Effect of End-Restraint Conditions on Energy Pile Behavior

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Abstract

Energy piles are deep foundation elements designed to utilize the relatively constant temperature of the ground for efficient heating and cooling of the buildings while at the same time serve as foundations. The temperature changes during the operation of energy piles result in axial displacements, a part of which is restrained by the surrounding soil or the building on top. The restrained part of the axial displacements induces compressive stresses during temperature increase and tensile stresses during temperature decrease along energy piles. Moreover, the unrestrained part of the displacement results in changes in the mobilized shaft resistance, which need to be taken into consideration during design of energy piles. With the aim of quantifying these effects, a series of full-scale field tests on three energy piles with different end-restraint conditions was carried out in Richmond, TX. The field test program included conventional pile load tests and application of temperature. Temperature changes were applied to the test piles with and without maintained mechanical loads to investigate the effects of structural loads on energy piles. Moreover, the lengths of the test piles were determined to represent different end-restraint conditions at the toe. In this paper, a comparison of the thermally induced axial stresses and mobilized shaft resistance of two identical, end-bearing test piles with and without maintained mechanical loads are presented along with the details from the full-scale field test.

INTRODUCTION

Energy piles are exposed to daily and seasonal temperature variations during their lifetime. These temperature changes cause axial elongation and contraction of energy piles, which can alter the shaft resistance mobilization. Moreover, temperature-induced pile behavior can also result in axial compressive and tensile stresses along the energy piles. In order to identify these effects, there have been several field tests performed on energy piles, in the literature. The two pioneering thermo-mechanical field tests on energy piles have been performed in Switzerland and in the UK.

In Switzerland, one of the piles under a new four-story building at École Polytechnique Fédérale de Lausanne (EPFL) was equipped as an energy pile (Laloui et al. 2006). Thermal load applications were performed on the test pile before the construction of the building as well as after the construction of each story in order to couple different the thermal and mechanical loads.

This field test implemented by EPFL is significant in terms of investigating the influence of various structural load magnitudes on the thermally induced axial stresses and shaft resistance generation.

In the UK, at Lambeth College, heating-cooling cycles were applied to an energy pile under a maintained mechanical load for a period of seven weeks (Bourne-Webb et al. 2009; Amatya et al. 2012). A second pile was employed as a heat sink pile during the field test, which allowed the extraction of the heat energy from the ground during heating and rejection of the heat into the ground during the cooling of the test pile. The results were presented for both the test pile and the heat sink pile, which had opposite heating-cooling episodes, as well as different end-restraint conditions (test pile being restricted from elongation by the mechanical load and heat sink pile being free on top). In addition to these field tests, Goode and McCartney (2014) investigated the effects of head restraint conditions by centrifuge testing. In this study, the temperature changes were applied to the centrifuge-scale end-bearing piles under load-controlled and stiffness controlled conditions.

For the present research project, a full-scale field test has been performed on three energy piles in order to further investigate the effects of end-restraint conditions on their thermo-mechanical behavior. For this purpose, the lengths of the test piles were determined to represent end-bearing and semi-floating pile cases. Furthermore, the temperature cycles were applied to the end-bearing piles with and without mechanical loads to evaluate the effects of maintained mechanical load on top. In this paper, the results of the end-bearing piles will be provided, in order to highlight the effects of structural loads.

DETAILS ON THE FIELD TEST

Soil profile. The test site is located in Richmond, TX, at the regional office of Berkel and Company Contactors. Prior to the present thermo-mechanical field tests, a thermal conductivity test was performed at the field test site (Brettmann et al. 2010) for which the soil profile was obtained from a soil boring extending to 21.3 m depth. According to this study, the ground water table is at 3.4 m depth. The upper soil profile consists of sandy/silty, highly overconsolidated clay with a thin silty sand layer between 5.2-5.6 m. After the clay dominant layer, very dense sand layer containing gravels is present between 9.8-17.4 m depths. Below this level, a thin layer of medium stiff clay and medium dense sand are present between depths 17.4-19.1 m and 19.1-20.7 m, respectively. Finally, the bottom of the soil boring consists of very dense cemented sand.

Pile properties. Three test piles of 45.7 cm in diameter were installed using Augered Cast-In Place (ACIP) pile installation technique. Two of the piles, Test Pile-1 (TP-1) and Test Pile-3 (TP-3), were 15.24 m and the Test Pile-2 (TP-2) is 9.14 m in length. The reinforcing cage consisting of four vertically placed #7 bars and a #8 center bar, was constructed as one single system with no splices to insure the ease of instrumentation fitting and installation into the ground. For the heating system, a single loop polyethylene (PEX) pipe with 28.6 mm outer diameter and 3.2 mm wall thickness was attached to the #8 center bar. The reinforcing cage and geothermal pipe loops were then installed through the fluid column of grout to complete the pile installation process.

The profile of the test piles along with the soil properties deduced from the standard penetration test and pocket penetrometer test results are presented in Figure 1 (Brettmann and Amis 2011).

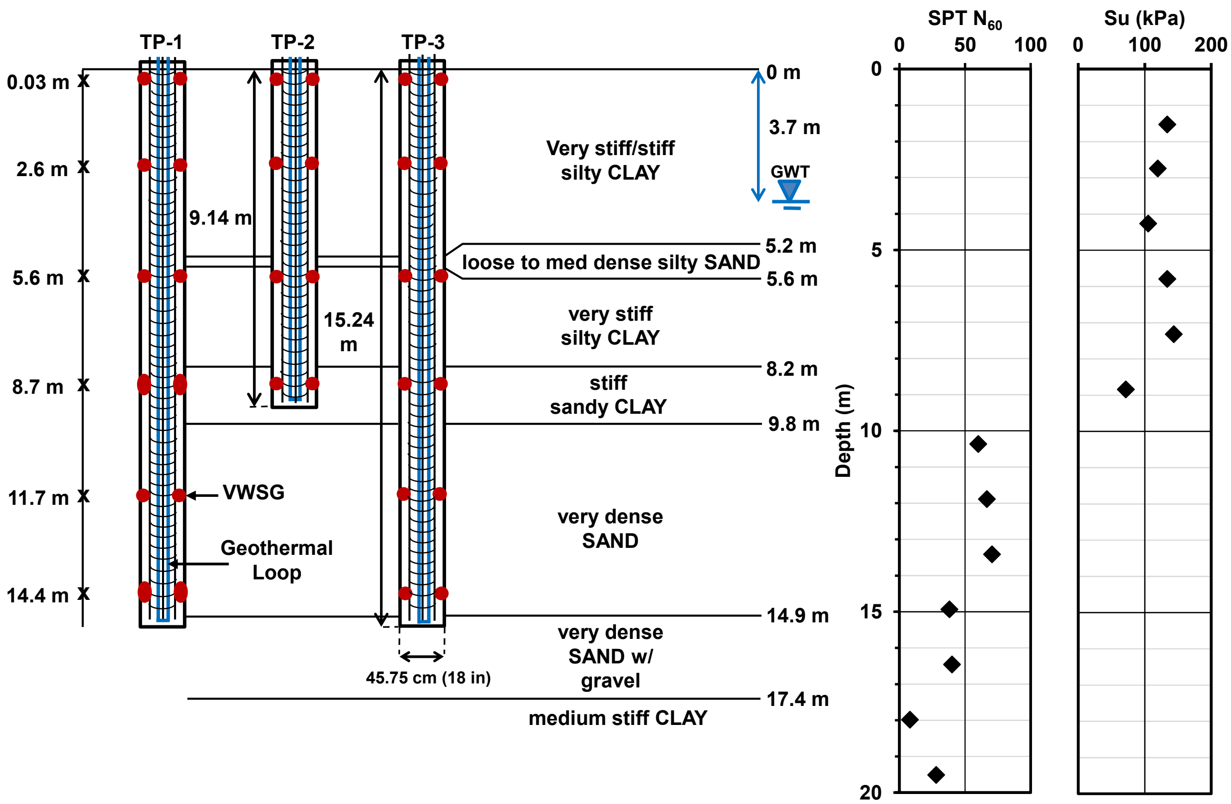

Figure 1. Test piles and soil profile.

Field test setup and site layout. In addition to the three test piles, eight reaction piles were installed as a part of the field test setup. The reaction piles were not only used for the conventional pile load tests but also for the application of maintained mechanical loads to the test piles during when the piles were exposed to temperature changes. Moreover, three piles that were previously used for thermal conductivity tests in 2009 (Brettmann and Amis 2011) were re-used as heat sink piles in this study.

Construction of the test piles was followed by the installation of the heating and circulating equipment. The test setup involved two water to water, ground source heat pumps. The use of two heat pumps enabled the thermal load application to two piles at the same time, which was convenient for the total duration of the field test. One of the heat pumps was connected directly to TP-1 and the other one was connected to and switched between TP-2 and TP-3. Furthermore, in order to enable the heat exchange, each heat pump was connected to a test pile and a heat sink pile. The heat sink piles in this research can be viewed as the elements to extract the heat energy from the ground during the heating of the test piles and to inject the energy into the ground during the cooling of the test piles.

In addition to the ground source heat pumps, geothermal circulation pumps, flow meters, pressure meters, storage tanks, heat sink tank and thermal expansion tanks were utilized as part of the heating equipment, as shown in Figure 2.

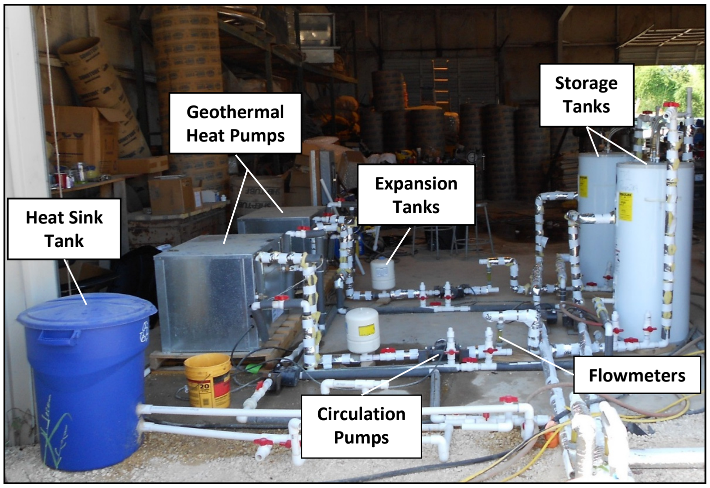

Figure 2. Equipment used for thermal load applications.

The test piles were instrumented with various types of sensors to monitor the temperature changes and axial strain generation during the thermo-mechanical tests. The pile instrumentation consisted of vibrating wire strain gages (VWSG), thermistors, thermal integrity profiler wires (TIP), and two types of fiber optic cables (strain and temperature), along with two LVDTs placed at the top of each pile to measure the axial displacements. In order to monitor the temperature of the heat exchanger fluid, two thermistors were attached to the geothermal loops entering and exiting each test pile, with the help of thermal wells.

Schedule of the field test. Two types of thermo-mechanical tests were implemented during the field test campaign. For the first type of the field test, five heating-cooling cycles, with maximum of 43°C and minimum of 8°C were applied on TP-1 without a maintained mechanical load on top. The thermal cycles that were applied to TP-1 are shown in Figure 3.

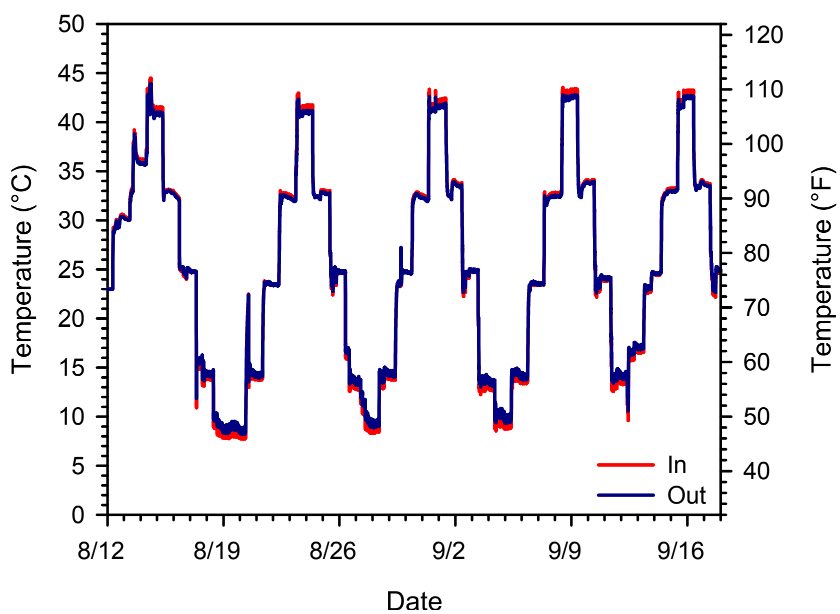

Figure 3. Temperature cycles applied to TP-1.

For the second type of the test, TP-3 was loaded to a design load with a factor of safety of 2. This design load was maintained during thermal loading, through the entire test. Then, a single heating-cooling cycle with a maximum temperature of 45°C and a minimum temperature of 8°C was applied for two-week period. The thermal cycles that were applied to TP-3 are shown in Figure 4.

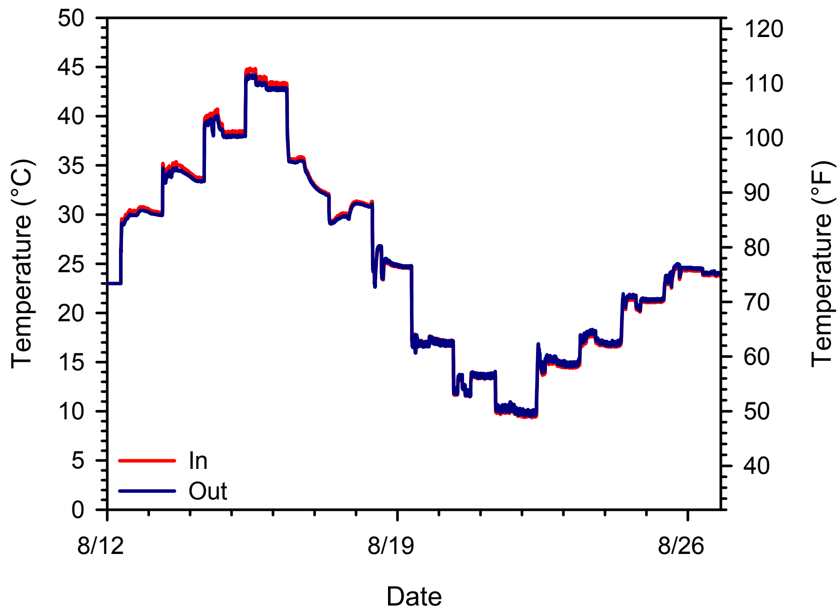

Figure 4. Temperature cycles applied to TP-3.

THERMO-MECHANICAL BEHAVIOR OF ENERGY PILES

The effects of temperature increase or decrease on the behavior of the energy piles have a rather complex mechanism compared to a conventional pile under only a structural load, which are explained in detail by Bourne-Webb et al. (2012). The mechanism behind the behavior of energy piles triggered by temperature changes is explained very briefly herein. When the temperature of an energy pile is increased, it tends to elongate proportional to the coefficient of thermal expansion of the pile material and the magnitude of temperature change. In practice, this case would take place during summer, when the extra heat is injected into the ground with the help of energy piles for cooling the buildings. If the pile was completely free of any restrictions, it would elongate in opposite directions from its mid depth, and there would not be any thermally induced axial stresses along the pile.

In reality, the soil around the shaft and at the toe of the pile, along with the structural load on top induces restrictions to its elongation. The part of the elongation that cannot take place due to restrictions results in thermally induced axial compressive stresses along the pile. On the other hand, the unrestricted part of the elongation results in upward displacement at the upper portion of the pile and downward displacement at the lower portion of the pile (unless the pile is completely restrained at the top or the toe, then the displacement would be in one direction). The relative movement of the pile with respect to the surrounding soil mobilizes downward shaft resistance at the upper part of the pile and upward shaft resistance at the lower part of the pile. For the case of temperature decrease along the energy piles, which would occur during winter, an inverse behavior is expected in terms of axial stresses and shaft resistance mobilization.

FIELD TEST RESULTS

Absence of maintained mechanical load. All the sensors remained operational throughout the field test period. The temperature profile of TP-1 after the first heating episode is presented in Figure 5. The black line on the figure represents the in-situ temperature of the ground, recorded before the application of thermal cycles, which is 22-23°C, except the fact that it increases closer to the ground surface. The maximum temperature along TP-1 was obtained just before starting to decrease the temperature of the heat exchanger fluid, in order to identify the highest temperature experienced by TP-1. An average of 7.6°C temperature increase was imposed on TP-1, during the first heating episode.

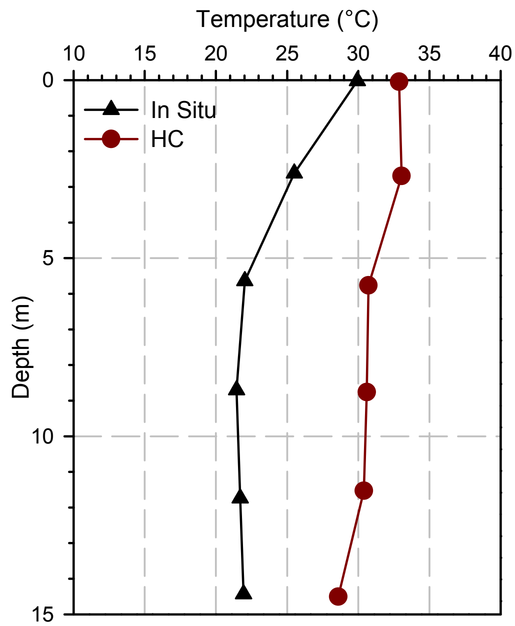

Figure 5. Temperature profiles along TP-1.

The thermally induced axial stress and mobilized shaft resistance profiles along TP-1 are presented in Figure 6a and 6b, respectively. It is observed in Figure 6a that maximum axial thermal stress, which is compressive in nature due to temperature increase, is around 1570 kPa, which corresponds to 172 kPa/°C. At 5.7 m depth, the compressive axial stress is in the order of 1000 kPa, corresponding to 115 kPa/°C. As there weren't any mechanical load application on top of TP-1 during the thermal cycles, the observed strains are equal to the free thermal elongation of the pile, resulting in zero blocked strains. Hence, the thermally induced axial stresses at the top of TP-1 are equal to or very close to zero. On the other hand, the presence of very dense sand layer at the toe restricted some portion of the thermal elongation of the pile, resulting in compressive axial stresses. At the VWSG level that is closest to the pile toe (14.4 m depth), maximum compressive stress of 128.4 kPa/°C is induced during the first heating cycle. It should be noted that thermally induced axial stresses per unit temperature change shows almost linear behavior, which is confirmed with the analysis for lower temperature changes.

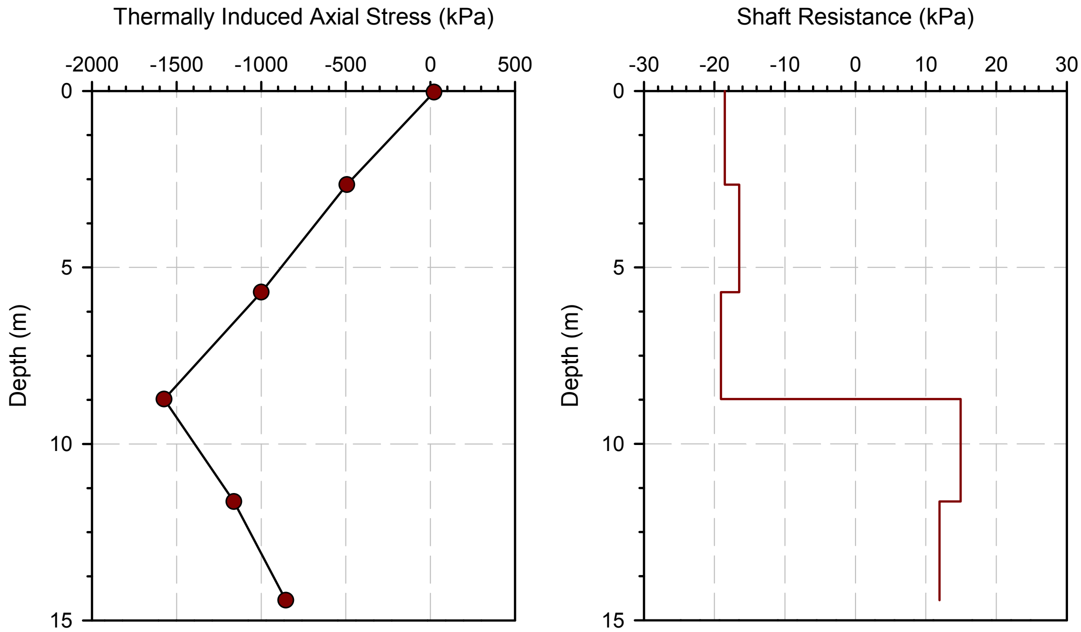

Figure 6. a) Thermally induced axial stresses b) Mobilized shaft resistance along TP-1.

As shown in Figure 6b, an average of 20.9 kPa of downward shaft resistance is mobilized above 8.7 m depth due to upward displacement of TP-1 with temperature increase, which corresponds to 2.9 kPa/°C. At the lower portion of TP-1, an average upward shaft resistance of 14.4 kPa is mobilized, due to downward displacement of the pile corresponding to 1.7 kPa/°C. The depth at which the mobilized shaft resistance changes direction depends on the balance of overall resistance along the length of the pile. For a pile completely free of restrictions, it would be at the mid-depth. However, due to the presence of the very dense sand layer at the toe of TP-1, this depth is shifted towards the toe of the pile, which is at 8.7 m. In other words, as TP-1 is restrained at the toe, a larger portion of it elongates upwards, where it is free at the head.

Presence of maintained mechanical load. The economic advantage of the energy piles comes from the fact that they are already required for structural support. Hence, there will always be a structural load on energy piles, the effect of which needs to be investigated for the future design considerations. The thermo-mechanical load test on TP-3 has been designed for this purpose. The temperature profile along TP-3 is shown in Figure 7. At the peak heating period an average temperature increase of 8.4°C along TP-3 is observed.

The axial stress profiles along TP-3 are presented in Figure 8a. The mechanical stress profile represents the axial compressive stresses only due to the maintained mechanical load throughout the temperature cycles. The thermo-mechanical stresses are the combined effects of mechanical and thermal load on TP-3. Finally, the thermal stresses are deduced from the mechanical and thermo-mechanical stresses. Unlike TP-1, the axial thermal stresses at the head of TP-3 are higher than zero (1150 kPa), which is due to the maintained mechanical load restricting the free elongation of TP-3 with temperature increase. Maximum thermally induced axial compressive stress along TP-3 is 1810 kPa at 5.7 m depth, which corresponds to 160 kPa/°C. At 8.8 m depth, 1430 kPa of thermally induced axial stress is observed, which corresponds to 147 kPa/°C.

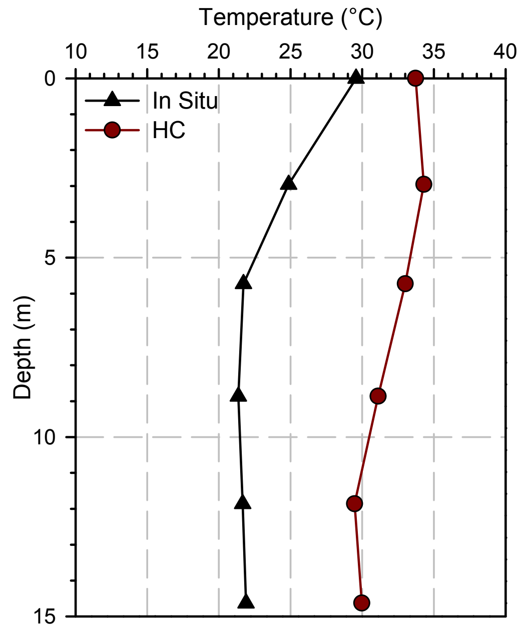

Figure 7. Temperature profiles along TP-3.

The mobilized shaft resistance along TP-3 due to mechanical load, combined effects of thermal and mechanical loads and only thermal load are shown in Figure 8b. As a result of the elongation of TP-3 with temperature increase, the shaft resistance above 5.7 m depth decreases by 13.1 kPa, compared to the only mechanical load case, which corresponds to 1.93 kPa/°C. On the other hand, the shaft resistance below this depth increases in average by 18.1 kPa, which corresponds to 1.9 kPa/°C.

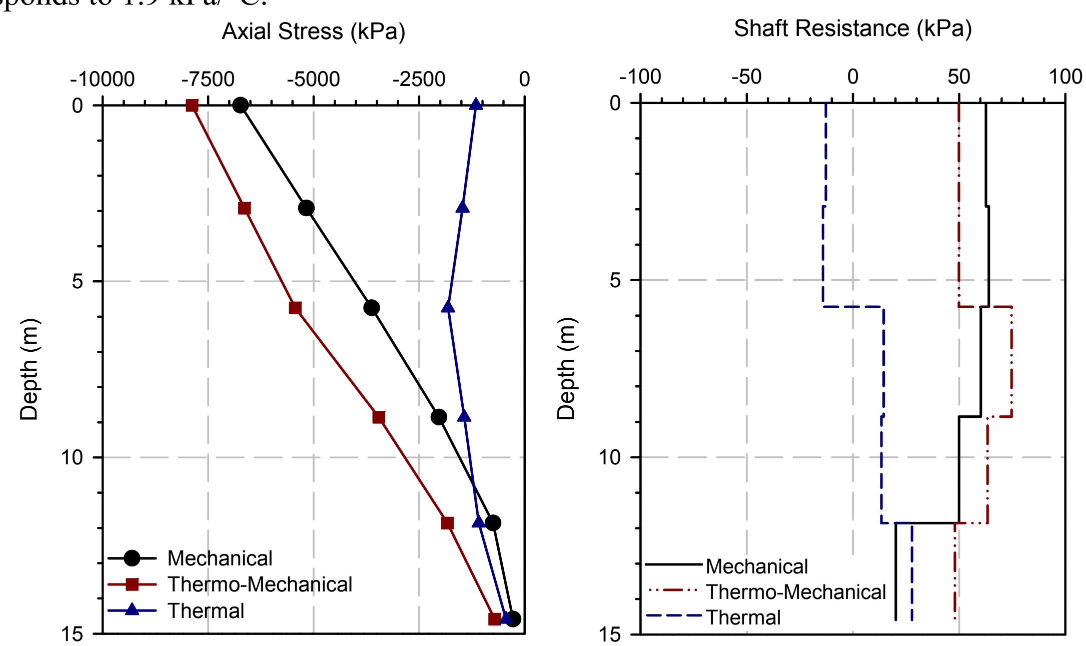

Figure 8. a) Thermally induced axial stresses b) Mobilized shaft resistance along TP-3.

In order to have a better comparison of the restraining effects of the mechanical load during the field test, thermally induced axial stresses are normalized by the fully restrained conditions, which are 460 kPa/°C and 422 kPa/°C for TP-1 and TP-3, respectively. These theoretical stresses, which would occur if the piles were completely restrained from thermal elongation, are determined using the coefficient of thermal expansion and modulus of the pile material. TP-1 had slightly higher pile modulus compared to TP-3, hence higher compressive axial stresses are expected to occur along TP-1 if all the other factors are held equal (i.e. applied mechanical load, temperature increase). The normalized thermally induced axial stresses along TP-1 show that, the axial compressive stresses at 5.7 m depth and 8.7 m depth are 25% and 37% of the theoretical fully restrained condition, respectively. On the other hand, along TP-3 at depths 5.8 and 8.9 m, the compressive axial stresses are 38% and 35% of the fully restrained condition, respectively.

As shown previously in Figure 6a, the maximum compressive stress along TP-1 is induced at 8.7 m depth, closer to the toe of the pile, due to the absence of the mechanical load on top. At 8.7 m, TP-1 has slightly higher compressive axial stresses (%2) compared to TP-3. For TP-3, the highest compressive stresses are induced at 5.8 m depth, closer to the head of the pile and the compressive axial stresses at TP-3 are significantly higher (13%) than TP-1. These results show that the presence of the maintained mechanical load has an influence on both the magnitude and distribution of the axial stresses induced by temperature changes.

The restriction due to the maintained mechanical load has two main effects on the mobilization of shaft resistance. Firstly, the depth at which the mobilized shaft resistance due to temperature increase changes direction is shifted towards to head of the pile in the case with maintained mechanical load, which is at 5.8 m for TP-3 compared to 8.7 m for TP-1. This is mainly because of the fact that a longer portion of TP-3 tends to elongate downwards with temperature increase, due to being restricted at the head by the mechanical load. Similarly, TP-1 tends to elongate more upwards due to the absence of mechanical load on top. Secondly, the thermally mobilized shaft resistance of TP-3 is less than the one of TP-1, caused by the fact that TP-1 is freer to elongate compared to TP-3, resulting in higher axial displacement with respect to the surrounding soil, hence higher changes in shaft resistance.

CONCLUSIONS

A full-scale thermo-mechanical field test has been performed on three energy piles with various end-restraint conditions, in order to investigate their behavior during temperature changes. With the purpose of evaluating the effects of structural load, the field test results of the two identical piles, having end-bearing in very dense sand layer, one subjected to temperature cycles with (TP-1) and one without (TP-3) maintained mechanical load on top have been compared in this paper. Conclusions have been drawn for the effects of maintained mechanical load on both thermally induced axial stresses and mobilized shaft resistance.

The thermally induced axial compressive stresses along both of the test piles have been normalized with the theoretical fully restrained stresses in order to discard the effects of pile moduli. It is concluded that 25% and 37% of the theoretical fully restrained stresses have been induced along TP-1 at depths 5.7 m and 8.7 m, respectively. On the other hand, 38% and 35% of the fully restrained stresses have been observed along TP-3 at 5.8 and 8.8 m depth, respectively. The results of the full-scale field test show that higher compressive axial stresses are induced along TP-3, due to the restraining effect from the maintained mechanical load.

Regarding the mobilized shaft resistance due to temperature increase, TP-1 has higher shaft resistance mobilization at the upper portion and lower shaft resistance mobilization at the lower portion compared to TP-3. Finally, the depth where the thermally mobilized shaft resistance changes direction is at 8.7 m for TP-1, while it is closer to the pile head, at 5.7 m, for TP-3. The main reason behind this behavior can be attributed to the presence of the mechanical load on top of TP-3, due to which it tends to elongate more in the direction of the toe.

In brief, the tendency of the energy piles to elongate due to temperature increase is inevitable. The effects of this tendency on the axial stresses and mobilized shaft resistance are highly dependent on the level of restrictions along the energy piles. In case of a low toe resistance or absence of structural load, a higher portion of the elongation will result in axial displacements and alter the mobilized shaft resistance. On the other hand, in case of a high toe resistance or structural load on top, the elongation that cannot take place which will induce thermal axial compressive stresses.

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REFERENCES

Amatya, B. L., Soga, K., Bourne-Webb, P. J., Amis, T., and Laloui, L. (2012). "Thermo-mechanical behaviour of energy piles." *Géotechnique*, Vol. 62, No. 6, pp. 503-519.

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, Vol. 59, No. 3, pp. 237–248.

Bourne-Webb, P., J., Amatya, B., and Soga, K., 2012. A Framework for understanding energy pile behaviour. Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, Vol. 166, No. GE2, pp: 170-177.

Brettmann, T., and Amis, T., 2011. Thermal conductivity evaluation of a pile group using geothermal energy piles. Proceedings of the Geo-Frontiers 2011 Conference, Dallas, TX, 10p.

Goode, J. C., and McCartney, J. S., 2014. Evaluation of head restraint effects on energy foundations. Proceedings of GeoCongress 2014 (GSP 234), ASCE, Reston, VA, pp. 2685-2694.

Laloui, L., Nuth, M., and Vulliet, L., 2006. Experimental and numerical investigations of the behaviour of a heat exchanger pile. International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 30, pp. 763–781.