Experimental Investigation of a Full-Scale Energy Pile Installed in Multi-Layered Soil

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ABSTRACT: The use of energy piles to harness shallow geothermal energy (SGE) for sustainable air conditioning systems is a promising technology in Brazil. Due to the imbalance in thermal load demand throughout the year, understanding the performance of heat exchange piles is crucial for the advancement of this technology in Brazil. This study focused on the energy foundations of a living lab building under construction at the University of São Paulo, in São Paulo city, characterized by a multi-layered soil profile predominantly composed by clayey sand layers interspersed with thin organic clay. In multi-layered soils, thermal conductivity and permeability vary with depth. Granular soils can enhance underground heat dissipation in the presence of a groundwater flow. However, clayey soils exhibit a very different thermal behavior. This paper aims to analyze heat propagation in multi-layered soil through a Thermal Performance Test (TPT) conducted on a continuous flight auger (CFA) energy pile in São Paulo. This test maintained an inlet fluid temperature of 35°C with a fluid flow rate of 10.85 L/min, lasting almost 11 days. Pile monitoring revealed higher increases in the pile temperature along the section installed in the organic clayey layer, while the heat dissipation was faster in pile sections installed in the sand layers.

KEYWORDS: Shallow Geothermal Energy, Energy Piles, Deep Foundations, Multi-Layered Soil, Thermal Performance Test, Soil Thermal Conductivity.

RESUMO: A utilização de estacas trocadoras de calor para aproveitamento da energia geotérmica superficial (EGS) em sistemas de climatização sustentável é uma tecnologia promissora no Brasil. Devido ao desequilíbrio na demanda de carga térmica ao longo do ano, compreender o desempenho das estacas trocadoras de calor é crucial para o avanço dessa tecnologia no país. Este estudo concentrou-se nas fundações geotérmicas de um edifício do tipo *living lab* em construção na Universidade de São Paulo, na cidade de São Paulo, caracterizado por um perfil de solo multicamadas, predominantemente composto por areia argilosa intercalada a finas camadas de argila orgânica. Em solos multicamadas, a condutividade térmica e a permeabilidade variam com a profundidade. Solos granulares podem melhorar a dissipação de calor na presença de um fluxo de água subterrâneo. No entanto, solos argilosos exibem um comportamento térmico muito diferente. Este artigo tem como objetivo analisar a propagação de calor em solo multicamadas por meio de um Ensaio de Desempenho Térmico (TPT) conduzido em uma estaca trocadora de calor do tipo hélice contínua em São Paulo. Este ensaio, com duração de quase 11 dias, manteve uma temperatura do fluido de entrada à 35°C, com uma vazão de 10,85 L/min. O monitoramento da estaca revelou maiores aumentos na temperatura da estaca ao longo da seção instalada na camada argilosa orgânica, enquanto a dissipação de calor foi mais rápida nas camadas de areia.

PALAVRAS-CHAVE: Energia Geotérmica Superficial, Estacas Trocadoras de Calor, Fundações Profundas, Solo Multicamadas, Ensaio de Desempenho Térmico, Condutividade Térmica do Solo.

1 INTRODUCTION

Electricity consumption for air-conditioning in Brazil has more than tripled in the last 12 years (Brasil, 2019). In the commercial sector, air-conditioning accounts for 30% to 40% of the total energy consumption

(Abrava, 2013; Oliveira, Rupp and Ghisi, 2021). This increasing demand for artificial climate control can have serious consequences, particularly giving the rising electricity prices and significant global climatic changes.

Hence, the use of shallow geothermal energy is a promising energy-saving alternative for cooling buildings in Brazil through ground heat exchangers (GHE). However, as these systems utilize the ground as a heat source, the design of energy piles, usually used as a GHE, must consider the soil stratigraphy, as the thermal properties of the soils are variable. Typically, heat transfer in soils is dominated by conduction, but in soils with high permeability and high groundwater flow rate, convection can be significant (Alrtimi, Rouainia and Haigh, 2016). In practice, the subsoil is often multi-layered, resulting in varying thermal conductivities and permeabilities along the pile length, which can impact heat propagation through the subsoil over the operational lifespan of an energy pile foundation.

While some authors have studied GHEs behavior in layered subsurface conditions experimentally (Olfman, Woodbury and Bartley, 2014; Li *et al*., 2017; Gou, Zhang, and Liu, 2018; Pessin and Tsuha, 2023), most of the literature considering ground stratification relies on numerical or analytical approaches. This paper presents an *in-situ* test - thermal performance test (TPT) - conducted on a continuous flight auger (CFA) energy pile installed in multi-layered soil in order to better understand the heat propagation along the depth. The tested pile was instrumented with Platinum Thermistor Sensors (Pt-100) to record pile temperature variation during the test. Understanding heat propagation in multi-layered soil due to energy pile installation is crucial, considering the unbalanced thermal load demand over the year in Brazilian climate conditions. These findings can help to understand how heat rejection in the ground over several years may affect system thermal performance.

2 TEST DETAILS

2.1 Test site, Energy Pile, and Instrumentation

The test site is located at the campus of the University of São Paulo, in the southeastern region of Brazil, state of São Paulo (latitude: 23°33’15.8”S e longitude: 46°43’51.2”W). CFA energy piles were installed as the foundation solution for the living lab building - currently under construction on this campus - to demonstrate sustainable and innovative solutions. This paper analyses a CFA energy pile with high-density polyethylene (HDPE) heat exchanger pipes configured in a triple-U shape attached to the reinforcement cage. The characteristics of the energy pile are presented in Table 1.

Table 1. Characteristics of the tested energy pile.

	Concrete characteristics	Type	Diameter (mm)	Length (m)	Active Length (m)
Energy Pile	High filler low water (HFLW) concrete (John *et al*., 2018)	CFA	700	15	10.5

Standard Penetration Tests (SPT) conducted at the test site revealed the subsoil stratigraphy, consisting predominantly of medium-dense slightly clayey sand, interspersed with thin layers of very soft silty clay. The groundwater table level fluctuates seasonally between 2 and 4 m below the ground surface, which could enhance the heat exchange operations in saturated soils, particularly in granular soil layers with high permeability (You *et al*., 2017).

The presence of a thick layer of saturated sand can facilitate the dissipation of heat rejected by the piles into the soil. This can be explained by the higher thermal conductivity of saturated sands compared to clayey soils (or even dry sand), associated with its higher permeability to improve the groundwater flow rate. In contrast, the organic clay layer exhibits low thermal conductivity and permeability, likely leading to heat retention around the pile section, as observed by Pessin and Tsuha (2023).

Murari, Tsuha and Loveridge (2022) determined a thermal conductivity value of approximately 2.6 W/mºC for the sand of the current test site using analytical and numerical methods applied to the experimental results. Finally, Pessin *et al*. (2022) investigated the groundwater flow velocity in sand layers at this site, identifying the highest flow velocity (ranging from 0.05 to 0.2 m/day) in the uniform sand layer (5 to 6 m deep), while observing a flow velocity of about 3.3×10^{-4} m/day in the layer at 10 to 11 m depth.

The temperature variation along different depths during the test was measured using platinum thermistor sensors (Pt-100, class A, accuracy of ±0.15 for 0ºC and ±0.35 for 100ºC) installed in a bar positioned on the central axis of the CFA energy pile, at 1.30 m, 3.5 m, 5.5 m, 8.0 m, 10.5 m, and 14.0 m bellow the land surface. There was also strain gauges installed at the same depths as the Pt-100 for this pile, but their results will be not evaluated at this paper. Figure 1 illustrates the soil profile, the CFA pile, and the Pt-100 sensors.

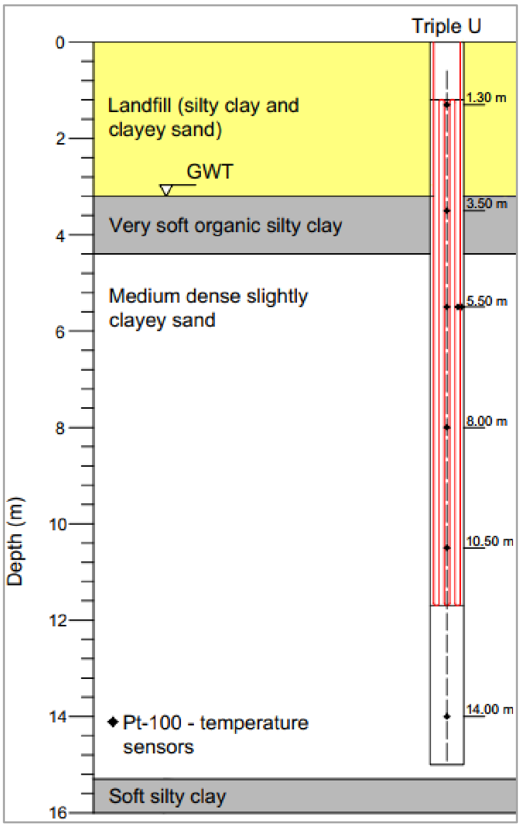

Figure 1. Soil profile, CFA pile and instrumentation with Pt-100 sensors along the pile length.

2.2 Experimental Set Up

A thermal performance test unit was used to carry out the test in the study area, simulating an operation of a geothermal heat pump. The test equipment was installed in a container. The main components of this system are:

- a hot water reservoir of 0.1 m³.
- two electrical resistances, one with 1000 W and the other with 500 W of power.
- a mini circulator pump.
- a turbine-type flowmeter.
- temperature sensors.
- a data acquisition system of high-resolution.

The horizontal HDPE pipes used to connect the test system with the pipes inside the pile were insulated with three layers of material (glass wool, elastomeric foam and, aluminized adhesive tape) to prevent heat loss and room air temperature effect in the results. In this study, during the continuous TPT performed, the inlet temperature of the heat exchange fluid was kept constant at 35ºC and the flow rate at 10.85 L/min. The test duration was 257h (~11 days).

3 RESULTS AND DISCUSSION

3.1 Initial ground temperature

The initial ground temperature distribution of this site was obtained from temperature sensors installed in CFA piles by Pessin and Tsuha (2023), including the tested pile. These sensors indicated that the subsoil temperature remains relatively constant along the year, around 24ºC, from 4 to 5 m below the ground surface, while until this depth the atmospheric temperature changes apparently influences the ground temperature.

3.2 Fluid Temperature, Flow Rate and Ambient Temperature

As previously mentioned, the inlet temperature of the transfer fluid remains constant during the TPT. When this fluid circulates in the heat exchanger pile at a certain flow rate, the heat is rejected in the soil, resulting in a temperature difference between the outlet and the inlet. During the test performed on the CFA energy pile, the inlet and outlet fluid temperatures, the transfer fluid flow rate and the ambient temperature were monitored, as presented at Figure 2. The TPT performed followed the continuous operation mode (TPT C), in which the system operates 24h/day.

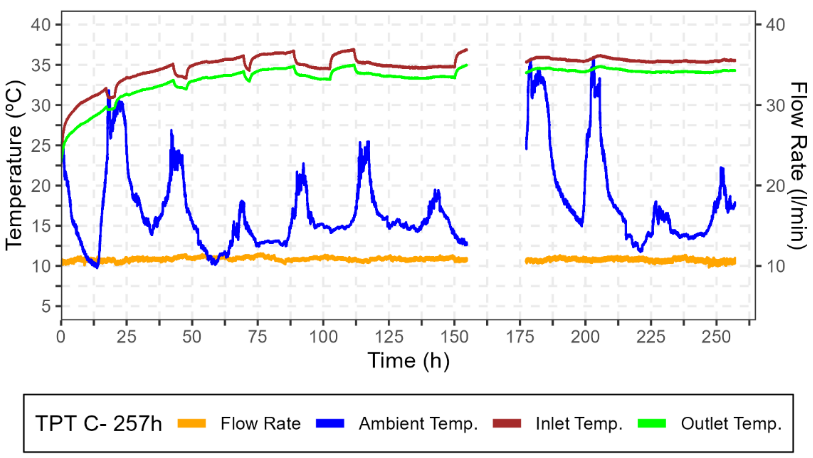

Figure 2. Measured values of ambient temperature, inlet and outlet fluid temperatures and transfer fluid flow rate during TPT.

Analyzing Figure 2, it appears that the inlet fluid temperature remained approximately constant at 35ºC, as expected, with some oscillations probably resulting from thermostat operation to stabilize the temperature at this predetermined value. Additionally, the flow rate stayed nearly stable throughout the test. The test was conducted in September, with ambient temperature fluctuating between 10ºC and 35ºC, exhibiting significant variations. However, they were not observed notable interferences in the inlet fluid temperature due to these fluctuations, probably because of the effectiveness of the system thermal insulation.

Between approximately 155h and 177h, the data acquisition system stopped functioning, resulting in a period without data acquisition for 22 h (almost a day). Subsequently, the system came back to its normal operation.

3.3 Effect of Soil Stratigraphy on Heat Propagation

The heat propagation in the multi-layered soil of the study area is analyzed through Figure 3 and Figure 4. It is evident that the temperature increases rapidly in the initial hours of the test, with progressively larger values, until reaching stabilization with the temperature diminishes over time. Figure 4 presents temperature increments registered at different times during the test at depths containing temperature sensors, comprising since the test beginning to its conclusion. These temperature increments exhibit non-uniform behavior, stratified along the depth, which can be attributed to the different thermal conductivities in multi-layered ground condition.

At a depth of 3.5 m, where the organic clay layer is situated, the highest temperature increments occurred, probably due to the low thermal conductivity of the clayey soil. After 200h of testing, the organic silty clay layer experienced a temperature increment of 11.2°C. In contrast, at the depths within saturated sand, which has higher thermal conductivity, the temperature increments were smaller after 200h: 9.4°C at 1.3m; 9.9°C at 5.5m; 10.4°C at 8.0 m, and 9.0°C at 10.5m, with a mean value of 9.7°C. Comparing the mean temperature increase of the other layers with the clay layer, it was observed that this layer had an increment 1.5°C higher. This behavior is consistent with the results found by Guo, Zhang and Liu (2018). These authors suggested that soils with higher thermal conductivity dissipate excess of heat from the energy pile to distant places more easily, resulting in a lower temperature near the pile. Instead, soils with low thermal conductivity, such as clayey soils, tend to accumulate heat around the pile. Additionally, as the time progresses, the effect of temperature difference along a multi-layered soil becomes more pronounced, as can be seen in Figure 4.

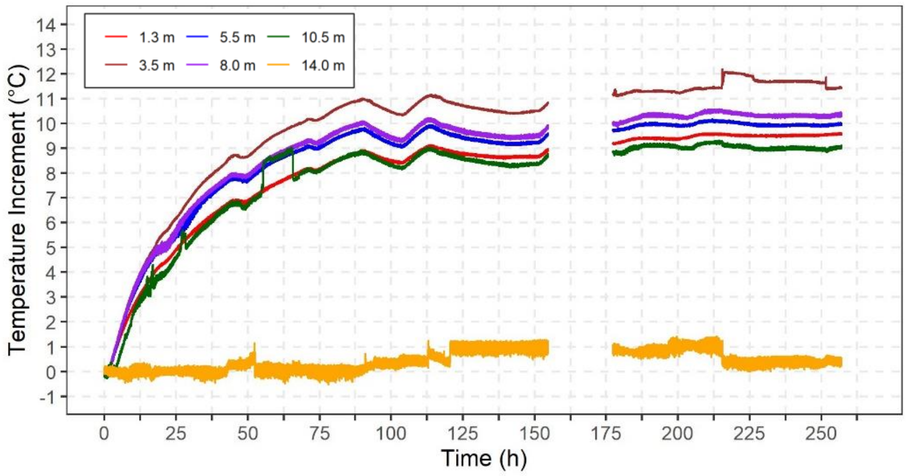

Figure 3. Temperature variation in the CFA energy pile during the TPT.

Although the layer at 3.5 m may be influenced by atmospheric temperatures due to its proximity to the surface, the unquestionable effect of the soil type due to the lower thermal conductivity becomes evident. This is clear when comparing with the upper layer, positioned at 1.3m below the land surface, where the temperature increment was even lower than that observed in the deepest layers of saturated sand.

At a depth of 10.5 m, the average temperature increase was 0.7°C lower than at other depths containing saturated sand (5.5 m and 8.0 m). This difference can be attributed to the influence of the heat dissipation in the soil outside the active length of the pile, just below this depth. Furthermore, at a depth of 14.0 m, outside the active length of the tested pile, temperature increment values were almost negligible, with an increase of approximately 1°C after 200h of heating. Consequently, at around 2.5 m below the active length zone, the heat rejected into the soil by the system no longer exerts significant influence. Similar results were found by Pessin and Tsuha (2023).

The findings presented in this section are crucial, as numerical and analytical models sometimes oversimplify soil as homogeneous along the pile depth for calculation purposes. However, this approach can be risky given the observed temperature stratification along the energy pile over time.

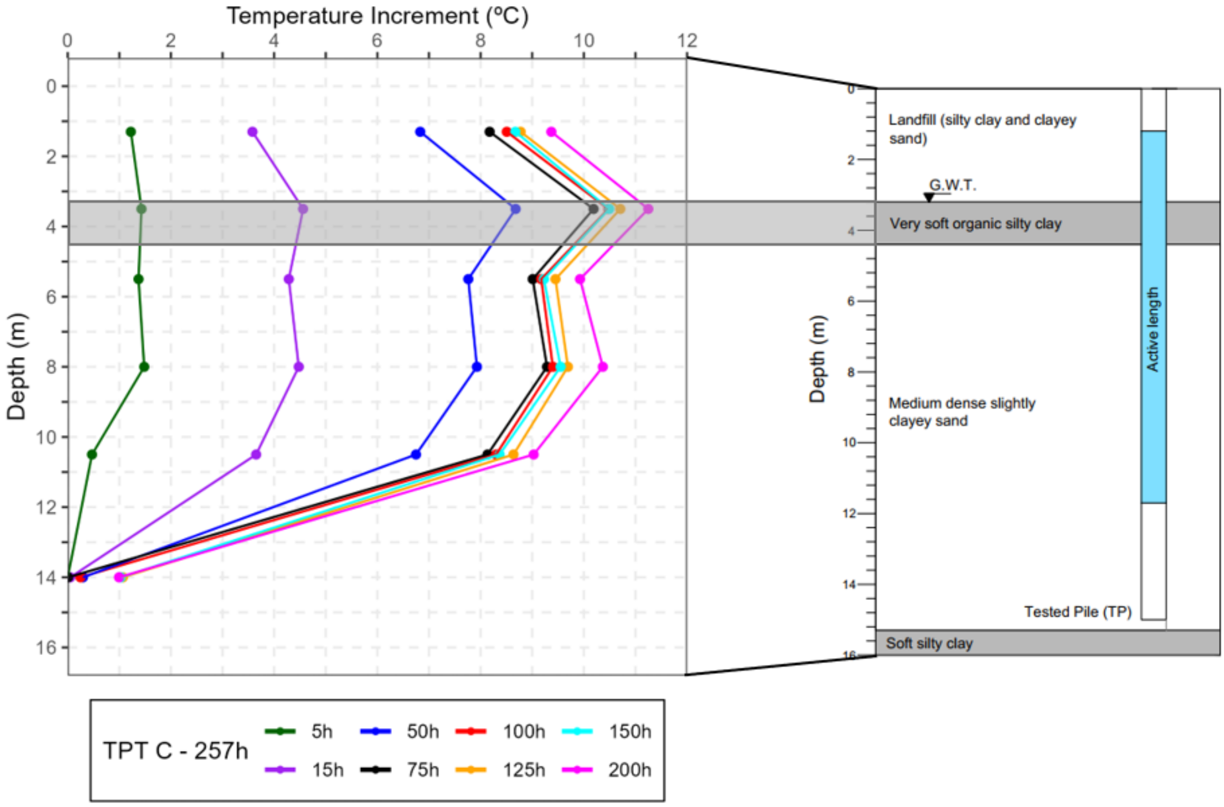

Figure 4. Temperature variation along the depth for different moments in the test.

5 CONCLUSIONS

The current case study analyzed the influence of soil stratification on the thermal behavior of a CFA energy pile located at São Paulo, Brazil, using an in-situ thermal performance test. The multi-layered soil profile is the cause of different temperature evolution along the pile length and heat propagation along the depth according to soil stratigraphy. The pile section installed in the organic clay layer showed higher temperature increments compared to the sections installed in the saturated sand layers, indicating heat accumulation around the pile in soils with low thermal conductivity. Moreover, the deeper pile section below the thermal active zone experienced lower temperature increases, suggesting reduced heat dissipation beyond the active length of the pile. These findings emphasize the importance of considering the thermal effects of multi-layered soil profiles in the design and modeling of energy piles, to ensure accurate performance predictions and avoid oversimplifications, especially in cases where there is a significant difference in the thermal conductivity of the soil layers along the pile.

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REFERÊNCIAS BIBLIOGRÁFICAS

Abrava (2013*) O uso do ar-condicionado e o consumo de energia elétrica*. Disponível em: <http://abrava.com.br/?p=11091>. Acesso em: 20 nov. 2022.

Alrtimi, A., Rouainia, M., Haigh, S. (2016) Thermal conductivity of a sandy soil. *Applied Thermal Engineering*, 106, p. 551-560.

Brasil (2019) *Balanço Energético Nacional - Relatório Síntese/ Ano Base 2018 - Empresa de Pesquisa Energética (EPE)*. Disponível em: <http://www.epe.gov.br/>. Acesso em: 20 out. 2021.

Oliveira, C. C., Rupp, R. F., Ghisi, E. (2021) Influence of environmental variables on thermal comfort and air quality perception in office buildings in the humid subtropical climate zone of Brazil. *Energy and buildings*, 243, p. 110982.

Guo, Y., Zhang, G., Liu, S. (2018) Investigation on the thermal response of full-scale PHC energy pile and ground temperature in multi-layer strata. *Applied Thermal Engineering*, 143, p. 836-848.

Li, Yong *et al*. Study the performance of borehole heat exchanger considering layered subsurface based on field investigations. *Applied Thermal Engineering*, 126, p. 296-304.

Murari, M.C. de F., Tsuha, C. de H.C., Loveridge, F. (2022) Investigation on the thermal response of steel pipe energy piles with different backfill materials. *Renewable Energy*. 199, p. 44–61.

Olfman, M. Z., Woodbury, A. D., Bartley, J. (2014) Effects of depth and material property variations on the ground temperature response to heating by a deep vertical ground heat exchanger in purely conductive media. *Geothermics*, 51, p. 9-30.

Pessin, J., Tsuha, C. de H.C. (2023) In-field performance of continuous flight auger (CFA) energy piles with different configurations. *Applied Thermal Engineering* 224, p. 120113.

Pessin, J. *et al*. (2022) Avaliação experimental do fluxo de água subterrânea para projetos de sistemas geotérmicos por estacas trocadoras de calor. In: Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica – COBRAMSEG 20, Campinas. *Anais*...ABMS. v.1., p. 4219-4226.

You, S. *et al*. (2017) Effects of groundwater flow on the heat transfer performance of energy piles: Experimental and numerical analysis. *Energy and Buildings*, 155, p. 249–259.