Experimental Study of the Uplift Resistance of Energy Piles in Soft Clay

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Abstract

Geothermal piles present a sustainable energy conservation option in situations where deep foundations are required to support substantial structural loads in relatively poor ground. The piles then play dual role of load transfer elements to the subsurface strata and heat exchangers delivering and/or extracting heat to/from the surrounding soil. The thermal cycles may induce additional loads which lead to the contraction/expansion of the pile along its length. These loads may also affect the pile-soil interface by modifying the soil mechanical characteristics at that location. At present, this impact is not fully understood, particularly when combined with effects associated with the large-scale loading of the surrounding soils. This paper attempts to explore the implications of thermal cycling on the uplift resistance of piles in slightly overconsolidated clays. Laboratory tests on scaled models are presented in which piles are loaded with a sustained static uplift load that is roughly 30% of the ultimate capacity, subjected to heating/cooling cycles, and then loaded to failure. The testing program consists of one control pile and two thermal piles. Results indicated that the vertical deformation of the geothermal piles due to sustained loading increased due to heating and cooling whereas the ultimate capacity decreased compared to the control pile. These observations point to the importance of catering for thermal effects on the serviceability and ultimate capacity in normally to slightly overconsolidated clay.

Introduction

Geothermal piles are potential energy “sources/sinks” that exchange heat with the surrounding soil contributing to the energy needs of the structure they support. The primary role of these elements however, is to safely transfer the superstructure loads to the subsurface, while assuring acceptable serviceability conditions.

Upon exposure to thermal cycles, the pile will tend to contract/expand. This tendency is resisted by the soil-pile contacts along the pile shaft and at its base. For piles that are embedded in normally to slightly over consolidated clays that may suffer from plastic deformations due to repeated heating/cooling cycles, the pile-clay interface resistance may be negatively affected by the geothermal effects, as a contractile behavior is expected for these types clay of when heated (Cekerevac & Laloui, 2004). The serviceability and safety of structures supported by these piles may be then affected. This aspect of energy piles was discussed by previous work which focused on their thermo-mechanical behavior in different soil types using centrifuge tests (Ng et al. 2015), 1-g small scale tests (Yavari et al. 2016, Wang et al. 2017, and Nguyen et al. 2017) and large scale field tests (Akrouch et al. 2014, Murphy & McCartney 2015, and Wang et al. 2015).

Most of these studies involved geothermal piles in granular soils. Wang et al. (2015) suggested that the shaft resistance behaves in a thermo-elastic manner for piles in dense sand. Using a small-scale test of energy piles loaded to 50% of their ultimate capacity with different tube configurations in sand, Wang et al. (2017) noticed that the pile settlement was accumulating after each thermal cycle, but with a decreasing rate. The same behavior was reported by Nguyen et al. (2017) after performing long-term thermal cycles on piles under working loads varying from 0 to 60% of the pile capacity in dry sand. They introduced an asymptotic prediction for the evolution of the irreversible pile deformations with heating/cooling cycles.

The behavior of energy piles in clay differs from that in sand, especially for clays with low overconsolidation ratios. According to Ng et al. (2014) who investigated the thermo-mechanical behavior of energy piles in slightly and heavily overconsolidated clays using centrifuge tests, energy piles continue to settle with thermal cycles in both cases, with larger settlement accumulation for piles in the slightly overconsolidated clay. The resulting plastic deformations due to heat cycles may have increased soil creep and reduced the stresses at the soil-pile interface. This effect was also reported by Akrouch et al. (2014) who observed displacement changes in energy piles that were 2.3 times larger than regular piles due to a possible increase in the rate of clay creep with temperature. Yavari et al. (2016) found that thermal loading induces an irreversible settlement that increases with the applied axial load after performing tests on a small-scale energy pile in saturated clay.

These studies highlight the importance of the effect of coupled loading on the soil-pile interface and load-deformation mechanisms. More work is needed to further develop our understanding of this effect in order to inform serviceability and ultimate limit state design of energy piles in clays. Since most of the published studies tackle energy piles in compression where both skin and tip resistance are mobilized, it is believed that tests on piles loaded in uplift will allow a more focused evaluation of processes related to the shaft interface. Furthermore, the reported small-scale tests in clay focused on typical tubing configurations and on aluminum piles. The pile material and tubing configurations change the thermal efficiency of energy piles (Luo et al. 2016) and may affect their mechanical performance.

This study presents the results of a laboratory scale experimental program that was designed to explore some of the aforementioned limitations in the literature. The test setup was designed as an economic platform to conduct experiments aimed at isolating and observing the effects of relevant variables while minimizing uncertainties. Three small-scaled piles were installed in a slightly overconsolidated clay bed and loaded to 30% of their ultimate uplift capacity. Two piles were energy piles equipped with two different tubing configurations (2U and S), while the third was a control pile. After the application of the sustained upwards load, the first energy pile was subjected to three thermal cycles while the other endure nine cycles. Displacements were measured continuously in order to document the effect of heating and cooling cycles on the pile/interface response. Once the thermal loading cycles were completed, the piles were loaded in uplift until failure, and the impact of creep due to thermal cycles on the ultimate capacity of the piles was examined. It is to be noted that in order to maximize the number of piles tested in the bed, a relatively small spacing between the outer piles and the tank in the order of ~1D (12 cm) was necessary. Whereas it may be argued that such a distance to the boundary may reduce the temperature of the soil between the boundary and the piles during the heating cycles, the results as seen in the temperature distributions throughout the bed suggested that the effect was minor.

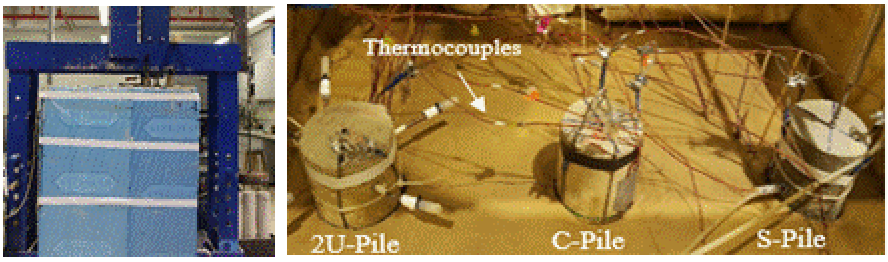

Fig 1. Experimental setup: (a) Soil tank and (b) close-up view of test setup with the model geo-thermal piles installed in clay

Experimental Program

A homogeneous saturated clay bed was carefully prepared/consolidated within an insulated steel tank 1000mmx1000mmx1200mm in size. Three small-scale concrete piles 120 mm in diameter and 600 mm long (i.e. relatively "short", with a slenderness ratio L/D of 5) were installed in the testing chamber/tank (Figure 1). Copper tubes of 4 mm inner diameter were embedded in two of the piles with a double U (2U-Pile) and a spiral (S-Pile) configuration respectively, whereas the third pile was a control pile (C-Pile).

The soil was slightly overconsolidated clay with 25.3 % sand and 74.7 % fines. It had a specific gravity of 2.6, liquid limit of 28.9 %, and plastic limit of 16.4 %. The soil was mixed at the liquid limit and placed in 50 mm layers in the tank. It was then consolidated at 20 kPa for 3 weeks using a specially designed loading system consisting of a lever arm and weights. Drainage was assured at the base through a gravel layer overlain by geo-textile filter. The geotextile covered the inner sides of the tank to further facilitate drainage. After consolidation, Shelby tube samples were taken at the location of the piles and the piles were installed with the C-Pile in the center. Results from 9 UU-triaxial tests indicated average undrained shear strengths of 17.7, 18.8 and 19.2 kPa respectively for the C-pile, S-pile and 2U-pile locations, with corresponding average water contents of 22.9, 22.3 and 22.6%, respectively. Results from a 1-D consolidation test indicated a preconsolidation stress of ~19 kPa, a compression index of 0.13, and a swelling index of 0.02 (Fig 2).

The experimental setup was equipped with a data acquisition system that reads a displacement transducer (LVDT) placed at the pile head and a load cell connected to the loading system. In addition, temperature was monitored using thermocouples distributed over the pile circumference, on the inlet and outlet, and in the soil at different horizontal distances from the pile surface at 80mm and 400 mm depth as shown in Fig 3(c). Each thermal cycle consisted of two phases, heating and recovery. During heating, water was pumped at a constant flow rate of 260 ml/min and a constant temperature of 52° from a water bath. While during recovery, water pumping was stopped and the temperature was set to room temperature 22°.

Testing of each pile was initiated with sustained loading at 30% of the ultimate capacity for three days using a simple load-controlled system. The ultimate capacity of the pile in uplift was estimated to be approximately 1000 N based on a previous experimental test that was conducted with the same setup (Houhou et al. 2018). After sustaining the working load for three days, the 2U-Pile was subjected to three thermal cycles. The first cycle consisted of 3-days heating and 1-day recovery while the subsequent two cycles consisted of 1-day heating followed by 1-day recovery. At the end of cycles, the pile was pulled-out at a “fast” rate to estimate its undrained ultimate capacity. The same sequence of thermal cycles was imposed on the S-Pile with 6 additional cycles of 1-day heating and 1-day recovery. Similarly, an uplift test was carried out for the S-Pile after the completion of the thermal cycling phase.

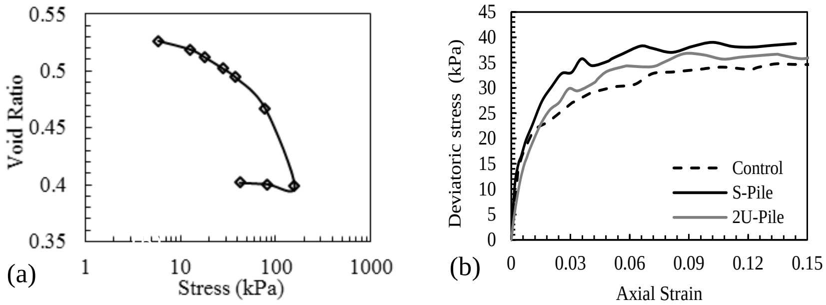

Fig 2. Soil characteristics: (a) Sample UU test results and (b) consolidation test results

Results and Analyses

Temperature Variation

The variation of the temperature with time at the surface of the pile and within the soil is shown in Fig 3. The temperature of the pile increased during the first 7 hours of heating reaching maximum values of 42°C for the S-Pile and 40.5°C for the 2U-Pile. As expected, the temperature in the soil was lower as we move away from the pile surface.

At the end of the heating the net increase in the soil temperature (compared to ambient) was 12°C at a distance of 80 mm and 4.5°C at 360 mm for the S-Pile. Similar temperature increases were noticed for the soil around the 2U-Pile but with somewhat lower values (10°C and 3°C at 80 mm and 360 mm). The difference in the increase of temperature in the soil around the two geothermal piles shows that the S-configuration has a higher heat exchange rate than the 2U-configuration. It is worth noting that due to technical problems with the water pump, sudden changes in temperature occurred (see Figure 3b) in the first heating cycle for the 2U Pile. These did not impact the following results as the target temperatures were reached and maintained beyond that point.

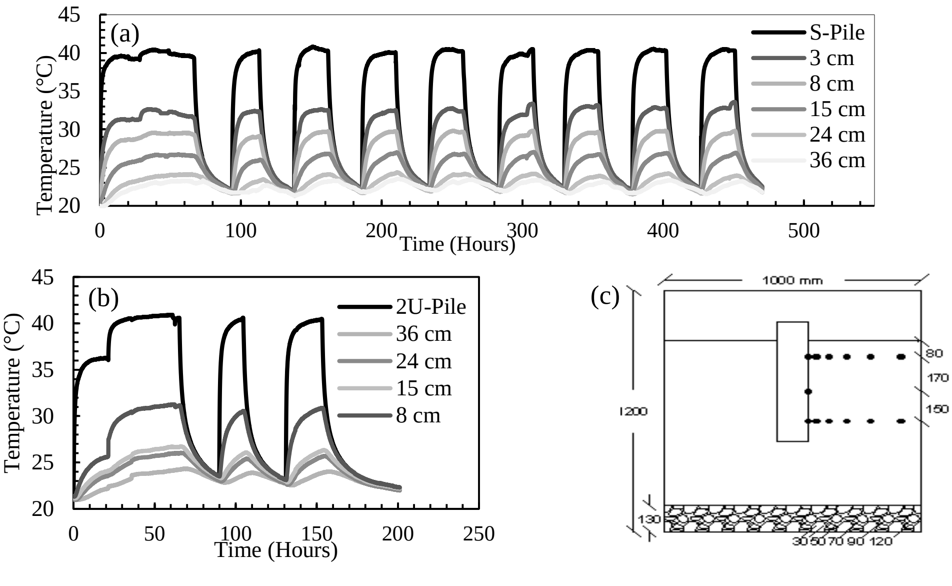

Fig 3.Piles and soil temperatures at 400 mm depth (a) during S-Pile cycles and (b) during 2U-Pile cycles and (c) schematic of the scale model pile and thermocouples distribution

Pile Head Displacement

The three piles were initially subjected to a 300 N tension force for three days. Upon the application of the sustained load, an immediate upward movement was measured. This movement slightly increased with time and became constant at around 0.22 mm, 0.20 mm, and 0.16 mm for the C-Pile, 2U-Pile and S-Pile, respectively. For the energy piles, thermal cycles were then initiated in the presence of the sustained load. The variation of the pile head displacement with temperature is presented in Fig. 4. Results indicated that the pile heads moved upward during heating with partial recovery of deformation measured during cooling (Fig. 4). The head of the pile retained a cumulative plastic movement, which increased in value with thermal cycles. This ratcheting effect was also observed by Ng. et al (2014) for the pile placed in slightly overconsolidated clay but with a downward trend due to the applied compression load. The final irreversible pile displacement was 0.6 mm for the 2U-Pile and 1.5 mm for the S-Pile. It is interesting to note that the S-Pile exhibited larger displacement than 2U-Pile during the initial three identical thermal cycles. This may be due to the higher heat transfer efficiency of the S-configuration which induced higher temperatures at the soil/pile interface and within the soil.

To investigate the possible contribution of free thermal expansion to the observed top pile displacements, the free thermal expansion was calculated and plotted in Fig. 4 assuming that the pile toe is fixed and ignoring the side resistance. Results show that the free thermal expansion constituted a small part of the observed pile displacement which accounted to more than 5 to 8 times the calculated thermal expansion for the 2U-Pile and S-Pile, respectively. The observed displacements that are in excess of the estimated thermal expansion are attributed to a phenomenon occurring within/at the soil/pile interface zone as a result of thermal cycling. This phenomenon resulted in additional creep that increased with the number of heating cycles. It is worth noting that the partial displacement recovery that was observed in the cooling part of each cycle was accompanied by slight increases in the loads measured as indicated in Fig. 5. This minor increase in the load during cooling could be attributed to contraction in the pile material or to a thermally triggered "downdrag" where the clay around the pile pulls the pile downwards.

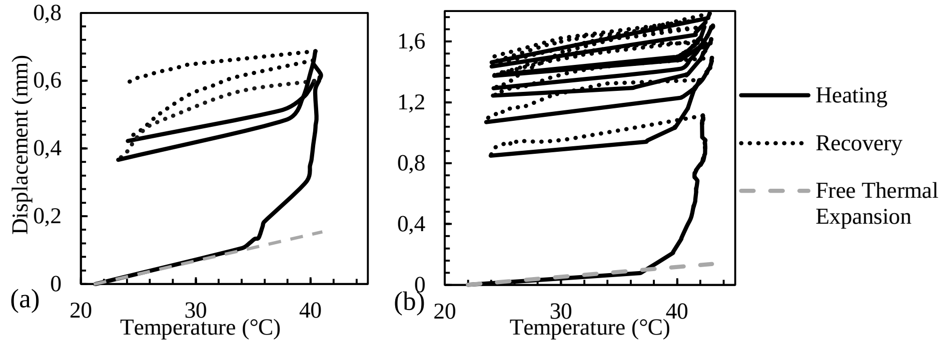

Fig 4. Displacement as function of temperature for (a) 2U-Pile cycles and (b) S-Pile cycles

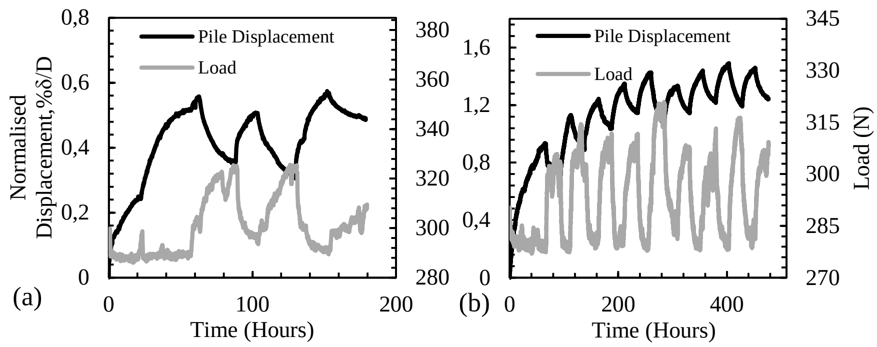

Fig 5.Variation of load and pile head displacement for (a) 2U-Pile and (b) S-Pile

Uplift Pile Capacity

At the end of the thermal cycles, the piles were pulled out to measure their mobilised skin friction and examine any change due to heating. The results of the pullout tests are presented in Fig. 6. The mobilized skin friction was calculated as the ratio of the applied uplift force to the embedded shaft area of the pile. Results point to some differences in the response of the geothermal piles. The S-Pile presented an initially stiffer response compared to the 2U pile and the Control pile, but failed in a more brittle manner compared to the other two piles (Fig. 6). At failure, the geothermal piles exhibited a slight reduction in skin friction compared to the control pile. The maximum mobilised skin friction was 5.7 kPa, 5.46 kPa (4.2% reduction), and 5.2 kPa (8.74% reduction) for the C-Pile, 2U-Pile, and S-Pile respectively. The adhesion factor (α) was calculated as α = fskin / Su,average , in which fskin is the ultimate skin friction (kPa) and Su,average is the average undrained shear strength. The adhesion factor also exhibited reduction upon heating/cooling with the reduction estimated as 11.52% for the 2U-Pile and 14.45 % for the S-Pile. This suggests that using the piles as energy sinks may affect their ultimate capacity. The negative effect seems to be greater for the S-Pile, which was subjected to additional heating cycles indicating that the response of the energy piles at ultimate may be related to the number of thermal cycles they are subjected to.. These concerns may have to be taken into consideration when designing energy friction piles in slightly overconsolidated clays.

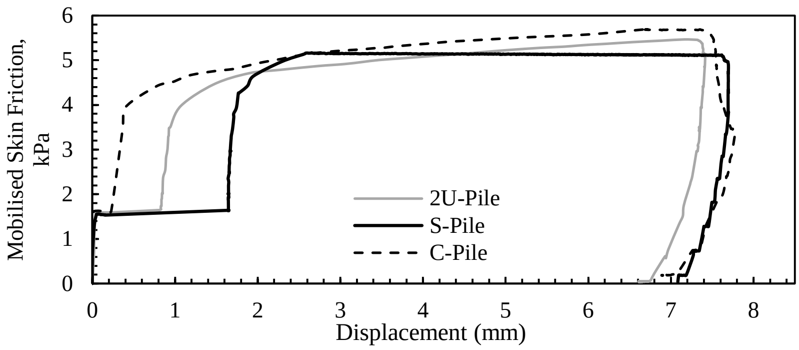

Fig. *6*: Results of the uplift tests for the control and geothermal piles

Conclusions

The thermo-mechanical behaviour of two types of heat exchanger piles in slightly overconsolidated clay was investigated. An uplift working load was first applied to the model piles head and then the energy piles were subjected to two different thermal cycle regimes. Finally, three uplift tests were performed. The following conclusions can be drawn from the observations and test results:

- Irreversible upward pile displacements were generated during thermal cycles with a decreasing rate. The accumulated displacement reached 0.6 mm for the 2U-Pile and 1.5 mm for the S-Pile at the end of the cycles under a sustained service load that is equal to about 30% of the ultimate load.
- The S-configuration of the tubing inside the energy pile is more efficient than the 2U-configuration. It generated higher heat flow, and its efficiency was reflected in higher values of temperature in the soil and pile around the S-tubing.
- The thermal capacity of the pile given by a specific tubing configuration affects the magnitude of the pile deformation/creep during thermal cycling. Larger pile displacements were noticed for the pile having a higher heat exchange.
- The creep/displacement at the pile top increased with increasing number of thermal cycles. In addition, the mechanical response of the piles as reflected in the initial stiffness and the ultimate skin friction was affected by the thermal cycling. Reductions in the adhesion factors controlling skin friction were observed in thermal piles and this reduction increased with the number of cycles.

References

Akrouch, G. A., Sánchez, M., & Briaud, J.-L. (2014). Thermo-mechanical behavior of energy piles in high plasticity clays. *Acta Geotechnica*, *9*(3), 399–412

Cekerevac, C., & Laloui, L. (2004). Experimental study of thermal effects on the mechanical behaviour of a *clay*, *228* (April 2003), 209–228.

Houhou, R., Awad, A., Sadek, S., & Najjar, S.S. (2018). Effect of heating and cooling cycles on the skin friction of energy piles in soft clays", Proceedings of International Foundations Exposition and Equipment Exposition, Orlando, Florida, March 5-10

Luo, J., Zhao, H., Gui, S., Xiang, W., Rohn, J., & Blum, P. (2016).Thermo-economic analysis of four different types of ground heat exchangers in energy piles. *Applied Thermal Engineering*, *108*,11–19

Murphy, K. D., & McCartney, J. S. (2015). Seasonal Response of Energy Foundations During Building Operation. *Geotechnical and Geological Engineering*, *33*(2), 343–356

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

Ng, C. W. W., Shi, C., Gunawan, A., Laloui, L., & Liu, H. L. (2015). Centrifuge modelling of heating effects on energy pile performance in saturated sand. *Canadian Geotechnical J.*, *52*(8), 1045–1057

Nguyen, V. T., Tang, A. M., & Pereira, J. M. (2017). Long-term thermo-mechanical behavior of energy pile in dry sand. *Acta Geotechnica*, *12*(4), 729–737

Wang, B., Bouazza, A., Singh, R. M., Haberfield, C., Barry-macaulay, D., & Baycan, S. (2015). Posttemperature Effects on Shaft Capacity of a Full-Scale Geothermal Energy Pile, *141*(4), 1–12

Wang, C.-L., Liu, H.-L., Kong, G.-Q., & Ng, C. W. W. (2017). Different types of energy piles with heating-cooling cycles. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*.

Yavari, N., Tang, A. M., Pereira, J. M., & Hassen, G. (2016). Mechanical behaviour of a small-scale energy pile in saturated clay. *Géotechnique*, *66*(11), 878–887