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Geostatistical data analysis of the Standard Penetration Test (SPT) conducted in Maringá-Brazil and correlations with geomorphology

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Article

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Abstract
The Standard Penetration Test (SPT), widely used in Brazil, provides reference data to geotechnical projects. The data obtained are punctual and often dispersed due to its execution, that is, there is no concern in gathering and analyzing such information jointly for a specific region. In addition to the wide dispersion of these data, due to their anisotropic nature, classical statistics may not be the best approach for data with spatial variability. In this way, the application of methods that use spatial analysis, especially Geostatistics, become essential in the mapping of geotechnical variables. Therefore, this study proposes to gather, organize, and analyze data originated from SPT conducted in the municipality of Maringá, Brazil, applying the ordinary kriging geostatistical technique to identify correlations with the Geomorphology of the studied region. To achieve the proposed objectives, we selected 109 boreholes distributed in the municipality of Maringá, between the years of 2011 to 2015, and treated them using the ArcGis geostatistical analysis software. It was noticed a relationship between the thickness of the subsoil layers considering the position and slope form, reflecting on the depth to bedrock and, consequently, on the resistance of the layers associated with N-value of the SPT.

1. Introduction

The success of geotechnical works fundamentally depends on extensive knowledge of the characteristics and properties of the constituent materials of the subsoil. When laboratory tests are impractical to perform, the field tests allow a satisfactory definition of the substrate stratigraphy and, in some cases, a more realistic estimate of the geotechnical properties of the materials involved, indispensable in the preparation of geotechnical projects.

The data obtained in subsoil prospecting for a specific region, when available, are usually found in a dispersed manner, that is, there is no concern to gather and present them to the general community, which often lacks the knowledge regarding the soils on which they support their buildings.

According to Zhang et al. (2019), one of the most popular in-situ testing procedures in Geotechnics, the Standard Penetration Test (SPT), was developed to provide values in order to collaborate with soil classification concerning its consistency and compactness through its resistance to vertical penetration.

The SPT has been recently considered as an instrument for acquiring primary data to elaborate maps or geotechnical charts that can aid in urban zoning, using the Geographic Information System (GIS). Auvinet et al. (2009) highlight the numerous geotechnical surveys performed in urban area of Mexico City and emphasize its use to obtain a better knowledge of the subsoil and improve the accuracy of geotechnical zoning maps for regulatory purposes of construction. El May et al. (2010) analyzed boreholes data to obtain the water table depth, as well as geotechnical and liquefaction potential layers. Sharma & Rhaman (2016) analyzed boreholes of 30 m depth, performed in 200 locations in Guwahati City and prepared contour maps of standard penetration test N-value at different depth and average contour map of N value. Razmyar & Eslamini (2018) used different geotechnical field tests, such as standard penetration test and cone penetrometer test (CPT), to estimate geotechnical parameters and presented them through zoning maps.

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Considering the availability of data obtained from standard penetration tests and the features, properties, and behavioral characteristics of a silty clay founded in the study site, this paper illustrates the direct application of geostatistical methods for the municipality of Maringá, Brazil and presents them using the Geographic Information System (GIS), emphasizing the evolution of soils layers, the depth to the bedrock, and the N-value at different depths.

2. Standard Penetration Test (SPT)

The first reports on soil sampling through the dynamic driving process occurred at approximately 1902 (Fletcher, 1965). According to Belincanta (1998), before this, the geological investigation was performed by digging wells of considerable diameter or by drilling with water circulation, it is worth noting that during the water circulation there was no concern in determining mechanical properties of soils. The sample removal process in a borehole was gradually enhanced after the emergence of the percussion drilling method, reflecting of the on quality of the soil samples. Even so, there was no consensus about the proportions of SPT apparatus, such as sampler dimensions, hammer weight, drop height and the count the number of blows.

In the following years, several authors (Terzaghi & Peck, 1948; Hvorslev, 1949; Mello, 1971) pointed out the importance of using standardized proceedings and standardized measurements on SPT, in order to ensure the reliability of this test to estimate soil parameters.

The SPT standardized in Brazil consists of driving a standard sampler until reaching 45 cm of soil penetration, using a 65 kg hammer falling from a height of 75 cm, noting the number of blows for each segment of 15 cm. The parameter obtained in this test is denominated N-value, which corresponds to the number of blows required to drive the last 30 cm of the standard soil sampler (ABNT NBR 6484, 2001).

The SPT also allows the removal of deformed samples from the subsoil during the sampling driving meter-by-meter, allowing direct contact with the soil through the tactile and visual analysis of the samples, thus consolidating an expedient method of subsoil reconnaissance.

The semi-empirical methods used to predict the load capacity of the soils requires parameters obtained through correlations with the N-value and the expeditious characterization of the subsoil. Despite not being the only ones, these methodologies are widespread in Brazil justifying the relevance of this test as a tool to design a foundation project.

3. Characterization of the study area

The municipality of Maringá is in the northern portion of the state of Paraná (Figure 1), approximately 430 km from its capital, Curitiba, and 650 km from the municipality of São Paulo. It has an average altitude of 596 m above sea level and is spread over an area of approximately 473 km^2.

The study area is in the Serra Geral Group that was formed by successive volcanic spills that occurred over the years. These volcanic events were responsible for the formation of the basaltic rock on which the Paraná Basin is based on and which generally vary in thickness, position within the slope, degree of weathering among other factors according to the number of spills (Besser et al., 2018).

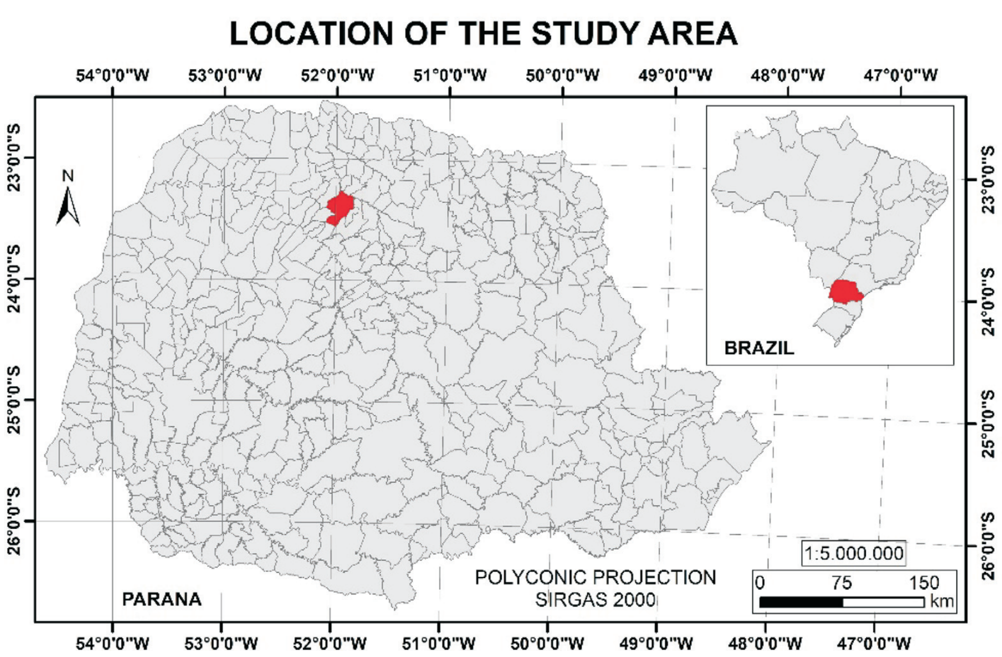

Figure 1. Location of the municipality of Maringá.

These eruptions have occurred horizontally, which determines the current configuration of soft corrugated hills with deep soils and high nutrient contents (França Junior et al., 2010).

According to Nakashima & Nóbrega (2003), Red Latosol of clayey texture predominates in the top regions (high and middle slope). Towards the valley regions (low slope) the Red Nitosol begin to emerge.

Santos et al. (2018) defines the Latosols as a highly weathered soils that presents clays with the predominance of iron, aluminum, and silicon oxides, among other minerals, in their composition. The Red Latosols are a type of Latosol in which the amount of iron oxides is predominant, justifying its marked red coloration. According to the mapping presented by Bhering et al. (2007), these soils occur mainly in regions of flat and slightly undulating relief, as occurs in most of the central region of Maringá.

Figure 2 shows part of the survey conducted by Bhering et al. (2007) on the recognition of the soils of the state of Paraná, highlighting the region of the municipality of Maringá. The Nitosols are predominantly located in the proximity of the drainage network, following its outline. The Latosols occur in the intermediate portions, coinciding with medium to high slope regions.

A study conducted on the Maringá subsoil by Gutierrez & Belincanta (2004) found the existence of two well-individualized sets in terms of color, characteristics, and behavior: a) An upper set composed of porous silty clay of a reddish-brown color, with variable thickness, reaching up to 12 m in the regions of a high and medium slope. This set corresponds to an evolved material (mature soil) - the dystroferric Red Latosol; b) a lower set consisting of silty clay and clay-sandy silt of predominantly purple and yellowish-gray colors, with the presence of black or yellow diaclases. This set corresponds to the layer of altered soil from basalt rock - the saprolite.

Two geopedological profiles typical of the north-south and east-west regions of Maringá were presented by Gutierrez et al. (2015) demonstrating how materials from the alteration of basaltic rock are associated to the soil types (Latosols and Nitosols).

Along the top of the interfluvial region (Figure 3), where most of the urban area is installed, the data obtained from the SPT indicate the occurrence of a young soil that can reach up to 30 m of thickness or more. The surface layer consists of a mature soil with a clayey texture (up to 12 m depth) with a clay-silty or silt-clayey saprolite below.

In the low slope or higher positions where the breaks in the slope are accentuated, the young soil suffers a significant reduction in its thickness and the Latosol gives place to the typical Eutrophic Red Nitosol or Latosolic Eutrophic Red Nitosol, also clayey but less thick than the first.

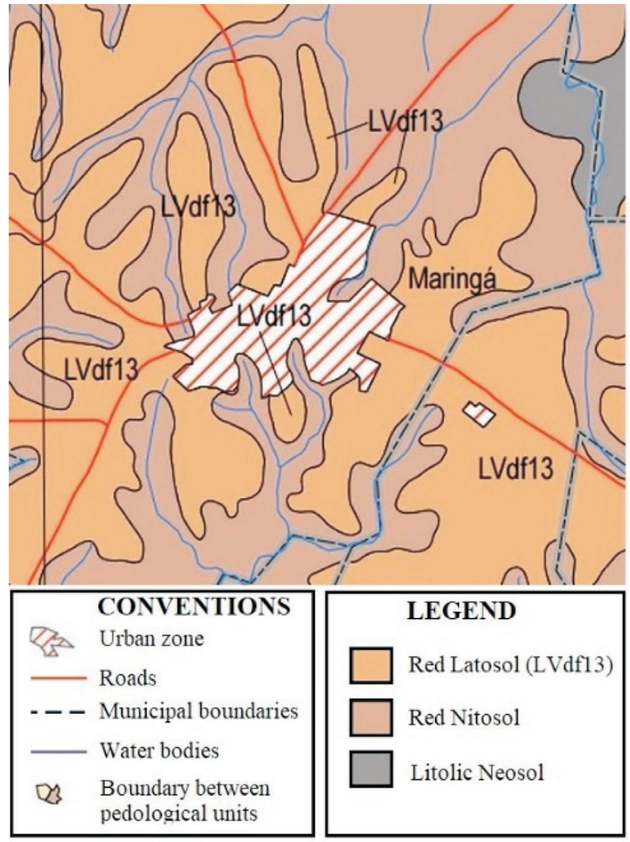

Figure 2. Reconnaissance of the soils of the region of Maringá, highlighting the Latosols and Nitosols (adapted from Bhering et al., 2007).

4. Geostatistics in geotechnics

Even though a soil originated from the same rock commonly presents different mechanical and hydraulic behavior, some characteristics are preserved because these soils present the same origin. Thus, the study of Geotechnics is combined with statistics to understand how these relations develop and identify similar behaviors or properties for the soil of a specific region.

Within this concept, the geotechnical mapping allows to visualize similarities and differences in the considered properties, on a regional scale, also pondering the spatial variability of the data through a more refined statistical tool: geostatistics.

In Mining Engineering, the use of software for modeling the spatial distribution of the ores is already widespread (Olea, 1999; Yunsel, 2012). The mineral exploration projects are based on the concept that the concentration of a given ore, in an unexplored region, can be estimated in function of a few points where this data is known. It is necessary to apply statistical methods that consider the variability of this parameter (concentration) both on the surface and at depth for such estimates to be made valid. In this scenario, geostatistics aims to solve problems of this nature.

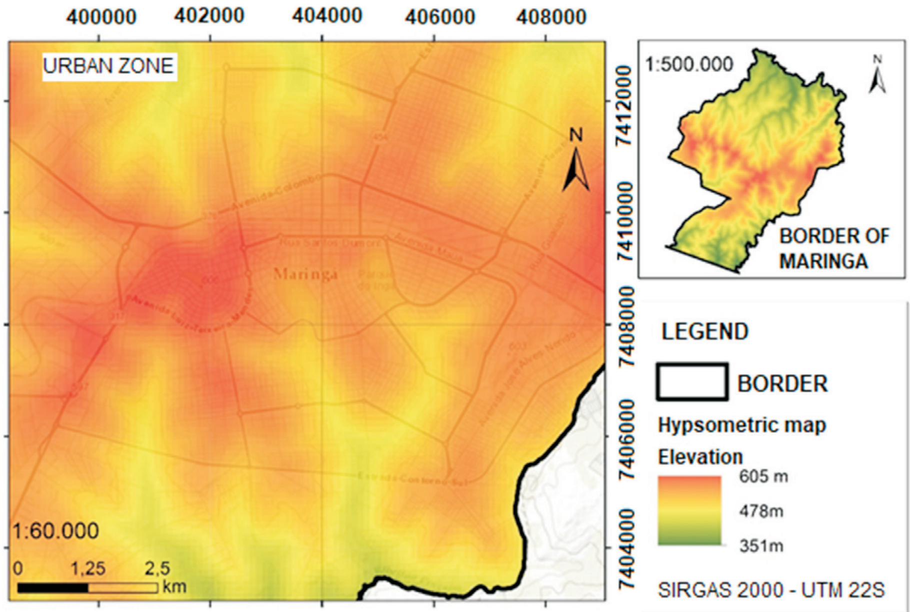

Figure 3. Hypsometric map of the municipality of Maringá, Brazil.

The main objective of geostatistics is to provide an estimator based on a few sample points that allow the reconnection of the complete spatial distribution of the concentrations of metals, for example, inside the studied body of ore (Folle, 2009). Geostatistics is considered a special topic of applied statistics that deals with problems related to regionalized variables. These variables present two distinct aspects: a random factor characterized by irregularities and unpredictable variation from one point to the other in space, and a structural factor characterized by the relationships between these points in space and their genesis (origin), as described by Matheron (1963).

When studying the behavior of generalized variables, there are two fundamental tools for the geostatistical methods: semivariogram and kriging. The semivariogram function γ (h) shows the measure of the spatial dependence degree between samples along with specific support (vector h) and, to build them, the squared differences of the obtained values are used, assuming stationarity in the increments (Landim, 2006). Kriging consists of a punctual value estimation process of variables distributed in space and time while considered as interdependent by the semivariogram considering the sample distance and the grouping.

In recent years, some authors have sought to associate geostatistics, already consolidated in other areas, with the field of Geotechnics (Thallak & Samui, 2007; Samui & Thallak, 2010; Boezio et al., 2013, Maroufpoor et al., 2017). These studies are based mainly on the systematized organization of data, obtained in geotechnical tests, for mapping such as the water level in wells, simulation of the behavior of the subsoil in terms of the plots of the constituent materials, rock genesis, N-value estimation, and a variety of other spatial variability data.

5. Materials and methods

The methodology applied in this study consists of collecting data to elaborate a database structured on the GIS platform for the posterior verification of the applicability of geostatistical techniques and later model employing ordinary kriging.

The surveys that comprise the databank were conducted by civil construction companies and by the Soil Mechanics Laboratory of the State University of Maringá (Paraná-Brazil). Aiming to save time and processing resources, it is worth noting that only single borehole was selected to represent the terrain. When there was more than one borehole available on the terrain, the selection criteria was based on its spatial location: it was selected the borehole nearest the front of the terrain, where its spatial coordinates were determined. Thus, the databank presents 109 boreholes distributed in the municipality of Maringá, made from 2011 to 2015. Most points are concentrated in the central region of the municipality, in the neighborhoods that present a more significant development of civil construction in recent years, as can be observed in Figure 4.

The SPT data selected to comprise the database were performed according to the Brazilian Standard (ABNT NBR 6484, 2001) presenting the boreholes location plan, reference level, borehole elevation, N-value, division of the soil layers meter by meter, and the groundwater level. The structure of the tables used as collection storage instruments was elaborated in function of the information contained in the survey bulletins.

The geostatistical modeling by ordinary kriging, including the exploratory data analysis, spatial correla-

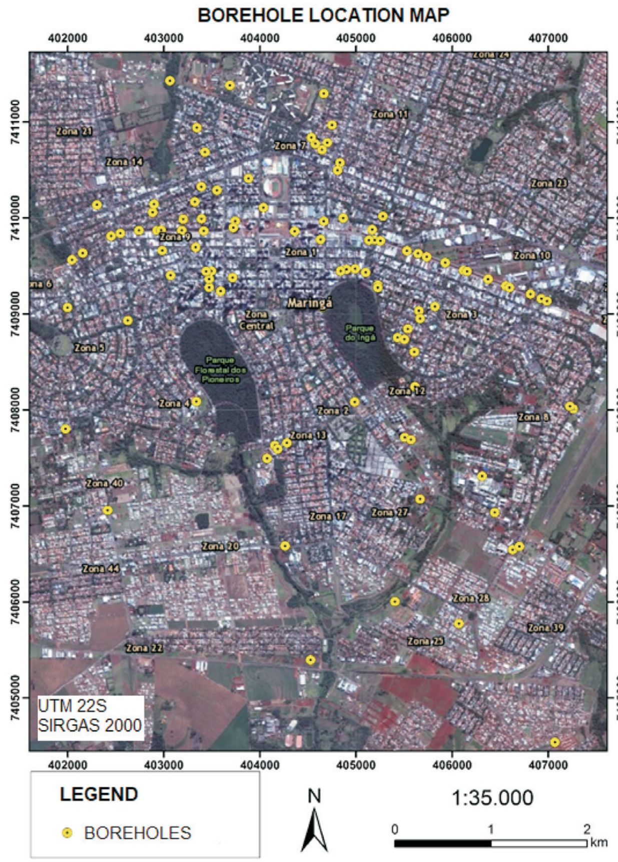

Figure 4. Location of the boreholes in Maringá.

tion structure analysis/modeling, and surface statistical interpolation was conducted using the ArcGIS 10.3 software.

6. Results

The declivity map was elaborated to verify the possible relationships between these data with the topography (top, high, intermediate, and low slope areas), as well as the form of these slopes, especially the pedological types: Latosol and Nitosol. Furthermore, it was elaborated geotechnical maps based on the impenetrable layer depth and the N-value at different depths.

6.1 Declivity map

In the northern section of the urban site (domain of the Pirapó River basin, affluent of the Paranapanema River), the slopes are generally long, convex-rectilinear, with slight declivities but that increase in the inferior third, while the southern section (Ivai River basin) has shorter slopes, convex and convex-rectilinear, with increased declivities, as presented in Figure 5.

The central region of the municipality has relief declivities ranging from flat to slightly corrugated (up to 8 %), apart from the regions near the bodies of water, where it ranges from moderately corrugated to corrugated (up to 20 %). We verified that this characteristic could be correlated to the soils pedology and N-value of the SPT.

6.2 Evolution of soil layers

Despite presenting specific intrinsic variability to natural materials, it was verified a pattern in the behavior and properties of soils originating from the same parent rock due to geomorphology and pedology.

As demonstrated in Figure 6, until the depth of 8 m, most soil samples were classified as mature soil. The same does not occur at 12 m depth, in which more altered soils

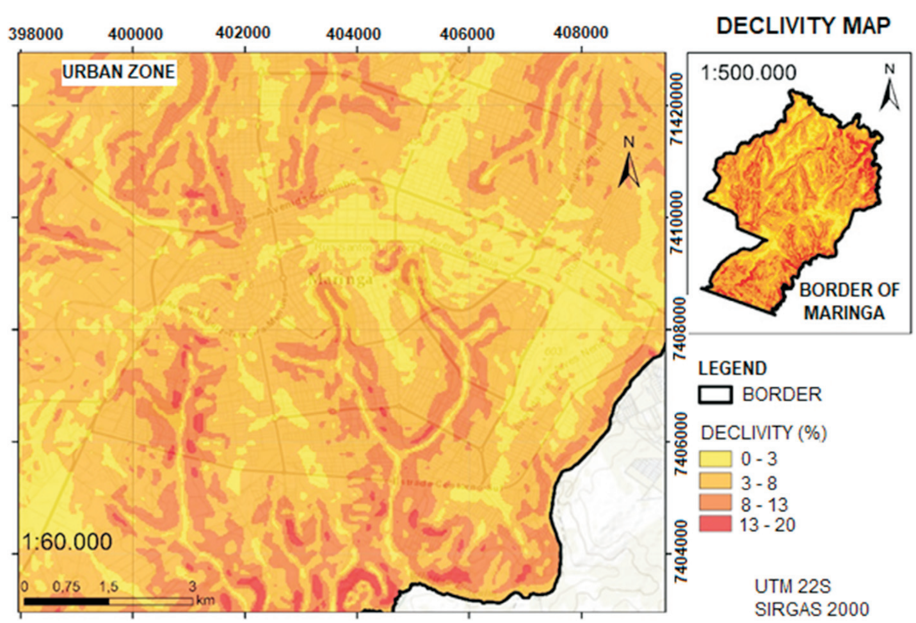

Figure 5. Declivity map of Maringá.

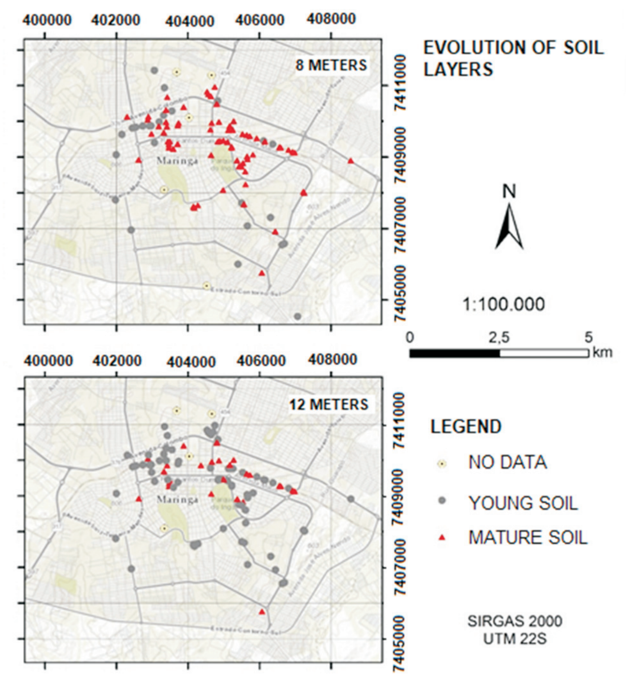

Figure 6. Evolution of soils at the depths of 8 and 12 m.

(with traces of parent rock) predominate indicating that, between the depths of 8 and 12 m there is a transition zone.

In particular, a few surveys presented very thick profiles, superior to 15 m, of mature soil in the central region of Maringá. The soil evolution can indicate the proximity to the bedrock since the unweathered rock is subjacent to the young soil (saprolite) and can be more or less thick due to the weathering that occurs in the region.

6.3 Impenetrable layer depth

The depth of the impenetrable to the SPT, which can be measured as corresponding to the quota of the bedrock (N-value higher than 60 blows/30 cm), has significant variations in the interval of the studied region. Figures 8 and 9 illustrate this phenomenon for a northern and southern section of the region, respectively, thus divided to obtain better results during the kriging stage. The boreholes are distributed over an area of approximately 10 km^2 and 11,5 km^2 in the northern and southern section, respectively.

Note that in the central region of the northern section (Figure 7), the bedrock is located at greater depths. This is a top region characterized by altimetric quotas superior to 560 m and a flat relief. On east side of the northern section

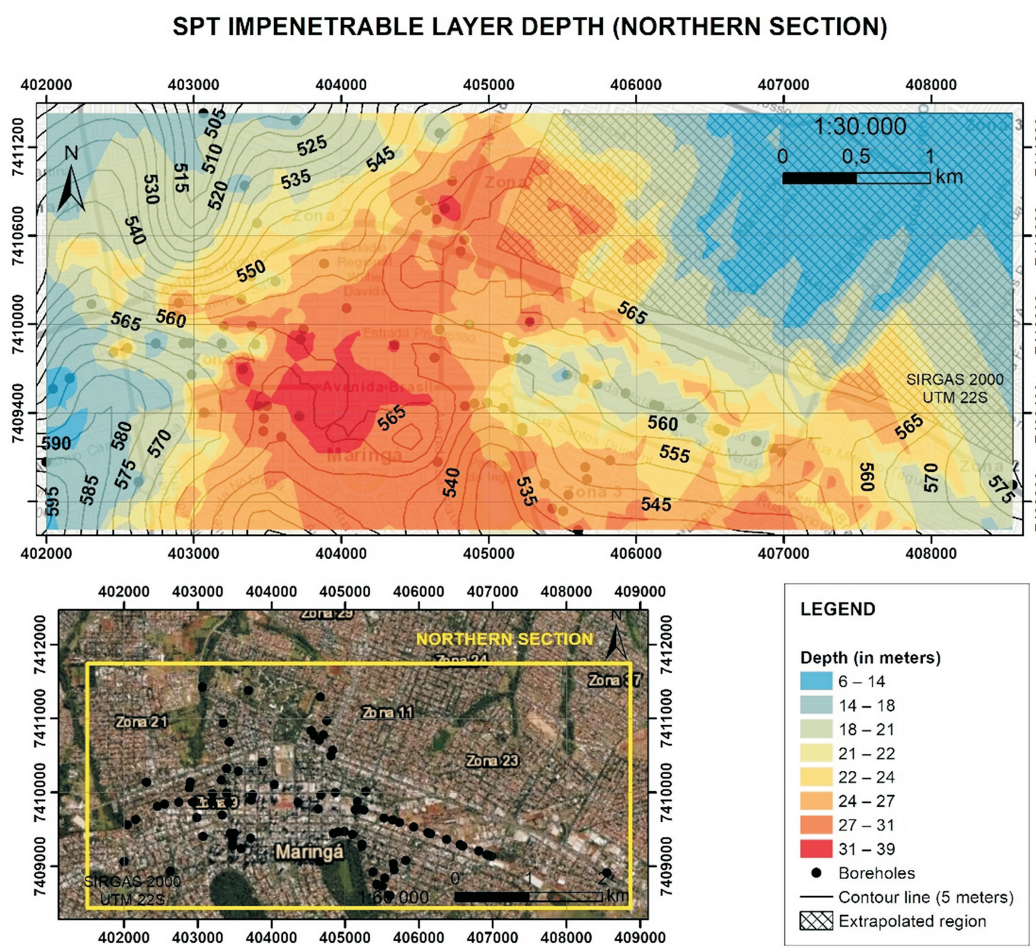

Figure 7. Impenetrable layer depth for a microregion north of Maringá.

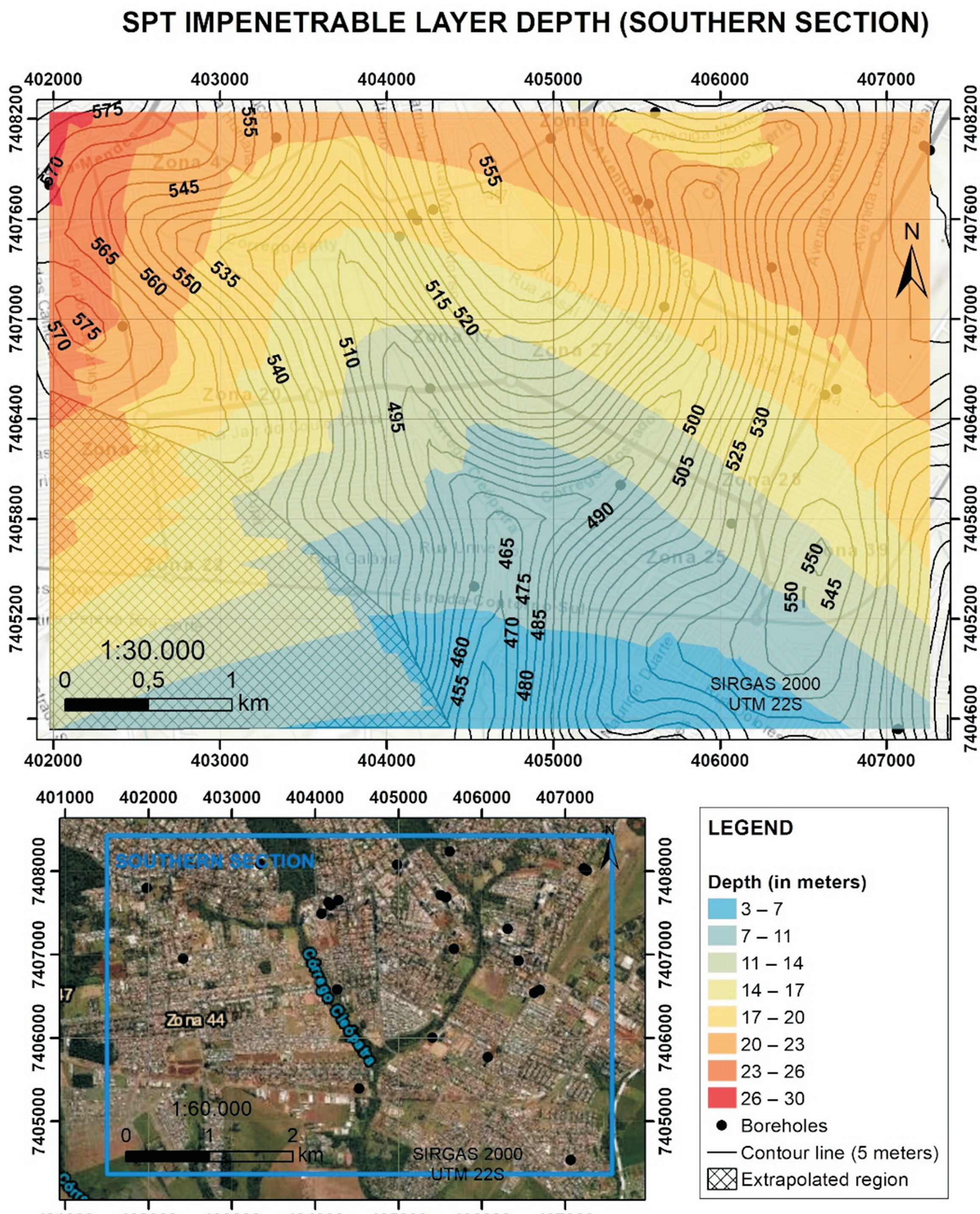

Figure 8. SPT impenetrable layer depth for a microregion south of Maringá.

there is an inversion in this behavior, although it is a peak region (high slope), presents declivities ranging from moderately corrugated to corrugated, justifying the presence of thinner layers until reacting the bedrock. Such occurs in other points of the northern and southern sections of the municipality.

Besides, even in a top region (high slope), the thickness of the soil layers varies due to the form of the relief. When comparing the top regions of the northern section to the declivity of the region, we can observe the tendency for more pronounced high slope terrains to present thinner soil profiles while top regions with flatter relief present thicker soil profiles until reaching the parent rock.

The center-south region presented in Figure 8 has a moderate to low slope with rugged relief. It is also in the regions of more pronounced slopes that we can find the Red Nitosols, while the Red Latosols occur in the central region (Figure 2). The disposition of both soil groups can be associated with soil resistance, correlated to N-value.

6.4 N-value

The N-value, obtained for the more superficial depths, hardly surpasses the value of 20 blows/30 cm for the analyzed region. Most of the index values range from 2 to 10 blows/30 cm, as demonstrated in Figure 9. Note that, around the coordinates of 4,040,000 m and 7,410,000 m, which coincides with the flatter region of the study area and with the predominance of Red Latosols, the N-value presented the lowest values for the depth of 4 m.

From 8 m depth, some of the surveys presented N-value superior to 60 blows/30 cm, which corresponds to the soil layers with high load capacity. This region is characterized by a moderately corrugated relief and the presence of Red Nitosols and corresponds to locations with intermediate to low slope in the southern portion, presented in Figure 10. At this depth, in the central region of the municipality (around coordinated 4,040,000 m and 7,410,000 m), the N-value hardly surpasses the value of 10 blows/30 cm, demonstrating a more linear growth in the regions where the soil profiles are thicker when compared to the thinner layers.

At the depth of 25 m, only the surveys located in the central portion of Maringá had not reached the SPT impenetrable layer. Figure 11 shows the tendency of the N-value to be higher in steep regions (top left and bottom right). In the central portion, where the relief is flatter, the N-value does not exceed 42 blows/30 cm.

7. Discussion

It was identified well-defined regions in the studied area in which the soil layers are thinner and other regions where they are thicker due to its position and form of the slope. There is a tendency of regions of intermediate to high slopes with flat relief present thicker soil profiles and, consequently, greater depths until reaching the impenetrable to the SPT. The increase of the N-value with the depth is slighter in these thicker profiles in which Red Latosols predominate, allowing the association of such behavior with the type of soil in the studied area.

In regions of intermediate to low slopes, or even in regions of high slopes but with pronounced declivities, the soil profiles are thinner, revealing lower depths until the SPT impenetrable layer (superficial rocks). In these low slope regions in which the Red Nitosol predominates, we verified that the increase in the N-value is more significant,

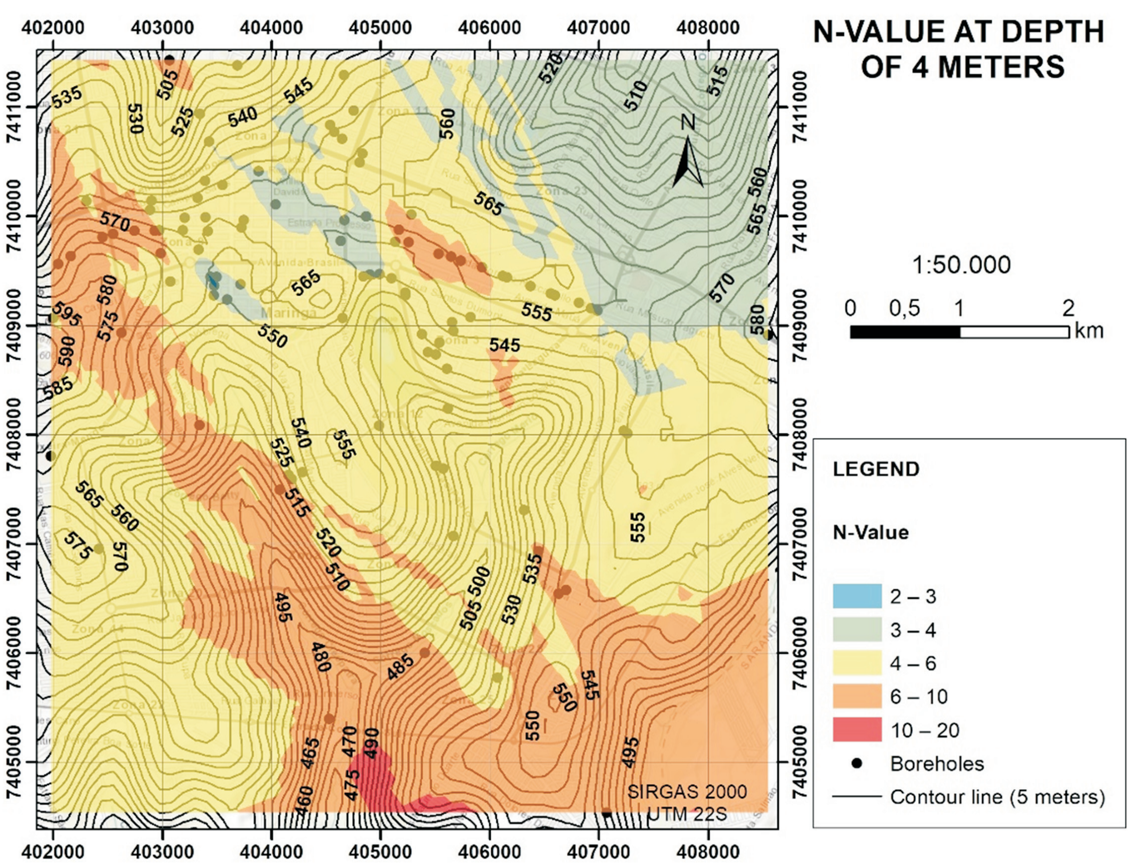

Figure 9. N-value at a depth of 4 m.

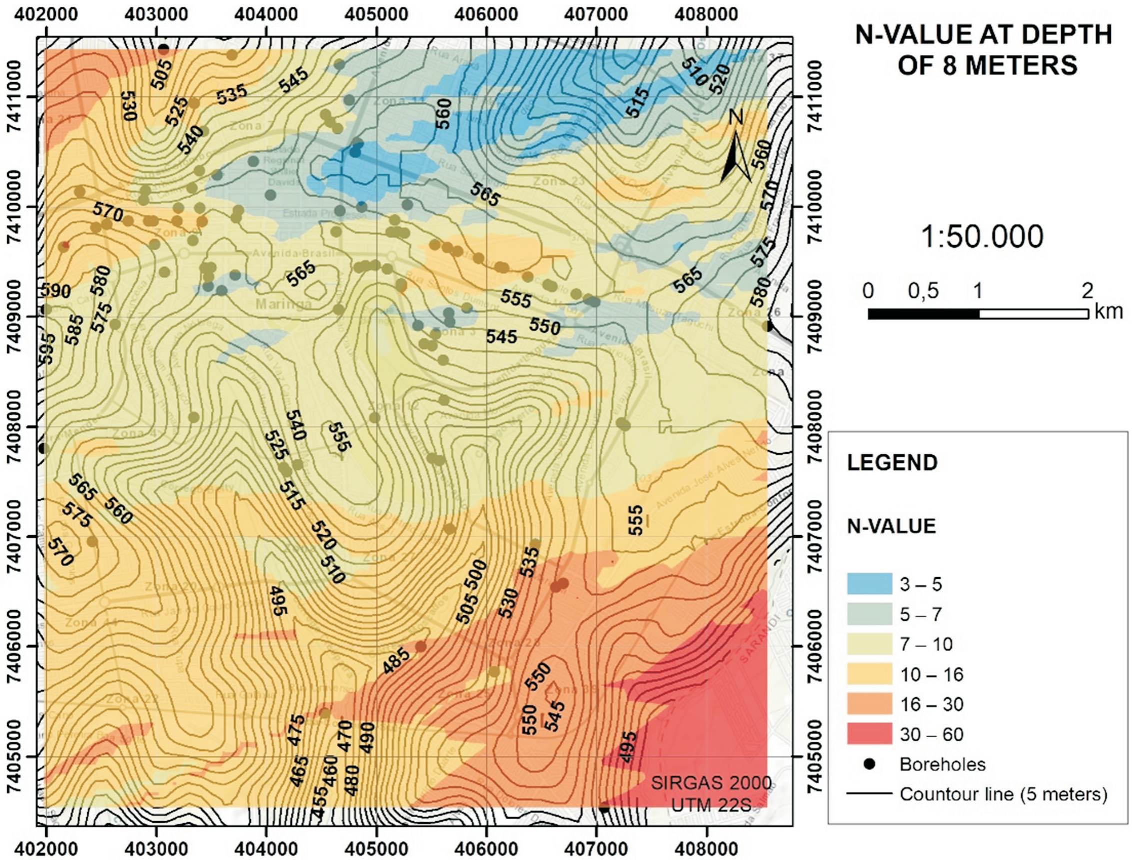

Figure 10. N-value at a depth of 8 m.

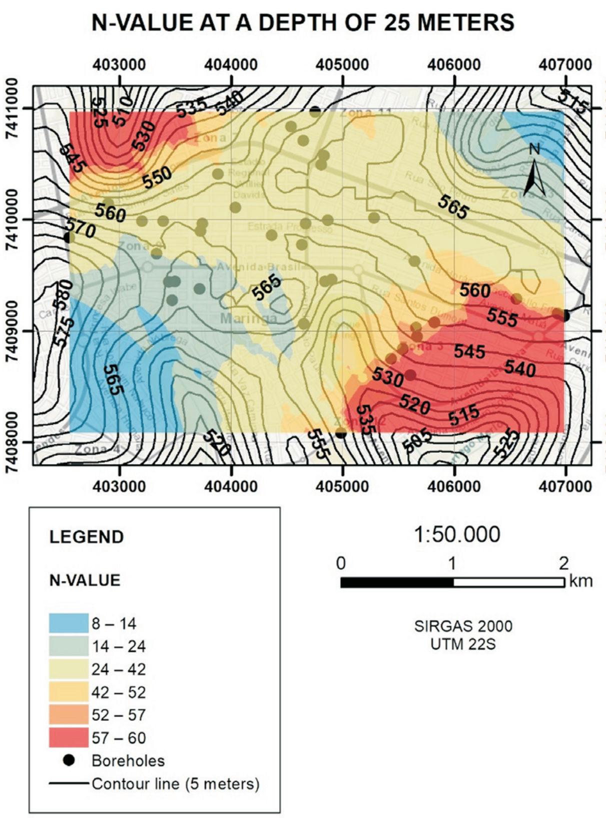

Figure 11. N-value at a depth of 25 m.

presenting soil of intermediate to stiff consistency at more superficial depths.

Due to the presence of little resistant soils on the more superficial layers of the soil, solutions in shallow foundations can be considered unfeasible in most of the central region of the municipality. Solutions in deep foundations are routine in the entire municipality but the possibility of adopting other alternatives due to the better soil resistance at more superficial depths, especially in regions of low to intermediate slopes with steeper declivities, should be verified.

8. Conclusions

The gathering of data from the SPT, in a single database, proves to be extremely positive, since it allows to easily identify some similarities, in addition to allowing several information to be crossed for a better knowledge of the soils. The use of the ordinary kriging technique of geostatistics was satisfactory when considering a general idea of the behavior of soils associated with other variables presenting spatial variability, allowing us to identify possible correlations between its geomorphological properties and characteristics, as was the objective of this study.

This type of study shows how factors such as the shape of the slope and its position are linked to soil behavior, being decisive in the estimation of the impenetrable to the SPT and in the evolution of the N-value, in this particular case. Thus, a series of variables can be studied trying to associate them with the behavior of the soil.

The significant variability of the soils indicates that the results obtained through statistical interpolators must be cautiously analyzed. The higher the density of the sampled points is, the more reliable will be the final products. Thus, insofar as new surveys are conducted, the database can be expanded, reflecting on more accurate estimates and, consequently, more reliable results on the knowledge and applicability of the soils.

Acknowledgments

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