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# Geological-Geotechnical Database from Standard Penetration Test Investigations Using Geographic Information Systems

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.74208>

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## Abstract

The study describes applications of Geographic Information Systems (GIS) associated with Standard Penetration Test (SPT) reports as a support tool for planning and decision-making in public and private spheres. The chapter begins with a bibliography compilation showing recent applications carried out around the world. Following this, the description of the geological-geotechnical method using SPT information applied in two case studies is presented in particular. For that, an extensive detailing of SPT reports treatment is done to enable the composition of a geological-geotechnical database. Two cases are shown to exemplify the method application and its results, including the characterization of the topographic relief through Digital Elevation Model (DEM), slope and hydrographic map and the development of soil, groundwater and foundation maps using a geological-geotechnical database composed basically by SPT data. The cases approach a larger scale using 507 SPT boreholes to analyze a university campus with 1 km<sup>2</sup> and on a smaller scale using 537 SPT boreholes to analyze a city with 207.2 km<sup>2</sup> of urban area. Different possibilities of applications for information management are discussed over the chapter.

**Keywords:** information management, Geographic Information Systems (GIS), Standard Penetration Test (SPT), geological-geotechnical analysis, foundation maps

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## 1. Introduction

In recent years, Geographic Information Systems (GIS) has allowed the improvement of works involving georeferenced data due to enabling complex spatial analysis. Graphic and

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alphanumeric data are combined and processed simultaneously with agility and efficiency. The application of GIS tools in soil studies has been consolidated around the world, because of the advance of the data analysis for professionals, and since modeling results, expressed in maps, provide a better interpretation for the decision makers.

Digital maps have a great manipulation potential and high dynamism in the analyses, allowing to work with a large number of data and providing flexibility for updates and adjustments. [1] point out that the technological environment which the tool is inserted provides, in addition to the collection and treatment of spatial information, the development of new systems and applications.

Considering that the advent of numerical models for spatial inference of the variations of soil types or their properties allows the digital mapping of the soils [2], GIS is a powerful tool for performing innovative analyses inherent to the physical environment. Thus, the results obtained from geotechnical investigations present an interesting alternative to analysis, since they provide valuable subsidies to geological-geotechnical understanding.

According to [3], records of geotechnical logs, stratigraphic profile, and water wells are extremely useful reference data for geologic, hydrologic, and geotechnical applications. Among the soil reconnaissance tests, the Standard Penetration Test (SPT) is the most popular, useful and economical test in practically all over the world [4]. In Brazil, SPTs have specific legislation and are regulated by [5]. Recently, different publications are looking for improvement in geological-geotechnical information management through association of spatial location with soil parameters obtained by means SPT reports. Therefore, this chapter presents how to structure SPT reports in a geological-geotechnical database to apply it as a tool to assist planning and management actions.

In addition, in order to present geotechnical applications in GIS environment, digital maps are shown for two cases in Brazil: one in the head campus of the Federal University of Santa Catarina (UFSC) and other in the urban area of Blumenau city. Besides contributing to the establishment of guidelines for the region expansion planning by its managers, the results demonstrate that the prior knowledge of the geological and geotechnical parameters makes possible to supervise the next SPT services to be contracted. This because it has organized and spatialized pre-existing data of several SPT reports already executed, making possible the estimation of the information contained in these data for the entire study area.

## 2. GIS and geological-geotechnical information: recent applications

Currently, different studies seek to represent soil surfaces taking advantage of parameters obtained from SPT reports. Commonly, these researches occur in countries where seismic activities are present with severe consequences, such as India. Studies to define the dynamic properties of the soil, through the use of SPT data to obtain the shear-wave velocity ( $V_s$ ), are essential in terms of engineering to predict soil responses under earthquake. Correlations

between N-value and  $V_s$  were applied and studied in 2006 in Yenişehir/Turkey [6], in 2008 in Bangalore/India [7]; in 2011 in Mumbai/India [8]; in 2012 in Hamedan/Iran [9]; in 2013 [10] and 2016 [11] in the city of Guwahati/India.

Countries such as Malaysia, Thailand, India, Turkey, Iraq, Iran, Brazil, United States of America (USA), and Australia carry out researches using SPT data to create surfaces of soils with different goals. In 2013, [12] conducted a soil characterization study using 110 SPT reports in the city of Hilla/Iraq. As a result, soil resistance trend was presented as a function of the N-value, and an empirical equation was developed to represent the region. In southern Chennai/India, in 2014, [13] developed water level, N-value contour lines and bearing capacity maps at different depths. Foundation suitability map was developed by using weighted overlay analysis.

In 2001, in Bangkok/Thailand, using 200,000 STP boreholes, [14] performed a three-dimensional soil profile generation, proposing the composition of a database for that. N-value contour lines at Surfers Paradise/Australia, based on 35 SPT reports, were developed in 2014 [15]. In 2012, [16] developed a map of N-value contour lines to assist in the design of foundations projects in the city of Rajshahi/Bangladesh, with the purpose of assisting in the design of small and low-cost structures. In 2013, [10] proposed the mapping of N-value and groundwater depth in the city of Guwahati/India. This study was carried out from a database of 200 SPT boreholes, covering 262 km<sup>2</sup>.

In João Pessoa/Brazil, in 2011, impenetrable layer, admissible stress, N-value, foundation suitability maps, as well as temporal analysis of the water table (reflecting the seasonality of rainy and dry periods) were developed [17]. In 2015, in Fortaleza/Brazil, N-value contour lines for three different depths and groundwater level map were generated [18].

In 2016, [19] identified and mapped the Blumenau/Brazil soil characteristics through 537 SPT reports. In this study, maps were developed portraying: SPT impenetrable layer depth, groundwater level, allowable stress for shallow foundation and N-value contour lines oriented for the deep foundation, from which the maximum length for common types of piles were calculated. The prediction of the foundation type (shallow and deep), admissible stress, type and the approximate length of piles, was performed using semi-empirical methods available in the literature. Complementary, geotechnical engineering mapping was associated with geomechanical information from SPT reports, resulting in stratigraphic reference profiles for the geotechnical soil units of the city.

In 2016, [20] collected 507 SPT boreholes from the head campus of the Federal University of Santa Catarina (UFSC) to analyze the geological-geotechnical profile of the study area, through the development of soil maps for each depth layer and foundation suitability maps. Impenetrable layer surface, groundwater level (considering the seasonality), as well as N-value contour lines were developed. Furthermore, through empirical and semi-empirical approaches available in the literature, this study produced orientation maps regarding foundation type: shallow or deep, allowable stress of the soil and maximum length of the piles commonly performed in the region. In the end, the theoretical results were validated by means of the information contained in 20 foundation designs executed at UFSC.

The methods and results of these two studies will be detailed as cases in this chapter. While [19] is focused on a large-scale analysis, the [20] is applied to a smaller one.

Considering the above, it is verified that studies related to geotechnical investigation associated with geospatial analyses have been carried out worldwide and have been aroused interest in practical and academic scope. A fact that encourages the growth of the works is the existence of numerous investigation reports already carried out in urban areas, becoming a potential subsoil characteristic database [21]. So, in order to stimulate further studies in the field, this chapter intends to clarify some ways to take advantage of pre-existing geotechnical data (SPT reports) and the methods of mapping and data processing, exemplifying the results by means of two cases.

### 3. Method

This section consolidates the processes used to analyze geological-geotechnical profile, through pre-existing soil data obtained via SPT reports, applied in the studies of [19, 20]. The method includes data collection, digitization and treatment (pre-processing), in order to compose a geotechnical database, further processed in GIS environment. The steps are schematically shown in a diagram (**Figure 1**) and detailed in the sequence.

#### 3.1. Data collection

The first step of the method is the data collection. They can be obtained from different sources, such as official agencies, companies, previous publications and, when the required data is not available, it can be collected by the researcher. The accuracy of the results is directly related to the initial data input; therefore, data collection becomes an essential step for optimal results.

The process of data collection, together with the data treatment (next step), might be one of the most time-consuming steps, and it requires an advance planning. It is interesting to elaborate list of contacts, schedule the activities and establish goals for assisting in this step.

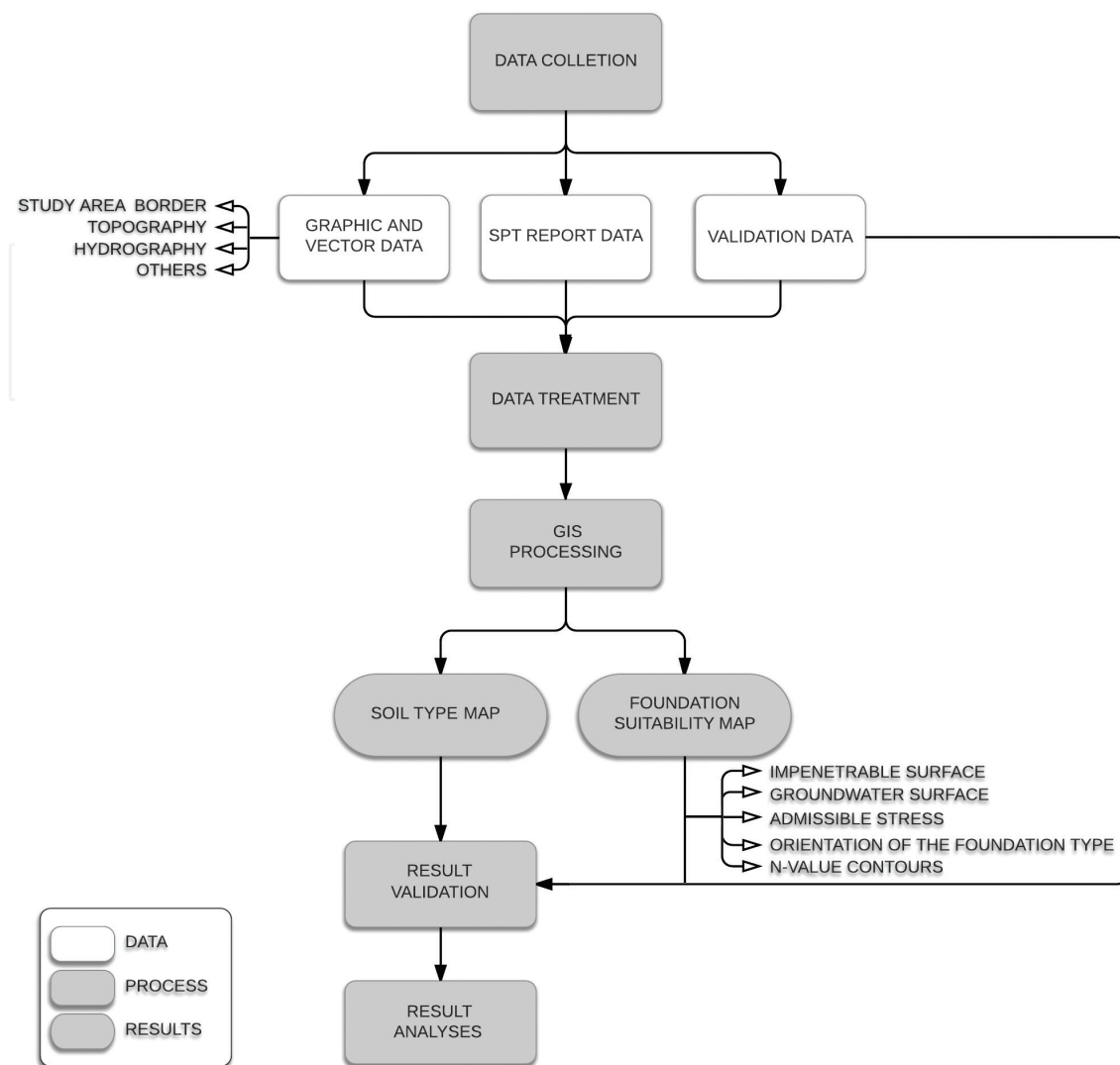
#### 3.2. Data treatment

After gathering all the necessary data, the data treatment step begins. As shown in **Figure 1**, for the presented case studies (Section 4), the data treatments (pre-processing) are mainly done on the graphical data and on the SPT data, which are detailed hereafter.

##### 3.2.1. Graphic and vector data

Using secondary data, a careful data treatment may be necessary. Data processing allows a fine-tuning of the data according to the required results. Much effort can be applied in this step, particularly when data obtained is not prepared to be handled in a GIS environment.

The routine previously published [22] guides the compatibility of the DGN or DWG (vectorial extension used by AutoCAD®) formats for SHP (extension used by QGIS® and ArcGIS®). For the presented cases, the following adjustments can be performed:



**Figure 1.** Work method diagram.

- Grouping thematically homogeneous elements;
- Merging broken lines (creating a single line from multiple lines);
- Resetting elements that were represented as lines into polygons;
- Closing polygons;
- Eliminating duplicate elements;
- Georeferencing of graphic elements.

Parallel to the treatment of graphic data, SPT reports are digitized and organized in a database, as described in the following subsections.

### 3.2.2. SPT report data

The composition of SPT reports database depends directly on the required results. Thus, this chapter emphasizes the data treatment processing for some applications of SPT report data



regarding groundwater level, impenetrable depth to SPT percussion, soil resistance and types of soil according to the particle size, used in the case studies.

All information available in the SPT report can be utilized. However, some inputs are important for basic analyses. **Table 1** lists the information available in the SPT report associated with some possible applications, mostly used in the case studies (Section 4).

Since SPT reports are often available in individual notes (usually printed or in PDF format), normally the data digitalization is required. Furthermore, specifically for the SPT data on the cases, it was performed a preliminary treatment prior to the database composition. This pre-processing was proceeded for each individual SPT borehole.

The location of the SPT boreholes (i) was not available directly on the report. The georeferencing of each SPT borehole was carried out using Google Earth®, through the indirect information of the reports (such as address, sketch, name of the enterprise). This information was used as a reference to obtain the most probable location of the borehole. The Google Earth® timeline tool, combined with the date of the SPT investigation, can also be useful. Since it was obtained indirectly, this SPT borehole georeferencing was not as accurate as a topographical georeferencing, however good enough to proceed some analyses.

| SPT borehole data                   | Applications   |
|-------------------------------------|--|
| (i) Location of the SPT borehole    | The location of the SPT borehole is essential to proceed a geospatial analysis of all SPT report data. This step always includes the use of a coordinate reference system, to be chosen by the researcher, and the identification of the horizontal location of each borehole  |
| (ii) Borehole depth                 | The depth reached by the SPT borehole up to the impenetrable is essential to develop the impenetrable to SPT percussion surfaces   |
| (iii) Groundwater depth             | <p>The groundwater depth is used to obtain the groundwater level. This information allows understanding the behavior of the water table among the studied region and, associated with the topography, to understand the directions of the groundwater flow. It can be used to construct a potentiometric map, for example</p> <p>It can be associated with other information and/or can help to understand lacks of other data sources</p> |
| (iv) N-value of each depth          | For more detailed analyses, such as foundation maps or iso-stress maps, it is necessary to have the N-value resistance for each meter of depth   |
| (v) Geotechnical investigation date | For a temporal analysis, the date of the SPT report is required. For instance, it can be used to get a seasonal variation of the groundwater level   |
| (vi) Soil stratigraphy              | Soil characteristics by depth provide information such as type (clay, silt, sand), color, compactness and consistency. This information can be associated with empirical correlations which allow associating new information and new analysis for each layer of soil, such as: to simulate shallow and deep foundations for each type of soil; to associate a specific weight to the soil, to analyze the stress according to soil type   |

N-value: abbreviation of the standard penetration resistance, the determination is given by the corresponding number of hits to driving 30 cm of standard sampler after an initial driving of 15 cm [5]

**Table 1.** SPT report data and its applications.

Borehole depth (ii), groundwater depth (iii), N-value of each depth (iv), geotechnical investigation date (v) and soil stratigraphy (vi) had their raw data digitized in electronic spreadsheets, along with the coordinates of each borehole (**Figure 2**), without preliminary treatments or filters. Spurious data can be removed during this process, according to the researcher's interpretation.

The SPT digitization and database organization aims to structure geological-geotechnical information in order to enable processing and data interpolation in GIS environment. In this sense, for the propose of all SPT borehole are considered in the interpolations, an N-value equal to 50 was inserted for the depths below the impenetrable. The idea is to establish a high N-value below of the SPT borehole last layer (the impenetrable layer) to prevent empty data, which could undermine the numerical modeling. As a simplification, the name rock was inserted after the impenetrable layer.

Subsequently, considering that reliable data are fundamental for database composing, the reports are analyzed to identify discrepancies in their information. A dry borehole near a water body or a shallow impenetrable depth near a deeper one is examples of possible inconsistencies. Furthermore, depending on the spacing between the SPT boreholes and the data application, it can be necessary and recommended to filter the SPT boreholes, aiming to save time and processing resources. In the case of [19], for example, to benefit data interpolation since clusters of SPT boreholes does not favor numerical modeling, for each cluster of SPT borehole it was selected one single borehole to represent the terrain. Thus, in order to obtain a better spatial distribution of SPT boreholes, the selection of the representative borehole of each cluster occurred in a more conservative scenario, considering the critical information in terms of foundation. The filtering was defined according to the steps [19]:

Step 1. Select the borehole with the greatest impenetrable depth;

Step 2. In the case of similarity of impenetrable depth, from the boreholes with the greatest impenetrable depth, select the hole with lower groundwater depth;

Step 3. In case of similarity of the greatest depth of impenetrable and lower groundwater depth, select the borehole with the lowest sum of N-value along the length of the borehole.

| Name   | X      | Y       | SPT_date   | h_borehole | h_groundwater | n-value_1m | n-value_2m | n-value_25m | soil_1m | soil_2m | soil_25m   |
|--------|--------|---------|------------|------------|---------------|------------|------------|-------------|---------|---------|------------|
| ID_292 | 744817 | 6944599 | 05/11/2009 | 12         |               | 1,1        | 4          | 2           | 50      | Sand    | Rock       |
| ID_293 | 744576 | 6944828 | 19/07/2003 | 25,35      |               | 8,1        | 8          | 10          | 43      | Sand    | Pebble     |
| ID_294 | 744564 | 6944814 | 21/07/2003 | 25,4       |               | 8,3        | 14         | 14          | 41      | Clay    | Pebble     |
| ID_295 | 744546 | 6944829 | 18/07/2003 | 24,35      |               | 8,3        | 6          | 6           | 50      | Clay    | Rock       |
| ID_296 | 744559 | 6944843 | 17/07/2003 | 25,35      |               | 8,15       | 5          | 5           | 40      | Clay    | Pebble     |
| ID_297 | 744561 | 6944827 | 21/07/2003 | 25,38      |               | 8,7        | 6          | 7           | 40      | Clay    | Pebble     |
| ID_298 | 744943 | 6944357 | 20/11/2010 | 3,07       |               | 1,1        | 16         | 46          | 50      | Clay    | Rock       |
| ID_299 | 744933 | 6944369 | 21/11/2010 | 1,2        |               | 1,12       | 50         | (...)       | 50      | Clay    | Rock (...) |
| ID_300 | 744916 | 6944377 | 21/11/2010 | 6,39       |               | 1,2        | 9          | 7           | 50      | Clay    | Rock       |
| ID_301 | 744946 | 6944390 | 21/11/2010 | 1,27       |               | 1,1        | 50         | 50          | 50      | Clay    | Rock       |
| ID_302 | 744973 | 6944376 | 20/11/2010 | 4,07       |               | 1,4        | 14         | 8           | 50      | Silt    | Rock       |
| ID_303 | 744954 | 6944366 | 21/11/2010 | 3,08       |               | 0,9        | 9          | 15          | 50      | Clay    | Rock       |
| ID_304 | 744969 | 6944357 | 21/11/2010 | 3,41       |               | 0,8        | 7          | 7           | 50      | Clay    | Rock       |
| ID_305 | 744536 | 6944351 | 20/11/2010 | 18,4       |               | 1,8        | 9          | 13          | 50      | Clay    | Rock       |
| ID_306 | 744535 | 6944341 | 19/11/2010 | 14,38      |               | 2,3        | 8          | 5           | 50      | Clay    | Rock       |
| ID_307 | 744515 | 6944341 | 19/11/2010 | 22,03      |               | 3,7        | 8          | 11          | 50      | Clay    | Rock       |

**Figure 2.** Geological-geotechnical database.



With the structured data, it is possible to start the data processing in a GIS environment, by consolidating and georeferencing the acquired data (graphical and SPT data), developing thematic maps and a geodatabase (associated with the boreholes location).

3.3. GIS processing

In this step, based on the graphic and vector data, the objects referring to each layer (administrative limit and hydrography, for example) are isolated in their own layer and georeferenced. Graphic and vector data and SPT borehole locations are imported to a GIS environment. All data must be handled to the same coordinate reference system and imported to the same GIS environment.

Through georeferenced data, thematic maps are developed for the understanding of the characteristics of the study area, which will assist in the geotechnical analyses and data validation. As an example of thematic maps, **Figure 3** presents the Digital Elevation Model (DEM), the slope map, and the hydrographic map produced by [20].

These maps are a basis for the characterization of the topography. In addition, they contribute to the identification of the soil type in each borehole analyzed (sedimentary or residual, for example). The hydrographic map, in turn, is used to aid the consistency analyses of the SPT groundwater level and can improve the groundwater data, as performed in [19, 20], who incorporated fictitious SPT groundwater data along the main river of the study area.

The geological-geotechnical database developed (**Figure 2**) outside of the GIS environment can be incorporated into the SPT borehole already in GIS, using the ID of each borehole as a reference. Thus, each row of the database, which refers to a single SPT borehole, begins to contemplate the information of its report and location.

When the altimetry information is not available on the STP report, since the database is georeferenced, the elevation of each borehole can also be added by crossing the altimetry information arranged in the DEM with the location of the points. Additional columns can be created

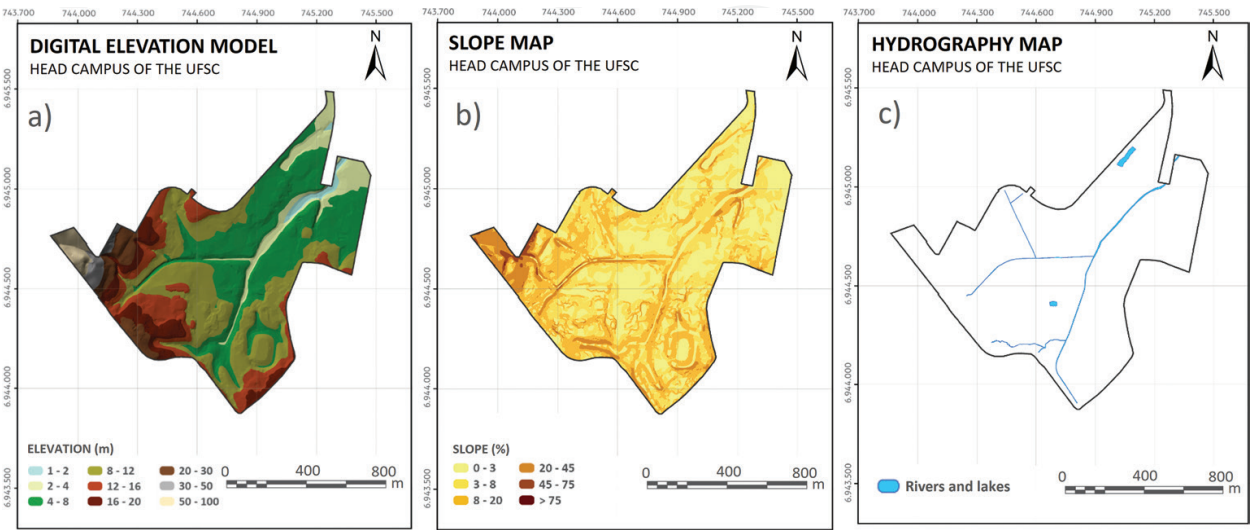


Figure 3. Thematic maps [20].

in the database for calculating the impenetrable and groundwater elevation, subtracting the altimetry value from the respective depths of impenetrable and groundwater. Likewise, other information can be added to the database, depending on the available data and analysis interest, such as the terrain steepness (from a slope map) and the geotechnical unit (from the geotechnical engineering map).

The database can be handled to create secondary information. For instance, to generate admissible stress ( $\sigma_a$ ) surface from N-value, [23] performed the analysis soil stress with an empirical model. The admissible soil stress for the shallow foundation is defined in [24] as:

$$\sigma_a = 0.02 \times \text{N-value (MPa)} \quad (1)$$

Valid for natural soils with  $5 \leq \text{N-value} \leq 20$ .

It is necessary to prepare the database for creating an elevation map of specific admissible stress: setting up the N-value corresponding to the desired stress and identifying the depth of each borehole where this N-value is found. Since coordinates are associated with these depths, a spatial interpolation can be carried out to obtain the elevation of the desired stress (isobaric).

Another possibility is to generate the surfaces of admissible stress isovalues. In order to do it, for each meter of depth, the values of admissible stress are calculated according to Eq. (1). Since the equation is valid for a certain range, the isobaric of 0.4 MPa (4 kgf/cm<sup>2</sup> or 400 kN/m<sup>2</sup>) is adopted as the upper limit of admissible stress, and 0.1 MPa (1 kgf/cm<sup>2</sup> or 100 kN/m<sup>2</sup>) as the lower limit.

Also handling the database, [19, 20] used the N-value to create an orientation map of the foundation type (shallow or deep). The authors proposed criteria to guide the foundation type algorithm based on the precepts of economic feasibility exposed in [25] for shallow foundations and the limitations of the Eq. (1). The adopted criteria were:

- Maximum limit of two meters depth for shallow foundation settling. [19] adopted four meters, instead of two, in order to contemplate the possibility of an excavation of a subsoil up to two meters;
- N-value  $\geq 5$  in the analyzed depth and below it, in order to avoid shallow foundation laying on soft soil;
- Zones not consistent with previous criteria were directed to the deep foundation;
- Considering that the groundwater level is fundamental for the evaluating the foundation type, for each depth analyzed, the groundwater was plotted on the maps.

Finally, with the database consolidated in the GIS environment, the information generated can be used for management and analyze of the registered data. In this context, geostatistics is indicated to transform a database into maps that enable the geological-geotechnical characterization of the study area. Geostatistics is distinguished from the conventional statistics because it considers the spatial or spatiotemporal location of the data in the analyses. The cases presented in the chapter made use of interpolations, applying ordinary kriging

processes since it is a consolidated method in the soil science literature [26]. However, for each type of map elaborated, it is necessary to verify the semivariogram that best conforms to the data, i. e., the one which results in a smaller average error.

3.4. Result validation

This section intends to clarify briefly some ways to validate the results and to understand their coverage. The first approach for validating the results is through numerical analyses. It can be done using a subset (training set) to build the map, and a test set to analyze it by comparing the predicted results with the test set. This holdout concept is highly applied in machine learning and can be used to geotechnical data as well. The holdout method is shown in **Figure 4**.

Some maps can be validated through on-site information collection. In addition, the foundation suitability map and a study about foundation characteristics, such as pile lengths, can be validated by analyzing the foundations executed in the study area.

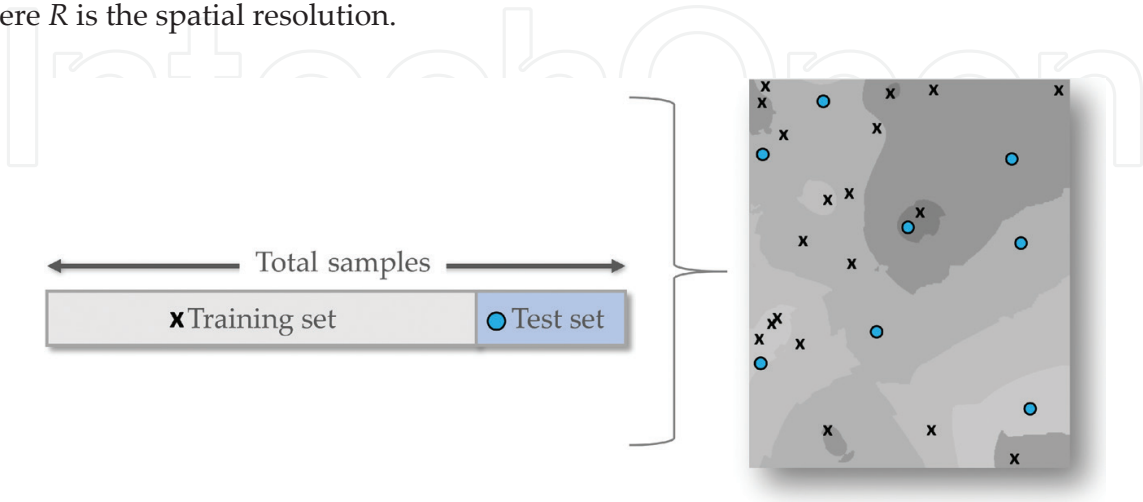
[19] used on-site information to validate the soil units of Blumenau with experts of the city hall, while [20] carried out validations through the analysis of the executed foundation reports provided by the University. Based on the type and length of the foundations executed in 20 buildings distributed along the study area, the foundation suitability and the pile maximum length maps could be validated [20].

Another possibility is defining the number of the dataset and its distribution according to the spatial resolution required for the study. However, when working with pre-existing data, usually it is not possible to choose the dataset. In this case, the spatial resolution analysis can help to understand the coverage of the dataset.

In [27] (as cited in [28]), the spatial resolution of georeferenced data is defined as the content of the geometric domain divided by the number of observations, as shown in the Eq. (2).

$$R = \sqrt{\text{area}/\text{number of observations}}$$
 (2)

Where *R* is the spatial resolution.



**Figure 4.** Data validation—numerical analyses using the holdout approach.

[19] applied this spatial resolution approach to visualize the data distribution and coverage and to calculate, through literature comparison, the scale of the developed maps (Figure 5).

An analysis based on the background knowledge and visual inspection is also effective to understand the coverage of the dataset qualitatively. The resulting information is increasingly closer to reality when in possession of a robust database, that means a larger number of SPT boreholes distributed throughout the study area associated with a validation process. As part

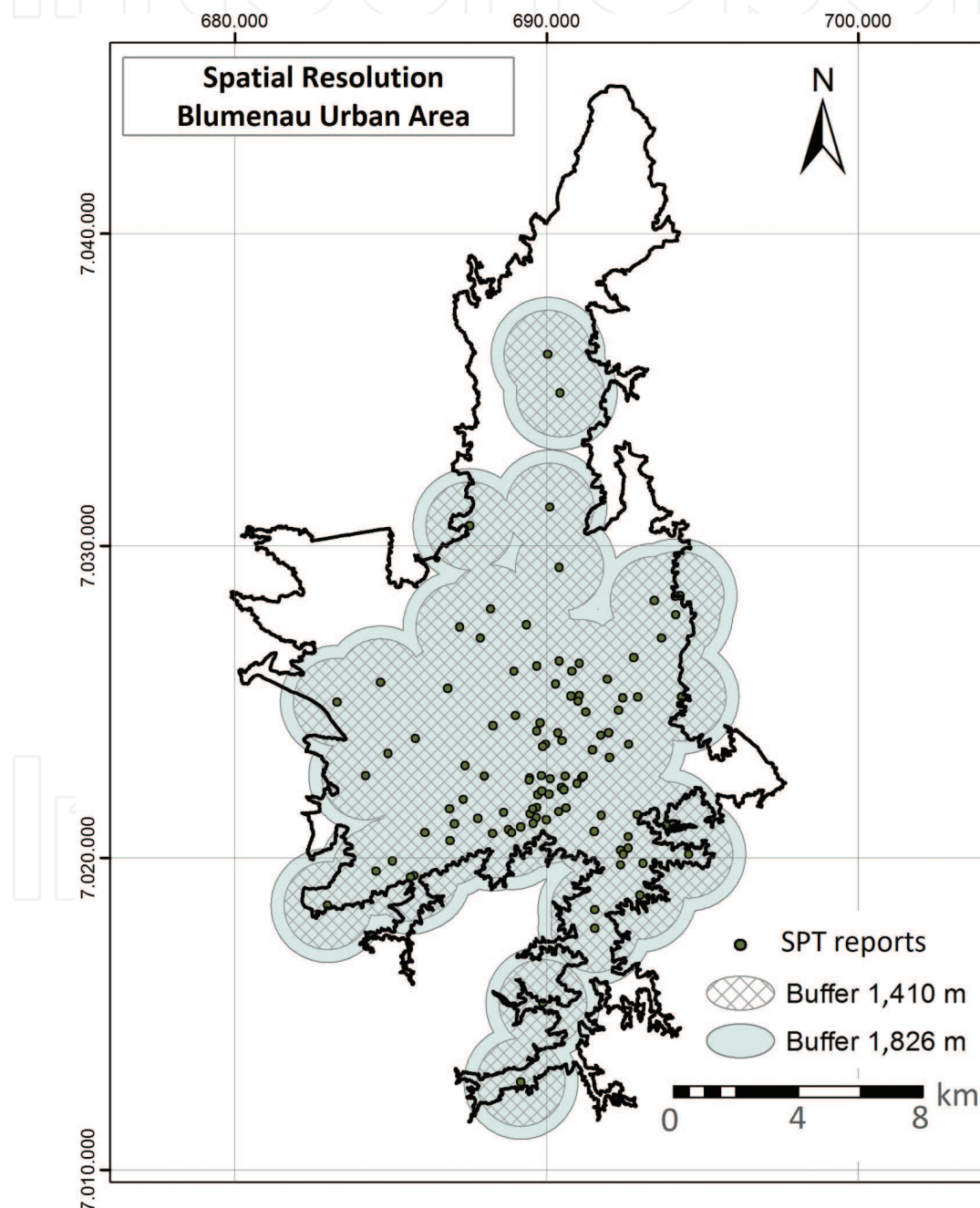
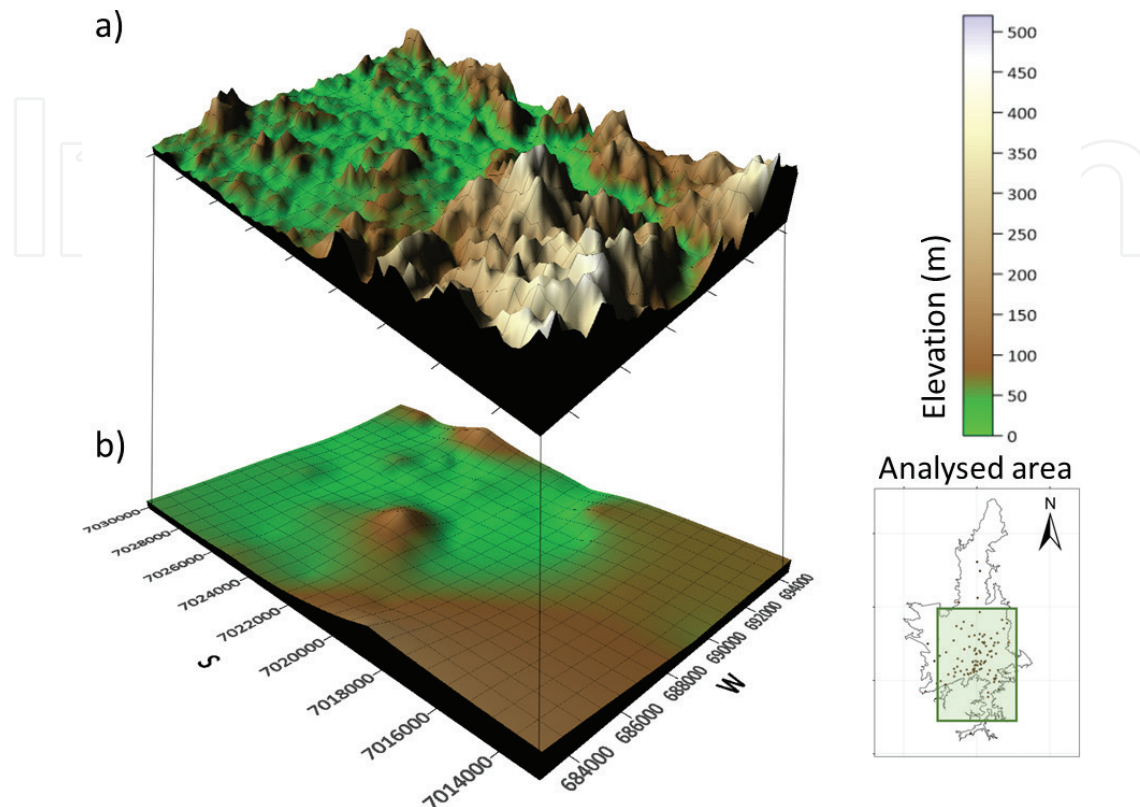


Figure 5. Coverage of the dataset—spatial resolution [19].



of the visual analysis, [19] exemplifies the comparison between the elevation surface modeled from SPT reports (**Figure 6b**, developed with limited dataset) and from one modeled from contour lines (**Figure 6a**, developed with a rich dataset).



**Figure 6.** 3D Digital Elevation Model. Surfaces modeled from contour lines (a) and from SPT borehole coordinates (b) [19].

The data validation is an essential step because it helps to improve the results and prevent the elaboration of maps with unreal results. This stage can provide a better comprehension of the solution developed, and clarify the strengths and limitations of the study.

## 4. Results and cases

This section introduces some examples of the results achieved with the application of the presented method. The two cases discussed are deeply detailed in [19, 20].

### 4.1. Soil type map

Soil type maps were developed in [20] using the kriging technique exclusively from the data of SPT reports, starting at 1-m depth and ending at 25-m depth. **Figure 7** shows a compilation of all generated maps, in order to simultaneously visualize the variation of the soil composition along the layers.

Visually, it was verified that the subsoil of the head campus of UFSC has an increase of soil granulometry from northwest to southeast and along the depth. By calculating areas according



## SOIL TYPES

### HEAD CAMPUS OF THE UFSC

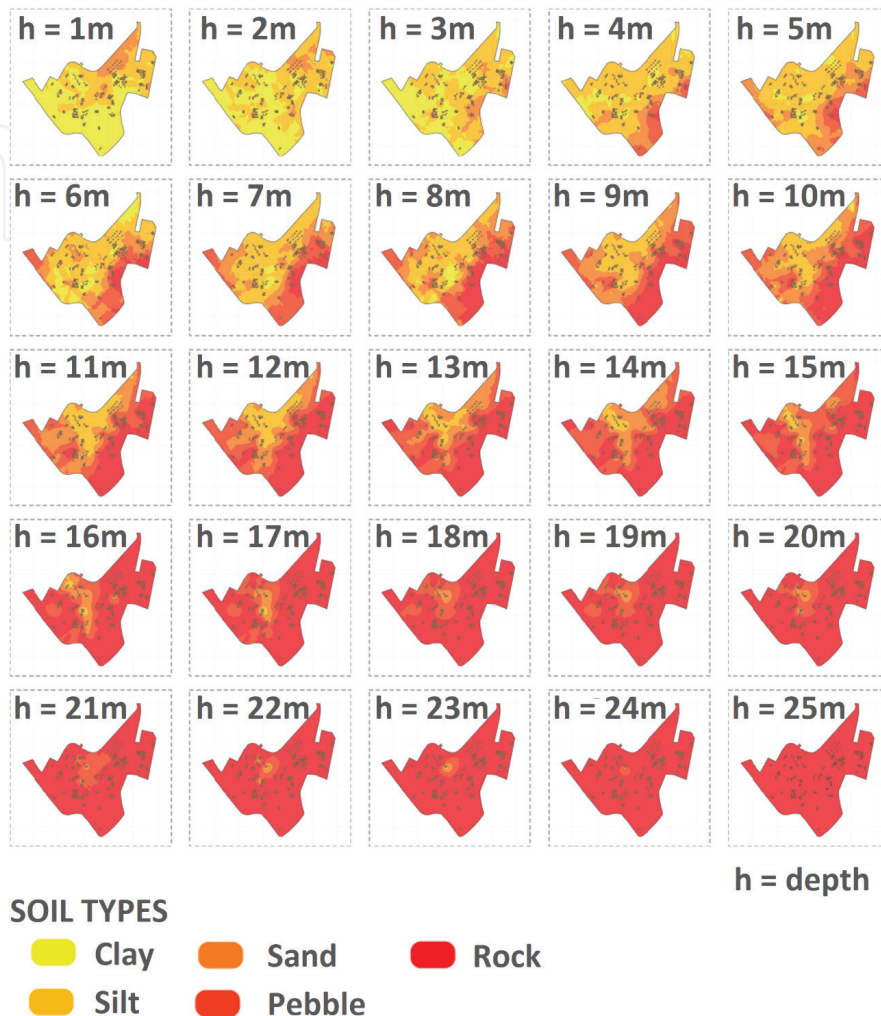


Figure 7. Soil types maps [20].

to the type of soil, quantitatively, up to the depth of 11 m, there are 50% or more of the area covered by clay, silt and sand, while in the following layers, there is a predominance of pebble and rock.

#### 4.2. Impenetrable surface

The surface of the impenetrable to the SPT percussion was generated by interpolating the values in each SPT borehole. As one of the results, the impenetrable map available in [20] is displayed in **Figure 8**.

It is verified that the regions with fewer SPT boreholes (map boundaries) present a contour for the impenetrable depth zones with fewer details, covering larger areas and having a shallower impenetrable when compared to regions with more SPT boreholes.

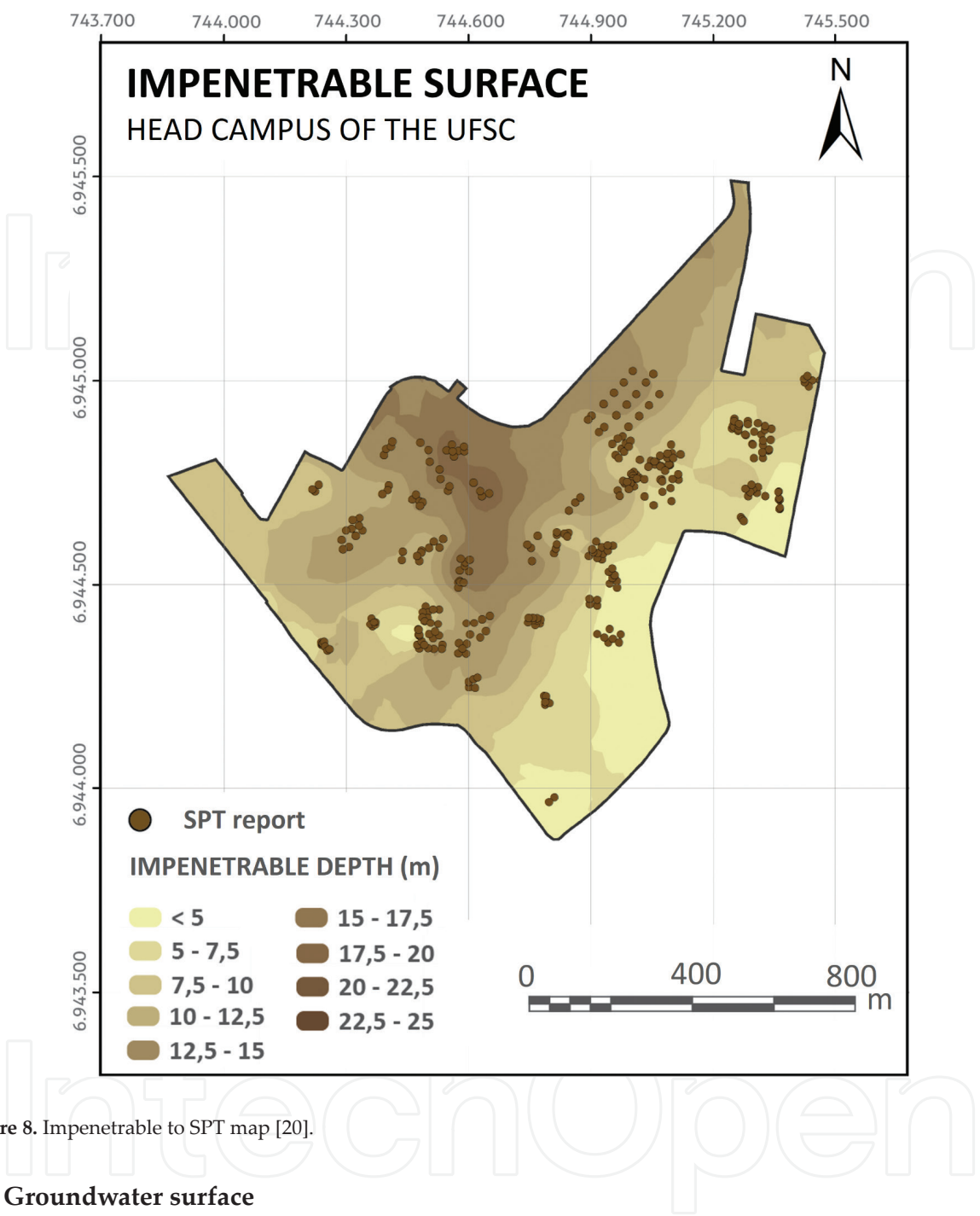


Figure 8. Impenetrable to SPT map [20].

4.3. Groundwater surface

The maps generated by the interpolation of the groundwater elevation in each SPT borehole allow to understand the behavior of the water table and can be used to verify the groundwater flow. A **Figure 9** shows the groundwater surface generated [19].

In this case, it is observed that groundwater flows from the higher elevations to the lower elevations, tending to flow to the main river of the city. The shorter the color shade transition in **Figure 10**, the greater the hydraulic gradient is.

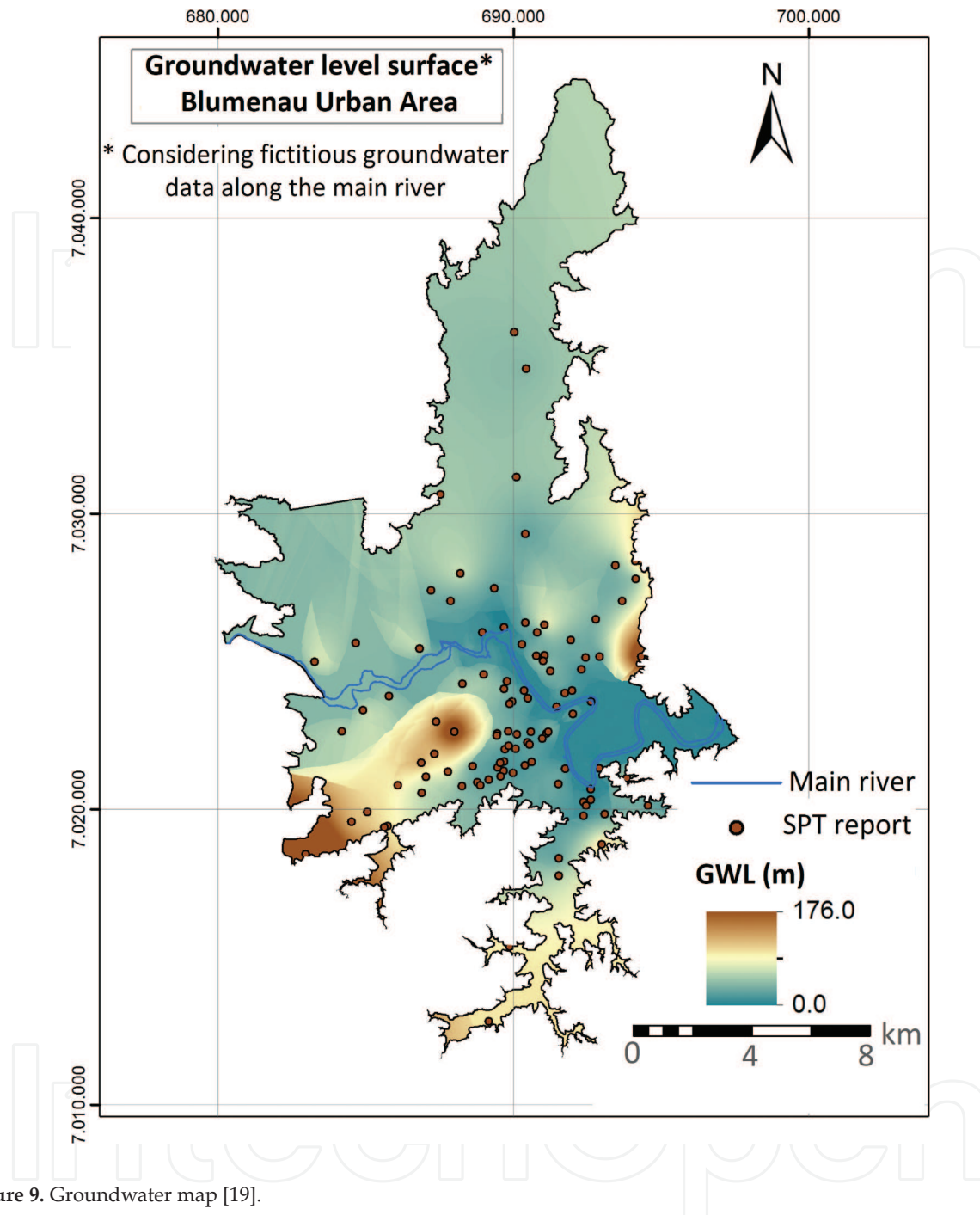


Figure 9. Groundwater map [19].

For an analysis of seasonality, the groundwater data can be separated according to the rainy and dry periods of the year. [20] performed a historical series analysis of daily precipitation data to obtain the rainy and dry seasons, and based on it the SPT boreholes were classified as belonging to the rainy season (**Figure 10a**) and dry season (**Figure 10b**).

The comparison between the two maps makes it possible to evaluate the temporal variation of the water table. In the case presented, it is possible to understand the difference between the

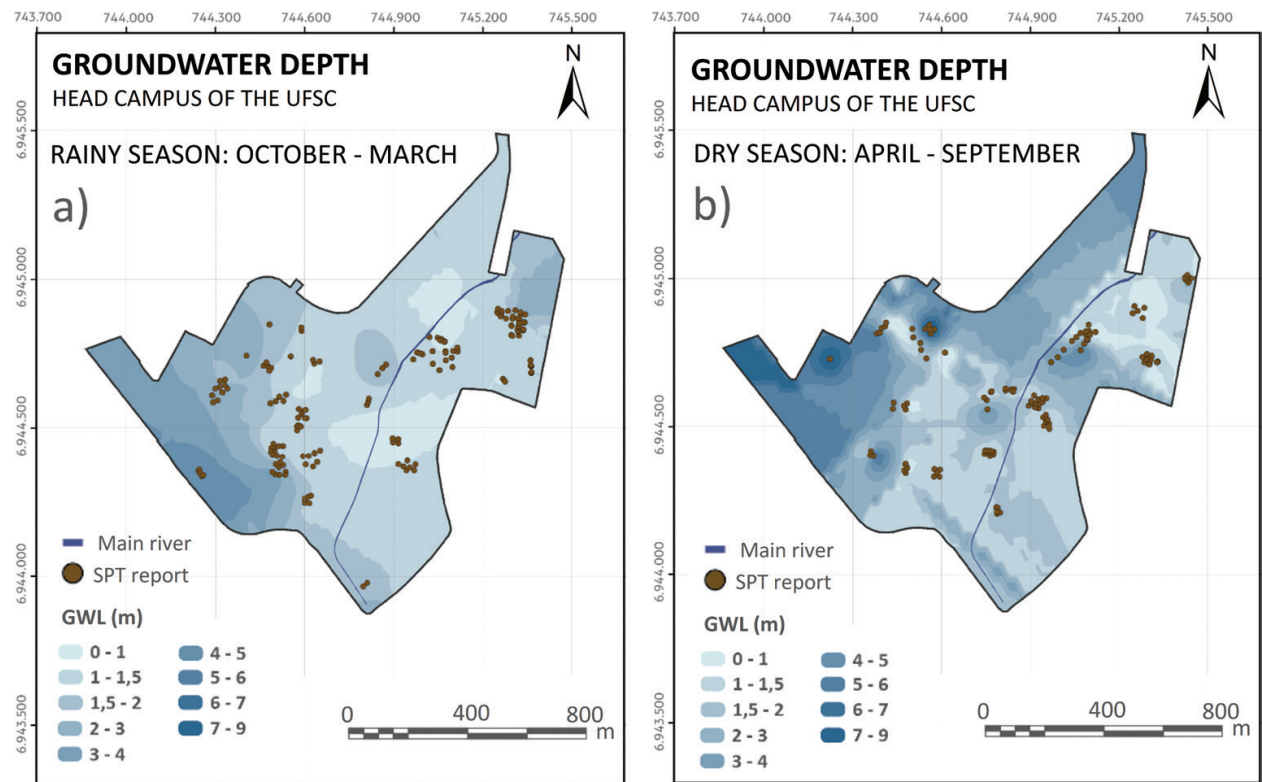


Figure 10. Groundwater seasonality map. Rainy season (a). Dry season (b) [20].

water table level in each period, with higher groundwater level during the rainy season and smaller one in the dry season, as expected. These maps are a valuable tool to plan schedules for foundation execution, for example.

4.4. Admissible stress map

The maps developed by means of the admissible stress values of each borehole, at the required depths, guide the design of direct foundations. Based on Eq. (1), the regions where the admissible stress ( $\sigma_a$ ) is smaller than 100 kN/m<sup>2</sup> are not valid, because they correspond to areas where the N-value is smaller than 5 (lower limit of the Eq. (1)). Likewise, the N-value greater than 20 (higher limit of the Eq. (1)) corresponds to 400 kN/m<sup>2</sup> of admissible stress, also a limit range to create the map for safety reasons. **Figure 11** displays an example of a map generated for three different soil depths in [20].

In this case, there is a tendency to increase the stress supported by the soil along the depths, growing from west and southeastern regions to north-central areas.

4.5. Orientation of the foundation type map

The orientation of the foundation type maps indicates the propensity to execution shallow or deep foundations. They are generated by means of the interpolation of the values assigned to the SPT boreholes according to the established criteria. It is recommended to include information about water table, considering that the presence of groundwater can guide the decision-making regarding the foundation type to be adopted.

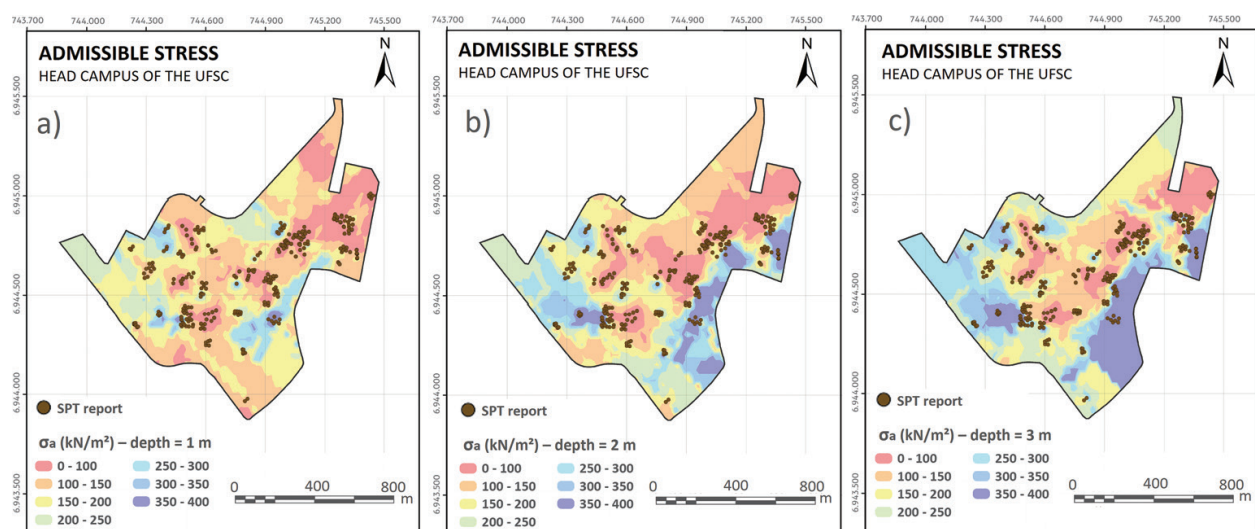


An example developed in [19] of these maps is showed in **Figure 12**, for the Blumenau urban area.

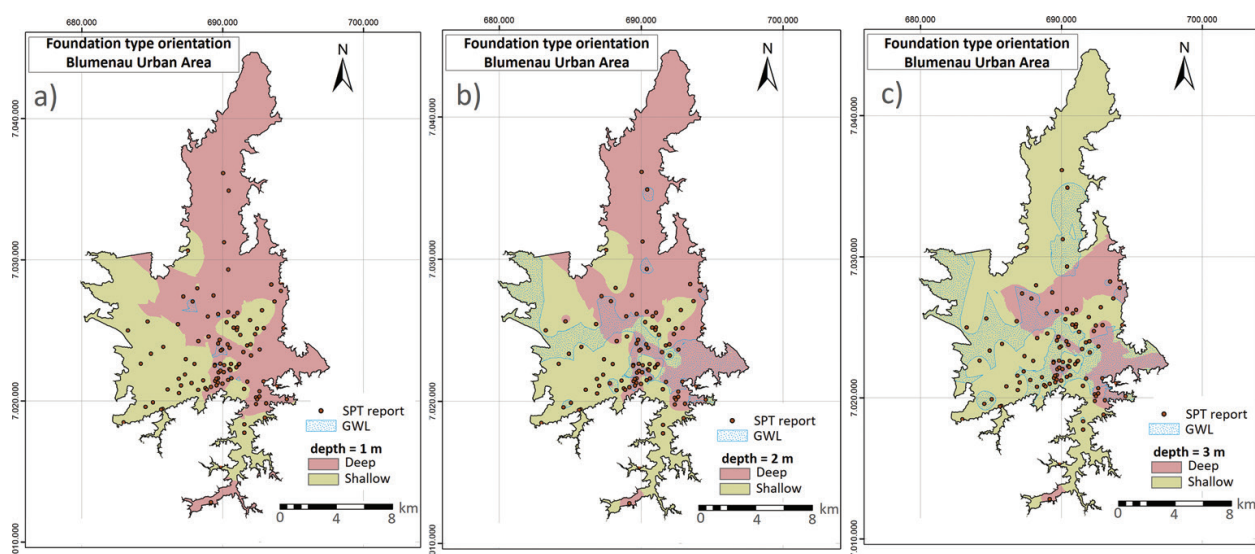
The maps developed to one and two meters of depth divides the Blumenau urban area into two large regions, the southwest, orientated to shallow foundations, and the northwest, tending to deep foundation mostly. Due to the higher resistance of the deeper soil layers, the susceptibility to shallow foundation covers 39.1, 45.9 and 79.0% of the total area, to the depths of 1 (Figure 12a), 2 (Figure 12b), 3 m (Figure 12a), respectively.

#### 4.6. N-value contours map

N-value contours maps can be elaborated through the established database in order to allow an orientation according to the type of deep foundation to be used. Through the interpolation of



**Figure 11.** Admissible stress for depths equal 1 m (a), 2 m (b) and 3 m (c) [20].



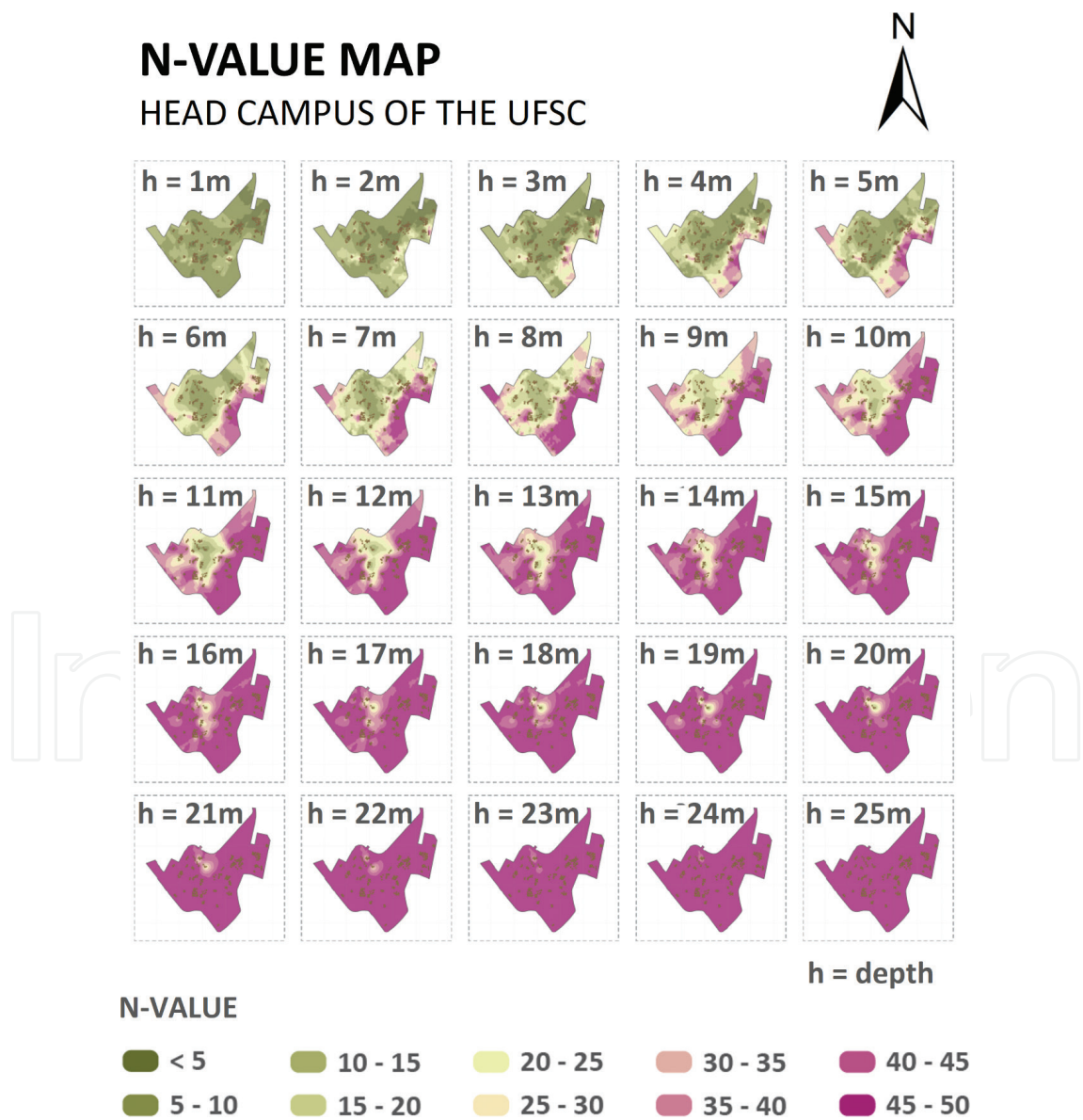
**Figure 12.** Foundation type orientation for depths equal 1 m (a), 2 m (b) and 3 m (c) [19].



the N-value in each analyzed depth, curves of the soil resistance for the study area are obtained. This kind of maps, for instance, enable to evaluate the geotechnical soil profiles in various sectors of the study area, in order to observe the occurrence of layers with lower resistance index and the evolution of the soil resistance with increasing depth.

**Figure 13** shows a compilation of all generated N-value maps presented in [20], in order to simultaneously visualize the variation of the soil resistance along the depths.

It is verified in **Figure 13** that there is a growing tendency of the areas containing high N-values (darker color) with the increase of the analyzed depth. The analysis was performed until 25 m deep, where the impenetrable to percussion layer is completely achieved. The UFSC subsoil shows that the N-values decrease from the east, west and south regions to the central-north portion, which contains soft soils and, consequently, with lower resistance.



**Figure 13.** N-value map—matrix of comparisons [20].

## 5. Conclusion

This chapter described practical applications of modeling and processing of database in GIS environment, using pre-existing data such as Standard Penetration Test Investigations. It detailed the process behind the elaboration, treatment and application of a geological-geotechnical database, through a method description and display of practical results using two case studies [19, 20].

The operations using geological-geotechnical data can bring important information for planning and decision-making. In this way, N-value contour lines, soil types and groundwater level maps were developed to guide land use and occupation policies, due to their strategic information for elaboration of risk and flooding maps, for example. Knowledge of the depth of the impenetrable to SPT percussion, groundwater, admissible soil stress for shallow foundation and N-value contour lines are fundamental information regarding technical designs, foundation costs planning and services validation, and so they were also addressed in the chapter.

Since working with a digital database, there is also the possibility of the further addition of information in the analyses, such as soil and rock mechanic and dynamic properties. This is a significant advantage of the method because the analyses can be repeated countless times, complemented and updated according to interest.

Due to the flexibility of digital database, the possibilities of analyses and results are countless. Different results than those presented in this chapter can be explored. Pile maximum length map and stratigraphic reference profiles for the geotechnical units are examples presented in greater details in [19, 20]. The diversity of results depends on the interest and creativity of the researcher.

Finally, the organization of different applications and methods to treat geological-geotechnical information in GIS environment intended to show the efficiency of to take advantage of pre-existing data. The results presented can assist decision-making providing strategic information in the public sphere and in the private sector.

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