Title

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Journal

Geotechnical and Geological Engineering, 40(5)

ISSN

0960-3182

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Publication Date

2022-05-01

DOI

10.1007/s10706-021-02043-z

Peer reviewed

Thermal response testing of a thermal pile in a tropical climate region

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Abstract

This study focuses on a sequence of thermal response tests carried out on a 12 m-long instrumented thermal pile performed at different times throughout a year in a location in Brazil with a tropical climate. The thermal pile was a cast-in-place concrete bored pile, installed in a stratified sedimentary deposit typical of the Brazilian coastal region. The results from the tests permit assessment of the heat transfer characteristics to evaluate the feasibility using thermal piles as a heat sink for building cooling purposes. Interesting thermo-mechanical phenomena were observed in the tests, including deformations of the concrete and the steel reinforcement, along with localized deformations at the tip attributed to the pile construction process. The results presented in this study indicate the feasibility of using this technology in tropical climate regions, and features regarding thermo-mechanical response of thermal piles in stratified soil profiles common to tropic regions were assessed and highlighted.

Keywords: Thermal pile, Thermal response test, Thermal induced stress

Introduction

According to official data, 60% of the energetic matrix in Brazil in 2014 came from non-renewable sources and approximately 80% of this fraction is responsible for emission of gases that lead to global heating effects (EPE 2016). According to data collected by SEEG in 2016, the energy sector was responsible for 31.7% of the emission of gases in Brazil that provoke greenhouse effects (Brasil MME 2015). Moreover, Brazil is a signatory of the Montreal Protocol and is committed to drastically reduce the use of hydrofluorocarbons (HFCs) in air conditioning systems commonly used in houses, companies, and public spaces.

The motivations to reduce greenhouse gas emissions and the use of HFCs are driving policy makers and engineers in Brazil to incorporate cleaner and more environmentally-friendly energy technologies into the energetic matrix. These technologies, including thermo-active geothermal structures combined with ground-source heat pumps, are of great appeal. Amongst these structures, thermal piles (also referred to as energy piles or thermo-active piles) are very attractive because they build upon a mandatory part of the structural support for heavy structures. Heat is transferred in thermal piles by circulating heated or cooled fluid through a closed-loop network of pipes embedded in reinforced concrete. Incorporating heat exchange pipes into deep foundations can be achieved with negligible additional costs beyond those expected for the structural element. The large contact area of thermal piles with soil along with their thermal properties makes the heat exchange mechanism in thermal piles more effective than conventional borehole heat exchangers (Loveridge and Powrie 2013). On the other hand, despite being a cooling-dominated tropical country, Brazil has not encountered a marked use of this technology. Studies to confirm the heat transfer characteristics of thermal piles in tropic soils are necessary, along with studies to help understand the impacts of heat transfer of the thermo-mechanical response of thermal piles in typical Brazilian stratified soil profiles.

Background

Due to their advantages, thermal piles have been used in practice throughout the world for the past two or three decades. According to Koene and Geelen (2000), the idea of using closed-loop heat exchanger pipes embedded inside concrete or steel piles to exchange heat with soil gave life to the first prototype in the 1990’s. Since that time, there have been several full-scale evaluations of the thermo-mechanical response of thermal piles and other structures such as walls and tunnels (Adam and Markiewicz 2009; Brandl 2006; Laloui et al. 2006; Bourne-Webb et al. 2009; Amatya et al. 2012; Bourne-Webb 2013a; Murphy et al. 2014; Bouazza et al. 2015; Murphy and McCartney 2015; Akrouch et al. 2014). There have also been several applications of thermal piles in practice. Laloui and Di Donna (2011) reported that as of 2011 more than forty large projects in Switzerland including schools, industrial buildings, and airports have implemented thermal piles~~,~~. However, in most of these cases, the thermal piles were being installed in heating-driven climates and in soil deposits that are not representative of those encountered in tropical regions like Brazil. The limited research studies on the feasibility of thermal piles in Brazil are theoretical and do not provide conclusive evidence of the behavior of thermal piles in the particular hydrogeological setting in Brazil (Bandeira Neto 2015; Morais and Tsuha 2016). Liu et al. (2019) performed tests on reduced scale models of thermal piles under varying climate conditions and found that the pile response due to temperature variations was somewhat dependent on the climate condition. Sutman et al. (2020) carried out numerical analyses to study the feasibility of thermal piles in different climates aiming to assess the life-cycle response of these structures, and found that the climate setting was an important issue to consider.

To address the need to characterize full-scale energy piles in tropical climates, this study focuses on the evaluation of an instrumented, 12 m-long concrete thermal pile installed at the State University of Norte Fluminense (UENF) site in Campos dos Goytacazes, Brazil, in a sedimentary stratified soil deposit with intercalation of clay and sandy layers typical of the Brazilian coastal region. The site under investigation is characterized by high annual temperatures throughout the year, which lead to ground temperatures well above those observed in previous studies on thermal piles installed in temperate climate regions. The tested area is close to the Paraíba River, where considerable fluctuations of the groundwater table (GWT) occur on an annual basis. To better understand the seasonal effects on system efficiency and the role of soil stratification and GWT fluctuations on the thermo-mechanical response of the pile, three thermal response tests (TRTs) were performed on the thermal pile at different times through a 180-day period. During this period, the first two TRTs were carried out when the air temperature was close to the annual maximum and the GWT was at its maximum elevation, while the last TRT was performed when air temperatures were cooler and after the GWT had dropped by approximately 3.5 m, as depicted in Figure 1. The soil layer affected by the GWT fluctuation is composed of clean sand. The thermal pile evaluated in this study is a cast-in-place bored pile, installed with rotary steel pipes with water circulation similar to a micropile. This type of pile and its installation method has received limited attention in the literature compared to other types of thermal piles (e.g., Akrouch et al. 2014, Bourne-Webb 2013b). The results from the three TRTs permit definition of the system thermal properties of the thermal pile and surrounding soil (thermal resistance and thermal conductivity) considering the characteristics of tropical regions with significant GWT fluctuations. Further, the thermal pile was instrumented with strain gauges oriented axially and radially to evaluate the corresponding changes in stresses and strains resulting from the temperature variations in the thermal pile over several heating/recovering cycles. The succession of TRTs performed over a period of 180 days also permits the assessment of potential effects of different temperature changes on the surrounding soil layers and related soil-structure interaction mechanisms. Special attention was paid to the effects of the organic soft soil layer at depths of 8.0 to 10.0m where plastic strains may occur due to thermal consolidation stemming from the heating-cooling processes. Therefore, a series of TRTs was necessary to investigate the long-term behavior of the pile regarding thermo-mechanical hysteresis resulting from thermal consolidation and ground water table lowering.

Thermal Response Tests

One of the key points for understanding thermal pile behavior is the mechanism of heat transfer in the system. The heat exchange between a thermal pile and the surrounding soil can occur due to three mechanisms: conduction, convection and radiation (Brandl 2006). Conduction is the predominant mechanism of heat exchange between the thermal pile and soils and depends on the contacts between soil grains, typically quantified using the dry density, and the degree of saturation. Convection should be considered in the presence of ground water flow, thermally induced buoyancy driven water flow, and in vapor flow in unsaturated soils. Convection is typically most relevant in high permeability soils (Catolico et al. 2016).. Radiation is important near the ground surface where vapor diffusion and water phase change may lead to large increases in heat transfer. In low-permeability, saturated soil deposits it is conventional to consider conduction as the primary mode of heat transfer.

Heat transfer by conduction is governed by Fick’s law of diffusion, and the key parameters governing conductive heat transfer are the thermal conductivity (λ) and the specific heat capacity (C_s) of the system. Thermal conductivity (W/m°C) refers to the amount of heat (W) that is transferred through a medium having a unit length (m) under a unit change in temperature (°C). The specific heat capacity is defined as the amount of heat that must be input (or withdraw) to change the temperature of 1 gram of a certain material by 1°C and is typically reported in units of J/kg°C. The other two key pieces of information that should be quantified in evaluating heat transfer are the initial soil temperature and the thermal gradient induced by a given heat transfer process.

The thermal conductivity of a pile-soil system is typically quantified using a thermal response test (TRT), which involves heating the thermal pile under a constant heat transfer rate and measuring the change in temperature with time (Hamada et al. 2007; Gehlin 2002; Austin 1998; Roth 2004; Moel et al. 2010; Murphy et al. 2014; Lhendup et al. 2014; Koene and Geelen 2000, Loveridge and Powrie 2013). Several theories have been investigated in these studies to interpret the results from a thermal response test. Analytical solutions for infinite line heat sources and cylindrical heat sources as well as numerical methods have been used to interpret thermal response tests, although the prior two methods are preferable due to their simplicity as long as the heat transfer process meets the basic assumptions of the analysis. This study focuses on the application of the infinite line source theory to interpret the TRT results.

According to the infinite line source theory, the temperature at a distance r from the heat source for a time t is given by:

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

where λ is the thermal conductivity, $\alpha = \lambda/\rho C_s$ is the thermal diffusivity, C_s is the specific heat capacity, ρ is the total density of the soil, Q is the heat transfer rate in W, and γ is the Euler constant. Equation (1) can be rearranged to solve for the thermal conductivity but can also be used to evaluate the thermal resistivity R_b, which is a measure of the impedance for heat transfer through a system, as follows:

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

Minimizing the thermal resistance R_b of thermal piles by incorporating concrete additives, changing the embedded tubes configuration or adjusting the input flow velocity are approaches to improve the efficiency of geothermal heat exchangers (Sanner et al. 2005; Kim et al. 2003).

During a thermal response test (TRT) heat is injected into the pile at a constant heat transfer rate Q, corresponding to a heat transfer rate per unit length of the heat exchanger q. In this case the thermal conductivity can be calculated from measurements of the average thermal pile temperature at two times t_1 and t_2, as follows:

$$\lambda=\frac{q}{4\pi}\frac{\ln(t_2)-\ln(t_1)}{\acute{T}_2-\acute{T}_1} \tag{3}$$

where $\acute{T}_i$ is the average thermal pile temperature at time t_i, which can be assumed to be the mean of the input and output fluid temperatures. The values of times t_1 and t_2 should be any two times larger than 6 hours. Loveridge and Powrie (2013) presented a comprehensive study of the thermal response of thermal piles, involving an evaluation of different variables such as the pile aspect ratio, internal pipe arrangement and the theory used in the TRT interpretation. They found that the use of Eq. 1 shows some deviation for the first six hours of heating as compared to numerical solution, so a criterion is needed to define the portion of the temperature rise curve when calculating the thermal conductivity.

Typical values of λ calculated using this approach can be found in Murphy et al. (2013) for thermal piles and in Wagner and Clauser (2005) for conventional borehole-type geothermal heat exchangers.

Several other studies have evaluated various aspects of the thermal response of thermal piles. For example, Park et al. (2015) presented results from field studies on a large diameter drilled thermal shaft with coiled heat exchangers on with two different pitches to evaluate their constructability and efficiency. They found that the internal pipe coil-type system may not be well represented by traditional analytical models and that a tighter coil is not necessarily more efficient than one that has a wider spacing. Park et al. (2013) carried out a field test to investigate the influence of the internal pipe shape in pre-cast concrete thermal piles and they found that “3U-shaped” and “W-shaped” configurations do not affect significantly the performance of the thermal pile for continuous operation. Hamada et al. (2007) tested several internal pipe arrangements and found that a “U” shape for the heat exchanger is the optimal choice for both constructability and economic efficiency. You et al. (2014) evaluated the impact of the heat transfer rate, inlet water temperature, and fluid flow velocity and found that the heat transfer process is most dependent on the fluid flow velocity.

Structural Behavior of Thermal Piles

It is well known that temperature changes in thermal piles can lead to thermal deformations that may induce changes in stresses that should be considered to avoid compromising their safe operation from a structural perspective. The earliest comprehensive thermo-mechanical test on thermal piles was reported by Laloui et al. (2006), who evaluated the temperature distribution and strains in thermal pile in overconsolidated clay during monotonic heating and they found a good match with predictions from a thermo-elastic finite element model. Bourne-Webb et al. (2009) along with a follow-up paper by Amatya et al. (2012) presented the results from heat injection and extraction tests on a free-head thermal pile and used fiber-optic sensors to evaluate the thermally-induced strains which were used to assess the restraints provided by the ends of the pile (the head and tip), and the side shear resistance. Stewart and McCartney (2013) and Goode and McCartney (2015) evaluated the thermo-mechanical responses of centrifuge-scale thermal piles having different end restraints and were able to assess the load-settlement behavior of the piles after heating. Murphy et al. (2014) presented the results from TRTs performed on eight 14 m long concrete thermal piles under the mechanical load and stiffness restraints of an actual one-story building. A variation in average pile temperature of 18°C was observed in the pile, resulting in an increase in axial stress up to 25% of the compressive strength of the concrete used in the project (approximately 21 MPa), the maximum strains were located near the pile head, and the maximum stresses were located near the bottom of the piles. Murphy and McCartney (2015) and McCartney and Murphy (2017) reported on the long-term behavior of two thermal piles installed beneath an eight-story building in a claystone layer during operation of a heat pump over a period of six years and observed a gradual change in the axial strains and stresses over time. This temporal change was attributed to a dragdown effect that may be associated with temperature effects on the thermal volume change of the surrounding subsurface. Rotta Loria and Laloui (2018) have studied the effect of differential thermal expansion of sandstone strata on the thermal response of a thermal pile. Several authors have also evaluated the thermo-mechanical response of thermal piles by means of numerical methods (e.g., Wang et al. 2014; Gashti et al. 2014; Dupray et al. 2014; Laloui et al. 2006; Suryatriyastuti et al. 2014; Chen and McCartney 2016). The model of Suryatriyastuti et al. (2014) permitted consideration of the evolution of axial stress and shaft friction during thermal cycles.

Despite the wide range of observations from the previous studies noted above, the thermo-mechanical response of thermal piles in tropical regions and stratified subsoil has not been entirely evaluated. Specific conditions that are common in tropical regions that may lead to a different response compared to other climate zones, including high surface and ground temperatures during both night and day, fluctuations in the level of the GWT, high air humidity, and upper layers of unsaturated soils. In such regions, the ground temperature has been recorded to be around 24 to 28 °C (Morais and Tsuha 2016) and the temperature gradient between day and night can be as wide as 20°C. In addition, thermal piles installed in stratified subsoil are expected to show a particular mechanical response when heated due to different properties of the pile-soil interface with depth. This variation in pile-soil interface behavior with depth can give rise to differential strain distributions, which is investigated herein.

Materials and Methods

Test Set-Up

This study involves the evaluation of a cast-in-place concrete bored pile with a diameter of 0.4 m and a length of 12.0 m installed at the Campus of UENF, located in the city of Campos dos Goytacazes in Rio de Janeiro State, Brazil. The site is located on the right margin of the Paraiba River, in the sedimentary Paraiba basin soil deposit (21°45’38”S, 41°17’34”W, Datum WGS84). The local subsoil is composed of thick layers of sand and thin layers of silt and clay. A soft organic clay layer with a thickness of approximately 2.0 m is located at a depth of approximately 8.2 m. The low standard penetration test (SPT) blow count, N_{spt}, shown in Figure 1 indicates that this clay layer has low shear strength and may be susceptible to contractile thermal volume changes such as those observed by Hueckel et al. (1987). The low shear strength and potential for thermal volume change of the clay layer may influence the axial stress-strain response of the thermal pile over time.

The installation of the thermal pile consisted of a pre-bored shaft made with rotary steel pipes and water circulation to loosen and remove the excavated soil. The bored shaft was stabilized with bentonite slurry. After the excavation, the cage was inserted into the slurry and fluid concrete was poured from the bottom of the shaft through a PVC tremie tube to expel the bentonite. The concrete used in the pile was very fluid with a low aggregate content composed by quartz sand and gravel (D_{50}=2.36 mm), as recommended for this type of pile. This construction technique is commonly used for micropiles in Brazil and may lead to different characteristics from a bored shaft in overconsolidated clay like those characterized by Laloui et al. (2006), Bourne-Webb et al. (2009), or McCartney and Murphy (2017) or in sandstone like Murphy et al. (2015).

After curing, the concrete had a compressive strength of 29MPa and a tensile strength of 3.4 MPa measured from a diametric Brazilian test. The compressive uniaxial test has shown an elastic modulus of 30 MPa at 50% of the maximum strength. For the longitudinal reinforcement, three steel bars having a diameter of 9.5 mm were configured in a triangular arrangement. The heat exchange tubing embedded in the pile was composed of PEX-A monolayer tube having an external diameter of 25 mm and a thickness of 2.3mm. The heat exchange tubing was placed in a simple “U” shape extending along the entire length of the pile.

Vibrating wire strain gauges with embedded thermistors were attached to the reinforcing cage (Geokon model 4150) and embedded in the concrete (Geokon model 4200) at the different locations shown in Figure 1, in order to understand the strains in the piles resulting from temperature variations. A total of nine concrete embedment strain gauges and six strain gauges welded to the steel cage were included along the length of the pile. The thermistors within the vibrating wire strain gauges were useful in measuring local temperatures. Three of the strain gauges were concentrated near the pile tip to evaluate the effects of end restraint boundary condition, which is critical in this type of installation. One strain gauge of each type (concrete and steel) was placed horizontally at the mid-depth of pile in the center to capture the horizontal strains during the heating-cooling cycles. Dividing these horizontal strains by 2 provides the radial strain in the pile.

After pile installation, curing of the concrete, and the setting up of the facilities (128 days), a series of three TRTs were performed on the thermal pile. The test setup includes tubes for circulating fluid (water) through the pile for heat exchange, an isolated water tank with temperature control, a water pump, two thermistors for measurement of the inlet and outlet fluid temperatures, a flow meter, and a data acquisition system for the embedded strain gauges and thermistors (Figure 2). The data acquisition for the TRT was developed with an

Arduino-based platform, and a manual (not continuous) data reader from Geokon was used to monitor the strain gauge readings during TRTs.

TRT Tests - General Initial Conditions

The TRTs were performed in three different periods to capture the behavior of the thermal pile during different seasons. The time gap between each TRT was sufficient for the thermal pile to return to ambient temperature after heating from the prior TRT. TRT 1 and TRT 2 were carried out close together, with only 28 days between the end of TRT1 and the start of TRT 2. A longer waiting time of 150 days between TRT2 and TRT3 was used to help investigate the impact of performing TRT3 in the cooler season where the groundwater table was expected to be at its low point. The first two TRTs were performed in the summer where the ambient air temperature was about 30°C (the mean temperature for December 2016), while TRT3 was performed in the winter where the average air temperature is approximately 22°C. This schedule allowed assessment of seasonal effects on the thermal pile in addition to the effects of GWT fluctuations. The GWT was not directly measured in this study, but was interpreted from the elevation of the river as the site under investigation is only 50 m from the riverbank. This assumption is reasonable as the uppermost 8 m of soil at the site is high-permeability sand. Accordingly, it is expected that the GWT level with be the same as the level of the river, which decreased by 3.5 m between TRT2 and TRT3.

Before starting the TRTs, it was necessary to define the heat exchange fluid flow rate required to maintain turbulent flow conditions in the heat exchanger tubing to maximize heat transfer. For the diameter of tubing evaluated in this study, the flow rate had to be higher than 3.8l/min. The mean flow rates adopted for TRT1, TRT2 and TRT3 are presented in Table 1 and all correspond to turbulent regime conditions.

Next, to determine the mean temperature of the ground at the start of the tests, the circulating pump was operated for 30 minutes until the inlet and outlet heat exchange fluid temperatures became constant. The input and output heat exchange fluid temperatures were recorded, and the mean temperature of the subsoil was obtained by a simple arithmetic mean as shown in Table 1.. Despite the fact that the mean ground temperature in TRT3 was smaller than during the other two TRT tests, itwas highly influenced by the temperature of the organic clay layer, which was up to 4°C below the ground temperatures at this depth recorded in TRT1 and TRT2 (in the summer). This seems to be associated to the recharge of the GWT and heat retention capacity of this organic clay layer. Table 1 also shows the heat power used in the three TRTs and the final pile temperature along with the duration of each test up to stabilization under the constant heat transfer rate.

Table 1. Characteristics of the three TRTs

TRT	Heat Exchanger Fluid Flow Rate (l/min)	Initial Ground Temperature (°C)	Heater Power (W)	Final Pile Temperature (°C)	Duration (h)
TRT 1	19.4	28.7	1000	49	140
TRT 2	23.4	30.3	1000	49	115
TRT 3	15.0	28.3	1300	52	150

Results

Thermal analysis

The thermal properties of the subsoil were estimated from the measured data using the infinite line source equation given in Eq. 1. To apply this equation, it is necessary to calculate the heat transfer into the system, which can be calculated as follows:

$$\dot{Q} = C_s \cdot \dot{V}_m \cdot (T_i - T_o) \tag{4}$$

where C_s is the specific heat of the fluid (J/kg°C), $\dot{V}_m$ is the mass flow rate (kg/s), T_o is the output temperature (°C) and T_i is the input temperature (°C). Clean tap water was used as the heat transfer fluid and its specific heat capacity is 4187 J/kg°C. Table 2 shows that the mass flow rates were different in each of the TRTs. According to Equation (4) a higher mass flow rate should lead to a higher heat transfer rate.

With this information, the next step was to calculate the heat transfer for each instant of the tests using Eq. (4), whose values are depicted in Table 2. According to the values presented in Table 2, a significant increase in heat transfer was observed for TRT 3 despite the lower mass flow rate in this experiment. This was attributed to a new more powerful heater supplying a heat power input 1300W. The heat losses are due to installation features due to insulation of the tank and the distance from the heat source and the pile of approximately 5m. An important piece of information from the TRT tests is the rate of the heat exchange per length of the thermal pile during heating, which are also summarized in Table 2 and were obtained by dividing the measured heat transfer rates by the total length of the pile. These values are at the lower boundary of the range in heat transfer rates per unit length of 44 to 139 W/m obtained from several previous TRT studies on thermal piles summarized by Olgun and McCartney (2014).

Table 2. Thermal analysis results

TRT	Mass Flow Rate (kg/s)	Heat Transfer Rate (W)	Heat Exchange Per Unit Pile Length (W/m)
TRT1	0.32	484	40
TRT2	0.39	552	46
TRT3	0.25	778	65

Time series of temperature at different locations in the thermal pile for each TRT are shown in Figure 3. The initial temperatures at some of the depths are different for each of the TRTs, likely due to ambient surface temperature interactions and the possibility of groundwater recharge at different depths. The time series indicate that slightly higher temperatures, around 45 °C were reached in TRT2 and TRT3. This partly occurred due to the higher heat transfer rates in these two tests, and because TRT3 started from lower ground temperatures. When investigating the maximum temperature at different depths, the greatest temperatures were achieved in TRT3. Relatively high temperatures may have been achieved in TRT2, despite its shorter duration due to power failure, because of the higher thermal conductivity of the ground associated with a higher GWT.

Profiles of the initial and final temperatures with depth in the pile for each of the three TRTs are shown in Figure 4a, while profiles of the changes in temperature with depth are shown in Figure 4b. These profiles indicate that the temperature is not uniform along the length of the thermal pile, an observation that was made by Murphy et al. (2015) for a thermal pile in uniform sandstone. The difference in temperature may be due to non-uniform heat transfer from the thermal pile in the different soil strata shown in Figure 1. The heat transfers and resulting changes in temperature of the pile may also depend on the initial temperature of the soil layer at the beginning of each TRT and the GWT level.

When determining the thermal conductivity using the line source method, the mean fluid temperature ($\left(T_i+T_o\right)/2$) (in °C) was plotted against the natural logarithm of time (Figure 5). The slopes of these curves were then determined, disregarding the data from the first 46 hours, as recommended by Loveridge (2012) and Loveridge et al. (2014) in order to attend the Eq.1. The thermal conductivity expressed in W/(m°C) was then calculated using Eq. 3, and the found thermal conductivity values are shown in Table 3. The thermal conductivity appears to be sensitive to the heat transfer rate applied in the experiments, but the thermal conductivity of the ground could also be affected by changes in ambient surface temperature and GWT fluctuation. For saturated clean sands, the typical value of thermal conductivity is around 2 to 3 W/(m°C). For loose sands, the thermal conductivity is less sensitive to the degree of saturation than denser sands (Chen 2008). The lowering of the groundwater table may lead to a decrease in the thermal conductivity of sandy soil layers, but convective heat transfer in unsaturated soil may occur due to vapor diffusion. The lowering of the groundwater table leads to an increase in effective stress, which may lead to a densification of the soil and corresponding increase in thermal conductivity.

According to Eurocode (CEN 341 N525 2011), thermal conductivities higher than 1.7 W/m°C are considered suitable for the application of thermal piles. Therefore, it can be said that the values measured in the three TRTs indicate that the thermal pile evaluated in this study could be appropriate for establishing a geothermal heat exchange system. The thermal resistance of the system can be calculated from the thermal conductivity values using Eq. 2. However, it is first necessary to estimate the thermal diffusivity of the system, which requires an estimate of the specific heat capacity, C_s of the subsoil components. Herein, the value of C_s was estimated as function of the mineralogy of the soil layers surrounding the thermal pile that were projected from values presented by Lhendup (2014). Specifically, C_s was estimated as a weighed mean of the values likely for each layer (shown in Figure 1), as follows:

$$C_s = \frac{\sum_{i=1}^{n} C_{s,i} . l_i}{\sum_{i=1}^{n} l_i} \tag{5}$$

where $C_{s,i}$ and l_i are the specific heat capacity and thickness of each soil layer.. This resulted in an equivalent specific heat capacity of 1.82 kJ/(kg°C) (which corresponds to a volumetric heat capacity of $2.92 \text{x} 10^6$J/(m^3°C)). The values of thermal diffusivity α of the soil calculated from the measured thermal conductivity values in each TRT and the estimated values of specific heat capacity of the system can be seen in Table 3. Based on these values, the mean thermal resistance values calculated using Eq. 2 and the resulting values shown in Table 3 are in accordance with those reported in the literature (e.g., Abuel-Naga et al. 2015).

Table 3. TRTs system results

TRT	Thermal Conductivity W/(m°C)	Specific Heat Capacity (m^2/s)	Thermal Resistance (m°C/W)
TRT1	2.15	$7.40\text{x}10^{-7}$	0.43
TRT2	2.14	$8.24\text{x}10^{-7}$	0.41
TRT3	2.59	$8.9\text{x}10^{-7}$	0.30

Mechanical Analysis

The impacts of temperature changes in each soil layer on the strain distribution along the thermal pile in each of the three TRTs were evaluated using the results from the strain gauge measurements. The thermal strains can then be used to evaluate the resulting stresses generated due to the restraint of the thermal pile by the surrounding ground. For the vibrating wire strain gauges, the shortening or stretching of the steel wire due to the variation in the temperature should be accounted for using a correction equation to identify the actual strain ($\varepsilon_{\text{real}}$) measured by the gauge during heating, given as follows:

$$\varepsilon_{real} = B\left(R_1 - R_0\right) + \left(T_1 - T_0\right)\alpha_{steel} \tag{6}$$

where B is the strain gauge manufacturer constant (equal to 0.962), and R_1 and R_0 are the readings of the strain gauge at different times, α_{steel} is the coefficient of thermal expansion for the steel wire, which was reported by the manufacturer to be 12.2 $\mu\varepsilon$/°C. As no mechanical load was applied to the pile, the initial strains were due to curing of the concrete and they were zeroed out before the start of each TRT. Accordingly, any changes in strain after the start of each TRT are expected to be due to the thermo-elastic movements of the thermal pile and to the impact of thermal volume changes of the surrounding soil on the deformation of the thermal pile. Therefore, it is understood that the strains shown herein were resulting only from the temperature changes in the specific TRT (i.e. they were zeroed at the beginning of each TRT). The strains mentioned here did not accumulate from one TRT to the subsequent TRT.

Profiles of the real strain in the thermal pile with depth measured from the concrete strain gauges at the end of each TRT are shown in Figure 6. Unfortunately, two strain gauges, one installed in the cage close to the top of the pile and the other embedded in the at a depth of 4.0m, malfunctioned just before TRT3. Accordingly, this part of the curve for TRT3 is not shown in Figure 6. During heating, tensile (negative) strain increments were observed in all tests, indicating thermal expansion of the pile, as expected. Horizontally-oriented strain gauges placed at a mid-depth of 5.8 m indicate thermal expansion with magnitudes similar to those of the axial direction. Although the pile experienced the greatest increases in temperature in TRT3, the thermal pile did not expand proportionally to it when compared with the strains in TRT1 and TRT2. As will be discussed, the unexpected response during TRT3 is attributed to the lowering of the GWT to a depth of 7.5m, leading to an increase in effective stress in the sandy layer.

Higher thermal strains, around 180 to 210 $\mu\varepsilon$, were observed near the tip of the thermal pile in all three TRTs. This can be attributed to the lower end bearing capacity expected for piles built with the construction technique described above (where the shaft was bored with circulating water that strongly disaggregates the soil in the base). Regarding the strain near the head of the thermal pile, strains around 160 $\mu\varepsilon$ were observed despite lower increases in temperature compared to the rest of the pile. The large magnitude of strain near the head of the pile is closely related to the higher degree of freedom in piles with low head restraint. It is also interesting to mention that higher strain of approximately 240 με were recorded in the vicinity of sensor SC2 (in the organic clay layer), which may be attributed to higher temperature increments in this layer associated with the higher values of specific heat capacity for this layer. This observation emphasizes the importance of considering the effects of each soil layer in a stratified soil deposit.

In order to make a cautious comparison among the three TRTs, it is important to note that, due to non-uniform temperature distribution in the pile, the resulting strains should be compared to those from the subsequent TRTs at the same location, taking into account the local temperature, as well. Similar strains do not necessarily mean similar response if the local temperature is different for each TRT. Comparison based only on the strain values may lead to incorrect conclusions. In TRT1, according to the temperature change ($\Delta T = 13^{o}C$), the thermal strain observed near the tip of the pile was about 197 με. However, the tip did not show the same response in the two subsequent TRTs. TRT2 imposed an increment of temperature of 14ºC and the resulting strain was 185 με when the expected value should have been 210 με if the same coefficient obtained in TRT1 was used. Using the same reasoning for TRT3 the expected value would be 225 με but the recorded value was 210 με. The greater restraint implied by the reduction in this ratio in subsequent TRTs may be attributed to thermal consolidation of the soil near the tip of the pile. It is important to stress that the pile tip is placed in a transition region between organic soft clay and sand that was strongly affected by the pile installation method. However, strains calculated from the steel sensor indicated a lower strain at the tip than those measured by the concrete embedment strain gauge. This indicates that some slippage may be occurring between the cage and the concrete near the tip during thermal expansion in TRT1, which could be caused by the incomplete removal of bentonite slurry used during pile installation and/or the presence of cracks in the concrete. This has been corroborated by the fact that a sudden strain of 36.1 $\mu\varepsilon$ was observed at the location of SC1 (near the tip) during the first few minutes of TRT1, while the other sensors did not record any similar extra strains. This marginal strain was then subtracted from the sensor (SC1) readings. Therefore, the results presented in Figure 6 for the tip during TRT1 did not consider this initial strain, which is not a standard thermally induced response. This effect was not observed during subsequent TRT 2 and TRT3.

The accumulated thermal strain increments as a function of the change in temperature for each sensor are shown in Figure 7a. The slope of these curves permits an estimate of the mean mobilized coefficient of thermal expansion of the reinforced concrete α_{mob}. It is important to call attention for the line for TRT1 observed at the pile tip (SC1), where considerably strains occurred during the very initial heating process, corroborating with the findings discussed in Figure 6. This is represented by a sudden increase in strain occurred without an enough increment in temperature that justifies such behavior (Fig.

7a). The mobilized coefficients of thermal expansion plotted as a function of depth from each of the three TRTs are presented in Figure 7b. The induced pile strains are directly linked to the changes in local temperature as well as the side shear resistance and end restraints. Higher mobilized coefficients of thermal expansion were observed for maximum strain loci (i.e. near the tip and the head of the thermal pile). It is important to note that between depths of 2.0 and 4.0 m, the mobilized coefficients of thermal expansion for TRT1 and TRT2, was approximately 80% of the free thermal expansion of that of the concrete (α_{free} = 16 $\mu\varepsilon$/°C), indicating that the pile had a considerable degree of freedom to deform in the soft soil layer. The horizontal mobilized thermal expansion becomes progressively smaller from TRT1 to subsequent TRT2 and TRT3, varying from 12 to 8 $\mu\varepsilon$/ºC. Unfortunately, the GWT level was not recorded during TRT2. However, it is known that the GWT was lowered from a depth of around 3.5m to 7.0m between the times that TRT1 to TRT3 were performed, which can explain the behavior of horizontal strain pattern of the pile at this particular depth.

For the assessment of increment of stress σ_T due to thermal expansion of the pile, the mobilized coefficient of thermal expansion is used for each point of the pile in the following equation:

$$\sigma_T = E(\varepsilon_T - \alpha_{free} . \Delta T) \tag{7}$$

where E is the elastic modulus of concrete (30GPa) and ε_T is the thermal strain of a given sensor. The product $\alpha_{free} \cdot \Delta T$ represents the unrestricted (free) thermal strain of the pile. The thermal expansion coefficient of the concrete, α_{free} used was, as shown before, estimated to be 16 $\mu\varepsilon$/°C, which is a representative value of fluid concrete with high proportion of fine aggregate. Similar values of the coefficient of thermal expansion of concrete with high fines fractions were also reported by Goode and McCartney (2015).

Profiles of thermal axial stress with depth in the thermal pile, at the point of the maximum changes in temperature for the three TRTs are shown in Figure 8. Similar to the thermal axial stress profiles presented by Murphy et al. (2015), the maximum thermal axial stress of around 3 MPa in the first two TRTs occurs near the zone above the tip of the pile, due to both the higher restraint in this zone and the progressive consolidation of the clay layer that increases the lateral restraint for TRT2 and TRT3. This indicates that the null-point of the pile is in this region and that the pile is moving upward in the upper length of 8.0 m and moving downward below this elevation. The magnitudes of maximum thermal axial stress range from 2 to 2.8 MPa in these first two TRTs, which is lower than the magnitudes observed in the thermal piles in sandstone measured by Murphy et al. (2015). A change in radial stress in the pile, at 6.0 m depth, was also observed in TRT1 and TRT2, with values higher than of axial stress. In TRT1, the thermal radial stresses are considerably lower than in TRT 2 and TRT3. The maximum thermal compression radial stress of 3.5 MPa was observed in TRT3. This can be an indication of the change in confinement in this particular subsoil region where the hysteresis is more pronounced. In TRT3, the shapes of the profiles of thermal axial stress are similar to those in TRT1 and TRT2, disregarding the sensor at 4.0m deep due to malfunctioning for TRT3. The magnitude of the thermal axial stress calculated from Eq.7 may not be accurate for representing the axial stress in the pile because the stress at this depth, about 10m deep, could have occurred due to mechanical strains (possibly dragdown), even though the analysis in Figures 7b and 8 indicates that an increase in thermal axial stress should be expected due to the smaller mobilized coefficient of thermal expansion. These additional mechanical strains could be due to effects associated to changes in effective stress related due to the lowering of GWT between TRT2 and TRT3 increasing, thus, the weight of the soil in this region and therefore the horizontal stress that is directly related to lateral resistance.

To investigate the reasons for the different response in each TRT the initial axial strains at the end of natural cooling for TRT1 and TRT2 (i.e., before zeroing the strain values at the beginning of TRT2 and TRT3 to evaluate the thermal axial strains) along with changes in temperature at these times with respect to the beginning of TRT1 are plotted in Figure 9a. Here it is possible to notice some residual strains around 70με near the soft clay layer. This may be an indicative of thermal consolidation of this layer. The difference between these two initial strain profiles can be assumed to represent the mechanical strain in the pile at the beginning of TRT3, shown in Figure 9b resulting from the change in effective stress (and also the soil weight) in this subsoil region. This mechanical strain can be multiplied by the

Young’s modulus of the pile to define a side shear stress, which can be added to the thermal axial stresses from TRT3 to define the total axial stresses in the thermal pile as shown in Figure 9c. The addition of the mechanical and thermal stresses indicates high compression stresses near the tip, with values of up to 6.0 MPa. This may have been caused by a component related to downward movement due to thermal consolidation of the soft clay layer resulting from the thermal load applied in the earliest TRTs (seen in the bottom of Figure 9a) actin along with the GWT variation.

The results in Figure 9a indicate that there were two marked temperature variations due to natural seasonal effects between November-December (28 days) and December-June (150 days), which are the months when TRT1, TRT2 and TRT3 were carried out, respectively. The temperature variation for each sensor also indicates that the soft organic clay layer at depths between 8.0 and 10.0 m cooled by around 4 °C from December to June. It is interesting to notice that the sensors close to the surface also registered negative temperature variations, as June is winter in Brazil where records have shown air temperatures around 22°C, while for December 2016 the mean temperature was around 31 °C. Between these two specific points in time, i.e. during natural cooling, the pile shows a compressive behavior as depicted in Figure 9b. The zone between 2.5 and 6.5m could not be analyzed because of the sensor malfunctioning during TRT3.

It is important to evaluate the evolution of the recovered strain in the period of natural cooling of the pile for the three TRTs. The curves shown in Figure 10 represent the thermal axial strains at the maximum heating in each TRT (which were zeroed at the beginning of each TRT) and after the full period of ambient cooling down between each TRT that is indicated in the figure. Consistent with the discussion of results in Figure 9, significant residual strains were observed for TRT1. This indicates that a substantial permanent deformation around 80 $\mu\varepsilon$ at the soil-pile interface occurred near tip from a source of pile deformation other than thermal. It is reasonable to attribute this feature to the thermal consolidation process at the tip zone. The steel strain gauges near this concrete embedment strain gauge at this depth also captured this feature

Another possible effect of the lowering of the groundwater table is that the sand layer may have increased in unit weight from submerged (buoyant) conditions to partially saturated or dry conditions, leading to an increase in effective stress on the clay layer, as already stated before. Effects due to temperature changes in the clay layer could also be present but it is quite difficult to assess without a measurement of the historical series of the soil temperature at this location. The mechanism of excess of pore water pressure generation due to heating of clay soils has been presented in detail by Booker and Savvidou (1985) and can be used to explain the lower thermal strains and the consequent higher thermal stress developed in this region (cf. Figures 6 and 8).

Horizontal Strain Response

The pile instrumentation includes two strain gauges (SC6 and SS6) in horizontal orientations at a depth of 5.8 m, which can be used to compare the thermal expansion of the pile in the horizontal direction with that in the vertical direction during the three TRTs. A comparison between the degree of freedom in the horizontal and vertical directions in the concrete during each TRTs is shown in Figure 11. The degree of freedom can be understood as the ratio between the actual strain and the strain relative to the unrestricted condition (Bochon 1992). As there was no vertically-oriented strain gauge at a depth of 5.8 m, the mean of the vertical axial strains from sensors SC5 and SC7 were used for comparison. Two interesting observations can be drawn from the results in Figure 11. First, for all TRTs, the vertical strain was greater than the horizontal strain, while this ratio is becoming smaller for each subsequent TRT. This may have been caused by an increase in side shear stress due to lowering of GWT that affected the vertical strain during the third TRT. Second, the degrees of freedom in both the horizontal and vertical directions decrease during each TRT, indicating an increase in lateral and vertical restraint during each TRT. This behavior has also been captured by the thermal stress as presented in Figure 8, which shows higher stress for the horizontal gauge in TRT3.

Tip Analysis

An unexpected observation regarding the structural response of the pile that was captured during the tests was the response pattern of the tip of the pile, especially during TRT1. At the tip, there is a concrete sensor (Strain Gauge SC1) and a cage sensor (Steel Strain Gauge SS5) installed at the same depth. Further, a second concrete sensor (Strain Gauge SC2) was placed at approximately 0.70 m above the tip sensors. The deformation time history of these three sensors during the three TRTs are shown in Figure 12. The sensors at the tip (both concrete and steel) show almost the same strain results for TRT2 and TRT3, as expected. However, for TRT1, there is a “gap” between the measured strains, indicating a different response between the steel and concrete at the tip of 36.1 $\mu\varepsilon$. This strain was recorded just during the first minutes of heating. This observation may indicate a slippage between the reinforcement and concrete, possibly due to the adopted construction process, which was revealed when the pile started to deform due to thermal loading. (i.e., fissures in the concrete or bentonite grouting remaining attached to the reinforcements after concrete injection from the bottom). In the plot for TRT1, the dotted curves are for the free expansion of the concrete. It can be clearly observed that the readings from the concrete sensor SC1 are always greater than that of the free concrete expansion, which is structurally inadmissible. This indicates that an unexpected pattern of deformation is occurring near the pile tip. Comparing concrete sensor SC1 with concrete sensor SC2 a discontinuity in strain is observed. For TRT1 both the concrete sensor SC1 and steel sensor

SS5 should have shown almost the same results that could indicate a reasonable structural condition of the pile tip. However, the steel sensor SS5 shows smaller strains, indicating an irregular strain field in the concrete near the tip. This feature seems to be the reason why low compressive stresses had been developed in this region. For subsequent tests TRT2 and TRT3, this feature was not observed, and the expected strain field (i.e., the tip SC1) has shown smaller strains than of the region above it (SC2) and the concrete and steel strain values matched). This may have been due to the consolidation of the soil near the toe of the pile after the first TRT.

Conclusions

The goal of this study was to demonstrate the suitability of thermal piles in a tropical climate as an approach to help reduce HCF emissions. Relatively high thermal conductivity values of 2.15 to 2.59 W/m°C were observed for a 12 m-long thermal pile in the form of a bored pile installed in a sedimentary stratified soil deposit with a relatively high ground water level after a series of three thermal response tests (TRTs) performed at different times of the year. These thermal conductivity values reflect the efficiency of the tested pile in stratified soil deposits.

Interesting observations were drawn due to the impact of the stratified soil layer on the thermal response of the thermal pile. A non-uniform pile temperature was observed at the end of each thermal response tests due to the different thermal conductivity and specific heat capacity of each soil layer. A drop in the elevation of the ground water table by 3.5 m between the second and third TRTs led to an unexpected increase in the system thermal conductivity. It was expected that the thermal conductivity of the sandy soil in the depths where the groundwater table lowered would have decreased due to a decrease in degree of saturation, but this decrease may have been compensated by convective heat transfer in the unsaturated soil under the higher heat transfer rate applied in the third TRT. The lowering of the ground water table also led to an increase in effective stress which may have densified the soil along the pile, leading to an increase in thermal conductivity.

Regarding the thermo-mechanical response of the pile, heating resulted in expansion of the pile in all three TRTs, as expected, however each soil layer had a different role in the overall pile thermal response. When converted to thermal axial stress, the free-head thermal pile was consistently in compression due to the restraint provided by side shear stresses from the surrounding subsurface. The magnitude of thermal axial stress was greatest near the lower two-thirds of the pile length, with lower values near the head, which was free to displace upwards during heating, as well as at the tip, which is quite disturbed as part of pile construction method used and provides a softer end restraint. As to the degree of freedom for the three TRTs, it has been observed that the pile shows progressively smaller values with the time, indicating that a mechanism that make the restraint to increase is present, at least for the depths where the arrange is highly affected by the lowering of GWT and by the thermal consolidation of clayey layers. The ratio between horizontal and vertical degrees of freedom in the zone where the lowering of GWT took place indicated an increase in restraint, but this ratio became progressively smaller for each subsequent TRT. Another important feature captured by the instrumentation was the recovery of the tip structural conditions. Instruments near the tip of the pile showed that a sudden strain occurred during the first minutes of heating in the first TRT causing part of the tip to deform more than that expected for unrestricted concrete.

Acknowledgments

The Authors are grateful to Riscado Engineering Company for the services of pile installation and field support and the Coplan Engineering for the pile cage. They are also thankful to CAPES (Brazilian Scholarship Agency) for the scholarship of the first Author and the Rio de Janeiro Research Agency FAPERJ.

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FIGURE CAPTIONS

Fig. 1 Geotechnical subsoil profile and pile instrumentation scheme

Fig. 2 Overview of the system used to perform the Thermal Response Tests (TRTs).

Fig. 3 Temperature variations at the locations of the concrete strain gauges for each TRT.

Fig. 4 a) Initial and final profiles of temperature in the pile for all three TRTs, b) Temperature change in the pile at the end of heating in each TRT

Fig. 5 Mean temperature vs logarithm of time plots for TRT 1, TRT2, and TRT3 along with the slopes identified for thermal conductivity estimation.

Fig. 6 Profiles of thermal axial strain and pile temperature at the end of heating in the TRTs.

Fig. 7 (a) Relationships between the change in temperature and induced thermal strain at different depths in the pile for the three TRTs; (b)Profiles of the mobilized coefficients of thermal expansion α_{mob} for the pile in the three TRTs.

Fig. 8 Profiles of thermal stress in the thermal pile at the end of heating in each TRT.

Fig. 9 Profiles of a) Concrete strain after natural cooling and temperature profile at the beginning of TRT2 and the beginning of

TRT3, b) Difference in residual strain TRT1-TRT3; c) Stresses at the end of heating in TRT3

Fig. 10 Thermal and residual strains at the end of heating and the end of natural cooling (i.e., before the start of the subsequent TRT) in the three TRTs.

Fig. 11 Ratio between vertical and radial pile degrees of freedom at a depth of 6.0 m at the end of heating in the three TRTs

Fig. 12 Strains at the pile tip during heating