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Centrifuge modelling of an energy pile group within seepage

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ABSTRACT: For several decades, energy piles, consisting of using foundations piles as heat exchangers, have been developed. However, the thermal loading of these structures directly affects their mechanical behavior. Centrifuge modeling of a thermally loaded pile group within a groundwater flow makes it possible to improve the understanding of the hydro-thermo-mechanical behavior of this type of foundation.

1 INTRODUCTION

Energy geo-structures, which consist of attaching heat exchanger tubes to the reinforcement cages of foundations of buildings, have been developed since the 1980s. This way, structures whose primary role is to ensure mechanical stability, are given a second energy based role in order to make them low-enthalpy geothermal solutions with a low carbon impact. These energy geostructures are often used in a soil where a groundwater flow is present (Ding *et al*., 2008), without considering the potential interaction between several geostructures. Some guidelines have been published by Bourne-Webb *et al*., (2016) that look at such interactions. On the one hand, groundwater flow is a good way to avoid multi-year soil thermal drift but on the other hand, this advection phenomenon creates a thermal plume likely to affect the behavior of other downstream structures (Delerablee, 2019). Moreover, the behavior of foundations like piles and pile groups remains uninvestigated, especially when the thermal loading is not symmetrical and when the soil contains a groundwater flow. Indeed, unlike thermal boreholes cases, in energy pile system, it is common that only part of the piles is thermally activated. This is for example the case for Zürich airport where 300 of the 440 piles are subjected to thermal loading (*Pahud et al.,* 2007). In order to understand better the behavior of a pile group in this particular case, a test on a reduced scale model was conducted in the geotechnical centrifuge of the Schofield Centre of the University of Cambridge. A 2x2 pile group was placed in Hostun sand and one of the four piles was heated. The two main objectives were to observe the heat transfer in the soil and to study the thermomechanical behavior of the group, especially when ground water seepage is present.

2 MATERIAL AND METHOD

2.1 The centrifuge

Located at the Schofield Centre in the Department of Engineering at the University of Cambridge, the centrifuge consists of a 10 m rotor arm in a 2 m high chamber located underground. The model to be tested is prepared beforehand in a room above. It is also from this control room that the speed of rotation of the centrifuge arm and thus the acceleration applied to the model is imposed. This rotation speed can reach 180 rpm, which corresponds to a centrifugal acceleration of 150g.

Once the model is ready, it is placed in one of the two swings located at the ends of the centrifuge arm and a precise counter-weight is set up at the other end in order to balance the moment. In this research, the experiment is performed at a centrifugal acceleration equal to 50g. According to the scaling laws, the group of four piles corresponds to a real one that would be 50 times larger in reality (called prototype).

2.2 The model pile group and the sensors

The model piles are made of cement paste and have a diameter of 20 mm and a length of 300 mm, or a slenderness ratio of 15. At prototype scale, the pile would have a diameter of 1 m and a length of 15 m. As shown in Figure 1, each pile is equipped with a U-shaped copper tube with an internal diameter of 2 mm and a thickness of 0.5 mm, giving an external diameter of 3 mm. This copper tube is used to heat (or cool) the pile by circulating hot (or cold) water inside. Although only one of the four piles that make up the group is heated, all the piles are equipped with a copper tube so that they all have the same mechanical characteristics. Finally, in order to better reflect the soil-pile interaction, all the piles are roughened by gluing sand on their surface with silicone glue.

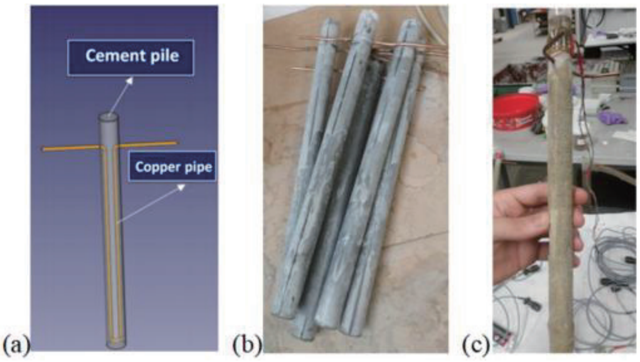

Fig. 1. (a): Schematic representation of a model geothermal pile, (b): photograph of piles before and (c) after sandblasting

An aluminum raft with a mass of 0.440 kg connects the four piles. Once the model is subjected to a centrifugal acceleration of 50*g*, this raft will impose a vertical load of 215 N on the four piles that corresponds to a load of 537.5 kN at prototype scale (i.e 22 kPa).

Fig. 2. Photograph of the model raft seen in profile and from above

To measure the load carried by each pile, a load cell is screwed at the head of each pile and fixed to the raft with a nut as shown in Figure 2. In addition, to measure the displacement of the group during the experiment, displacement transducers (LVDTs) are attached to the lid of the model box, and positioned at the four corners of the raft. These sensors allow characterising the mechanical response of the pile group. Furthermore, in order to monitor the water flow in the model, seven pore pressure transducers (PPTs) are placed at the bottom of the model along the box. Finally, to measure the heat transfer in the model, temperature sensors are placed on a horizontal plane at a depth of 130 mm from the model surface, as well as on each of the piles.

2.3 The heating system

In order to heat the pile, a Peltier system was developed. This system allows heating the water that will then circulate in the tube inside the pile using a peristaltic pump. The water transits through the pile exchanging heat with it before being evacuated from the model (see Fig. 3). It is therefore an open loop heating system, not equivalent to a heat pump. It is a simpler system but less efficient (for the same thermal power produced, the Peltier requires more electrical power). However, working in open loop ensures a constant temperature of water entering the pile. By calibrating the pump and the Peltier, it is thus possible to evaluate this parameter. Moreover, by measuring the water temperatures at the inlet and outlet of the geothermal pile, we can access the thermal power, P, exchanged between the pile and the ground by knowing the pump flow rate, q, and the thermal capacity of the water, C_v, using the following equation:

$$\boldsymbol{P = C_v q \Delta T} \tag{1}$$

The tests carried out during this study aim at an inlet temperature in the pile of 45°C with a flow rate of 40 ml/min for the pump. The Peltier system, as well as the pump, was therefore supplied with electricity in order to obtain these values. However, under the effect of the centrifugal force, the calibrations which were carried out at 1*g* were no longer valid. Finally, a flow rate of 20 ml/min circulated through the pump. This resulted in lower thermal loads than expected.

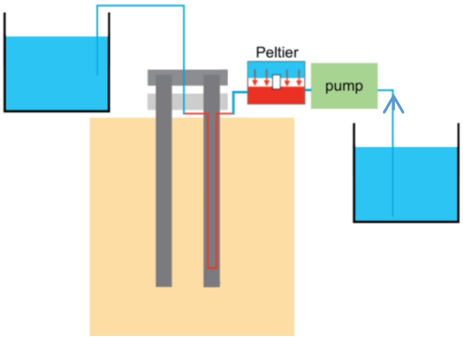

Fig. 3. Schematic of the model geothermal pile heating system

2.4 Setting up the model and establishing the flow

The model is made in a box whose dimensions are L×W×H= 790×200×550 mm^3. One side of the box is made of Perspex.

In order to be able to establish a water flow in this model, the box is divided lengthwise into three parts: the two ends, each 70 mm long, are filled with gravel and the central part is filled with dense Hostun sand with a relative density, $D_r \cong 90\%$. Geotextile separates the three parts (see Fig. 4) in order to avoid sand/gravel mixing while allowing the seepage flow. In order to have a homogeneous soil, the model was prepared using a mechanical system of automated rainfall present at the Schofield Centre (Madabhushi *et al*., 2006). This allows to obtain the target relative density of the soil, by adjusting the height of fall, the size of the slot through which the sand flows and the speed of movement. From a thermal point of view, heating needle tests have made it possible to estimate the thermal conductivity of saturated Hostun sand between 2.4 and 3 $W.m^{-1}.K^{-1}$. The heat capacity of saturated sand is estimated between 2.2 and 2.4 $MJ/m^3.K$ (Fromentin *et al.,* 1997)

In geotechnical engineering, there are two main ways of placing piles: by driving or by drilling. In this study model, since driving is technically difficult, the piles are placed before sand pouring, simulating cast *in situ* piles. Once the sand and gravel are in place, saturation of the model is done by injecting water from the bottom of the model at a low rate. The degree of saturation is assumed to be satisfactory for this study.

The permeability difference between the gravel and the sand allows maintaining two different water levels in the gravels. Thus, a groundwater flow is established according to Darcy's equation:

$$Q = kiS \tag{2}$$

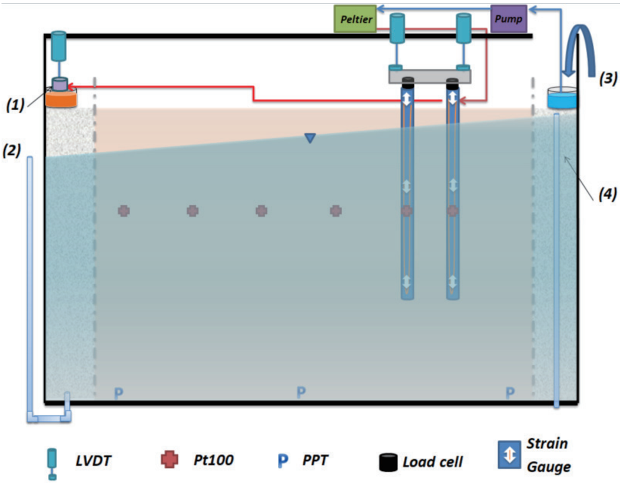

Fig. 4. Schematic presentation of the model tested in a centrifuge – (1): floater system allowing measuring the flow rate of the pump, (2): Syphon system, (3): running water supplying the system, (4): tube evacuating the water at the upstream side

where Q (m^3/s) is the flow rate, i $(-)$ is the hydraulic gradient, k (m/s), is the soil permeability, and S (m^2) is the hydraulic surface. A mechanical system is used to supply the model with water during the rotation of the centrifuge model. This water supply is controlled in flow rate and once the flow in the model reaches a steady state, the water height upstream remains constant. To impose a constant water height downstream, a siphon system is set up by creating a hole in the bottom and connecting it to a standpipe outside the box. Thus, the water height in the gravels downstream cannot be higher than the siphon height.

3 RESULTS

During the initial swing-up phase, the model is progressively accelerated until it reaches 50g, in five 10g increments. During this stage, monitoring of the load and pore pressure sensors gives a good account of the rise in acceleration. Indeed, it appears that there is an increase in the pile loads (Fig. 5) and pore pressures at each step. Moreover, it is important to notice here that at the end of the last stage, the total force is constant (Fig. 5) as well as the different pore pressures. This allows us to consider the next evolutions - once the heating system is activated - as being induced by the thermal load. This is also the case for the displacement measurements: during swing-up, a settlement of the raft is observed induced by the increase in centrifugal acceleration. This settlement was not perfectly uniform and a small rotation was observed. However, at the end of the last stage, no more displacement is observed and we can consider that the next displacements will be due to the thermal load.

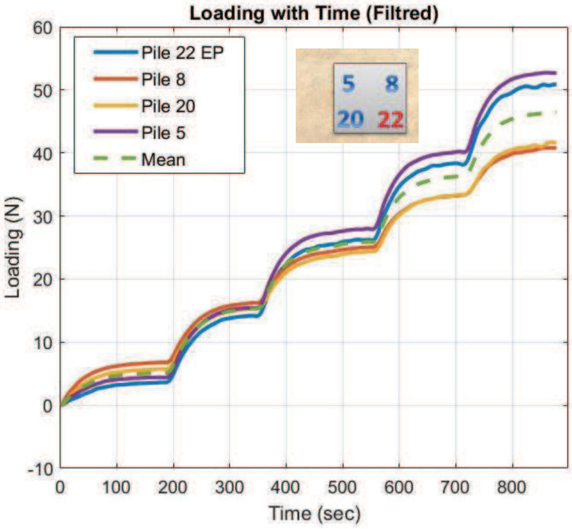

Fig. 5. Evolution of pile head as a function of time during the swing up

3.1 Thermal loading in a saturated model

Once the centrifugal acceleration reaches the target value of 50g, the heating system is activated by switching on the pump and the Peltier. Figure 6a shows that the temperature of the energy pile surface increases very quickly but was not as high as expected. This is most likely due to flow rate of the pump that was not large enough because of the centrifugal acceleration. However, the effects induced by the increase in temperature are still observable. The displacement sensor above the energy pile records heave while the opposite pile experiences settlement. These results correspond to a rotation of the raft in the direction of the geothermal pile towards the opposite pile. Moreover, when the pile is heated, the load on the geothermal pile and that taken up by the opposite pile (on the diagonal) increase. Indeed, the heave of the energy pile induced by the thermal expansion is constrained by the loading from the raft, which creates a compression at the head of the pile and on the pile located on the opposite diagonal. This increase in the load at the top of these two piles corresponds to a reduction in the load carried by the other two piles. In fact, the total sum of the loads taken by the four piles remains constant during the experiment, as required to satisfy vertical equilibrium. Surprisingly, the measured loads and displacements tend to redistribute after the initial "sudden" changes, even if heating continues.

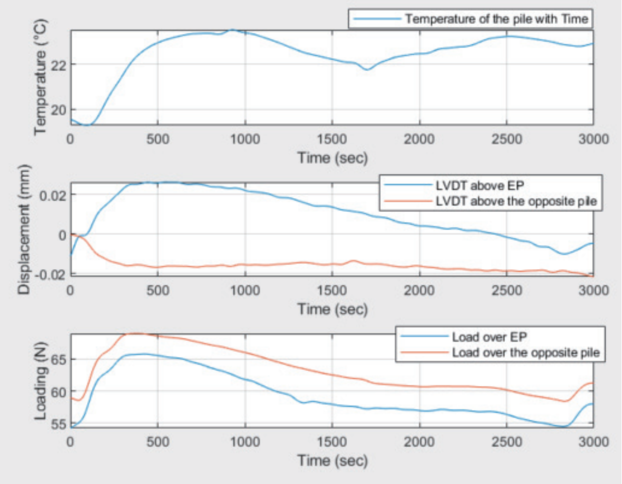

Fig. 6. Evolution of pile surface temperature (a), head load (b) and displacement (c) of the heated pile and the opposite pile as a function of time - case without flow

3.2 Thermal loading in a model with ground water flow

After heating the model energy pile for about one hour, the heating system is turned off and the model seepage is activated with a flow rate of about 2 l/min upstream. This is a cooling phase, in which the water flow controls (reduces) the temperature in the model. Once the soil is at a constant ambient temperature, the flow of water is maintained and the heating system is turned on again. The system enters in a new heating phase for the energy pile but this time with a groundwater flow. The electrical powers supplied to the Peltier and the pump are identical to those of the first heating phase. In other words, for the sake of comparison of results, the temperature of the water entering the pile is identical.

The same phenomenon as before was observed for the case with seepage. The model energy pile rises when it is heated and the pile located opposite on the raft undergoes the opposite effect. Moreover, these two piles register an increase in the head load. Again, the total load is constant throughout the experiment and the increase in the load on the energy pile and the pile opposite on the diagonal is compensated by a loss of head load for the other two piles.

3.3 Impact of the flow on the thermomechanical interaction

When water flow is present in the model, the thermal convection phenomenon limits the thermal expansion and thus the pile heave and the increase of its head load, which are induced effects. This result appeared when one focuses on the mean settlement of the raft (average of the displacements measured by the 4 LVDTs). Indeed, the raft heave is less in the case where a flow dissipates the thermal anomaly. Similarly, and logically, the head load variations are lower in the case with ground water flow as shown in Figure 7.

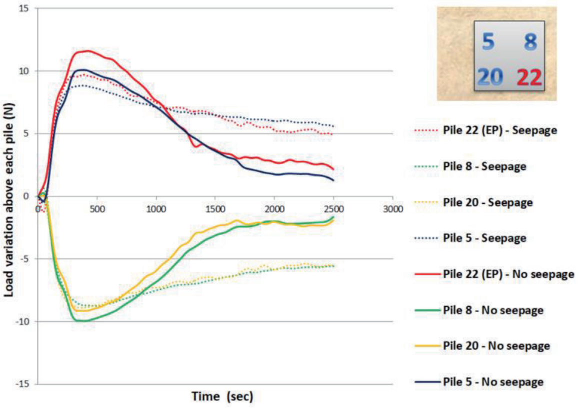

Fig. 7. Variation of the head load of each pile as a function of time for the two configuration cases

4 CONCLUSIONS

In a summer-time operation of the energy pile, heat is injected into the ground. In this experimental work, a group of four geothermal piles was modeled in a centrifuge in saturated sand. Only one of the piles was subjected to a thermal load by circulating hot water through the pile. The study of the thermomechanical behavior of the pile group shows a heave of the raft above the heated pile and an increase in the head load. It also appears that these variations tend to re-equilibrate over time although the thermal load is maintained. The main innovative point was to establish a water flow through the model. The experiment was therefore also conducted under groundwater flow conditions. It was found that the thermomechanical impact is significantly mitigated with ground water flow. However, these results should be viewed with caution since the cyclic aspect of thermal loading is also responsible for the attenuation of the thermomechanical impact (Ng, 2019). Thus, further studies need to be conducted to determine the effect of each phenomenon in this decrease in thermal loading induced effects.

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