Physical Modelling in Geotechnics

Development of a model pile for heat transfer experiments in the centrifuge

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ABSTRACT: Conventional energy piles use embedded plastic pipes to circulate a fluid through solid concrete which enables transfer of heat into, or out of, the ground as required. Such piles are relatively low efficiency owing to the poor conductivity of the concrete in which the pipes are embedded. They are also known to be susceptible to damage during construction and their adoption as a sustainable energy source has, as a result, been limited. A novel method of heat transfer, which is much less susceptible to damage during construction, and has been found in field trials to be more energy efficient, exploits the significantly higher conductivity of water in a rotary augured hollow, cast in-situ, or precast pile. In such a pile the plastic pipes are placed in the water filled central void of the pile. Such an arrangement will lead to the ground around the pile experiencing a lower range of temperature variation compared with standard energy piles and the influence of this effect on pile capacity will be explored. In order to model multiple cycles of temperature variation to which the ground around a prototype pile may be subjected it is necessary design experimental apparatus that is capable of rapid heating and cooling and with high thermal conductivity materials. The paper will describe the design of a model pile which incorporates an immersed heating element capable of bringing the pile temperature to a specific maximum value and a means of quickly purging the heated water to return the pile temperature to the desired minimum value whilst the pile carries a constant axial load in the centrifuge.

Keywords: hollow pile, sustainable energy, energy pile.

1 INTRODUCTION

Energy piles offer sustainable heating and cooling for buildings and it is generally thought that they will have an important part to play in reducing carbon footprints and tackling the threats posed by climate change. Although such piles have been used for around 20 years in the UK with the first installation having been undertaken at Keble College, Oxford (Suckling and Smith, 2002) widespread take up has been relatively slow largely owing to acknowledged difficulties with maintaining quality during construction. Conventional energy piles rely on the inclusion of plastic pipes in bored cast in situ piles which are used to circulate water for heating and cooling purposes. After pile construction these tubes protrude from the top of the piles. Subsequent site activities such as pile trimming, bulk excavation and pile cap construction are aggressive and, as a consequence, the tubes are extremely vulnerable to damage; a factor that has remained a significant deterrent to their use.

The recent commercialisation of City, University of London patented technology associated with hollow rotary bored piles (McNamara *et al.*, 2014) is expected to result in renewed interest in energy piles owing to an ability to construct the piles without the need to cast in plastic tubes. With a hollow pile the void can be filled with water into which the plastic tube can be placed long after potentially damaging site operations have ceased. This means that energy piles can be constructed with greater confidence of success; whilst field tests on their performance have shown them to significantly outperform conventional solid concrete energy piles owing to improved thermal conductivity associated with the water filled bored.

Along with efficiency gains from improved heat transfer the piles subject the ground around them to a greater range of temperature variation. This may influence the performance of the piles as load bearing foundations. The aim is to explore the effect of cycles of temperature on pile performance under axial load.

2 PARAMETERS FOR DESIGN OF THE EXPERIMENTAL APPARATUS

As previously stated, there have been limited experimental works on soil-structure interaction problems under thermo-mechanical loads. The evidence on this theme for clay soils are extremely scarce, mainly because of the complexity of exploring the problem in a meaningful way.

A recent study (Ng *et al.*, 2014) modelled a temperature range, ΔT, of about 20°C over thermal cycles of long duration. They found that temperature induced settlement in piles is greater in lightly consolidated clays than in heavily overconsolidated clay. This study suggests that there is merit in a detailed invesitgation into pile performance under contant load with thermal cycles.

As a first step to tackle the problem, the Multi Scale Geotechnical Research Centre at City, set out to develop novel experimental apparatus capable of simulating a number of thermal cycles on a vertically loaded pile embedded in an overconsolidated clay layer at 50g in the geotechnical centrifuge.

The primary goals of the project are:

- To design and manufacture a miniature pile suitable for use in a geotechnical centrifuge. The pile apparatus is required to undergo thermal cycles and mechanical loads whilst embedded in an overconsolidated clay sample,
- The model pile apparatus should allow measurements of temperature changes in the pile as well as temperature changes and pore pressure measurements in the soil surrounding the pile,
- Understand thermo-mechanical interaction effects on the pile response,

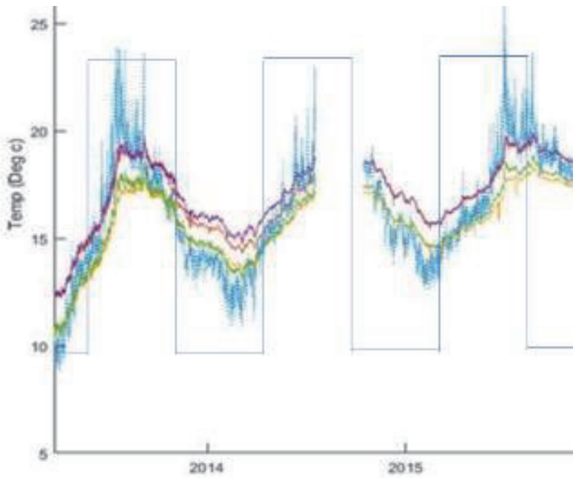

Fig. 1. Complex thermal variation within the pile and the simplification used in modelling (modified from Turner *et al.*, 2021).

When approaching relatively unexplored themes one of the key factors for success is in keeping the design of the apparatus simple. In view of this significant effort has been made to simply as much of the problem as possible. The complex thermal variation within the pile, see Figure 1, has been simplified in a squared wave, compared to the field measurements, where the temperature changes instantaneously and is then kept constant over a specific time period (typically for months at the prototype scale). Temperature changes can be achieved by flushing water into the hollow section of the model pile and heating it by means of a heating element controlled from the outside of the centrifuge.

The data shown in Figure 1 is of temperatures experienced by an energy pile in London. The blue (centre) data is the pile temperature close to the heat transfer pipes in the centre of a CFA pile, the other colours are on the steel reinforcing cage near to the pile edges. It can be seen that the near pipe temperature fluctuates significantly, but remains within a range of 10°C - 30°C. This system is cooling dominant hence the general small rise in temperature overall.

The important point here is that overall the amount of temperature change is quite small. A conservative estimate of operating range would be between about 2°C - 35°C.

For the experimental work it is desirable to impose a less fluctuating pattern than in the field case, and typically a constant T or constant heat flux for periods of time is preferred, followed either by recovering or cycling.

The aim therefore, as a reasonable starting point, is to use ambient temperature water (say 10°C) which is heated to 30°C and cooled again to ambient temperature. At some later stage cooling to about 2°C may be advantageous. Duration of any cycles is dependent on materials being used with permeability being a key consideration owing to porewater pressure response time. For practical reasons a balance needs to be drawn between prototype soil/pile interface temperature changes which happen over protracted timescales and which are seasonal in nature and the constraints of centrifuge modelling where scaling laws apply. For these reasons a slower temperature change over a longer timescale, rather than rapid change and short cycling is preferred.

3 THE MODEL PILE

The pile has been manufactured but not yet tested and is shown in Figure 2. It is made from a piece of 22mm external diameter x 1.2mm thick copper tube of a type that is routinely used for domestic plumbing systems. The total length of the tube is 230mm, 220mm of which is embedded into the clay bed. The toe of the pile is closed by a Perspex plate tight fitted to the shaft and glued. The excess length of 10mm above the soil surface allows for pile movements without damaging the instrumentation and the pile cap.

The pile cap which has the heating element attached to it is made from an 80mm long x 25mm diameter Perspex cylinder that is sealed into the copper tube with an 'o' ring. The pile cap protrudes 5mm into the pile owing to a small shoulder machined on the lower edge. The 'o'-ring ensures a good seal between the pile and the cap. The pile cap also incorporates water feed and drain as well as a small diameter water feed pipe that ensures cold water delivery to the base of the pile for efficient water flushing.

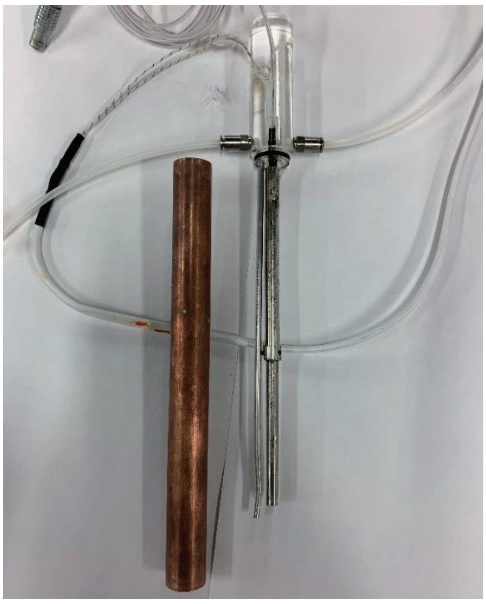

Fig. 2. Photograph of the pile components.

Perspex is preferred to the more classical aluminium because of its lower thermal conductivity (λ=0.19 W/m°C) compared to that of the aluminium (λ=200 W/m°C). The top of the pile cap is machined to house the rigid aluminium plate for the LVDTs used to measure the pile settlements and the concave dish above which sits the ball bearing. During the loading stage, the ball bearing is in contact with the loading pin.

The tests will be carried out in a circular tub, 420mm in diameter, Figure 3. The final depth of the soil samples would be 300mm. The model would have two testing sites spaced 210mm apart; each site is at least 105mm from the boundary of the tub. Since the model piles are 220mm long and 22mm in diameter, the boundary effects and interaction between the piles can be regarded as negligible.

Testing two piles in the same model allows for good use of the centrifuge time and the clay available. However, it also provides a larger set of data and ensures that there is an identical reference test carried out during every individual experiment; and from which data can be assembled over the testing period to provide information on any variation over the period. All these advantages combine to largely overcome the potential small boundary effects that may occur in the tests.

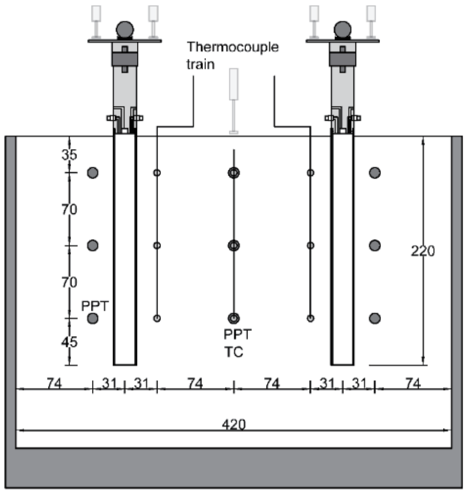

Fig. 3. General arrangement of apparatus in thermal pile test.

In the following, a detailed description of the experimental arrangement of only one pile is reported, but as shown in Figure 2 the two piles are essentially identical, hence the arrangement is the same for both piles.

4 LOADING APPARATUS

A levered system applies a constant amount of load at the pile head after the equalisation phase. The system is devised in such a manner as to allow a range of vertical loads to be applied, from estimated working load to pile failure.

Measurements of pore pressure, temperature and movement are recorded in the soil at various distances from the pile. Load, settlement and temperature are measured in the pile as well. As noted previously, two piles will be tested in each soil sample to enlarge the data set and account for eventual inconsistencies across the different tests.

The aim is to install bored piles into an overconsolidated kaolin clay sample on the workbench in the laboratory at 1g and then bring the model to 50g on the centrifuge. The model will then be left spinning to establish conditions of pore pressure equilibrium. At this stage the piles will be subjected to working load conditions which will be established through preliminary centrifuge tests. The working load is not expected to be particularly high given that the soil/pile interface (copper/clay) is very smooth compared to that which might be expected of a bored cast in place concrete pile. However, a low capacity pile is thought to be advantageous in these circumstances as it could help to highlight sensitivity to temperature effects. Loading is achieved by filling a reservoir with water which reacts against to overcome the force of a counterweight through a pivot system thereby allowing a loading pin to contact the head of the pile as shown in Figure 4. Three load cells sandwiched between two aluminium plates are connected at the base of the rod and measure the load taken by the pile.

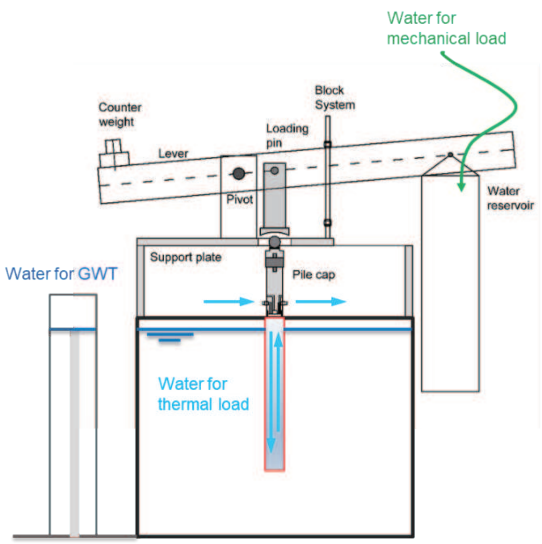

Fig. 4. Sketch showing method of loading pile during heating and cooling cycles in thermal pile test.

5 PILE HEATING AND COOLING

After the pile becomes loaded it will be subjected to cycles of heating and cooling whilst maintaining constant axial load; indicated in Figure 5 and as described in the schematic figure below. In reality, however, the pile heating and cooling will be much closer to the pattern shown in Figure 1.

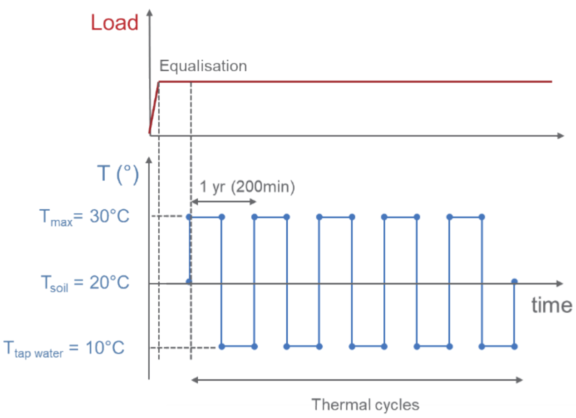

Fig. 5. Schematic representation of thermal changes in pile under constant axial load.

- Cold water is heated by means of a miniature heating element in the pile.
- When the water reaches the required temperature, as determined by a temperature sensor in the pile the heating element is turned off.
- As temperature dissipates the heating element is re energised to maintain the temperature for the required period.
- When the heating cycle is no longer required the water in the pile is flushed through and dumped; being replaced with cold water for the required duration.
- This cycle is repeated over a period of 24 – 48 hours as necessary whilst axial load is maintained and pile displacements are measured.

The key aspect to be monitored is the vertical displacement of the pile using LVDTs although other instruments will measure temperature changes inside the pile and in the soil around the piles.

6 CONCLUSIONS AND FURTHER WORK

As with many pieces of apparatus designed to operate in the aggressive environment of the geotechnical centrifuge the main challenges with the design and production of the pile have proved to be the miniaturisation coupled with robustness. Potentially suitable components are inexpensive and readily available but the challenge in development is in the time taken to manufacture some of the bespoke components that are required owing to a need for high precision. Concerns remain about the ability of the apparatus to maintain a constant temperature in the pile which will require feedback control to allow the heating element to operate according to the output of a temperature sensor in the pile. The water flush that is necessary to allow the pile temperature to be reduced quickly will rely on water flow through a small-bore pipe connected to the centrifuge slip rings. Temperature reduction may take longer than desired owing to the convoluted route through which water will need to pass in order to achieve this.

ACKNOWLEDGEMENTS

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