COMPARATIVE ANALYSIS BETWEEN THE RESULTS OF SEISMIC INVESTIGATION AND SPT TEST OF A TROPICAL SOIL PROFILE IN THE BRASÍLIA REGION - DF

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ABSTRACT

In geotechnical engineering constructions, technical regulations prescribe a minimum number of drilling tests to allow the definition of the geotechnical profile of the site. However, even meeting this prerogative, obtaining data through this type of investigation is punctual, which can lead to errors in geological-geotechnical interpretations. In this context, this work aims to evaluate the use of seismic refraction and MASW methods as complementary tests to the SPT geotechnical investigation method, to validate the use of these methodologies to interpret a tropical soil profile. The seismic and geotechnical investigations were carried out in a vertical excavation located in the northwest region of the city of Brasília – DF, Brazil. The results showed a good correlation between the seismic methods and the SPT regarding the identification of soil layers present at the site. For both seismic methods, it was possible to verify an increase in the velocities of the VS and VP waves with increasing depth, which allowed the evaluation of the interfaces between the soil layers in the first 15 meters. It can also be verified that both methodologies have the potential to identify layers of porous soils with collapsible behaviour.

KEYWORDS: *Seismic Refraction, MASW, SPT, Collapsible Soil & Brasília-Brazil.*

I. INTRODUCTION

Soil is a heterogeneous medium with varying compositions and geological characteristics [21, 26, 27, 29, 38, 42, 43]. Variations in material type, consistency, compactness, and mechanical behavior are commonly observed. The degree of variability of these properties depends on the rock material underlying the soil. Therefore, a preliminary geotechnical investigation is necessary to identify and quantify the geological-geotechnical characteristics of the site where the civil project will be implemented. In Brazil, the Standard Penetration Test (SPT) is the most commonly used procedure for subsurface investigations [6, 7, 10, 12, 30, 33, 36].

The main purpose of a geotechnical investigation is to provide information on the soil parameters and stratigraphy of a site to support engineering projects and studies. Subsurface instrumentation can be used to carry out a geotechnical field investigation. Despite their good accuracy, these methods often provide data and analysis promptly and do not allow for continuous evaluation of the massif's condition, which can compromise an investigation process, especially in unstable scenarios. Thus, it is essential to search for methodologies that aim to complement conventional geotechnical studies for the characterization of soil profiles [27].

[31] point out that geophysical methods have a high potential to evaluate geotechnical structures since, in addition to being considered non-destructive, they allow obtaining data both in a punctual and two-dimensional way, in addition to, in some cases, allowing to carry out continuous monitoring. In this

context, [31] points out that seismic geophysical methods are a potential tool for identifying and predicting instability scenarios, as they allow the verification and characterization of the local stratigraphy and the profile stiffness variation during a state of movement, enabling the prediction of possible scenarios of instability.

Despite the potential applications, there is currently a lack of scientific studies in the national geotechnical scenario that aim to satisfactorily correlate data obtained by seismic methods with the conventional geotechnical investigation. For instance, this can be seen in the creation of geological models. Therefore, this study aims to evaluate the use of seismic methods as a complementary methodology to conventional geotechnical methods for investigating slopes [24].

This article is divided into seven sections: an introduction (describing the thematic content and objectives of the study), a literature review (explaining the theoretical concepts related to the subjects discussed in this article), an area of study and materials/methods section (detailing the materials and equipment used for seismic and conventional field investigations), results and discussion section (presenting, analyzing, and discussing the results obtained in the field investigations), and a conclusions section (providing final considerations and suggestions for future studies).

II. LITERATURE REVIEW

The SPT is a dynamic test that evaluates the resistance to penetration of material and allows measuring geotechnical parameters such as cohesion and friction angle. The executive process of this test consists of driving a sampler through the application of blows with the aid of a metal mass (hammer), weighing 65 kg, raised to a fixed height of 75 cm. This process verifies the number of blows necessary to penetrate a given soil thickness. The result is presented in Nspt, which refers to the penetration of the last two advances of 15 cm, of a total of three advances (45 cm), every 1 m of depth. As a result, this test allows for obtaining the soil stratigraphy, the position of the water level, the layer thickness, and the compactness, of sand, or consistency, for clays [1].

In engineering projects such as foundations, slope stability, and containment structures, technical regulations recommend a minimum number of drilling tests, depending on the area, necessary to define the subsoil's geotechnical profile. However, obtaining data through this type of investigation is only described in a unidimensional way, which can lead to significant errors in geological-geotechnical interpretations. In scenarios where rock blocks are present, as reported by [13], [2], [18], [17] and [16] it is recommended to adopt complementary methods to the SPT, to increase the reliability of the investigation results and reduce the occurrence of errors in interpretation.

In this context, geophysical methods can be used as a complementary tool to the use of SPT during a geotechnical investigation procedure. Geophysical methods allow for investigations with a high level of detail. This condition makes it possible to identify geological, hydrogeological, and geotechnical properties of a material, and may even recognize possible anomalous scenarios such as contaminated areas and saturation zones in dams [23].

Among the main types of geophysical methods used in geotechnics, seismic methods are a good choice, once it allows the evaluation of physical properties which are directly related to the elastic properties, density of materials, and geometry of the layers in the subsurface. [31] defines seismic methods as geophysical methods that aim to evaluate the distribution, in-depth, of the velocity of propagation of seismic waves in a medium. These methods are based on techniques involving the use of body and surface waves, depending on the type of object to be investigated. Among the main methodologies applied in the field of geotechnics, the seismic methods of Seismic Refraction and Multi-Channel Analysis of Surface Waves (MASW) are the most used.

Seismic Refraction measures the travel time of seismic waves refracted through a stratified medium. The method uses seismic sources and focuses on body waves, which propagate through a solid and cause compressional or shearing behavior. These waves can be P or S waves, with P waves inducing particle movement in the same direction as wave propagation and S waves inducing perpendicular movement. In general, the application of this method aims to identify refracting interfaces, and in engineering, its field of application is concentrated on the evaluation of soil properties such as the Poisson ratio, incompressibility modulus, and stiffness modulus [28], [31] and [33].

Surface waves propagate along a medium's surface or between different materials. They cannot penetrate great depths and exert less influence on particles away from the surface. However, on the surface, they can travel great distances with low energy depreciation compared to body waves. Surface wave methods are based on the use of Rayleigh or Love waves to investigate areas that present heterogeneous physical characteristics. The operational concept of these methods consists of capturing surface waves that are processed to obtain the S-wave propagation velocity profile over an area. Among the variations for its use, the MASW method is the most used. The use of seismic methods integrated with SPT has been explored in studies to define soil parameters, as can be seen in [11], [34], [28], [19], [32], [20] and [24]. The data obtained from the SPT are compared to correlations involving the use of shear (Vs) and compressional (Vp) seismic waves.

In tropical regions, such as Brazil, due to their physicochemical characteristics originating from the formation process, most soils present high porosity, presenting a bimodal pore distribution predominantly divided into macro and micropores. These soils have a collapsible behavior, being responsible for problems in engineering works due to their unstable structure. In Brasilia, the capital of Brazil, the geomorphology with a predominance of flatter relief associated with the climate favored a more accentuated weathering, generating deeper soil layers subject to the leaching process [4].

The surface layers are formed by collapsible soils. For the most part, geotechnical interventions intersect the collapsible soil horizon, which is subject to changes in the stress state and hydromechanical behavior. Thus, there are important conditions to take into account in geotechnical designs. Due to the impacts caused by the collapse, the identification of these collapsible soil horizons is very important. Thus, the present study aimed to identify the presence of collapsible soil layers using seismic investigations and the Standard Penetration Test (SPT) as a reference. Based on this context, this work aims to evaluate the use of seismic refraction and MASW method complementarily to the SPT geotechnical investigation method to interpret a tropical soil profile located in Brasilia and for validating the integrated use of these methodologies for geotechnical purposes.

III. STUDY AREA

The data acquisition was carried out in a vertical excavation located in the Northwest Region of the Brasília - DF, with latitude 15°44'40.99" S and longitude 47°54'42.78" W. The excavation is part of a residential development consisting of a building with a maximum basement depth of 9 meters. In Figure 1 it is possible to verify the location and the photographic survey of the investigation site before the start of the excavation. Photographic records show the visual aspect of Brasilia's soil. The surface layers have granulometry typical of sandy soils but refer to the interconnection of clay particles.

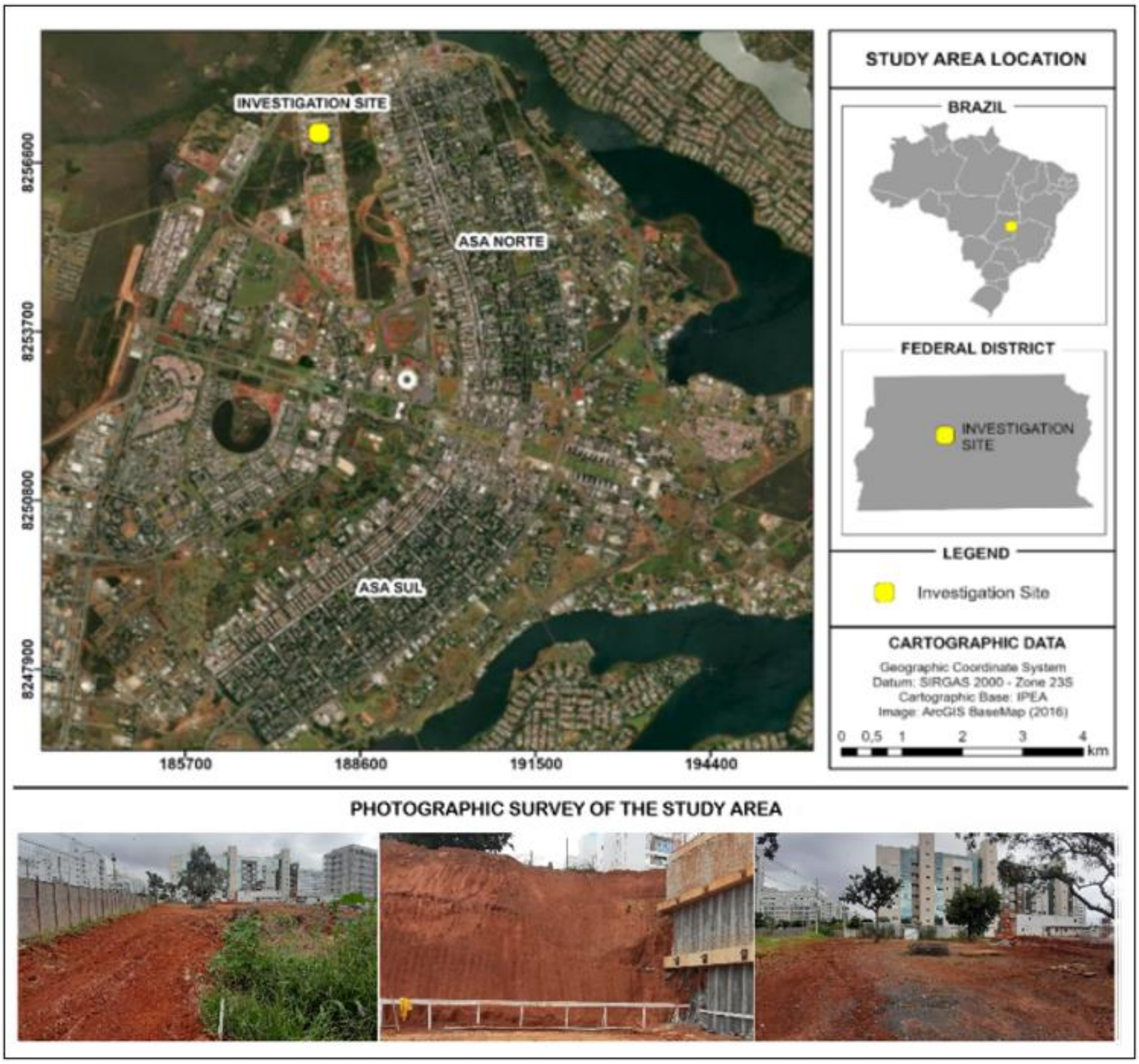

Figure 1. Location and photographic survey of the study area. In the middle photo, the soil profile of the research region can be seen. In the other photos, it is possible to see the region where the seismic acquisition was made.

The investigation site is inserted within the Paranoá geological group (Figure 2), highlighting the S unit (Argilous Metasilt). [3] state that this unit is formed by a set of homogeneous greenish metasiltites with a greenish-gray color, making it possible to identify sandy intercalations composed of metarrhythmites, limestone lenses, and red-dish dolomites with increasing weathering, which may contain sandy intercalations. Its exposure area is very restricted, with rare outcrops being found. Due to its variability, the S unit can reach thicknesses greater than 500 meters.

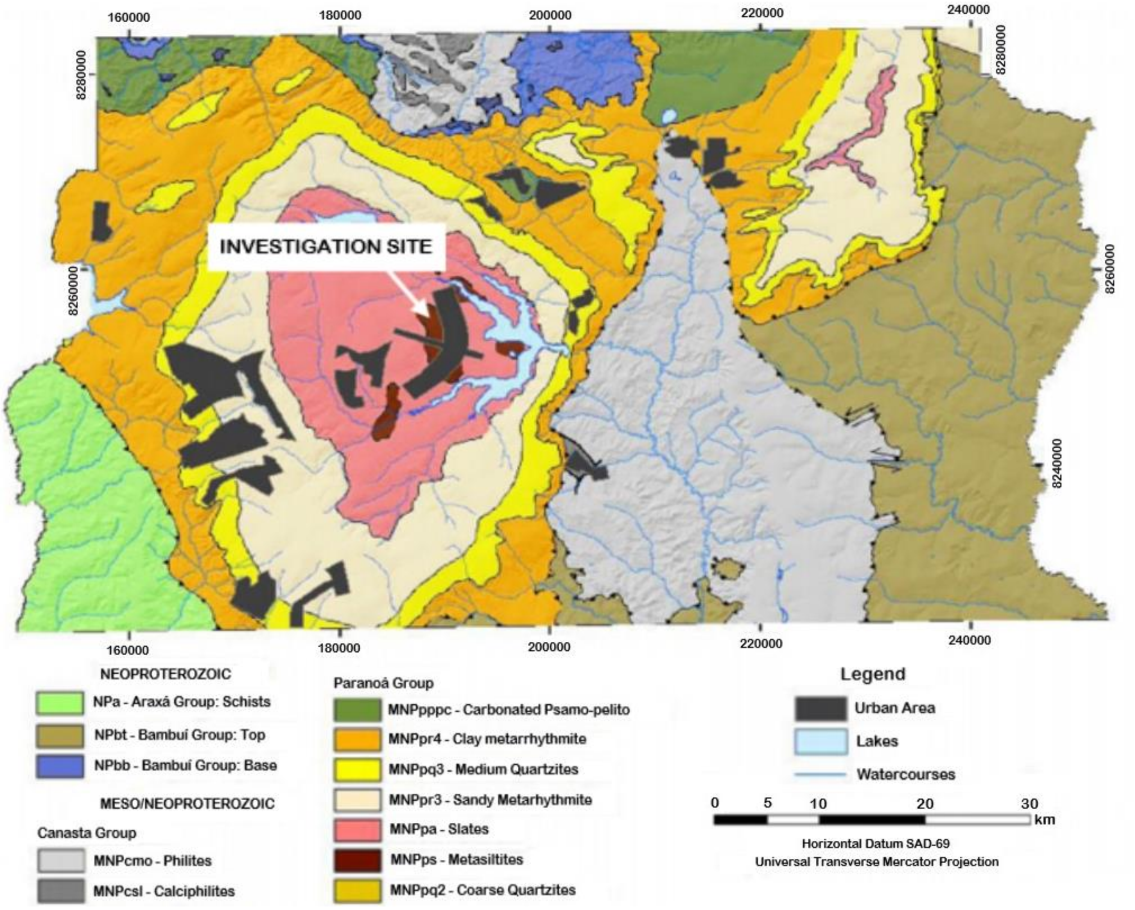

Figure 2. Geological map of the Federal District (Adapted from [3]). The predominant geological unit in the study area is the Metasiltites.

From a geotechnical point of view, the Federal District (DF) is covered by a mantle of soil resulting from the strong action of weathering, associated with leaching and lateralization processes. Due to the formation process of this soil, its structure is very porous, and metastable, with high levels of voids and consequently low specific weights, characterizing it as a collapsible soil. This layer has a low load capacity when in a saturated condition, however, it normally appears in unsaturated conditions, whose variations in humidity and, therefore, in suction influence the results of drillings.

This material, known by local technicians as Brasilia porous clay, has low penetration resistance (N_{SPT} ranging from 1 to 6 blows) and high permeability (10-3 to 10-4 m/s), similar to the permeability of fine granular soils. The bottom of the porous clay layer is identified in percussion soundings by the significant increase of the NSPT when it is in contact with the underlying saprolite soil. In the soil profile, it is verified, that the structure of the material becomes more homogeneous in terms of porosity and distribution of pores. It is also observed that, commonly, the water level is located at high depths [4].

Due to its high porosity and the type of cementitious connections, this porous material has a highly unstable structure when subjected to increases in humidity and/or changes in its state of tension, almost always presenting a sudden volume change, known as collapse [15]. Still according to the same author, in granulometric terms, it is observed that the samples present different results when made with and without de-flocculant. When executed without deflocculant, the clay parcel forms sandy-silt micro-aggregates that make the sample soil characteristics sandy-silty in the upper portions (5 to 7 m deep) and sandy-silty in the underlying layer. The generation of clayey aggregates considerably increases the void content and, consequently, influences the mechanical behavior of soils. The studied material has a behavior compatible with the granulometry obtained in the tests without deflocculant (in situ condition), therefore, to obtain correlations, this classification was used.

Other characteristics concerning the behavior of soils in the Brasília region can be observed in works by [9], [37], [14] and [5].

IV. MATERIALS AND METHODS

The seismic investigations procedure was performed using the MASW and Seis-mic Refraction methods. For both methodologies, the same seismic arrangement was adopted, consisting of two Geode seismographs (Geometrics Inc) and 48 vertical geo-phones, with a resonance frequency of 14 Hz. The geophones were arranged in a 70.5 m long longitudinal line, that is, with a spacing of 1.5 meters between them. In Figures 3 and 4 it is possible to observe the main equipment used during the data acquisition and the arrangement adopted for the acquisition, respectively.

Figure 3. The identification of each equipment is indicated in the rectangles. The installation site is located inside the construction site.

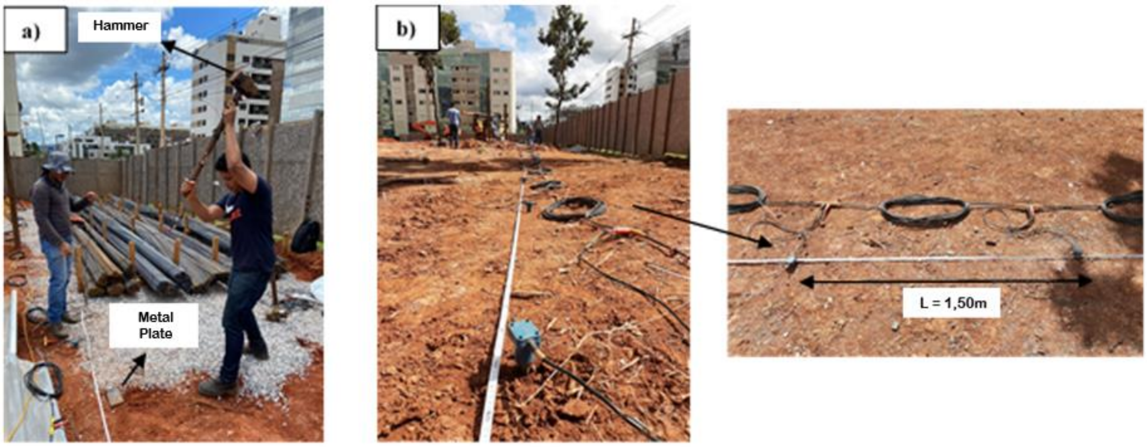

Figure 4. Acquisition of seismic data: (a) Seismic source and (b) Arrangement and spacing between geophones. The metallic plate was used to avoid the loss of energy applied to the ground.

For the creation of seismic waves, an active source was adopted, which was executed using blows on the ground, between each pair of geophones, coming from a sledgehammer and a metal plate (Figure 4a). This type of seismic source was adopted because the site is in an urban environment, and considering the depth of the interest. Six sledgehammer blows were applied to each pair of sensors (Figure 4b). In total, 24 sledgehammer shooting points were executed. Each point was 1.5 m away from the previous point. In addition, the first shooting point was performed 2.0 m away from the first geophone.

For processing the data acquired from the MASW and the Seismic Refraction, the software SeisImager/2D (Geometrics) was used, following, respectively, the steps described in Figure 5 and Figure 6. For the MASW method, after data acquisition, different steps are applied for data processing

(Figure 5). The first step is to consolidate the records into multichannel seismograms organized by source offset (Generating of Seismograms). Based on filtering techniques, signals with specific periods are isolated (Dispersion Image), and those with higher energy are representative of the propagation time of that period of the surface wave, from the source to the receiver, making it possible to obtain its velocity since the distance between source and receiver is known. This process is repeated for several periods (Dispersion Curves) for several subarrays within the acquisition line. Finally, the dispersion curves of the subarrays are inverted to obtain a 2D model of S-wave velocity with depth (2D Model).

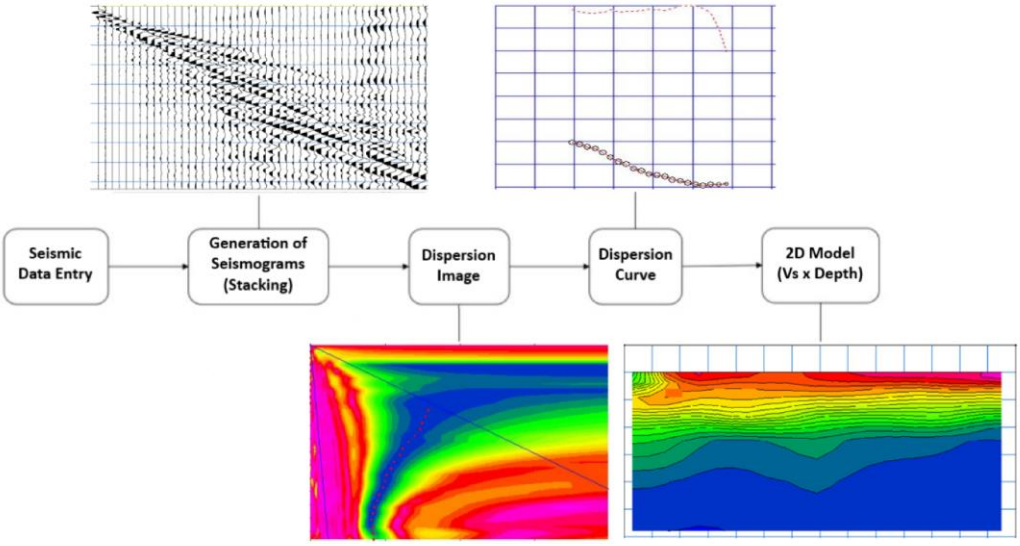

Figure 5. Data processing flowchart adopted for the MASW method. The illustrative images represent the product generated in the respective processing step.

The processing of Refraction Seismic data also follows some steps (Figure 6). After the acquisition, the seismograms are also organized by common source (Generating of Seismograms), so that the first arrivals relative to the direct and refracted waves are marked, generating graphs of time by distance (Travel-time curves). After identifying which times belong to which layers, based on the slope of the lines adjusted to the arrival times, an initial inversion is performed to obtain the initial velocity model (Initial 2D Velocity Model). Finally, an iterative inversion (often called Seismic Tomography) is performed using the Initial 2D Velocity Model as the input model, obtaining the final model, with a gradual variation of velocity with depth (Final 2D Velocity Model).

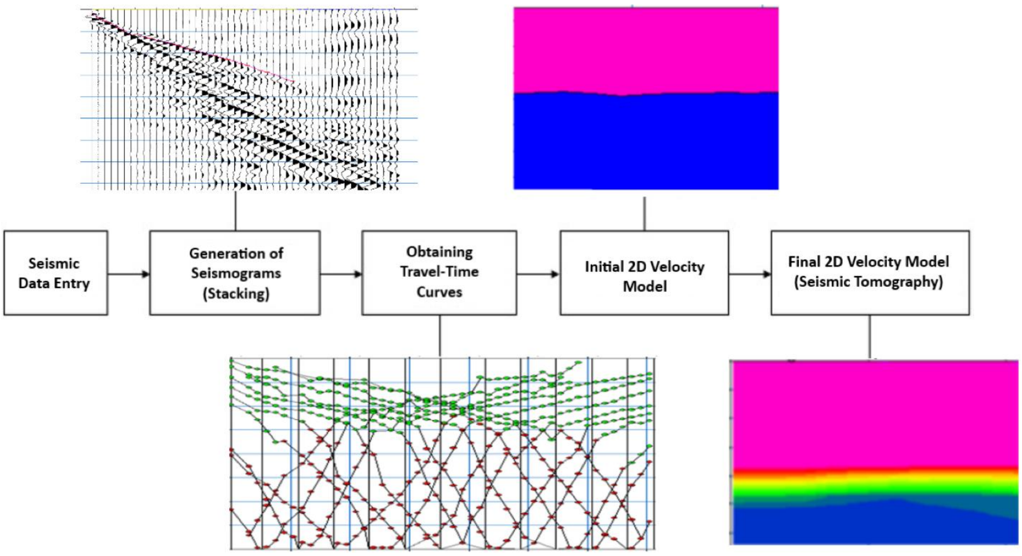

Figure 6. Data processing flowchart adopted for the seismic refraction method. The illustrative images represent the product generated in the respective processing step.

For the subsurface geotechnical investigation, data from the SPT was used. For this, were executed five boreholes were drilled with an average investigation depth of 18m, where the impenetrable was identified, and distributed longitudinally along the land area. The drillings were carried out by the recommendations of the normative instruction NBR 6484/2020 of the Brazilian Association of Technical Standards (ABNT). In Table 1 it is possible to observe the main characteristics (coordinates, depth, and water table) referring to each of the drillings.

Table 1. Data of the SPT-type percussion surveys.

Identify	Coordinates – SIRGAS 2000 – ZONE 23S		Depth (m)	W.T.[1]
	X	Y		
SPT-01	187.910,23	8.257.063,94	18,52	Dry
SPT-02	187.896,75	8.257.138,90	17,51	Dry
SPT-03	187.902,86	8.257.101,40	20,14	Dry
SPT-04	187.910,69	8.257.122,54	18,82	Dry
SPT-05	187.915,17	8.257.081,68	18,20	Dry

[1] W.T.: Water Table.

V. RESULTS

The 2D section, modeled from field data obtained by the MASW method, can be seen in Figure 7. There is a variation in the velocity of the S-wave (Vs) along the depth of the investigation profile, ranging from 136 m/s to 356 m/s, and it is possible to observe a gradual increase in Vs as the depth increases of the soil profile. It is observed that this increase is more expressive in the interval from 0 to 15 m and, from this depth onwards, the velocity of Vs becomes more stable.

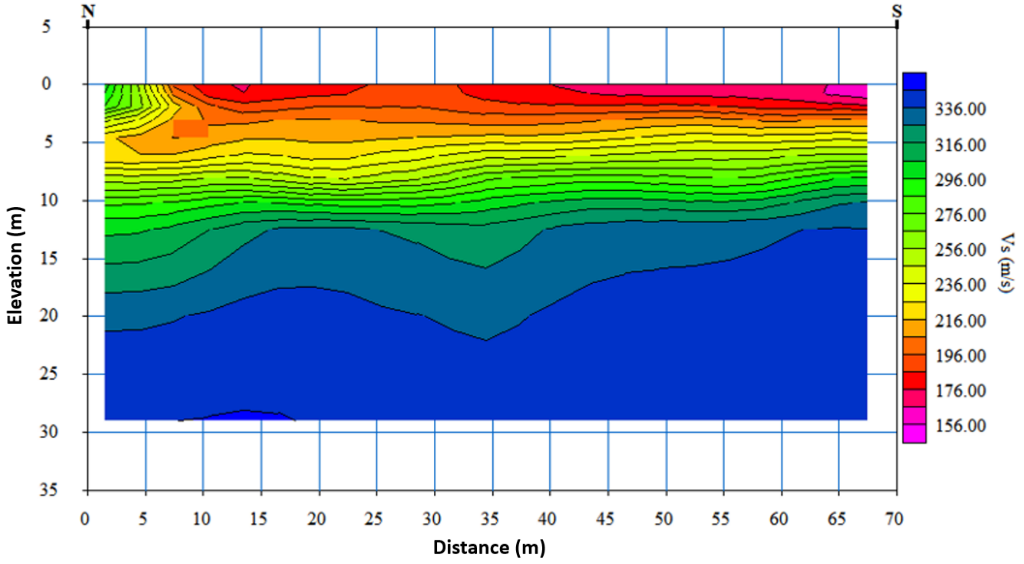

Figure 7. S-wave velocity profile obtained from the MASW method. The values of each domain represent the propagation velocity of the S wave in the investigated medium in m/s.

This scenario allows segmenting the geophysical profile into three main seismic wave velocity domains, as can be seen in Figure 8. The first domain is characterized by the presence of a low S-wave velocity zone (136 m/s to 216 m/s) up to an average depth of 5 m. The second can be defined by the velocity gradient in the range from 5 m to 13 m (216 m/s to 316 m/s). The third is delimited from the depth of 13 m (greater than 316 m/s) in which it is possible to observe a greater stability of the propagation velocity compared to the initial depths.

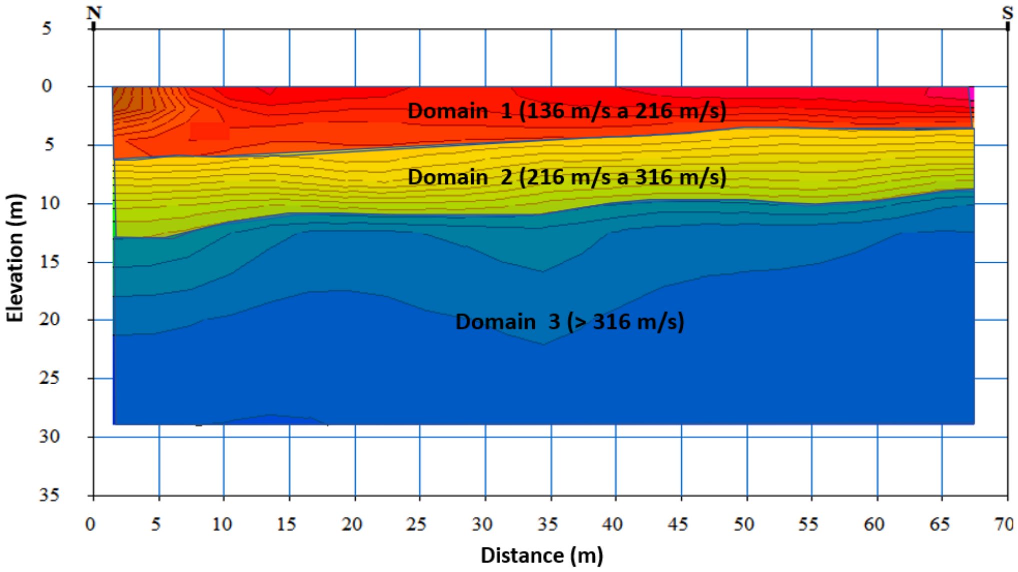

Figure 8. Background seismic line VS wave velocity domains were obtained using the MASW method. The values of each domain represent the propagation velocity of the S wave in the investigated medium in m/s. Each color represents a preliminary estimate of a soil layer.

Regarding Seismic Refraction, the two-layer model can be seen in Figure 9 and the seismic tomography model can be seen in Figure 10. The presence of two stratifications is observed, with an interface located at an approximate depth of 7.0 m. This scenario shows the presence of two velocity zones, the first at 300 m/s and the second at 1600 m/s.

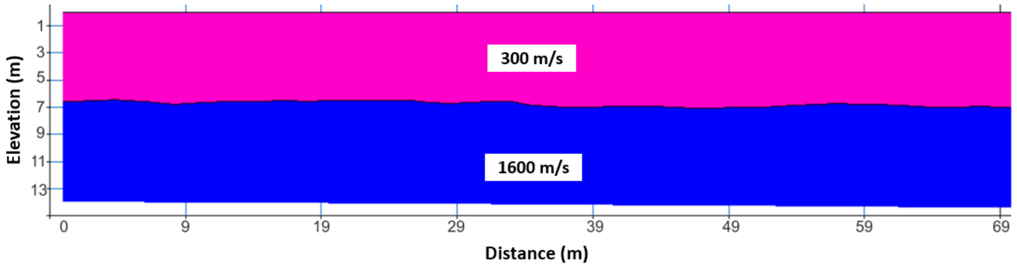

Figure 9. Two-layer model was obtained using the seismic refraction method. The values highlighted in white represent the propagation velocity of the P wave in the investigated medium in m/s.

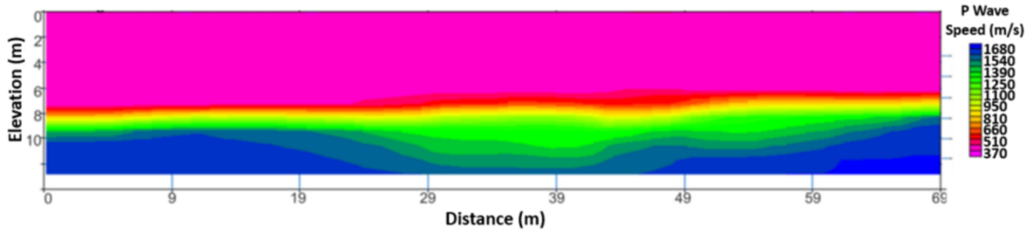

Figure 10. The seismic tomography model was obtained using the seismic refraction method. The values highlighted in white represent the propagation velocity of the P wave in the investigated medium in m/s.

About the results from the geotechnical investigation (SPT) in Figure 11, it is possible to verify the soil profile of the investigation site obtained through the interpretation of data from the percussion drilling type SPT. Based on the profile, it is possible to observe the presence of a horizon with a strong weathering process, consisting of sandy clay, a little silty, and red in color, up to an average depth of 12 m. A material of soft consistency is observed in the first 6 m with an average N_{SPT} of 4, characteristic of collapsible soils presents in the region (Figure 12). Finally, a material with a consistency ranging from medium to hard in the remaining 6 m with an N_{SPT} of 11.

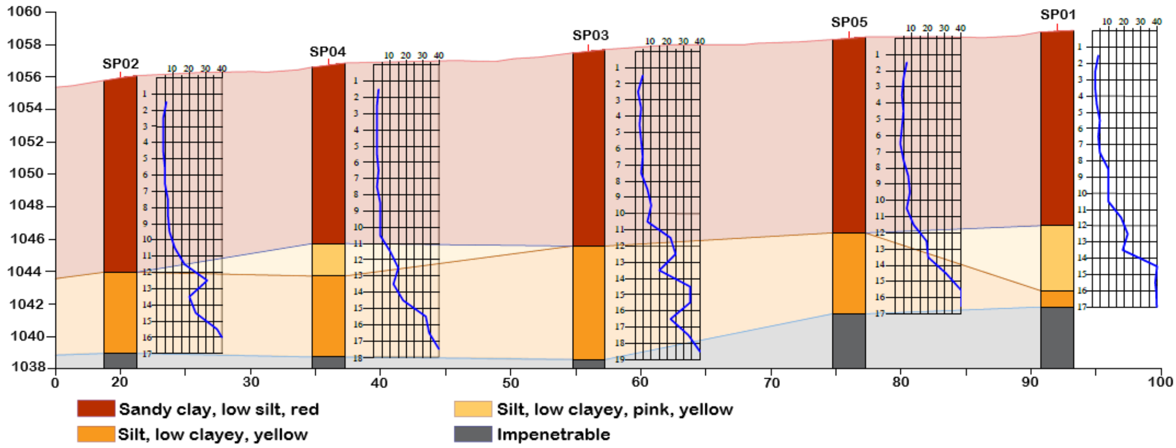

Figure 11. The soil profile of the investigation site was obtained using SPT. The values expressed in graphic form represent the penetration resistance (horizontal axis) and depth (vertical axis).

Figure 12. Sandy clay layer present at the investigation site (collapsible soil). The cylinders in the center of the image are the molds used to collect the material.

VI. DISCUSSION

As shown in Figure 8, the results obtained using the MASW method allowed the observation of three expressive domains of Vs velocity variation. The first is characterized by the presence of a low-velocity zone up to a depth of 5 m, the second is defined by the high-velocity gradient in the range from 5 m to 13 m, and the third is de-limited from the depth of 13 m. To identify the materials based on wave velocity Vs, the classification proposed by UBC Site Classifications [41] was used as an aid, together with the classification proposed by [22].

Table 2. Classification of soil substrates according to the standard established by the UBC (Adapted from [41]).

Site Class	Soil Type	Average property for the upper 30 m of the soil profile
		V_s
A	Hard rock	$V_s \geq 1500$ m/s
B	Rock	1500 m/s $\geq V_s \geq$ 760 m/s
C	Very dense soil/soft rock	760 m/s $\geq V_s \geq$ 360 m/s
D	Stiff soil	360 m/s $\geq V_s \geq$ 180 m/s
E	Soft soil	$V_s \leq 180$ m/s

Based on the classification in Table 2, it is possible to observe that the gradual increase in velocity Vs along the depth indicates that the soil profile has a gradual increase in its consistency/compactness along the profile. With this, the presence of two terrain classes can be verified. The first refers to soil with soft consistency or fluffy compactness (type E) up to an average depth of 4.5 m. The second refers to rigid soil (type D) up to the maximum depth of investigation. When comparing the Vs values, according to the classification proposed by [22], it is also possible to visualize the presence of two types of materials, where the first can be interpreted as a layer of sandy soil up to an average depth of 5 meters, and the second a layer of sandy or clay soil reaching the maximum depth of investigation (2nd interface).

By joining the classifications, it was possible to identify a thinner layer of soft sandy soil. For the next layer, the presence of a soil layer of greater resistance is observed, however, it is not possible to define whether it refers to sandy or clayey soil, making the result ambiguous. The result of this interpretation is shown in Figure 13.

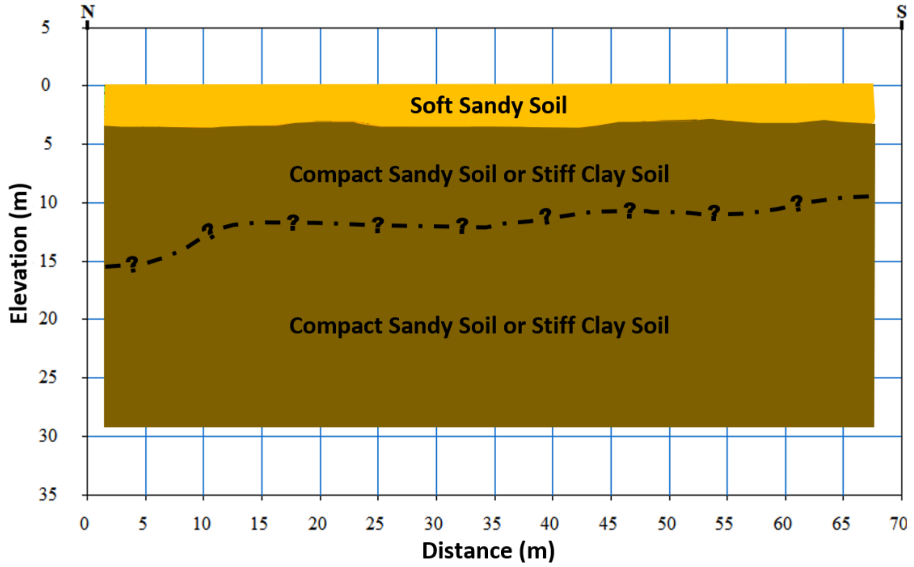

Figure 13. Final classification of the background seismic line profile using the MASW method. It was possible to define two or three types of materials. The dashed line, with question mark symbols, represents a probable interface between two materials. It was not possible to define the exact position and shape of the interface.

When evaluating the results obtained from the MASW method together with the SPT data (Figure 14), it is observed that the profile starts with a layer of soft clay up to an average depth of 7.5 m, followed by a clay, of medium to rigid consistency with a thickness of 4.5 m. Afterward, it's possible to verify the existence of a layer of silt, of hard consistency, up to an average depth of 21 m.

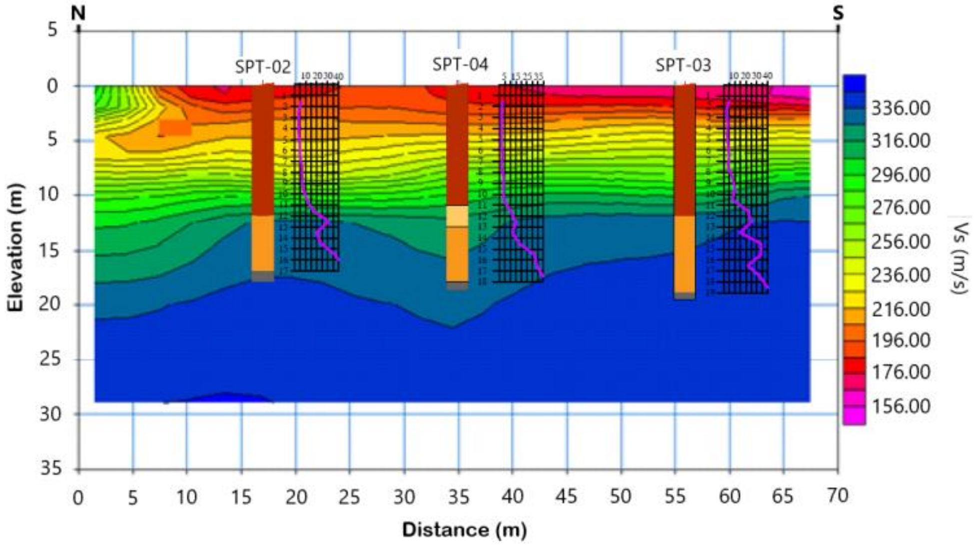

Figure 14. Comparative profile between the MASW and the SPT. The values expressed in graphic form represent the penetration resistance (horizontal axis) and depth (vertical axis).

Based on this classification, it is observed that the layer classified as sandy soil by geophysics corresponds to a layer of clayey soil of soft consistency and that the layer of ambiguous geophysical result is segmented into hard clayey soil, silt of hard consistency and impenetrable material. In this context, it can be inferred that the range of wave velocity Vs of the soft clay layer is from 146 m/s to 266 m/s, the medium, and hard clay layer corresponds to 266 m/s to 316 m/s, the hard silty soil from 316 m/s to 336 and impenetrable material with a velocity greater than 336 m/s. Through this comparative analysis, it can be inferred that the reclassification of the geophysical profile can be expressed as indicated in Figure 15.

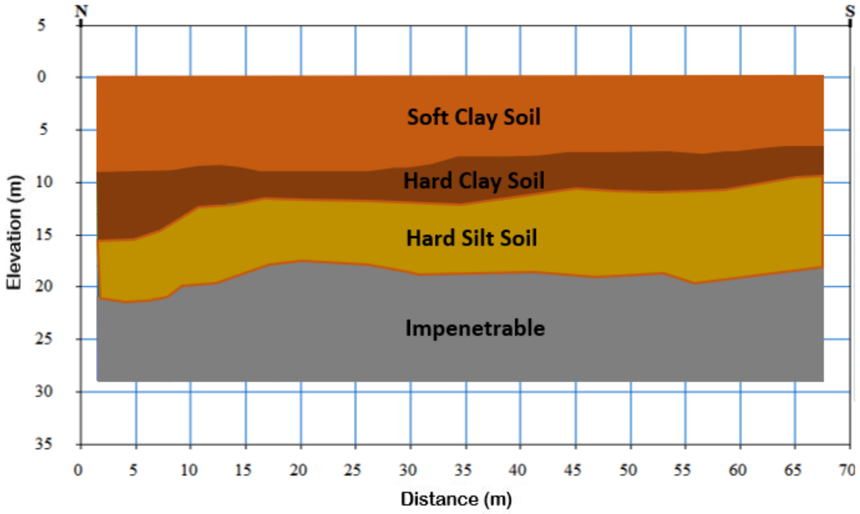

Figure 15. Soil profile interpreted from the integration of the results of the MASW and SPT. It was possible to define four types of materials

Thus, it can be seen that there is a disparity between the layer limits of the profiles obtained through the MASW seismic survey and the profile reclassified from the SPT. In Table 3 it is possible to observe the difference between the thickness and the type of material between each of the methodologies.

Table 3. Comparison between layer thicknesses obtained by MASW and SPT investigations.

Soil Type	Depth of Layers	
	MASW	MASW+SPT
Soft sand	0,0 m a 4,0 m	-
Soft clay	-	0,0 m a 7,5 m
Medium to hard clay	4,0 m a 15,0 m	7,5 m a 12,0 m
Hard silt	15,0 m a 28,0 m	12,0 m a 21,0 m
Impenetrable	> 28,0 m	> 21,0 m

Regarding the type of material, for the first soil layer of the profile, the seismic test indicated the existence of soft sandy soil, while the SPT identified the existence of porous clayey soil. This difference in classification is directly related to the characteristics and geotechnical behavior of the soils in the Brasília region. According to [4], the surface layers of the soils in this region present an intense process of weathering and leaching, which influences the existence of aggregates of clayey matrix interconnected to quartz grains using clay bridges, influencing the formation of material with a structure porous and high void ratio (1.0 to 2.0).

This condition causes these soils to have an internal structural characteristic similar to that of sandy soils, generating a behavior different from that expected for this type of material. Studies carried out by [8] show that this behavior of soils in Brasilia is frequent only in its in-situ condition (sample in natural condition according to location in the field). If it undergoes any changes such as increased humidity and/or loading, the internal structure changes due to the breaking of the cementing bonds between the particles. Because of this behavior, this soil can be characterized as a collapsible porous clayey soil.

Regarding the seismic refraction (Figure 9), the result obtained through the two-layer model allows observing the presence of two layers of materials with strong contrast, the first with a lower velocity Vp and the second layer with a higher velocity. This behavior indicates the presence of a layer of less compact material in the first meters of the profile, followed by a more compact material up to a depth of 12 meters. It was not possible to obtain a greater depth of investigation due to the seismic arrangement adopted for the execution of the seismic test. To identify the materials based on the velocity of the Vp wave, it was decided to use the classification presented by Souza et al. (1998), shown in Table 4, and [22], shown in Table 3.

Table 4. Comparison between layer thicknesses obtained by MASW and SPT investigations.

Velocity (m/s)	Soil Type
200-400	Soils, surface deposits of unconsolidated sediments.
400-1400	Clays and sands, unconsolidated.
1400-1800	Saturated sands, compact clays, and heavily weathered rocks.
1800-2400	Consolidated and probably saturated sediments, metamorphic or igneous rocks, highly fractured and/or weathered, sandstone and shales.
2400-3700	Shales, sandstones, altered and/or fractured igneous and metamorphic rocks.
3700-4500	Weakly weathered and/or fractured igneous and metamorphic rocks.
4500-6000	Unfractured igneous and metamorphic rocks.

Based on the above, it can be identified, from Figure 16, e presence of two types of materials, the first referring to a layer of unconsolidated sandy soil up to an average depth of 7 m, followed by a layer of soil saturated sandy or compact clay. As can be seen, it was possible to identify the layer of sandy soil, however, for the next layer, there is the possibility of the existence of more than one type of material, making the result found to be considered ambiguous.

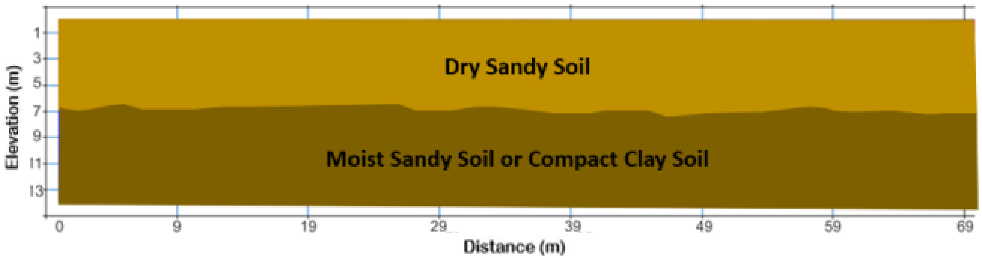

Figure 16. Soil profile obtained from the seismic refraction method using the two-layer model. In the second layer, there is the possibility of double classification, thus obtaining an ambiguous interpretation.

When comparing the data from the seismic refraction models with the SPT results (Figure 17), it is observed that using the direct investigation method, the profile characterization is similar to that obtained in the seismic method, with the profile being composed of a sandy clay material with soft consistency up to an average depth of 7 m followed by a more rigid clay, up to the maximum depth of the seismic profile. This behavior can be visualized by the considerable increase of the NSPT from the intersection of the layers.

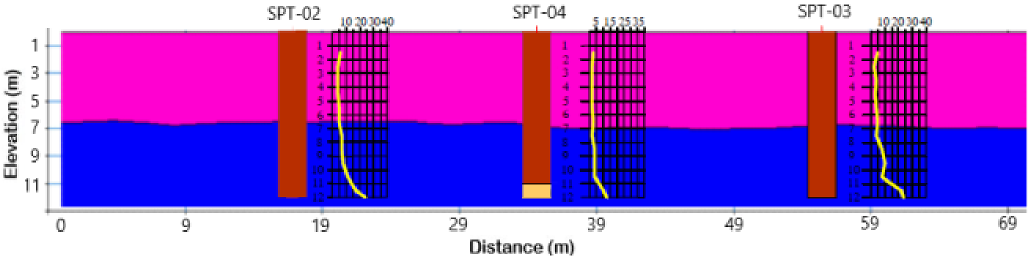

Figure 17. The comparative profile between refraction seismic and SPT. The values expressed in graphic form represent the penetration resistance (horizontal axis) and depth (vertical axis).

Due to this classification, it is observed that the layer classified as sandy soil by seismic analysis corresponds to the layer of soft clayey soil and that the layer with an ambiguous result is hard clay (compact). Then, a reclassification of the soil profile obtained from the seismic data was performed. The result can be seen in Figure 18.

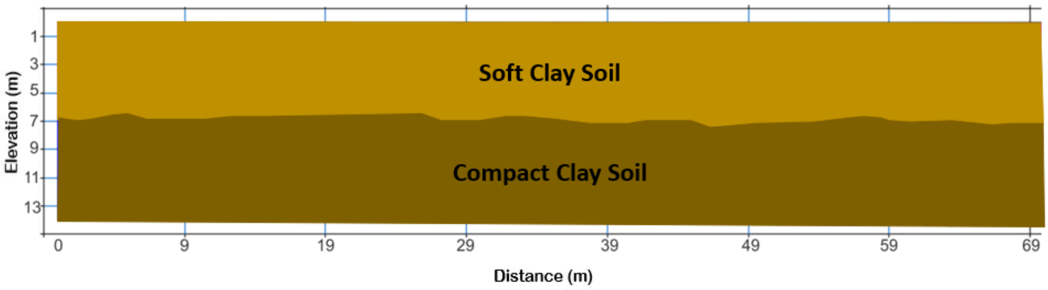

Figure 18. The comparative profile between refraction seismic and SPT. The values expressed in graphic form represent the penetration resistance (horizontal axis) and depth (vertical axis).

Based on the above, it can be seen that, up to the depth of investigation reached by the geophysical method, there was a convergence between the layer thicknesses, however, the methods alerted different types of materials. In Table 5 it is possible to observe a comparison between the thickness of each soil layer and the type of material about the profile obtained by the geophysical method in isolation and the profile estimated by the coupling with the SPT test.

Table 5. Comparison between layer thicknesses obtained by MASW and SPT investigations.

Soil Type	Depth of Layers	
	Refraction	Refraction+SPT
Soft sand	0,0 m a 7,0 m	-
Soft clay	-	0,0 m a 7,5 m
Saturated sand or Compact clay	> 7,0 m	-
Compact clay	-	> 7,5 m

Regarding the type of material, as observed in the MASW seismic test, the refraction test identified a layer of soft sand in the most superficial part of the profile, while the SPT test identified the existence of porous clay. As previously explained, the fact that the geophysical test identified sandy soil on the surface is related to the in situ geotechnical behavior typical of porous clay from Brasilia. Regarding the second layer of soil, the coupling with the SPT test allowed to eliminate the ambiguity raised by the geophysical method used in isolation, establishing the presence of compact clay.

Studies by [28], in Brasilia, involving the use of seismic refraction, also identified a layer of porous clay located in the first 6 m of depth (with a velocity of Vs equivalent to 481 m/s). As observed in this work, the comparative results, between the seismic re-fraction and the SPT, obtained by [28] were satisfactory in the investigation of the layers of a soil profile.

Regarding the thickness of each layer, it was possible to delimit the porous clay layer of the profile with greater equivalence to that obtained by the SPT method (Table 5). This condition may be associated with the fact of seismic refraction, as shown by [40], have a good efficiency to evaluate the state of compaction of the soils, being this one of the main factors that distinguish the porous clay of Brasília from the more compact clay. Due to the depth limit of the seismic investigation, it was not possible to delimit the total thickness of the most compact clay layer, however, it is noted that it would be greater than 6 m, which is also by what was obtained by the SPT test.

With this, it can be inferred that the seismic refraction method proved to be more satisfactory in the delimitation of the depth and the identification of each material than the MASW method, which favors its use to evaluate soil profiles similar to Brasília. Even with this condition, its use in isolation was also insufficient due to the ambiguity identified in the second layer of the profile. This condition calls for the use of a direct investigation test to assist in the process of identifying a soil profile.

VII. CONCLUSIONS

Based on the results obtained and, on the discussions, exposed, it is observed that, for the study area, there was a good correlation between the MASW seismic methods and refraction with the SPT, about the identification of the soil layers present in the region. For both seismic models, it was possible to verify an increase in the velocities of the VS and VP waves with increasing depth, which allowed the evaluation of the interfaces between the soil layers.

It was also verified that this delimitation presented a correlation compatible with the consistency/compactness of the materials obtained by the SPT, mainly in the most superficial layers of the profile. In addition, it can also be concluded that the seismic refraction and MASW methods have the potential to identify layers of porous soils with collapsible behavior, given the detection of the contrast between the porous clay layer and the compacted clay layer. In this context, it was possible to conclude that the MASW and seismic refraction methods have the potential to be used as complementary methodologies to subsurface investigation methods.

In order to enhance and continue this study, it is recommended to research the following topics in the future: deepening the application of seismic methods in identifying and characterizing collapsible soils; verifying the use of seismic methods as a complement to geotechnical characterization of soils located at great depths; creating a geophysical database to aid in calibration of these methods in geotechnical engineering; and using different seismic arrangements to evaluate their influence on geotechnical characterization of soil profiles.

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