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The Role of Spatial Distribution of Geotechnical Soil Parameters in Site Investigation

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Abstract: The correct investigation of the foundation soil is essential for the optimal and efficient design of any structure. The interaction of a structure with the foundation soil can only be evaluated through the physical and mechanical characteristics of the intercepted geotechnical layers on the entire zone of influence. For this reason, the role of technical documentation that includes and summarizes field investigations and laboratory tests is particularly important. An important and sometimes complicated component in providing useful design information is the division into geotechnical or computational layers. This can be done at different levels, starting from the physical characteristics such as color, grain size distribution, plasticity and consistency and can continue with the evaluation of the mechanical characteristics of compressibility and shear strength. The aim of the paper is to create a graphical representation of the geotechnical parameters using a spatial interpolation technique (Kriging method). The creation of 2D maps using SURFER software assists geotechnical engineers in the correct interpretation of the geotechnical parameters. This interpolation technique for division into layers is also useful in quarries and borrows pits, when soil is used as construction material.

Keywords: Site investigation; Geotechnical parameters; Spatial distribution; Kriging.

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1 Introduction

Geotechnical investigations are essential for every civil engineering project, and they are a fundamental requirement. They play a crucial role in ensuring the right implementation of the project and enhancing its feasibility, planning, and design stages. Geotechnical engineers face a growing challenge in accurately quantifying foundation soil properties, taking into account potential variations between sampling points. To evaluate, understand, and characterize properly the foundation soils from a site it is very important to have a precise variation of the geotechnical parameters in depth.

In noncohesive soils, onsite tests (standard penetration tests [SPTs], cone penetration tests [CPTs], dynamic penetration tests [DPTs] play a major role in characterizing the subsoil. In cohesive soils, the multitude of results from laboratory tests makes it challenging to characterize and divide the foundation soil into geological layers. Due to this complexity, creating a 2D model of the terrain using precise software tools becomes necessary. The spatial variability of soil properties in horizontal and vertical directions facilitates the creation of models for the subsoil per parameter (geotechnical maps). Studies related to geotechnical site characterization using the spatial distribution of soil parameters utilize tools within GIS or SURFER software. To graphically visualize the foundation soils from the analyzed site, the study proposes to integrate geotechnical data with contouring software SURFER. For this reason, the Kriging method of geostatistical analysis was identified to be more feasible for generating geotechnical cross sections.

SURFER software is employed in various fields such as agriculture [1, 2], environmental science [3, 4], erosion control [5], geotechnical engineering [6, 7], geology, mining, and others, where the analysis and visualization of spatial data are crucial.

A study developed by Camacho-Tamayo et al. [1] identified the variations in soil pH, organic matter content, and nutrient levels resulting from agricultural activities in Colombia. The paper describes the spatial distribution of analyzed parameters and highlights the importance of considering agricultural interventions and their implications for soil health and productivity.

The Kriging method of geostatistical analysis was investigated by López-Granados et al. [2]; the study presents soil properties for optimizing agricultural practices. Variation graphs of soil texture were created to assess fertility and water retention capacity. Soil moisture variation was tracked for irrigation planning, and nutrient concentration variation in soil was monitored for crop quality evaluation. A conclusion of this study highlights the importance of using geostatistical methods and remote sensing in monitoring soil properties.

Detailed analysis of horizontal and vertical variations of heavy metal pollution was conducted by Sichorova et al [3]. Researchers examined the concentrations of heavy metals in a polluted area, as well as the variation in heavy metal content (lead, cadmium, mercury, and others). It was observed that the variation in heavy metal content is influenced by the processes of transport and distribution of metals in soil, soil characteristics, and pollution history. The data obtained in this article are crucial for the development and implementation of effective strategies for managing and remediating areas contaminated with heavy metals.

Research on developing a program based on SURFER software automation that assesses the spatial distribution of heavy metals in soil was presented by Liu et al. [4]. Based on laboratory results, the researchers evaluated the risk of soil contamination with heavy metals and produced detailed maps using an extension of the SURFER, named the HMCA-Contour program.

The erosion hazard analysis was conducted based on the universal soil loss equation (USLE) methodology and SURFER software for an area in Indonesia [5]. The erosion phenomenon was estimated considering rainfall intensity, land use, soil type, and based on the 3D maps generated by SURFER. Researchers concluded that the maps generated in SURFER provide accurate images of erosion intensity throughout the analyzed watershed. In addition, it was reported that the 3D maps are essential for the development and implementation of conservation and land management strategies in the analyzed watershed.

The creation of geotechnical maps using the Kriging technique and the integration of this method into a geotechnical database were studied by Arshid and Kamal [6]. The researchers highlight the importance of geotechnical mapping for the implementation of construction projects. By analyzing geotechnical maps, areas with high geotechnical risk, difficult foundation conditions, areas where the foundation soil has reduced compressibility, and areas with landslides can be identified. Geotechnical maps can be useful when choosing highway routes, potentially allowing avoidance of their passage through unstable or difficult areas.

The 2D variation plots of shear strength parameters (cohesion and internal friction angle) were generated in a study conducted by Balarabe et al. [7]. These parameters are crucial for stability analyses, which are mandatory in road infrastructure development projects of any country. Researchers found that the 2D representation of geotechnical parameters can be efficiently applied in field investigations and infrastructure design.

The aim of the paper is to create a graphical representation of the geotechnical parameters using a spatial interpolation technique (the Kriging method). The creation of 2D maps using SURFER software is a suitable technique for generating geotechnical cross sections and assisting geotechnical engineers in the correct interpretation of the geotechnical parameters.

2 Related work

2.1 Site characteristics

The investigated site is located in Bucharest, Romania, and it was analyzed to obtain a geotechnical study for the construction and development of a residential complex. The terrain surface is relatively flat, with absolute elevations of approximately 86.50 m (above Black Sea level). In the studied area, there had been industrial buildings and underground networks that were demolished. At the time of the geotechnical investigations, it was not known whether the building foundations were filled with compacted soil or not.

To characterize the foundation soils from the site, 13 geotechnical boreholes were made with depths ranging from 45 to 60 m, and five CPTs were conducted with depths ranging from 10.50 to 14.50 m (Fig. 1). For the entire site, 630 linear meters of boreholes and approx. 66 linear meters of CPTs have been carried out.

2.2 Soil investigation

The following physical and mechanical properties of soils were determined (according to Romanian legislation in force) on samples taken from geotechnical boreholes: 237 grain size distributions, 439 moisture contents, 139 plasticity limits, 92 densities of the mineral skeleton, 119 consolidation tests in oedometer, 140 direct shear

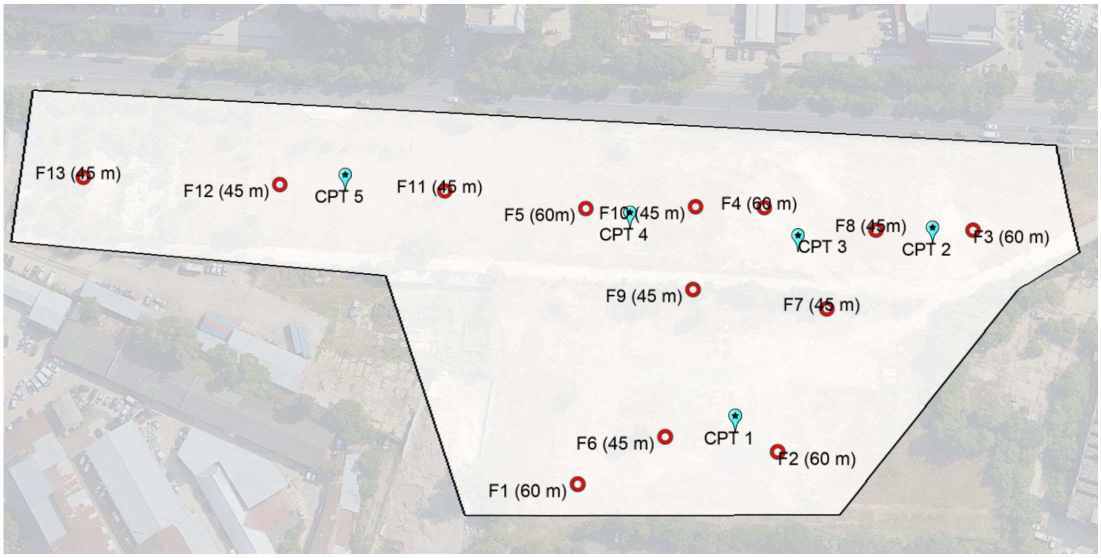


Figure 1: The studied site and the positions of the geotechnical investigations (source: Google Earth).

tests (consolidated-drained [CD] and consolidated-undrained [CU] types). From the mechanical tests, a total of 253 derived values were obtained for the following parameters: density, dry density, porosity, void ratio, and saturation degree. Based on SPT, 91 values were obtained for characterizing the soils according to their consistency state.

2.3 The establishment of the geotechnical layers

Spatial variation graphs of geotechnical parameters provide an approximate image of the stratification of the investigated site. The final stratification is determined only after analyzing the values obtained from laboratory tests and after the determination of the characteristic values according to NP 122-2010 [8]. According to NP 122-2010, the division into geological layers is based on natural unit weight (γ, kN/m^3), moisture content (w, %), consistency index (I_C, -), porosity index (n, %), degree of compaction (I_D, %), and plasticity index (I_P, %). For these parameters, variation coefficients (V_x) are calculated, which must not exceed the values presented in Table 1. *In situ* and laboratory tests provide measured values of the geotechnical parameters; however, these values cannot be directly used in geotechnical design [9]. Characteristic values are mandatory in geotechnical design, and they are calculated using mathematical statistical methods to ensure a 95% confidence level.

The calculation of variation coefficient [8]:

$$V_x = \frac{s_x}{X_m} = \frac{\sqrt{\frac{1}{n-1} \times \sum (X_i - X_m)^2}}{\frac{\sum X_i}{n}} \tag{1}$$

where s_x is the standard deviation of the X_i values, X_i is the measured or derived value resulting from laboratory or onsite test, X_m is the arithmetic mean of the X_i values, and n is the number of X_i values.

It should be noted that this division into layers is based on mathematical statistics, which must be complemented by an appropriate engineering judgment. The coefficient of variation is influenced by both the dispersion of the values and their number. For a large number of laboratory determinations, the dispersion of values can be very large and, nevertheless, the coefficient of variation falls within acceptable limits for the delimitation of a geotechnical layer [10]. Situations may result where, for example, the state of consistency varies from soft to stiff and yet the samples are considered to be part of the same layer.

Table 2 presents a theoretical situation in which the measured values of the consistency index are uniformly distributed in a range of values for which the coefficient of variation is the one recommended for the delimitation of a geotechnical layer, respectively, V_{xmax} = 0.15. The mean of the firm domain (I_c = 0.625) was chosen as the reference value. It is found that for a small number of determinations (n = 3), they remain in the firm domain, but the lower characteristic value classifies the soil as soft and the upper one as stiff. For 11 determinations uniformly distributed in a range of values that give V_x = 0.15, the

Table 1: Recommended maximum values of the coefficient of variation (Vxmax) for the division into geological layers [8].

Geotechnical parameter	$V_{x\,max}$
Unit weight, γ (kN/m³)	0.05
Moisture content, w (%) Consistency index, I_c Porosity index, e Degree of compaction, I_D (%)	0.15
Plasticity index, I_P (%)	0.30

Table 2: Example of uniform distribution of measured values confirmed as being part of the same geotechnical layer.

Measured values of consistency index, I_c (-)					0.484
				0.488	0.512
			0.495	0.522	0.540
		0.507	0.538	0.557	0.568
	0.531	0.566	0.582	0.591	0.597
	0.625	0.625	0.625	0.625	0.625
	0.719	0.684	0.668	0.659	0.653
		0.743	0.712	0.693	0.682
			0.755	0.728	0.710
				0.762	0.738
					0.766
Minimum values, X_{min}	0.531	0.507	0.495	0.488	0.484
Maximum values, X_{max}	0.719	0.743	0.755	0.762	0.766
Average values, X_m	0.625	0.625	0.625	0.625	0.625
Number of selected values, n	3	5	7	9	11
Standard deviation, s_x	0.094	0.094	0.094	0.094	0.094
Coefficient of variation, V_x	0.15	0.15	0.15	0.15	0.15
k_n for $V_{x\,unknown}$	1.69	0.96	0.73	0.61	0.54
$X_{k\,sup} = X_m(1 + k_n V_{x\,unknown})$	**0.78**	**0.71**	**0.69**	**0.68**	**0.68**
$X_{k\,inf} = X_m(1 - k_n V_{x\,unknown})$	**0.47**	**0.54**	**0.56**	**0.57**	**0.57**

layer covers values that classify it from soft to stiff, but the characteristic values are in the firm domain.

It should be mentioned that the consistency index is a physical parameter that classifies the soil as good ($I_c > 0.75$), average ($0.5 < I_c < 0.75$), or difficult ($I_c < 0.5$) foundation soil, which has an important impact in detailing the geotechnical investigation and design, according to NP 074-2022 [9].

From the previously presented statistical simulation, it appears that an engineering judgment is required related to the implications of the classification of geotechnical layers in a certain category.

2.4 SURFER software

SURFER is a software program developed by Golden software that specializes in the visualization and analysis of geospatial data. It is commonly used for creating contour maps, 3D surfaces plots, terrain models, and other visual representations of spatial data [11].

The user-friendly interface and diverse functionality make SURFER a popular choice for professionals working with geospatial information. Some of its features and functionalities are: interpolation and extrapolation, 3D visualization, data analysis and manipulation, data import and export, customization, and reporting.

2.5 Spatial interpolation – Kriging method

Kriging represents a geostatistical interpolation technique whereby nearby data points are weighted based on their distance from the interpolation location and the level of autocorrelation or spatial arrangement observed for those distances. Optimal weights are computed at each sampling distance to derive the interpolated values. This method was used to realize the spatial (2D) variation of the geotechnical parameters with depth.

Physical measurements can sometimes be inaccurate due to uncertainties inherent in the process, which can compromise the validity of the resulting interpolation. The larger the study area and the greater the amount of data available, the more reliable the variogram tends to be. Conversely, the accuracy of local analysis decreases when the amount of data is limited. The general equation of Kriging is as follows [12]:

$$Z(s) = \mu(s) + \varepsilon'(s) \qquad (2)$$

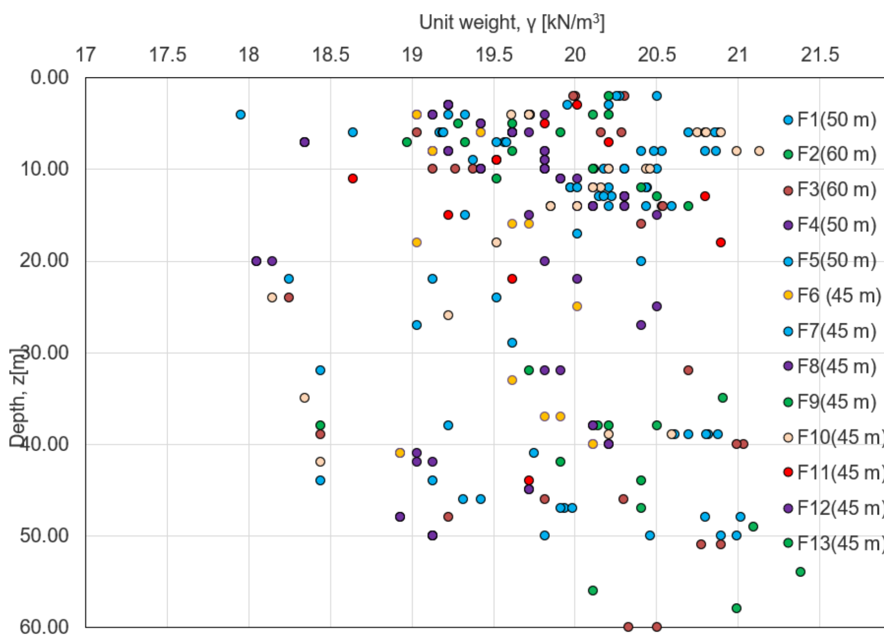
where: $Z(s)$ is the variable of interest, decomposed into a deterministic trend $\mu(s)$ and a random, autocorrelated $\varepsilon'(s)$. The symbol simply indicates the location (containing x and y coordinates).

3 Results and discussion

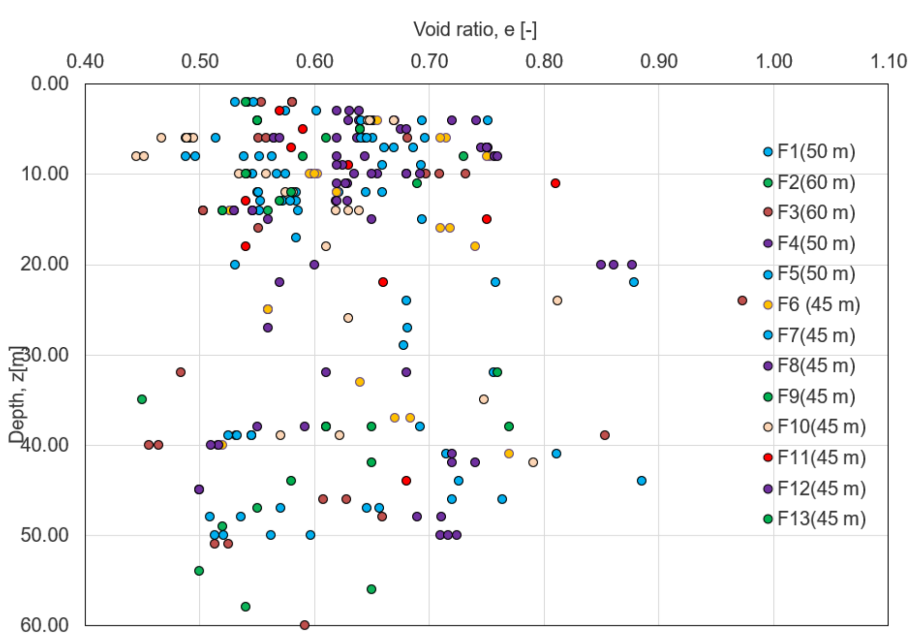
3.1 The variation of parameters with depth

The graphs that are presented below, in which the spatial distribution of the different geotechnical parameters is presented, are not used to identify a certain value of a parameter in the foundation soil, but only to visualize the stratification of the foundation soil. The geotechnical parameters that describe each of the geotechnical layers will be established by statistical analysis, according to NP 122-2010 [8] and Eurocode 7 [13, 14].

To identify the stratification of the foundation soil, variation graphs of the main geotechnical parameters

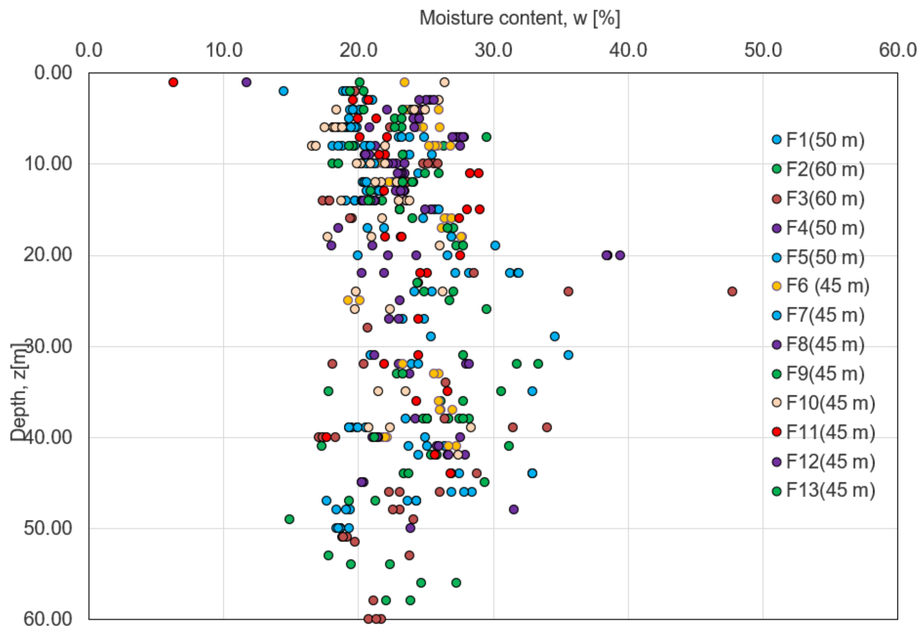


a) unit weight, γ (kN/m³)

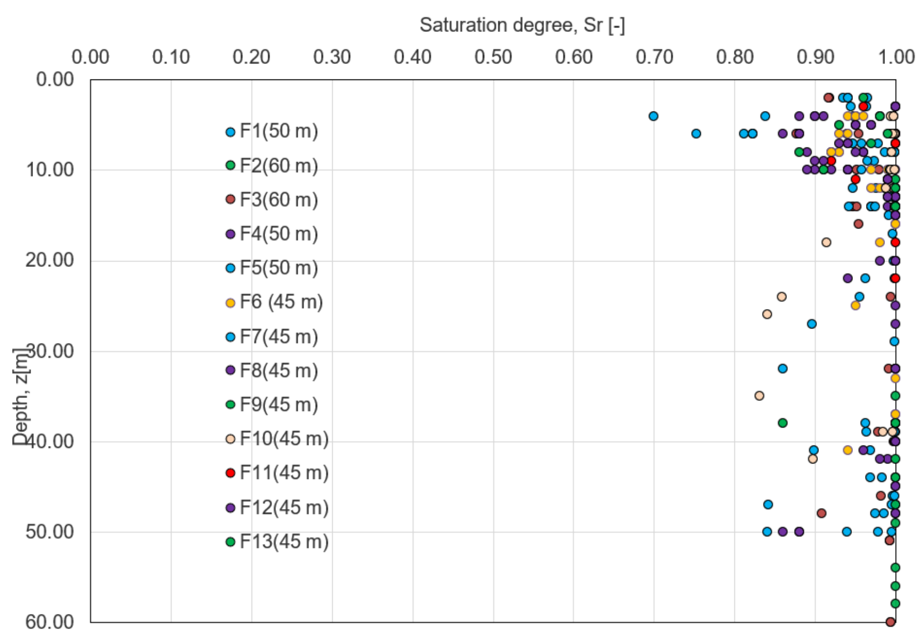


b) void ratio, e (-)

Figure 2: Variation of physical parameters with depth.



a) moisture content, w (%)



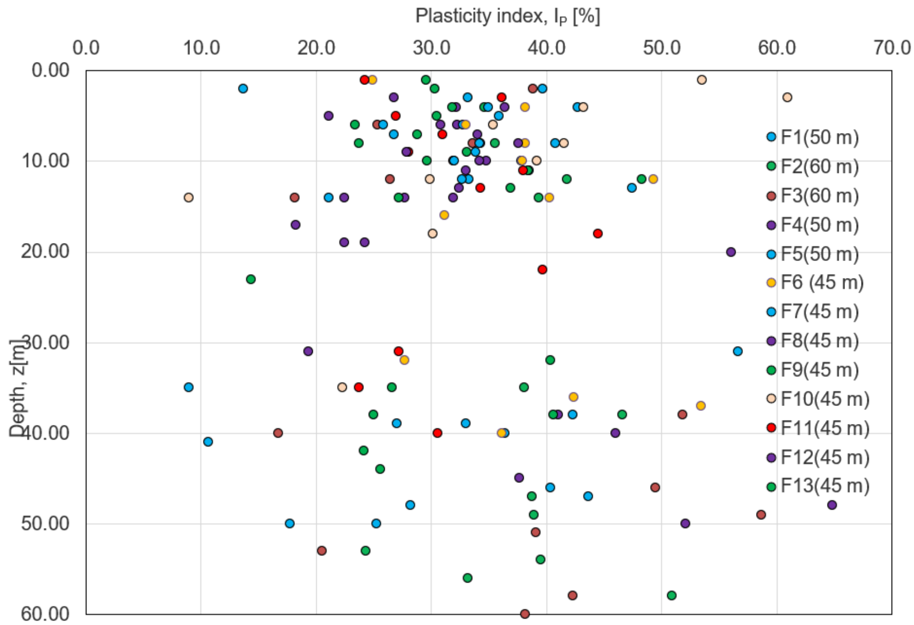
b) degree of saturation, Sr (-)

Figure 3: Variation of physical geotechnical parameters with depth.

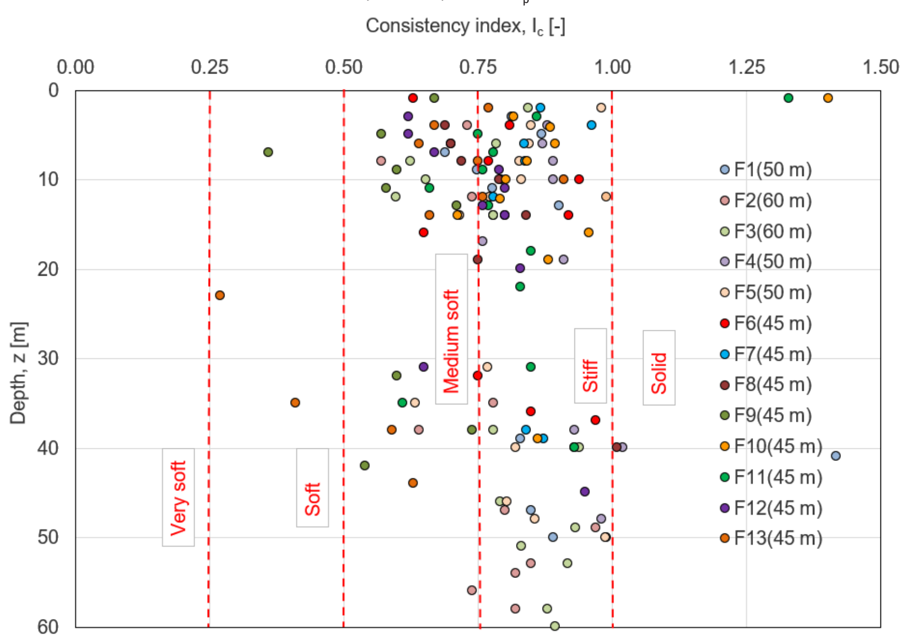
with depth are used; these graphs are based on the values measured in laboratory tests. The analyzed parameters are as follows:

– the parameters indicated by NP 122-2010 as mandatory to identify a geotechnical layer, respectively: unit weight, moisture content, consistency index, void ratio, plasticity index (Figs 2–4) and
– other significant parameters in description of the foundation soil: oedometric modulus, cohesion, and internal friction angle (Figs 5 and 6).

As for the bulk unit weight in natural state, it can be found that it varies in a very wide range, which leads to the idea that the soil has, both horizontally and vertically, large variations in moisture content and porosity. There is



a) plasticity index, I_p (%)



b) consistency index, I_c (-)

Figure 4: Variation of physical geotechnical parameters with depth.

some uniformity in terms of the degree of saturation that defines most of the foundation soil as being in a saturated state, but locally, there are also soils classified as being wet, not saturated.

As for the plasticity of the soils, it also varies in a very wide range. The state of consistency is firm to stiff. Even these variations do not provide a vision of the layering of the foundation soil. Because the laboratory tests were programmed uniformly throughout the depth of the boreholes and in sufficient number, which respects the minimum number of samples imposed by NP 074-2022 [9], in these graphs it can be seen that in the depth range of 20–30 m, there are very few determinations of these parameters specific to cohesive soils. This observation indicates that noncohesive soils are intercepted in this depth range in all boreholes.

The values of the oedometric deformation modulus between 200 and 300 kPa classify the soil, according to

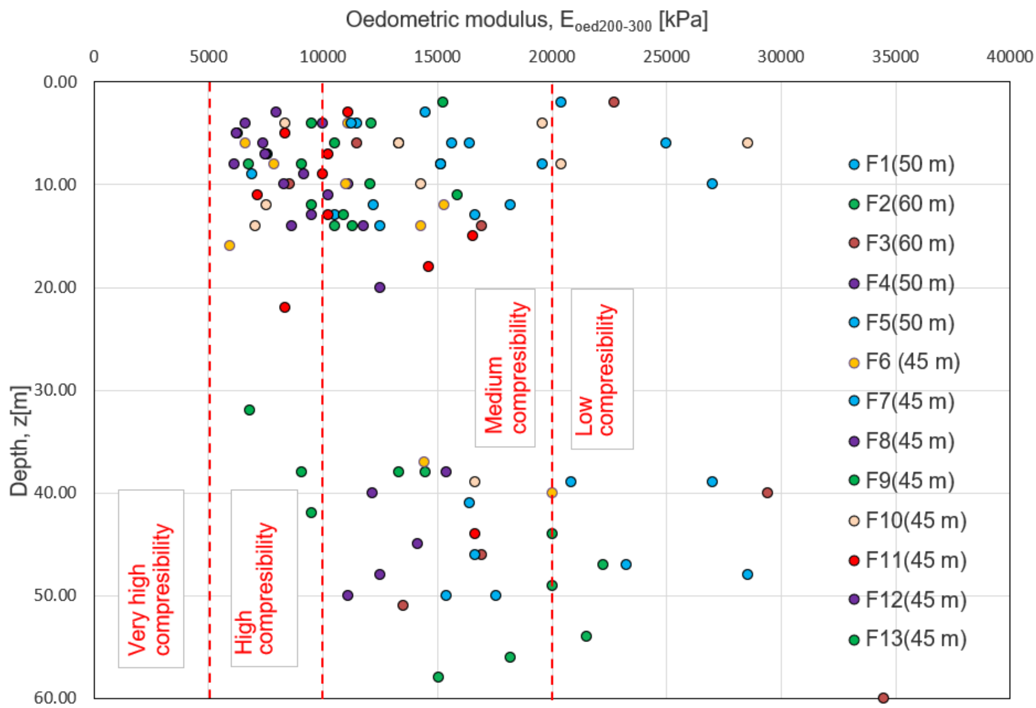


Figure 5: Variation of oedometric modulus, $E_{oed200-300}$ (kPa), with depth.

a classification that was only found in STAS 1243-88 and which has been cancelled, as high, medium, and low compressibility [15].

In a horizontally homogeneous foundation soil, vertical variations of the various parameters presented in Figs 2–6 could be observed and the division into geotechnical layers is visible.

In this particular case, based on the graphs in Figs 2–6, the layers constituting the foundation soil cannot be identified. For this reason, spatial distribution of geotechnical parameters in 2D graphs were generated for three profiles, but only the results from Profile 1 are presented. The variation graphs were generated using the Kriging method in SURFER software. This representation was chosen to facilitate the work of the geotechnical engineer in stratifying the foundation soil.

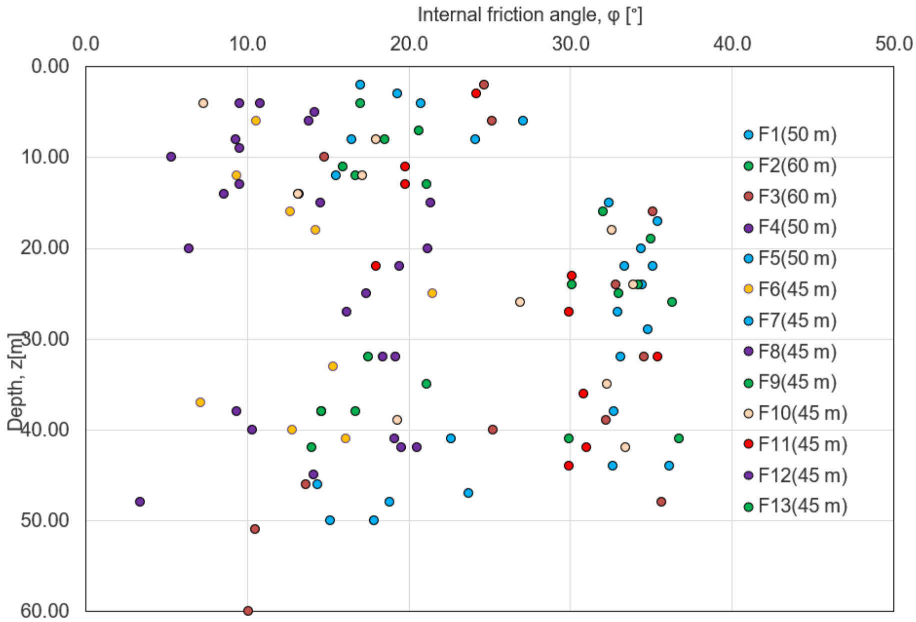
3.2 Spatial (2D) variation of parameters versus depth

In Figs 2–6, the 2D spatial distribution graphs of the main geotechnical parameters are presented.

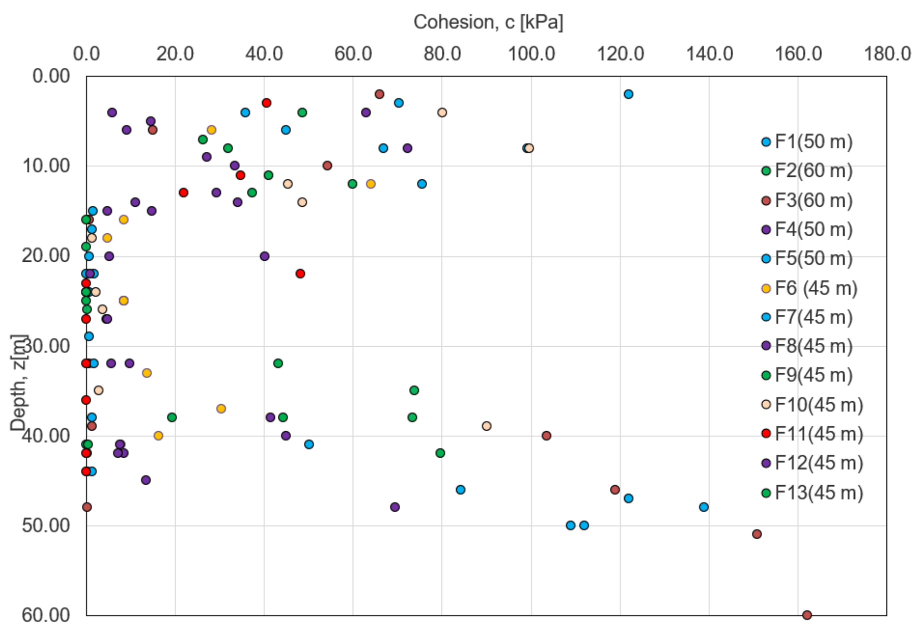
From Fig. 7 to Fig. 10, it can be observed that the foundation soil consists of a succession of cohesive and noncohesive layers as follows: a cohesive layer up to approximately 15.00 m, a noncohesive layer up to approximately 35.00 m, and a cohesive layer followed by another noncohesive layer to the bottom of the boreholes. This stratification is confirmed particularly in Fig. 9c, where the sand layer is clearly defined between 15 and 30 m depth. At the same depth, the noncohesive layer is characterized by the highest values of the internal friction angle, as confirmed in Fig. 10. Based on moisture content variation, it is confirmed that the groundwater table is encountered in the noncohesive layer.

From the compressibility point of view, zones with high compressibility have been identified at the surface (up to 10 m depth) near boreholes F12 and F8, while at the same depth, in the area with boreholes F5, F10, and F4, soils with medium to low compressibility are encountered (Fig. 10a). This indicates that, in the hypothesis of direct foundation, the constructions in the area with boreholes F12 and F8 can develop differential settlements. The areas defined as having high compressibility correspond to the areas with the lowest unit weight in natural state, as shown in Fig. 7a.

The variation of the physical and mechanical parameters creates a clear picture regarding the vertical and horizontal distribution. On the one hand, areas where the parameters fall within certain domains can be identified at a general level and on the other hand,



a) internal friction angle, Φ (°)



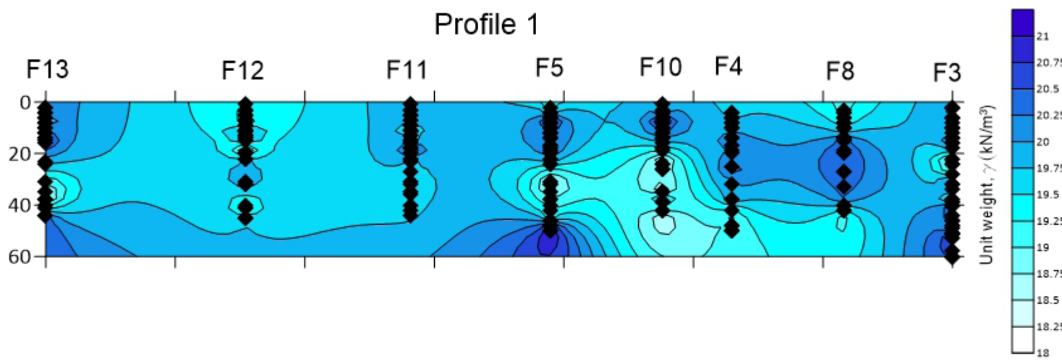
b) cohesion, c (kPa)

Figure 6: Variation of shear strength parameters with depth.

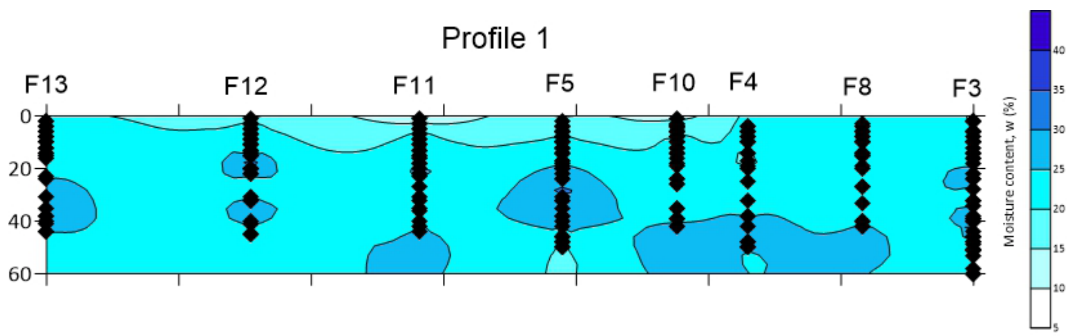
at local level, areas of geological accidents or change in stratigraphy, where the parameters are significantly different, are clearly visible.

Based on the analysis of spatial variation graphs in SURFER, the measured values from laboratory tests, and the characteristic values required for design, the following stratification has been obtained (Fig. 11):

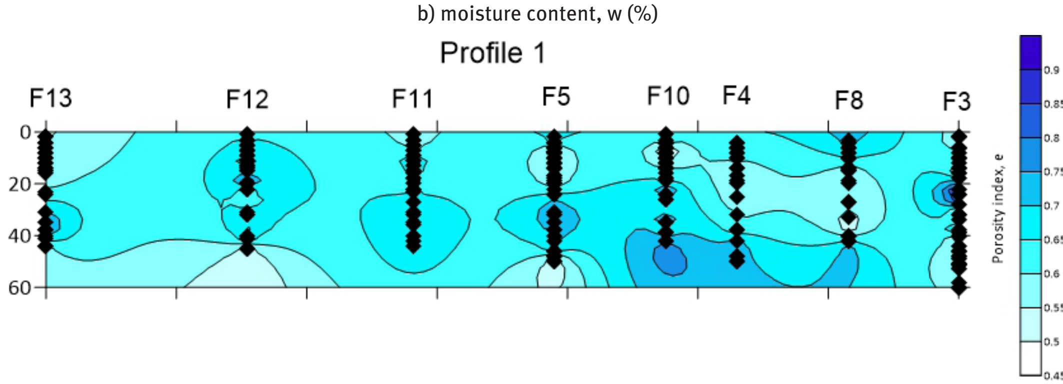
- *Heterogeneous anthropogenic fill* from the ground level to a depth of 0.40–3.90 m – identified as a difficult foundation soil; this layer should be removed when the construction begins;
- *Layer 1 – cohesive soil*: clay – silty clay – sandy clay until a depth of 12.80–16.00 m – identified as a medium foundation soil;
- *Layer 2 – noncohesive soil*: sand – sand with gravel – silty sand – clayey sand until a depth of 30.70–38.40 m;
- *Layer 3 – cohesive soil*: clay – fat clay – silty clay until a depth of 32.90–41.60 m;



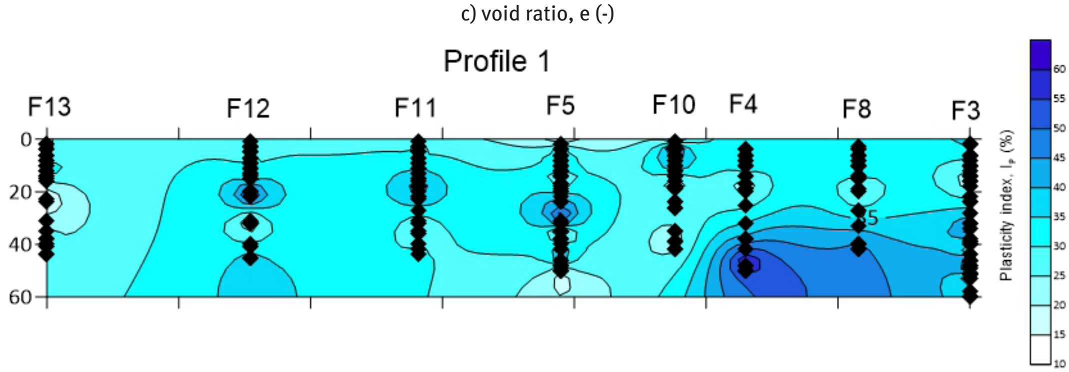
a) unit weight of soil in natural state, γ (kN/m³)



b) moisture content, w (%)



c) void ratio, e (-)



d) plasticity index, I_p (%)

Figure 7: Spatial (2D) variation of physical geotechnical parameters with depth.

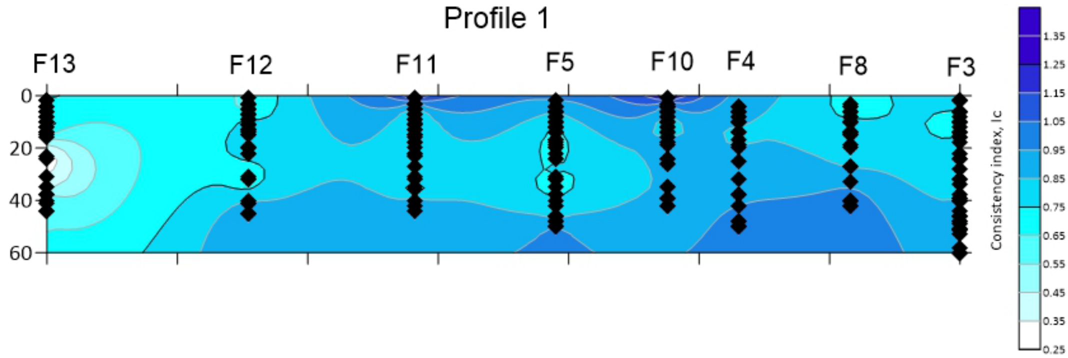


Figure 8: Spatial (2D) variation of consistency index (I_C, -) with depth.

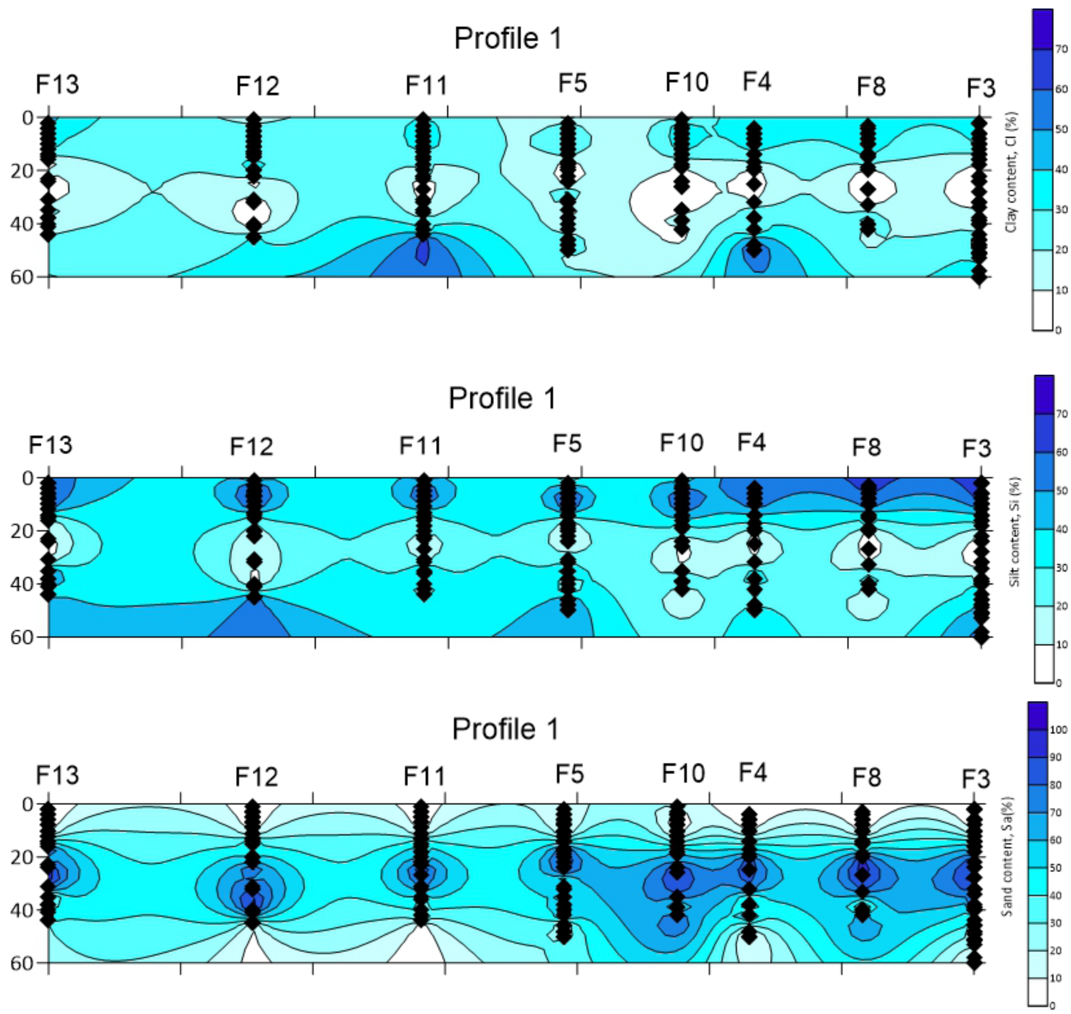
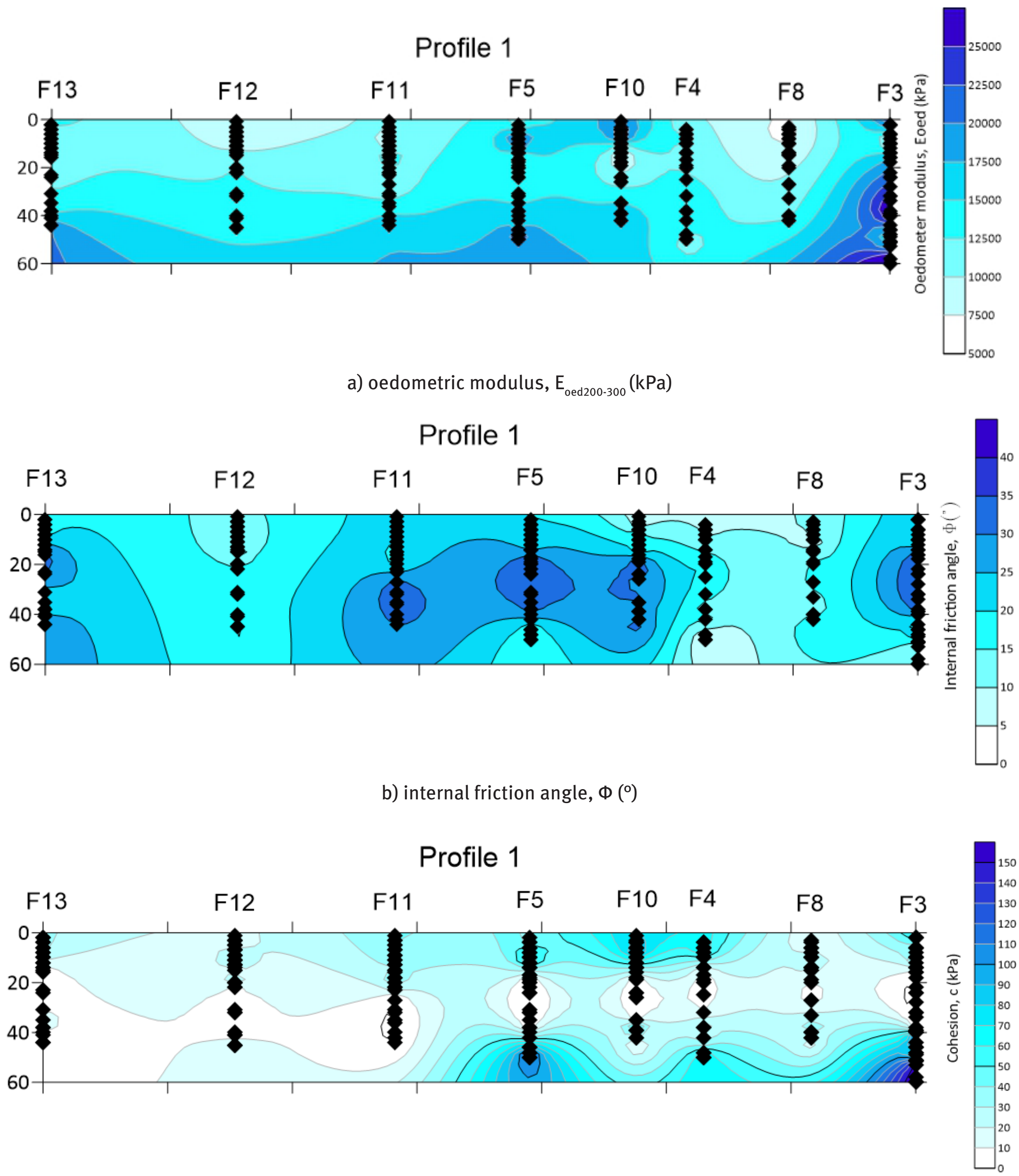


Figure 9: Spatial (2D) variation of percentage of clay (top), silt (middle), and sand (bottom) with depth.



a) oedometric modulus, $E_{oed200\text{-}300}$ (kPa)

b) internal friction angle, Φ (°)

c) cohesion, c (kPa)

Figure 10: Spatial (2D) variation of mechanical parameters with depth.

– *Layer 4 – noncohesive soil*: sand – silty sand – clayey sand until a depth of 43.20–47.00 m; and
– *Layer 5 – cohesive soil*: clay – silty clay – sandy clay until the toe of the boreholes (45.00–60.00 m).

The groundwater table was intercepted in *Layer 2 – noncohesive soil* in the form of a pressurized aquifer; at depths of 14.30–19.50 m, it was observed to have an ascending character, stabilizing at 12.10–12.70 m.

4 Conclusions

The spatial representation of physical and mechanical soil parameters was not used to obtain an extrapolated value of a parameter but to give an indication of the division into geotechnical calculation layers.

The ground model is the most important element provided by the geotechnical investigation report (geotechnical study). It must indicate the stratification of the foundation soil and characteristic values or domains

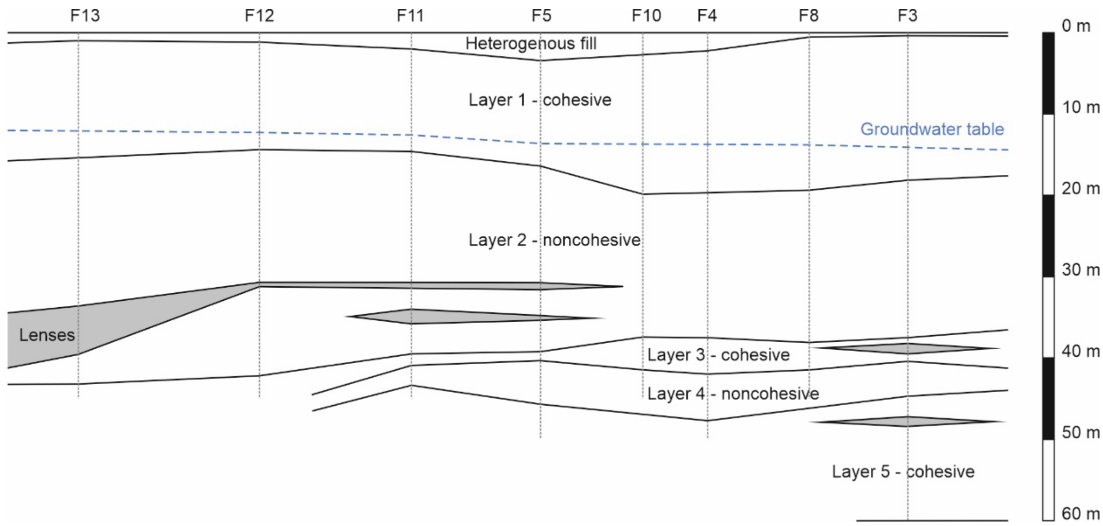


Figure 11: Geotechnical cross section.

of variation for measured and derived values of the geotechnical parameters. If there is no clear picture of the distribution of these parameters, in the event that they are assimilated to the same layer, although they come from different layers, the errors can be significant.

The 2D spatial distribution maps of geotechnical parameters, developed in this paper, demonstrated that soil properties that resulted from the laboratory tests combined with spatial distribution using software that allows the spatial distribution of the parameters are adequate to create a more accurately terrain model which can be used in geotechnical studies. In addition, this graphical method will serve as a supplement for site characterization and identification of the foundation soils for future projects.

The spatial distribution of geotechnical parameters can be applied in the case of sites with onsite tests and laboratory investigations, where more than two boreholes exist.

From this case study, it can be concluded that geostatistical techniques provide good-quality spatial distribution mapping of geotechnical parameters which are necessary in the geotechnical investigations of large infrastructure projects such as large residential complexes, highways, national roads, railways, mining fields, and quarries.

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