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Centrifuge modelling of the effect of temperature on the capacity of novel thermal piles in clay

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ABSTRACT: The HIPER™ pile is a novel cast in situ or precast hollow pile that reduces the amount of concrete normally required for a pile of a given capacity, facilitates reuse of foundations in the long term and can be used as a thermal pile. When used as a thermal pile the central cavity is filled with water in which the heat exchange pipes are placed. This ensures that exchange of heat with the surrounding ground is significantly more efficient than for a conventional solid concrete pile, both when the pile is being used for cooling and heating. A series of tests has been undertaken using a geotechnical centrifuge to investigate whether changing the temperature of the pile and surrounding soil affects the ultimate capacity and load displacement response of the pile. The soil used was Speswhite kaolin clay and the pile was heated and cooled by circulating water through the pile in flight. The temperature gradient in the soil and in the pile was monitored by temperature sensors. The paper will report the apparatus used and the results of the study.

1 INTRODUCTION

HIPER pile is an acronym for a Hollow, Impression, Precast, Energy generating and Reusable pile (Keltbray Ltd 2021). It has been developed to maximise the sustainability of piled foundations and Keltbray Ltd have found that the void in the hollow pile is well suited for thermal energy storage. Field tests showed that the HIPER pile outperforms the conductivity of traditional thermal piles by over 60% (Keltbray Ltd, 2021).

The idea of using a hollow pile, either *in situ* or precast, decreases the amount of concrete being used especially when large diameter piles, greater than 900mm and up to 2500mm, are required to take greater loads. This means that HIPER piles would often be single piles not part of a larger group. This further increases the thermal efficiency of the pile. Using the pile to help heat and cool a building will provide an improved design which not only reduces carbon emissions but also reduces energy costs. However, the heating and cooling of the pile and surrounding soil may affect the pile capacity. This paper specifically looks at how the change in temperature affects the pile capacity and load-displacement response of a pile in overconsolidated clay.

2 BACKGROUND

There is a general understanding that heating and cooling of the soil surrounding a piled foundation used as a thermal pile will affect the interaction between the pile and the soil leading to; relative displacement at the pile soil interface, changes to the internal stresses in the pile and changes to the stresses mobilised at the pile soil-interface, as described by Bourne Webb et al. (2009). At working loads these effects may be recoverable as reported by Bourne-Webb et al. (2009). Nevertheless, there have been a number of model test studies undertaken (for example centrifuge model tests by Ng et al. (2014)) to investigate these phenomena and in particular to examine how cycles of heating and cooling might lead to cumulative displacements and contribute to a reduction in the pile capacity. In addition, model tests have looked specifically at changes in pile capacity caused by thermo-mechanical effects by loading a pile to failure under different temperatures. The majority of these tests have been undertaken in compacted silts and sands as summarised in Loveridge et al. (2020), but tests by Ghaaowd et al. (2018) and Ng et al. (2014) have been undertaken in saturated clay.

Ghaaowd et al (2018) found that the pull-out capacity of piles heated from 26 to 63.4°C at 50g for 30 hours increased by 20% and also noted an increase in the undrained strength profile of the clay, particularly towards the base of the clay layer which was around 230mm deep. The kaolinite clay bed used for these tests was largely normally consolidated with an overconsolidated layer at the top. The water table was above ground surface. The maximum temperature change they measured in the soil around 20mm from the pile was 15°C reached after 25 hours, although 60% of this change had been achieved after 1 hour.

Ng et al. (2014) tested piles in lightly overconsolidated and heavily overconsolidated clay beds. Unlike the tests by Ghaaowd et al. (2018) the piles were floating and subjected to heating and cooling cycles by passing a fluid through the piles. The piles were constructed from aluminium but had an epoxy coating to reduce the thermal conductivity of the piles. They were subjected to a constant load representing a factor of safety equal to 2.5. The temperature varied between 36 and 12°C in the test in overconsolidated clay and each cycle lasted 3 hours at model scale. The variation in temperature in the soil 20mm from the pile was approximately 7.5°C. This is approximately 30% of the imposed change in temperature compared to 40% in the tests by Ghaoowd et al. (2018). However, the prototype heating time was much greater in the latter tests. There do not appear to be any tests specifically investigating changes in pile capacity in overconsolidated clays reported in the literature.

3 METHODOLOGY

Three model tests were carried out at 50g using the Acutronic 661 geotechnical centrifuge at City, University of London.

3.1 Soil

The soil used was Speswhite kaolin. The bed of soil was formed by consolidating Speswhite Kaolin from a slurry with a water content of between 106 -110%. At this water content the slurry can be poured into the tub minimising trapped air bubbles. The clay slurry was consolidated in the tub in a consolidation press to a vertical effective stress of 500kN/m^2. The sample was then swelled to a vertical effective stress of 250kN/m^2 at which point three miniature pore pressure transducers (PPTs) were installed in the clay at the positions shown in Figure 1. Following a further 8 hours, the tub was removed from the consolidation press and the model constructed prior to placing on the centrifuge swing. Once on the swing the model was accelerated to 50g and left to consolidate until pore pressure equilibrium was reached, usually around 48 hours. At this point all the soil was overconsolidated with the overconsolidation ratio varying from about 62 at ground surface, where the effective vertical stress is 8 kN/m^2 reducing to 4 at the base of the tub.

3.2 Equipment

The model consisted of a hollow pile constructed from a copper tube, a system for pumping heated or cooled water through the pile and displacement-controlled loading with the load measured by a load plate. The set up can be seen in Figure 1. Two of the temperature probes measure the soil temperature and one measures the temperature of the water in the pile. Pore pressure transducers are used to demonstrate pore pressure equilibrium before heating and then loading the pile.

The pile is 210mm deep and has a diameter of 22mm. The boreholes made for the temperature probes are 105mm deep, ie mid-way down the pile. The pile has a rough outer surface created by gluing sand to the copper tube to enhance friction between the outer surface of the pile and the soil. The first bored hole for temperature probe 1 is 10mm away from the pile and the second bored hole for temperature probe 2 is 20mm away from the pile.

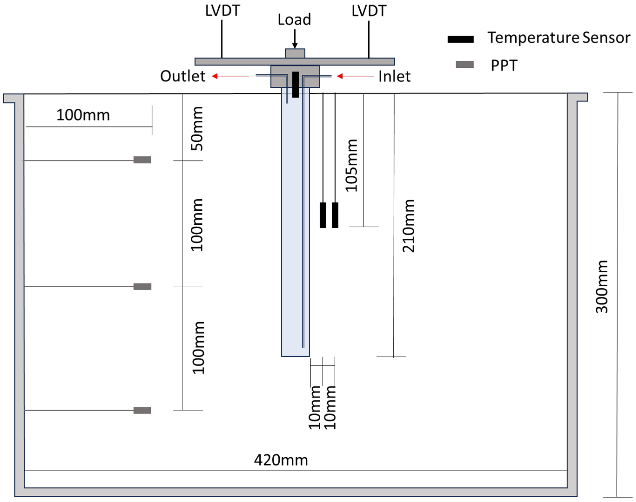

Figure 1. Sketch of model (not to scale)

The temperature probes (in size only slightly longer than the miniature pore pressure transducers) are placed into the boreholes and back-filled with clay. A standpipe is positioned behind the tub on the swing and for this model maintains the water table at 16.5mm below ground surface. This ensures that the water table is below ground surface everywhere. Pipes attached to the pile are connected to a pump and heated water tank on the roof of the centrifuge chamber through the centrifuge hydraulic slip rings. This system means that it is possible to control the temperature in the pile by pumping heated water through the pile. The temperature was brought to the value required for the test by adjusting the temperature of the water in the tank and the pump speed. Once the correct temperature had been reached sufficient time was left for the temperature in the soil to begin to stabilise, but probably not to reach equilibrium. Measurements of temperature versus time indicate that equilibrium was reached 10mm from the pile and the temperature was at around 80% of the equilibrium value at 20mm. The pile was then loaded using an actuator operating at 1mm/min. This meant that the loading was effectively undrained. The resulting load was measured by three load cells arranged in a force plate (Tanghetti et al., 2018). Figure 2 shows the configuration of the equipment at the top of the model. The orange film on the clay is PlastiDip, a synthetic rubber, which seals the clay surface to prevent evaporation of water during the test.

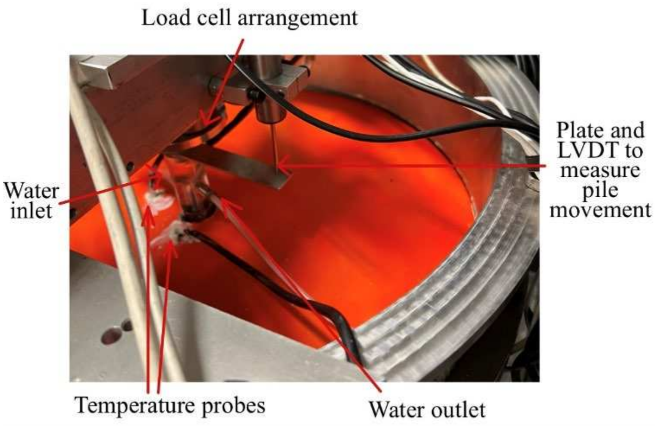

Figure 2. Photograph of model surface

The pile was full of tap water during the consolidation stage but no heated water was circulated through the pile until approximately 20 to 30 minutes before the pile was loaded. The pile temperatures at the end of the consolidation stage and immediately prior to loading for the three tests undertaken are given in Table 1. After the pile had been loaded to failure, greater than 10% of pile diameter, the test was stopped and the undrained strength of the clay was profiled using a hand shear vane. The resulting profiles of undrained strength are discussed below.

Table 1. Pile temperatures before and after loading in the three tests completed

Test	Temperature after consolidation, °C	Temperature before pile loaded, °C
1	13	29-30
2	13	35-36
3	13	40-41

3.3 Undrained strength of clay

Once the test was completed a shear vane was used to measure the undrained strengths at gradually increasing depths in the model. The undrained shear strength, S_u, can be found from the vane measurement, S_{uv}, using Equation 1.

$$S_{uv} \times 1.346 = S_u \qquad (1)$$

Measurements were made for all three tests and are plotted in Figure 3. The measurements were taken after the test in the clay approximately 100mm away from the pile. For every depth the shear vane values were taken from three different locations and averaged to give the values plotted. For tests 1 and 2 the profiles of undrained strength with depth are very similar, ±7%, whereas the undrained strengths are higher in the upper 100mm of the soil in Test 3, in particular near to the soil surface where the strength was 20% higher.

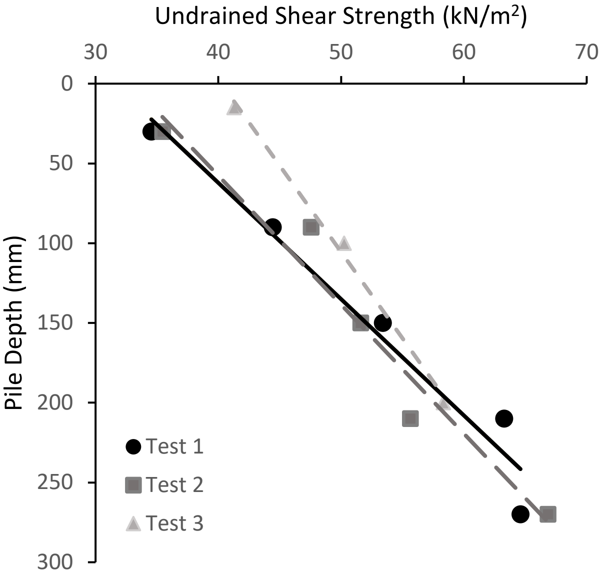

Figure 3. Undrained shear strength graph

4 TEST RESULTS

In the three tests completed, the pile was loaded at three temperatures, 29-30°C, 35-36°C and 40-41°C, as shown in Table 1. Figure 4 shows the temperature change in the pile and the soil adjacent to the pile in these tests immediately before the piles were loaded. At 20mm from the pile there is little diffence in the temperature increase in the soil which is 3.8°C for all tests, whereas 10mm from the pile the temperature increase varies from 7.0 to 10.8°C reflecting the difference in pile temperature and approximately 40% of the change in temperature at the pile.

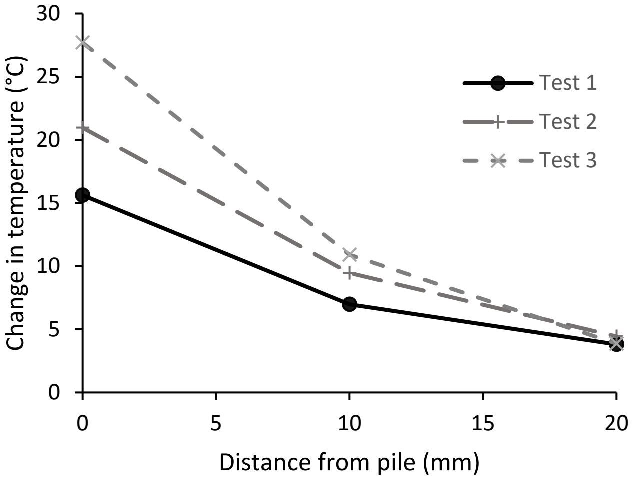

Figure 4. Change in temperature in the soil with distance from the pile

4.1 Load - Settlement

The load displacement response from all three tests are compared in Figure 5. The capacity of the piles has been defined as the load at a displacement of 10% of the pile diameter, identified in Figure 5. These values are given in Table 2. This table and the curves shown in Figure 5 indicate that for these loading and heating conditions, increasing the temperature of the pile reduces the capacity of the pile.

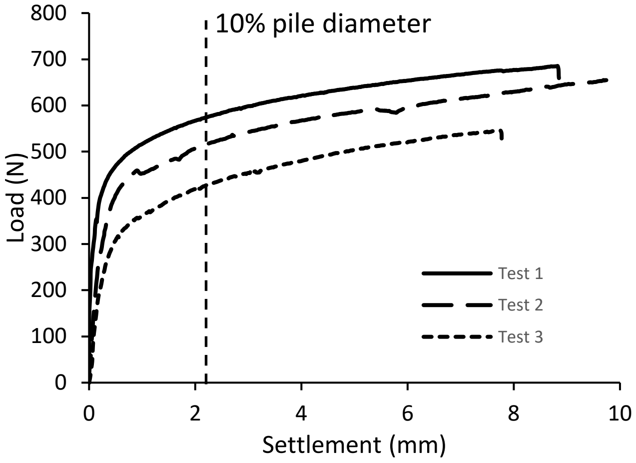

Figure 5. Load vs settlement graph

Table 2. Ultimate compressive capacity estimated from graph

Test	Capacity, Q (N)
1	574
2	515
3	427

The pile capacity may also be affected by variation in undrained strength and so the loads have been normalised by the averaged undrained strength at the midpoint of the pile.

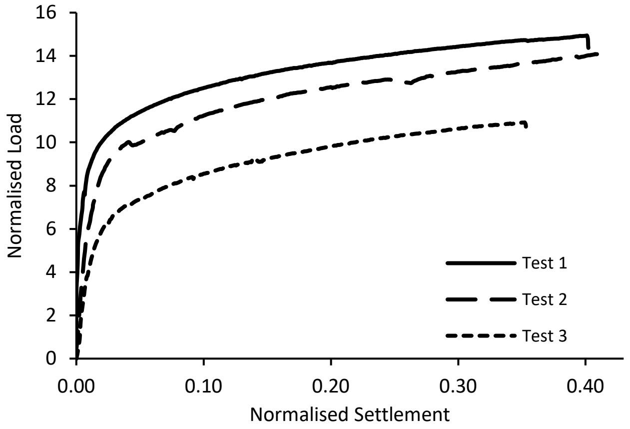

Figure 6. Normalised load vs normalised settlement graph

These normalised data are shown in Figure 6. Normalising with respect to undrained strength emphasises the difference caused by heating the pile. In order to understand the effect of temperature during loading, contours of normalised load are plotted against the pile temperature at displacements corresponding to set percentages of the pile diameter. Figure 7 shows the variation in normalised load for displacements which are 1%, 5% and 10% of the diameter of the pile. At low displacements there is a more linear relationship between temperature increase and reduction in normalised load.

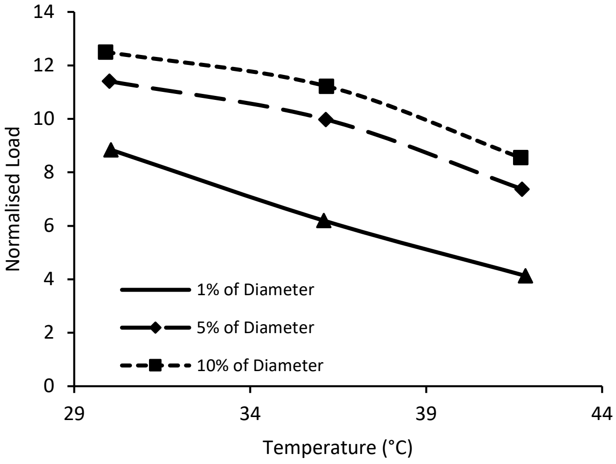

Figure 8. Normalised load vs temperature graph

5 DISCUSSION

As the temperature increases, the pile capacity decreases. This is first seen in Figure 6. The pile heated to 29-30°C has an ultimate capacity of 680N, whereas the pile at 40-41°C has an ultimate capacity of 550N, or 24% lower. Test 2 heated to 35-36°C has an ultimate capacity that is between these two. In Test 3 where the pile was heated to the highest temperature the undrained strength was highest, similar to the tests undertaken by Ghaaowd et al (2018) but in the tests reported here, the undrained strengths were measured 100mm from the pile which was only heated for around 20 minutes so it is highly unlikely that the higher undrained strength is a function of the heating of the pile. This is why the ultimate capacity was normalised eliminating any effect due to the variation in soil strength.

In these tests the pile has reached the required temperature relatively quickly, in around 12 minutes, before being left for a further 8 to 18 minutes before being loaded. Assuming scaling laws proposed by Savvidou (1988) are valid for this diffusive conductivity dominated process this is equivalent to heating the pile over 13 days at prototype scale. It appears that this has resulted in undrained loading of the overconsolidated soil and the generation of positive excess pore pressures as discussed by Loveridge et al. (2020). These excess pore pressures would lead to a reduction in the capacity of the pile as observed in these tests. Figure 4 indicates that the change in temperature in the soil only reflects the pile temperature at 10mm from the pile and consequently the effect of the different pile temperatures must be very local to the pile. This suggests that any restraining effect caused by the soil swelling is minimised.

6 CONCLUSIONS

Three centrifuge model tests have been undertaken to examine the effect of heating on the load-displacement response of a thermal pile constructed in heaviliy overconsolidated clay. In each test the piles were heated to a fixed temperature between 29 and 40°C. The piles were heated and then tested sufficiently rapidly for these processes to be undrained and for changes in temperature to be only significant within a diameter of the pile. It was found that in these circumstances the ultimate capacity of the pile was reduced by up to 25% when the temperature was increased from 29 to 40°C. Although there was a non linear relationship between the load carried at displacements close to failure, 0.1D, and temperature, at 0.01D there was a linear relationship between temperature and load carried. Further work is necessary to assess the effect of the time taken to heat the pile.

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REFERENCES

Bourne-Webb, P.J., Amatya, B., Soga, A., Amis, T. and Payne, P. (2009) Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspect of pile response to heat cycles, Géotechnique, 59:3, pp. 237-248. https://doi.org/10.1680/geot.2009.59.3.237

Ghaaowd, I., McCartney, J.S., Huang, X., Saboya, F., & Tibana, S. (2018) Issues with centrifuge modeling of energy piles in soft clays. 9th Int Conf on Physical Modelling in Geotechnics. London, England. Jul. 17-20. 1-6.

Keltbray "Keltbray HIPER™ Pile Brochure" Available at [https://issuu.com/keltbraygroup/docs/keltbray_-_hiper__pile], accessed: 14/02/2023

Ng, C.W.W., Shi, C., Gunawan, A., & Laloui, L. (2014) Centrifuge modelling of energy piles subjected to heat ing and cooling cycles in clay. Géotechnique Letters 4: 310–316.

Savvidou, C. (1988) Centrifuge modelling of heat transfer in soil. Proc., Centrifuge 88, J.-P. Corté, ed., Balkema, Rotterdam. 583–591.

Tanghetti, G., Goodey, R.J., McNamara, A. M. & Halai, H. (2018). Plate bearing tests for working platforms. Proc 9th Int Conf on Physical Modelling in Geotechnics (ICPMG 2018) London, United Kingdom.

Loveridge, F, McCartney, JS, Narsilio, GA and Sanchez, M (2020) Energy geostructures: A review of analysis approaches, in situ testing and model scale experiments. Geomechanics for Energy and the Environment, 22. 100173. https://doi.org/10.1016/j.gete.2019.100173

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