APPLYING MASW AND NSPT TO EVALUATE EMBANKMENT FOUNDATION IN TROPICAL AREAS - CASE STUDIES FROM QUADRILÁTERO FERRÍFERO, SOUTHEAST BRAZIL

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Resumo – Ambientes tropicais são caracterizados por um manto de intemperismo espesso e heterogêneo que pode atingir profundidades de dezenas de metros, e sua caracterização representa um desafio significativo para projetos de engenharia. Na região do Quadrilátero Ferrífero, localizada no sudeste do Brasil e centro de Minas Gerais, este desafio é mais complexo devido à variabilidade litológica e contexto geológico-estrutural complexo que culmina em perfis de intemperismo irregulares e por vezes invertidos. Neste cenário, a sondagem à percussão (SPT) é comumente utilizada para a caracterização geológico-geotécnica de fundações de barragens até profundidades de aproximadamente 30 metros. Ao longo dos anos, o SPT provou ser um método eficaz. No entanto, dado o contexto complexo da caracterização geológico-geotécnica, é necessário utilizar outros métodos capazes de fornecer informações sobre toda a área de investigação. O método geofísico MASW (Análise Multicanal de Ondas de Superfície) serve a este propósito, fornecendo informações do subsolo baseadas na velocidade de propagação das ondas S (cisalhamento), que estão diretamente relacionadas à rigidez dos materiais. Este artigo apresenta dois estudos de caso em que uma correlação entre os valores de NSPT e velocidades de ondas de cisalhamento (Vs) foi estabelecida com sucesso. Perfis MASW 1D verticais foram realizados para obter valores de Vs em intervalos de 3 a 5 metros, atingindo uma profundidade máxima de 30 metros. Estes perfis foram executados adjacentes às sondagens à percussão, permitindo uma correlação direta entre o Vs (m/s) e o número de golpes do SPT. Nos estudos de caso, as fundações consistem em litologias típicas encontradas no Quadrilátero Ferrífero, como itabiritos intemperizados, filitos, metadolomitos e quartzitos, todos exibindo alta variabilidade em seus perfis de intemperismo. A integração de SPT e MASW nos estudos de caso apresentados levou a uma caracterização mais abrangente e confiável das propriedades do solo e sua distribuição espacial. Esta abordagem é crucial para aprimorar o entendimento geotécnico das fundações de barragens, influenciando diretamente a segurança e o sucesso dos projetos de barragens.

Abstract – Tropical environments are characterized by a thick and heterogeneous weathering mantle that can reach depths of tens of meters, and its characterization poses a significant challenge for engineering projects. In the Quadrilátero Ferrífero region, located in the southeast of Brazil and central Minas Gerais, this challenge is more complex due to the lithological variability and a complex geological-structural network that culminates in erratic and sometimes inverted weathering profiles. In such scenario, percussion drilling (SPT) is commonly used for the geological-geotechnical characterization of dam foundations to depths of approximately 30 meters. Over the years, SPT has proven to be an effective method. However, given the complex context of geological-geotechnical characterization, it is necessary to use other methods capable of providing information about the entire area of investigation. The MASW (Multichannel Analysis of Surface Waves) geophysical method serves this purpose, providing subsurface information based on the propagation speed of S (shear) waves, which are directly related to the stiffness of the materials. This paper presents two case studies where a correlation between NSPT values and shear wave velocities (Vs) has been successfully established. Vertical MASW 1D profiles were conducted to obtain Vs values at intervals of 3 to 5 meters, reaching a maximum depth of 30 meters. These

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profiles were performed adjacent to percussion drillings, allowing for a direct correlation between the Vs (m/s) and number of blows of SPT. In the case studies, the foundations consist of typical lithologies found in the Quadrilátero Ferrífero such as weathered itabirites, phyllites, metadolomites, and quartzites, all of which exhibit high variability in their weathering profiles. The integration of SPT and MASW in the presented case studies led to a more comprehensive and reliable characterization of soil properties and their spatial distribution. This approach is crucial for enhancing the geotechnical understanding of dam foundations, directly influencing the safety and success of dam projects.

Key words – MASW; Investigações Geotécnicas; Geotecnia

1. INTRODUCTION

The Brazilian territory is predominantly marked by a thick tropical weathering profile, characterized by heterogeneous soil and saprolite layers. Particularly in the Quadrilátero Ferrífero region, the intense history of tectonism has resulted in high lithological variability and a complex structural geological framework, leading to erratic and occasionally inverted weathering profiles. In addition, the Quadrilátero Ferrífero, known for its extensive mining history and hosting world-class deposits of iron and gold, is home of innumerous tailings dams settled over residual soils and saprolites. Understanding the mechanical behavior and spatial distribution of these materials is therefore crucial to ensure the dam safety.

Investigations such as Standard Penetration Tests (SPT) are commonly used to evaluate the foundations of such structures and it has proven its importance over the years providing essential data for geotechnical studies, in order to estimate the strength of the soil. However, SPT tests are punctual, and others investigation methods that cover larger areas are needed to optimize investigation campaigns and for a better geological understanding of the subsurface. In this context, shear wave geophysical surveys have proven to be excellent tools for geotechnical investigations, providing reliable and consistent results applicable to the assessment of dam foundations.

Shear wave velocity (Vs) is a fundamental parameter in geotechnical engineering and plays a key role in the characterization of soil and rock properties. Unlike compressional (P) waves, shear waves propagate through the medium without any volumetric change, making them particularly sensitive to the shear modulus of the material, which is directly related to its stiffness and deformation behavior. In geotechnical applications, shear waves serve as a reliable indicator for determining soil stiffness profiles, evaluating liquefaction potential, and designing earthquake-resistant infrastructure. The Multichannel Analysis of Surface Waves (MASW) geophysical method is the primary survey technique used to obtain subsurface shear wave data.

This article aims to explore the correlation between data obtained from SPT and MASW tests, both qualitatively and quantitatively, to achieve a more accurate and reliable geological-geotechnical interpretation of subsurface conditions in complex weathering profiles, such as those found in the Quadrilátero Ferrífero region.

Attempts to correlate Vs and NSPT values across various regions worldwide have been made, with initial studies conducted by Japanese scientists in the 1960s and early 1970s (Wair et al., 2012), also correlating these values with soil type and the geologic age of the material. More recent studies have been developed for different regions globally (Wair et al., 2012). Other authors (Kirar et al., 2016) also presented correlations for sandy and clayey soils in an area of India for seismic studies.

Correlations between shear wave velocity and NSPT values are also widely used for seismic soil classification, with significant applications in seismic engineering. Two commonly adopted classification systems, the NEHRP (National Earthquake Hazard Reduction Program (NEHRP,2021) and Eurocode 8 (CEN,2004), define ground classes based primarily on the shear wave velocity in the upper 30 meters of the subsurface (Vs30).

However, most of these studies and classifications focus on recent Quaternary sediments, mainly fluvial deposits. As a result, data correlating shear wave and NSPT for residual soils and saprolites are scarce, especially in the Quadrilátero Ferrífero region, where such correlations have not been reported yet in the literature.

In the present study, the relationship between Vs and NSPT values was evaluated for two areas within the Quadrilátero Ferrífero. MASW surveys and SPT tests were conducted in residual soils and saprolites of itabirites, phyllites and quartzites, materials that are commonly found at the foundation of dams along in the Quadrilátero Ferrífero. In this paper, a preliminary correlation of the data is presented.

2. METHODOLOGY

This paper includes the analysis of two case studies in the Quadrilátero Ferrífero region. To improve the correlation between NSPT and Vs values, percussion drillings were selected close to the 1D Vs profiles. Since the vertical Vs profiles provide results at 3 to 5 meters intervals, while the NSPT are at every 1 meter interval, the NSPT values were matched to the corresponding depths of the Vs measurements. Values of Vs and NSPT near the interfaces between residual soil/saprolite and saprolite/rock were excluded, as these may be influenced by the properties of the geological contact.

The Vs and NSPT values in this study were not corrected for overburden stress. Several studies have concluded that the use of NSPT values corrected for overburden stress in correlations with Vs is significantly less reliable (Wair et al., 2012). Furthermore, for soil classification through design codes and the calculation of Vs30, it is not appropriate to apply corrections to NSPT values.

2.1. Geotechnical Concepts

Geotechnical investigations were carried out using standard penetration tests (SPT), according to ABNT NBR 6484:2020, with recovery of borehole cores. The soil samples were classified based on their weathering grade, lithology and grain size. At the same sites, geophysical surveys were conducted using the MASW method.

For the classification of residual soils and saprolites, the definition adopted (Blight, 1997), distinguishes three types of residual soils: saprolites, lateritic soils, and mature soils. Saprolite is characterized as a material with soil-like strength that still retains the original structure and fabric of the parent rock. The mature residual soil represents a more advanced degree of weathering where the parent rock structure has been completely obliterated, leaving no visible trace.

2.2. Geophysical Investigation

The propagation velocity of surface waves is primarily defined by the velocity of S waves (secondary or transverse) in the medium. Seismically, S waves are the best indicators for determining the shear modulus. The shear modulus is directly related to the stiffness of the material and is one of the most important parameters in foundation engineering. Surface waves, commonly known as ground roll, are always generated in seismic surveys and have more intense energy than other recorded waves (refracted and reflected). Surface waves are dispersive, meaning that their propagation speed varies with frequency. On the other hand, their penetration depth is directly proportional to the wavelength of the surface waves.

The Multichannel Analysis of Surface Waves (MASW) method uses the dispersive nature of surface waves to obtain the variation of S-wave velocity with depth, either as a 1D profile or as a 2D section. Essentially, MASW is a seismic method that uses a multichannel acquisition system (24 or more channels) with arrays ranging from a few meters to several hundred meters in length. It uses special geophones for surface wave recording and special software for surface wave processing. In this study, data acquisition was performed using the active MASW method. A sledgehammer was used as an energy source, allowing subsurface imaging to depths of up to 30 meters.

The MASW method involves recording surface waves and constructing a dispersion image of these waves as a function of frequency. From this dispersion image, where the pattern associated with surface waves is defined, it is possible to derive the 1D model of S-wave velocity variation with depth (Figure 1). Multiple 1D models positioned along a survey line enable the creation of a 2D section (Figure 1) showing S-wave velocity variation with depth. Three-dimensional models of Vs distribution can also be developed based on the interpolation of 2D sections (Figure 1).

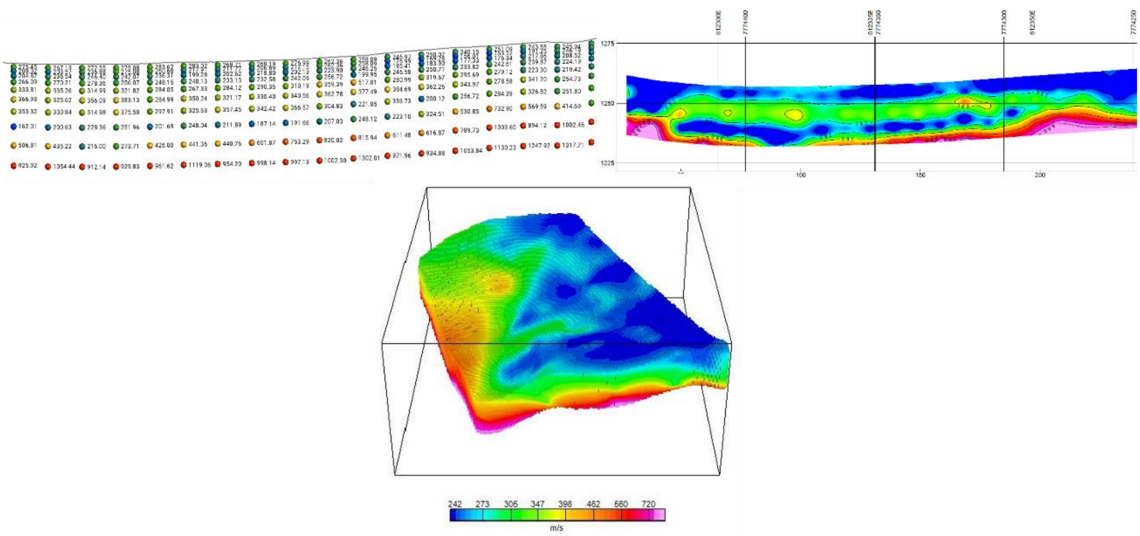

Figure 1 – Top Left: 1D Vs Profile, Top Right: 2D Vs Section; Bottom Center: 3D Vs Model.

3. GEOLOGICAL SETTING

The study areas are in the Moeda Syncline region, in the western portion of the Quadrilátero Ferrífero (QFe). The QFe covers an area of 7,000 km² located in the central part of the state of Minas Gerais, at the southeastern boundary of the São Francisco Craton (Figure 2-A; Door, 1969). According to Alkmim & Marshak (1998), the QFe is subdivided into the following macrounits:

- Crystalline Basement: Corresponding to the Metamorphic Complexes, composed of granitoid gneissic rocks;
- Rio das Velhas Supergroup: Archaean greenstone belt, composed of metavolcanic and metasedimentary rocks;
- Minas Supergroup: Paleoproterozoic metasedimentary rocks, consisting of four units:
  - Caraça Group, composed of quartzites (Moeda Formation) and phyllites (Batatal Formation), frequently intercalated with each other;
  - Itabira Group, characterized by itabirites and hematitites belonging to the Cauê Formation and dolomites of the Gandarela Formation;
  - Piracicaba Group;
  - Sabará Group, recently grouped along with the Itacolomi Group (Endo et al., 2019), forming the Estrada Real Supergroup;
  - Itacolomi Group: A pre-Cambrian restricted basin metasedimentary deposit.
- Cenozoic Deposits: Corresponding to cangas and recent colluvial, eluviated, and alluvial sedimentary deposits.

In the study areas, rocks from the Minas Supergroup are found, mainly belonging to the Itabira Group (itabirites, hematitites, phyllites, and quartzites) and the Piracicaba Group (phyllites, quartzites, and dolomites), as shown in Figure 2. There are also occurrences of Cenozoic units, such as cangas and alluvium.

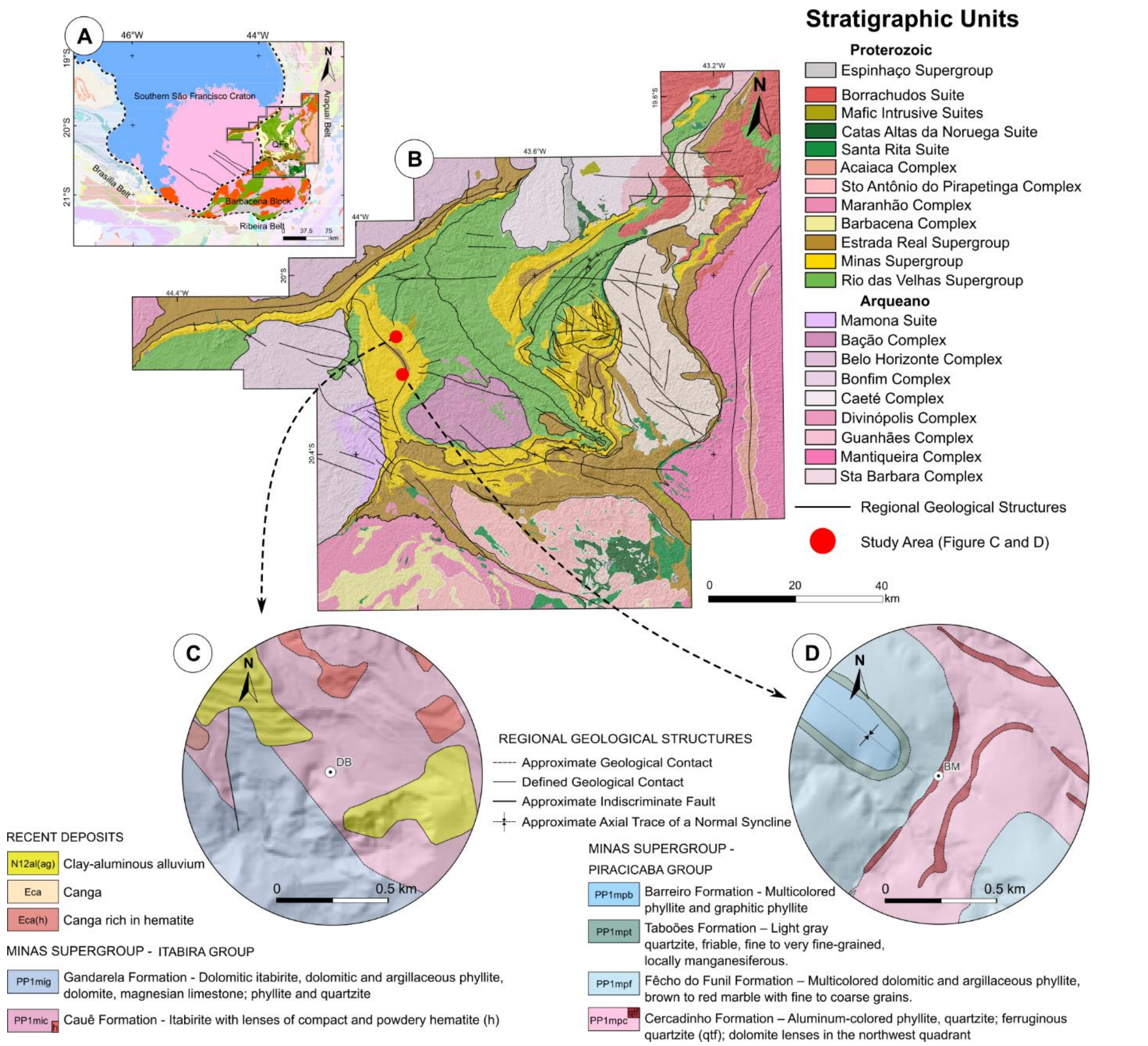

Figure 2 – Geological Context of the Study Areas. A) Location of the Quadrilátero Ferrífero (QFe) in the South American geological context. Modified from Endo et al., 2019); B) Geological map of the major units of the QFe. Modified from Endo et al., 2019; C) and D) Geological maps with the locations of the study areas. Modified from Baltazar et al., 2005.

4. CASE STUDIES DISCUSSION

4.1. Case Study 1 – Phyllites Residual Soil and Saprolite

Case Study 1 focuses on a region with soft residual phyllite soils, that is the foundation of a tailings dam. As a result, these materials needed foundation treatment to increase their strength, making the geotechnical-geological understanding of this material essential. The variation of NSPT and Vs with depth, for selected boreholes, is shown in Figure 3.Table 1 shows correlations between Vs and NSPT values for the main geological units.

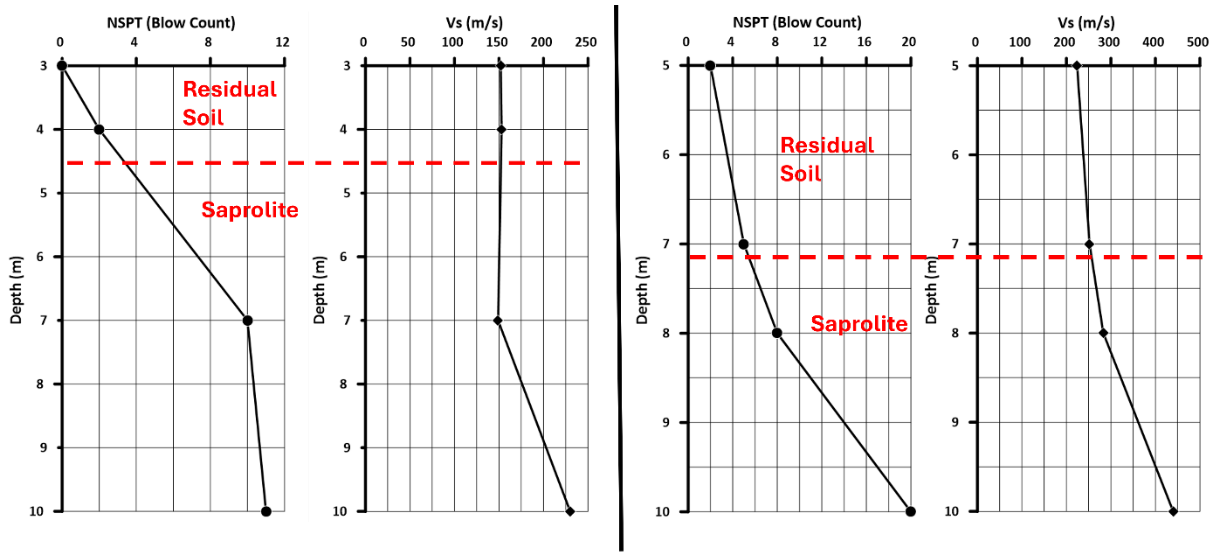

Figure 3 - Variation of shear velocity and NSPT with depth residual and saprolite materials.

Table 1 – Correlation between Vs and NSPT data for case study 1.

Geological-Geotechnical Unit	**Statistics**	**Vs (m/s)**	**NSPT (Blows)**
Residual Soil of Phyllite	Mean	194	3
	Median	191	3
	Standard Deviation	39	2
Saprolite of Phyllite	Mean	327	18
	Median	295	17
	Standard Deviation	118	9

It is observed that both parameters tend to increase with depth, particularly where the transition from residual soils to saprolites occurs. The Vs of the residual soil ranges from 150 to 250 m/s, with NSPT values between 0 and 5 blows. The saprolites have higher values for both parameters, with a mean Vs of 327 m/s, reaching up to 590 m/s, and a mean NSPT value of 18 blows.

2D Vs sections (Figure 4) were also used to interpret the geological materials, providing additional understanding into the lateral continuity of these low strength soils. These sections were compared with SPT boreholes and showed a good correlation: low NSPT values (<7 blows) corresponded to low Vs values (<200 m/s).

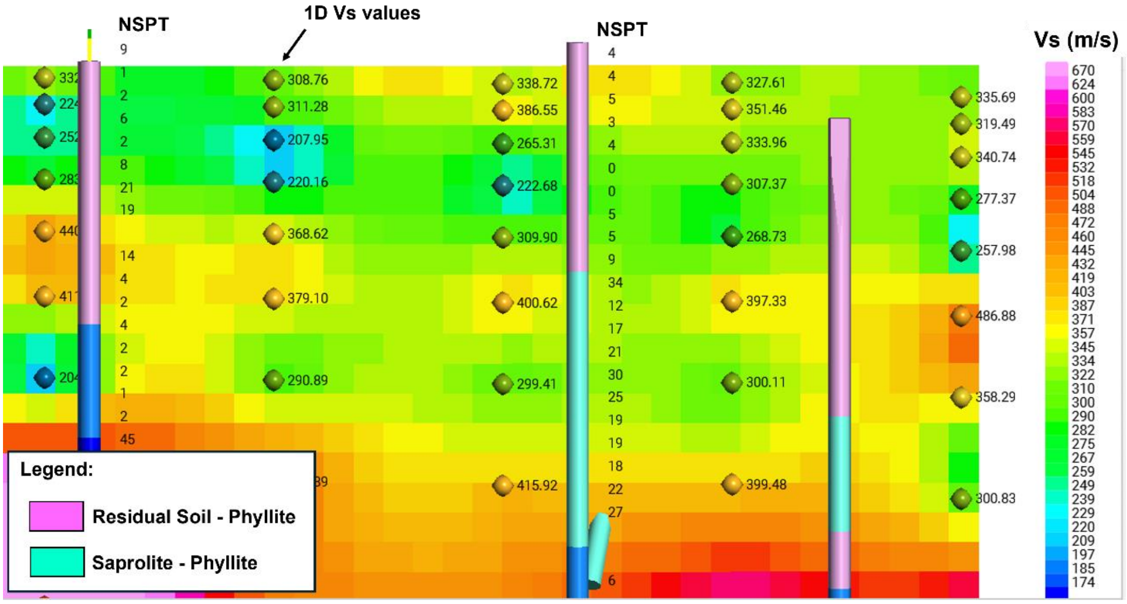

Figure 4 – 2D Vs section with 1D Vs profiles and boreholes with NSPT values (blow count), showing good correlation between the data.

4.2. Case Study 2 – Dolomitic Itabirite Residual Soil and Saprolite

Case study 2 focuses on an existing dam built on residual soils and saprolites derived from dolomitic itabirites. These materials include intercalations of dolomitic phyllites; however, due to their similar geotechnical behavior, they have been grouped into a single geological-geotechnical unit.

Compared to the materials from case study 1, the residual soils and saprolites of itabirites show higher strength, due to their composition and a higher density of gravel and rock blocks commonly present in their weathering profiles. Vs common values for residual soils range from 200 to 380 m/s, with NSPT mean value of 22 blows. Saprolites, as expected, have higher Vs values, averaging around 580m/s, with a mean NSPT value of 32. Figure 5 illustrates the variation of Vs and NSPT with depth. Table 2 shows correlations between Vs and NSPT values for the main geological units.

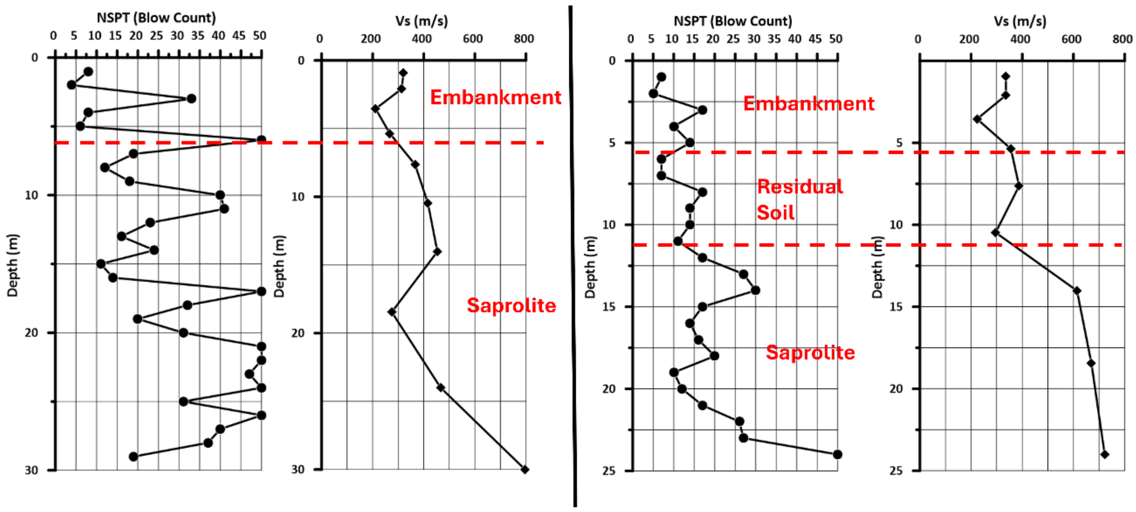

Figure 5 - Variation of shear velocity and NSPT with depth of residual and saprolite materials. Data was gathered from the embankment as well.

Table 2 - Correlation between Vs and NSPT data for case study 2.

Geological-Geotechnical Unit	Statistics	Vs (m/s)	NSPT (Blows)
Embankment	Mean	262	19
	Median	277	12
	Standard Deviation	72	16
Residual Soil of Dolomitic Itabirite	Mean	375	22
	Median	351	21
	Standard Deviation	130	12
Saprolite of Dolomitic Itabirite	Mean	583	32
	Median	531	31
	Standard Deviation	214	14

Shear wave sections, as shown in Figure 6, were also used in the geotechnical interpretation. These show high Vs values in the foundation, which correlate with elevated NSPT values. It is important to note that the investigations were carried out on an existing structure, allowing data to be collected on the dam embankment materials. It is important to note that the MASW survey also demonstrates significant applicability to studies focused on earthfill materials, such as dam embankments.

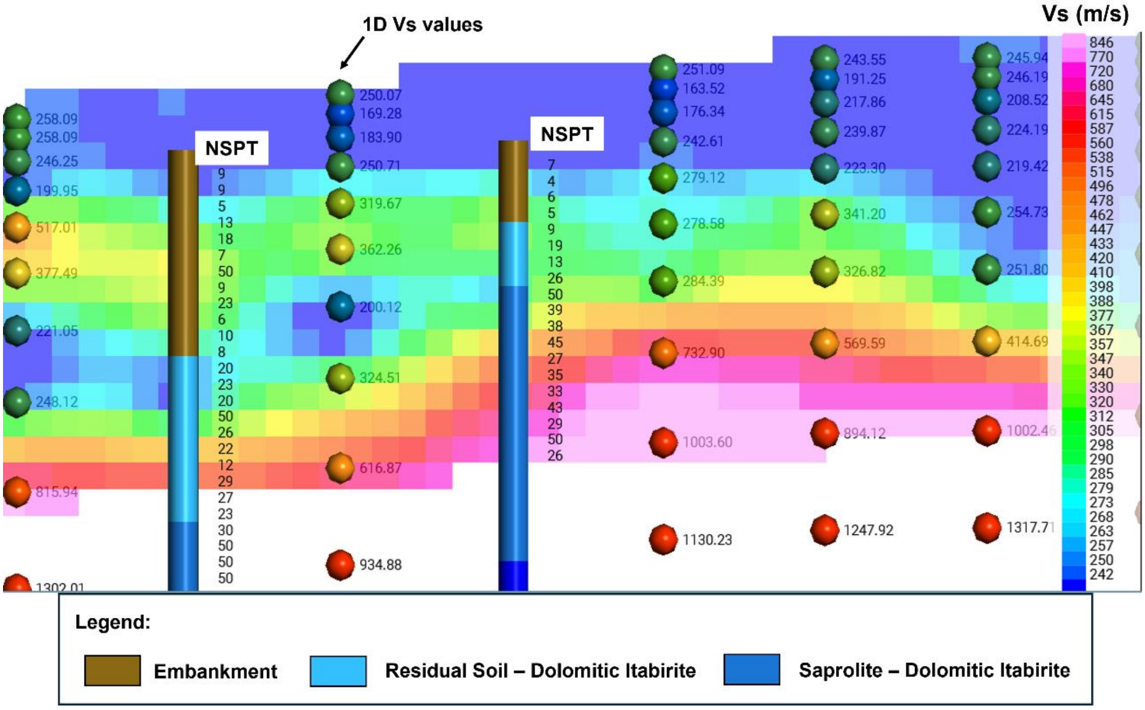

Figure 6 - 2D Vs section with 1D Vs profiles and boreholes with NSPT values (blow count), showing good correlation between the data. It is noted that the MASW survey enabled the acquisition of Vs data on the existing embankment, which also allows for the assessment of the material's competence.

4.3. Proposed Empirical Relation NSPT x Vs

Many empirical correlations between Vs and NSPT have been published in the literature (Figure 7). These correlations have been developed for various materials, including sand, silts, clays, and gravels. In general, these correlations do not include overburden-stress corrections; however, corrections for SPT energy are applied, using the N60 value in mathematical formulations.

Author(s)	V_s (m/s)		
	All soils	Sands	Clays
Hanumantharao and Ramana [5]	$V_s = 82.6N^{0.430}$	$V_s = 79.0N^{0.434}$	–
Maheshwari et al. [6]	–	$V_s = 95N^{0.300}$	–
Ohba and Toriumi [7]	$V_s = 84N^{0.310}$	–	–
Imai [8]	$V_s = 91N^{0.340}$	$V_s = 80.6N^{0.331}$	$V_s = 80.2N^{0.292}$
Ohta and Goto [9]	$V_s = 85.35N^{0.348}$	$V_s = 88.0N^{0.340}$	–
Jafari et al. [10]	$V_s = 121.0N^{0.270}$	$V_s = 80.0N^{0.330}$	$V_s = 100.0N^{0.330}$
Seed and Idriss [11]	$V_s = 61N^{0.500}$	–	–
Lee [12]	–	$V_s = 57.4N^{0.490}$	$V_s = 114.4N^{0.310}$
Sykora and Stokoe [22]	–	$V_s = 100.5N^{0.290}$	–
Okamoto et al. [23]	–	$V_s = 125.0N^{0.300}$	–
Pitilakis et al. [24]	–	$V_s = 162.0N^{0.170}$	$V_s = 165.7N^{0.190}$
Athanasopoulos [25]	$V_s = 107.6N^{0.360}$	–	–
Raptakis et al. [26]	–	$V_s = 123.4N^{0.290}$	$V_s = 184.2N^{0.170}$
Hasancebi and Ulusay [27]	$V_s = 90N^{0.309}$	$V_s = 90.8N^{0.319}$	$V_s =z97.9N^{0.269}$
Uma Maheswari et al. [28]	$V_s = 95.64N^{0.301}$	$V_s = 100.53N^{0.265}$	$V_s = 89.31N^{0.358}$
Esfehanizadeh et al. [29]	–	$V_s = 107.2N^{0.34}$	–
Fatehnia et al. [30]	–	$V_s = 77.1N^{0.355}$	$V_s = 77.1N^{0.355}$

Figure 7 – Existing correlations between Vs and NSPT (Kirar et al., 2016).

The correlations generally follow the mathematical equation:

$$Vs = a \times N^b \quad (1)$$

Where a and b are coefficients associated with the local soil type. In this study, a preliminary correlation has been developed using data from the two case studies presented (Figure 8). It is important to note that as further investigations are carried out, additional data will be incorporated to help refine the curve for typical residual soils and saprolites in the Quadrilátero Ferrífero. Data from granular soils in the Quadrilátero Ferrífero region were also analyzed; however, they showed a distinct pattern due to high NSPT values, requiring further data for a better understanding. Therefore, only data from cohesive soils were used in this equation.

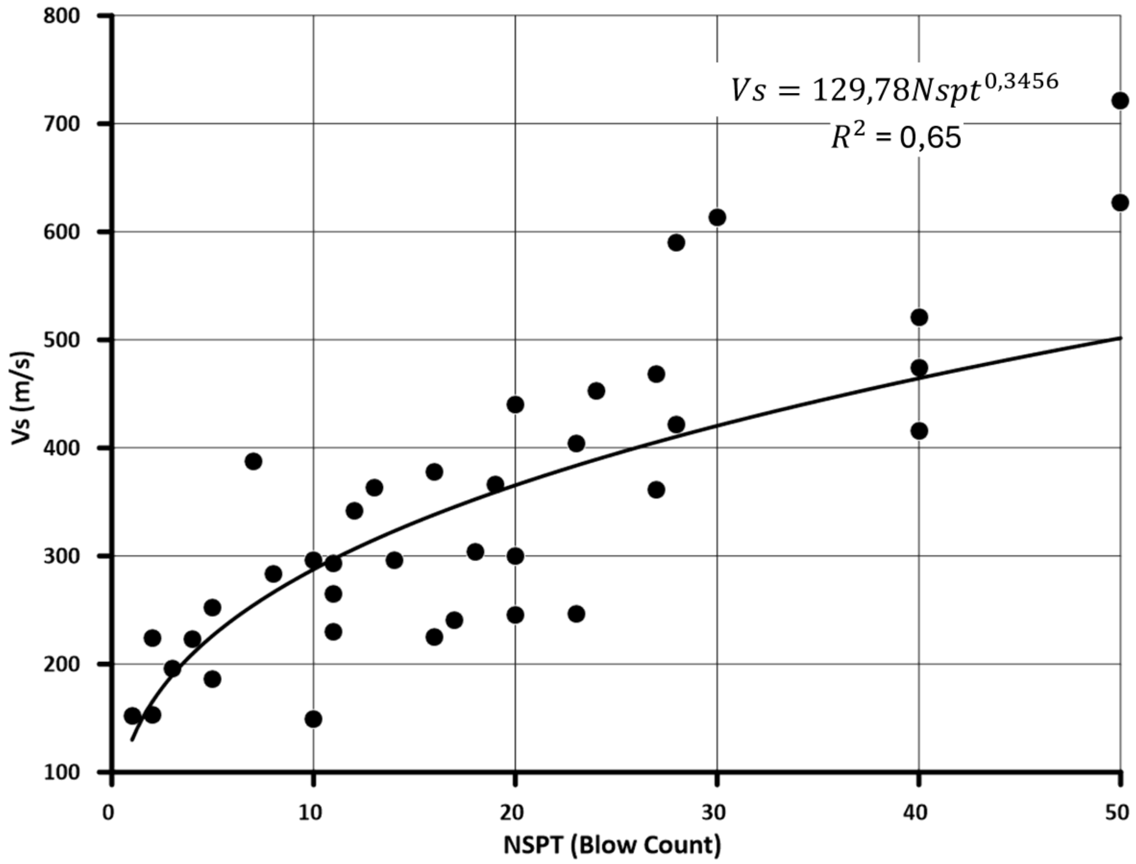

Figure 8 – Correlation between Vs and NSPT for all soils studied in the two cases.

5. CONCLUSION

The correlation between NSPT and shear wave values shows a directly proportional relationship. The MASW seismic method, combined with boreholes drilling and standard penetration tests, provides a more comprehensive and reliable characterization of soil properties and their spatial distribution. In addition, MASW surveys provide parameters as the shear modulus, which are valuable for foundation studies.

A preliminary equation has been presented for the materials studied in the two case studies, the equation proposed is mostly applicable to cohesive soils in tropical areas, as the Quadrilátero Ferrífero Region. The development of an equation for correlating NSPT and shear wave allows the shear wave velocity to be estimated as new NSPT data become available.

Continuous data compilation through ongoing investigations will enhance the robustness of these correlations and support more accurate classifications of the tropical soils found in the Quadrilátero Ferrífero.

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