Geotechnical Implicit Modelling Application in Viability Study of Solar Photovoltaic Power Plants, a Case Study in Rio Grande do Norte.

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Resumo – A geração de eletricidade a partir de usinas fotovoltaicas tem evoluído significativamente ao redor do mundo como parte do cenário de transição energética e matrizes de baixo carbono, permitindo o movimento de transição dos combustíveis fósseis, que ainda figuram como principal fonte de energia. O presente estudo tem como objetivo compreender as condições geológicas e geotécnicas em subsuperfície de forma a subsidiar o desenvolvimento de um projeto de engenharia para implementação de usina fotovoltaica. A modelagem implícita, principal ferramenta utilizada, tem se mostrado mais eficaz do que a modelagem tradicional em casos complexos, como o abordado neste estudo. Os resultados obtidos neste estudo oferecem maior detalhamento e foram concluídos em um prazo mais curto em comparação com a maioria dos modelos tradicionais bidimensionais interpretados manualmente em CAD para a mesma aplicação. O modelo geológico-geotécnico obtido tem sido fundamental para estimar os custos relacionados ao projeto, analisar a viabilidade do empreendimento e planejar os estudos de engenharia subsequentes.

Abstract – Electricity generation from photovoltaic power plants has evolved significantly around the world as part of the energy transition and low-carbon energy matrix movement, enabling the shift away from fossil fuels, which still remain the main energy source in many countries. The aim of this study is to understand the subsurface geological and geotechnical conditions in order to support the development of an engineering project for the implementation of a photovoltaic power plant. Implicit modeling, the main tool used, has proven to be more effective than traditional modeling in complex cases such as the one addressed in this study. The results obtained offer greater detail and were completed in a shorter timeframe compared to most traditional two-dimensional models manually interpreted in CAD for the same application. The resulting geological-geotechnical model has been essential for estimating project-related costs, analyzing the feasibility of the enterprise, and planning subsequent engineering studies.

Palavras-Chave – Transição energética; geotecnia; modelagem implícita.

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1. INTRODUCTION

The primary advantage of solar energy is its ability to generate electricity without direct greenhouse gas (GHG) emissions. Unlike coal, oil, or natural gas power plants, photovoltaic systems convert sunlight into electricity without burning fuel, significantly reducing the carbon footprint of human activities.

The growing demand for renewable energy sources drives the expansion of wind and solar power plants in various regions around the world. Brazil, due to its favorable climatic conditions, presents great potential for clean energy generation. The project aims to implement these technologies in Rio Grande do Norte state, requiring a detailed geological and geotechnical study to ensure structural feasibility and optimize engineering costs. Geological and geotechnical investigation plays a key role in the design of appropriate trackers foundations (structure where the solar panels are attached), allowing for the mitigation of risks associated with low-bearing capacity soils and the presence of karst in the rocks.

2. REGIONAL GEOLOGY

Regionally, the study area is located within the geological context of the emerged portion of the Potiguar Basin, specifically in the Potiguar Rift, a structure that is part of the Cretaceous Rift System of Northeast Brazil. The area specifically encompasses parts of the structural features of the Guamaré Graben and Alto Macau and is surrounded to the southwest by the Carnaubas Fault, which also limits the Potiguar Rift.

The Guamaré Graben, located in the southeastern portion of the study area, is a linear physiographic depression-oriented NE-SW, with an asymmetric shape and surrounded to the southeast by faults that can exceed 5000 meters of displacement. The Macau (horst) Plateau, located in the northwestern portion of the study area, corresponds to the elongated ridges of the basement, arranged parallel to the main axis of the rift (ANP, 2017). Conceptually, the structural context of the study area is illustrated in Figure 1.

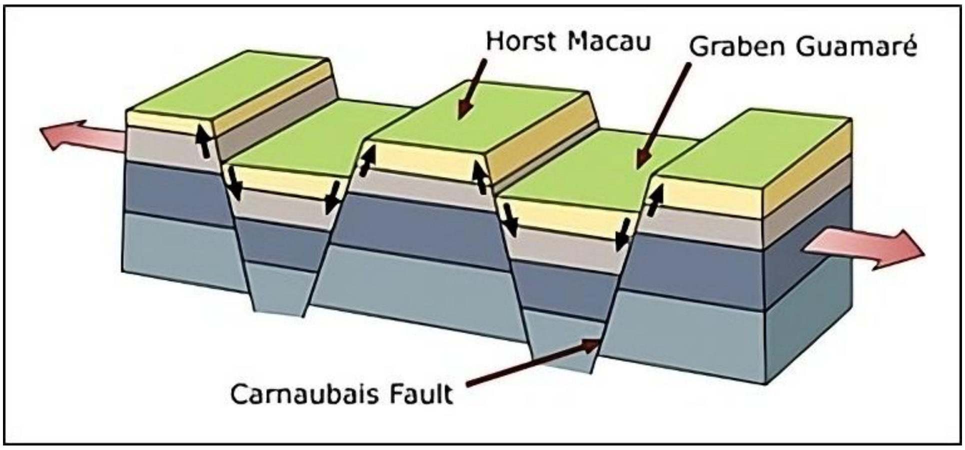

Figure 1. Structural features of the study area.

The basin filling developed according to each phase of its tectonic evolution. Most of these lithostratigraphic units were defined based on the interpretation of the extensive seismic survey and various oil wells present in the Potiguar Basin, which has been the target of oil exploration. In the present study, focusing on surface and outcropping units, the Açu, Jandaíra, Tibau, and Barreiras formations stand out.

The project area for the photovoltaic plant is predominantly situated over the sediments of the Tibau Formation (E3N1t), consisting of fine to conglomerate sandstones, grey in color, sometimes silicified (Angelim et al., 2006).

3. METHODOLOGY

Fieldwork was carried out between October 2024 and December 2024 and was based on three geotechnical investigation techniques: (i) Standard Penetration Test (SPT), (ii) Pull Out Test (POT) and (iii) combined drilling, including 16 POT trials, 02 pile driving tests (type of variation of POT), 40 SPTs and 01 combined drilling (SPT and rotary drilling).

The field work complied with the standards and technical guidelines outlined in the following documents: ABNT NBR 6484/2020, ABNT NBR 16796/2020, ABGE Standard 103/2023, ABGE Standard 104/2023, ABGE Standard 109/2024 and ABNT NBR 16903/2020.

Data obtained from field investigations, recorded in physical format on-site, was immediately digitized to ensure information preservation. Lithological descriptions provided by the teams were standardized and unified according to the AGS-BR Guideline SP03/2018 and Diretriz Normativa ABGE 301 (under discussion). The standardization of NSPT results from different methods and equipment was based on specialized technical literature regarding reference procedures in such cases (BELICANTE, 1998).

Implicit 3D geological-geotechnical modeling for the area designated for the photovoltaic plant was performed using the LeapFrog® software. The methodology developed for the study is summarized in Figure 2.

Figure 2. Methodology Developed for the Study.

3.1. Pull Out Test (POT)

The methodology for POT is based on internationally static load testing standards for foundations, adapted to supplier structures needs and structural behavior. For the present procedure, the permanent critical efforts of the tracker was considered, added to the variable loads (wind), considering the last configuration of modules and the number of modules per tracker projected.

The POT field campaign consisted of 16 pull-out test points conducted with two types of profiles, C140x80 (SOP002) and W6x8.5 (SAC401). Of these, 14 points were driven using the direct driving method, and 02 points were driven using direct driving with concrete reinforcement. Additionally, 04 driving tests were carried out to verify the maximum depth reached (impenetrable level) for both profile types, SOP002 and SAC401.

Horizontal tension and vertical compression tests were performed for the SOP 002 piles (C 140x85x25x3) and SAC 401 piles (W6x8.5), reaching up to 200% of the load limit value of the structure (SLS).

The vertical test consists of applying compressive loads in progressive stages (25% increase each stage) and consequently measuring the applied force as well as the vertical displacement. The horizontal test consists of applying lateral traction load (90° about the pile) in progressive stages (25% increase each stage) and measuring the applied force as well as the horizontal displacement.

Loads must be applied progressively, avoiding sudden increments that could affect the results. The displacement measuring equipment indicates a potential failure of the foundation if the displacement achieves 22 mm for horizontal tests or 15 mm for vertical tests.

At least 30% of POTs must be executed under saturated conditions to evaluate soil behavior in critical situations. Additional tests with alternative concrete foundation (40 cm thickness) solutions were necessary based on the first results.

The driving pile method for foundations in low and medium compaction soils was used as a complementary test. This method consists of driving the piles C140x80 (SOP002) e W6x8.5 (SAC401) through a "driver" machine, which applies successive blows to the top of the pile until the desired depth (03 meters) is reached, monitoring the depth and time.

3.2. Standard Penetration Test (SPT) and Correlations of NSPT Measurements

The SPT aims to provide information about soil types and lithologies, their respective depths, indication of the groundwater level (when present), and the penetration resistance index N at each meter (the number of blows required for the sampler to advance 30 cm in the investigated soil). The field procedure follows the ABNT NBR 6484, 2020. A hammer with a wooden cushion was used in the field, manually operated with a sisal rope and with the assistance of a fixed pulley.

The NSPT provides an indication of the compactness (for sandy or silty soils) or the consistency (for predominantly clayey soils) of the soils under study. Table 1 presents the average NSPT values for the different compaction designations.

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Table 1 Relative density and consistency of soil.

Soil Type	Penetration Resitance Index N	Classification
Sands e Silty Sands	≤ 4	Very loose
	5 to 8	Loose
	9 to 18	Medium dense
	19 to 40	Dense
	>40	Very dense
Clays e Silty Clays	≤ 2	Very soft
	3 to 5	Soft
	6 to 10	Medium Stiff
	11 to 19	Stiff
	20 to 30	Very Stiff
	>30	Hard

Source: (ABNT NBR 6484, 2020).

3.3. Implicit 3D Modeling

The implicit 3D modeling methodology used in this study is a particularly useful tool when dealing with complex data sets and aggregated uncertainties, commonly found in mineral exploration and geotechnical engineering. As an alternative to the traditional method of manual interpolations, implicit geological modeling relies on the assistance of mathematical algorithms to infer the geometry and distribution of geological bodies based on the available data.

This methodology allows professionals involved to spend more effort on designing complex details of the local geology, such as sub-meter lenses of sedimentary units, and the development of various test models from the interpretation of the same data. In addition to these advantages, implicit modeling allows for the automatic update of the model with the addition of new boreholes and relative data at any time.

The Leapfrog® software, developed by Seequent, is a consolidated tool in the field of implicit 3D modeling. Leapfrog® uses the FastRBF™ (Radial Basis Functions) algorithm to fit mathematical models to a large set of 3D data representing complex and non-linear patterns.

The process culminating in implicit modeling is of utmost importance for the quality of the result and consists of the four steps outlined below, which are detailed in the following subsections: 1) contextualizing the local geology using secondary data, such as academic publications and government organization publications; 2) macroscopic (tactile and visual) analysis of the stored core samples and field recognition of the study area; 3) compilation, technical evaluation, and selection of data; and 4) formatting the data to fit the input standards of the modeling.

4. RESULTS

The lithostratigraphy of the photovoltaic plant project area was subdivided into two packages for the purpose of analyzing soil competency for foundations. The upper package predominantly consists of coarser-grained sediments, such as Silty Sand and Sandy Clay, and the NSPT can be correlated to its relative density. The lower package is mainly composed of finer-grained sediments, such as Silty Clay, Clayed Gravel and the Lower Silty Clay, and the NSPT can be correlated to its consistency.

The lower unit of the model corresponds to the Lower Silty Clay, a silty clay with little sand and grayish coloration. This unit appears to result from the alteration of limestones identified at a depth of 16 m in a rotary borehole located about 500 m from the modeled area. However, it was not possible to determine whether these sediments are transported or autochthonous. The spatial distribution of the identified lithostratigraphy is presented in Figure 3.

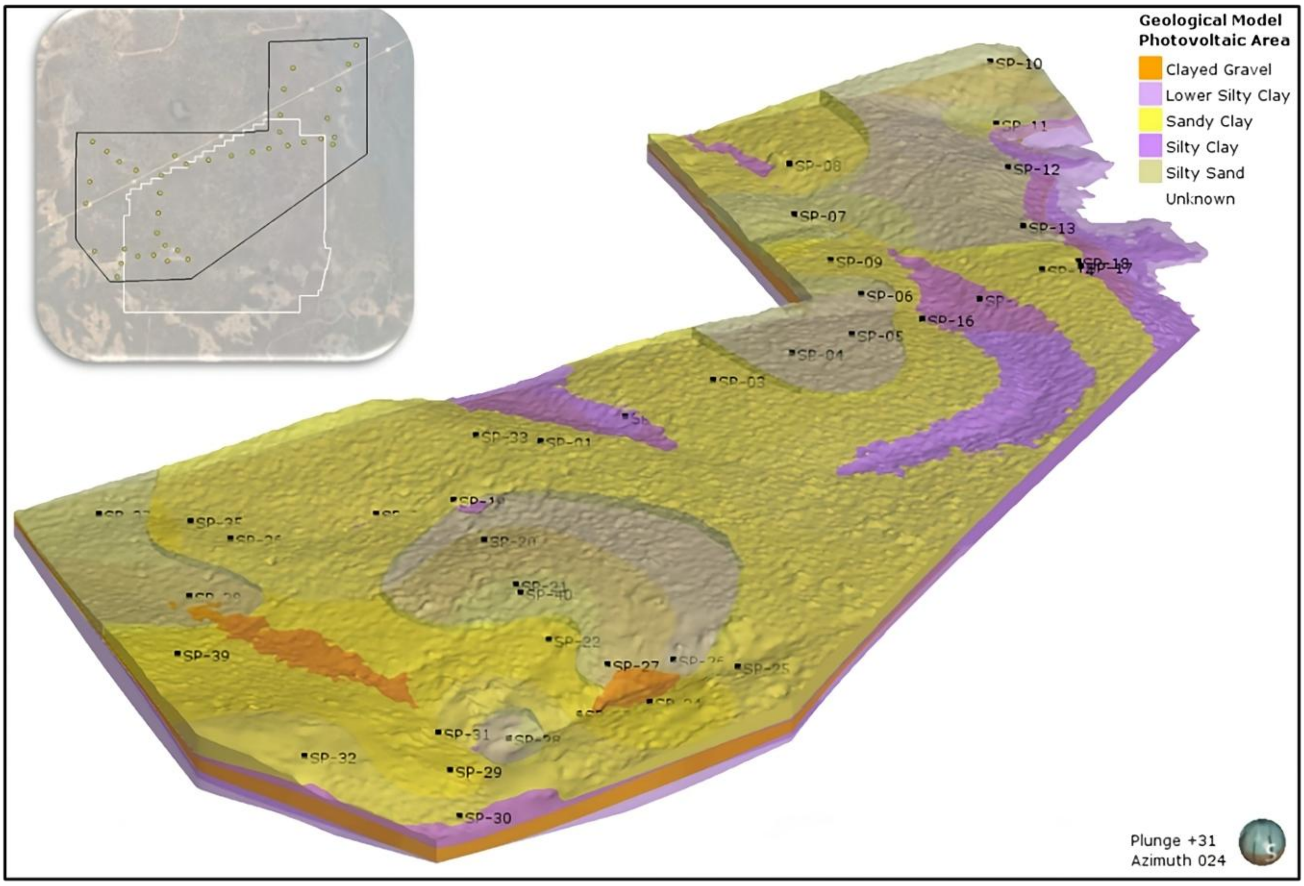

Figure 3. Geological Model of the Photovoltaic Power Plant Area.

It is noted that in the topographic depression regions of the area, the units of the lower package outcrop at the surface. The regions where the Clayed Gravel outcrops correspond to areas with lower vegetation density and higher density of cavities and bioturbation.

The upper package, represented by the Sandy Clay and Silty Sand units, predominantly comprises sandy sediments; therefore, the NSPT values can be correlated to their relative density. The Sandy Clay unit shows the highest frequency of NSPT values within the Medium Dense density range (NSPT: 9–18), while the Silty Sand unit displays the highest frequency between the Medium Dense (NSPT: 9–18) and Dense (NSPT: 19–40) ranges, as shown in Figure 4.

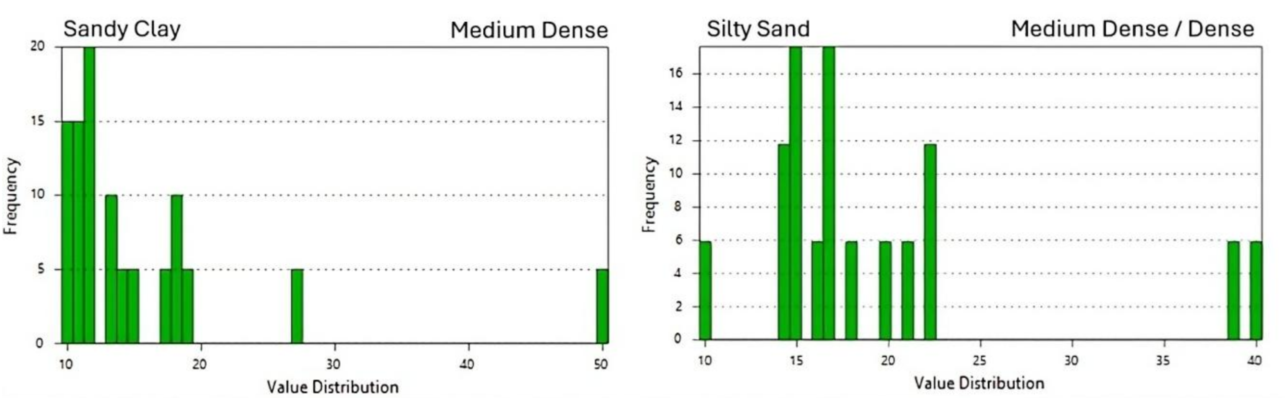

Figure 4. Frequency of NSPT values for the upper package, Sandy Clay and Silty Sand units.

The lower package, represented by the Silty Clay, Clayed Gravel, and Lower Silty Clay units, predominantly consists of silt and clay sediments; therefore, the NSPT values can be correlated to their consistency. The upper layer of this package, the Silty Clay, has the highest frequency of NSPT values in the Stiff range (NSPT: 11–19). The two underlying layers, Clayed Gravel and Lower Silty Clay, show the highest frequency in the Hard density range (NSPT: >30), as shown in Figure 5.

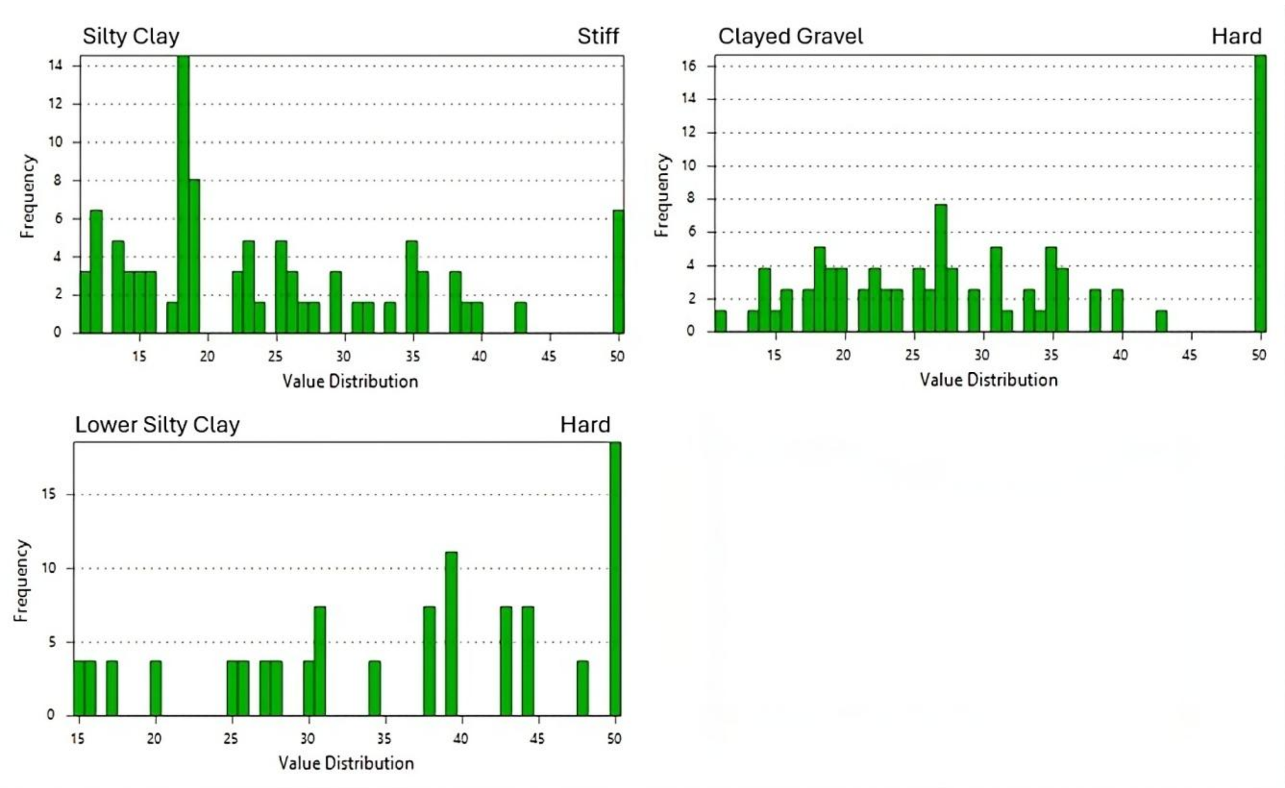

Figure 5. Frequency of NSPT values for the lower package, Silty Clay, Clayed Gravel, and Lower Silty Clay units.

The NSPT values were interpolated using the linear method and integrated into the geological model. These products are presented in the form of geological-geotechnical sections, as presented in Figure 6.

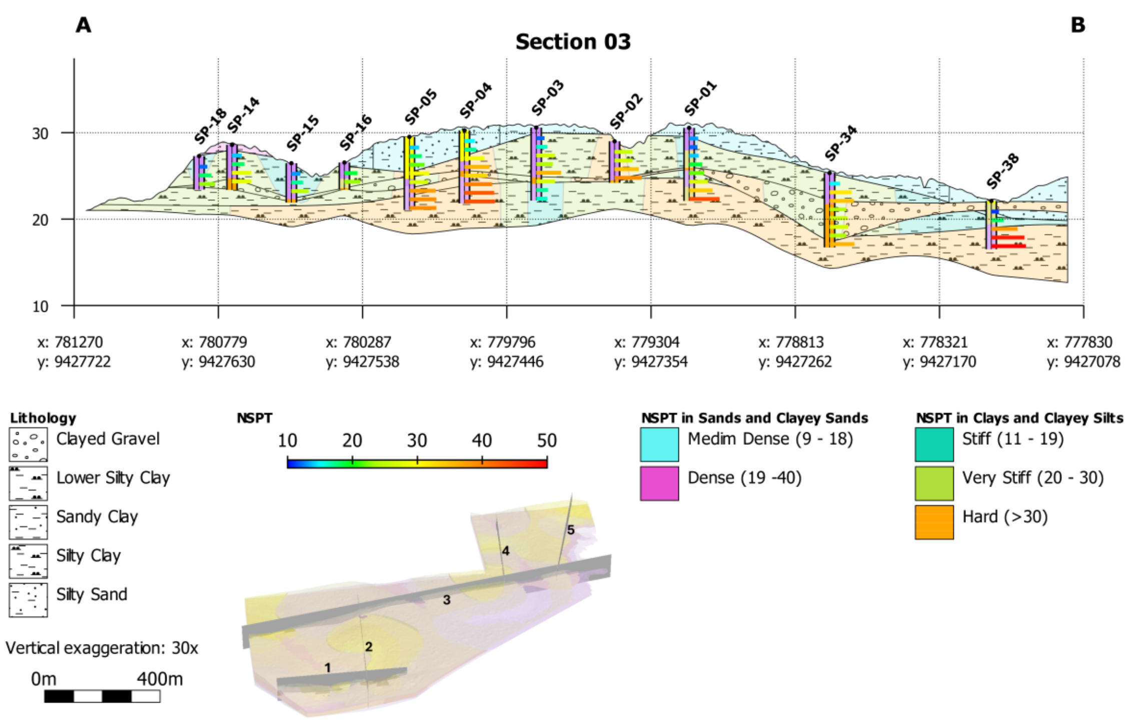

Figure 6. Geological Geotechnical Section 03 in Solar Photovoltaic Power Plant Area.

The pull-out tests were conducted generally led to the conclusion of the definitive unfeasibility of the SOP002 pile and the potential feasibility of the SAC401 pile. The results of the pile driving tests in these locations indicate that the times were relatively high at all points, reaching up to more than 240 seconds for 2.00 m of driving, and the impenetrable layer was reached for the method at point CRV-02, which corresponds to the region where the Clayed Gravel and Lower Silty Clay, the higher competence units (very stiff and hard), are in shallow depths.

5. CONCLUSION

Implicit modeling analysis enabled a deeper understanding of the correlation between geotechnical test results and the lithological units of the area. Through statistical interpolation of the SPT results and their superposition with the lithology, it became evident that the layers designated as “Lower Silty Clay” and “Clayed Gravel” from the base of the lower package exhibit the highest relative lateral continuity in zones with very stiff (NSPT: 20–30) and hard consistencies (NSPT: >30).

Therefore, this horizon demonstrates a high probability of exhibiting relatively high soil consistencies and, if intercepted at shallow depths, could represent an impenetrable barrier for photovoltaic foundations. However, if intercepted at depths greater than 2 meters, they would provide the necessary characteristics for a stable foundation. The implicit modeling approach successfully estimated the depth of these layers across the entire study area, resulting in a viability map for photovoltaic foundations in the area.

The implicit modelling methodology enables automatic model updates with the addition of new boreholes. In practice, this means the model can be updated after each new drilling campaign, transforming it into a dynamic tool for the team’s daily operations. The geotechnical model obtained is essential for estimating project-related costs, analyzing the feasibility of the venture, and planning subsequent engineering studies.

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