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Centrifuge modelling of an energy pile group in sand: instrumentation and testing details

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ABSTRACT: Energy piles are being widely used worldwide to harness shallow geothermal energy for building cooling and heating. Recent studies have shown that a balanced operation of a thermo-active foundation system, alternating heating, and cooling loads, can improve its efficiency. However, cyclic alternate thermal loads can affect the pile-soil interaction mechanism of heat exchanger piles and of nearby piles. A centrifuge model was designed and tested at the Université Gustave Eiffel (Nantes) to evaluate the thermal-mechanical behavior of a group of two piles in very dense saturated sand: one energy pile and one conventional pile. This paper introduces some challenges and insights into centrifuge testing to study the behavior of heat exchanger piles. Details of the experimental program and instrumentation used for the model tests, a description of the difficulties and the solutions founded, and some recommendations for future research are presented. Finally, the instrumentation used for the experiments allowed measurement of different parameters providing a better understanding of the problem investigated.

1 INTRODUCTION

The pursuit of sustainable energy demands a transformation of energy systems on a global scale. Over the next 30 years, crucial changes must be made to limit global warming by reducing CO_2 and greenhouse gas (GHG) emissions through decreased fossil fuel consumption and increased use of low or zero-carbon sources (IPCC, 2022).

Traditionally, shallow geothermal energy extraction involved boreholes drilled into the ground. Since the 1980s, these systems have evolved to be integrated with geostructures, like energy piles, diaphragm walls, among others. Originally designed for supporting structural loads and mitigating construction settlements, deep foundations now serve a dual purpose as heat exchanger piles, conducting thermal exchanges with the soil and replacing a substantial portion of traditional energy sources for space air-conditioning (Brandl, 2006; Laloui and Di Donna, 2013; Pessin and Tsuha, 2023).

In Brazilian climate conditions, shallow geothermal energy systems primarily focus on space cooling, resulting in heat rejection to the ground over the years. This operational dynamic, in contrast to temperate climates where this technology is well established, may affect the soil temperature around foundations over the lifetime of the building, resulting in an unbalanced demand for thermal energy during operation (Olgun et al., 2015).

Mitigation strategies, such as using alternative operation modes that alternate heating and cooling cycles, aim to prevent soil temperature increases over time. The heat extraction from the soil contributes to the cooling process by increasing the heat exchange rate (Cui et al., 2008; Jalaluddin and Miyara, 2012).

However, cyclic alternate thermal loads can affect the pile-soil interaction mechanism of energy piles and of nearby piles, resulting from temperature variations occurring in the soil around the piles during thermal cycles. For instance, Yang et al. (2023) observed that the alternate cooling and heating cycles of energy piles with various pile top building loads can result in additional settlement at the pile top.

Investigations into the behavior of energy pile groups have been done by some authors. Ng and Ma (2019) conducted a study on the thermomechanical response of floating energy piles groups in saturated sand subject to a constant vertical working load and asymmetric cyclic thermal load, using centrifuge modeling. Ouzzinne et al. (2023) studied the impact of the groundwater flow on a group of piles in saturated sand under non-symmetrical thermal loading.

Despite there being some papers addressing this topic, while the thermomechanical behavior of individual piles subjected to thermal cycles has been extensively studied, there is a notable gap in research assessing the thermal-mechanical behavior of groups containing energy piles.

In this paper, a centrifuge model was designed to understand the behavior of a group of piles in saturated sand (one energy pile and one conventional pile), simulating field conditions with significantly reduced efforts and observing the effects over time (almost 13 cycles of heating and cooling over ~ 216 min in model scale, i.e., ~ 3,5 months in prototype scale, under 26.7 g level, and a temperature range from ~11ºC to 40ºC in each cycle, ΔT= ~29ºC), as well as the thermomechanical response. In this scenario, the main objective of this paper is to outline the experimental program details, present the instrumentation employed in model tests, discuss encountered challenges along with corresponding solutions, and provide recommendations for prospective research.

2 EXPERIMENTAL PROGRAM

2.1 Materials

2.1.1 Piles and sand

The model box was filled using the sand pouring technique with Fontainebleau NE34 sand, that has the characteristics presented in Table 1, according to Klinkvort (2018). The relative density (D_R) of sand was 88% (very dense).

Table 1. Characteristics of Fontainebleau NE34 sand (Klinkvort,2018).

Fontainebleau NE34					
$C_u = d_{60}/d_{10}$	D_{50} [μm]	$\rho_{d\,min}$ [g/cm^3]	$\rho_{d\,max}$ [g/cm^3]	e_{min}	e_{max}
1.53	210	1.434	1.746	0.549	0.753

Four aluminum piles, two conventional piles and two energy piles, were manufactured. All of them had an external diameter of 30 mm, a wall thickness of 2 mm and a length of 300 mm (290 mm of aluminum tube plus 10 mm of plastic cover at the bottom, to close the tip of the hollow cylinder), corresponding to a prototype with an external diameter of ~ 0.8 m, wall thickness of 0.0534 m and ~8.0 m of length, considering the scaling laws for a 26.7g level. Furthermore, the distance between the piles in the group (center-to-center) is two times the external diameter of the pile.

All these piles were filled with water to improve thermal exchange. Additionally, the energy piles were equipped with a helicoidal-shaped copper tube which has an internal diameter of 2 mm, a wall thickness of 1 mm and a pitch of 25 mm. The energy piles had an active length of 290 mm (Figure 1).

Inside this copper tube, hot (or cold) water circulated during the tests, allowing the heat to be injected or extracted into/from the soil. A special top cover was adapted to allow the passage of the copper tube, permitting water circulation in the system.

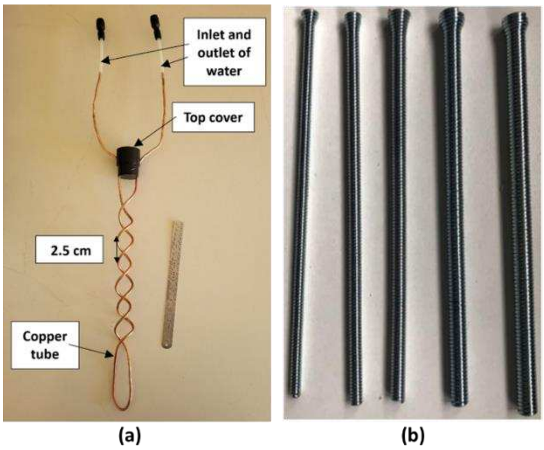

Figure 1. (a) Copper tube and plastic top cover; (b) springs with different sizes for shaping the copper tube.

2.1.2 Cap

An aluminum cap was manufactured to connect the two piles as a group. The cap had 160 mm of length, 60 mm of width, and 10 mm of thickness (4.272 m x 1.602 m x 0.267 m, in prototype scale) and maintained the piles separated by 2 times the pile diameter (2D) from center to center. This distance was chosen to maximize the thermal interaction between the conventional and the energy piles, simulating a case more unsafe than reality, when the minimum distance between the piles in a group used to be 3D. The cap was far from the ground surface, so that the entire load was transferred to pile heads.

2.2 Centrifuge

The test was performed at the Geotechnical Centrifuge Laboratory, at the Université Gustave Eiffel - Campus Nantes, which has one of the largest centrifuges in the world, with 5.5 m of radius and a maximum acceleration of 100***g***. More details about the centrifuge can be found at Thorel et al. (2009).

2.3 Model box set up

The model box prepared had a group of two piles (one energy and one conventional pile) and two extra single piles - one conventional, to evaluate the failure load, and one energy pile, to verify the service load – in saturated sand. A hydraulic circuit was installed to allow heat exchange between the pile and the soil and to apply thermal cycles during the test (Figure 2). It contained:

- A Peltier modulus, to control the water temperature based on the Peltier effect, manufactured by Laird Thermal Systems (model LA-160-24-02), with an operating temperature range from -10ºC to 46ºC.
- A peristaltic pump, which circulates water in the system at a flow rate value imposed by the user.
- A water reservoir that also works as a bubble trap.
- An energy pile, connected to the system to exchange heat with the soil.
- Platinum thermistors sensors (Pt-100) to measure the temperature variation along the flow path at the most critical points and the atmospheric temperature externally to the model box.
- Semi-rigid PVC (polyvinyl chloride) tubes connecting the system and insulated using elastomeric thermal foam to avoid heat loss or gain to/from the atmosphere.

2.3.1 Piles installation and sand pouring

Firstly, the bottom of the model box was prepared to ensure uniform rise of water throughout the soil mass. After, the sand pouring started (Figure 3a), with the sand falling from an automated hopper moving horizontally. The use of an automated sand pouring technique (Garnier, 2001) ensured the uniform distribution of sand within the model box.

The sand descended from a fixed height of 1000 mm and the slot opening of the hopper was precisely set at 3 mm. Initially, a sand layer with 100 mm of thickness covered the bottom of the container and metallic piles were placed on this layer. Thin strings were used to mark the right place of the piles according to the plan (Figure 3b). The piles were placed in its specific positions at the container before continue sand raining. This condition, which is referred to as wished-in-place (WIP), enables the simulation of model piles performance within a sand mass undisturbed by the model pile installation process. It is worth to mention that the WIP condition may cause local changes in density around the piles and near the container walls due to the “umbrella” effect (Schiavon et al., 2020). However, this effect was not analyzed in this paper.

Once the piles were fixed, the sand pouring continued until reaching the level where the thermocouples and Pt-100 were placed – 200 mm from the bottom of the piles. Finally, the sand pouring continued until the top of the model box. A special top had been designed to assure the right distance between the piles in the group during sand pouring and to allow the sand to fall properly in the space between the two piles (Figure 4).

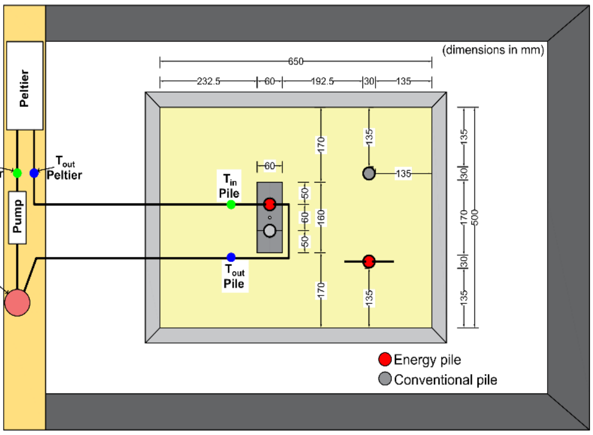

Figure 2. Top view (dimensions in mm): first model box, where T_{in} is inlet temperature and T_{out}, outlet temperature, measured by Pt-100 sensors.

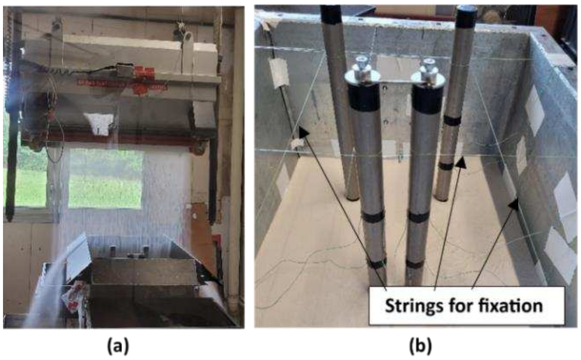

Figure 3. (a) Sand pouring; (b) fixation of the piles.

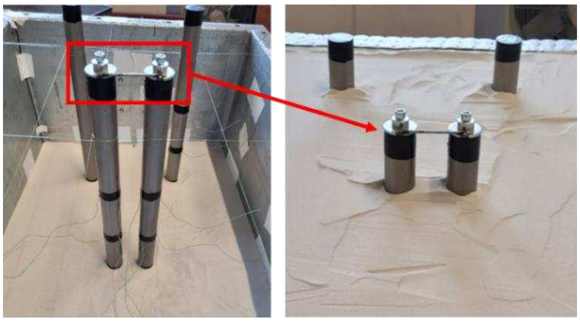

Figure 4. Detail of the special top used to maintain the distance between the piles in the group during sand pouring.

2.3.2 Saturation

After the sand pouring was completed, the model was saturated by capillarity, using an elevated reservoir connected through semi-rigid PVC tubes to a hydraulic system in the bottom of the container. Thus, the soil mass was systematically saturated up to the top of the model box at a low flow rate as can be seen in Figure 5 (Maatouk, 2022).

2.3.3 Installation in centrifuge

Finally, the model box was placed in centrifuge: hydraulic actuator device to apply mechanical load was positioned; geothermal apparatus was connected to the system and tested at 1g; flexible tubes and the water reservoir were properly insulated to avoid heat exchange with the environment air; lasers were put in the right position and all the sensors were connected to the data acquisition system; and a new project was created in the data acquisition software with the initial information about the test.

3 INSTRUMENTATION

3.1 Temperature sensors

3.1.1 Platinum thermistors sensors (Pt-100)

Platinum thermistors sensors (Pt-100) were strategically positioned for temperature measurements: in the soil, to measure temperature within the heat exchange system; to monitor the water temperature (T1, T2, T3 and T4); and to check the atmospheric temperature (T6) externally on the container (Figure 6).

1.1.1 Thermocouples

Thermocouples type K (diameter = 500 µm) were attached at the external face of all tested piles, two per level, diametrically opposed, at two different levels: the first, situated 100 mm from the pile base, and the second, 200 mm (Figure 6). Additionally, some thermocouples were positioned in the soil close to the piles to assess the influence of the thermal cycles in the vicinity.

3.2 Load sensors

Load sensors (load range: 0 to 200 daN) were fixed at the head of each pile from the group, to measure the load carried by them during the tests. For individual piles, the load sensors were not necessary as the force actuator was directly placed at their top.

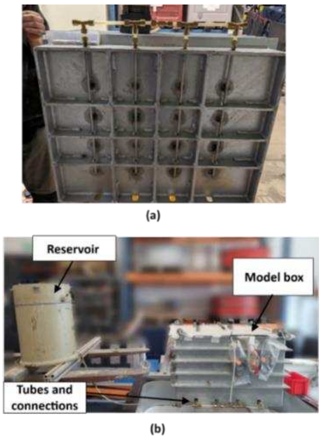

Figure 5. (a) Saturation system at the bottom of the model box (Maatouk, 2022) and (b) overview of saturation system.

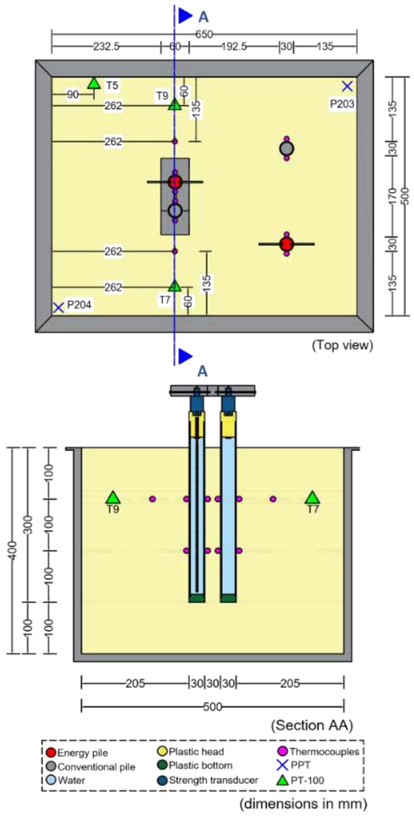

Figure 6. Instrumentation of the model box - top view and section AA.

3.3 Pore pressure sensors

Pore pressure sensors (PPTs) were installed at the bottom of the container to measure water pressure and verify saturation during the test (measurement range: 0 to 500 kPa) (Figure 6).

3.4 Laser displacement sensors

Laser displacement sensors were positioned in a metallic beam to measure settlement, longitudinal and transversal displacement of the group.

4 CHALLENGES AND INSIGTHS

4.1.1 Design of the cap

A temporary cap was used during sand pouring, enabling sand to pass between the piles, as presented in Figure 4. Furthermore, the definitive cap, divided in three parts linked by screws, was easily installed, and connected with the load sensors after the sand pouring (Figure 6).

4.1.2 Pile filling material and temperature uniformity along copper tube depth

Selecting the most suitable material to fill the piles to enhance heat exchange with the soil was a crucial step. Additionally, the helicoidal shape of the copper tube was select to minimize horizontal displacements at pile head and transverse bending of the pile under thermal loading, as can happen with U-shaped tubes due to the temperature differences between entrance and exit, during heating and cooling operations.

To make these decisions, the heat exchange system presented in Figure 2 was connected to one of the energy piles, which remained exposed to the external air.

Thermocouples were placed in the copper tube within the pile and on its external surface to monitor temperature changes. Subsequently, the heat exchange system was activated, and the pile was tested with different materials inside - water, dry sand, saturated sand, and air.

The results obtained showed that for all the filling materials studied, there was no significant temperature gradient along the length of the cooper tube. This suggested that the helicoidal shape chosen was appropriately. Furthermore, differences in thermocouple measurements between the exterior and interior of the pile were more pronounced for air and dry sand, as expected due to their lower thermal conductivity compared to wet sand and water.

According to the results, both saturated sand and water seemed to be the most suitable filling materials for the centrifuge tests. Despite saturated sand showed slightly better results, concerns about the potential increase in pile rigidity using saturated sand led to water being chosen as the filling material.

4.1.3 System insulation

Ensuring proper insulation of the system proved to be essential as it prevents heat losses or gains to/from the atmospheric air, which could interfere with the results. Therefore, all pipes connecting the heat exchange system were insulated with elastomeric thermal foam, and the reservoir was covered with a polyethylene protection to avoid heat exchanges with the air.

4.1.4 Evaluation of the flow rate of the pump in flight

Since the pump was designed for use at 1g, a subsequent experiment was conducted after the main test to assess if the flow rate during flight. The conclusion was that, during flight, the flow rate was lower than the theoretical value set in the pump software and this real value must be considered for the calculations.

5 PRELIMINARY RESULTS

The tests conducted on both single piles and group of piles were successful. Preliminary results derived from the analysis of the test on the single energy pile are presented here. Initially, this pile was loaded, without the application of thermal cycles. Subsequently, the load was maintained at a constant value for some hours (in the model) to wait for soil creep. Finally, thermal cycles were applied under constant load conditions.

Figure 7 shows the inlet and outlet water temperatures observed in the tested pile throughout the application of the thermal cycles, along with the ambient temperature variation during this test. In this test, ten complete cycles were applied to the pile, with temperatures ranging from 11ºC to 40ºC.

Additionally, Figure 8 illustrates a comparison between the inlet temperature in the pile of the circulating fluid (water), the temperature at the soil/pile interface, and the vertical displacement verified during the cooling and heating cycles. As is possible to see, the variation in circulating fluid temperature induced thermal effects on the surface of the pile. Energy pile settlements were observed during cooling phases, while in the heating phase there were heaves.

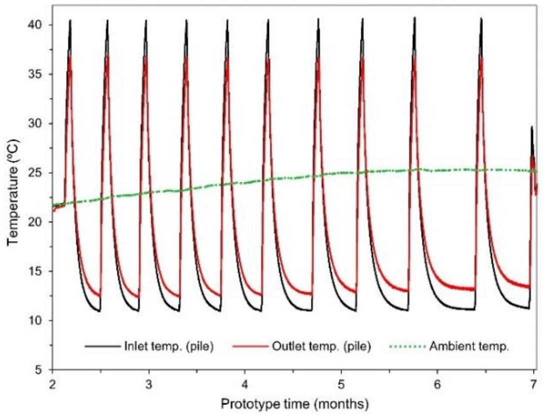

Figure 7. Temperature variation during the application of the thermal cycles in the single energy pile: inlet and outlet fluid temperature and ambient temperature.

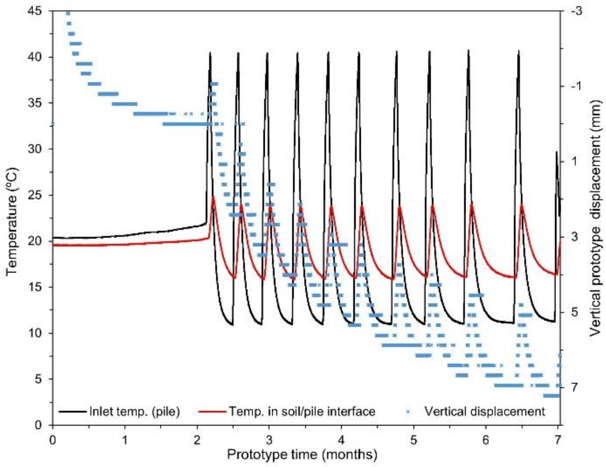

Figure 8. Temperature of water in the pile entrance and at soil/pile interface and vertical displacement of the pile.

6 CONCLUSIONS

This study focused on the thermomechanical behavior of energy piles in a group, addressing an important research gap. Despite challenges during model preparation, such as deciding on the filling material for the pile, evaluating pump flow rate in flight, and system insulation, valuable insights were acquired. Preliminary results from the test in the single energy pile indicated that the applied thermal cycles resulted in vertical displacement of the pile and temperature variation in pile soil/interface. Recommendations for further investigation include replicating the same test with clayey soil to analyze the group effect in a soil with lower thermal conductivity and conducting long-term numerical analysis to obtain more details.

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