is the acceleration of gravity (used here as 9.81 m/s²). A 1D Vp profile was extracted from the 2D tomographic model at the center of the profile, and, along with the 1D profile of Vs from the inversion of the dispersion curve, the parameters E, υ, G_0 and ρ were calculated.

RESULTS

At the investigation site, the solid waste layer is thinner than at the center of the JCCL. The thickness of the dumped waste is approximately 24 m, as described by drilling holes carried out close to the site.

The 2D Vp section obtained from SRT and the Vs vertical profile obtained from MASW are shown in Figure 8A. In the tomogram, it is possible to observe a gradual increase in Vp from 200 m/s up to 1,550 m/s. In the first 10 meters, Vp ranges from 200 to 490 m/s and Vs ranges from 120 to 320 m/s. In the intermediate range of 10 to 30 m, Vp increases from 500 to 900 m/s, while Vs decreases to 250 m/s.

It is possible that this decrease in Vs is correlated with the beginning of zones considerably saturated by leachate from the organic waste composition, since water saturation significantly decreases the shear modulus (Baechle et al., 2009), and, unlike Vp, the increase in medium saturation causes Vs to remain constant or decrease sharply (Baechle et al., 2009; Kassab and Weller, 2015; Konstantaki et al., 2016; Foti et al., 2018). At the depth below 25 meters, Vp reaches up to 900 m/s, while Vs returns to an increasing behavior, reaching up to 450 m/s at the bottom of the vertical profile. This change in trend in Vs may be related to the location of the oxisol at the base of the JCCL and less presence of fluids.

By analyzing the values calculated for Vp, Vs, υ, E and G_0 in depth, according to Figure 8B, it was possible to individualize the three layers in the JCCL and their respective thicknesses. The civil construction residual material layer is about 10 meters thick (Figure 8B). The solid waste layer is about 18 meters thick and, below 28 meters, we estimate the landfill in contact with the oxisol layer, not being possible, however, to identify the contact between the oxisol and the bedrock, probably due to the large thickness that these oxisols can achieve.

To better correlate the Vp and Vs values associated with landfills, Table 2 presents the variation of Vp and Vs obtained at different landfills by several authors, with different geophysical methods based on seismic wave propagation. Figure 9 presents the graphic comparison of these values with those obtained in the present work, which are within the same range, slightly above the average.

In general, the Poisson ratio (υ) varies between 0 to 0.5, where higher values (close to 0.5) indicate less rigid materials and the presence of incompressible fluid (Uhlemann et al., 2016; Alam and Jaiswal, 2017). The Poisson ratio ranging from 0.05 to 0.35 is reasonable for municipal solid waste (Zekkos et al., 2011). The obtained υ presented a minimum of 0.11 and a maximum of 0.41. Below the surface, the calculated values were decreasing from 0.38 to 0.11 down to 10 meters in depth. After 10 meters, υ

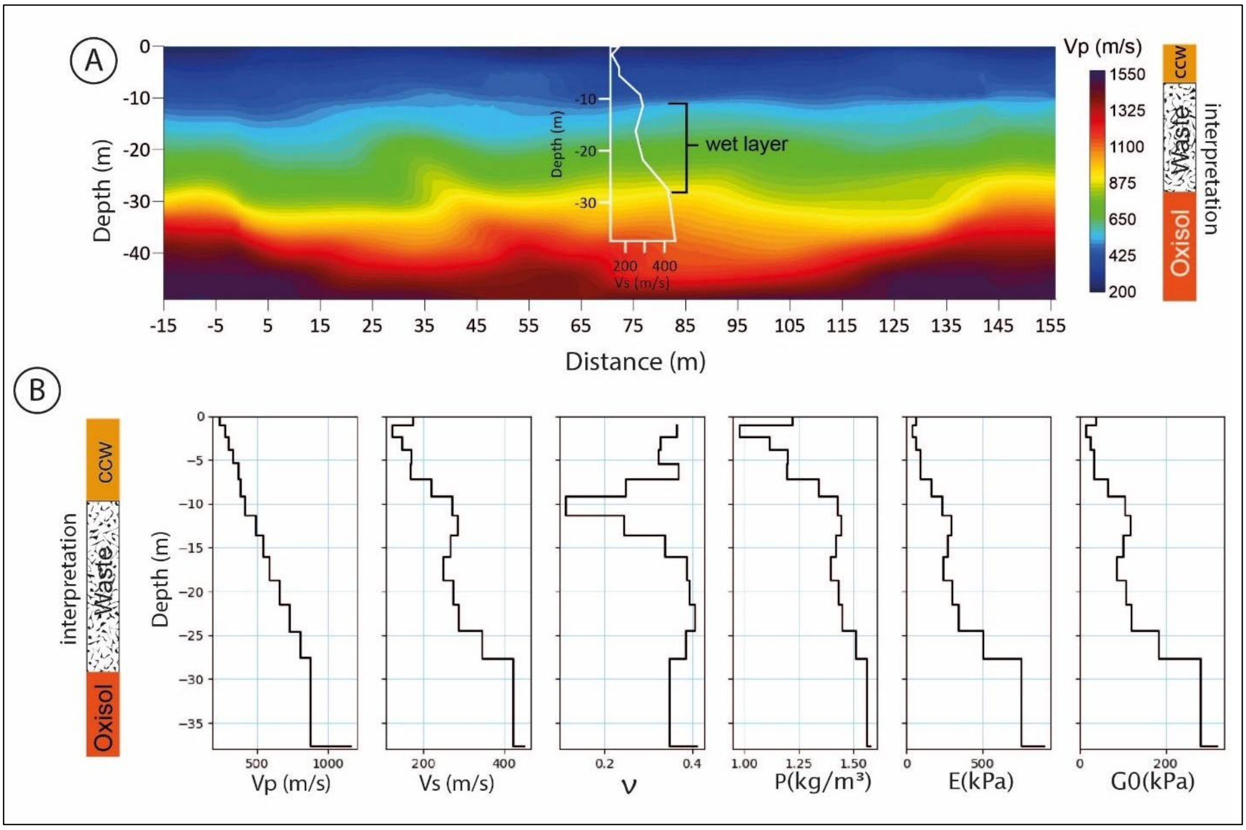

Figure 8: A) The 2D Vp section from SRT, together with the Vs vertical velocity profile obtained by the MASW method, and the interpretation of the three layers in the JCCL and their respective thicknesses. B) Vp, Vs, Poisson ratio (υ), Density (ρ), Young's modulus (E), and shear modulus (G_0) calculated in depth for the central zone of the profile analyzed and the interpretation of the three layers in the JCCL.

increased up to 0.41, corresponding to a depth of 25 meters. Below that layer, υ began to decrease smoothly up to 0.38. These values indicate how the Vp/Vs ratio can contribute to the interpretation of wet areas, in a way that the wet interval between 10 m and 25 m clearly presents itself as a zone with a higher Poisson ratio, characteristic of the influence of saturation in the medium. Between the intervals of 0 to 10 m and 25 to 37 m, υ decreases, suggesting a relatively dry area, with a progressive increase of moisture in the first layer.

Applying the empirical relationship between Vs and unit weight proposed by Choudhury and Savoikar (2009) previously presented, the average unit weight was 0.013 kN/m^3. The unit weight is related to waste compaction and low amount of soil in relation to natural terrains (Zekkos et al., 2006). The shear modulus (G_0) is essential for evaluating material stiffness and for designing soil movement analysis in areas with high seismicity or subject to dynamic loads that can cause landslides (Zekkos et al., 2008; Abreu et al., 2016). The shear modulus (G_0) and Young's modulus (E) have a similar behavior in depth distribution. We obtained a minimum G_0 value of 15 kPa and a maximum of 319 kPa. For the Young's modulus, we calculated a minimum value of 42 kPa and a maximum of 901 kPa. This range of values indicates the presence of an extremely incompetent material. Up to 12 meters in depth, the calculated G_0 values increased in depth from 15 kPa to 111 kPa. After this point, the value of G_0 decreased to 88 kPa, corresponding to a depth of 18 m. Below this depth, the value of G_0 progressively increased up to the maximum value of 319 kPa. Likewise, in the range of depth below the surface down to 12 meters, E increased from 42 to 295 kPa and began to decrease smoothly until 255 kPa, corresponding to a depth of 17 meters. Below this depth, the value of E underwent a progressive increase to the maximum of 901 kPa. Table 3 presents a description of the range of values obtained for each of the analyzed properties derived in this work.

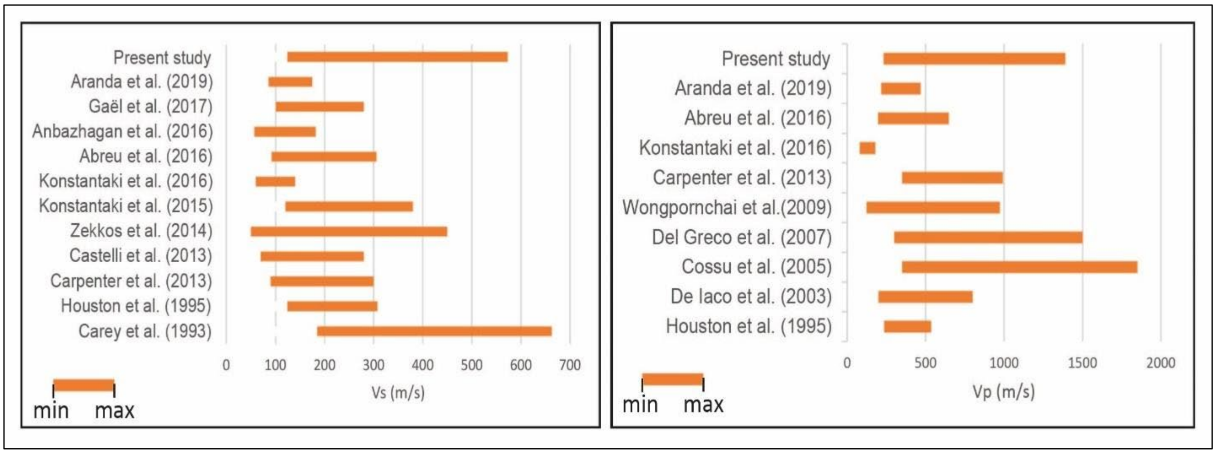

Figure 9: Comparison of Vs and Vp variation obtained in other works with those from the present study.

Table 2: Values of Vs, Vp calculated in landfill seismic investigations. Source: adapted from Abreu et al. (2016) and Aranda et al. (2019).

Reference	**Method**	**Vs**		**Vp**	
		min	**max**	**min**	**max**
Carey et al. (1993)	*Crosshole*	185	478	-	-
Houston et al. (1995)	*Downhole*	124	184	235	300
De Iaco et al. (2003)	Seismic reflection and refraction	-	-	200	600
Cossu et al. (2005)	Seismic refraction	-	-	350	1500
Del Greco et al. (2007)	Seismic refraction	-	-	300	1200
Wongpornchai et al. (2009)	Seismic refraction	-	-	124	849
Carpenter et al. (2013)	Seismic refraction and MASW	90	210	350	643
Zekkos et al. (2014)	MASW and MAM	100	150	-	-
		100	170	-	-
		90	160	-	-
		70	210	-	-
Castelli et al. (2013)	SDMT	50	400	-	-
Konstantaki et al. (2015)	Seismic reflection and MASW	120	260	-	-
Konstantaki et al. (2016)	Seismic reflection and MASW	60	80	80	100
Abreu et al. (2016)	*Crosshole* and MASW	92	214	197	451
Anbazhagan et al. (2016)	MASW	57	125	-	-
Gaël et al. (2017)	MASW	100	180	-	-
Aranda et al. (2019)	*Crosshole*	86	89	217	252

Table 3: Range of values of *Vp*, *Vs*, ρ, υ, G_0, and E calculated in the present study.

Depth	Vp (m/s)	Vs (m/s)	ρ (kN/m)	υ	G_0 (kPa)	E(kPa)
0 - 37 m	231 - 1160	124 - 449	0.97 - 1.58	0.11 - 0.41	15 - 319	42 - 901

CONCLUSIONS

The use of seismic refraction and MASW to obtain the P and S-wave velocity models was a practical and efficient approach to delineate the thickness of the JCCL waste layer. Factors such as high content of organic material, competency difference between dumped materials and difference in pore-fluid saturation between layers contributed to better delineate the layers that make up the JCCL, which have implications in the velocity of seismic waves.

The joint analysis of the elastic parameters υ, E and G_0 derived from seismic data contributes to better represent the configuration of the JCCL waste disposal. These parameters provide valuable information about the strength, competence, and saturation properties of materials grounded in the JCCL.

Knowledge regarding the distribution of wetlands in a landfill is necessary for its efficient operation and treatment. The combined interpretation of the values of Vp and Vs allowed the definition of a wet layer in the JCCL's subsurface. The zones with an increase in Vp, together with a decrease in Vs, and the relatively high Poisson ratio were interpreted as a leachate saturated layer with thickness of approximately 15 meters.

The shear wave velocity, obtained from MASW, ranged from 124 to 449 m/s. The compression wave velocity, obtained from SRT, ranged from 231 to 1,160 m/s. The calculated Poisson ratio ranged from 0.11 to 0.4. The G_0 ranged from 15 to 319 kPa. The E ranged from 42 to 901 kPa. The investigation depth was slightly over 40 meters, which is high when compared with most values reported in landfill studies. The calculated values of the elastic parameters allow classifying the landfill materials as poorly competent.

From the comparison of seismograms obtained with a sledgehammer impact and with a weight drop system, the use of the more powerful energy source was necessary, since data recorded with the sledgehammer did not show enough signal-to-noise ratio for the observation of P-wave first arrivals. This is likely to be associated with high scattering and attenuation effects around the propagation of body waves throughout solid waste.

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