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Centrifuge modelling of hollow heated piles in saturated sand

Modélisation centrifuge de pieux creux chauffés dans du sable saturé

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ABSTRACT: Thermal piles are a sustainable foundation solution which support structural load whilst generating geothermal energy. Current design practice has been developed for conventional solid concrete thermal piles. This paper focusses on the use of a new innovative hollow thermal pile, the HIPER pile, developed in collaboration with Keltbray Piling. This pile is significantly more thermally efficient; leading to greater temperature gradients than could be expected with conventional thermal piles. A total of four centrifuge model tests at 50g in sand have been conducted to investigate the effects of heating and cooling cycles on pile behaviour under constant load. During testing the pile head movement, pile temperature, and soil temperature were recorded. Relationships between pile movement and thermal cycles are presented.

RÉSUMÉ: Les pieux thermiques sont une solution de fondation durable qui supporte la charge structurelle tout en générant de l'énergie géothermique. Les pratiques de conception actuelles ont été développées pour les pieux thermiques en béton massif conventionnels. Cet article se concentre sur l'utilisation d'un nouveau pieu thermique creux innovant, le pieu HIPER, développé en collaboration avec Keltbray Piling. Ce pieu est nettement plus efficace thermiquement; conduisant à des gradients de température plus importants que ceux auxquels on pourrait s'attendre avec des pieux thermiques conventionnels. Au total, quatre essais sur modèle de centrifugeuse à 50 g dans du sable ont été réalisés pour étudier les effets des cycles de chauffage et de refroidissement sur le comportement des pieux sous charge constante. Au cours des tests, le mouvement de la tête du pieu, la température du pieu et la température du sol ont été enregistrés. Les relations entre le mouvement des pieux et les cycles thermiques sont présentées.

Keywords: Centrifuge modelling; thermal piles; temperature effects.

1 INTRODUCTION

The drive towards efficiency and sustainability within the construction industry has led to an increased demand and use of energy geostructures (Laloui & Di Donna, 2013). One such structure is the thermal pile. Thermal piles use geothermal energy thereby reducing the need to use conventional energy sources, whilst also providing structural support.

Current design practice for thermal piles in the UK is presented by the Ground Source Heat Pump Association (2018). Such piles are assumed to be solid concrete. However, the HIPER (Hollow, Impression, Precast, Energy, Reusable) pile differs significantly from a solid concrete thermal pile both in geometry and thermal efficiency and the expectation is that the behaviour of this pile will not be adequately represented by the current guidance. In order to gain a better understanding of the behaviour of these piles and the effect thermal cycles have on them a short series of centrifuge tests have been undertaken.

McNamara et al. (2014) described a field study for a novel type of hollow, cast-in-situ pile, noting that this type of pile may be suited for use as a thermal pile. Adopting a large diameter hollow pile offers the prospect of energy generation from standard length bored piles that carry structural load rather than very deep dedicated energy collectors. In addition, such piles can provide high efficiency heat transfer because they are water filled with only a narrow concrete annulus, typically 200mm.

A limited number of field tests have been undertaken in order to investigate the thermal performance of HIPER piles (Ground Engineering, 2022). The available information from these tests has provided promising data on heat efficiency as noted earlier. However, the lack of control of boundary effects can lead to variability in the results of such tests making them difficult to interpret with confidence, particularly when investigating the effect of temperature cycles on pile performance.

In order to obtain reliable data from an equivalent physical event, centrifuge testing can be used to model reduced-scale piles under controlled conditions, allowing isolation of specific variables of interest. The tests reported sought to investigate the effect of thermal cycles on pile settlement and establish how these compare to typical data in the literature.

2 PREVIOUS WORK

Previous work on centrifuge modelling of heat transfer in soil (Savvidou, 1988) states that for coarse grained soils heat transfer is primarily by free convection through the pore fluid, assuming the soil is saturated. Savvidou (1988) reviewed scaling laws for heat transfer by convection and concluded that the heat transfer would occur N^2 times faster in the model than in the prototype.

Ng et al (2020) undertook a modelling of models exercise to investigate scaling effects on loaded thermal piles subjected to temperature cycles. They found that there were no scaling effects for tests in sands with a D/d_{50} greater than 92, where D is the diameter of the pile and d_{50} is the mean particle size. In the tests reported by Ng et al. (2020), 7 cycles of change in temperature of 20°C, resulted in an overall pile head settlement of 1.3%D. There have been a number of other centrifuge test results reported in the literature but these relate to dry sands and silts, for example Wang et al (2017) and Goode and McCartney (2015) where the heat transfer mechanism will be different, or tests to examine the effect of temperature on pile capacity rather than settlement, for example Ng et al. (2015).

3 OBJECTIVES

The objective was to carry out centrifuge tests at 50g using the 40g-tonne centrifuge at City, University of London, to examine the influence of cycles of temperature on the displacement of a pile under constant axial load. The length of the temperature cycles and the height of the water table were varied.

The piles were placed in a bed of dense 0.7 – 1.25 mm alluvial sand. The temperature was cycled between 17-18°C and 43-45°C for 4 cycles of 30 minutes and then 4 cycles of 60 minutes. The piles had a relatively low length to diameter ratio and were filled with water leading to a good exchange of temperature between the pile and soil; characteristics typical of those expected of a HIPER pile.

4 APPARATUS

The tests were conducted in a 375mm deep cylindrical stainless steel tub with a diameter of 420mm (Figure 1).

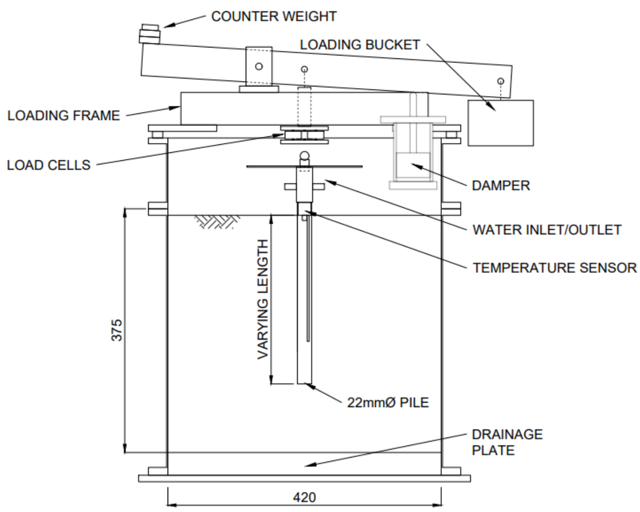


Figure 1. Model pile and loading frame set up.

The pile was modelled using 22mm outside diameter (1.10m diameter prototype) cylindrical copper tubes, coated in 0.7 – 1.25 mm alluvial sand ensuring good and consistent interface friction. This was the same sand that was used to create the soil bed. The pile cap was made from a Perspex body which housed inlet/outlet tubes for water to flow through the pile as well as a temperature sensor (Figure 2). An aluminium plate on top of the pile cap allowed LVDTs to measure vertical pile displacement.

The constant load apparatus comprised a loading beam with a water bucket at one end and a set of counterweights at the other. During the test, the loading bucket was filled with water corresponding to the desired axial load and that load was applied to the pile head. The load was measured by a load plate consisting of three load cells sandwiched between two aluminium plates ensuring that the load cells were not subjected to bending. Load was applied through a steel ball bearing at the top of the Perspex body ensuring pure axial load. To avoid a sudden movement of the bucket, and therefore an impact on the pile head, a damping mechanism was introduced.

Figure 2. Model pile embedded in sand.

5 MODEL PREPARATION AND TESTING PROCEDURE

Correct placement of the pile and soil temperature sensors was achieved with an installation guide. The pile and temperature sensors remained attached to the guide until the required height of soil was reached.

The sand was carefully placed into the tub, around the pile and soil temperature sensors, in layers of approximately 10mm, with compaction taking place after each layer of sand was placed. Pore pressure transducers were inserted through openings in the walls of the tub. A smoothing tool was used to level out the surface of the soil.

Once the top of the soil model was levelled, the installation guide was removed and the loading frame, with the load cells and LVDTs was carefully fixed onto the tub. The model was then placed on the centrifuge swing for connections to be made. A standpipe was connected to the model to establish and maintain the required water table for each test and the model was accelerated to 50g. When the water table was established the pile was loaded by filling the bucket with water to achieve the desired load. Thereafter, heating and cooling cycles began.

The pile embedment depth, water table levels, and factors of safety (FOS) for the two tests presented are summarised in Table 1.

Table 1. Summary of test variables.

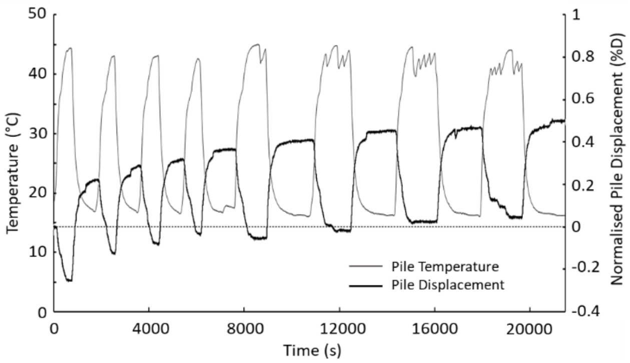
Test ID	Pile embedment depth (mm)	Water table in mm below ground level	FOS
Test 1	265	129	2.6
Test 2		31	1.7

6 RESULTS

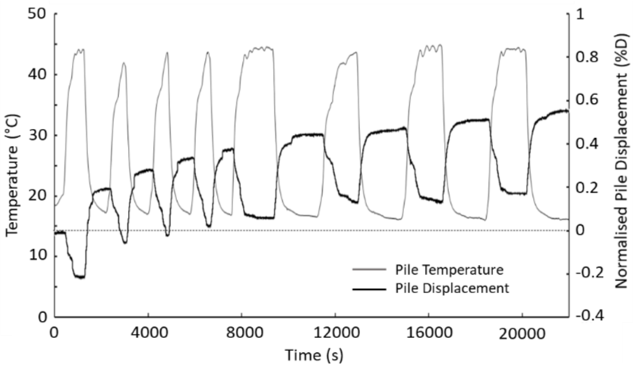
For Tests 1 and 2, the pile embedment depth was 265mm at model scale, equivalent to 13.25m at prototype scale. As noted above the first four cycles of temperature each took 30 minutes, which is equivalent to 52 days of heat transfer at prototype scale; owing to the N^2 scaling factor for heat transfer (Savvidou 1988). The second four cycles were 104 days at prototype scale. The normalised pile displacements during heating and cooling stages are shown in Figure 3.

The initial temperature of the piles was between 17 and 18°C and this was governed by the mains supply temperature. The piles were then heated to 43°C by circulating hot water through the pile, applying a temperature change of approximately 26°C between heating and cooling cycles. A slight variation in both maximum and minimum temperatures of the pile was observed owing to heat loss during cycling.

Pile heave of just under 0.3%D was observed during the first heating phase for Test 1, followed by a settlement of approximately 0.5%D during the first cooling phase. During subsequent heating and cooling cycles, ratcheting settlement of the pile was observed, with a final settlement of 0.5%D, but at this stage the net settlement at the end of a temperature cycle had reduced to 0.03%D. There was a smooth non-linear reduction in net settlement per cycle which was not affected by the length of the temperature cycle. In this test the water table was approximately half way down the pile and below the temperature sensors.



Test 1



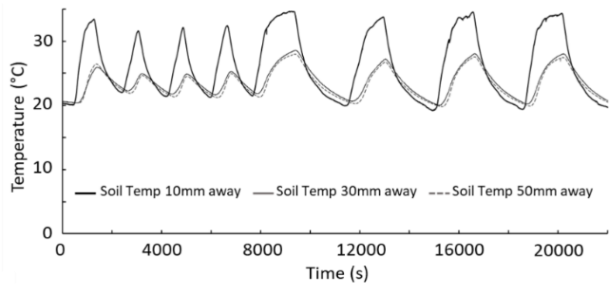
Test 2

Figure 3. Normalised pile displacements during temperature cycles. Negative pile displacement is heave.

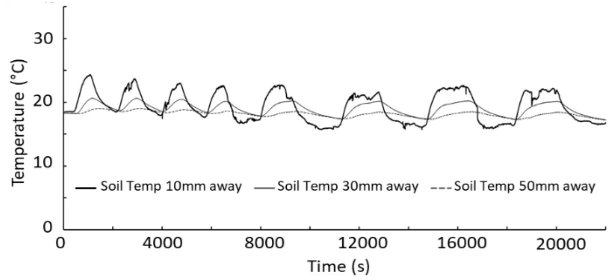
In Test 2 the water table was near ground surface, and pile displacement was reduced; just over 0.2%D of heave occurred when the pile was initially heated, followed by 0.45%D of settlement during the first cooling phase. During subsequent heating and cooling cycles the net settlement increased more significantly than in Test 1 with a final settlement after 8 cycles of 0.53%D. The net settlement for the final cycle was approximately 0.03%D. In this test it appears that the cycle duration influenced the net settlement in each cycle, as there was an increase in net settlement during the first long cycle; although it is possible that this may be a function of slight disparities in the temperature cycles.

7 DISCUSSION

There was heave at the pile cap upon initial heating, followed by settlement as the pile and surrounding soil cooled and contracted. Settlement always exceeded heave but by gradually lesser amounts. The factor of safety for Test 2 was lower than that for Test 1 because the water table was near the surface and this should lead to significantly greater settlements during this test. However, the increase in settlement was marginal and this may be explained by examining the change in temperature in the soil surrounding the pile. Figure 4 shows the temperature measured at sensors placed 10, 30 and 50 mm away from the pile.



Test 1



Test 2

Figure 4. Temperature variation away from the pile.

It is clear from this figure that temperature dissipates more rapidly with distance from the pile when the sand is saturated. This might be expected as the primary mechanism of heat transfer in a coarse-grained soil is convection due to motion of the pore fluid (Savvidou, 1988). In the unsaturated/dry sand at the top of the pile in Test 1 this mechanism of heat transfer will not occur and the soil surrounding the pile will be subjected to more dramatic changes in temperature leading to greater heave and settlement than might occur in a saturated sand at an equivalent factor of safety. This may also cause a pile in saturated sand to be less thermally efficient, but this is not something that could be easily established from these tests. The temperature changes are consistent with those seen by Ng et al. (2020) for thermal piles in saturated sands. Wang et al. (2017) testing piles in dry sand recorded greater temperature changes at similar distances from the pile, but in Test 1 half of the pile is in saturated soil. The overall pile head settlement after 7 cycles of temperature observed by Ng et al. (2020) was greater than in Test 2, but the pile length to diameter ratio in those tests was 19, whereas in the tests reported here it is only 12 representing a realistic geometry for a HIPER pile. A longer pile should generate greater displacement at the pile head when heated and cooled.

8 CONCLUSIONS

A short series of centrifuge testing of piles in sand has confirmed that heat transfer through saturated sand by convection within the pore fluid reduces temperature changes in the soil surrounding the pile. This in turn reduces temperature induced settlements under axial load. In comparison with similar tests on piles with higher length to diameter ratios these wider and shorter hollow piles seem to develop less net settlement, even at quite low factors of safety.

The series of tests was limited in number and further work is necessary to explore the effect of varying the water table for constant factor of safety piles.

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