Mechanical Behaviour of Energy Piles in Dry Sand

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ABSTRACT: In this study, for investigating the mechanical behaviour of energy pile, the behaviour of an axially loaded pile under thermal cycles was investigated using a physical model. After applying the axial load by dead weights on the pile's head, the pile was heated from 25 °C to 50 °C and subsequently cooled to 25 °C. Four tests (corresponding to four values of axial load) were performed and two temperature cycles were undertaken in each test. When low axial loads were applied, the heating induced heave and cooling induced settlement of the pile's head. In the case of higher axial loads, the heave of the pile's head, obtained during heating, was lower than the thermal expansion of the pile demonstrating the settlement of the pile's toe.

1. INTRODUCTION

A heat exchanger or geothermal pile is one of the sustainable technologies for intermittent energy storage in soil. It consists of a foundation pile equipped with a tube or a pipe network through which a fluid flows in order to exchange heat with the surrounding soil. Although this technology has widely been used recently in Austria, Germany, Switzerland, and the United Kingdom (Moel et al., 2010), it is still rarely used in France, mainly due to the absence of reliable technical assessment and guarantees. Actually, the design of geothermal piles is derived primarily from the building energy demands and the thermal properties of its main components. According to Peron et al. (2011), there is currently a lack of established calculation method for the geotechnical design of geothermal piles and dimensioning has been based on empirical considerations. Improved knowledge on geotechnical design methods and the mechanisms induced by heat transfer is at the forefront of research today in geotechnical engineering. Recent studies include in situ tests (Laloui et al., 2003; Bourne Webb et al., 2009), numerical simulations (Peron et al., 2011; Silvani et al., 2009; Laloui et al., 2006; Brandl, 2006; Yavari et al., 2014*a*), laboratory tests in centrifuge (McCartney and Rosenberg, 2011) and in small-scale model (Kalantidou et al., 2012; Tang et al., 2013; Yavari et al., 2014*b*). In these studies, the main effect induced by temperature increase was observed to be the appearance of additional stresses inside the pile, which can be twice higher than those observed from the application of mechanical loading. In fact, the thermal expansion of the pile during heating can modify the soil/pile friction mobilisation and create further compressive or tensile stresses in the pile. Nevertheless, the in situ tests conducted have shown that the strains induced during heating/cooling are reversible and their impact on the performance is negligible.

The present study aims at investigating the effects of a pile head loading on the pile/soil behaviour under thermal cycles using 1 g model tests in sand.

2. EXPERIMENTAL METHOD

The experimental setup is presented in Figure 1. The model pile is a closed end aluminium tube of 800 mm length, with external and internal diameters of 20 mm and 18 mm respectively. After fixing the pile in the centre of a 570-mm inner diameter cylindrical steel tank with the aid of a temporary support, dry Fontainebleau sand (with a mean grain size value 0.23 mm) was compacted around the pile by using a wood tamper. The target dry density was set to 1.51 Mg/m^3 (corresponding to a relative density of 46%), equal to that chosen in the work of De Gennaro et al. (1999). According to De Gennaro et al. (1999), the utilised sand has a internal friction angle of 36.5°. This method of pile installation represents more closely the installation of non-displacement piles, mainly used in the technology of geothermal foundations and in experimental tests aiming at simulating the behaviour of bored piles (Fioravante, 2002). For the control of the pile's temperature, a metallic U-tube of 3-mm external diameter and 2-mm internal diameter was inserted inside the pile in its total length. The U-tube is connected with a temperature-controlled bath and a peristaltic pump. This system allows the circulation of temperature-controlled water inside the U-tube and is thus able to both heat and cool the pile to the target temperature. The uniform heating and cooling of the pile was achieved by filling the pile's interior with water, while the temperature was measured by placing a temperature sensor at the middle of the pile. Actually, the temperature distribution in the model pile could be different to that of a concrete pile. The thermal currents inside the pile were not considered and the pile's temperature is assumed homogeneous and equal to the temperature measured by the temperature sensor.

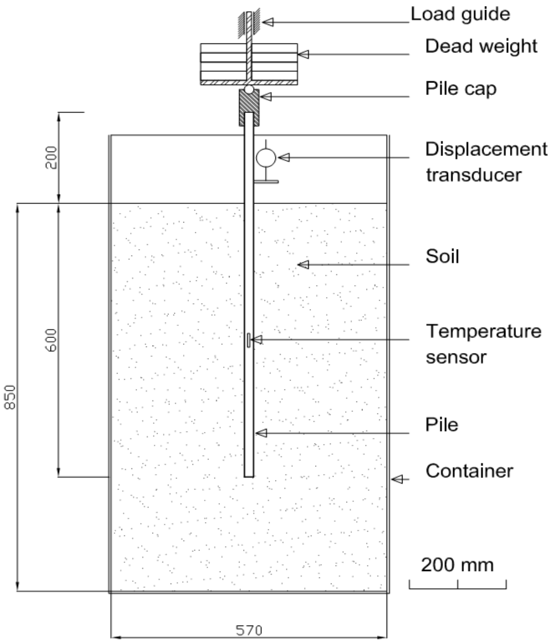

Figure 1 Experimental setup

The load was vertically applied by dead weights at the top of the pile using a loading guide system. For the measurement of the pile's vertical displacement, a displacement transducer was fixed at its head via a small steel plate.

Four tests were performed, each of them included the following steps: (1) soil compaction and installation of the experimental setup; (2) loading of the pile's head in increments; (3) application of heating and cooling cycles. The axial pile head loads in each test are: 0, 200, 400, and 500 N for Tests 1, 2, 3 and 4 respectively. The thermal cycles were applied immediately after mechanical loading. The temperature of the pile was first increased from the laboratory temperature (close to 25 °C) to 50 °C and then decreased to 25 °C. Two thermal cycles were applied for each test.

3. EXPERIMENTAL RESULTS

The pile head settlement obtained by the application of different pile head loads (Tests 2, 3, 4) is presented in Figure 2. It can be observed that the displacement is relatively small (less than 0.2 mm or 1% of pile diameter) for a load lower than 200 N. An exponential equation was fitted to the results in order to be able to infer the ultimate load. Assuming that the ultimate load of the pile corresponds to the load causing a settlement of 10% pile diameter, the ultimate bearing capacity of the pile was estimated at 525 N. In Figure 2, the interval of the pile head displacement obtained during the subsequent thermal phase is also plotted for each test. It should be noted that the interval, which is shown by vertical lines, is defined by the maximum and minimum vertical displacements encountered during the two thermal cycles.

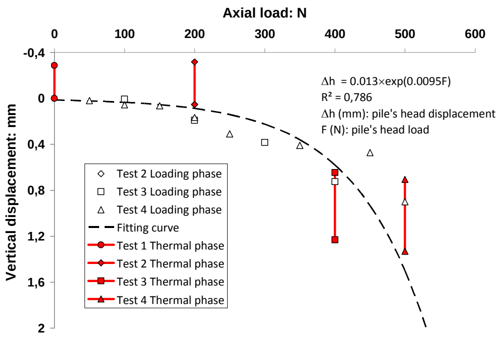

Figure 2 Load-settlement curve for loading and thermal phases

The results of Test 1 are shown in Figure 3. It can be seen that incremental heating induced incremental heaves of the pile head (Figure 3b). In Figure 3c, the pile head settlement is plotted versus the pile's temperature for the two cycles. In this figure, the thermal expansion/contraction curve of the aluminium pile is also plotted. This reference curve corresponds to the head displacement of a pile subjected to temperature changes, when its toe is fixed. The experimental results of Test 1 (Figure 3c) during the first heating show a settlement/temperature slope similar to that of the pile's thermal expansion curve and subsequently the first cooling path joins the thermal contraction curve progressively. At the same time, a hysteresis phenomenon, i.e. distinct heating and cooling paths, can be observed in both cycles. The results of the Test 2 (Figure 4) are similar to that of the Test 1.

The results of Test 3 (Figure 5) in terms of pile head displacement show a settlement of 0.4 mm after the first cycle (Figure 5b). This phenomenon was not observed for the tests having lower pile head load (Test 1).

In Figure 5c, it can be seen that the pile head heave obtained during the first heating path is significantly lower than the pile thermal expansion curve. Yet, the cooling path follows the same slope as that of the pile thermal contraction curve. The second heating induced heave and resulted in a settlement/temperature change slope relatively higher than that of the first heating path but still lower than that of the pile thermal expansion curve. On the other hand, the pile behaviour during the second cooling path is similar to the first cooling path and the total settlement of the pile head after two thermal cycles is 0.5 mm. The results of the Test 4, which are shown in Figure 6, are similar to that of the Test 3.

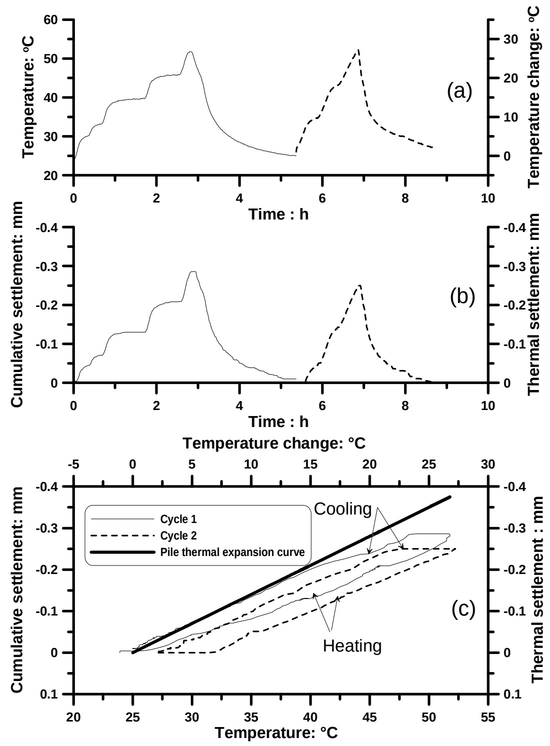

Figure 3 Experimental results of Test 1

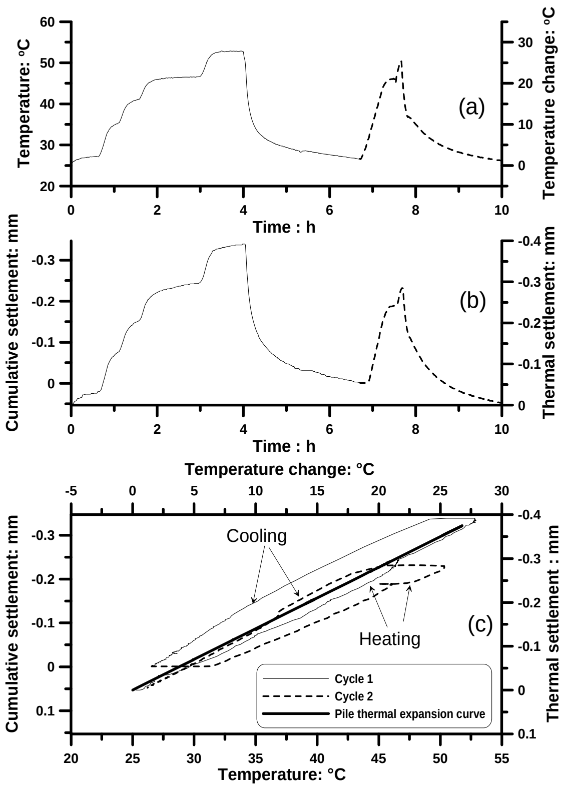

Figure 4 Experimental results of Test 2

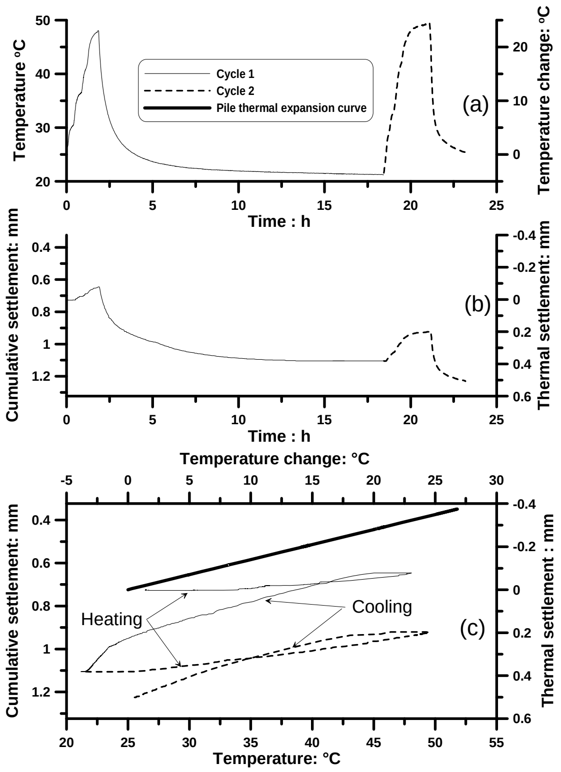

Figure 5 Experimental results of Test 3

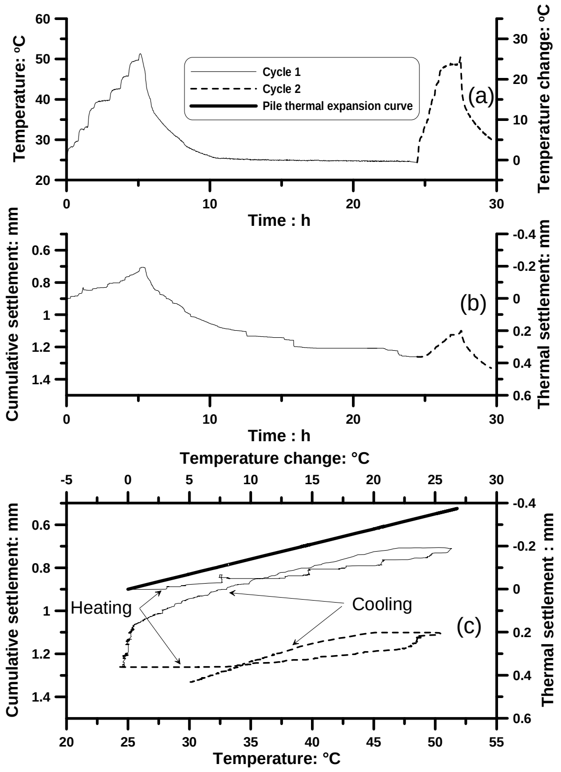

Figure 6 Experimental results of Test 4

4. DISCUSSION

In this preliminary study, the pile can be assumed incompressible under mechanical loading in the considered mechanical loading range (0 – 500 N). Actually, for a given load of 525 N, the amount of compression is equal 0.076 mm. As a result, the measured pile's head displacement during the loading phase represents the pile's toe displacement. In the case of Test 1 and Test 2, the pile's head (and toe) displacement obtained during the loading phase is small (less than 1% of the pile's diameter). Heating induced a thermal dilation of the pile and a pile head displacement similar to the reference thermal expansion curve (head displacement of a pile subjected to temperature changes when its toe is fixed). This means that the mobilized pile base capacity remains small, much lower than the ultimate resistance. In fact, the axial dilation of the pile during heating would inverse the direction of the mobilized shaft friction. Taking into account that the soil has a tendency to restrain the heave of the pile's head, additional stress can be developed in the pile's toe (as explained by Laloui et al., 2003; Bourne-Webb et al., 2009). Nevertheless, the additional stress induced by heating did not cause settlement of the pile's toe.

This is not the case for Test 3 and Test 4 where higher loads were applied. As shown in the load-settlement curve (Figure 2), the load applied in these tests (400 N in Test 3 and 500 N in Test 4) is close to the ultimate load (estimated at 525 N following the fitting curve). As a result, additional stress at the pile's toe induced by heating would lead to additional settlement and the development of irreversible strain. That explains why the pile head heave obtained during heating is significantly lower than the pile thermal expansion curve (Figures 5 and 6) and why irreversible settlement were observed after the thermal cycles of these tests.

An analysis on the time-dependent behaviour of the pile in Tests 1 and 2 shows a slight difference between the first and second thermal cycle of each test. At the same temperature, the pile's head in the second cycle is situated lower than the first cycle. And it can be expected that the pile continued to settle during these cycles. This creep behaviour can be also used to explain the large increase in displacement for a small temperature change at the end of each cooling phase in Tests 3 (Figure 5). Actually, the duration of these cooling phases is high (comparing to the duration of heating phases) and the measured pile displacement would include both thermal contraction and creep settlement.

At the beginning of each cooling phase, there is a plateau in the temperature-displacement curve where displacement does not appear to be mobilised although cooling has begun. This would be explained by the temperature heterogeneity along the pile and between its various elements (temperature sensor, U-tube, aluminium tube, etc.). In addition, heat diffusion from the pile to the surrounding soil can be equally considered to explain this phenomenon.

Finally, it should be noted that the significant scattering of the experimental data of the load-displacement plots (Figure 2) is mainly related to load application method. Actually, the application of dead weighs, that was chosen to achieve a constant load on the pile's head during thermal cycles, induces slight shocks on its head. In the future work, the loading system will be improved allowing a progressive increase of weigh. At the same time, strain gauges will be added along the pile in order to monitor the stress distribution.

5. CONCLUSION

In this preliminary study, the behaviour of piles subjected to thermal cycles under different constant axial loads was investigated using a physical model. The results would be useful to improve the knowledge on the mechanical behaviour of heat exchanger piles in geothermal foundations. Four tests were performed in compacted Fontainebleau sand with different axial pile head loads. The pile response appears to be "thermo-elastic" under thermal cycles when the mechanical load is less than about 40% of the ultimate resistance, i.e. the global factor-of-safety is greater than 2.5. So, at least for this case, conventional factors-of-safety appear adequate to ensure stable pile response under thermal load. Of course, the effect of many cycles of loading needs to be investigated to confirm this finding. When the mechanical load exceeds 40% of the ultimate resistance, irreversible pile settlement appears to develop. However, at loads close to the pile ultimate resistance, any temperature effects are combined with creep and further work is needed in order to decouple these effects.

6. ACKNOWLEDGEMENT

The authors would like to express their great appreciation to the French National Research Agency for funding the present study, which is part of the project PiNRJ "Geotechnical aspects of foundation energy piles" – ANR 2010 JCJC 0908 01.

7. REFERENCES

Bourne-Webb, P., Amatya, B., Soga, K., Amis, T., Davidson, C. and Payne, P. (2009). "Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles." Géotechnique, 59, Issue 3, 2009, pp 237–248.

Brandl, H. (2006). "Energy foundations and other thermo-active ground structures." Géotechnique, 56, Issue 2, 2006, pp 81–122.

De Gennaro, V., Frank, R., Pande, G.N. and Canou, J., (1999). "Finite element modelling of model piles in calibration chamber." Proc. 7th Int. Sym. Num. Models Geomechanics (Pande, G.N., Pietruszczak, S. and Schweiger, H.F. (eds)), Balkema, Rotterdam, 1999, pp 419-424.

Fioravante, V. (2002). "On the shaft friction modelling of non displacement piles in sand." Soils and Foundation, 42, Issue 2, 2002, pp 23–33.

Kalantidou, A., Tang, A.M., Pereira, and J.M., Hassen, G. (2012), "Preliminary study on the mechanical behaviour of heat exchanger pile in physical model." Géotechnique, 62, Issue 11, 2012, pp.1047 - 1051.

Laloui, L., Moreni, M. and Vuilliet, L. (2003). "Comportement d'un pieu bi-fonction, fondation et échangeur de chaleur.", Canadian Geotechnical Journal, 40, Issue 2, 2003, pp. 388 – 402.

Laloui, L., Nuth, M., Vulliet, L. (2006). "Experimental and numerical investigation of the behaviour of a heat exchanger pile. Int. J. Num. Anal. Meth. Geomechanics, 30, Issue 8, 2006, pp. 763 – 781.

McCartney, J.S. and Rosenberg, J. (2011). "Impact of Heat Exchange on Side Shear in Thermo-Active Foundations." Proc. Geo-Frontiers 2011 Conf. (Jie Han, Daniel E. and Alzamora P.E. (eds)), ASTM, Geotechnical Special Publications (GSP) 211, 2011. Pp. 488 – 498.

Moel, M.D., Bach, P. M., Bouazza, A., Singh, R.M. and Sun, J.L.O. (2010). "Technological advances and applications of geothermal energy pile foundations and their feasibility in Australia." Renewable and Sustainable Energy Reviews, 14, Issue 9, 2010, pp. 2683-2696.

Peron, H., Knellwolf, C. and Laloui, L. (2011). "A method for the geotechnical design of heat exchanger piles." Proc. Geo-Frontiers 2011 Conf. (Jie Han, Daniel E. and Alzamora P.E. (eds)), ASTM, Geotechnical Special Publications (GSP) 211, 2011, pp. 470-479.

Silvani, C., Nuth, M., Laloui, L. and Peron, H. (2009). "Understanding the thermomechanical response of heat exchanger piles." Proc. 1st Int. Symp. Comp. Geomechanics (Pietruszczak S., Pande G., Tamagnini C. and Wan R. (eds.)), 2009, pp. 589-596.

Tang, A.M., Pereira, J.M., Hassen, G., and Yavari, N. (2013). "Behavior of Heat-Exchanger Piles from Physical Modeling." Energy geostructures: innovation in underground engineering (Laloui, L., Di Donna, A. (eds)), Chapter 4, 2013.

Yavari, N., Tang, A.M., Pereira, J.M. and Hassen, G. (2014). "A simple method for numerical modelling of mechanical behaviour of an energy pile." Géotechnique Letters, 2014a. (doi: 10.1680/geolett.13.00053)

Yavari, N., Tang, A.M., Pereira, J.M. and Hassen, G. (2014), "Experimental study on the mechanical behaviour of a heat exchanger pile using physical modelling." Acta Geotechnica, 2014b. (doi: 10.1007/s11440-014-0310-7)