Model tests of energy piles with and without a vertical load

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The thermomechanical behaviour of energy piles during heating and cooling through model tests was studied. These model tests were carried out both with and without a vertical load and dry sand was used. The axial load distribution, load-settlement of the pile head, pile and soil temperature, soil pressure at the pile tip, horizontal soil pressure, thermal stress and mobilised side shear stress were investigated. The magnitude of stress and displacement influenced by vertical load or no load was comparatively analysed. The results show that heating and cooling induced thermal stress in piles and residual thermal stress was introduced after a heating and cooling cycle. Horizontal soil pressure also varied and changes in soil pressure at the pile tip differed depending on whether or not a vertical load was applied. Moreover, the pile temperature and the temperature within one pile diameter of the pile axis varied noticeably in the condition of this paper. The heave under no load was 143% of that under a vertical load after heating, while the settlement under no load was only 64% of that under vertical load after cooling.

Notation

D	pile diameter
E	modulus of elasticity of concrete
f	mobilised shear stress
$f_{s,mob,j}$	mobilised shear stress in layer j
L	embedded pile length
P_M	mechanical load
P_{T1}	restrained thermal load when heating
P_{T2}	restrained thermal load when cooling
P_{Total1}	total load when heating
P_{Total2}	total load when cooling
α_c	coefficient of liner thermal expansion
ε_T	thermal strain
$\varepsilon_{T,free}$	free thermal strain
σ_T	thermal stress

Introduction

Energy geostructure is an innovative technology equipped with a closed-loop heat exchanger in general to transfer heat between the surrounding soil and upper building. It takes advantage of the geothermal energy as seasons change, reducing the use of fossil fuels and saving more cost and space than the conventional heat pump system. Thus it can maximise economic, as well as environmental, benefits (Colls *et al.*, 2012; Johnston *et al.*, 2011). Energy geostructure is mainly composed of walls, piles, tunnel

linings (Barla *et al.*, 2014), slabs and so on. Especially, the energy pile is used more widely and thus selected as the study target here. Energy pile is increasingly adopted in many countries for the dual purpose of supporting the building load and deriving geothermal energy (Adam *et al.*, 2009; Brandl, 2006; De Moel *et al.*, 2010; Laloui *et al.*, 2003; Nicholson *et al.*, 2013). During heating and cooling, the piles and soil will expand and contract accordingly resulting in thermomechanical phenomena, which may threaten the safety of the building (Hueckel *et al.*, 2009, 2011). In the past years, some research has been made to study the mechanisms of thermomechanical soil-structure interaction.

Field tests were carried out by Amatya *et al.* (2012), Brandl (2006), Bourne-Webb *et al.* (2009), Laloui *et al.* (2003, 2006), McCartney and Murphy (2012), and Olgun *et al.* (2012) to investigate the pile and soil temperature, strain and load distribution, and side shear resistance. These field tests have shed light on the thermomechanical behaviour in the real conditions, but extensive field tests are costly to conduct.

Kramer *et al.* (2015) and Stewart and McCartney (2012) performed centrifuge testing and laboratory thermal performance tests to study the strain distribution and thermal conduction, respectively. Yavari *et al.* (2014) studied the pile settlement, side shear resistance, and soil pressure under various axial loads

through model tests. Mimouni and Laloui (2014) analysed the design of geothermal piles through investigating the mobilised bearing capacities of piles influenced by temperature. Laloui and Di Donna (2013) gave a comprehensive overview of energy geostructures. These studies have addressed the basic thermomechanical behaviour of the pile. A comparative analysis of piles with and without a vertical load is seldom conducted. A complete heating, natural recovery and cooling process is essential for studying seasonal operation. Moreover, the analysis of thermal strain and load in the literature is far from perfect. To better understand the behaviour of energy piles during heating and cooling, more research is needed.

This paper investigates the behaviour of concrete piles with and without a vertical load in unsaturated sand during a heating and cooling cycle through model tests. The results provide excellent insights into the thermomechanical behaviour of energy piles.

Experimental method

Model setup

A model tank with dimensions $1750 \times 2000 \times 3000$ mm (length $\times$ width $\times$ height) was used in the model tests. Figure 1(a) shows the instrument layout. The piles were 1600 mm long with a diameter of 104 mm. The embedded length (L) of the piles in the soil was

Figure 1. (a) Instrumentation layout; (b) cross-section of an energy pile

Figure 2. Physical layout of the thermal and static load system

1400 mm. The scale was 1:20 to the prototype piles. Adjacent piles were spaced 1000 mm ($9.6 D$) apart in the length and 667 mm ($6.4 D$) in the width. The toe of the energy pile prototypes was 350 mm distant from the bottom of the tank ($3.3 D$), which was larger than the distance in Goode *et al.* (2014) and McCartney and Rosenberg (2011). And the results would not be affected.

At the depths of 240, 650 and 1060 mm, three sets of strain gauges and thermocouples (TS1–TS3) were installed in the reinforcement cage to monitor the pile behaviour. Figure 1(b) shows strain gauges and thermocouples distribution in the pile. To investigate the thermal effects on the soil, another nine thermocouples (T1–T9) were installed, with three at each of the depths of 240, 650 and 1060 mm in the soil. The distance of the three thermocouples at each depth from the pile axis was 104, 208 and 312 mm. Four pressure transducers (P1–P4) were placed in the soil to measure soil pressure in various directions. P2 and P3, which were located near the pile, measured the horizontal pressure at the depths of 1060 and 240 mm, respectively. P1 and P4 measured the vertical soil pressure at the pile tip. Two dial indicators were fixed with a load cell to measure the corresponding settlement. Figure 2 shows the physical layout of the thermal and static load system.

The concrete mix of the piles was made using a 0.44:1:1.79:3 ratio of water to cement to fine aggregate to coarse aggregate by mass. The compressive strength was 30.9 MPa, and the coefficient of linear expansion was $1 \times 10^{-5}/^{\circ}\text{C}$. The modulus of elasticity was $3 \times 10^4 \text{ N/mm}^2$. The energy piles were fitted with heat transfer pipes forming U-shaped loops with an inner diameter of 9 mm and an outer diameter of 11 mm. The temperature of the water travelling through the pipes during heating and cooling

were 55 and 5°C , respectively. The tests were carried out in closed chambers, and the temperature ranges were from 12 to 15°C at day and night as measured with a thermometer.

Soil properties

Dry Nanjing sand was used in the model tests. The maximum and minimum dry densities are equal to 1.77 and 1.40 g/cm^3 , respectively. The uniformity coefficient (C_u) and curvature coefficient (C_c) are equal to 2.69 and 0.97, respectively. The pile-soil interface angles were about 30.1° – 32.2° . The mean particle size d_{50} was equal to 0.28 mm. Fioravante (2002) suggested that the minimum ratio of pile diameter to soil d_{50} was 50. The ratio of pile diameter to d_{50} of the soil was 371, so the scaling effect can be neglected (Fioravante, 2002). The model tests were

Figure 3. Load-settlement curve for single pile

prepared using the pluvial deposition method in which a hopper deposited sand at a constant height of 350 mm above the sand surface. The relative density measured was 63%.

Testing procedure

The first pile was loaded to failure from 0 kN and at an increment of 1 kN at an interval of 15 min. As shown in Figure 3, an obvious inflexion point appeared under 20 kN which was the ultimate resistance. The vertical load 10 kN (50% of the ultimate resistance of the pile) was derived.

The second pile was unloaded and heated for 305 min until the settlement stabilised. After natural recovery, the second pile was cooled for 265 min.

After natural recovery, the vertical load 10 kN was applied to the pile in an increment of 1 kN and at an interval of 15 min. Then the heating-cooling cycle was applied to the pile, repeating that under no load.

Results and discussion

The pile and soil temperature, soil pressure at the pile tip, horizontal soil pressure, strain distribution, thermal stress, mobilised side shear stress, axial load and pile head settlement were recorded. The results are shown in Figures 4 to 12.

In Figure 4, the measured temperature of the pile body and soil is shown. The temperature of the pile and soil increased during heating and decreased during cooling. As mentioned above, the water was

Figure 4. Temperature distribution along the length of the tested pile prototype and in its vicinity for (a) heating (no load), (b) cooling (no load), (c) heating (vertical load), (d) cooling (vertical load)

heated to 55°C for 305 min and cooled to 5°C for 265 min. The thermocouples T1, T2 and T3 (T4, T5 and T6) were situated 104 mm (208 mm) away from the pile axis. In the vertical direction, TS3, T3 and T6 recorded the maximum temperatures of 35.4, 23.25 and 17.44°C, respectively, under a vertical load. Under no load, the maximum temperatures were slightly lower because the initial temperatures were lower. After cooling, TS1, T3 and T6 recorded the minimum temperatures of 8.5, 12.88 and 13.63°C, respectively, under a vertical load. The temperature of the pile differed slightly depending on whether or not a vertical load was applied. This is because the upper part of the pile and soil were under the influence of the air temperature and the temperature recovered at differing rates along the pile. In the horizontal direction, thermocouples TS1, TS2 and TS3 captured variations in pile temperature that were nearly twice as large as the variations in soil temperature captured by thermocouples T1, T2 and T3. Thermocouples T4, T5 and T6 recorded only negligible soil temperature variations during heating

and cooling. The soil temperature captured by thermocouples T7, T8 and T9 did not change over time and so are not shown in Figure 4.

In Figure 5, soil pressure at the pile tip is plotted against time for the thermal test with and without a vertical load. The value captured by P4 was insignificant and hence is not shown. The pile tip resistance can be extrapolated from soil pressure. The pile tip resistance captured by P1 increased during heating and decreased during cooling under no load. The value of the resistance increased 46 kPa after heating and -16 kPa after cooling. The pile tip resistance exhibited a similar trend to that observed by Yavari *et al.* (2014) during heating with no load. Under a vertical load, soil pressure at the pile tip increased first before decreasing slightly during heating. During cooling, soil pressure at the pile tip decreased first and then increased over time. The value of the resistance increased 33 kPa after heating and decreased -1.3 kPa after cooling. This phenomenon is different from that under no

Figure 5. Soil pressure at pile tip during cooling and heating

Figure 6. Horizontal soil pressure during cooling and heating

load. It is possible that the soil was more compacted when the vertical load was applied, and the shaft resistance was different from that under no load, resulting in less change in tip resistance. Hence during heating and cooling, further research on the tip resistance was still needed.

Figure 6 plots the horizontal soil pressure at different locations in the soil against time. The soil pressure increased during heating and decreased during cooling. The curve shape was similar with and without a vertical load. The maximum horizontal soil pressure was equal to 7.8 kPa after heating and -3.4 kPa after cooling. During cooling, the change in horizontal soil pressure was greater far from the soil surface (as captured by P2) than near the soil surface (as captured by P3), because the temperature of the soil surface was under the influence of the ambient temperature. This phenomenon was also observed during heating.

Figure 7 shows the thermal axial strain during heating and cooling. The thermal axial strain is defined as positive during heating (i.e. expansion) and negative during cooling (i.e.

Figure 7. Strain distribution during heating and cooling under (a) no load and (b) vertical load

compression). On the soil surface, strain could be extrapolated from values recorded by TS1 and TS2. The change in thermal axial strain was greater during heating than during cooling for the greater change in pile temperature when heating. Figure 7(a) shows large thermal axial strain at the upper part of the pile during heating. This is because no load was applied to the pile, and the head can freely expand. Lower thermal axial strain was observed at the tip for pile tip restraint. As shown in Figure 7(b), the thermal strain in the top half of the pile, owing to higher temperature change, is still higher than that in the bottom half.

Figure 8 shows the effect of heating and cooling on energy pile behaviour under no load. The pile could freely expand or constrict without the frictional shaft resistance or boundary restriction at the pile head and pile toe. The heating under no load allowed the pile top to freely expand, but constrained the pile tip. Thus, thermal stress and mobilised side shear stress were induced (Figure 8(a)). Under vertical load, the pile head was partially constrained. Thus, the pile head exceeded that under no load. During cooling, at the pile toe, free movement was assumed during contraction owing to no restriction in the sand under the

Figure 8. Effect of heating and cooling on energy pile behaviour under no load (Bourne-Webb *et al.*, 2012)

Figure 9. Profiles of thermal axial stress under (a) no load and (b) vertical load

pile toe. The pile head could also freely move owing to no restriction under no load or vertical load. The distributions of thermal stress and mobilised side shear stress during cooling were shown in Figure 8(b) (Bourne-Webb *et al.*, 2012).

Figure 9 shows the profile of axial stress along the depth of the soil under no load and vertical load. For restrained expansion and contraction, the actual thermal axial strain ε_T was less than $\varepsilon_{T,free}$, and thermal axial stress σ_T was produced which can be calculated as follows (Amatya *et al.*, 2012)

$$1. \quad \sigma_T = E(\varepsilon_T - \alpha_c \Delta T)$$

where E is the modulus of elasticity of concrete, α_c is the coefficient of linear thermal expansion of reinforced concrete and ΔT is the change in temperature.

During heating, the compressive stress was produced which was negative and the tension was positive during cooling. In

Figure 9(a), during heating, σ_T increased along with depth to a maximum of -544 kPa, and the null point moved downward to the tip for the end restraint (Murphy *et al.*, 2014). During cooling, the maximum stress of 242 kPa appeared at 650 mm from the soil surface which was away from the pile tip. It is possible that end restraint has less of an influence under contraction. Although tension was produced, it was far below the limit of 1450 kPa specified in the China Design Code (GB 50010–2010). The thermal stress distribution was consistent with that shown in Figure 8. In Figure 9(b), during heating and cooling, the maximum tensions were, respectively, -450 and 360 kPa, and these were generated near the halfway point of the pile. After heating, thermal stress in the upper half of the pile was larger under a vertical load than under no load owing to restraint. The null point moved upward and was near the middle of the pile. The curve trend when cooling was similar to Figure 8(b) as expected.

The pile-soil displacement induced by temperature variations will mobilise side friction at the pile-soil interface (Laloui, 2011). The mobilised side shear stress $f_{s,mob,j}$ at different heights in the soil layer can be determined as follows (Murphy *et al.*, 2015)

$$2. \quad f_{s,mob,j} = (\sigma_{T,j} - \sigma_{T,j-1})D/4\Delta l$$

where D is the shaft diameter and Δl is the distance between two gauges. A positive sign implies the side shear stress is upward and a negative sign indicates downward.

The profile of mobilised side shear stress calculated is shown in Figure 10. The curve trends under no load and vertical load were similar. During heating, the sign in the upper part was negative and positive in the lower part, which indicates upward and downward in different sections. During cooling, the sign in the upper part of the pile was positive and negative in the lower part

Figure 10. Profiles of mobilised side shear stress after heating and cooling

Figure 11. Axial load distribution along depth (a) load distribution in Lausanne test pile (Loloui *et al.*, 2006), (b) heating, (c) cooling

of the pile. A near-zero shear stress corresponded to the maximum thermal stress. The curve trend indicated the pile-soil interaction restraint and it was reasonable compared with Figure 8. Moreover, under no load, the total mobilised side shear stress along depth was larger than that under vertical load during heating and cooling, which influenced the tip resistance possibly.

Figure 11 plots the axial load distribution along depth. The thermal response of the energy pile tested in Lausanne is shown in Figure 11(a). The mechanical load decreased to nearly zero along depth. After application of thermal load, thermal stress was induced and the total stress increased. Obviously, thermal stress increased most at the pile toe. As shown in Figure 10(b), the load at the pile toe and pile head where no gauges were installed could be extrapolated from values recorded by TS1, TS2, TS3 and P1. The curve indicating mechanical load describes the axial load distribution before heating. This curve shows the linear decrease

of load with depth similar to Figure 11(a). But owing to the shorter distance of the pile, the mechanical load in the pile toe was still large. The mechanical load was $P_M = 10$ kN. After heating, the pile pressure increased to P_{Total1} which was expected because the foundation was restrained at the head and bottom. The restrained thermal load was $P_{T1} = P_{Total1} - P_M$. This load distribution can be explained according to Bourne-Webb *et al.* (2009). The maximum load induced was only 42% of the mechanical load, which was smaller compared with that in Figure 11(a). This was attributed to the differences in boundary conditions and soil properties.

Figure 11(c) shows the axial load distribution before cooling. The axial load of the pile was still P_M , but on the curve, the mechanical load throughout the pile before cooling was larger than that before heating. The linear decrease in the load with depth is not shown because residual thermal strain existed in the

Figure 12. Displacement of pile head during heating and cooling

pile. The axial load after cooling decreased to P_{Total2} , which indicates tension was induced. The restrained thermal load was $P_{T2} = P_{\text{Total2}} - P_M$.

Figure 12 shows the variations of pile-head displacement against time with and without vertical load, and the results are compared with the study by Knellwolf *et al.* (2012). In their study, the pile was first heated for 180 min and then cooled for 120 min under no load to the initial temperature (Knellwolf *et al.*, 2012). The pile was heated first for 120 min and then cooled for 180 min under no load to the initial temperature. In this study, the pile was heated for 305 min and then cooled to the initial temperature during natural recovery. After that, the pile was cooled for 265 min.

Heating induced heave and cooling induced settlement. The displacements under different loads could be found in Knellwolf *et al.* (2012). The settlement was accumulative under a head load higher than 40% of the pile resistance. The settlement was reversible when a pile was not loaded axially. Moreover, the heave amplitude under no load was larger than that under vertical load. In this study, the maximum heave under no load was 0.199 mm which was 143% of that under vertical load during heating. The difference in the measured heave is owed to the vertical load, which is applied to the pile head, restricting the pile heave.

After natural recovery, the final settlement was 0.006 mm under no load and -0.117 mm under the vertical load. These results indicated that the deformation almost completely reversed under no load and the settlement was cumulative under vertical load, which was similar to their study (Knellwolf *et al.*, 2012). The settlement under the vertical load was larger, as the dead load which was 50% of the pile resistance contributed to the settlement when the soil contracted during recovery.

Although our testing time was different from theirs (Knellwolf *et al.*, 2012) and this study, the trends were consistent. The

displacement under lower temperature than initial temperature was studied in this study, which was a supplement of Knellwolf *et al.* (2012).

During cooling, the settlement was 0.065 mm under no load which was only 64% of that under vertical load. The reason for this difference is the same as that during natural recovery and the settlement under the vertical load should be considered in the design stage.

Conclusions

In this study, the behaviour of piles subjected to thermal cycle with and without a vertical load was investigated using a physical model. In the test, dry sand was used as the surrounding soil. Instruments were installed in the soil and to the pile to monitor the thermal effects. The model test results qualitatively reflect the behaviour of prototype piles. Based on the current study, the following conclusions can be made

1. The soil temperature 104 mm away from the pile axis was almost twice that 208 mm away from the pile axis after heating. The pile and soil temperature within 1 D away from the pile axis changed noticeably. Thus, the influence zone should be set to 1 D for analysis of soil thermal effects in future studies.
2. Pile tip resistance increased during heating and decreased during cooling. However, the differences in pile tip resistance with and without a vertical load deserve more attention. Horizontal soil pressure increased during heating and decreased during cooling regardless of whether or not a vertical load was applied.
3. The thermal strain along depth under no load differs from that under a vertical load. Heating and cooling resulted in compressive stress and tension to restrain the soil. The thermal stress along depth was different under no load and under a vertical load. Mobilised side shear stress was produced. After cooling, the sign of mobilised side shear

stress was positive for the upper part of the pile and negative for the pile tip; after heating, the sign of mobilised side shear stress was negative for the upper part of the pile and positive for the lower part.

4. The heating and cooling induce thermal load in the piles and residual thermal strain was induced after a heating and cooling cycle. In this test condition, during heating, the heave under no load was 143% of that under a vertical load. But the settlement under no load was only 64% of that under vertical load, and the mechanical load contributed to the settlement during cooling. The settlement of prototype piles under a building load deserves designers' attention.

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