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Mechanical Response of a Bored Thermal Pile Installed in Stratified Sedimentary Soil

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Abstract. Data regarding Energy pile behavior in tropical countries are not very much available as those compared to European or tempered climate regions, where most of the applications is directed to extracting heating from the subsoil. Notwithstanding this scenario, quite a few data have been published for thermal active excavated micro-piles, in which the installation process can be very disturbing for the surrounding soil, specially at the tip. Herein, it is shown a set of thermal response tests (TRT) in a 12m long instrumented micro-pile installed in a sedimentary tropical soil. Twelve vibrating wire strain gauges were embedded in the concrete and attached to the cage in order to assess the mechanical performance of the pile when subject to thermal loads only. Results have revealed that temperature distribution with depth and the resulting induced strains are strongly dependent on the subsoil conditions and it is far from being homogeneous through the entire length of the pile. The cage and concrete instrumentation at the tip have shown also an unsatisfactory mechanical behavior that is credited to the very disturbing pile installation process. These features were clearly revealed by the mobilized coefficient of thermal expansion. Some thermal hysteresis are also analyzed for the organic clay layer at 8-10m deep.

1 Introduction/Background

Energy is essential to enable socio-economic development; however, it represents one of the segments that has an adverse impact over the environment. According to Global Carbon Budget 2018, the carbon dioxide is responsible for 58,8% of the gases from the greenhouse effect.

To provide a solution, in developed Countries, geothermal energy has received tremendous attention as a largely untapped renewable resource that does not produce significant CO2 emissions during electricity generation. [1] Compared to other sources of energy the geothermal energy is beneficial because it is available daily and in all seasons of the year. [2] In order to use the geothermal energy, thermal piles are used to exchange heat between a building and the ground through the principle of ground-source heat pump (GSHP). Thermal piles support buildings while acting as underground heat exchangers coupled with closed-loop, flexible, high-density polyethylene (HDPE) tubing within the reinforcing cage, through which a heat exchange fluid (i.e., typically water mixed with propylene glycol) is circulated, maintaining thermal comfort in built structures. The temperature of the fluid is controlled using a heat pump within the building. [3,4].

During heating and cooling cycles, energy piles expand and contract, and it changes the pile–soil interaction. In some cases, this may result in unwanted consequences, such as additional building settlement, tensile axial stresses, large compressive axial stresses or mobilization of limiting resistance on the pile shaft.[5]

To account the soil thermal properties, it is used In the field the thermal response test (TRT) that can be performed directly with vertical ground heat exchangers through the injection of a fluid with a constant temperature A heat carrier fluid is circulated through the borehole in a closed circuit exchanging heat from the ground to the user unit. [6] Datas from inlet and outlet temperature are acquired.

Studies have been made, mostly in the last two decades, over the induced effects of the temperature gradient on thermal piles. [7-16],[4]. It is showed that increasing on thermal pile temperature generates deformations that can cause extra stresses and must be accounted on their design.

The effects of the temperature change on the soil around the pile can increase the interface shear strength due to heating, which may be explained by thermal consolidation. Recent studies on laboratory test [17] and on centrifuge modeling [18] have investigated this effect.

McCartney and Rosenberg 2011 conclude that foundations then loaded axially to failure experienced an increase in side shear of 40% above that of baseline foundations tested at ambient temperature. While Di Donna et al 2016 observed an increase of the interface shear strength due to heating. Although the cyclic thermal mechanism has been investigated through laboratory test and centrifuge modeling, it is not well understood and studied at field scale and this paper aims to show results from hysteresis on field scale experiments.

2 - Soil Profile

The pile is located in Campos dos Goytacazes on north of Rio de Janeiro state, Brazil. On the margin of Paraiba River. The predominant soil is sedimentary Paraiba basin deposit. The city has a tropical weather with winter dry season (Aw) according to Köppen e Geiger weather classification system. It has an annual

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temperature average of 24,1 °C reaching 26,7°C during the summer.

A site investigation was performed in July 2017 by Ferreira (2017). extending 12 m below the ground surface. The pile is located near the Paraiba river presenting an expressive ground water table fluctuation. At the site investigations the ground water table was at the depth of 6.5 m. Exploration results from the borehole showed three prominent strata: sand, organic clay and fill.

The top layer is approximately 3.5-m thick and consists of fill. Beneath the fill is a 1.5-m -silty-Sandy layer, followed by a 3-m layer of sand. An organic clay layer is presented between 8.50-10.80m, which is followed by a silty sand layer extending to the maximum depth explored. More detailed information on soil profile can be found on Fig. 1.

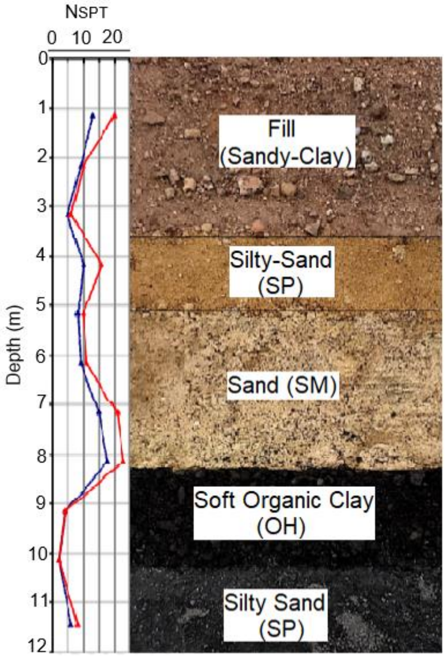

Fig. 1 - Soil Stata and Spt blows.

3 Experimental Set up

A cast in place 0.4-m diameter thermal pile was embedded in sedimentary soil to a depth of 12m. The concrete used in the pile had a tensile strength of 3.4 MPa and a compressive strength of 29MPa measured from a diametric Brazilian test. The foundation contains a 9.5mm-diameter steel reinforcing cage configure in a triangular arrangement that extends the full length of the shaft. A 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 reinforced cage. [19].

The thermal pile was equipped with four Geokon model 4150 vibrating wire strain gauges attached to the reinforcing cage at different locations along the length of the pile which are shown in Fig. 2. The Strain gauges were named corresponding to its depth A05 correspond to the depth of 11.55m, A04 to 8.77m, A03 to 6.1 and A02 to 3.2m according to Fig. 2. They were able to account temperature and distribution of axial strain with depth during the heating process. The sensor cables were connected to a Geokon data acquisition system allowing to monitory temperature and strain variations on the energy foundation in 10 minutes intervals. Separately, in order to measure the inlet and outlet temperatures of the heat exchanger fluid on the foundation, thermistors using pipe plug were installed in within the inlet and outlet of the heat exchange tubing.

The final configuration of the test consists basically of a water pump, a flow meter, water heaters, thermally isolated water tank.

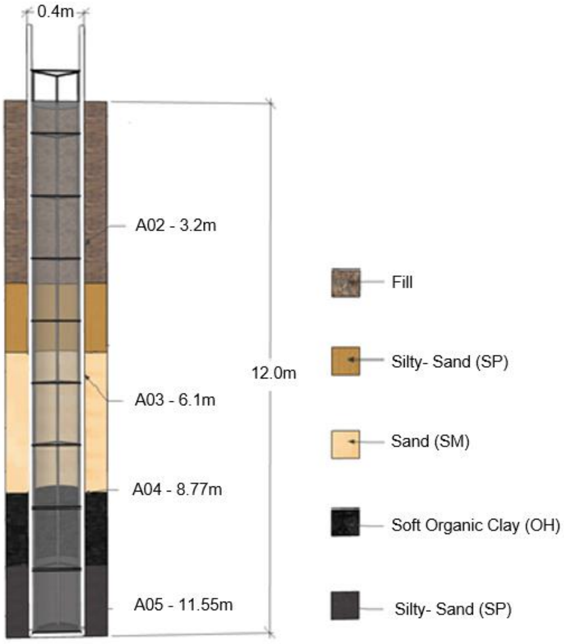

Fig. 2 Pile instrumentation scheme

4 Test Procedures

Three Thermal Response Tests were performed on the thermal pile, the flow rate of 30.1l/min was observed on the first test, 19.7 l/min on the second and third tests. The first two Thermal Response Tests were executed with 1.2 kW and the third one with 2.4 kW, so an evaluation of the effect of the pile and the surrounding soil when submitted to a higher temperature gradient could be made. During the test, the inlet and outlet temperatures of the heat exchanger fluid were continuously monitored. The duration of TRT#1, TRT#2 and TRT#3 were 115, 90 and 140 hours respectively.

5 Results

The average temperature gradient reached during TRT#1, TRT#2 and TRT#3 were 25, 23 and 40 °C respectively. The temperature versus depth for each test are shown in Fig. 3a The thermal axial strain versus depth are also plotted in Fig. 3b.

The Thermal Response Test #2 shows slightly smaller temperature when compared to the other tests, that is due to a technical problem that occurred on the heater during the second test. The same can be observed on the axial strain. Smaller thermal strains and temperatures are observed on the depth of 9 m, that is possibly due the presence of a clay layer. On the other hand, higher thermal strains were observed near the tip and head of the thermal pile in all three TRTs, which can be attribute to the degree of freedom of the pile, that is free to move towards its directions.

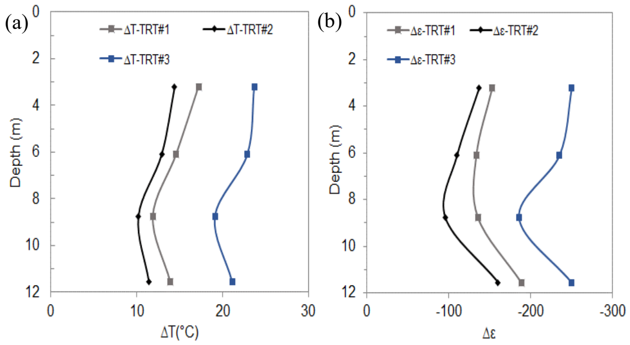

Fig. 3 - Profiles of **(a)** temperature gradient and **(b)** thermal axial strain for three Thermal Response tests.

Thermal strain increments versus the change in temperature for each depth in each test are shown in Fig. 4a;b;c The slope of each curve allows to estimate the mobilized coefficient of thermal expansion. The profiles of this coefficient with depth are plotted in Fig. 4d A linear change in thermal axial strain with changes in temperature on the tests it is noticed. The linear behavior was observed by Murphy et al 2015.

At the depth of 11.55 m the mobilized coefficient of thermal expansion reaches higher values Fig. 4d observed in locations of maximum strain. located near the thermal pile tip likely due to the lower amount of restraint provided by the deepest soil layer and the low-end bearing capacity expected for the construction technique used for the pile because this foundation is typically not used to provide a high-end bearing. Conversely lowest values of the mobilized coefficient of thermal expansion was observed at a depth of 8-10 m, agreeable with the location of the minimum thermal axial strain possibly due to the clay layer.

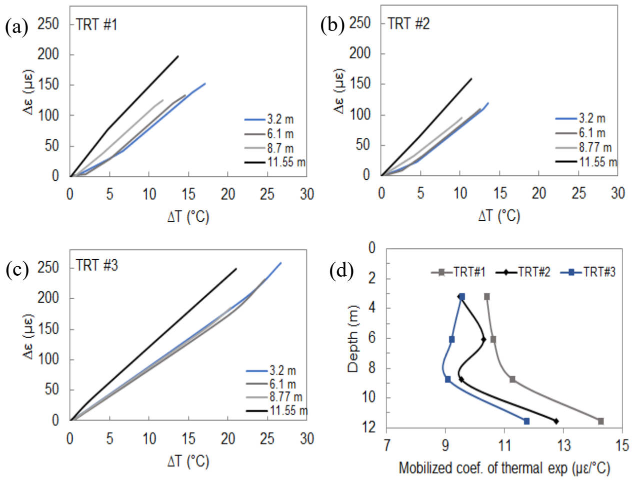

Fig. 4 -Thermal axial strain with change in foundation temperature at each test: **a** TRT#1; **b** TRT#2; **c** TRT#3; **d** mobilized mobilized coefficient of thermal expansion with depth for the three tests on the energy foundations

The mobilized coefficient of thermal expansion for each depth in each test is plotted in Fig. 5 .Even with the technical issue induced by the heater on TRT #2 where the fluid reached smaller temperature and consequently smaller strains when compared to the other TRTs a decrease on the mobilized coefficient of thermal expansion was observed, this possibly results from the fact that the soil surrounding the pile had already undergone thermal consolidation during the first heating cycle, this is known as thermally induced overconsolidation [20] and results in the fact that higher energy is now necessary to achieve deformation being imposed by a higher temperature gradient, which occurred on TRT#3, therefore the soil reached higher strains.

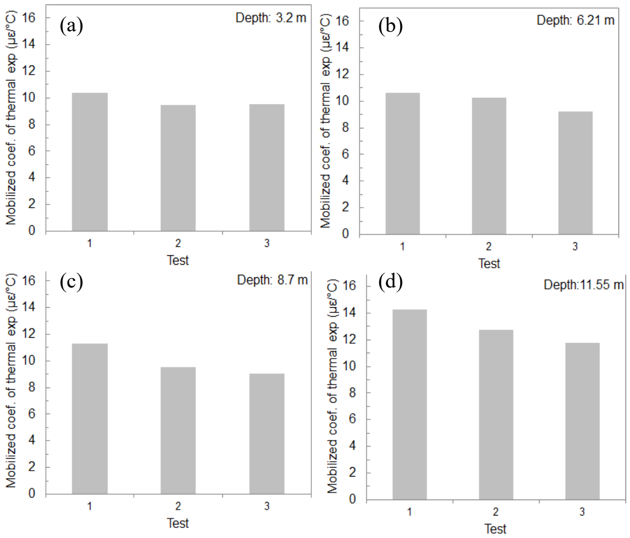

Fig. 5 - Profile of mobilized coefficient of thermal expansion for each depth in each test: **a** 3,2m; **b** 8,7m; **c** 6,21m and **d** 11,55m.

As mentioned before, during the process of heating it was observed a decreasing of mobilized coefficient of thermal expansion in each test, indicating a smaller deformation for the same amount of temperature characterizing hysteresis

Analyzing the increment of deformation versus increment of temperature plotted on Fig. 6 for each TRT it is easy to observe hysteresis on the sensor located at a depth of 8.77m on a clay layer (figure 7 c), conceivably related to what was reported by Di Donna et al,2015. that affirmed, through laboratory tests, that the response of clay–concrete interface changes at different temperatures, showing an increase of strength with increasing temperature. Conversely, on the depths of 3.2 and 6.1m located on fill and sand layers respectively (figure 7 a and b), the hysteresis was found to be negligible, also according to what was specified by Di Donna et al, 2015 about the limited effect of temperature cycles on sandy soil pile interface deformation Without regard to the depth of 11.55m a hysteresis can also be observed (figure 7d), possibly on the grounds that the pile tip is placed in a transition region between organic soft clay and clean sand.

It is important to notice that on the works of Di Donna and Laloui (2013) and Di Donna et al. (2015) on clay/concrete interface, the shear resistance increases with the increase of temperature it was explained by the thermal consolidation of the clay during heating by samples that were not pre-consolidated. On the other hand, on the work presented by Yavari et al 2016, all the samples were pre-consolidated and heated prior to beginning of tests. For this reason, the effect of temperature on the shear strength of sand, clay and clay/concrete interface was found to be negligible. This present work confirms that the effect of a temperature gradient on a clay interface on a non-pre-consolidated soil is not negligible and can works towards the security in case of increasing the soil strength [5].

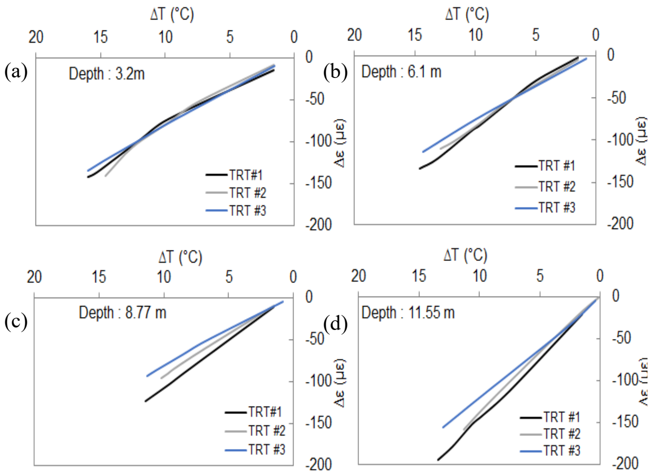

Fig. 6 - Increment of deformation versus increment of temperature for each test: **a** 3,2m; **b** 8,77m; **c** 6,1m and **d** 11,55m.

3 Conclusions

Three TRTs were carried out in a cast in place micro pile with two distinctive flow rates. A higher temperature gradient was imposed from TRT #1 to TRT #2 and #3. Temperature and thermal strains were monitored. Consistent conclusions related to the analysis of the experimental results are as follows:

- Smaller thermal strains and temperatures were observed on the clay layer.
- A linear change in thermal axial strain with changes in temperature was observed.
- The mobilized coefficient of thermal expansion reached higher values in locations of maximum strain located near the thermal pile tip due to the lower restrain conditions. Conversely lowest values of the mobilized coefficient of thermal expansion were agreeable with the location of the minimum thermal axial strain
- Hysteresis was observed during the process of heating indicating smaller deformations for each test. due to thermally induced overconsolidation representing a decrease on the mobilized coefficient of thermal expansion.
- The effect of a temperature gradient on a clay interface on a non-pre-consolidated soil was found to be not negligible. Otherwise hysteresis was found to be negligible on fill and sand layers

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