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ARTICLE

Correlation of Ground Penetrating Radar Data with Geotechnical Prospect Profiles: Reduto Case Study, Belém-PA, Brazil

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ABSTRACT

The study presented in this manuscript aimed to relate the sedimentary strata imaged by the ground penetrating radar (GPR) method through numerical modeling with the mapping of sedimentary strata acquired through geotechnical surveys. The study aimed to expose how obtaining subsoil information through noninvasive/destructive electromagnetic waves is beneficial, as they are reliable and less costly than drilling holes beyond what is necessary to have a subsurface mapping. In this sense, physical-geological modeling was carried out. The information on the type of sediments, acquired through simple recognition surveys carried out in the city of Belém-PA, helped to create a model of a sedimentary package with its respective intrinsic physical properties. The result shows that the GPR recovered with good vertical and horizontal resolution at the beginning and end of the layers of the sedimentary package studied, proving to be very effective for locating geotechnical sounding points and safely reducing costs.

Keywords: Geotechnical prospecting; Ground penetrating radar; Numerical modeling

1. Introduction

The historical advance of the occupation of urban space promoted a great wave of verticalization of buildings, which became increasingly natural and every day to contain the large population contingent, increasingly growing in the city of Belém-PA [1].

The stage of designing and constructing foun-

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dation structures is paramount among the stages of civil construction, as the total load dissipation of the structure will depend on it, especially in densely occupied residential buildings [2].

Considering this scenario, obtaining information from the subsoil, such as that obtained from geophysical measurements, which use electromagnetic waves and electrical resistivity data from the soil, is critical, primarily because it provides essential information about the geological environment at the study site. Geophysical methods are widely used for soil and subsurface investigations. These methods involve the use of the physical properties of the subsurface materials to infer their composition and structure. Some commonly used geophysical methods for soil and subsurface investigations include ground penetrating radar, seismic refraction surveys, electrical resistivity imaging, and slingram.

The Ground Penetrating Radar (GPR) method involves using a radar antenna that emits high-frequency electromagnetic waves, typically 10 to 1000 MHz, propagating through the subsurface materials. The waves reflect the surface when they encounter a boundary between materials with different dielectric properties. By analyzing the amplitude, phase, and time delay of the reflected waves, it is possible to infer the subsurface materials and objects' depth, location, and properties. The GPR method can also create two- or three-dimensional images of the subsurface materials and objects.

The seismic refraction method uses a seismic source, such as a sledgehammer or a small explosive, to generate seismic waves propagating through the subsurface materials. The waves are detected by a series of geophones placed along a line on the surface. By analyzing the travel time and velocity of the seismic waves, it is possible to infer the depth and composition of the subsurface materials. The seismic waves refract or bend at the interfaces between materials with different seismic velocities, allowing the determination of the depth and thickness of each layer.

The electrical resistivity imaging (ERI) method involves using a series of electrodes placed on the ground surface and an electrical current source that injects a current into the ground through the electrodes. The resulting electrical potential is measured by a series of receiver electrodes, which are also placed on the ground surface. Analyzing the voltage and current data makes it possible to infer the electrical resistivity of the subsurface materials. The resistivity data can then be used to create two- or three-dimensional images of the subsurface materials, showing variations in their resistivity properties.

The Slingram method involves the use of a transmitting coil and a receiving coil. The transmitting coil generates an electromagnetic field that penetrates the subsurface materials. If there is a conductive object in the subsurface, it will affect the electromagnetic field and induce a secondary electromagnetic field that is detected by the receiving coil. For more details about geophysics methods [3-7].

The delimitation of layers and information about the beginning and end of different lithologies and soil strata through the response to electromagnetic stimuli is a great advantage, especially because geophysical methodologies are nondestructive and noninvasive and can be carried out quickly and often free of charge (under an agreement with the university to provide service to the community).

At the discretion of compliance, standardization, and mainly technical responsibility, the engineer carries out at least one survey of simple soil recognition for building foundations every 200 m^2 of the projected area in the plan before executing any building up to 1200 m^2 of area, see ABNT NBR 8036 [8]. However, in small works and even to reduce costs, it is common for some professional engineers to choose to minimize costly steps, such as geotechnical investigation, which, in turn, can result in unnecessary expenses with foundations or with the recovery of structures and settlements beyond those foreseen [9,10].

The use of GPR in engineering studies can be considered advantageous in the application of geophysics, as it allows the execution of continuous and high-resolution profiles, presents ease of data acquisition, performs measurements with different frequencies, and has the versatility of the equipment in the field, allowing its application even in urban areas and inside buildings. Compared to other investigation techniques, this method has a low cost-benefit ratio combined with the speed of execution. GPR numerical modeling is well established, with several works and studies published [11], which bring the state of the art of methodology to various fields of knowledge, including engineering.

Considering the previous events, the present work seeks to elucidate how and to what extent geophysical methodologies, particularly GPR and numerical modeling, can assist engineering in identifying geological features and bedding in the subsurface. The lack of prior knowledge about the typology of underground sediments in areas where it is intended to build buildings, mainly vertical ones, before carrying out direct studies such as the standard penetration test (SPT), combined with insufficient information about subsurface geology, can generate mistakes in the location of underground studies. It generates a lack of essential data for the designer, which, in turn, can lead to errors in the dimensioning of foundations, generating oversizing (in the case of the insertion of safety margins beyond the necessary ones), settlements (from insufficient sizing), and pathologies (from different origins). For more information about subsurface anomalies and their detection [12,13]. The present study aims to obtain information on the subsurface from indirect and nondestructive measurements, which use electromagnetic waves and information on electrical soil resistivity, to correlate the strata described by geophysical methodologies with the strata mapped by SPT soundings.

2. Materials and methods

2.1 Standard penetration test

The ABNT NBR 6122 [14] establishes that any building must undergo preliminary geotechnical investigations of at least percussion soundings. The Standard Penetration Test (SPT) provides information on the stratigraphy and lithological classification of soils, groundwater level, and measurements of penetration resistance indices according to ABNT NBR 6484 [15] and soil classification according to ABNT NBR 6502 [16]. The ABNT NBR 6484 [15] defines the SPT drilling procedure as follows: The drilling and dynamic driving of a standard sampler every meter result in the determination of the type of soil and a resistance index, as well as the observation of the water level inside the borehole. For the definition of these results, this standard incorporates two test systems: The manual system and the mechanized system. The two systems will give different resistance index results.

As a rule, the process is divided into stages, the first being the collection of the soil sample (zero level). Then, the excavation stage begins, in which a manual auger is usually used to remove the soil sample (zero level). Then, the excavation stage begins, in which a manual auger is usually used. Then, the insertion of the sampling rod is initiated using a manual or mechanical hammer. The descent of the rod occurs in three stretches of 15 cm, totaling 45 cm. The initial 15 cm is discarded for measurement purposes, and only the final 30 cm of soil penetration is considered ABNT NBR 6484 [15].

The SPT is performed (manual test method) using a trephine (rod with a bevel at the end) that promotes the perforation and deterioration of the soil layers and removes debris removed through water circulation. When the depth to be analyzed is reached, the sampler is inserted at the end of the rod in place of the trepan, and a typical weight (65 kg) is used as a hammer. The number of blows required to reach 45 cm (15 cm initial and 30 cm final) must be counted to calculate the Nspt. **Figure 1** shows a schematic drawing of how a manual SPT probe is performed.

According to the ABNT NBR 6484 [15] standard, as the sampler is introduced, in addition to providing Nspt, soil samples are collected and stored for later geological classification. At this stage, the depth of the water level and the thickness of each sediment layer (beginning and end) are also measured. In Belém, manual geotechnical surveys are the most common [18,19]. **Figure 2** depicts a photographic record of the manual execution of an SPT sounding in a city lot.

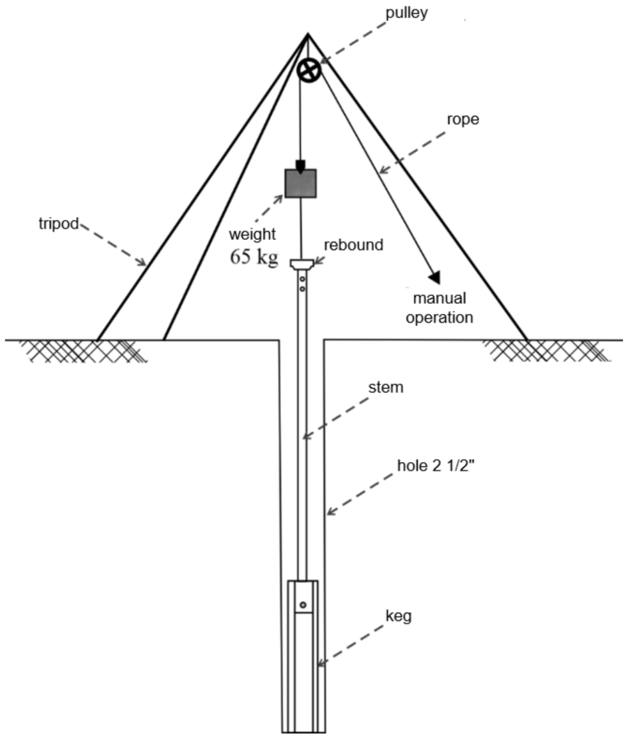

Figure 1. Schematic drawing of manual SPT sounding [17].

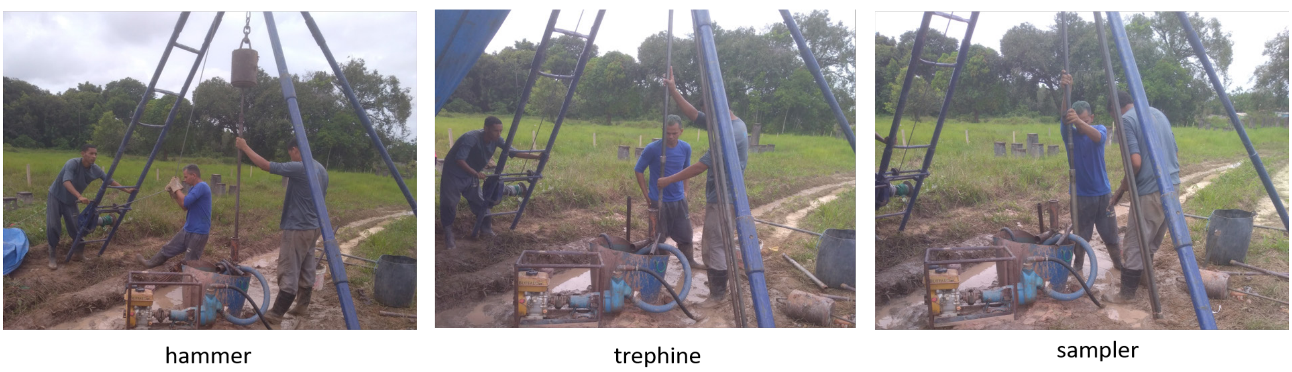

Figure 2. Photographic record of the manual SPT drilling process in the field.

2.2 Ground penetrating radar

Ground Penetrating Radar (GPR) is a geophysical method based on the propagation of high-frequency ElectroMagnetic (EM) waves. Practically speaking, EM energy waves are emitted from a transmitting antenna from 10 MHz to 1 GHz. When the EM wave reaches the interface between geological materials with different physical properties, part of its energy is reflected toward the surface, where it is captured by the same antenna or a second receiving antenna [20]. The propagation of the subsurface radar signal depends on the frequency of the emitted signal and the electrical properties of the medium. In the case of geological materials, the electrical properties are mainly controlled by the mineralogy of the constituents, the presence of clays, the content of metallic minerals, and the water content. If there is a contrast in at least one of the physical properties (electrical conductivity σ, dielectric constant K, and magnetic permeability μ) of subsurface materials, part of the signal is reflected and received by the receiving antenna that directs the signal received from underground to the receiver [20,21].

The resulting section, the radargram, is formed by each trace (scan) representing the arrival time of the reflected pulses, the pulse transmitted through the air, and the direct wave propagating through the ground. Early reflections appear later (or more significantly) in the scan. As the antenna is moved over the terrain, different scans are recorded at different points. The set of scans positioned side by side (**Figure 3**) in the sequence of their acquisitions forms an image, which is a display analogous to a magnetic resonance image performed in humans, changing the composition of the EM field from a magnetic field (Hx, Hy, and Hz) that GPR uses to image to mainly the electric field (Ex, Ey, and Ez) [22].

The depth of the reflection interfaces can be obtained from the radargram, thus facilitating the interpretation of the profile and providing an approximate location of the targets. For this, it is necessary to know two parameters: the transit time between the beginning of propagation and the arrival of the reflected wave and the propagation velocity of the wave; for more details [23]. The data collection procedure is straightforward, as illustrated in **Figure 4**, which shows a photographic record of surveys conducted in the city.

In the present study, the analysis and modeling were carried out in an area in the Reduto neighborhood (in this work, it will be treated as Report RE-001). The region was chosen because the neighborhood of Reduto has a high population density and areas with deep foundations [18,19]. The area has three boreholes that are not aligned laterally and a slightly uneven topography (a level similar to that of the street) (**Figure 5**).

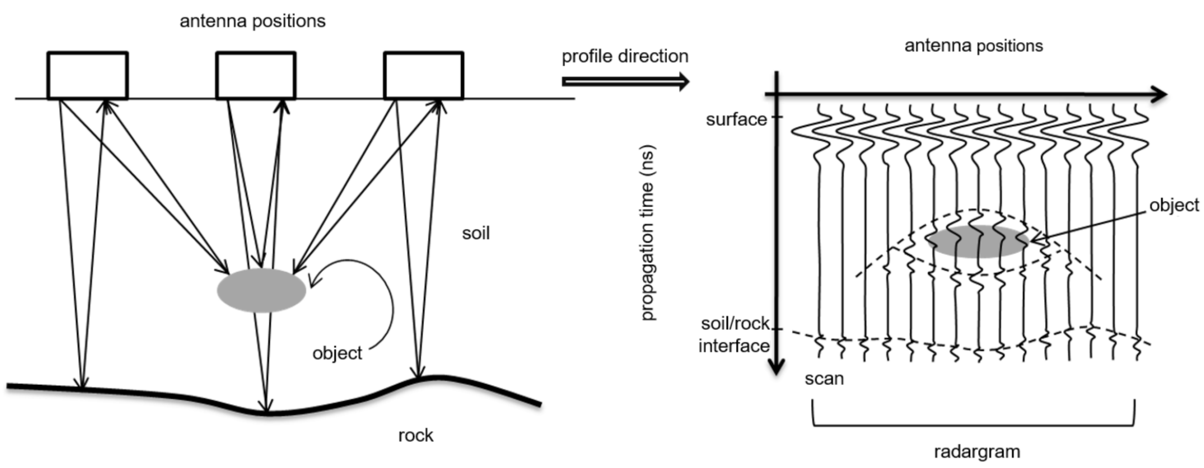

Figure 3. Exemplification of a GPR survey and a radargram [20].

Figure 4. Photographic record of the profile organization process and data acquisition with GPR.

The individual profiles of the holes show a good lateral correlation of the sedimentary layers with each other when placed side by side. Therefore, **Table 1** presents the primary information contained in drilling report RE-001.

Profile SP 01, in which excellent resistance to penetration is noted in a few meters of sampling (15.03 m) and that from 13.70 m down, the sampler was unable to descend the last 30 cm, leaving 8 cm for 46 blows, 5 cm for 49 strokes, and 3 cm for 55 strokes. The three asterisks (***) in the Nspt description indicate that the sampler could not exceed the initial 30 cm, as shown in **Figure 6**.

The sequence of sedimentary layers corresponds to the second hole, although the holes are not parallel. As in SP 01, borehole No. 02 ends at 15.05 m and has a resistant layer of thick white sand impenetrable to the standard sampler, descending only 5 cm in 58 strokes at the end of the borehole, as shown in **Figure 7**.

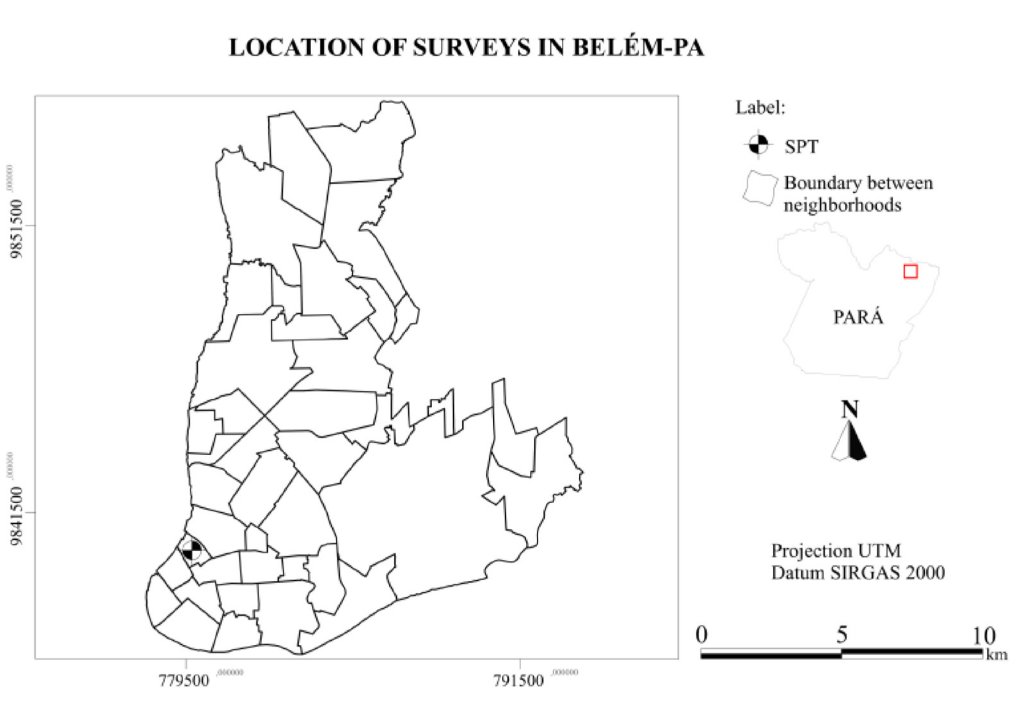

Figure 5. Location map of SPT Reduto reports in the city of Belém/PA.

Table 1. Organization of the information in the SPT RE-001 report.

SPT—REDUTO								
SP01	**prof**	**Nspt**	**SP02**	**prof**	**Nspt**	**SP03**	**prof**	**Nspt**
Variegated colored clayey silt	01,70	4	Variegated colored clayey silt	02,50	3	Variegated colored clayey silt	02,80	3
Light gray silty clay	02,80	6	Light gray silty clay	04,70	6	Light gray silty clay	03,90	14
Medium light gray sand	05,40	8	Medium light gray sand	06,30	8	Medium light gray sand	05,60	10
Variegated colored silty clay	13,70	7	Variegated colored silty clay	13,80	8	Variegated colored silty clay	13,50	7
Coarse white sand	15,03	55***	Coarse white sand	15,05	58***	Coarse white sand	15,08	55***

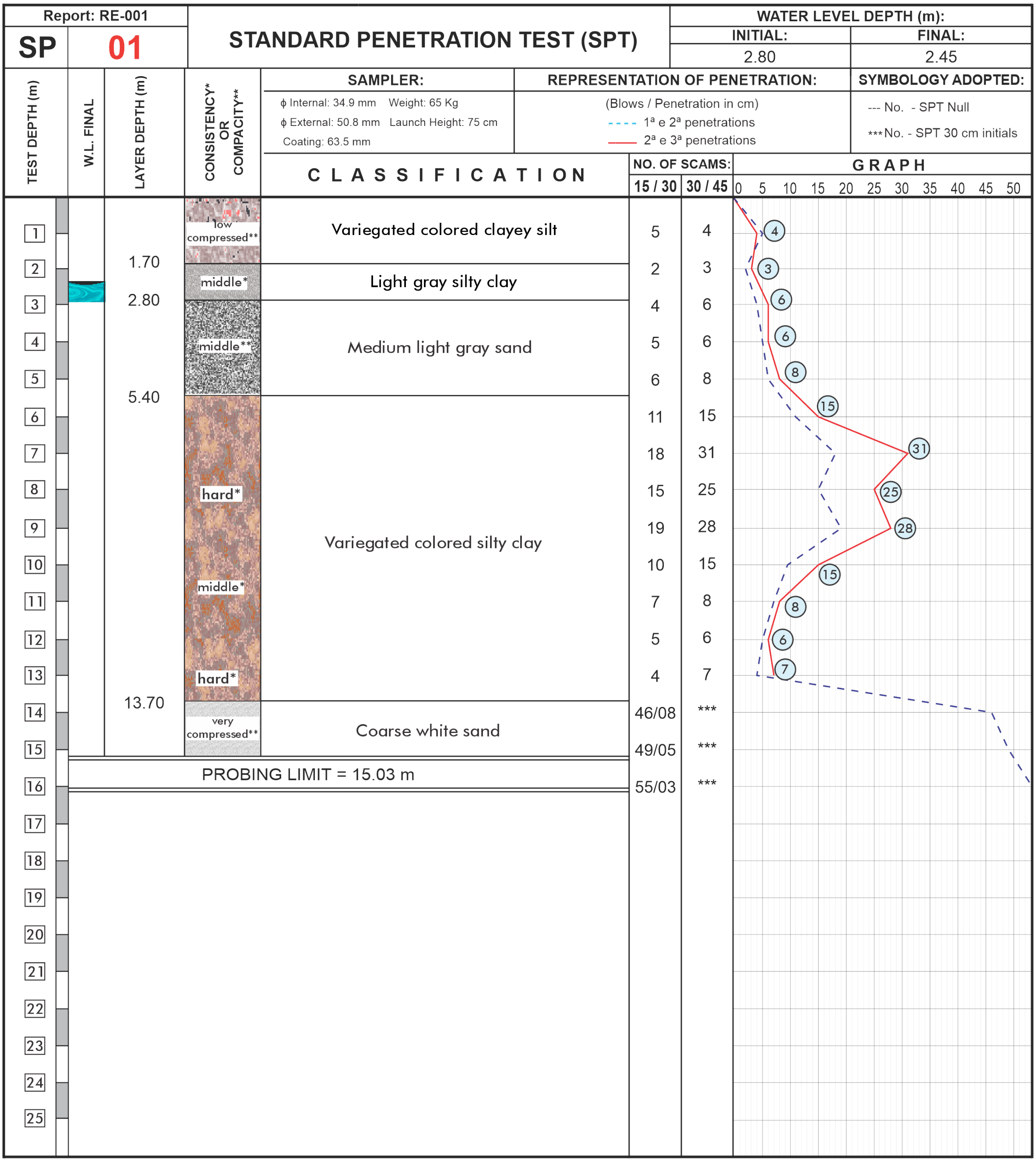

Figure 6. SP-01 of the RE-001 report.

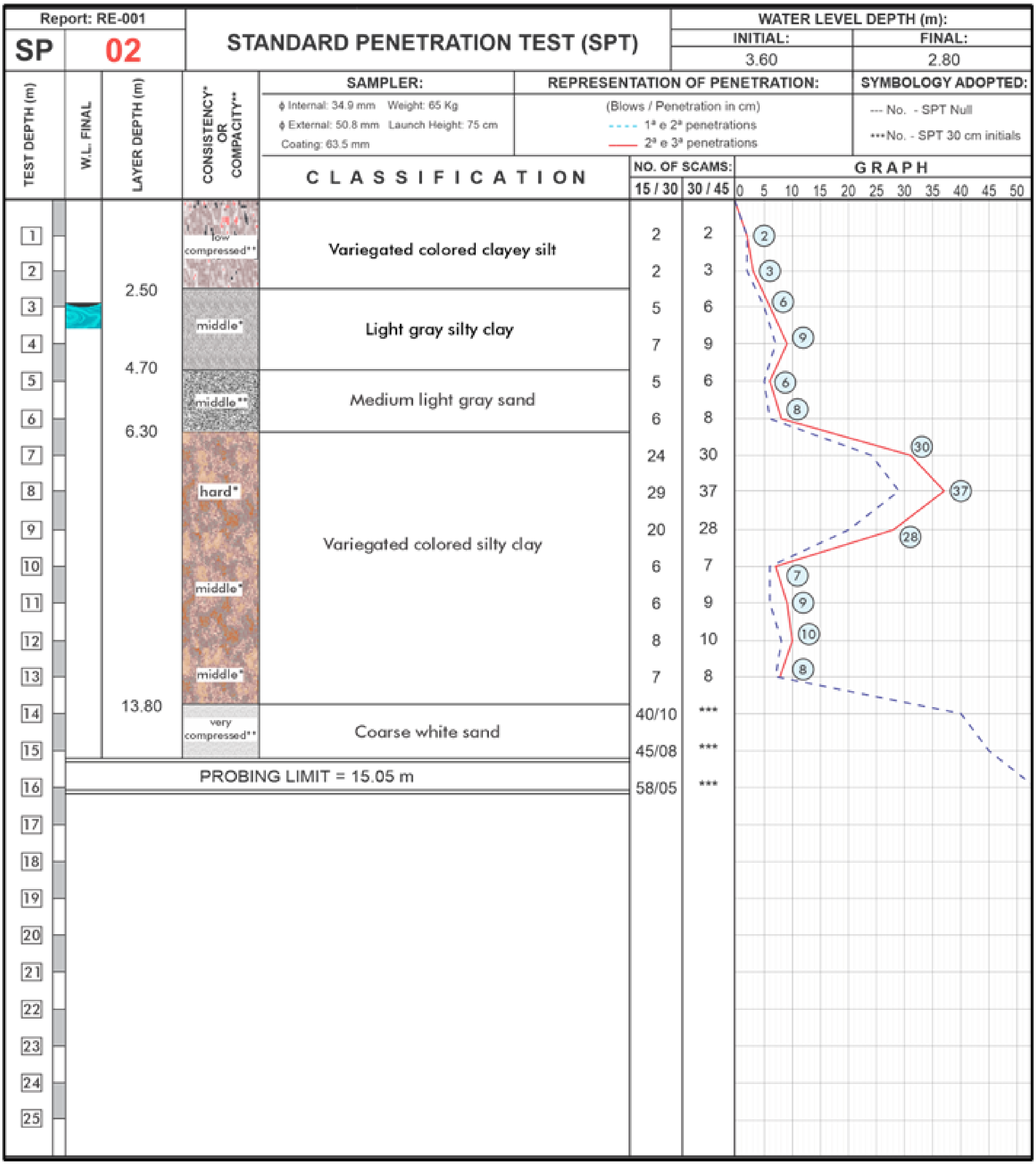

Figure 7. SP-02 of the RE-001 report.

Next, in the third hole SP 03, the lateralization of the layers is maintained, as shown in **Figure 8**.

The correlation between the layers can be seen more clearly in **Figure 9**, which illustrates the aforementioned lateral continuity by observing the description of the sequence of the layered sediments.

With the framework of information obtained from the SPT drillings, the modeling stage began, in which both geotechnical and physical information was inserted into the modeling software. The models used here were made in Reflex software to analyze the behavior of the electromagnetic field and the electrical properties that simulate a GPR survey. Modeling begins with the insertion of information about layer thickness (top and bottom depth), physical properties (σ, k[ε], and μ), and sediment type to form a data matrix in which each element (i, j) corresponds to information. Completing the modeling stage, correlating the information between the geotechnical soundings and the responses of the GPR profiles, which combine geological information with the inserted physical properties, began.

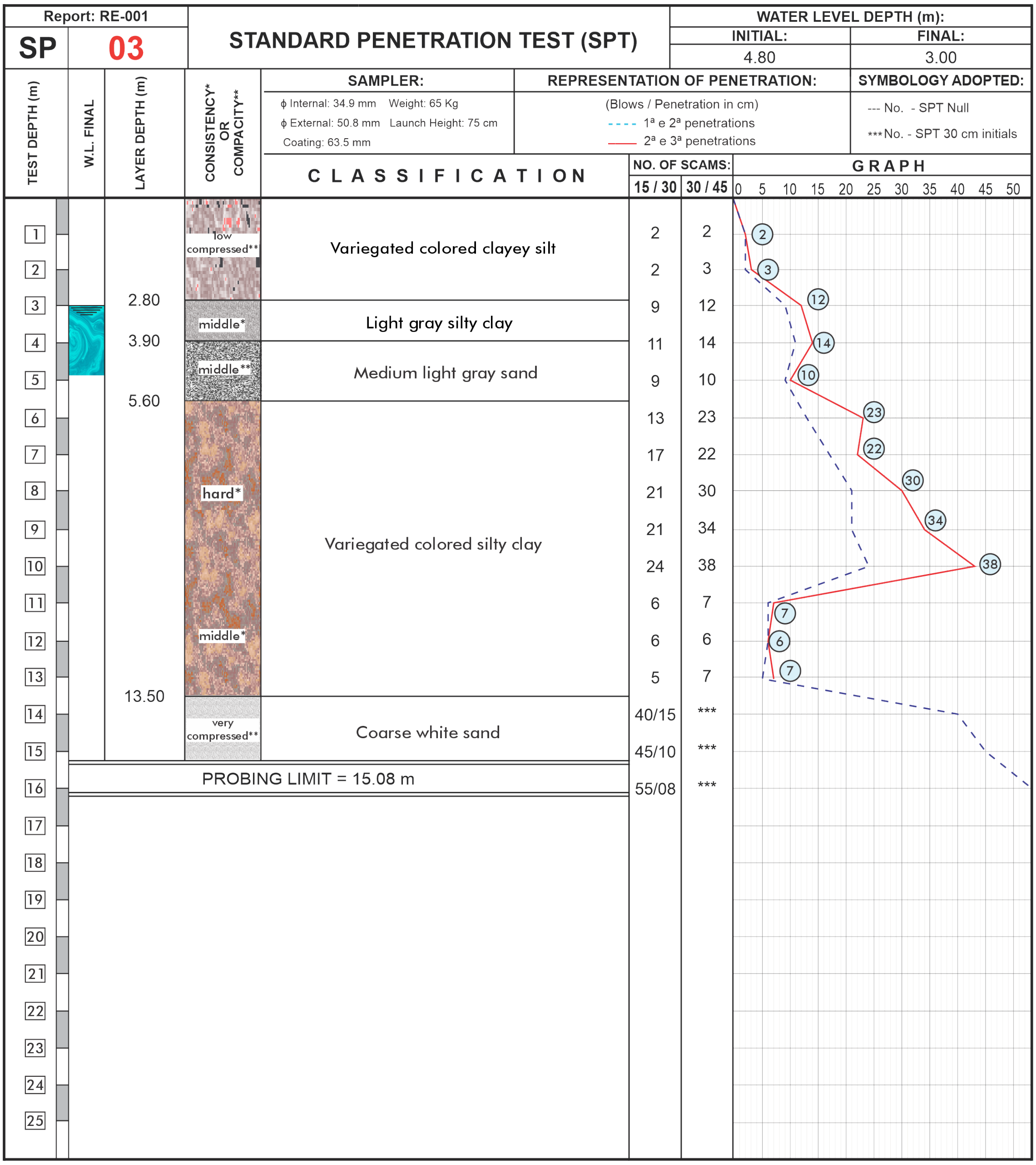

Figure 8. SP 03 of the RE-001 report.

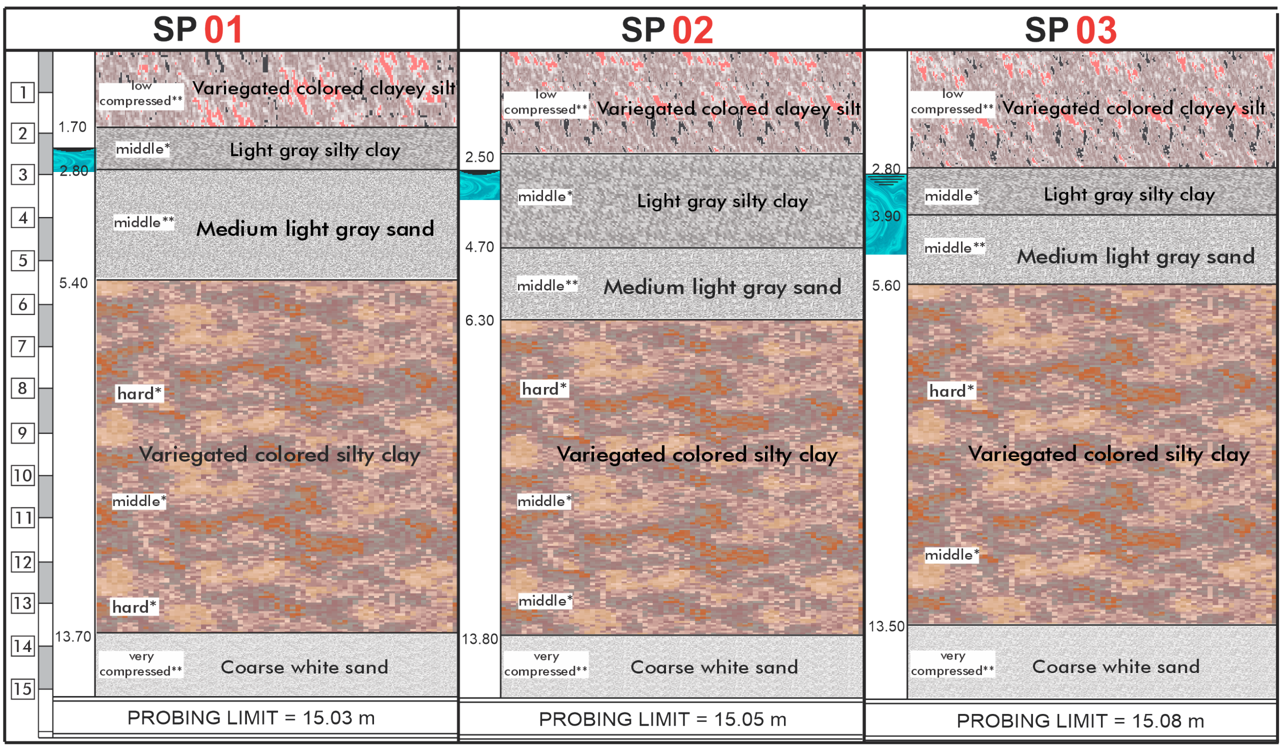

Figure 9. SPT profiles No. 01, No. 02, and No. 03—RE-001.

3. Results and discussion

Aiming to minimize errors in the dimensioning of foundations due to erroneous information about the subsurface region, the present work uses numerical modeling resources to simulate the behavior of different types of sediments and degrees of water saturation through electromagnetic stimulation, similar to a conventional GPR campaign.

Figure 10 shows the graphical interface of the Reflex software by Sandmeier [24] with physical parameters enabled. Entering layer information is simple to carry out. It defines the initial and final depth data in the "layer" field and the respective values of electrical conductivity, dielectric constant/electrical permittivity, magnetic permeability, and lateral extension.

The right part of **Figure 10** shows the configurations of the boundary conditions (absorbing edges), which prevent the energy emitted by the antenna from reverberating at the edges and contaminating the model. The source type (plane wave) establishes that the electromagnetic wavefront will arrive in each layer as a plane, thus disregarding its spherical aspect (simplification). The Kuepper signal simulates GPR equipment, and the wave propagation direction (Ey component) is from the transmitting antenna to the geological environment.

With the completion of the setting and configuration of the electromagnetic characteristics of the simulation, tomography (generation of multiple scans, called a "radargram") is generated and can be seen in **Figure 11**.

The scale on the left in **Figure 11** represents the propagation velocity window of the EM wave in the geological medium (m/ns); the scale in the upper center represents the distance (m) or length from SP 01 to SP 03, which is 10 m; and the correct scale represents the depth (m) of the layers, which can reach 15.08 m. Using interpolation, a three-dimensional model (**Figure 12**) was created with the information obtained from modeling the GPR response.

Analyzing the radargram, it is clear that the presence of saturated clay (clayey sediment with the presence of water in its pores) attenuated the propagation of the electromagnetic wave in an accelerated way, causing a fading of it in the deeper layers, even though these are composed of sand. More studies on the effects of clay presence on the attenuation of

GPR data [25-28]. This behavior is consistent with what is observed in the literature and real-world surveys carried out in other studies. This is because clay has high electrical conductivity and causes a large part of the energy sent to the medium to be absorbed and dissipated along the top of the layer.

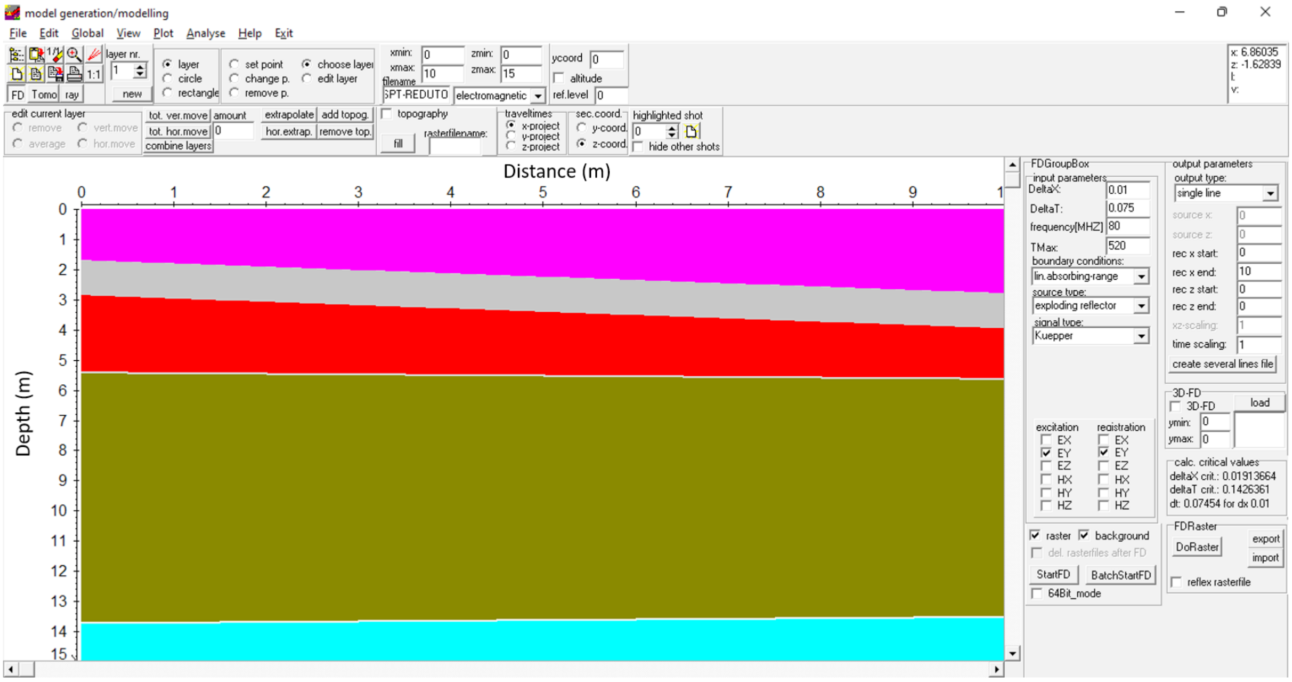

Figure 10. Information from the geological model of SPT RE-001 is being inserted into Reflex.

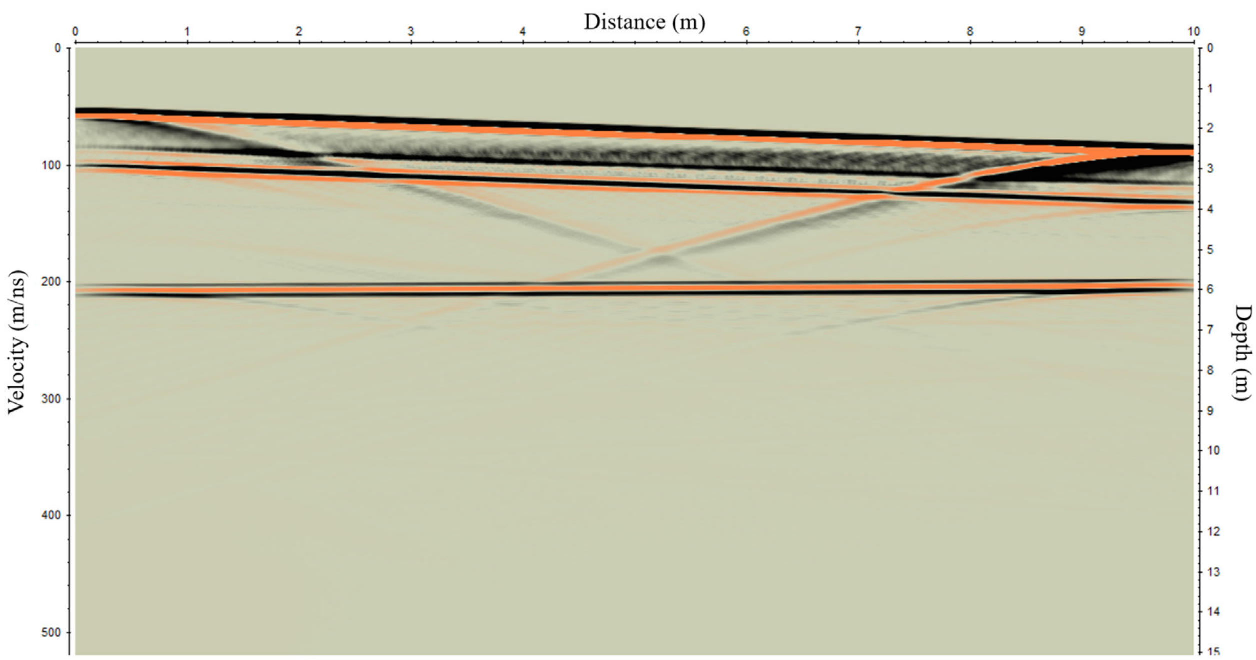

Figure 11. GPR response for the geological model of SPT RE-001.

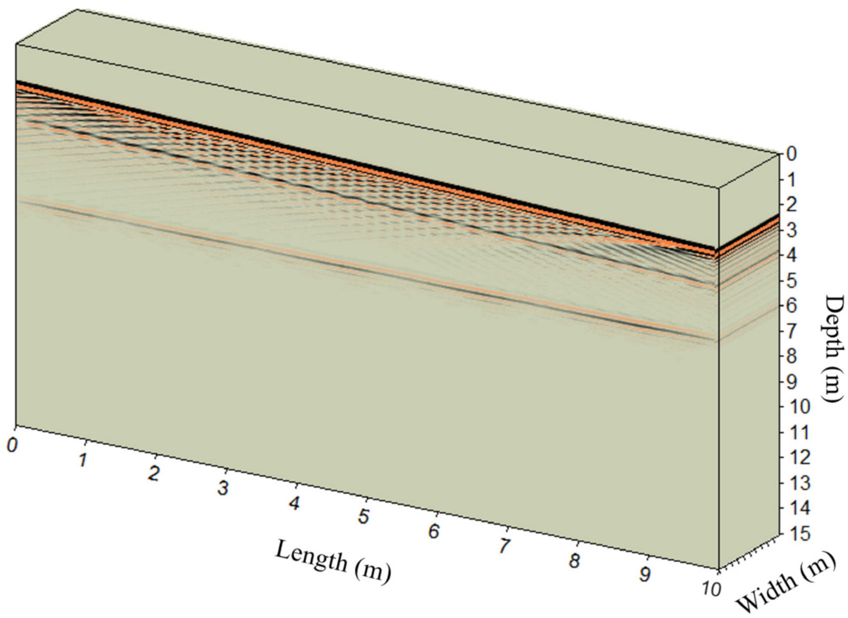

Figure 12. Data cube with the GPR response for the SPT RE-001 geological model.

4. Conclusions

By analyzing the results obtained with numerical modeling of the ground penetrating radar (GPR) geophysical method and correlating them with profiles of SPT soundings carried out in the city of Belém-PA, it was possible to create a correspondence between the geophysical responses and the geological environment in the subsurface. In short, it was possible to delimit the layers and obtain information about the beginning and end of different lithologies and soil strata by responding to electromagnetic stimuli.

Based on the boreholes, which even showed excellent lateral correlation with layers practically parallel and Nspt relatively equal, the response of the GPR modeling proved to be very effective since it recovered with good vertical and horizontal resolution at the beginning and end of layers. However, the presence of clay slowed the wave's arrival in deeper regions.

Although GPR modeling has fulfilled the role for which it was designed very well, it should be noted that it does not provide direct information on the mechanical strength of the layers and, therefore, should not be the only means for verifying the sedimentary package. The soil layers must be confirmed with SPT soundings, which will tie the information together.

Another essential aspect observed during this study is that the lithological description present in the geotechnical drilling bulletins refers to the sediments recovered by the sampler as sand, silt, and clay, as well as their variations: Silty sand and clayey sand, sandy silt and silt clayey, sandy clay and silty clay, not including the presence of other fragments such as pebbles and various materials buried in the soil. Such a description in the eyes of the GPR only refers to the size of the grains found and not their mineralogical composition per se, which generates extreme ambiguity in situations where different types of materials, as well as their proportions and water content, can produce electromagnetic anomalies that are very similar. The realization of the more practical survey in the study area is intended shortly, with the use of 250 MHz, 400 MHz, and 700 MHz antennas to verify the underground response to different operating frequencies.

Author Contributions

The first author acquired GPR data, accompanied the SPT survey in the field, built the numerical model, and wrote the manuscript. The coauthor supervised the data and revised the text of the manuscript.

Conflict of Interest

The authors declare not to have any conflict of interest.

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