Groundwater flow effect on the thermal behavior of energy pile groups

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ABSTRACT: Due to the technical complexity and high cost associated with full-scale field tests, centrifuge modelling is widely used as a practical alternative for investigating groundwater flow effects on energy pile behavior. While groundwater flow can help dissipate the thermal anomalies generated during energy pile operation, it can also transport heat downstream, potentially affecting adjacent piles. Centrifuge modelling enables controlled simulation of seepage and enables observation of its effects on energy pile groups under realistic stress conditions, allowing detailed analysis of these interactions. It allows for systematic variation of pile group orientation relative to flow direction, making it possible to assess how groundwater flow alignment influences both thermal and mechanical responses of energy and conventional piles, as well as downstream impacts. In this study, two pile groups were tested in saturated sand at 26.7g, each consisting of one conventional and one energy pile. One group was aligned parallel to the groundwater flow direction, and the other perpendicular. The primary objective was to evaluate the influence of groundwater flow on energy pile performance and its downstream thermal effects. The energy piles, simulating cast-in-situ systems, were subjected to cyclic thermal loading through alternating heating and cooling phases. Preliminary results show that groundwater flow direction significantly affects the thermal behavior of the pile groups, influencing both the temperature rise within the energy piles and the thermal impact on downstream foundations.

1 INTRODUCTION

Reproducing groundwater flow effect in full-scale field tests is often technically challenging and costly, which makes centrifuge modelling a practical alternative for simulating complex geotechnical problems, as the behavior of energy piles. In the case of heat exchanger piles, centrifuge testing enables the simulation of groundwater flow while allowing observation of its influence on isolated and grouped energy piles. As noted by Mayne (2009), centrifuge modelling offers several advantages, including relatively short test durations, generally modest costs, streamlined flow processes and the possibility of observing deformation and failure mechanisms.

Thermal exchange operations may generate anisotropic heat fields in the soil, particularly in unbalanced systems where the thermal energy extracted from the soil in winter is not compensated by the thermal energy rejected in the summer. Such variations in soil temperatures around the energy piles over time require careful investigation (Olgun et al., 2015).

Some studies have examined the influence of groundwater flow on energy piles. You et al. (2017) showed, through experimental and numerical analyses, that soil temperatures are higher when there is no groundwater flow perpendicular to the piles. In the presence of a groundwater flow, as the flow velocity increases, there is a reduction in soil temperature (contributing to the heat dissipation). Similarly, Yang et al. (2022), using small-scale laboratory tests, reported that heat transfer rate in the energy piles in saturated sand is 3.19 times higher compared to dry sand, reducing soil and pile temperatures, thermal pile deformation, and stress at the soil-pile interface. Centrifuge tests conducted by Ouzzinne et al. (2023) further demonstrated that groundwater flow significantly attenuates temperature rise and associated thermo-mechanical effects in energy piles.

Similar to conventional piles, isolated heat-exchanger piles exhibit different behavior when arranged in a group because of the “group effect,” which must be accounted for in the optimization of pile-foundation design. While previous studies primarily examined individual energy piles, investigations into thermomechanical interactions within pile groups remain limited (Rotta Loria and Laloui, 2017). Moreover, since only some of the foundation piles are used for heat exchange, the foundation often consists of mixed groups containing both energy and conventional piles (Wood et al., 2009). Therefore, within a given pile group, both heat-exchanger piles and conventional piles may be present. Consequently, determining whether heat extraction or injection alters the mechanical behavior of nearby conventional piles is crucial. Ng and Ma (2019), for example, observed a 30% increase in axial load compared to the initial working load on conventional piles within a group containing an energy pile, whereas Saggu and Chakraborty (2015) emphasized the risk of differential settlements between conventional and heat exchanger piles within a group that may induce group tilting and additional bending moments.

This study is part of a broader research program investigating the thermomechanical behaviour of energy pile foundations through centrifuge tests. Although the present paper focuses exclusively on the thermal behaviour (despite mechanical load was applied to the pile groups), the use of a geotechnical centrifuge is essential to correctly reproduce the in-situ stress conditions and groundwater flow mechanisms.

A key scientific hypothesis of the broader project is that groundwater flow can transport heat from the energy pile to downstream structures. This heat transfer process may cause a temperature increase in adjacent conventional piles within a pile group composed of one energy pile and one conventional pile. Therefore, thermal interaction between the piles is expected. When the groundwater flow is oriented either perpendicular or parallel to the pile group alignment, different thermal interactions between the piles are expected. This study aims to experimentally verify these thermal interaction mechanisms.

Although the present paper focuses only on the thermal response, it is anticipated that these temperature variations may later induce different mechanical effects, such as additional uplift or settlement due to thermally induced expansion and contraction of the pile–soil system. These thermo-mechanical interactions will be addressed in future work.

So that, the purpose of this study is to provide a preliminary assessment of thermal interactions between an energy pile (EP) and a conventional pile (CP) subjected to cyclic thermal loads (alternative operation mode), and to investigate how the direction of groundwater flow affects their heat-transfer performance. Specifically, the study examines how groundwater flow can promote dissipation of thermal anomalies generated by energy piles operation and affect downstream structures. The reduced-scale centrifuge model tests used in this study allow controlled adjustment of the pile-group orientation relative to the seepage direction, enabling systematic assessment of its impact on both energy and conventional piles.

2 EXPERIMENTAL PROGRAM

2.1 Materials, equipment and instrumentation

The experiments were carried out using saturated Fontainebleau NE34 sand. According to Beroya-Eitner et al. (2022), Fontainebleau NE34 sand has maximum and minimum void ratios of 0.87 and 0.53, respectively, and a critical friction angle of 31.5º. The ratio of the pile diameter to mean particle size (D/d_{50}) is 143. The relative density (I_d) of the sand was measured with a density box positioned at the bottom of the container prior to sand raining. Based on the parameters reported by Beroya-Eitner et al. (2022), the calculated I_d was 92%, classifying the sand as very dense according to Roy and Bhalla (2017) and Laloui and Rotta Loria (2020).

Model piles are composed of a hollow aluminum cylinder with an external diameter of 30 mm, wall thickness of 2 mm, and a length of 300 mm (model scale). To connect the piles in a group, two aluminium caps were manufactured to maintain the piles separated by two times the pile diameter (2D) from center to center. This distance was chosen to maximize the thermal interaction between the conventional and the energy pile, simulating a more critical case compared to the reality, when the recommended minimum distance between piles in a group is three times the pile diameter (3D). The pile’s caps have 160 mm of length, 60 mm of width and 15 mm of thickness in model scale, which corresponds in prototype scale to 4.272 m, 1.602 m and 0.4005 m, respectively. Between the aluminium piles and the cap, plastic heads were used to allow the connection and avoid heat transfer from one pile to another through the cap (Figure 1). More details are presented in Sá et al. (2024).

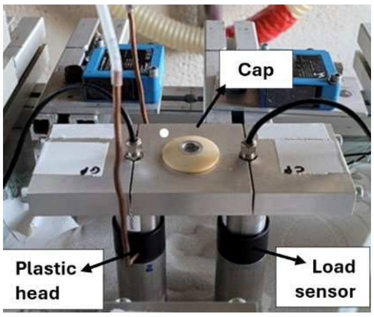

Figure 1. Cap connecting the piles in a group.

A centrifugal acceleration of 26.7g was imposed to the model, resulting in prototype dimensions as presented in Figure 2. Inside the piles a copper tube with an helicoidal shape was placed to allows the heat exchanger fluid transportation and the piles were filled with water to ensure the heat exchange between piles and ground during the system operation.

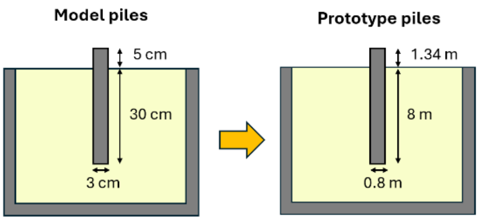

Figure 2. Pile dimensions: prototype and model scale.

Twelve Pt-100 platinum thermistors were strategically positioned throughout the setup to measure temperatures in the soil, the hydraulic system, the energy pile inlet and outlet, the container boundaries, and the ambient air surrounding the model box. Additionally, type-K thermocouples were employed to measure temperatures at the pile surface and in the adjacent soil.

Thermocouples installed on the piles' surface were positioned at two elevations: 200 mm (Level 1) and 100 mm (Level 2) above the pile tip. Vertical and horizontal laser displacement sensors were also installed to track group movements, although only the vertical sensor near the conventional pile functioned properly. Finally, pore-pressure transducers placed along the seepage path at the base of the container monitored the water level.

The system for heating and cooling comprised a Peltier module, a pump, and a reservoir (also a bubble trap), allowing heated or cooled water to flow through the energy pile.

2.2 Test set up

The experimental setup included two pile groups, each composed of one energy pile (EP) and one conventional pile (CP). These groups were installed both parallel (PAF) and perpendicular (PEF) to the groundwater flow (Figure 3). Model preparation began with the placement of gravel layers at both ends of the container. These layers were isolated by geotextile-lined barriers, after which sand was deposited using an automated pouring system to ensure uniform density. The piles were then set in a wished-in-place condition, replicating cast-in-situ installation, and arranged with a center-to-center spacing of 2D. To reduce boundary effects, they were positioned 3.5D above the base and at least 4.5D from the sidewalls, consistent with the configurations adopted in Laloui and Di Donna (2013) and Ng et al. (2014).

After installation, seepage was established in the system. Two tubes placed on opposite sides of the container produced a hydraulic head of 1.5 cm, with flow controlled via a pressure-regulated valve that allowed the system to be fully opened or closed. Finally, a heating–cooling unit was connected to the EP to impose the desired thermal cycles.

For the PAF group, a temperature increment of 24.5 °C was applied, with water temperatures ranging from 7.5 °C to 32 °C over 11 cycles, while for the PEF group, an increment of 25.5 °C was applied, with water temperatures varying between 10 °C and 35.5 °C over 13 cycles.

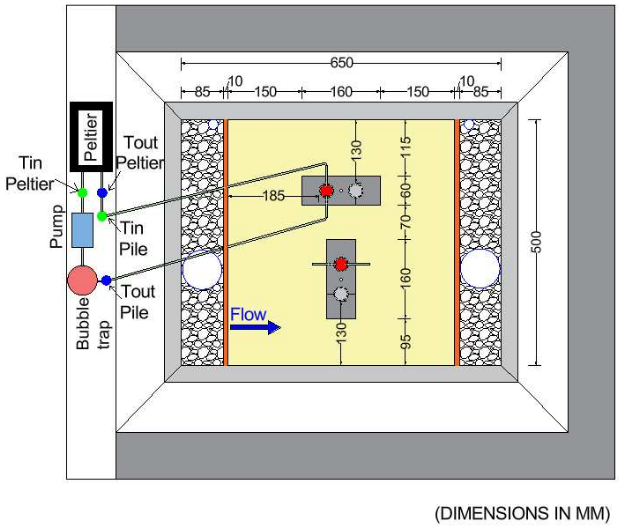

Figure 3. Model setup, showing the energy pile in red and the conventional pile in grey.

3 RESULTS AND DISCUSSION

Inlet and outlet water temperature as well as ambient temperature during the thermal cycles for the tests conducted on the pile groups (PAF and PEF) are shown in Figure 4.

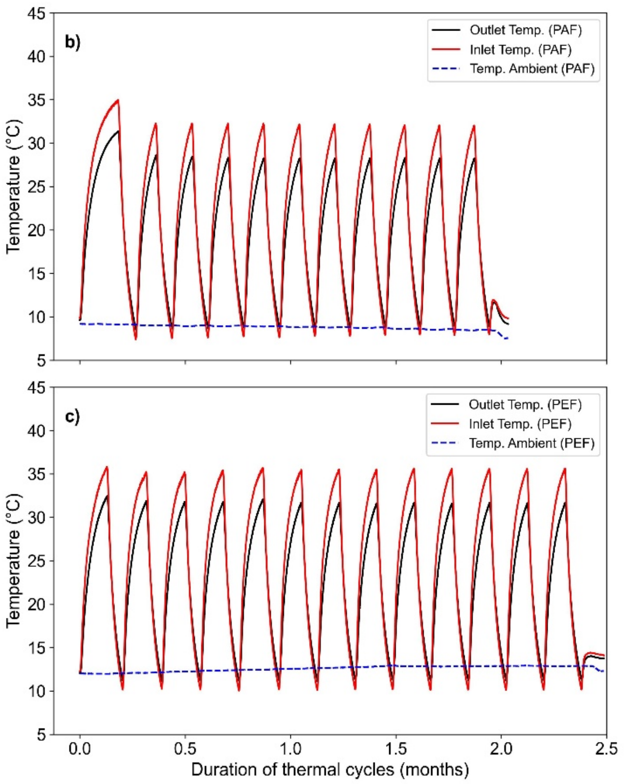

Figure 4. Outlet, inlet and ambient temperature for the tests performed.

To better understand the temperature variation patterns in the groundwater flow configurations studied (PAF and PEF), the temperature distribution at Level 1 of each model box was analysed. For clarity, the temperature increment is defined here as the difference between the instantaneous temperature recorded at a given sensor and its initial reference temperature. For each case, the horizontal plane containing all Level 1 temperature sensors was plotted, and the temperature increments corresponding to the heating peak and cooling peak of the final cycle were mapped. This approach allows visualization of the spatial distribution of the thermal plume and its interaction with the pile groups (Figure 5 and Figure 6).

In the PAF case (Figure 5), during the heating peak of the final cycle, the largest temperature increment was measured at sensor 5L located on the EP, reaching 6.7ºC. Downstream sensors installed in the CP and in the soil aligned with the pile group recorded increments ranging between 5.2 and 4.0ºC, consistent with heat transport in the direction of the groundwater flow. Upstream sensors showed minimal variation, except for sensor 1G located near the EP, which exhibited increases comparable to downstream sensors not aligned with the pile group. The container-border sensor (T3) showed no measurable temperature rise, confirming the thermal influence remained localized within the central region of the model.

During the cooling peak, the temperature increment at the EP surface decreased to 3.0 ºC, reflecting heat dissipation after the heating phase. However, the CP sensors recorded higher increments (5.4 and 5.1ºC), and the soil sensor immediately downstream the pile group reached 4.5ºC. This delayed temperature rise is a attributed to the heat transport through groundwater flow, which carries the heat generated during the heating phase toward downstream locations, where it accumulates with a time lag. The remaining sensors exhibit negligible variation during the cooling phase.

In the PEF case (Figure 6), during the heating peak of the final cycle, the temperature increments measured at the EP were higher, reaching 8.8 and 11.4ºC. On the other hand, the soil sensor located immediately downstream in the EP direction recorded an increase of 4.3ºC. The CP and most other sensors showed minimal temperature variation, except for T9 (2.9 °C).

During the cooling peak, temperature increments measured at the EP decreased to 1.5 °C, whereas the downstream soil sensor continued to increase, reaching 4.6 °C, again indicating delayed heat transport. All other sensors remained essentially unchanged.

Comparatively, the PEF configuration produced minimal temperature change in the CP because the perpendicular groundwater flow transported the heat generated by the EP away from the pile group. In contrast, in the PAF configuration, the flow direction carried heat toward the CP, resulting in measurable temperature increases. In both cases, the spatial distribution of temperature increments clearly illustrates the formation and evolution of the thermal plume and demonstrates the governing role of groundwater flow direction in controlling thermal interaction within the pile group.

4 CONCLUSIONS

This paper showed the results of a centrifuge modelling considering groups containing one energy pile and one conventional pile subjected to thermal cycles under seepage parallel and perpendicular to the group. Based on the results presented, it becomes clear that groundwater flow direction plays a decisive role in thermal response of the soil–pile system. In the PAF configuration, groundwater flow directed heat toward the pile group, increasing temperatures at the CP and downstream sensors, while in the PEF case the perpendicular flow quickly diverts heat away, resulting in minimal thermal influence on the CP. Together, these findings demonstrate that flow orientation must therefore be considered when evaluating the thermal performance and environmental impact of energy pile systems. This paper focuses exclusively on the thermal response of the system. The resulting thermo-mechanical interactions induced by the thermal plume are currently under detailed analysis and will be reported in a subsequent publication.

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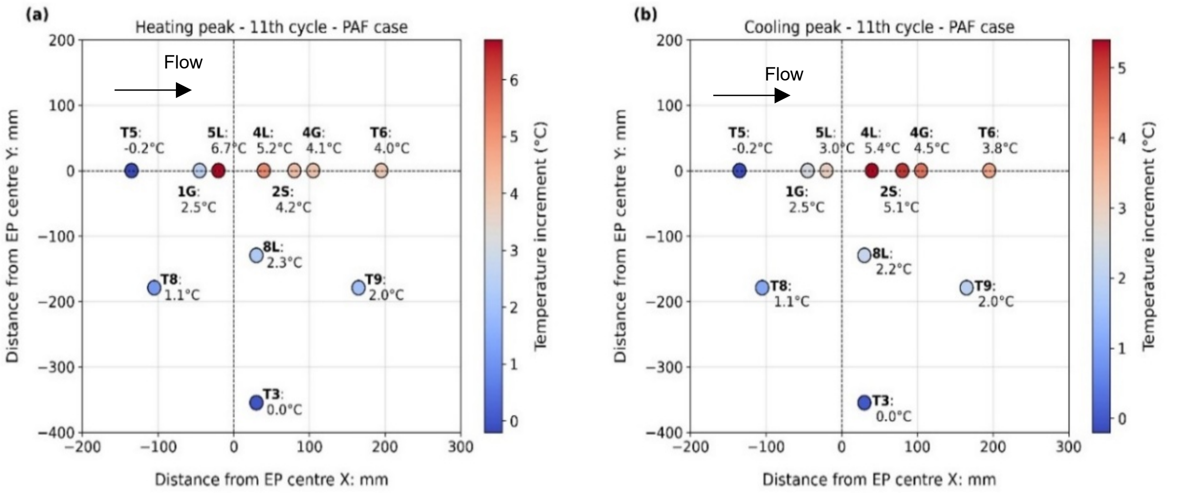

Figure 5. Two-dimensional representation of temperature increments at a depth of 100 mm (model scale) for the PAF case during the 11th cycle: (a) at the heating peak; (b) at the cooling peak.

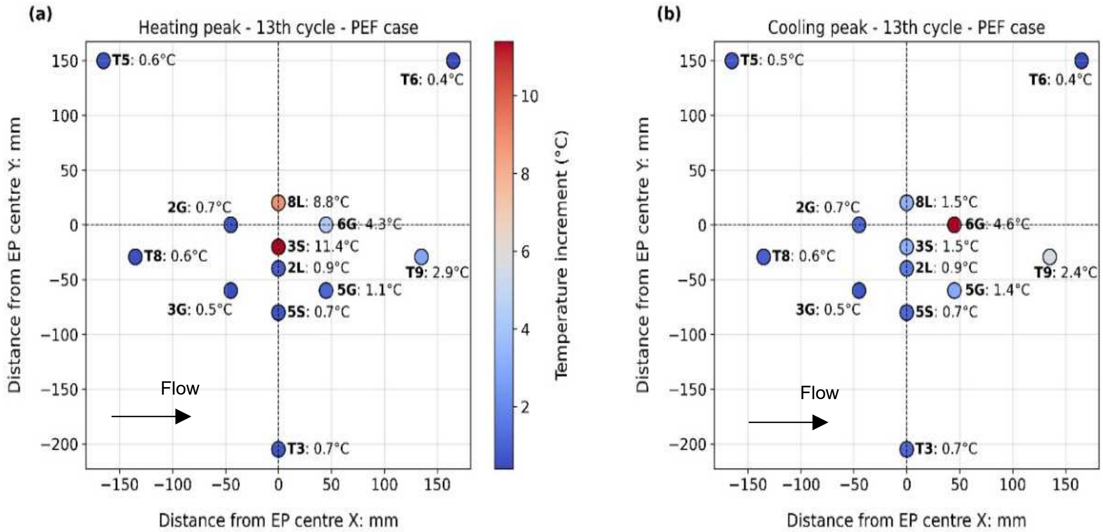

Figure 6. Two-dimensional representation of temperature increments at a depth of 100 mm (model scale) for the PEF case during the 13th cycle: (a) at the heating peak; (b) at the cooling peak.

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