HEAT TRANSFER PERFORMANCE AND STRUCTURE RESPONSE OF ENERGY PILES

by

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Energy pile becomes a new application of foundation, instead of the traditional ground source heat pump system. The heat exchange efficiency and its structural response induced by thermal stress is an urgent issue for the usage of shallow geothermal in foundations. In this study, the field experiments are systematically carried out by using engineering test pile as energy pile, the comprehensive thermal conductivity and heat exchange rate of each pile are achieved by thermal performance tests. Then the deformation and stress-strain of a heating or cooling pile at different temperature are analyzed to explore the influence of thermal stress on pile structure. Finally, the thermal stress distribution along the pile is calculated, and its bearing capability is analyzed. The results are applied to the design and application of energy piles.

Key words: *energy pile, field test, heat exchange, structural response, thermal stress*

Introduction

Heat exchange tubes buried in piles had dual effects on the mechanical properties of the piles. Energy piles led to temperatures changes in piles and surrounding soil during the heating/cooling process, and the expansion/contraction deformation resulting from heat exchange was restrained by the surrounding soil, which induced additional thermal stress occurred in bored piles and artificial digging-hole piles during the process of heat exchange could not be ignored, [1, 2]. Seriously, additional thermal stress induced to tensile/compression damage of the pile concrete or weakness of the pile-soil interface. The bored pile installed with sensors to study the changes in thermal stress along the pile [3, 4]. Under the effect of thermal loads (temperature difference at 15 °C), additional temperature compressive stress produced at the middle and lower parts of the testing pile was above 2 MPa, exceeded the stress (below 1 MPa) produced by the vertical building loads. Bourne-Webb *et al.* [5] carried out a structural response test of energy piles was at Lambeth College, the piles were located in London clay, it found that in the winter working conditions, an additional thermal tensile stress was up to 2.8 MPa in the middle part of a pile when the pile temperature dropped by 19 °C. Those additional thermal tensile stresses were superimposed on the compressive stress generated by the vertical loads. The tensile stress in the middle and lower parts was up to 2.1 MPa, which was not allowed in engineering. Gui *et al.* [6] reported the field tests on the structural response of

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artificial digging-hole piles buried with heat exchange pipes at the square of Xinyang High-speed Rail Station and proved that under a large temperature difference (temperature difference greater than +20 °C), the additional thermal stress on piles was about 3.9 MPa. In winter, a large additional tensile stress was also presented at the lower part of the pile. At the same, the settlement of energy piles during heating and cooling process was also unrecoverable. You *et al.* [7, 8] performed bearing capacity tests of cement fly-ash gravel piles, the results showed the bearing capacity reduced 14% for a cooling pile, and less effects for heating one, which indicated that pile deformation may be accumulated in the operational mode of multiple heating and cooling cycles. Those geotechnical responses of energy piles had become a challenge for the utilization of energy piles in engineering.

This study aimed to evaluate the thermal properties of a bored energy pile by the field experiments [9]. The testing pile was placed near the Binhai Lake, Tianjin, China. Thermal performance tests (TPT) will be carried out to measure the comprehensive thermal conductivity coefficient and heat exchange rate, and then the deformation and stress-strain of a heating or cooling pile at different temperature will be analyzed to explore the influence of thermal stress on pile structure. The thermal stress distribution along the pile will be calculated, and its bearing capability will be analyzed.

Laboratory tests

Geological conditions and thermal parameters of specimens

According to the special geological and hydrological conditions in Tianjin Binhai Lake area, the ground source heat pump air conditioning system is suitable for development and utilization. The geological formation is a marine depositional plain with artificial modification, stratigraphic distribution can be seen from fig. 1, the specimens of soil were drilled every 5 m in depth around the test pile. The thermal conductivity coefficients of the soil ranged from 1.27-2.01 W/m°C, the average value is 1.54 ± 0.27 W/m°C and the average specific heat capacity is 1.34 ± 0.15 kJ/kg°C.

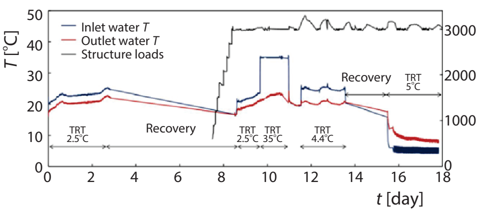

Figure 1. Field tests procedure skeleton

Testing procedures in situ

For the testing system, the heat exchange pipes were set in bored piles with diameters of 700 mm and lengths of 43 m, fixing double-U-shaped heat exchange pipes in the inner side of the reinforcement cage, and sinking the reinforcing cage into the unset concrete with the vibrating rod. The concrete strength grade was C40. Gauges were set in 8 cross-sections (interval distance is 5 m) along the depth of the pile, and each section contained 3 sensors to measure the strain and temperature distribution, which achieved average initial soil temperature is 14.6 °C. The heat exchange capacity (*e. g.* thermal conductivity coefficient, thermal resistance, and specific heat capacity) was measured by thermal transfer performance tests in field, included thermal responding test (TRT) and TPT [10]. The testing procedure is drawn in fig. 1. Structure loads was added on the testing pile, and keep constant at 3000 kN. Firstly, TRT tests were carried out with a heating power of 2.3 kW and 3.65 kW (temperature difference of inlet and outlet water was 2.5 °C and 4.4 °C separately), circulating fluid-flow rate of 0.8 m^3/h, the duration is 68 hours. After a recovery stage for 48 hours, TPT was conducted at an under simulated year-round operating conditions comprising continuous heating for 24 hours (inlet fluid temperature 35 ºC), recovery for 24 hours, cooling for 24 hours (inlet fluid temperature 5 ºC), and further recovery for 24 hours, circulating fluid-flow rate of 0.8 m^3/h. Finally, the ultimate bearing capacity of energy pile and normal piles with ambient temperature were performed to investigate the thermal influence on the pile bearing capacity [11].

Heat transfer performance of testing piles in the field

Field measurements of thermal physical properties are mainly based on TRT and TPT, which allow the direct determination of comprehensive thermal conductivity coefficients and heat exchange capacity, respectively. Thermal response tests keep constant heat power of 2.3 kW, and measurement of inlet and outlet fluid temperature. During the process of TPT, the inlet temperature was increased to 35 ºC for 24 hours, recovered at ambient temperature, and decreased to 5 ºC for 24 hours. Keeping constant inlet temperatures at 35 ºC and 5 ºC, the large difference in heat exchanging power are ΔT = 20.4 ºC in summer and ΔT = 9.6 ºC in winter, respectively. The average heat exchange rate per meter for the heating case is 258 W/m and the cooling case is –76 W/m. For more details of this test, see [12].

Heat transfer performance of testing piles in the field

Structural response of heat exchange pile under with or without loads

Energy piles may be subject to thermal expansion under the effect of temperature load. Due to the restraining effect of rock and soil around pile and building foundation on pile head, such thermal expansion could general additional thermal stress within a pile. Given the actually measured change of pile temperature, ΔT, and strain increment of pile at the corresponding position, $\Delta\varepsilon$, the axial additional thermal stress can be given [13]:

$$\sigma_T = -E(\varepsilon_f - \varepsilon_0) \tag{1}$$

$$\varepsilon_0 = \varepsilon_T - \varepsilon_M \tag{2}$$

where E represents elastic modulus of pile (it is assumed that E does not change with temperature), ε_f – the axial free temperature strain of pile, ε_0 – the strain increment of pile caused by temperature changes, and ε_M – the strain of pile only under upper structural load. When temperature at the place is changed, measured overall strain of pile is ε_T. The pile concrete is 40, the coefficient of thermal expansion is 10 με/°C, and the elastic modulus is E = 32.5 GPa.

Figure 2 indicates the changes of temperature, vertical strain, axial loads and additional thermal stress. After 58 hours of heating, average temperature of pile is increased from 14-16 °C, with temperature change ΔT = 2.5 °C. Pile is expanded, and strain increment is a positive value. Since there is no constraint on pile head, the monitored expansion strain in the middle of pile is high, it closes to free elongation strain on the top. However, the monitored strain at the bottom of pile is low, which means there has a big constraint on axial deformation at the bottom of pile. Therefore, when temperature rises, additional pressure stress induced by thermal at the bottom of pile is high due to axial expansion. Under the constant load on pile head, the temperature of pile is increased by 1.5 °C less than 48 hours of heating. Figure 2(b) is the change curve of pile axial strain along depth, which shows that affected by structural load on pile head, strain on pile head is big, obviously higher than free expanding/shrinking strain caused by temperature change. Figure 2(d) offers additional thermal stress caused by temperature change under the coupled effect of structural and temperature load and profiles of load stress along depth, maximum additional thermal pressure stress in the middle of pile (23 m) is

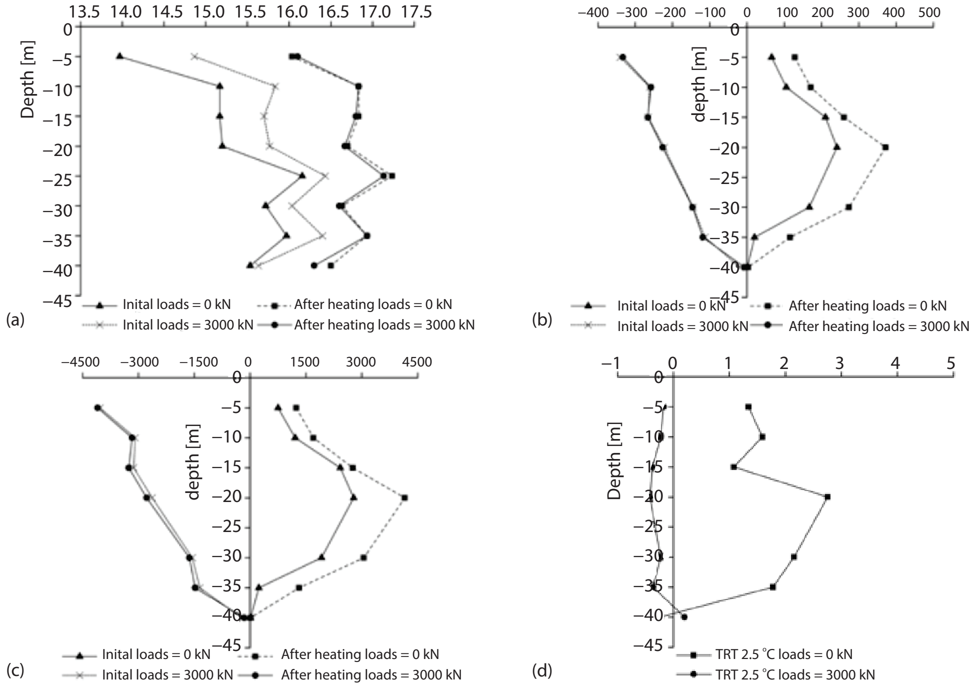

Figure 2. Thermal response test ΔT = 2.5 °C with loads at 300 0kN and without load; (a) temperature [°C], (b) axial strain [µε], (c) axial load [kN], and (d) thermal stress [MPa]

2.9 MPa. Compare thermal response test with temperature difference 2.5 °C with or without loads. It shows structure loads restrict the deformation for the pile seriously, the vertical strain and axial loads become to compress strain from tensile stain due to thermal expansion, and the axial load is largest in the top and reduced to almost zero, exhibiting a typical loading characteristic of a frictional pile. Here, additional thermal stress is calculated along the depth, the lower part exhibits expansion stress due to the heating process, the energy pile with constant loads at 3000 kN also show tensile stress at the lower part after heating.

Effect of heating power on structure response of pile under the constant structure loads

Figure 3 shows the thermal response tests for different temperature differences, 2.5 °C and 4.4 °C, respectively, both sets of tests were carried out under 3000 kN pile top loading conditions. Figure 3(c) shows the changes in the axial loads of the piles before and after the tests, showing the same trend. As the temperature of the pile increases, the pile has a tendency to expand due to heat, but the soil around the pile limits the free expansion of the pile. The limiting effect of the soil on the pile translates into an increase in pile load. The average axial load of TRT 2.5 °C and TRT 4.4 °C increased by 80.9 kN and 92.8 kN, respectively. Figure 3(d) shows the thermal stress generated by the pile heating in the two sets of experiments. Under the heating conditions, the piles have compressive stress due to the increase of temperature. The maximum thermal stress of TRT 4.4 °C appeared at –15 m, reaching –0.5M Pa, and the maximum thermal stress of TRT 2.5 °C appeared at –20 m, reaching –0.42 MPa. With the increase of depth, the thermal stress gradually decreased. At –40 m, TRT 2.5 °C showed a tensile stress of 0.19 MPa at the pile end. It can be considered that the temperature of the pile increases under

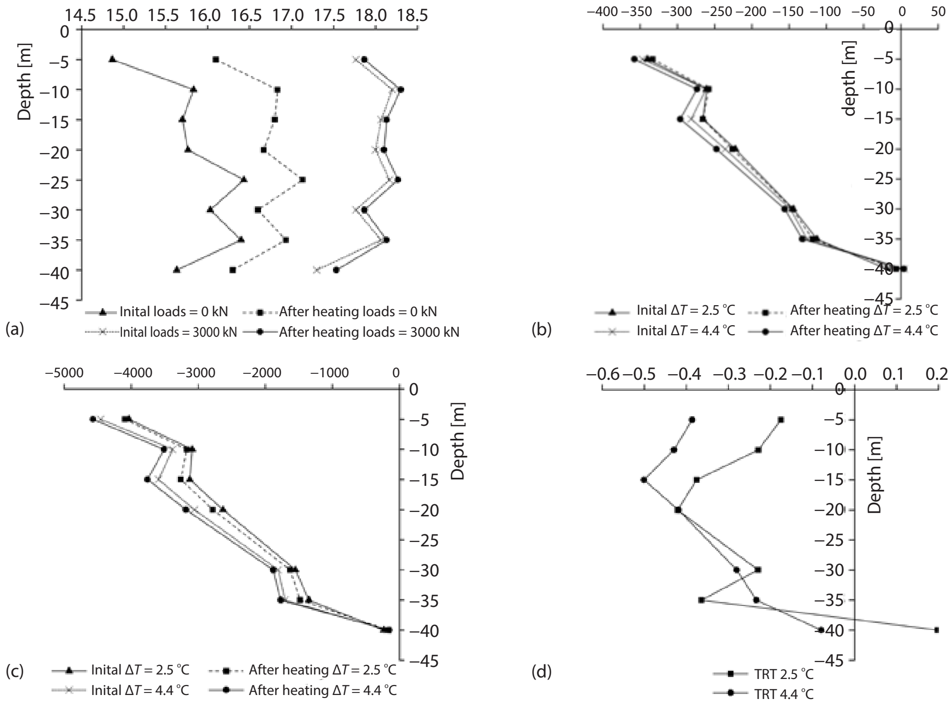

Figure 3. Thermal response test ΔT = 2.5 °C and ΔT = 4.4 °C; (a) temperature [°C], (b) axial strain [με], (c) axial load [kN], and (d) thermal stress [MPa]

heating conditions, which leads to an increase in the axial load of the pile. The pile is mainly subjected to the compressive stress caused by the temperature rise, and the greater the heating power, the more obvious the above-mentioned appearance.

Heating and cooling process influence on structure response of pile under constant structure loads

In the two sets of tests shown in fig. 4, the piles were subjected to a 3000 kN load at the top, showing the temperature, axial strain, axial force and thermal stress along the depth under heating/cooling conditions. Experiments were carried out using a constant inlet water temperature of 35 °C and 5 °C to simulate the operation of energy piles in summer and winter. Figure 4(a) shows that the ranges of temperature change of pile are 2.6-4°C and 1.2-2 °C when the temperature of inlet water is 5 °C and 35 °C, so the range of temperature change of pile is more sensitive to the cooling condition. Figure 4(b) shows the axial strain of the pile under two conditions. The expansion/contraction of the pile occurs under heating and cooling conditions, so positive/negative axial strain increments occur, respectively. The strain increase at the top of the pile is the largest, the strain is reduced by 54 με under cooling conditions, and 20 με is increased under heating conditions. As the depth increases, the axial strain increment gradually decreases, and the strain increment at the bottom of the pile is only about half of the pile top. Under heating conditions, the pile is mainly subjected to additional compressive stress due to temperature. The maximum thermal stress occurs at –35 m, reaching 0.33 MPa. Under cooling conditions, the pile cannot be freely contracted due to restrictions. An additional tensile stress is generated, and the maximum tensile stress also occurs at –35 m, reaching 1.16 MPa.

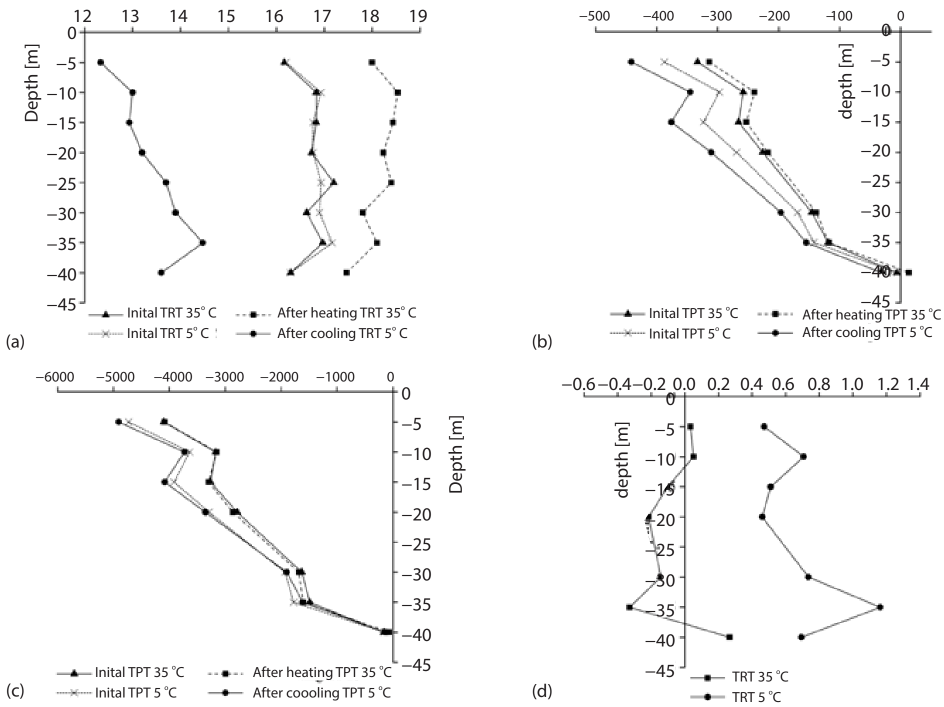

Figure 4. The TPT 35 °C and TPT 5 °C; (a) temperature [°C], (b) axial strain [με], (c) axial load [kN], and (d) thermal stress [MPa]

Comparing the two sets of experiments, it is not difficult to find that the effect of cooling conditions on the pile is usually greater than the heating condition. In particular, cooling conditions can create tensile stresses inside the pile, which will adversely affect concrete with weaker tensile strength. Therefore, special attention should be paid to the stress distribution of energy piles operating in winter.

Heat transfer performance of testing piles in the field

To study the ultimate bearing capacity of piles under different temperatures, slow maintenance load method is adopted in this test. The first loading is up to 2000 kN at 1000 kN step by step. The settlement was measured every 15 minutes after each stage loading. The next stage loading is carried out until the settlement rate at the top of the pile is relatively stable. Then the unloading is carried out and reduced to zero, the residual settlement is measured, the loads maintain 3 hours. Finally, Q-s curves are achieved to represent the load value *vs*. settlement in steps. For the Q-s curve of the slowly varying type, the load value corresponding to s = 40 mm can be determined according to the settlement. For pile longer than 40 m, the elastic compression of the pile body should be taken into account, for the pile whose diameter is greater than or equal to 800 mm, the load value corresponding to s = 0.05 D (D is the diameter of the pile end) can be taken. However, when the bearing capacity does not reach the limit, the ultimate bearing capacity is taken as the maximum test load.

For the energy pile, except for the first load of 2000 kN, the rest loaded 1000 kN at each step. During the process of maintaining load, the settlement rate reaches the relative stability standard. When the load is loaded step by step until the final control load is 13000 kN,

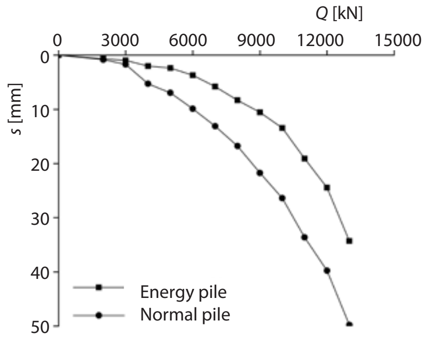

Figure 5. The Q-S curve of energy pile and testing pile with ambient temperature

the maximum settlement is 34.28 mm, and the total settlement is less than 40 mm. The maximum loading capacity reached the design requirements. Therefore, the ultimate bearing capacity of the energy pile is not less than 13000 kN. For the test pile with ambient temperature, the loading progress is the same with the energy pile. When the load is increased gradually to 13000 kN, the cumulative settlement is 49.78 mm, and the total settlement is more than 40 mm, so the loading is terminated. The Q-s curves show obvious changes in downward bending and slope when loading to 13000 kN. The total settlement has exceeded 40 mm. According to the design requirement, the measured ultimate bearing capacity of the pile is 12000 kN. It indicates the energy pile after heating has less impact on the ultimate bearing capacity.

Conclusion

The field experiments are systematically carried out by using engineering test pile as energy pile, the comprehensive thermal conductivity of surrounding soils and heat exchange rate of each pile were achieved by thermal performance tests. Under the coupling influence of structure and thermal loads, the deformation of energy pile is mainly affected by the structure loads. The constraint effect is more pronounced on the pile top, and the tension deformation can be found in the end of a pile. In the heating and cooling conditions, the thermal stress generated by the cooling process has a greater impact on the pile, the maximum tensile stress reaching 1.16 MPa. So, more attention needs to be paid to the stress distribution of the energy pile during winter operation. The energy pile after heating have less impact on the ultimate bearing capacity, however, the thermal induce pile expand cannot be ignored, which induced the irregular settlement of the foundation.

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Nomenclature

ε_f – axial free temperature strain of pile, [–]
ε_M – strain only under upper structural load, [–]
ε_0 – strain increment caused by temperature, [–]
ε_T – measured overall strain of pile, [–]

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