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In-situ measurements of the soil thermal properties for energy foundation applications in São Paulo, Brazil

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The consumption of electrical energy for air-cooling systems in Brazilian urban areas is very high. Therefore, under this scenario, the use of ground source heat pump (GSHP) systems with geothermal piles seems to be an interesting alternative for energy savings. For an efficient design of geothermal piles (also known as "energy piles"), it is necessary to determine the following parameters: (i) ground thermal conductivity, (ii) pile thermal resistance, and (iii) undisturbed ground temperature. Such parameters can be estimated from Thermal Response Tests (TRTs) on energy piles. In order to investigate the thermal properties of the ground at a site in São Paulo city, Brazil, a TRT was carried out during 10 days on an energy micropile with 15 m length and 350 mm diameter, with a single U-shaped tube. The current paper presents the results of this experimental investigation, which can be used to guide the design of geothermal pile systems in tropical areas of similar ground conditions.

Keywords: Shallow geothermal energy, energy piles, thermal response test, ground thermal properties, sub-tropical climate

INTRODUCTION

São Paulo is the most populous city in South America (12.2 million people), and is also one of the world's largest metropolitan areas. This city has a humid subtropical climate, and air conditioning (cooling) accounts for approximately 20 percent of the total electricity used in commercial buildings. In order to minimize this problem, the use of geothermal energy systems with energy piles could be an interesting alternative to reduce the consumption of electrical energy for air-cooling.

For the design of energy piles it is necessary to determine the ground thermal properties and the thermal performance of the pile. Parameters as undisturbed ground temperature, thermal conductivity, and pile thermal resistance can be estimated from the results of a Thermal Response Test (TRT) carried out on the pile loop.

The current paper describes the test procedure and results of the first TRT test performed in an energy pile installed at a site which represents a typical soil condition in large area of São Paulo. The current work is the first case reported in literature of a TRT conducted in the Brazilian subtropical region.

GROUND CONDITIONS

The TRT test was carried out at the campus of the University of São Paulo at Sao Paulo city, southeast of Brazil. In this area, the ground is predominantly composed of clayed sand with varied grain diameters, covered by a silt-sand clay layer with a thickness of approximately 2.5 m, and a dark organic-clayey layer with a thickness of 1 m.

Standard penetration tests (SPT) were performed at the test area (boreholes with 20 m depth), for initial soil characterization, according to Brazilian standard [1]. During the test, values of the penetration resistance N_{SPT} (number of blows by a hammer of a standard weight required to drive a standard sampling tube 300 mm into the ground) were measured along the soil depth. The results of average, maximum and minimum N_{SPT} are shown in Fig.1. The depth of the groundwater table varies seasonally from approximately 2 to 3 m at the site. When the current TRT was carried out, the groundwater table was 1.9 m bellow the ground surface.

ENERGY PILE

The use of energy piles is an innovative technology, in which GSHP systems based on energy pile foundations, installed in constant ground temperature, are used for heating and cooling of building.

For the current study, a small diameter (0.35 m) energy micropile of 15 m length was constructed at the test site. The micropile drilling process is illustrated in Fig.2a. Borehole casing pipes were used to ensure the stability of the drilled hole before

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grout placement (Fig.2b). After the hole has reached the final depth, water was pumped to expel the slurry out (until clean water is obtained in the returns).

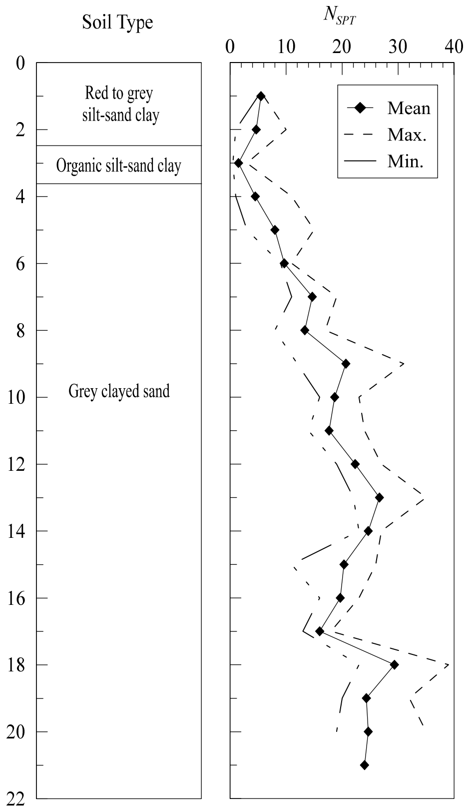


Fig.1. Soil profile at the test site of the University of São Paulo at São Paulo, Brazil

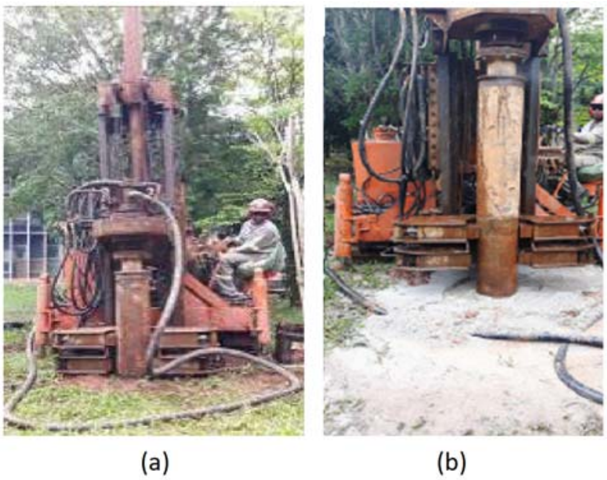


Fig.2. Construction of the energy pile: a) hydraulic drilling rig, and b) drilling process

After a cleaning procedure, high-density polyethylene (HDPE) heat exchanger tubes were installed into the cased hole. A high density polyethylene (HDPE) tube that forms U-shaped pipe (inner diameter of 26 mm and outer diameter of 32 mm) was attached to the reinforcement cage (Fig.3). Details of the tube installation into the energy micropile are presented in Fig.4. The U-loop was installed along the total length of the pile (active pipe length of 15m).

Fig.3. Installation of the U-shaped exchanger tubes in the reinforcement cage of the micropile

After the reinforcement cage installation, the hole was filled with grout, with cement/aggregate ratio of 0.55, and cement/water ratio of 0.5. Grouting was stopped after total removal of water from the borehole. The steps of the construction process of the energy pile are described in Fig.4.

Fig.4. Construction of the energy pile: installation of the reinforcement cage with a U-shaped heat exchanger tube

THERMAL RESPONSE TESTS

The thermal response testing involves applying a constant heating power to the ground via a heated circulating fluid.

Normally, the TRT interpretation is carried out by a simple analytical technique, based on the line source model. The number of the TRT carried on energy piles has been increasing, although some researchers [2] commented that longer duration tests are necessary for application of the line source model with piles. The test duration usually is set to a minimum of 48 hours; however, based on the recommendation of [2], for the current study the TRT duration was approximately 10 days.

In the present work, the thermal response test was performed based on the procedure described in the European Committee for Standardization document, TC 341 WI 00341067.6 [3], prepared by CEN/TC 341 – 'Geotechnical Investigation and Testing' and of few works available in the literature [2, 4 – 6].

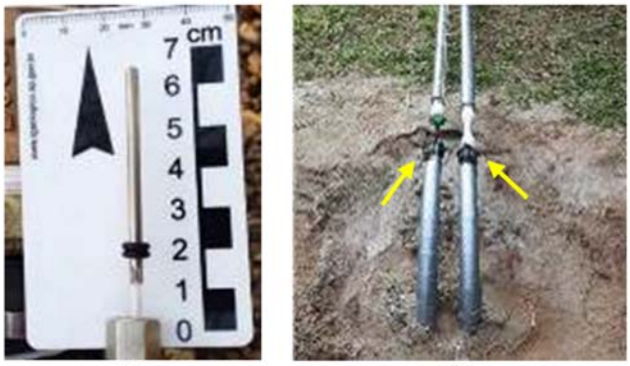
Test equipment

The TRT equipment used in this work was constructed for the investigation described partially in [7], performed to evaluate the feasibility of ground source heat pumps systems in Brazilian unsaturated soils. This cited work was carried out in order to evaluate the thermal performance of energy piles installed in unsaturated lateritic soils (typical in Brazil) [7].

The TRT was carried out by injecting a constant heat power into the heat exchanger pile. During the heat injection, the inlet and outlet fluid temperatures in the pile were monitored using two thermistors (PT-100) connected to a data acquisition system with a high temporal resolution (at least 0.1 Hz). The equipment used is composed of: a heater reservoir, a circulation pump, a flowmeter, three PT-100 thermistors sensors and a high resolution data acquisition system [7].

The PT-100 thermistors sensors have an operating range from 273.15 to 523.15 K. These sensors, used for monitoring the inlet (T_{in}) and outlet (T_{out}) temperatures of the heat carrier fluid, were attached to the U- shaped heat exchanger tube (Fig.5). A third PT-100 was used for monitoring the ambient temperature during the test.

The heater reservoir is a conventional electrical water heater with 0.1 m³ capacity and heating rate of 1 kW. For this study, water was used as the heat transfer fluid.



(a) (b)

Fig.5. (a) PT-100 resistance temperature sensors; (b) PT-100 installed in the inlet and outlet pipe

The turbine flowmeter used to measure the water flow rate through the U-tube, with a repeatability and straightness of ±0.5% (for liquids), was connected to the data acquisition system during the test.

After installation, the pipes were insulated to minimize heat loss or gain. The temperature sensors were equally insulated. Fig.6 presents a schematic of the experimental system.

The undisturbed ground temperature was recorded before the beginning of the of the thermal response test, according to the recommendations of the European Committee document TC 341 WI 00341067.6 [3]. During this initial step, the inlet and outlet temperatures of the heat carrier fluid were measured when the water was pumped through the tubes (without heat input).

The TRT was carried out with a flow rate of $3.52 \cdot 10^{-4}$ m³/s, to guarantee a turbulent flow inside the pipe. For the test, the applied power was approximately 1.061 Watts, or 70.8 W/m (amount of heat per length of pile).

TRT interpretation

The TRT results were interpreted based on the analytical Kelvin's linear heat source theory, considering the data corresponding to the steady-state heat transfer within the U-tube. In this case, the energy pile was assumed to be a finite linear heat source, the ground a semi-infinite homogeneous medium, and the heat transfer at the pile-ground interface constant and in radial direction [5, 8, 9]. The equation used to determine the changes in the ground temperature due to the heat flow, based in Kelvin's line source theory, is defined as:

$$\Delta T_g(t,r) = \frac{q_t}{4\pi\lambda}\left[\ln\left(\frac{4\alpha t}{r^2}\right) - \gamma\right] \tag{1}$$

where:
ΔTg – ground temperature change, K;
q_t – heat power injection supply per unit of geothermal exchanger, W/m;
λ – ground thermal conductivity, W/mK;
r – radial distance between the heat source and point of interest into ground, m;
t – TRT duration time, s;
γ – Euler's constant (γ = 0,5772)
α – ground thermal diffusivity, m²/s, Eq.2:

$$\alpha = \lambda / \rho S_C \qquad (2)$$

where :
ρ – mass density of the soil, Kg/m³
S_c – specific heat capacity, $Jkg^{-1}K^{-1}$.

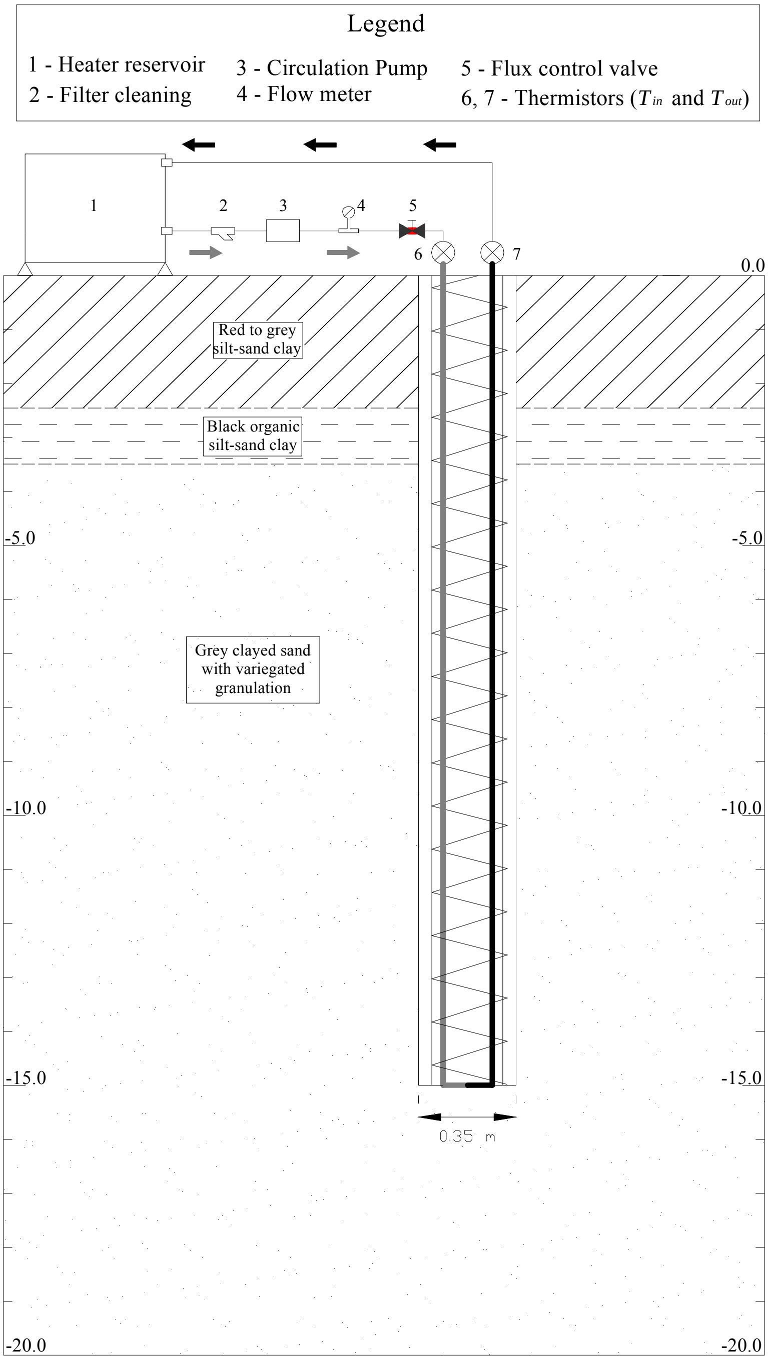


Fig.6. Schematic of the experimental system

The thermal resistance R_b between the heat carrier fluid and the pile wall can be obtained by the fundamental relation [5, 9] described in the Eq.3:

$$\Delta T_f = q_t R_b + \frac{q_t}{4\pi\lambda}\left[\ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right] \qquad (3)$$

where:
ΔT_f – change in mean temperature of the heat carried fluid during TRT tests, K;
R_b – overall thermal resistance of the geothermal heat exchanger, mK/W;
r_b – geothermal heat exchanger (pile) radius, m.

The effective ground thermal conductivity (λ_{eff}) can be determined from the variation of the fluid mean temperature versus logarithmic time recorded during the TRT, and are calculated by the Eq.4:

$$\lambda_{eff} = \frac{q_t}{4\pi k} \qquad (4)$$

where:
k – slope of the linear regression of mean fluid temperature versus logarithmic time.

To guarantee that the analysis were done considering the steady-state heat transfer condition, according to the recommendations of some authors [3 – 5, 9], we discarded the early test data before a minimum test period, t_{min}, calculated by the Eq.5.

$$t_{\min} = \frac{5 r_b^2}{\alpha} \qquad (5)$$

RESULTS

Natural Ground Temperature

The TRT was carried out in February 2017 (Brazilian summer). During the initial water circulation inside the energy pile, undisturbed ground temperature (estimated from the inlet and outlet fluid temperatures) and ambient temperature were determined. Table 1 shows the results of the temperature monitoring before the beginning of the TRT.

Table 1. Results of the mean temperature of the ground along the pile (water circulation test)

Duration time	Groundwater position	Temperature	
		Ambient	Ground*
s	m	K	
1,296	1.90	297.95	297.85

*average ground temperature considering 15 m depth.

Fig.7 illustrates the variation of the ambient temperature the mean inlet and outlet fluid temperatures during the water circulation test.

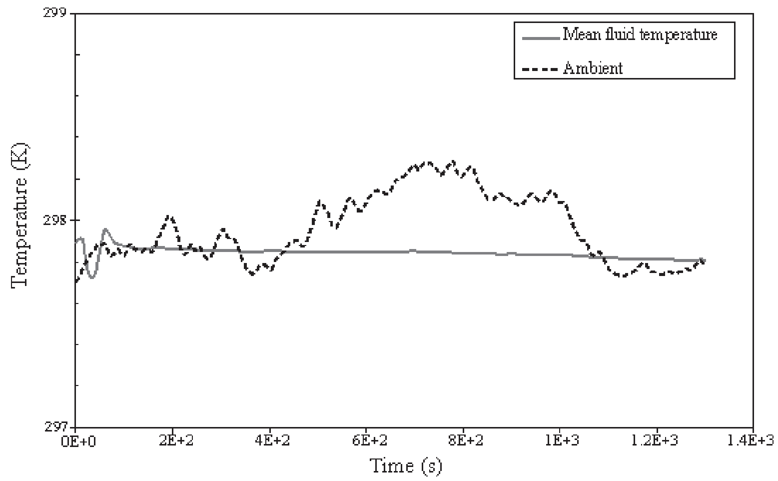


Fig.7. Results of the undisturbed ground temperature during water circulation inside the pile before the TRT

The undisturbed ground temperature of 297.85 K is inside the range observed for tropical climate areas found in the literature [4]. The ground temperature obtained in this study is comparable to the values measured in a site at Sao Carlos city, located in the central-east region of the State of Sao Paulo.

Heating test: ground thermal response and thermal properties

After the water circulation test, the thermal response test was performed during 246 hours to ensure the steady-state of heat exchange. Fig.8 presents the fluid temperature variation during the test. Tab.2 shows the values of fluid temperature at different times.

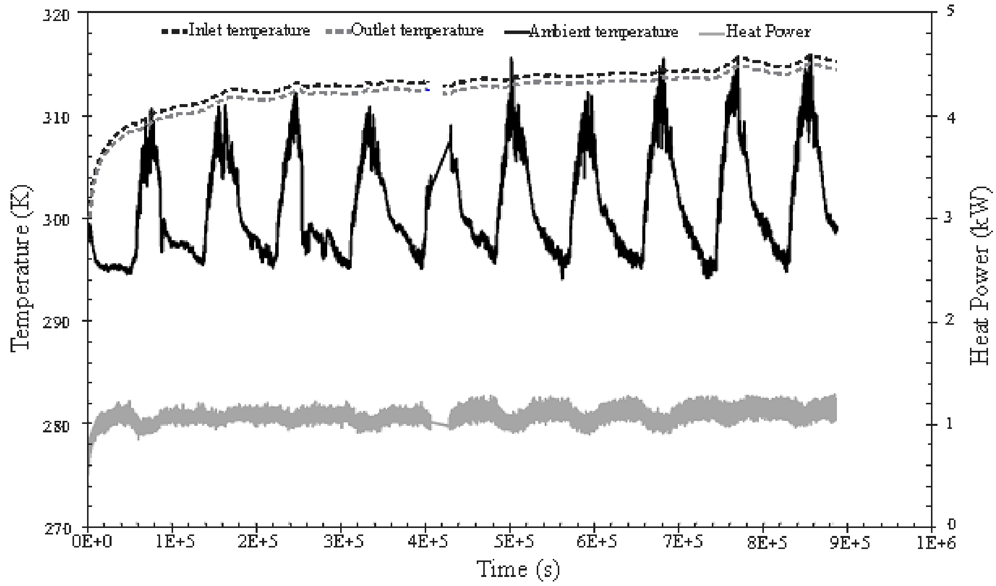


Fig.8. Variation of the fluid and ambient temperatures during the TRT

Table 2. Results of temperature measurements during the TRT.

TRT measurements	Unit	Value
Undisturbed ground temperature		297.85
Average ambient temperature		301.15
Maximum ambient temperature		315.95
Minimum ambient temperature		294.15
Average fluid temperature difference ($T_{in} - T_{out}$)	K	273.87
T_{in} at 50 hours		312.45
T_{out} at 50 hours		311.65
T_{in} at 100 hours		313.25
T_{out} at 100 hours		312.45
T_{in} at 200 hours		314.25
T_{out} at 200 hours		313.55
Flow rate	m/s	0.66
Average Heat power	kW	1.06

Fig.8 highlights the influence of the ambient temperature on the results of heat carrier fluid temperatures. This figure also illustrates that the heat power injection into the tubes was approximately constant during the period of test.

The parameters as thermal conductivity and pile thermal resistance are essential for the design of geothermal ground energy systems with energy piles. The thermal resistance (R_b) was calculated using Eq.3. Fig.9 presents the variation of the thermal resistance and ambient temperature during the TRT. The average value of the thermal resistance of the energy pile was 0.13 mK/W.

In this work, the Eq.4 was used for the determination of the ground thermal conductivity. The *k* value was obtained from the curve of mean fluid temperature versus the logarithm of time (*t*), as indicated in Fig.10.

Table 3 summarizes the main results estimated from the TRT carried out on the energy pile. As shown in this table, the effective ground thermal conductivity found for the soil investigated was 2.82 W/mK.

Table 3. Thermal response test results: thermal conductivity and pile thermal resistance.

	k	R^2	λ_{eff}	R_b
TRT	-	-	W/mK	mK/W
	1.99	0.85	2.82	0.13

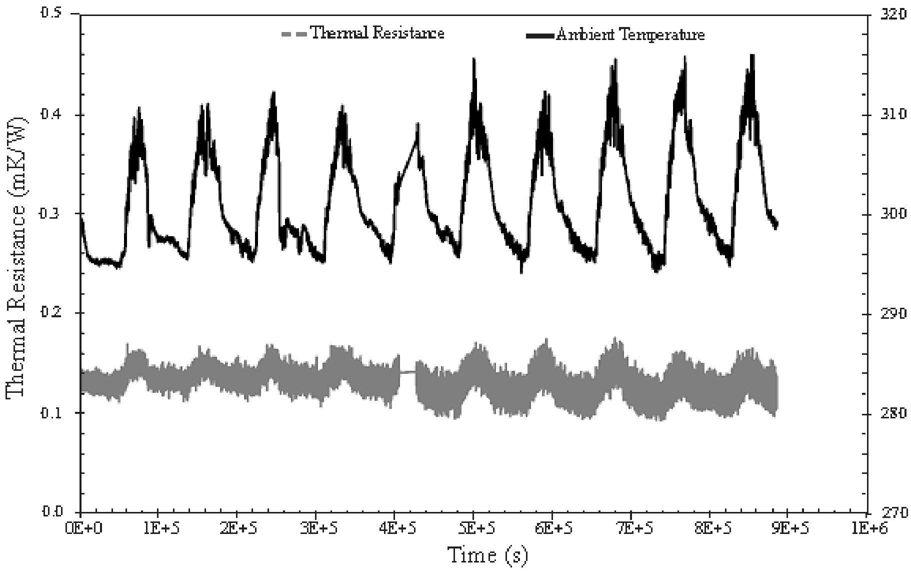


Fig.9. Energy pile thermal resistance during the TRT

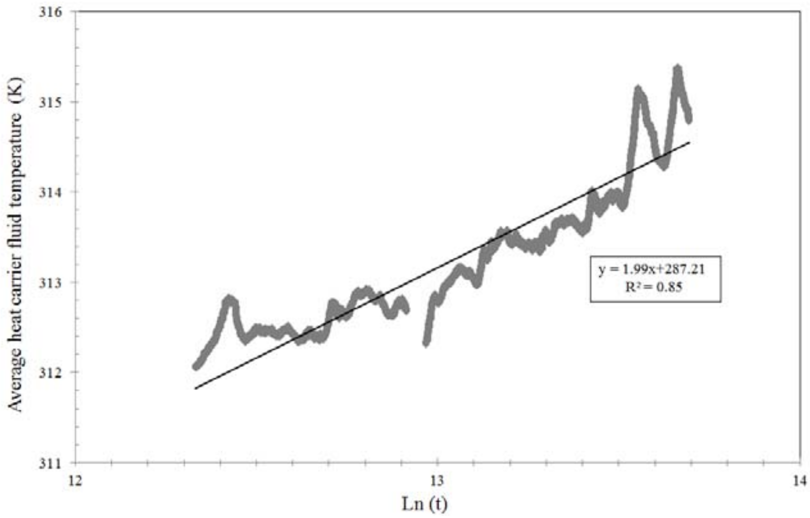


Fig.10. Mean fluid temperature versus the logarithm of time during the TRT

CONCLUSIONS

A thermal response test was conducted during approximately 10 days on an energy pile (micropile) of 15 m length with a U-shaped heat exchanger tube. The aim of the current investigation was to determine the ground thermal conductivity and the pile–thermal resistance of an energy pile installed in the campus of the University of São Paulo at São Paulo city (Brazilian subtropical region).

For analysing the TRT data, the line source model was used, and provided results of thermal parameters that are comparable to previous researches. Additionally, the undisturbed ground temperature of 297.85 K is similar to the results found from measurements in São Carlos city, located in the central-east region of the State of São Paulo.

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