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Short time temperature response of a continuous flight auger energy pile and nearby piles: a case study in São Paulo, Brazil

Resposta de temperatura à curto prazo de uma estaca hélice contínua trocadora de calor e estacas vizinhas: um estudo de caso em São Paulo, Brasil

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ABSTRACT: Ground source heat pump (GSHP) systems utilize shallow geothermal energy to cover the heating and cooling demands of buildings via GHE's (ground heat exchangers). Pile foundations, constructed for structural/geotechnical purposes, can also be used as a GHE, known as geothermal energy pile (GEP). A thermal performance test (TPT) on a CFA (continuous flight auger) energy pile, equipped with temperature sensors at varying depths was conducted at the Campus of the University of São Paulo, Brazil. This pile was installed in a saturated sand deposit intercalated by thin clayey layers. The TPT was carried out during a period of 165 h, with an inlet fluid temperature of ~35ºC. Additionally, the heat transfer in the surrounding soil was monitored by temperature sensors installed in nearby piles. The results indicated that: (i) the temperature distribution along the pile length was variable; (ii) the heat transfer to the surrounding soil was influenced by the soil type; (iii) the heat exchange rate slowed down and tended to be stable after 40hs of test; (iv) no significant temperature variation along the pile section below the thermoactivated zone was observed; (v) the temperature at pile center was higher compared to the values measured at the reinforcement cage.

KEYWORDS: Shallow geothermal energy, geothermal energy pile, thermal performance test, ground heat transfer.

1 INTRODUCTION

In a scenario of concerning about global climate changes, green energy systems have been a promising alternative to minimize CO_2 emissions. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2022) is expected that, on average, the global temperature reach or exceed 1.5ºC of warming in the next 20 years. Consequently, immediate, and large-scale actions to reduce greenhouse gases emissions are urgent.

Looking at this global issue and considering the important increase of air-conditioning consumption in Brazil in the last years, the National Energy Plan (PNE) 2050 (Brazil 2020) recommends the use of shallow geothermal energy as one of the potentially disruptive technologies to reduce electrical energy consumption used effectively for cooling and heating purposes.

Ground source heat pump systems (GSHP), employed to assess shallow geothermal energy, are an energy-saving solution to satisfy the cooling and heating needs of buildings. Beyond the traditional system, that uses boreholes as ground heat exchangers (GHE), it is possible to apply building pile foundations with the same purpose. In this case, these foundations are called “geothermal energy piles” (GEPs) and they acquire an additional function: to perform the heat exchange with the soil. This type of GHE is a cost-effective solution for building thermal comfort (Ferrantelli, Fadejev & Kurnitski 2019).

Given that the Brazilian Energy Research Office (EPE) is considering the use of shallow geothermal energy as a potential solution for sustainable climatization, it is important to understand the behavior of this system in Brazilian climate conditions. Therefore, this paper analyses the thermal performance of a continuous flight auger (CFA) energy pile installed at the site where the CICS (Center for Innovation in Sustainable Construction) Living Lab building is being constructed (CICS USP 2024). This project was designed to test advanced sustainable solutions in service condition at the Campus of University of São Paulo, in São Paulo city, Brazil.

The GEP tested in this research was previously studied by Pessin & Tsuha 2023, which was deeply evaluated using thermal response tests (TRT). Additionally, a thermal performance test (TPT) was conducted on this pile (Sá *et al.* 2022) to obtain the heat exchange rate. The main characteristic of a TPT test is that the inlet fluid temperature is kept constant, generally aiming to investigate the heat exchange performance of GHEs (Choi, Kikumoto e Ooka 2019). Other researchers have studied the performance of energy piles using TPTs, but most of them focused on temperate climate conditions and did not analyze the effect on nearby piles (Faizal, Bouazza & Singh 2016, Lee *et al.* 2021a, Ren *et al.* 2023).

In this context, this paper aims to examine the temperature variation along a GEP at different depths in a multilayered soil and the thermal effects due to the GEP operation on the nearby conventional piles. A thermal performance test (TPT) was performed to simulate the GSHP system operation for a building in a sub-tropical climate condition, where the demand for cooling is dominant over the year. Using temperature sensors installed in three different positions at a pile section, the temperature variation at this section was also monitored during the test. Additionally, the temperature increments along the pile length due to the applied thermal load were an important information obtained that helps to understand the impact on the thermomechanical response of this GEP during the service life of the building foundation. Finally, the effect of the geothermal pile operation in the neighboring piles is a crucial result to evaluate if there will be some thermal load effect motivated by the heat conducted through the soil to the other piles.

2 CASE STUDY OVERVIEW

2.1 *Subsoil profile*

The GEP tested in this paper was installed at the Campus of University of São Paulo, in São Paulo city (Southeast region of Brazil), where the CICS Living Lab building is being built (CICS USP 2024). Figure 1 present the subsoil profile and the ground temperature variation along the depth, that was previously obtained from four CFA piles instrumented and monitored by Pessin & Tsuha 2023.

As showed in Figure 1, the subsoil at the test site is predominantly composed by a medium dense slightly clayey sand, interspersed by thin clayey layers. The groundwater table varies seasonally from 2 and 4 m below the ground surface. Complementarily, the groundwater flow velocity in the sandy layers were determined by Pessin *et al.* 2022, and the uniform sand layer (5 to 6 m deep) presented the highest velocity values (from 0.05 to 0.2 m/day). For the layer from 10 to 11 m, a groundwater flow velocity of ~ 3.3×10^{-4} m/day was observed.

Additionally, Figure 1 reveals the ground temperature at the test site (measured in August/2021), obtained from sensors installed in four CFA energy piles tested by Pessin & Tsuha 2023. Comparing with the results found by Murari, Tsuha & Loveridge 2022 at the same test site, using sensors installed in a steel pipe energy pile filled with grout (measured in December/2019), it is noticed that the ground temperature tends to remain constant throughout the year from approximately 4 or 5 m below the ground surface, at a value around 24°C, due to the thermal inertia of the soil at this depth.

According to the results obtained from thermal response tests (TRTs) performed on steel piles with approximately 23 m of length and 244 mm of diameter, conducted by Murari, Tsuha & Loveridge 2022 near the pile tested in this paper, a value of ~ 2.60 W/m.°C of average ground thermal conductivity along the pile length was obtained.

2.2 *Tested GEP and nearby piles*

The pile studied in this research was a 15-m-long CFA heat exchanger pile, with 700 mm of diameter and a pile active length of 10.5 m, as illustrated in Figure 1. HDPE (high density polyethylene) pipes in a triple-U configuration were inserted in this pile to allow the water circulation during the test (inner diameter of 26 mm and outer diameter of 32 mm).

This pile was constructed using a High Filler Low Water (HFLW) concrete, which has low CO_2 emission (John *et al.* 2018). Although the thermal conductivity of the concrete used in the CFA pile has not been measured, as a reference, literature indicates that the thermal conductivity of conventional concrete ranges from 0.9 to 2.0 W/m.°C (Laloui & Loria 2019).

In addition, the pile was instrumented with Pt-100 (platinum thermistors sensors) at different depths, which were installed in a metallic bar, positioned on the central axis of the pile, as detailed in Table 1.

For the tested pile (TP), at 5.5 m deep, temperature sensors were installed in three different positions: at the pile central axis, at the pipe surface and at the reinforcement cage. The purpose of this instrumentation was to register the temperature variation in an intermediary section at the active pile length.

Temperature sensors were also installed in reinforced cage of three nearby piles (N). These nearby piles have the same dimensions of the TP and temperature sensors were placed in the depths presented in Table 1. In this paper, these piles were named N1, N2, and N3, with the location indicated in Figure 2.

The neighbor piles were also equipped with HDPE heat exchanger pipes, attached to the reinforcement cage, but they were deactivated during the test. Only the TP was submitted to thermal loads (heating).

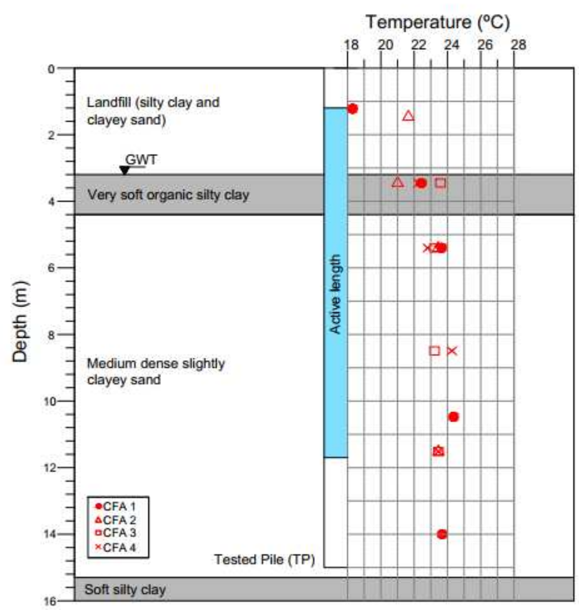

Figure 1. Subsoil profile of the test site, with temperature variation along depth of the tested pile (TP). CFA 1 to 4 refers to the energy piles used by Pessin & Tsuha 2023 to monitor the temperature along the depth.

Table 1. Distance from the tested pile (TP) to the neighbor piles (N) and depths where the Pt-100 were installed (D is pile diameter).

Pile	*Radial distance from TP (m)*	*Depths of Pt-100 sensors (m)*
TP	-	1.3 – 5.5 – 8.0 – 10.5 – 14.0
N1	2.94D	3.5 – 5.5 – 8.5
N2	2.87D	3.5 – 5.5 – 11.5
N3	3.22D	8.5 – 11.5

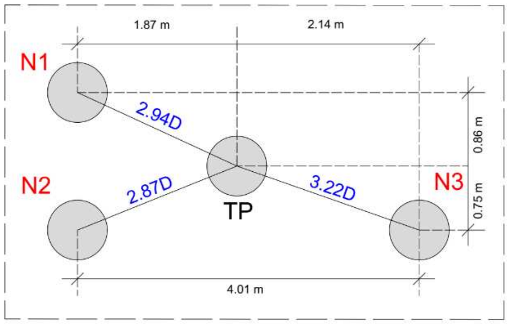

Figure 2. Location of the neighbor piles (N1, N2 and N3) related to the tested pile (TP).

2.3 *Thermal performance test*

Although thermal response tests (TRTs) are most used, the thermal performance tests (TPTs) are increasingly being applied to investigate the thermal performance of geothermal energy piles (Yoon *et al.* 2015, Luo *et al.* 2016, You *et al.* 2017, Lee *et al.* 2021b).

A continuous TPT was done at the TP. During this test, the inlet setpoint fluid (water) temperature was maintained constant at 35ºC, using a heater system regulated by a temperature controller. The TPT was carried out during a period of 165 h (~7 days), with a mean flow rate of 13 L/min. The inlet and outlet fluid temperatures were monitored through Pt-100 sensors, as well as the external ambient temperature.

2.3.1 *Test equipment*

The TPT was performed using the same TRT unit constructed at the University of São Paulo to perform the tests of Murari, Tsuha & Loveridge 2022 and Pessin & Tsuha 2023. A metallic container measuring 3.00 m long, and 2.30 m protected the equipment from weather damage. The main components of this system are listed at Table 2 and presented in Figure 3.

The horizontal pipes used to transport hot water from the reservoir to the TP were thermally insulated to prevent heat loss and influence of outdoor temperature on the results (Figure 4).

3 RESULTS AND DISCUSSIONS

3.1 *Test conditions*

During the test, ambient temperature, inlet, and outlet fluid temperature were monitored, as showed in Figure 5.

Despite of the large fluctuations registered in ambient temperature during the test, the inlet temperature of the fluid was satisfactorily maintained at approximately 35ºC.

The water flow rate was also monitored and remained stable during TPT, in a mean value of 13 L/min, sufficient to guarantee a turbulent flow inside the pipe. There were no registered problems in the supply of flow rate by the pump throughout the test.

Table 2. Equipment used to perform the TPT.

Equipment	*Characteristics*
Hot water reservoir	Capacity: 0.1 m³. Power: 1.5 kW. Thermistors to assure inlet water temperature: 02.
Circulation pump	Power switches: 120 W, 248 W and 350 W. Manufactured by Komeco.
Turbine flowmeter	Range of measurement: 5L/min to 35 L/min. Manufactured by Contech Industry and Electronic Equipment Commerce Ltda.
Pt-100 sensors	Absolute error: ±0.15 for 0ºC; ±0.35 for 100ºC. Range of measurement: 0ºC to 250ºC. Manufactured by Salcas Industry and Commerce Ltda.
Data acquisition system	High-resolution, model PMX (Catman®software). Manufactured by Hottinger Baldwin Messtechnik Gmbh (HBM).

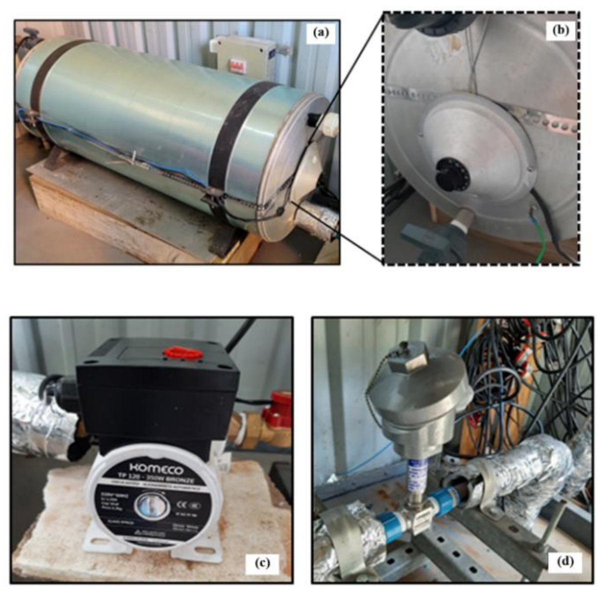

Figure 3. (a) Hot water reservoir; (b) detail highlighting the thermistor of the reservoir; (c) circulation pump and (d) flowmeter.

Figure 4. Overview of the system, showing the insulated pipes, the container, and a detail of the data acquisition system.

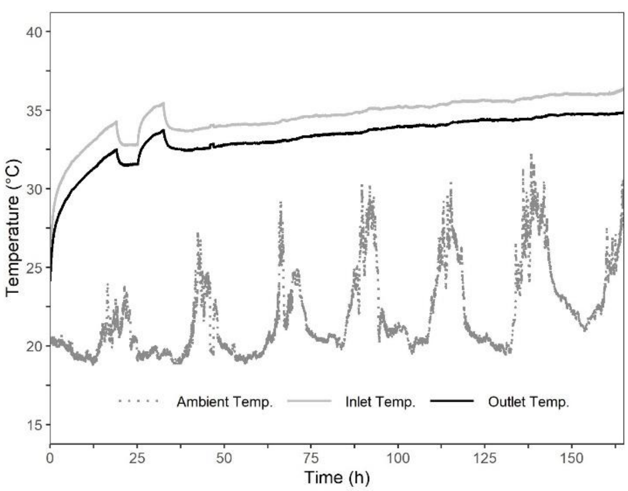

Figure 5. Ambient temperature and inlet and outlet fluid temperature during the test.

3.2 *Temperature variation along the pile*

The temperature in the pile was recorded by a data acquisition system with a high temporal resolution (at least 0.1 Hz), during the TPT. Figure 6 shows the temperature variation along the pile depth at different moments during the test (5h, 15h, 50h, 75h, 100h, 125h, 150h). Complementarily, Figure 7 presents the temperature variation over time during the test.

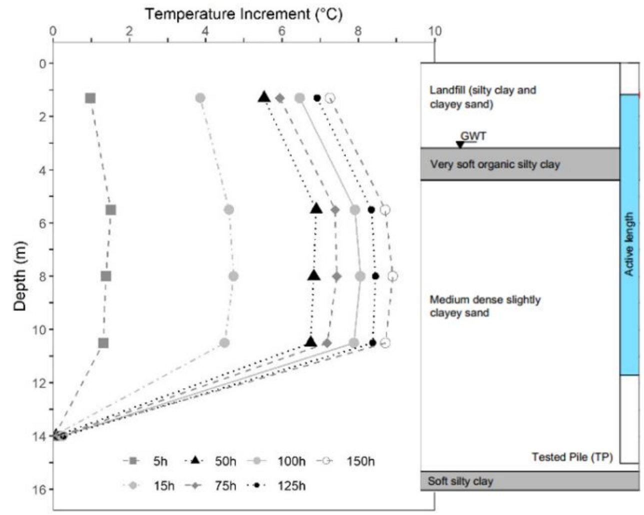

Figure 6. Temperature variation along the depth of the TP at different moments during the TPT.

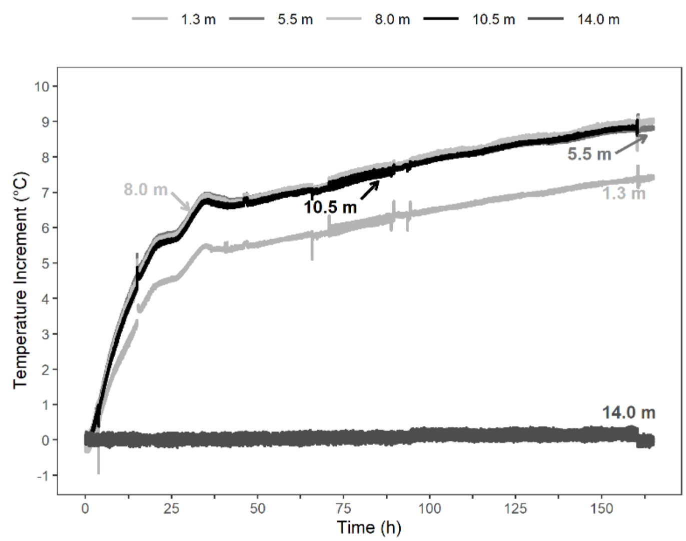

Figure 7. Temperature variation in the TP during the TPT at different depths.

As illustrated in Figure 6 and Figure 7, temperature distribution along pile depth is variable. At the top zone the temperature is lower comparing to other depths inside the thermoactivated zone (active pile length), probably due to heat loss to the environment.

Between 5.5 m and 10.5 m the temperatures are similar during the test period. However, at 14 m (2.5 m below the thermoactivated zone), after 150h of pile heating, the temperature change is negligible (Figure 7). It is important to mention that a sensor was installed at 3.5 m deep to analyze the thermal behavior in the clay layer. However, this sensor unfortunately presented a malfunctioning during the test and its records were lost.

Comparing Figure 6 and Figure 7, it is possible to observe that, during the first hours of pile heating, the pile temperature increases considerably, but after approximately 40 hours of test, the heating rate in the pile slows down and tends to be stable.

This behavior illustrated in Figure 7 is expected considering that the difference between the working fluid and the initial ground temperatures is higher at the beginning of the test and becomes smaller as time pass by.

3.3 *Influence of the pile heating on the neighbor piles*

The measurements of temperature in the nearby piles N1, N2 and N3 during the TPT performed at the TP revealed some interesting results (Figure 8).

After 165 h of test, the temperature of pile N3 (at 3.22D from TP) did not change at 8.5 m and at 11.5 m. However, in piles N1 and N2 (distant ~ 2.9D from TP), a small temperature increase (less than 1°C) was observed, specially at the depth of 5.5 m that corresponds to the sand layer with the highest values of groundwater flow velocity. As for pile N3 there were not sensors installed at 5.5 m, it was not possible to verify if some temperature increase was observed of pile N3 at this depth during the test.

At 3.5 m below the ground surface, in the zone containing a soft organic silty clay layer (soil of lower thermal conductivity), the temperature increases in the piles N1 and N2 were insignificant (near to zero). This behavior indicates a possible delay of the heat flux to reach the neighbor piles through this layer, due to the low ground thermal conductivity of the soil.

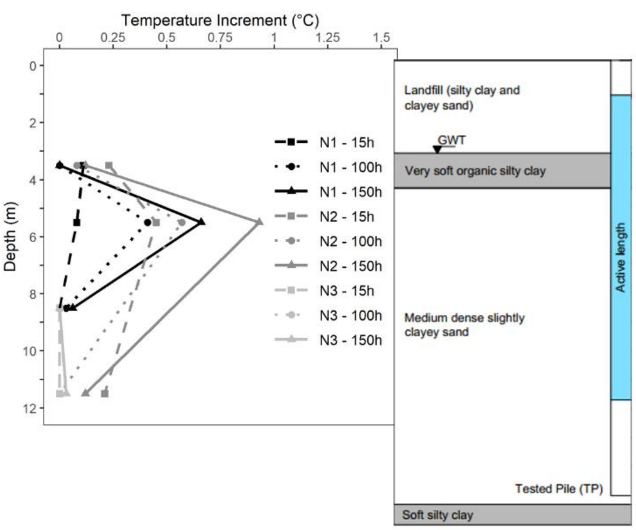

Figure 8. Temperature variation along the depth for piles N1, N2 and N3 - at horizontal distances from the TP of 2.94 D; 2.87 D and 3.22D, respectively - during the TPT.

3.4 *Temperature distribution in an energy pile section during the TPT*

Complementarily to the previous results, the temperature distribution along a transversal section of the TP, located at 5.5 m deep, was evaluated. Temperature sensors were installed at three different points in this section, as indicated at Figure 9.

Figure 10 shows that the temperature rise in pile center is higher than at the reinforcement cage. However, the highest increase was recorded at the sensor located near to the pipe surface, which received the direct influence of water temperature circulating into the pipe. The temperature measured in this sensor is similar to the average fluid temperature as shown in this figure. Finally, the difference between the measured temperatures is constant after approximately 20 hours of pile heating.

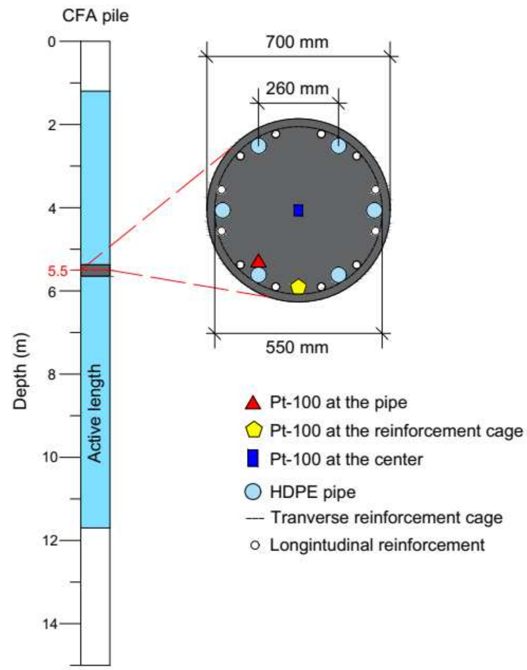

Figure 9. Instrumented section of the TP at a depth of 5.5 m: Pt-100 were installed at three different positions – at the center, attached to the external face of a HDPE pipe and fixed at the reinforcement cage, next to the external face of the energy pile.

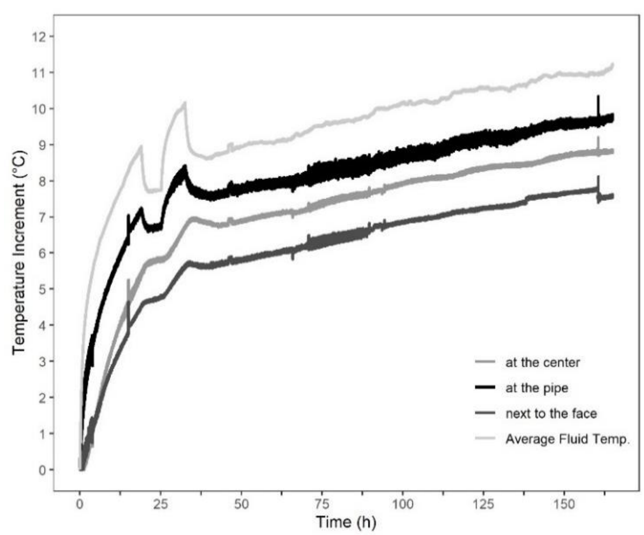

Figure 10. Temperature increment distribution over the time in a section of the TP placed at 5.5 m deep, compared to the increment in average fluid temperature.

3.5 *Heat exchange rate and heating velocity*

Based on the previous results, it was possible to calculate the heat exchange rate – an important value to understand the thermal performance of the TP. According to Eq. 1, the heat exchange rate can be calculated knowing that the fluid mass flow rate (m in kg.s^{-1}); the fluid specific heat capacity (c in J.kg^{-1}.K^{-1}); the fluid inlet and outlet temperature (respectively, T_{in} and T_{out} in K); and the active length of the pile (L in m).

$$q = m \cdot c \cdot (T_{in} - T_{out})/L \quad (1)$$

As seen in Figure 11, the heat exchange rate per active pile length (q in W/m) had a significant increase in the first hours of test and, after approximately 40h, it remained almost stable, in an average value around 109 W/m. In this figure, an oscillation at the heat exchange value near to 25h is observed, probably due to an instability in thermostat control. This same fluctuation can be observed at the inlet and outlet fluid temperatures presented in Figure 5.

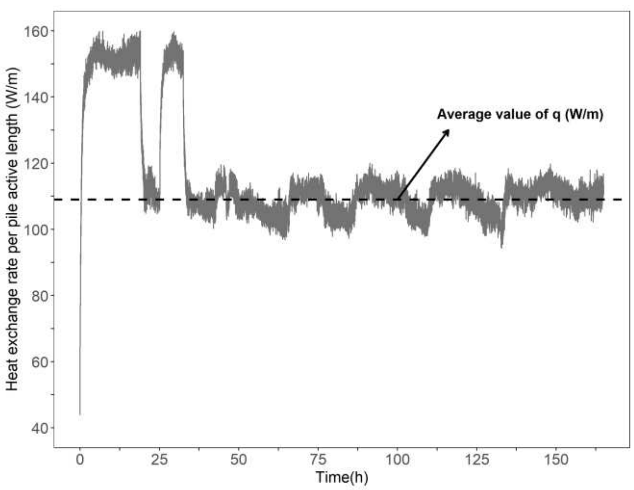

Figure 11. Heat exchange rate per pile active length (q) over the time and average value of q.

Complementarily, the average heating velocity in the tested pile (ºC/h) during the TPT was calculated considering intervals of one hour. This calculation provided a result similar to that obtained through the heat exchange rate. Throughout the first hours of TPT, the heating velocity is higher, but it decreases over the time and tends to be constant and closer to zero after about 40h for all different depths evaluated (Figure 12). This decreasing heat velocity is related with a reduction in the heat storage capacity, so that the heat transfer inside the GEP reached the steady state and the heating velocity became almost constant.

Additionally, between ~15h and ~35h after the beginning of the test, it was observed a small oscillation of heat injection that can be visualized in Figure 12 (in the same way as presented in Figures 5 and 11). Finally, for the depth of 14.0 m, located below the thermoactivated zone, the heating velocity remained almost constant and near to zero, as expected.

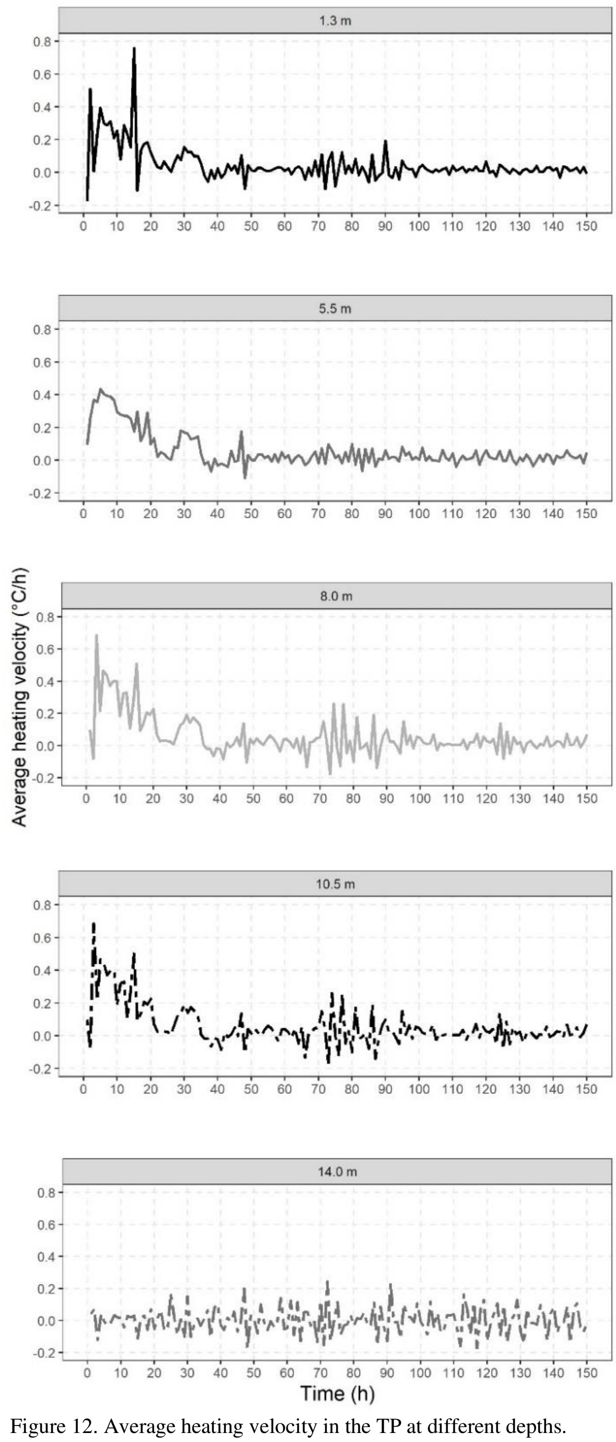

Figure 12. Average heating velocity in the TP at different depths.

4 CONCLUSIONS

A thermal performance test (TPT) was conducted on a CFA geothermal energy pile at São Paulo city, Brazil. Throughout this test, the thermal effects within the tested pile, as well as in the neighboring piles, were monitored and recorded. Based on the findings presented in this paper, the main conclusions can be summarized as follows:

1. The temperature along the pile length varied during the test according to the depth and the different soil layers. The top zone of the pile presented lower temperatures due to heat loss to the environment.
2. At 2.5 m below the thermoactivated zone of the TP, the temperature did not change after 165 hours of pile heating.
3. The nearby piles had a more significant temperature rise in the zones installed within soil layers characterized by higher groundwater flow velocities.
4. In the section studied, at a depth of 5.5 m, the energy pile temperature was higher in the center compared to the zone closer to the soil-pile interface. However, the highest temperatures were found at the sensor installed at the pipe surface, probably due to the contact with the circulant fluid temperature.
5. The energy pile heating velocity was higher in the first hours of test and decreased with time, tending to be constant and closer to zero after a certain period. This behavior was also observed for the heat exchange rate that tended to keep constant at ~109 W/m after 40h of heating.
6. The decrease in the heat velocity and heat exchange rate may be attributed to a reduction in the heat storage capacity, so that the heat transfer inside the GEP reached the steady state and the heating velocity became almost constant. Similarly, the rate of heat transfer became stable for the period of test observed in this work.

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