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Site characterization for a study on shallow geothermal energy exploitation in Southern Brazil

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Article

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Abstract

The energy crisis scenario currently going on in Brazil, along with the need to reduce greenhouse emissions, lead to an urgent need to design buildings with greater energy efficiency. Shallow geothermal energy surges as a sustainable alternative to reduce the electricity consumption in buildings related to air conditioning and water heating systems. In Brazil, the use of this technique is still incipient due to the lack of studies that demonstrate its viability in the country's climatic conditions, as well as underground temperature and demand for acclimatization of buildings. The aim of the current work is to present a site characterization for the first geothermal energy investigation carried out in the Brazilian South region. This study is being conducted at the Geotechnical Experimental Site of the State University of Ponta Grossa, and this paper describes the physical, mineralogical, thermal and mechanical characteristics of this site, which comprises a thick layer of a lateritic sandy clay soil over a silty sand layer. The preliminary results of the ground temperatures are consistent with the common trends reported in the literature, showing more expressive oscillations near the ground surface, and becoming approximately constant at higher depths.

1. Introduction

The effects associated with climate change, such as the increase in global temperature and extreme weather events, have been worsened due to greenhouse gas emissions in the atmosphere. Among the international measures adopted to mitigate the effects of anthropically caused climate change is the Paris Agreement, signed in 2015 by Brazil and 194 other countries, aiming to contain the increase in global temperature associated with the emission of greenhouse gases by 1.5 °C (Sani et al., 2019). However, according to data from the Electric Energy Statistical Yearbook (Brasil, 2020a), in 2019 there was a 6.8% increase in greenhouse gas emissions from electricity generation in Brazil. Total greenhouse gas emissions in the National Interconnected System (SIN) increased by 3% between 2018 and 2019, with highlights being natural gas (+9.6%) and coal (+9.2%). Nevertheless, the most significant contribution was from the Isolated System, whose increase in 2019 was 134.4% over the previous year, due to the growth of diesel generation (+72.9%) and the decisive entry of natural gas thermoelectric plants (+4,066.7%). This reality reinforces the need to reduce the global demand for fossil fuels, prioritizing renewable energy sources.

Regarding consumption, there has been a significant increase in global energy demand, driven by world population growth and the search for a better quality of life. According to Loveridge et al. (2020), the annual *per capita* energy consumption grew exponentially in the last century due to population growth. The growing demand must be absorbed by increasing the energy supply, increasing the existing installed capacity, and seeking previously unexplored sources with low greenhouse gas emissions. In Brazil, the building sector accounts for half of the country's total electricity consumption. Energy consumption with air conditioning systems is around 30% (Brasil, 2018). The Energy Research Company (EPE) projections point to significant growth in total energy consumption, with a considerable growth rate in air conditioners, which will practically double in fifteen years.

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Given the data presented above, there is an imminent need to design more sustainable buildings that seek more significant energy efficiency. In this context, shallow geothermal energy is an alternative for reducing electric energy consumption for the air conditioning of buildings. Besides being clean and renewable energy, its use system can be installed in the foundations of a building, using structures already foreseen in the project to exchange heat with the ground. Lee et al. (2007) also state that geothermal energy is available continuously, regardless of weather conditions and in any part of the Earth, which is advantageous compared to other renewable energy sources, such as solar and wind.

Amatya et al. (2012) comment that geothermal source heat pump (GSHP) has emerged as a promising technology for heating and cooling of buildings. In these systems, fluid is circulated between the heat pump and heat exchanger elements in the ground; with the cooler fluid being circulated to extract energy from the warmer ground for heating (winter) and the warmer fluid transferring heat from the building to the ground to provide cooling (summer). By incorporating the heat exchanger system between the building and the ground in the foundation elements, the advantage is that concrete is a suitable heat conduction medium, considering its thermal conductivity and thermal storage capacity.

The use of shallow geothermal energy is still developing in Brazil. However, the National Energy Plan (Brasil, 2020b) mentions the use of shallow geothermal energy as one of the disruptive technologies that can significantly change the energy market, highlighting China, the United States and Europe as leaders in these developments. The document points out that using this technology can reduce the final energy consumption for thermal energy production, above 60% for heating and between 20% and 60% for cooling, which may lead to a decrease in electricity consumption at peak hours. Finally, the Plan highlights that the technology is already viable in some international markets, based on concepts of energy efficiency, which may represent an opportunity for Brazil, that needs to expand the studies on this topic.

The first experimental study on shallow geothermal energy using the pile foundation as a ground heat exchanger in Brazil were carried out at the Experimental Site at São Carlos School of Engineering of University of São Paulo (EESC/USP), in the Southeast region of the country, in which Morais (2019) evaluated the use this technology in unsaturated sandy soil with an average ground temperature of approximately 24 °C. Additionally, the first Brazilian building that will use heat exchanger piles for space cooling is being built at the USP campus in São Paulo city.

To expand the development and utilization of shallow geothermal energy in Brazil, it is essential to carried out experimental studies in different Brazilian regions and climatic conditions. To investigate the potential of the use of this technology for a given region, it is necessary to determine the local ground thermal and geotechnical characteristics. In this context, this work aims to present the initial site characterization of an Experimental Site in the Southern region of Brazil, at the campus of the State University of Ponta Grossa, Paraná state, where the mean annual air temperature is below 20 °C.

2. Shallow geothermal energy

Geothermal energy can be defined, according to Laloui & Loria (2020), as the natural thermal energy or natural heat that exists inside the Earth, resulting from three processes: the formation of the planet, the radioactive decomposition of minerals and solar energy absorbed on the surface. The Earth is divided into the crust, mantle (upper and lower) and core (outer and inner). The average geothermal gradient is approximately 3 °C for every 100 meters depth to the upper mantle and may vary between 1 °C and 10 °C. According to the authors, the temperature variation in the Earth's most superficial layers, between 4 and 6 meters, presents a significant sensitivity to atmospheric conditions, being strongly influenced by daily and seasonal temperature fluctuations. Below this region, the temperature remains relatively stable throughout the year, between 10 °C and 25 °C depending on the region and is approximately equal to the mean annual outside air temperature, according to the typical behavior illustrated in Figure 1 for different seasons of the year. As mentioned in Narsilio et al. (2014), for most locations around the world, the soil tends to be warmer than the atmosphere during winter and cooler during summer, regardless of geology.

In order to use the heat from the ground, there are different types of geothermal systems, classified according to

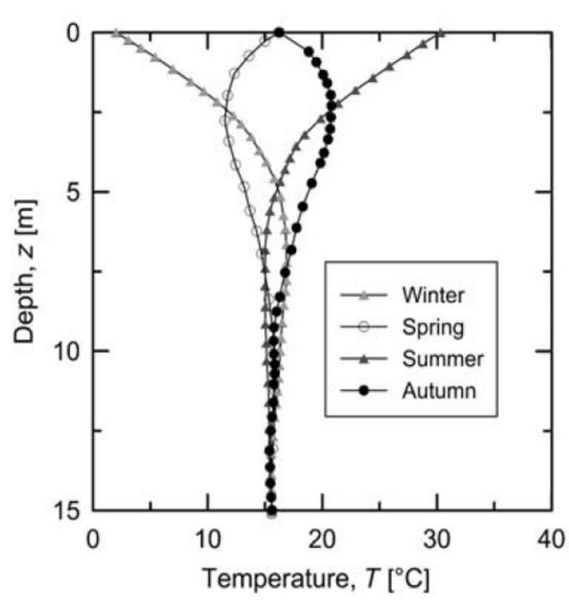

Figure 1. Typical temperature evolution with depth in the shallow subsurface throughout the year (Laloui & Loria, 2020).

the depth at which thermal energy is exploited. Geothermal systems with fewer than 400 meters are classified as shallow and work with low temperature and low enthalpy. Greater depths characterize deep geothermal systems with medium and high temperatures and enthalpies (Laloui & Loria, 2020).

Shallow geothermal systems can be used to provide space heating and cooling and water heating, using underground temperatures of up to 25 °C. These systems are suitable for domestic and small-scale use and can be used in almost all geographical locations. Deep geothermal systems can provide space and water heating using underground temperatures from 25 °C up to 200 °C, and electricity at temperatures above 175 °C. These systems are suitable for medium to large-scale use, requiring more specific deployment conditions than shallow systems (Narsilio et al., 2014).

Shallow geothermal systems are composed of three main components: a heat source, a heat sink and a heat exchanger (Sani et al., 2019). In winter, the heat source is the ground, and the heat sink is the built environment. In summer, the heat source is the built environment, and the heat sink is the ground. In both situations, the heat exchanger generally consists of one or more elements containing a fluid that transfers heat between the heat source and the heat sink. Heat exchanger pipes can be installed directly in specific trenches or attached to reinforce structures already planned for the construction, such as deep foundations, slabs, retaining walls and tunnel linings.

Regardless of the geothermal structure used, heat transfer is the physical phenomenon whereby energy is transferred between any two particles of matter at different temperatures. This heat transfer phenomenon can be quantified as a function of the amount of heat energy transferred per unit time. As heat transfer cannot be measured directly, its occurrence can be quantified by employing temperature, which is the variable that governs the heat transfer phenomenon (Laloui & Loria, 2020).

According to Rees et al. (2000), heat transfer in porous media can be induced by several mechanisms. The three most effective mechanisms are conduction, convection and heat transfer due to water phase change, also known as latent heat vaporization. Laloui & Loria (2020) point out that for engineering purposes, latent heat transfer processes are considered negligible. Sani et al. (2019) state that the portion referring to the mechanism of heat transfer by convection is small and that the conduction is the dominant mechanism, which depends on the type of soil, its porosity and moisture content.

A complete geotechnical characterization of the local soil is essential to understand the heat transfer mechanisms for the implementation of shallow geothermal energy utilization. Additionally, for the use of pile foundations as ground-coupled heat exchangers the characterization of the soil mechanical properties is also fundamental for the interpretation of the effect of thermal loads on the foundation mechanical behavior. As this subject has not yet been widely studied in Brazil, new investigations must be carried out at different experimental sites, with an appropriate geotechnical characterization. Furthermore, new studies on the use of shallow geothermal energy in different regions is necessary, considering that the performance of these systems is dependent on the climatic and ground characteristics. In this context, this study is focused on the geotechnical, thermal and mechanical characterization of the soil of a particular site, for future studies on the thermal performance and thermomechanical behaviour of heat exchanger piles.

3. Experimental programme

To characterize the soil of a site located in the Southern Brazil for an investigation on the feasibility of shallow geothermal energy utilization, the chosen location was the Geotechnical Experimental Site (CEEG-PG) of the State University of Ponta Grossa, located in the Ponta Grossa city, Paraná State, Brazil with an area of 11,419 m^2.

Ponta Grossa city is in the Second Plateau of Paraná and is inserted in the Paraná Basin, large sedimentary basin located in the central-eastern of South America. Its area of occurrence encompasses mainly the center-south of Brazil, from the Mato Grosso state to the Rio Grande do Sul state. Away from Brazil, it is also present in northeastern Argentina and the eastern portion of Paraguay. Ponta Grossa city has a certain geological heterogeneity, in its urban area has a prevalence of the Ponta Grossa Formation and the Furnas Formation, both of the Paraná Group of the Devonian period, and the Campo Mourão Formation and the Taciba Formation, both of the Itararé Group of the Permian period.

The Experimental Site is in the Ponta Grossa Formation, mainly composed of clay rocks, called shales, and is close to the Furnas Formation, composed mainly of quartz sandstones. The Itararé Group is represented mainly by sandstones, diamictites and conglomerates. Both groups had their origin in the Paleozoic. Because they are softer, the clay rocks of the Ponta Grossa Formation are crossed in some points by dikes and diabase sills of the Serra Geral Formation of the Mesozoic, also close to the Experimental Site. Based on the geological information of the region, it can be concluded that a large part of the Ponta Grossa city is covered by residual soils from sedimentary rocks, except for the regions with the presence of more mature residual soils from magmatic rocks. There is also the presence of alluvial and colluvial sediments of a more recent age.

Besides knowing the local geology, the knowledge of the local temperature and precipitation variations are also crucial for the use of geothermal energy. Figure 2 presents the monthly average temperature at Ponta Grossa city registered during the last ten years, and indicates a mean temperature of ~18.2 °C. The precipitation data, provided by SIMEPAR (2021) for the same period, indicates 127mm for average monthly precipitation.

The soil characterization of the CEEG-PG was performed using field tests complemented by laboratory tests, for determining physical, mineralogical, mechanical, and thermal characteristics.

Three Standard Penetration Tests (SP01 to SP03) were conducted at this site in October 2018, and their samples were used for characterization tests in laboratory. After analyzing the SPT results, it was realized that the water circulation used during the tests probably influenced the strength results of the local soil; as normally observed for lateritic soils. For this reason, in October 2019, an additional Standard Penetration Test was performed (SP04) without water circulation. The excavation was performed only with an auger until the depth of 5m, when it was no longer possible to advance without the addition of water. The samples from this borehole were stored for X-Ray diffraction tests, scanning electron microscopy, and disk method for tropical soil classification. The last Standard Penetration Test, SP05, was performed in September 2021 and it had its depth limited to 12.5m so that its borehole could be used for ground temperature measurements. Its samples were used to determine the natural soil moisture content.

Figure 3 illustrates the locations of the SPT tests in the Experimental Site and also indicates-three trenches with 2m deep used to collect disturbed and undisturbed soil samples (TR01 to TR03). These trenches were opened in November

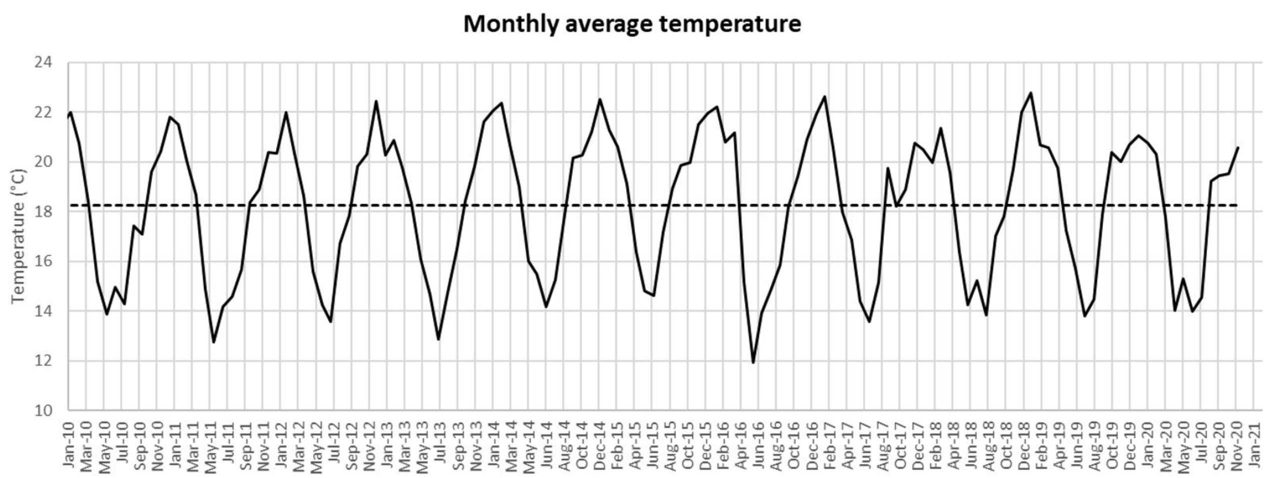

Figure 2. Monthly average temperature of Ponta Grossa city (Data provided by SIMEPAR, 2021).

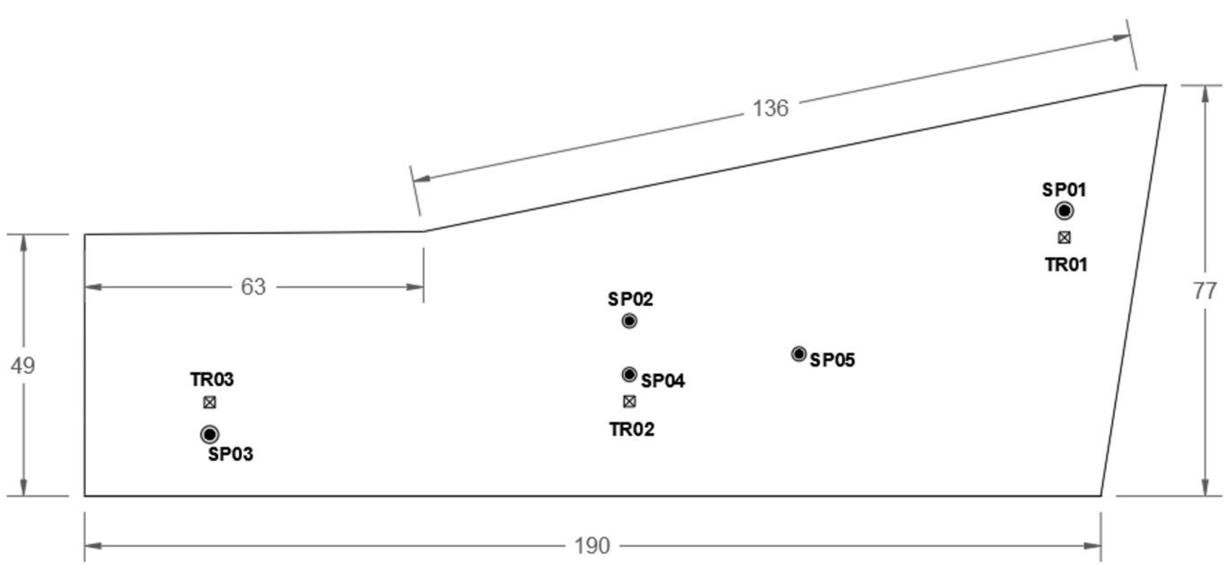

Figure 3. Location of Standard Penetration Tests and Trenches at the CEEG-PG site (distances in meters).

2019, and from each trench, three undisturbed soil blocks were collected. The disturbed soil samples were used for soil type characterization in laboratory and the undisturbed samples were used for obtaining soil strength information from direct shear tests.

From the Standard Penetration Tests, 76 soil samples were obtained at each meter depth, being 17 samples from borehole SP01, 15 samples from borehole SP02, 15 samples from borehole SP03, 17 samples from borehole SP04, and 12 samples from borehole SP05. The samples from boreholes SP01 to SP03 were taken to the Soil and Rock Mechanics Laboratory of UEPG to be tested for particle size analysis, density, liquid limit, and plastic limit. After these tests were performed, the soil was classified by the Unified Classification System (SUCS methodology). The samples from the SP04 borehole were used to perform the disk method to classify tropical soils (MCT methodology). Samples from the same borehole at depths of 3m, 6m, 9m, 12m, and 15m were sent to the Multiuser Laboratory Complex (C-Labmu) of UEPG to perform X-Ray diffraction tests and scanning electron microscopy tests intending to know the mineralogy of the local soil. The samples from borehole SP05, taken above the level where excavation with water circulation began, were immediately taken to the laboratory to determine their natural moisture content.

The undisturbed soil samples taken from the trenches (TR01 to TR03) were taken to the Materials and Structures Laboratory (LAME) of UFPR, kept in a humid chamber until the direct shear tests with flooded and natural moisture condition in samples of 50 × 50 × 20mm. For the tests in natural moisture, the samples were left for 24 hours in the consolidation phase followed by the rupture with a minimum of 200 minutes, the time recommended by ASTM D 3080 (ASTM, 2011) for the type of soil under study. To achieve the time established by the standard, a speed of 0.025 mm/min was used, corresponding to a total displacement of 5 mm, characterizing the rupture of the sample. The stresses defined for performing the two types of tests were 50kPa, 150kPa, and 300kPa. Deformed samples were also taken from each trench and were submitted to particle size analysis, density, liquid limit, and plastic limit in the Soil and Rock Mechanics Laboratory of UEPG.

Table 1 summarizes the number of laboratory tests performed in this research.

Regarding the thermal properties of the soil, the borehole of the test SP05 was used to install a 12m long steel bar with LM35 temperature sensors distributed in 8 different depths to measure the ground temperature variation over time. The LM35 sensor is a semiconductor temperature sensor, which consists of an integrated circuit based on PTAT (proportional to absolute temperature) and provides the temperature measurements as a function of the electrical voltage of the circuit, where 10mV is equivalent to 1 °C. The sensor has three pins, where pin 1 is the power input voltage from 4 to 30V, pin 2 is the data output and pin 3 is the negative (ground).

Table 1. Laboratory tests.

Test	Quantity	Samples
Particle size analysis	49	SP01, SP02 and SP03 TR01, TR02 and TR03
Density	49	
Liquid limit	49	
Plastic limit	49	
Disk method	17	SP04
X-Ray diffraction	5	
Electron microscopy	5	
Natural moisture	8	SP05
Direct shear	18	TR01, TR02 and TR03

Sixteen sensors were fixed to an angle steel bar, with 2 sensors in each depth. The sensor pairs were located at 0.80m; 2.80m; 4.30m; 5.80m; 7.30m; 8.80m; 9.80m and 11.80m from the ground surface. They were fixed by epoxy glue, and they were electrically isolated with 3M ScotchcastMR resin. Figure 4a shows the bar before being inserted into the borehole, divided into 4 segments of 3 meters that were joined by screws at installation, Figure 4b shows the bar being inserted into the hole along with a tube through which the grout injection was made, and Figure 4c shows the readings being performed with a protoboard connected to a 9V battery and the wires connected to each pin of the sensors and a multimeter.

4. Laboratory results

4.1 Physical characterization tests

Figure 5 shows the results of the tests and the classification of the soils by the Unified System for the samples from Standard Penetration Test SP01. Observing the particle size distribution curves, one notices that the clay fraction is predominant from 2 to 11 meters depth, resulting in silty-sand clay soil. The samples at 8 and 9 meters depths have the highest percentages of fine soil. Successively, between 12 and 17 meters, the clay fraction decreases significantly, and the sand and silt fractions increase, characterizing silty-clay sand and followed by clayey-silt sand.

The density values found varied between 2.63 and 2.85 g/cm^3 along the depth. The liquid limit values varied between 31% and 43% up to 14 meters depth, and below that decreased to approximately 25%. As for the plastic limit, up to 15 meters, it was impossible to perform the tests, that characterize non-plastic soil. Below that, the moistures obtained were between 18 and 22%, resulting in low plasticity index (between 3 and 8%). As for the classification by the Unified System, it is observed that up to 12 meters depth, the

(a) (b) (c)

Figure 4. Instrumented bar with LM35 sensors (a) before insertion in the hole; (b) being inserted in the hole; and (c) submitted to temperature reading.

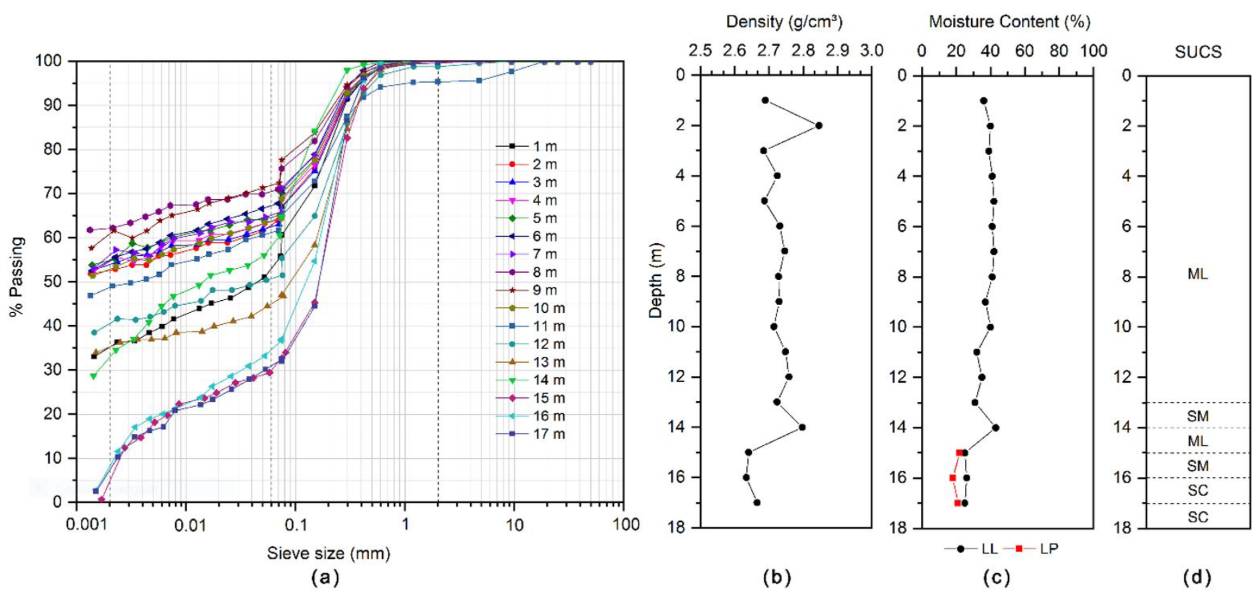

Figure 5. Characterization tests (SP01) - (a) Particle size curves (b) Density (c) Atterberg limits (d) SUCS classification.

soil is classified as silt of low plasticity (ML). In the sequence, from 15 to 17 meters, there is an intercalation between low plasticity silt (ML), silty sand (SM), and clayey sand (SC). For the samples from SP02 and SP03, very similar results were observed in the characterization tests.

The same characterization tests were performed for the deformed samples taken from trenches TR01 to TR03 at a depth of 2m and the three particle size curves obtained are very similar to those obtained for the shallowest samples from the boreholes. As for the density, the average value for the three trenches was 2.68 g/cm^3. For the liquid limit, the average value was 39%, and it was not possible to obtain a plastic limit value. Therefore, as expected, the tests performed with the samples from the trenches and with the samples from the boreholes were very similar.

So concluded that the subsoil of the Experimental Site is composed of a thick layer of predominantly thin, relatively homogeneous soil, around 12 meters. This soil is granulometric classified as silty-sand clay. However, as there is no plasticity when classified by the SUCS methodology, it results in the silt of low plasticity, which may indicate that the behavior of this soil may be more similar to the behavior of a silty soil than clayey soil. Below this thick layer, there is a layer of silty sand.

In order to obtain a classification of the soils more faithful to tropical soils, the MCT methodology, developed by Nogami & Villibor (1981), was applied. This methodology classifies the soils according to their lateritic or non-lateritic behavior. This classification is performed through the execution of mini-MCV and mass loss by immersion tests. However, in 1994, the same authors proposed a method for the expeditious identification of the groups of the MCT classification, known as the Disk Method. This test is performed on cylindrical samples 20mm in diameter and 5mm in height, molded from a paste made of water and the soil fraction passing the 0.42mm sieve (Nogami & Villibor, 1994).

Three cylindrical samples were molded for each of the 17 meters of borehole SP04. First, the diametral contraction of each sample was measured after drying. Then the samples were placed on a saturated porous plate covered with filter paper. After two hours, each sample was penetrated using a standard penetrometer. With the diametral contraction (Ct) and penetration data, the MCT methodology classification chart was used to perform the classification, as illustrated in Figure 6.

It is observed that in the region called LG' (lateritic clayey soils), there is a large concentration of points, which correspond to the soils obtained from the surface up to 11 meters and the 14 meters sample. In this region there is great diametrical contraction and small penetration. At 12 and 15 meters, a decrease in diametrical contraction and a considerable increase in penetration values are observed. The soils of these layers are in the LA'-LG' transition zone (lateritic sandy soils to lateritic clayey soils).

At 13, 16 and 17 meters, diametrical contractions were much smaller in relation to the other layers. At the last two depths the soils showed higher penetration values and were in the transition zone NA'-NS' (non-lateritic sandy soils and non-lateritic silty soils).

It is concluded that the subsoil of the Experimental Site is constituted in almost all the analyzed depth by lateritic soil, the first 12 meters being clay soil and, in the sequence, sandy soil, which confirms the results of the characterization analyses.

As the natural soil moisture significantly affects its thermal conductivity, the samples extracted from Standard Penetration Test SP05 were used to measure the natural soil moisture in depth. However, the excavation process during the drilling required water circulation from 7m, so the natural moistures could only be verified above this depth. There was not much variation in moisture for the depth studied, and the average value was around 36%. This unsaturated soil occurs until a depth of approximately 11m, where the water level is located, and the soil becomes saturated.

4.2 Mineralogical characterization tests

The mineralogical characterization of the CEEG-PG soil was performed through X-Ray diffraction (XRD) and scanning electron microscopy (SEM) at UEPG Multi-users Laboratories Complex (C-Labmu). Five samples, taken from Standard Penetration Test SP04 at depths of 3m, 6m, 9m, 12m, and 15m, were used. In the diffractogram analysis, a remarkable similarity between the results of the 3m, 6m, and 9m samples was noticed and between the 12m and 15m

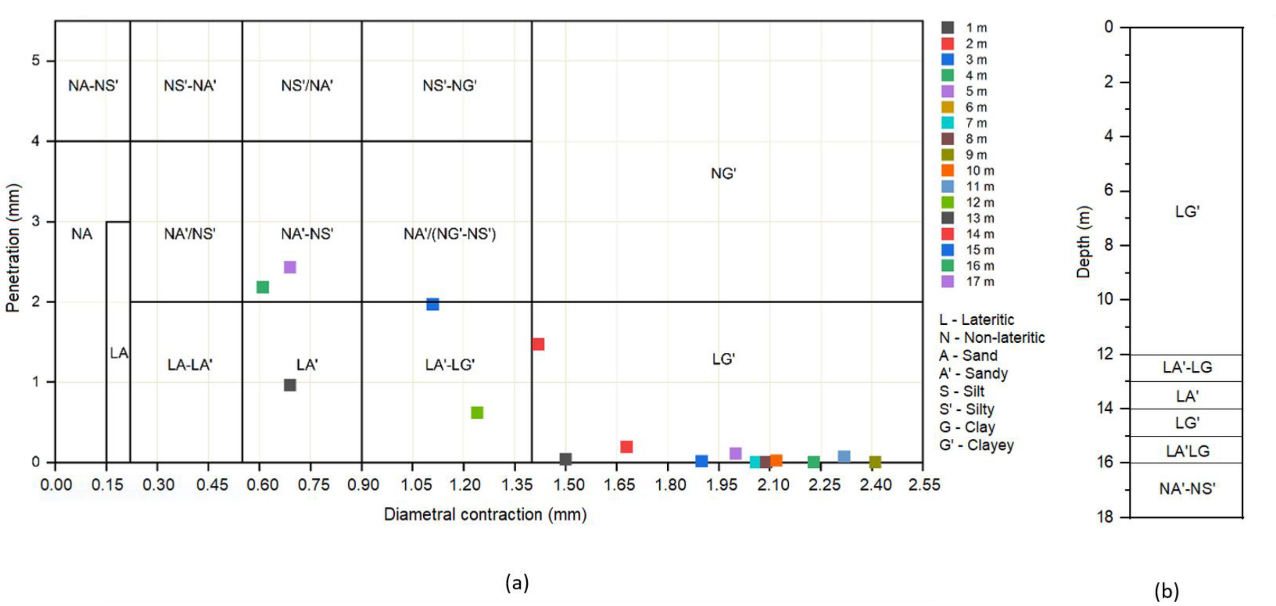

Figure 6. Classification test by Disk Method - (a) Classification chart (b) MCT classification.

samples. This was expected because the Standard Penetration Test and the physical characterizations in the laboratory indicated a thick upper layer of relatively homogeneous clay soil, followed by a layer of sandy soil. Figure 7 shows the XRD diffractograms for the clay soil (3m, 6m, and 9m samples), and Figure 8 shows the diffractograms for the sandy soil (12m and 15m samples).

Analyzing Figure 7, which corresponds to the diffractograms of the clayey soil, it is noted the presence of the quartz mineral, probably resulting from the weathering of the sandstone and mainly responsible for the portion of sand present in large quantities in this material, which makes it a sandy-clay soil as observed in the grain size curves. As for the lateritic nature of the soils, the presence of kaolinite, which is a hydrated

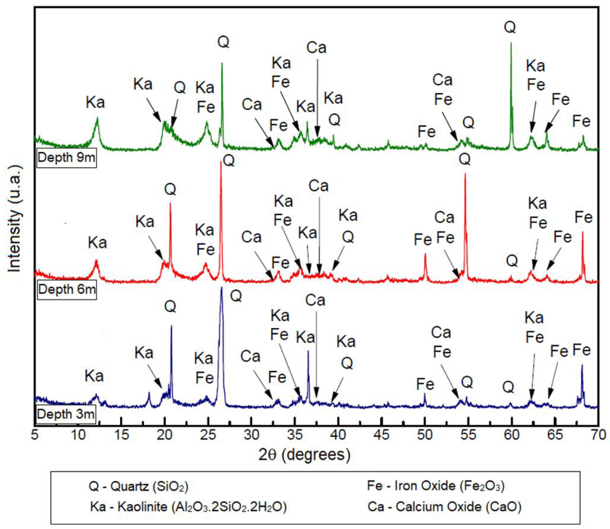

Figure 7. X-Ray diffractograms for the 3m, 6m, and 9m samples.

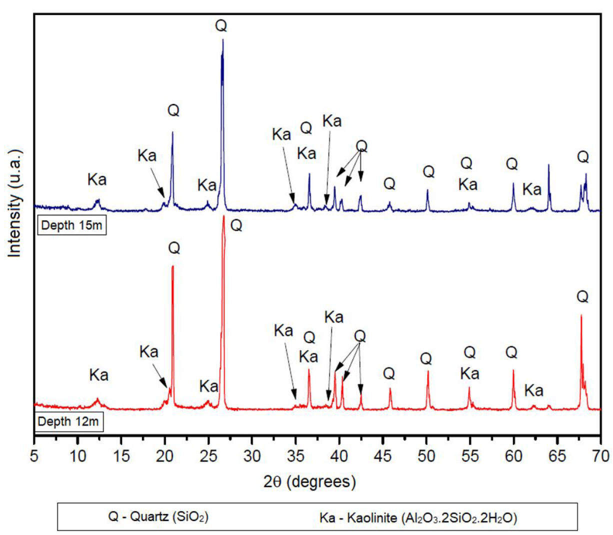

Figure 8. X-Ray diffractograms for the 12m, and 15m samples.

aluminum clay mineral, and iron oxide is observed. These minerals prove the lateritic behavior of the soil because the lateralization process results in the accumulation of large amounts of iron and aluminum oxides in the soil and gives it a reddish color. Another oxide observed was calcium oxide, which may result from the weathering of sandstone, which is a sedimentary rock composed of grains of silica or quartz, linked by siliceous, clay, or limestone cement.

For the sandy soil, with diffractograms shown in Figure 8, quartz and clay mineral kaolinite was also observed, probably quartz appears in greater quantity than in the clayey soil, the other oxides were not identified.

The analysis of these diffractograms reflects the geological origin of the soils in the region because the Experimental Site is located over the Ponta Grossa Formation, which is mainly composed of shales, which are clayey rocks, besides the presence of diabase dikes of the Serra Geral Formation. The topsoil layer in the Experimental Site is characterized as residual soil resulting from the rocks of these formations. Close by and beneath these formations is the Furnas Formation, composed of quartz sandstones, responsible for the presence of quartz in all the samples tested and for the residual origin of the lower sandy soil layer.

In the micrographs obtained for the same samples, a similarity in grain shape is noticed in the samples of 3m, 6m, and 9m. More angular grains are noted in the 15m sample, characteristic of sandy soils but with adhered clay minerals. The 12m sample shows a transition between the grain shapes. Figures 9 and 10 shows the scanning electron microscopy for the 3m and 15m samples.

4.3 Mechanical characterization tests

The trenches were excavated to obtain undisturbed samples at a depth of 2 meters to carry out direct shear tests. As the clay soil layer is relatively homogeneous, it is understood that the results obtained from these tests can be representative of the entire surface layer.

Figure 11 and Figure 12 present the shear strength envelopes obtained in the direct shear tests for trenches TR01 and TR02, respectively, for stresses of 50kPa, 150kPa, and 300kPa. When comparing the results, it can be seen that there is an increase in the shear stress of the natural moisture condition compared to the test with the flooded sample.

Note that for the samples in the natural moisture condition of trench TR01, an internal friction angle (ϕ') of 21.0° and a cohesive intercept (c') of 56.6kPa were obtained. For the saturated samples, the internal friction angle increased to 24.3º, and the cohesive intercept decreased to 16.4kPa.

For the samples in trench TR02, the internal friction angle obtained for the two conditions were very close, being 21.9º for natural moisture and 22.3º for the flooded tests. There was also a significant decrease in the cohesive intercept with increasing saturation, going from 50.8kPa to 19.1kPa.

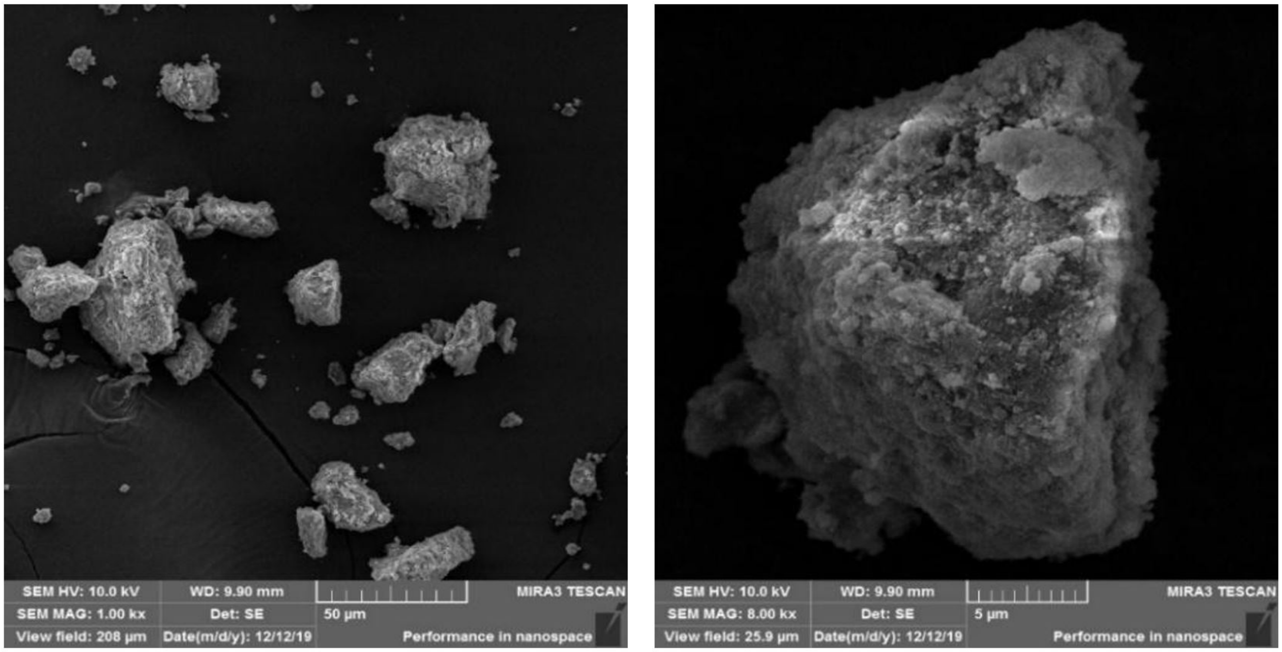

Figure 9. Scanning electron microscopy for the 3m sample.

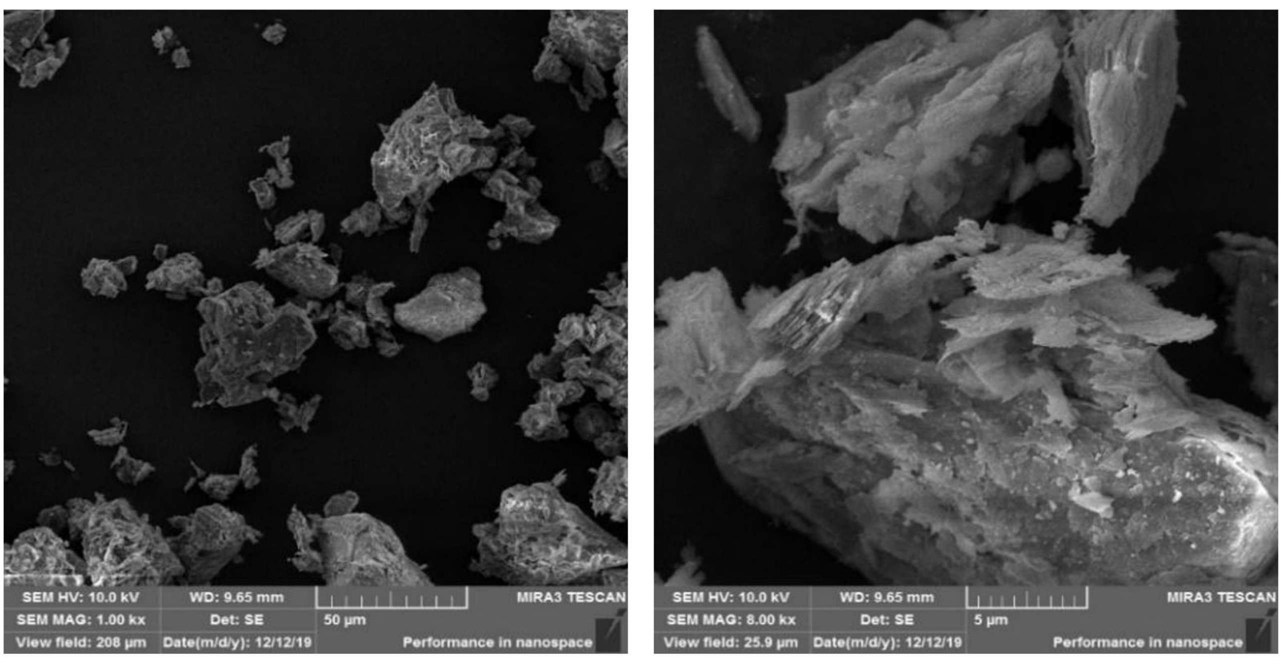

Figure 10. Scanning electron microscopy for the 15m sample.

The moisture variation in the direct shear test showed that the cohesive intercept showed more significant variability than the soil friction angle. As the water table is deep, the high cohesion at natural moisture results from the unsaturated soil suction.

5. Field results

The Standard Penetration Test (SPT) was performed in three separate stages, which totaled 5 tests. Table 2 summarizes the N_{SPT} obtained for each soil layer in the 5 boreholes and

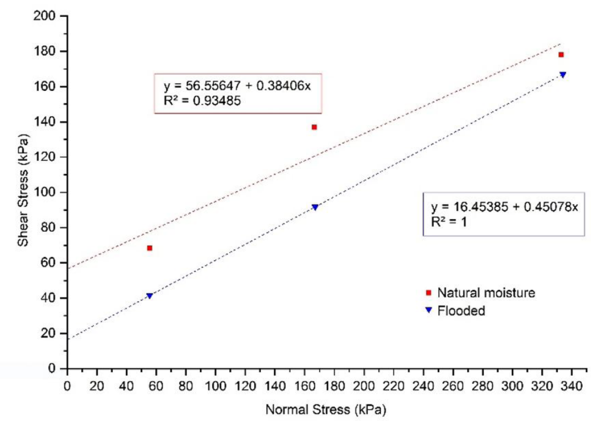

Figure 11. Shear strength envelopes for trench TR01.

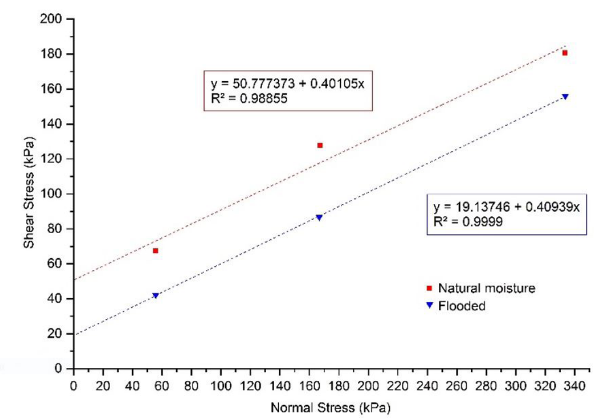

Figure 12. Shear strength envelopes for trench TR02.

presents information on soil type and water level position. It can be seen that all boreholes had a reasonably thick layer, around 12m, of sandy-silt clay with low consistency, followed by a layer of sand with a sudden increase in compactness. The average water level was found at 11.2m from the surface.

The present layer of clayey soil may have a probable residual origin of the Ponta Grossa Formation shale, and the sand may be a residual soil of the Furnas Formation, as the latter dips beneath the Ponta Grossa Formation. Petri (1948) named the interval between these two formations "transition layers" because it is a complicated contact to be observed in mapping since the shales of the Ponta Grossa Formation are little resistant to weathering, not forming relief breaks over the sandstones, besides presenting a relief aspect similar to the soil that occurs over the Furnas Formation.

Regarding the temperature measurements, they are being done using a multimeter and temperature sensors type LM35, which were fixed to a 12m long steel bar and inserted in the borehole SP05. Sixteen sensors were installed along the bar distributed in 8 different levels, 2 sensors at each level. The pair of sensors installed at the greatest depth, 11.80m from the surface, presented a defect, and it was not possible to take any readings. How these sensors were located below the water level, believed that they suffered some damage during installation that compromised the electrical isolation, leaving the sensors short-circuited.

After installing the bar, the readings were measured daily for two weeks, but as the variation in their value was small, the readings started to be taken every other day. The installation of the temperature sensors was done close to the writing of this article, so the history of readings collected is not yet significant for the analysis of temperature variation over time. However, Figure 13 shows the readings already

Table 2. Standard Penetration Test (SPT).

Dep. (m)	N_{SPT}					Soil
	SP01	SP02	SP03	SP04	SP05	
1	2/48	2/42	3	4	3	
2	2	2	6	5	6	
3	2	2/45	2	3	8	
4	2	2	3	4	6	
5	2	2	3	8	9	
6	4	5	5	9	9	Silty-sandy clay
7	5	7	7	5	6	
8	4	4	7	w6	7	
9	2/52	5	5	5	7	
10	1/45	6	5	7	11	
11	5	5	3	7	13	
12	5	7	5	11	14	
13	6	11	4	12	-	
14	9	8	10	15	-	Silty Sand
15	36	39/21	24	-	-	
16	48	-	-	-	-	
NA	10,2	11,9	12,1	10,2	11,8	m

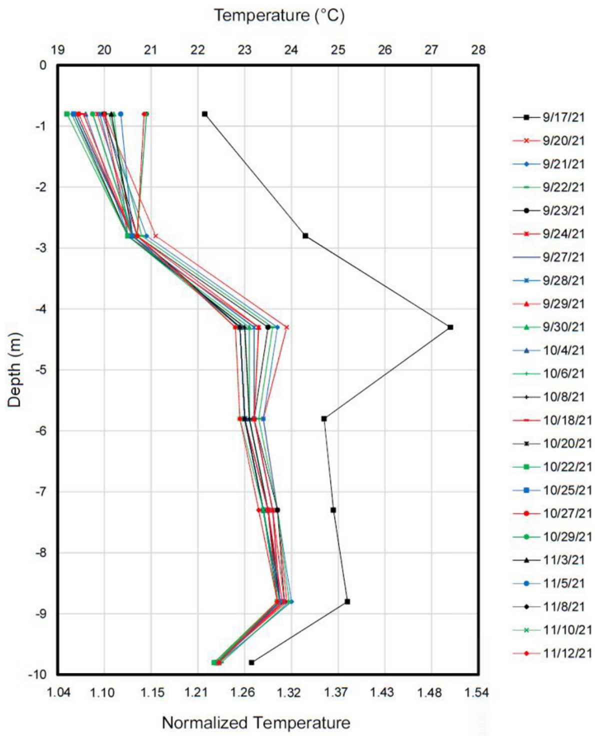

Figure 13. Underground temperature measurements and normalized temperature.

taken, and it is possible to verify the influence of the concrete heat hydration on the measurements taken the day after concreting, which resulted in much higher temperatures, which gradually decreased over the following days.

Even with a still small interval of readings, it can be seen that the temperature presents a greater variation in the first four meters of depth, becoming practically constant after this depth and reducing again when approaching the water level, which is approximately 11m. The observed behavior is comparable to that described by Laloui & Loria (2020), considering that the initial readings were taken in late winter and the most recent in spring.

On the lower axis in Figure 13 the soil temperature is shown divided by the local average temperature (18.2 °C), and it is possible to notice that the measured soil temperatures are on average 30% higher than the local average temperature.

6. Final remarks

Field studies to evaluate the feasibility of the use of shallow geothermal energy as a new renewable energy source in regions of different climatic conditions is fundamental for the development of this technology in Brazil, due to its continental extension. In particular, in the Brazilian Southern region, where the current study is being developed, the use of shallow geothermal energy may be feasible considering the annual average temperatures.

A complete soil site characterization is needed for the development of field studies on the shallow geothermal energy exploitation. In Brazil, studies of this nature have already been developed in the country's Southeast region, and this paper presents the first site characterization programme carried out in the Southern region, expanding the scope of the knowledge base applicable to geothermal utilization in the country.

Considering that the main phenomenon that controls the performance of shallow geothermal energy systems is the heat transfer by conduction, and that the ground parameters influence this phenomenon, the complete characterization of the soil is fundamental. The geotechnical profile of the test site, obtained from field and laboratory tests, revealed a thick layer of sandy-silt clay soil (around 12m), with lateritic behavior evidenced by the Disk Method analysis. The deepest layer is composed of silty sand, with markedly higher penetration resistance than the clay layer. The water level depth was around 11m.

The mineralogical characterization through X-Ray diffraction tests and scanning electron microscopy corroborated the lateritic nature of the soil due to the identification of iron oxides in addition to quartz and kaolinite. These analyses also reflected the geological origin of the soils in the region since CEEG-PG is located over the Ponta Grossa Formation, which is mainly composed of shales and the presence of diabase dikes of the Serra Geral Formation. The thick layer of a clayey soil is characterized as residual soil resulting from these formations. The influence of the Furnas Formation, consisting of quartz sandstones, was denoted by the presence of quartz in all samples tested and the residual origin of the lower sandy layer.

The soil strength characterization is crucial for future studies on the use of foundation piles for geothermal energy application. From the results of direct shear tests on flooded soil samples and in its natural moisture condition, it was observed that the internal friction angle was less sensitive to saturation degree, varying between 21° and 24° for all cases. However, the cohesive intercepts for the unsaturated condition, resulted slightly higher compared to the flooded conditions, indicating the relevance of the suction effect on the unsaturated soil resistance.

It is important to emphasize the relevance of the soil resistance characterization along the depth through Standard Penetration Tests (SPT), because the foundations mechanical behavior by piles is estimated with these tests and, subsequently, the thermomechanical behavior is evaluated when the foundation works as a heat exchanger with the ground.

Finally, the preliminary results of the ground temperatures variations are in accordance with that reported in the literature for a typical soil temperature profile, showing more expressive oscillations near the ground surface and apparent constancy in the deeper layers. The constant temperature found at deeper depths is around 30% higher than the annual average air temperature. This work also presents the thickness of the top soil zone influenced by the variation of the air temperature during the year (for different seasons).

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Bianca Penteado de Almeida Tonus: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review & editing. Carlos Emmanuel Ribeiro Lautenschläger: conceptualization, funding acquisition, resources, validation, visualization, writing – review & editing. Amanda Fetzer Visintin: Visualization, Writing – review & editing. Vítor Pereira Faro: conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation, writing – review & editing. Cristina de Hollanda Cavalcanti Tsuha: conceptualization, methodology, supervision, writing – review & editing.

List of symbols

ASTM	American Society for Testing and Materials
c´	Cohesive Intercept
Ca	Calcium Oxide
CEEG-PG	Geotechnical Experimental Site of Ponta Grossa City
C-Labmu	Multiuser Laboratory Complex of State University of Ponta Grossa
Ct	Diametral Contraction
EESC/USP	São Carlos School of Engineering of University of São Paulo
EPE	Energy Research Company
Fe	Iron Oxide
GSHP	Geothermal Source Heat Pump
Ka	Kaolinite
LA'-LG'	Lateritic Sandy Soils to Lateritic Clayey Soils
LAME	Materials and Structures Laboratory of Federal University of Parana
LG'	Lateritic Clayey Soils
LM35	Temperature sensor
MCT	Miniature, Compacted, Tropical
ML	Silt of Low Plasticity
NA´-NS	Non-lateritic Sandy Soils to Non-lateritic Silty Soils
Q	Quartz
SIMEPAR	Paraná Meteorological System
SIN	National Interconnected System
SC	Clayey Sand
SEM	Scanning Electron Microscopy
SM	Silty Sand
SPT	Standard Penetration Tests
SUCS	Unified Classification System
UEPG	State University of Ponta Grossa
UFPR	Federal University of Parana
XRD	X-Ray diffraction
ϕ'	Angle of Internal Friction

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