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Investigation of a Field-Scale Energy Micropile in Stratified Soil under Cyclic Temperature Changes

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Abstract: Data regarding energy pile behavior in tropical climate regions is not as readily available as in temperate climate regions, which are generally heating dominated (i.e., focused on extracting heat from a relatively cool subsurface). Further, there has not been a major effort to understand the behavior of micropiles converted into energy piles, which may have different behavior from other energy piles due to the disturbance associated with installation, especially at the toe. This paper presents the results of a series of thermal response tests (TRTs) on a 12 m-long instrumented energy micropile installed in a sedimentary tropical soil to understand the impacts of heating and cooling cycles. Vibrating wire strain gauges embedded within the energy micropile were used to assess the mechanical performance of the pile when subject to changes in temperature. Results indicate that the temperature distribution with depth and the resulting thermal axial strains are strongly dependent on the subsoil stratigraphy and are far from being homogeneous along the length of the pile. In particular, the temperature gradients across interfaces with an organic clay deposit were found to have a major effect on the thermal axial strains. Hysteresis in the thermal axial strains during the process of heating and cooling was also analyzed and was found to represent a diminishing effect on the mobilized coefficient of thermal expansion with each cycle.

Keywords: Energy Piles, Thermo-Mechanical Hysteresis, Thermal Response Test.

Introduction

While energy is essential to enable the socio-economic development of society, it represents a segment having one of the most adverse impacts on the environment. According to the Global Carbon Budget (2018), carbon dioxide is the gas that contributes 58.8% to the greenhouse effect. Geothermal heat exchange contributes to the reduction in CO_2 emissions through more efficient use of electricity when providing heating and cooling. Geothermal heat exchange can be used in any location and at any time of the year. In order to access geothermal energy in the shallow surface, energy piles are often used to exchange heat between a building and the subsurface using a ground-source heat pump (GSHP) (Brandl 2006; Laloui et al. 2006; Bourne-Webb et al. 2009).

Energy piles support buildings while acting as underground heat exchangers using closed-loop, flexible, high-density polyethylene (HDPE) tubing within the reinforcing cage, through which a heat carrier fluid is circulated to maintain thermal comfort the building. The temperature of the fluid is controlled using a heat pump within the building. During heating and cooling cycles, energy piles expand and contract volumetrically which may be restrained by pile–soil interaction (Laloui et al. 2006; Amatya et al. 2012; Chen et al. 2016; Faizal et al. 2018). In some cases, this may result in unwanted consequences, such as additional building heave or settlement, potential for tensile axial stresses during pile cooling, potential for large compressive axial stresses during heating, mobilization of nonlinear deformations, or potential for thermally induced soil dragdown on the pile (Laloui et al. 2006; Amatya et al. 2012; McCartney and Murphy 2017).

Thermal response tests (TRTs) are commonly used to estimate the thermal properties of the energy pile and surrounding subsurface (Loveridge et al. 2020), but they also provide an opportunity to characterize the thermo-mechanical response of the energy pile (Murphy et al. 2015). As TRTs typically involve injection of heat into the subsurface, they are particularly applicable in evaluating the conditions expected for energy pile use in tropical climates that are cooling dominated. In a TRT, a heat exchange carrier fluid is circulated through a closed-loop pipe, which may be embedded within an energy pile or a borehole leading to heat transfer primarily by conduction (Gehlin et al. 2002). Data on the evolution in the inlet and outlet fluid temperatures along with the fluid flow rate are acquired to understand the heat transfer rate into or from the subsurface, while embedded sensors are used to monitor the changes in axial or radial strain.

Along these lines, several studies have investigated the impacts of temperature changes on axial strains in energy piles (Laloui et al. 2006; Brandl 2006; Bourne-Webb et al. 2009; McCartney and Murphy 2012; Akrouch et al. 2014; Mimouni and Laloui 2014; Wang et al. 2014; Murphy et al. 2015; Sutman et al. 2015; Murphy and McCartney 2015; McCartney and Murphy 2017; Faizal et al. 2018). It has been well established that changes in temperature along the energy pile generate deformations that can cause additional axial stresses depending on the restraint conditions, and these stresses must be accounted for properly in energy pile design (Mimouni and Laloui 2014). Further, increases in temperature may affect the soil-pile interface shear strength, either due to thermal consolidation of saturated soils or thermally-induced drying of unsaturated soils. For example, recent studies involving laboratory tests (Di Donna et al. 2016) and centrifuge modeling (McCartney and Rosenberg 2011; Ng et al. 2014; Stewart and McCartney 2014; Goode and McCartney 2015; Ghaaowd and McCartney 2018) have investigated the impacts of soil on the thermo-mechanical response of energy pile.

Ghaaowd and McCartney (2018) found that the pullout capacity of energy piles in soft, saturated clays increased significantly due to thermal consolidation of the soil near the pile interface. McCartney and Rosenberg (2011) found that energy piles in unsaturated silt heated from 15 to 60°C and then loaded axially to failure had a side shear resistance that was 40% greater than that of baseline foundations tested at ambient temperature. Goode and McCartney (2015) performed additional testing that confirmed these trends, and Behbehani and McCartney (2020) found that these trends were due to an increase in effective stress along the pile associated with thermally induced drying of soil near the energy pile.

Several studies have investigated the effects of temperature on the interface behavior between soils and structural elements. Di Donna et al. (2016) observed an increase of the interface shear strength due to heating. Murphy and McCartney (2014) performed thermal borehole shear tests and found no changes in the soil-concrete interface frictional response with increased temperature, although changes in the undrained interface shear strength may occur due to thermal consolidation or thermally induced drying. Although the impact of cyclic heating and cooling on the volume change and shear strength has been investigated through laboratory test and centrifuge modeling (Di Donna et al. 2016; Vega and McCartney 2015), it is not well understood and studied at field scale and this paper aims to show results from hysteresis on field scale experiments. Mortara et al. (2007) evaluated the effect of the interaction between sand and structural materials and concluded that for cyclic tests the densification produced a gradual increase in the maximum shear stress during the cycles. Likewise, the final value of shear stress for an interface depends on the amount of densification of the sand at the interface due to cycling.

This study presents a field investigation involving cyclic thermal response tests on an energy micropile,a small-diameter, drilled and grouted non-displacement pile whose reinforcement cage is pushed into concrete after it is placed into the hole. Energy micropiles have not been thoroughly investigated and may have different behavior than typical bored piles that are thoroughly cleaned with placement of the reinforcement cage before concrete placement. In particular, a potentially nonuniform cross-sectional geometry with depth and a toe that may contain loose materials are two issues that may affect thermo-mechanical soil-structure interaction in energy micropiles. For example, Moradshahi et al. (2020) highlighted the potential impacts of poor cleanout of the toe on the thermal soil-structure response of a typical bored pile. The case that they investigated was an anomaly for a bored pile due to the poor cleanout, while micropiles routinely have poor cleanout at the toe. This means that restraint for thermal expansion and contraction is largely controlled by the side shear resistance in energy micropiles. Further, the cross-sectional geometry may also vary with depth when an energy micropile is installed through a stratified subsurface. This paper focuses on understanding the impact of different soil layers on the thermo-mechanical response of an energy micropile in a stratified soil layer using four thermal response tests. Specifically, these TRTs permit characterization of the hysteretic response at different depths in the energy pile and were also performed with different heat transfer rates, which helps understand the role of this variable on the thermo-mechanical behavior.

Field Test Site

The field test site is located in Campos dos Goytacazes in the north of Rio de Janeiro state, Brazil, on the margin of the Paraiba River at the coordinates 21º45'38.4S, 41º17'34.2" W as shown in Figure 1. The city has a tropical weather with winter dry season and is classified as Aw according to the Köppen and Geiger weather classification system. The city has an annual average temperature of 24.1 °C reaching a maximum of 35 °C during the summer.

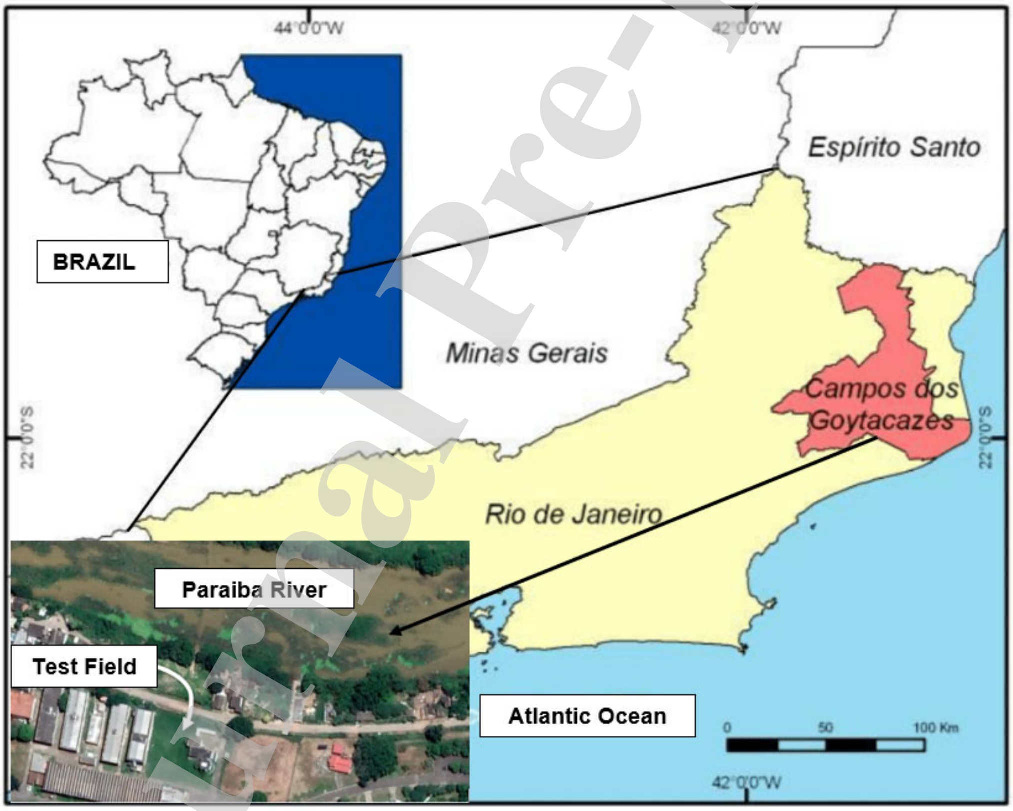


Figure 1 - Location of the site investigation.

A site investigation was performed in July 2017 extending 12 m below the ground surface. Exploration results from the borehole showed three prominent strata. The top layer is approximately 3.5 m-thick and consists of sandy-clay fill. Beneath the fill is a 1.5 m-thick silty-sandy layer, followed by a 3 m-thick layer of sand, which is assumed to be part of the Paraiba basin sediment. An organic clay layer was encountered between depths of 8.50 and 10.80 m, underlain by a silty sand layer extending to the maximum depth explored. More detailed information on soil profile is shown in Figure 2. Based on the SPT blow counts shown in Figure 2, it is likely that the organic clay layer is relatively soft and can be assumed to be normally consolidated. Since the site is located near the Paraiba river the soil deposit experiences a significant seasonal ground water table Fluctuation. At the time of the site investigation the ground water table was at a depth of 6.5 m, so the organic clay layer can be assumed to be saturated.

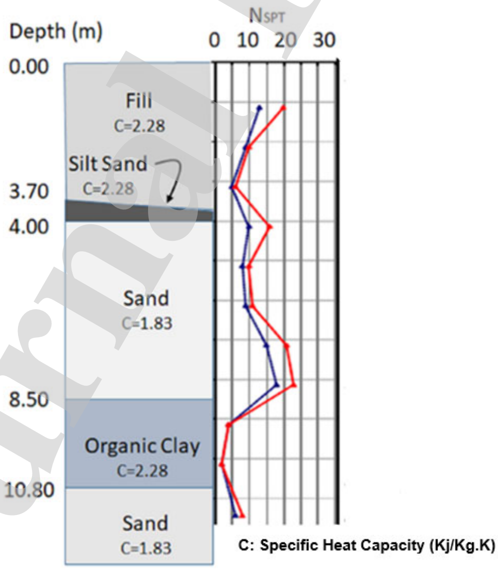


Figure 2 - Soil strata and standard penetration test (SPT) blow counts.

Experimental setup

A 0.4 m-diameter energy pile was installed in sedimentary soil to a depth of 12 m using procedures representative of micropiles. Specifically, the hole was drilled with an auger, concrete was placed during auger extraction, and the reinforcing cage was placed after auger extraction. The concrete used in the pile had a tensile strength of 3.4 MPa and a compressive strength of 29 MPa measured from a diametric Brazilian test. The foundation contains a 9.5 mm-diameter steel reinforcing cage configured in a triangular arrangement that extends along the full length of the shaft. A loop of 25 mm-diameter heat exchange tubing composed of PEX-A monolayer was installed in the pile and placed in a “U” shape attached to the inside of the reinforcing cage (Fig. 3a).

The energy pile was equipped with four Geokon model 4150 vibrating wire strain gauges attached to the reinforcing cage (Fig. 3b) at different locations along the length of the pile which are shown in Fig 3a. The strain gauges and thermistors were attached to the reinforcing cage so that their final positions would be at depths of 11.5 m (A05), 8.77 m (A04), 6.1 m (A03) and 3.2 m (A02). They were used to monitor the temporal and spatial distributions with depth in temperature and axial strain during the heating and cooling processes. The strain gauges and thermistor sensor cables were connected to a Geokon data acquisition system (Fig 3c) allowing to monitor temperature and strain variations on the energy foundation in 10 minutes intervals. Separately, pipe plug thermistors were installed at the inlet and outlet of the heat exchange tubing loop at the head of the pile to measure the inlet and outlet temperatures of the heat exchanger fluid on the foundation,. The final configuration of the test consists of a water circulation pump, a flow meter, a water heater that permits control of the input and thermally isolated water tank as shown in Fig. 4b and 4c. The energy micropile studied is not restrained at the head and is partially restrained at the bottom as the pile was not socketed into a stiff layer. The micropile construction process and the small SPT blow count of the soil layer at the toe of the pile (7 blows) indicates that the toe of the soil may experience deformations during heating and cooling cycles. Accordingly, the energy micropile can be characterized as a semi-floating energy pile whose main resistance to axial loading and thermal expansion is from side shear resistance.

(a) (b) (c)

Figure 3 - Details of the heat exchange tube installation, strain gauge installation on a reinforcing element, and Geokon data acquisition system.

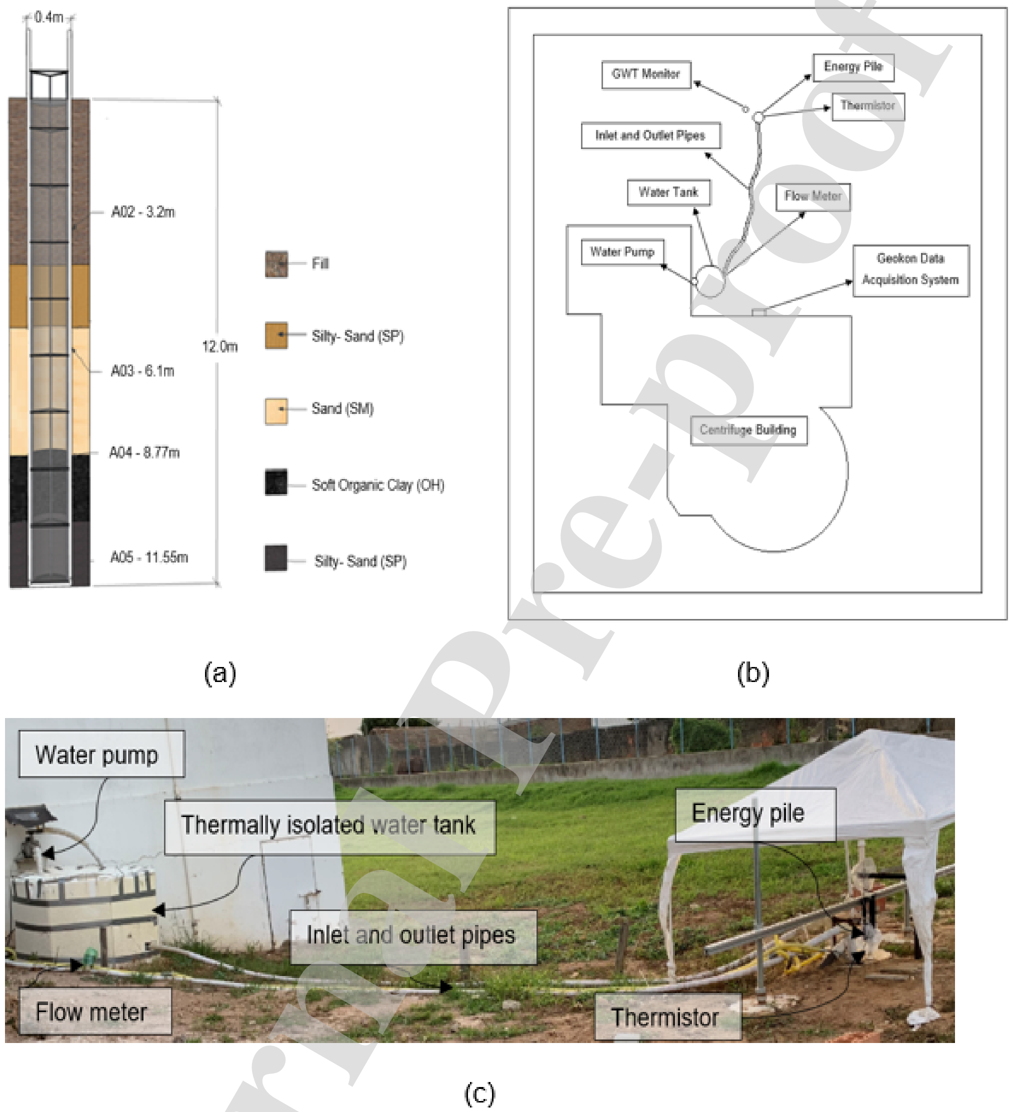


Figure 4 – (a) Pile instrumentation scheme; (b) Schematic of the system used to perform the Thermal Response Tests (c) Photograph of the system.

Test procedures

A series of four thermal response tests (TRT) were carried out on the same energy pile, referred to as Reference TRT, TRT #1, TRT #2, and TRT #3, as summarized in Table 1. The first test caried out on the pile by Ferreira (2017) was used as a Reference Test. During the TRTs performed in this study, the inlet and outlet heat exchange fluid temperatures were continuously monitored. The heat exchange fluid flow rate was different in each of the tests, with a flow rate of 19.4 l/min in the Reference Tests, 30.1l/min in the test #1, and a flow rate of 19.7 l/min in the tests #2 and #3. These flow rates correspond to a turbulent flow regime within the heat exchanger pipes. The Reference TRT was carried out with an inlet power source of 1.0 kW , TRTs #1 and 2 were executed with a heat transfer rate of 1.3 kW while TRT# 3 was executed with a heat transfer rate of 2.4 kW, allowing an evaluation of the effect of the pile and the surrounding soil when submitted to a higher temperature gradient.

Table 1 - Summary of thermal response testing details.

TRT	Test end date	Heat exchanger fluid flow rate (l/min)	Inlet power source (W)	Approximate heating duration (hours)	Approximate increase in temperature (°C)
Reference TRT	09/2016	19.4	1000	171	13
TRT #1	06/2019	30.1	1300	75	14
TRT #2	08/2019	19.7	1300	50	12
TRT #3	09/2019	19.7	2400	75	22

The durations of heating in the four TRTs were 171, 75, 50 and 75 hours, respectively, and time series of pile temperatures during heating and cooling along with the ambient air temperatures during the tests are shown in Figure 5. The temperatures at different locations in the pile were found to be similar during each test. The average increase in the water temperature recorded at the inlet and outlet of U-loop at the pile head during the Reference TRT, TRT#1, TRT#2 and TRT#3 were 13, 14, 12 and 22 °C, respectively. The ambient surface temperature only had a minor effect on the pile temperature, likely due to the effects of ambient surface temperature on the water storage tank used to supply the circulating water to the heater.

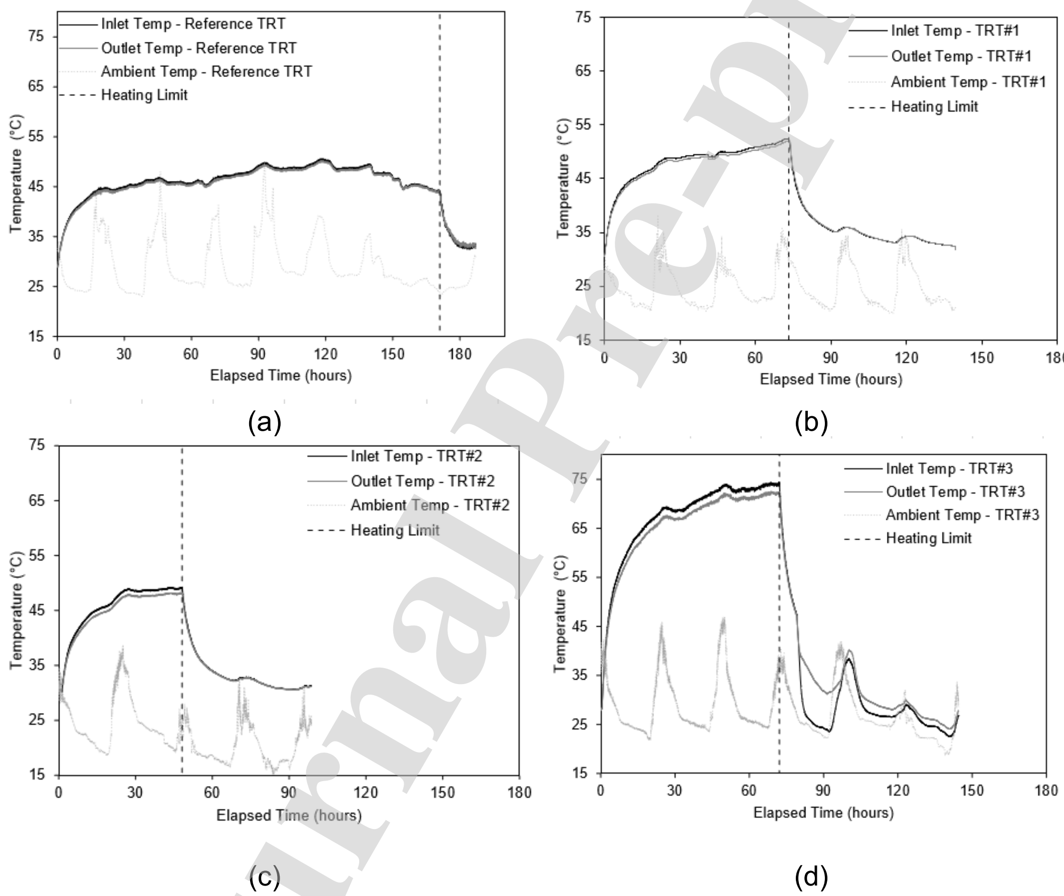


Figure 5 - Changes in pile temperature over time during the TRTs along with changes in the ambient surface temperature: (a) Reference TRT; (b)TRT#1; (c) TRT#2; (d) TRT#3.

Analysis

As noted, energy piles expand axially during heating and thermally induced strains may be observed depending on the restraint provided by the overlying structure and the surrounding subsurface (Amatya et al. 2012). The thermal axial strains caused by heating were measured in this study using the vibrating wire strain gauges, installed inside the micropile, which were corrected for the local temperature effects recorded by co-located thermistors, as follows:

$$\varepsilon_{real} = B(R_1 - R_0) + (T_1 - T_0)\alpha_{steel} \quad (1)$$

where B is a constant strain gauge Batch Factor (0.962), R_1 and R_0 are the readings of the strain gauge at different times, and α_{steel} is the coefficient of linear thermal expansion of the vibrating steel wire in the strain gauges (12 με/°C) and T_1 and T_0 are the readings of strain gauge temperature at different times. The thermal axial strains calculated using Equation 1 are plotted versus depth in Figure 6a. The average temperature changes reached during TRT#1, TRT#2 and TRT#3 were 14, 12 and 22°C, respectively. The thermal axial strains versus depth at the end of heating in each test, including the reference TRT, are shown in Figure 6b. Smaller thermal strains and temperatures are observed in each test at a depth of 9 m, possibly due the presence of the organic clay layer. Higher thermal strains are observed near the toe and the head of the energy pile in all three TRTs, which can be attributed to the high degree of freedom of the semi-floating pile in these locations. Specifically, the micro-pile was not connected to a superstructure, so it is free to move upward, and the construction approach used in micropiles leads to a considerable disturbance of the soil in the bottom boundary so it is relatively free to move downward. The highest thermal axial strains were observed in TRT#3 due to the higher temperature applied in this test.

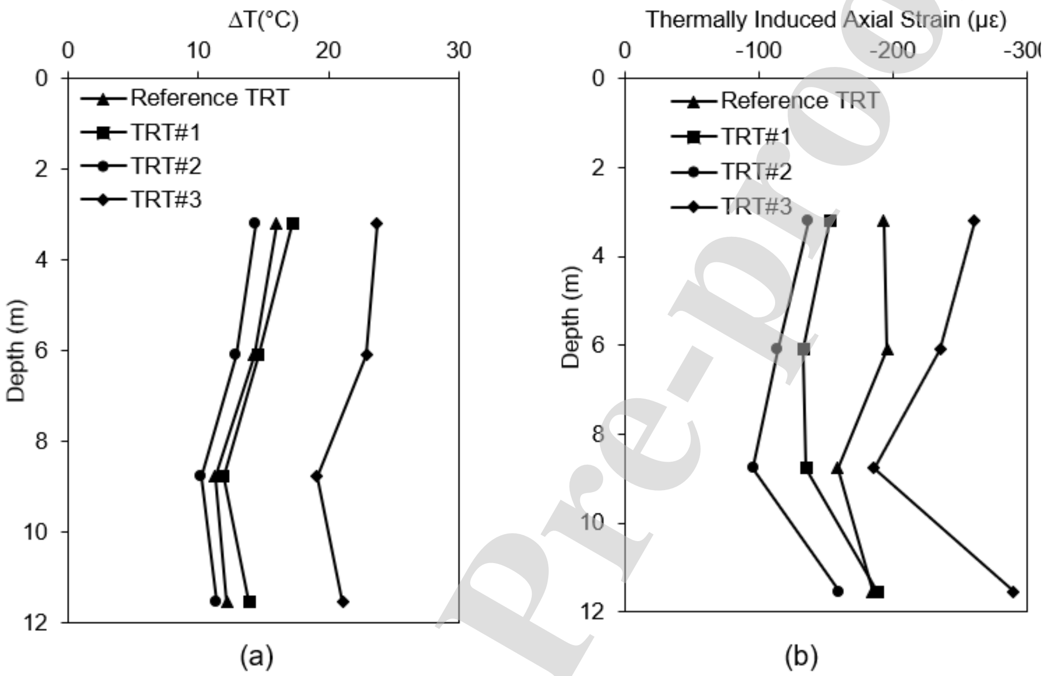


Figure 6 -(a) Profiles of temperature change; (b) Profiles of thermally induced strain.

When an energy pile is heated without restraint, it tends to expand freely with free thermal axial strains calculated as follows:

$$\varepsilon_{t-free} = (T_1 - T_0)\alpha_{concrete} \quad (2)$$

where $\alpha_{concrete}$ is the coefficient of thermal expansion of reinforced concrete. However, an energy pile in the ground will not be able to expand freely, owing to mobilization of side shear restraint at the pile–soil interface and possible restraint at the pile head or toe. Accordingly, the measured strain changes due to temperature change ($\varepsilon_{T-Observed}$) will be less than that given by Equation (2). The restrained strain ($\varepsilon_{T-Restrained}$) creates thermal stress in the pile and should be considered in structural design. The restrained axial strain can be estimated as (Knellwolf et al. 2011; Amatya et al. 2012):

$$\varepsilon_{T-Restrained} = \varepsilon_{T-Free} - \varepsilon_{T-observed} \qquad (3)$$

The profiles of thermally induced strain and free thermal strain (i.e., the strain present if there is no soil restraint) are shown in **Error! Reference source not found.** The maximum strain occurred at about mid-depth, reflecting a semi-floating energy pile described by Amatya et al. (2012). A comparison of the measured strain profiles and the free thermal strain profile shows that the differences between these profiles change with each subsequent heating-cooling cycle. In the Reference TRT, the thermal strain mobilized was almost 90% of the free thermal strain at both ends, while about 75% was mobilized at the depth of 8.77 m. In TRT#3 around 72% of the thermal strain was mobilized at the ends while about 53% at the mid-depth. This indicates that over the cycles of heating, a decrease in the mobilized strains in the pile of about 20% was observed. This is potentially due to a gradual increase in stiffness of the ground with each test, with the changes mainly attributed to temperature effects, more pronounced on the organic clay layers. The minimum value of $\varepsilon_{T-Observed}$ is expected to decrease with increasing interface resistance and depends on a number of factors including the type of ground (clayey, granular), ground stiffness, groundwater level and the magnitude of heat input (Amatya et al. 2012). This observation can be noticed by analyzing results from the Reference TRT, TRT#1 and TRT#2 (Figure 7. a, b and c) performed with a similar average on temperature gradient, showing smaller values of $\varepsilon_{T-Observed}$ for the temperature gradient imposed during each tests.

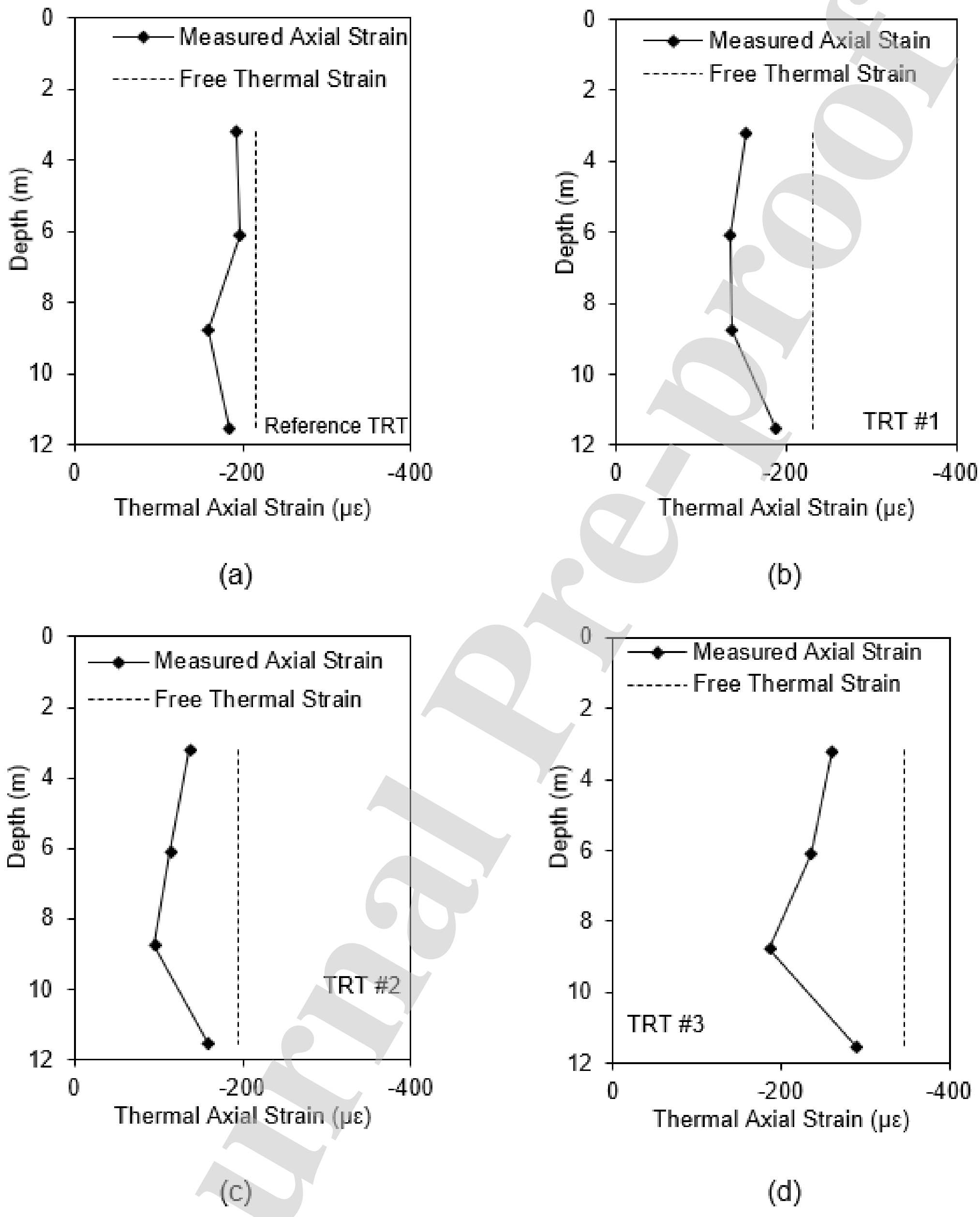
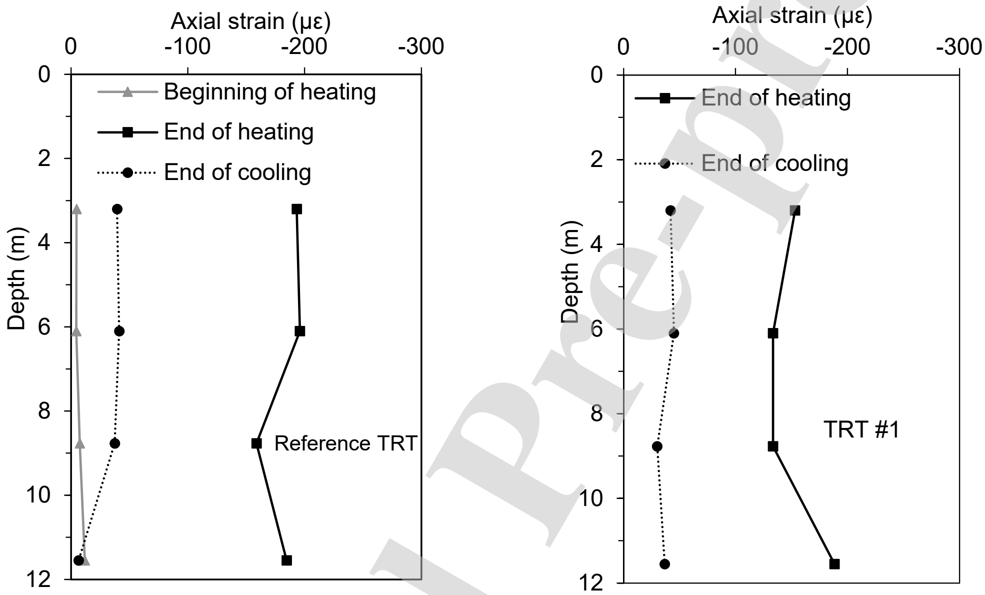
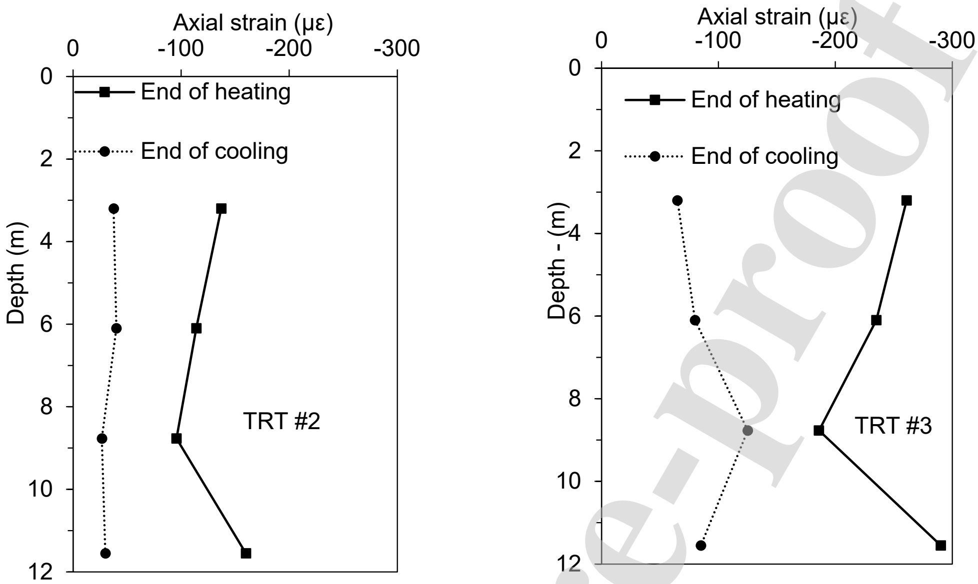


Figure 7 - Observed and free thermal strain profiles due to uniform heating with depth in the energy pile.

A comparison between thermal axial strain profile during heating and cooling for the four TRTs is shown in Figure 8, where the thermal axial strain was zeroed at the beginning of each test to show the differences in profiles at the end of heating and the end of cooling. The thermal axial strains during heating are slightly different due to the different imposed temperature gradients. Comparing the first 3 tests (Reference TRT, TRT#1 and TRT#2), in which the imposed temperature gradient was similar, the thermal axial strains during cooling returned to the values that were experienced before heating, indicating linear thermo-elastic behavior, meaning permanent thermo-plastic deformations did not occur in the energy pile-soil system, and consequently hysteresis can be neglected. On the other hand, data from the third test (TRT#3), in which a higher temperature gradient was imposed on the energy pile, approximately 50% higher than the temperature imposed on the first three cycles, it is possible to notice that irreversible strains on the clay-concrete interface. This is better highlighted in the comparison of thermal axial strains in (Figure 9). This indicates that permanent thermo-plastic deformations occur at the Interface between the energy pile and the organic clay interface, possibly indicating that the mobilized side shear resistance during the heating test lead to locked-in plastic strains at the interface. It should be noted that irreversible strains were observed during a thermal cycle in which a higher thermal load was imposed, meaning that at a certain temperature, the yield surface was expanded and thermal plastic deformations occurred in the clay layer beyond that experienced during the Reference TRT and the other two TRTs. After thermal plastic deformations, soils a lower void ratio and a higher undrained shear strength which will result in more restraint to thermal expansion of the pile. That would explain why the mechanical responses of the pile during the first 3 tests are quite similar, suggesting that the stage after maximum heating is sufficient for the organic clay to return to the conditions induced by the initial heating during Reference TRT.





302 Figure 8 - Thermal axial strain profiles during different stages of the TRTs.

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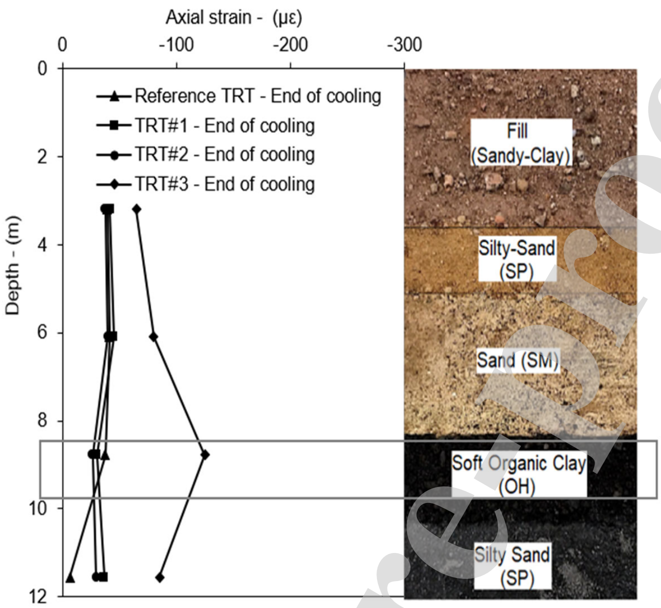

Figure 9 - Comparison of thermal axial strain profiles at the end of cooling for all TRTs.

Relationships between the thermal axial strain and the change in temperature for each depth in each test are shown in Figure 10a to Figure 10d. The slopes of each relationship correspond to the mobilized coefficient of thermal expansion. A linear relationship between the thermal axial strain and changes in temperature is noticed, similar to the behavior for an energy pile in sandstone reported by Murphy at al. (2015). At a depth between 8,77 and 11.55m (Figure 10c e 10d) correspond to the organic soft clay layer followed by a clean sand layer the slopes of the curves were observed to decrease with changes in temperature reflectinan increase in interface shear strength.. Similar behavior has been reported by Di Donna et al. (2015), who tested the response of clay–concrete interfaces at different temperatures after cyclic heating and cooling, and also by Ghaaowd and McCartney (2018) who performed pullout tests on energy piles after a heating-cooling cycle. Conversely, for the sensors located at depths of 3.2m in the fill layer composed mostly of sand (Figure 10a) and at a depth of 6.1 m in the sand layer (**Error! Reference source not found.**b), heating led to a negligible change in behavior. This behavior was observed by Goode and McCartney (2015) during heating semi-floating energy piles in dry sand and by Di Donna et al. (2015) during application of temperature cycles to a sandy soil pile interface. Overall, the results in Figure 10 indicate that when an energy pile is installed in a stratified soil layer that the effects of temperature on each soil layer should be carefully assessed, as the axial strains within each of the layers had a different variation with each TRT. The reduction in thermal axial strain with changes in temperature indicates an increase in resistance of the soil layers to thermal expansion. Moreover, the changes in behavior at a certain depth will have an influence on the profile of thermal axial strain after several cycles of heating and cooling. This may indicate that interface shear testing similar to Di Donna et al. (2015) should be performed for the different layers in a stratified soil deposit

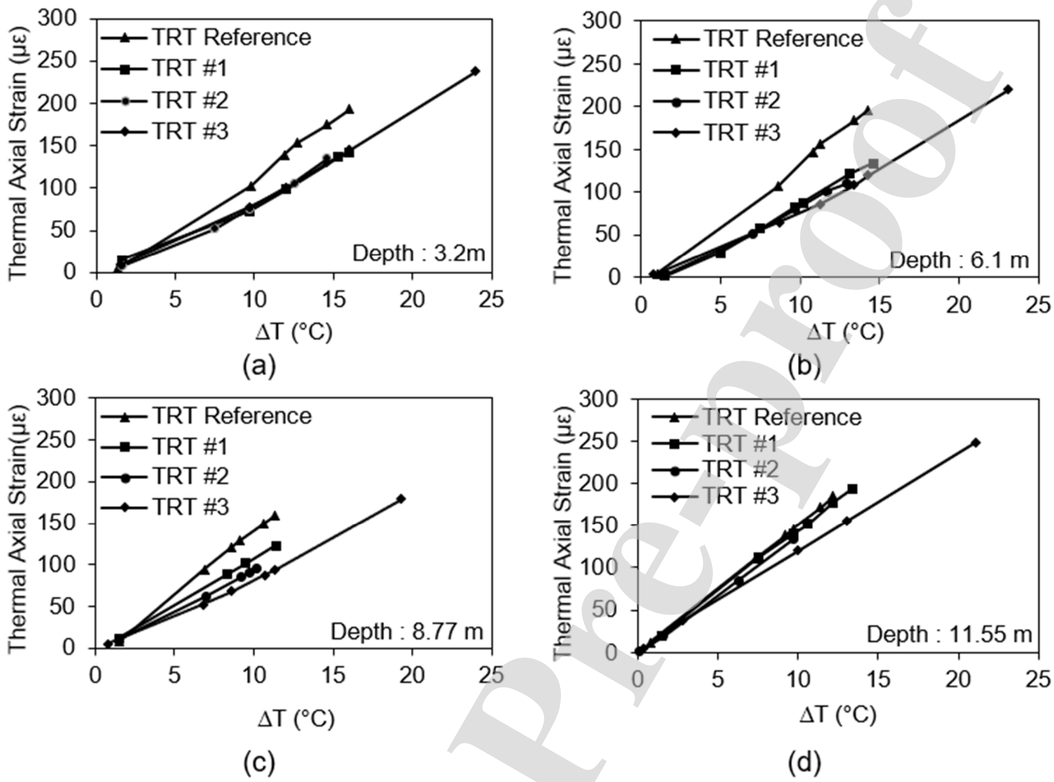

Figure 10 - Relationships between the thermal axial strain and the change in temperature at different depths along the energy pile: (a) 3.2 m; (b) 6.1 m; (c) 8.77 m; (d) 11.55 m.

The mobilized coefficients of thermal expansion for the depth of each strain gage during each test are plotted in Figure 11. The increase in each test temperature is shown in Table 1. In all cases, the values of the mobilized coefficient of thermal expansion decreased after each subsequent heating cycle, reflecting smaller displacements throughout the pile with temperatures increments. This behavior can be associated with an increase in side shear resistance along at the length of the pile due to heating. It is possible that thermally induced drying led to an increase in restraint in these tests as observed by Behbehani and McCartney (2020), but also could be related with thermal consolidation of the softer clay layer that results in greater restraint.

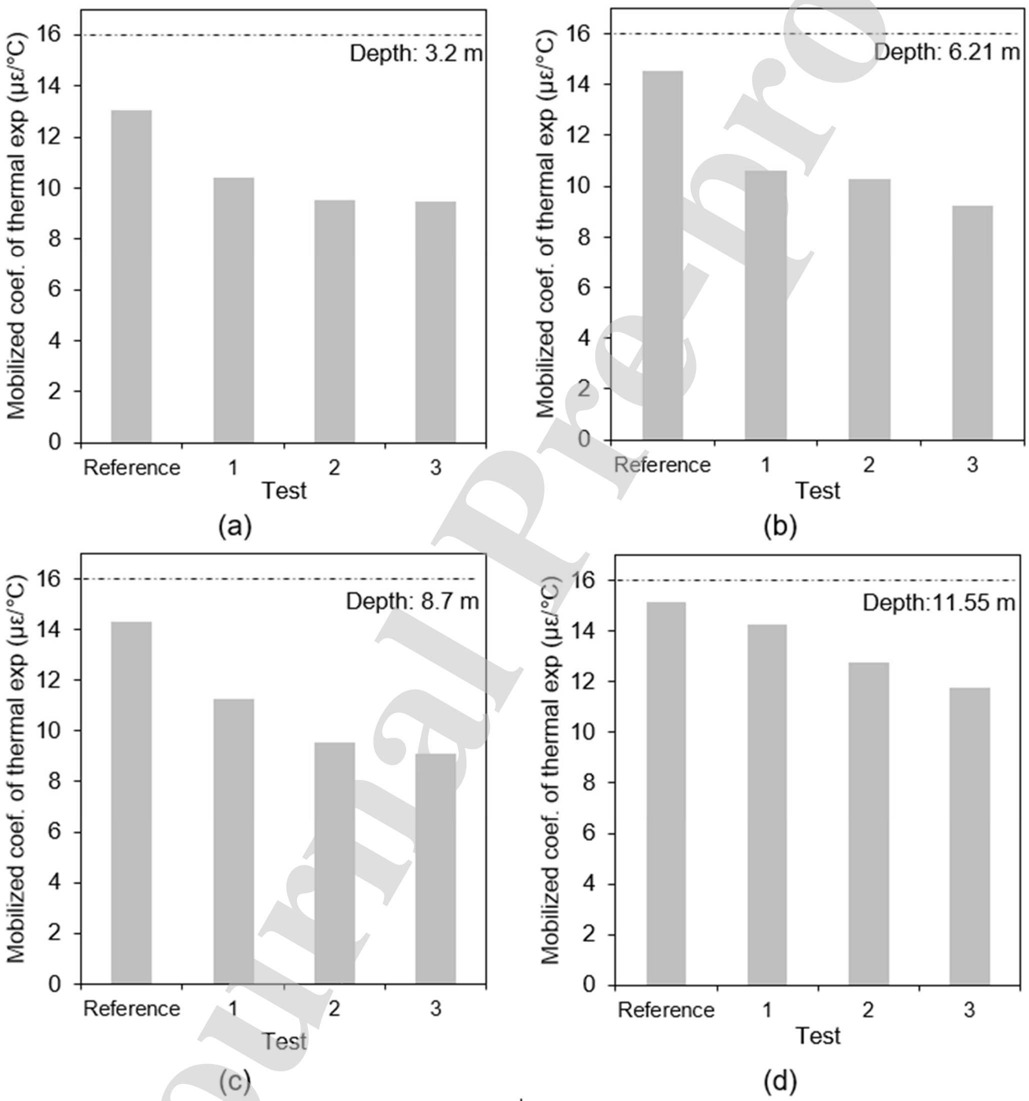

Figure 11 - Mobilized coefficients of thermal expansion measured in each test at different depths along the energy pile: (a) 3.2 m; (b) 6.1 m; (c) 8.77 m; (d) 11.55 m.

The effects of heating of the energy micropile on the surrounding soil layers were found to be not negligible. To better interpret this behavior, it is interesting to understand the degree of freedom of the pile defined by the ratio between the free and observed axial strains, ε_{T-free} and $\varepsilon_{T-observed}$ (Knellwolf et al. 2011).

$$DOF = \frac{\varepsilon_{T-free}}{\varepsilon_{T-observed}} \quad (4)$$

The degree of freedom is theoretically zero when the pile is fully restrained (blocked) and 1 when the pile is completely free to move. Generally, it ranges from zero to 1 because of the variable shaft friction mobilization and restraint at the two extremities of the pile (Knellwolf et al. 2011). The values of degree of freedom along the pile length achieved in all tests are shown in Figure 12. The minimum pile restraint is observed at a depth of 11.55 m, corresponding to points of maximum strain located near the energy pile toe. This is, likely due to the lower amount of restraint provided by the deepest soil layer and the low end bearing capacity expected for the micropile construction technique used for the pile on the grounds of a low end bearing capacity provided by this foundation. According to Brandl (2006) the pile installation has a great influence on the geotechnical performance of energy piles. Conversely, maximum pile restraint was observed at a depth of 8-10 m, corresponding to the location of the minimum thermal axial strain as a result of the presence of the organic clay layer. From the Reference TRT to the last TRT (TRT#3) a reduction of around 0.25 in the degree of freedom of the pile is observed. The rate of increase in the degree of freedom from test to test was about 60% at the toe of the pile and 29% at the head of the pile which shows an increase in the restraint provided by the surrounding soil over the four heating tests.

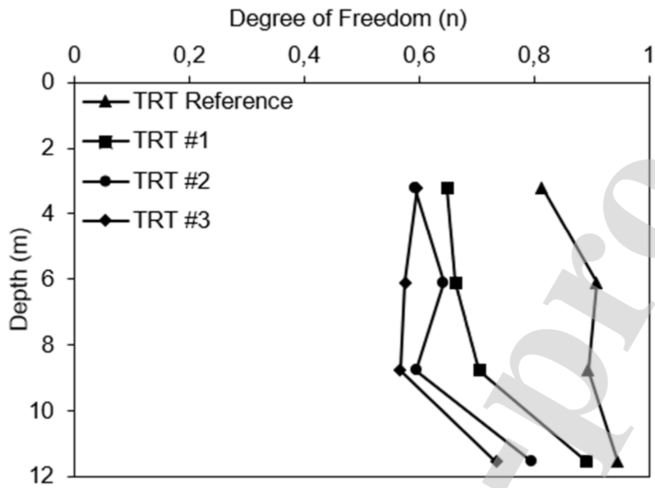

Figure 12 - Variations of degree of freedom along the pile for each TRT.

Because of the values of restrained strain and decreasing degree of freedom with each test, significant thermal axial stresses are induced by thermal loading that increase in each test are induced in the energy micropile and should be considered in structural design. Thermally induced axial pile stress change is a function of the restrained boundary condition of the pile, which is determined mainly by the lateral confining pressure and change in temperature. The thermal axial stress during each TRT shown in Figure 13 indicate that the development of axial stress is larger over the mid-length of the pile. This verifies the hypotheses of Bourne-Webb et al. (2012) and Amatya et al. (2012) that during heating the maximum thermally induced axial stress of a semi-floating energy pile should be near the mid-length of the pile. Further, the minimum thermal induced axial stress is located near the bottom portion of the pile at the depth of 11.5 m in all TRTs, whereas the maximum strain was observed at the toe which means that the end bearing resistance provides small resistance that may increase over several cycles of heating and cooling. A maximum thermal induced axial stress of about 2 MPa during a change in temperature of 13 C° was developed at a depth of 3.2 m. This depth lies within the sandy layer and represents the depth providing the maximum side shear restraint. On the other hand, in the last TRT (TRT #3) the maximum thermal induced axial stress of about 4 MPa observed during a change in temperature of 22 C° occurred at a depth of 6.1m. This depth also lies within the sandy layer but indicates that hysteretic heating-cooling cycles contribute to a gradual change in the location of maximum thermal axial stress.

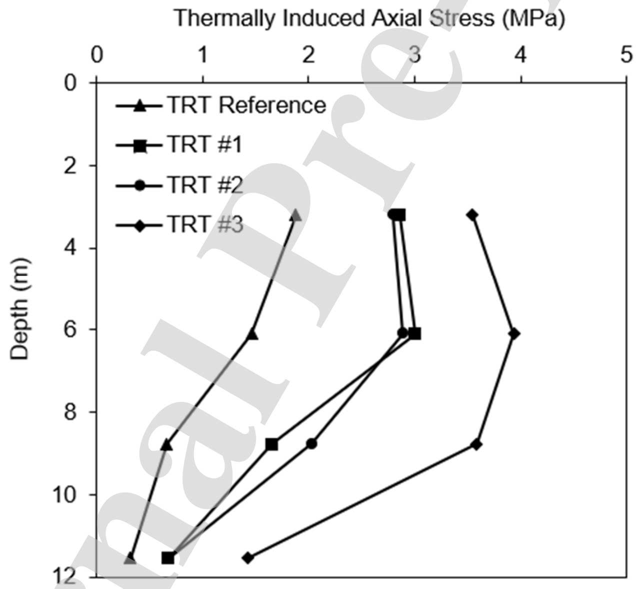

Figure 13 - Thermally induced axial stresses along the pile in each test.

Conclusion

Three thermal response tests were performed on a cast-in-place energy micropile in a stratified sedimentary soil layer typical of tropical regions to study the effects of heating and cooling cycles beyond a reference test performed in an earlier study. Due to different heat exchanges process in each test, an increase in the change in temperature was imposed in each test which permits thermal plasticity effects to be observed. The overall conclusions from this field study are that the construction techniques that greatly disturb the soil at the pile base and the soil stratigraphy with the presence of organic clay can cause considerable changes in thermo-mechanical soil structure interaction during cycles of heating and cooling. The following specific comments can be drawn:

- The energy micropile with no head load behaved like a semi-floating energy pile with maximum thermal axial strains near to the head and toe of the pile due to the micropile construction technique that leaves losing material near the end of the pile.
- The presence of an organic clay layer in the bottom half of the energy pile was found to have a major effect on the energy pile restraint, with the lowest thermal axial strains encountered at this depth. Although the thermal axial strains after cooling were similar for the Reference TRT and the first two TRTs performed in this study, the grater change in temperature during the third TRT led to permanent strains after heating which indicates thermo-plastic behavior in the organic clay layer induced by heating.
- A linear change in thermal axial strain with changes in temperature was observed for all depths indicating thermo-elastic response of the energy pile during several cycles of heating and cooling.
- The mobilized coefficients of thermal expansion changed during each test, possibly due to changes in side shear restraint and changes in the end bearing resistance. It reached the highest values in locations of maximum strain near the

energy pile toe due to the lower restraint associated with the micropile construction technique, although this increased with each cycle. Conversely, the lowest values of the mobilized coefficient of thermal expansion corresponded to the location of the minimum thermal axial strain in the organic clay layer.

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