Energy Piles

Subjects: Energy & Fuels | Engineering, Civil | Construction & Building Technology

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Energy piles are a relatively new technology that have dual function as heat transferring and load bearing. Due to the influence of temperature cycles, additional thermal stress and relative displacement of the pile will be generated; this is different from the load transferring mechanism of the conventional pile. In order to study the thermodynamic characteristics of the energy pipe pile under dual working conditions and temperature cycles, field tests were carried out on the PHC (prestressed high-strength concrete) energy pipe pile without constraining on the top of the piles. Displacement gauges were arranged on the top of the pile, and concrete strain gauges (temperature, strain) were embedded in the pile.

energy piles | thermo-mechanical behavior | pile top displacement | thermal stress

1. Introduction

Energy piles are a relatively new technique of building that are energy saving, have an economic benefit, and environment-friendly advantages. The ground source heat pump heat exchange tubes are embedded in the pile foundations of traditional buildings to provide heat exchange and cooling for the upper building space. Compared with traditional ground source heat pump systems, it can take full use of the larger thermal conductivity of concrete and the contact area with the surrounding soil to improve heat exchange efficiency and save underground space resources, and it has been implemented in many countries [1][2][3][4].

The energy pile plays the dual role of heat exchanging with the surrounding soil and bearing the load of the superstructure. At present, researchers mainly focus on heat transferring efficiency and mechanical property. Many previous studies only focused on underground thermal energy utilization and heat transferring efficiency of the heat pump system, but studying the mechanical performance of the energy pile under the impact of varying temperatures is limited. Some investigations of the field energy pile have been conducted while subjecting it to monotonic heating or cooling [5][6][7][8][9][10][11][12][13][14][15][16][17]. Laloui et al. [5] conducted a field test on a cast-in-place energy pile located in the Lausanne Institute of Technology; it was found that its average temperature was raised by 1 °C, generating an additional axial force of 100 kN. Similarly, Bourne-Webb et al. [6] found the ultimate lateral resistance was 75 Kpa under the impact of temperature cycling, which was slightly lower than the average ultimate lateral resistance of the London clay, of 90 Kpa. Murphy et al. [8] found that when the pile temperature increased by 18 °C, the maximum compressive stress was 4.0~5.1 MPa, which is about 25% of the compressive strength of concrete. Sung et al. [13] conducted an in-situ thermal response test on the cast-in-place pile, with the pile top on the gneiss; when the pile body was heated, the maximum temperature compressive stress was about 2.6 MPa, which is 10% of the design value of the concrete compressive strength. Murphy and McCartney [10] have numerically investigated seasonal temperature variation, and it was observed that the mobilized side shear stresses nonlinearly change with the depth; the magnitudes of thermomechanical axial stresses were observed to increase most greatly near the toe of both foundations while being heated. Fewer field-scale evaluations on radial thermal reactions of energy pile were conducted [11][14][15]. It is found that the axial strain of the pile is smaller than the radial strain when the pile body expands or contracts. The radial thermal strain is close to those corresponding to free thermal expansion/contraction, indicating that the soil can provide minimal resistance to radial thermal expansion/contraction [14].

However, the field test is always restricted by site condition, there are many uncontrollable factors, and the test period is long; so, the model test becomes a more effective method for energy pile research. Through the centrifuge test on the energy pile in the sand, Ng et al. [18][19][20] analyzed the thermal response of the energy pile under multiple temperature cycles and the development of the displacement of the pile top. The results showed that the side friction resistance of the soil around the pile changed under the action of heating and cooling cycles. By conducting indoor model tests, Yavari et al. [21] investigated the cumulative effect of the displacement of the energy pile top in saturated clay under the action of temperature cycling, and analyzed the effect of pile top load on the cumulative effect of pile top displacement; Goode et al. [22] studied the cumulative effect of pile top displacement and the influence of partial restraint on the thermodynamic characteristics of the energy pile under the impact of temperature cycling.

When the pile is heated or cooled, the contact between the soil and the pile will change, which leads to a change in the pile–soil load transferring mechanism [23][24][25][26]. It was found that the soli–concrete interface was affected by cyclic degradation, but not affected directly by temperature. Conversely, the response of the clay–concrete interface changed at different temperatures, showing an increase in strength with increasing temperature [23]. Although some scholars use the load transfer method to analyze the pile–soil load transfer, this mechanism cannot be completely understood [27][28][29][30]. Guo et al. [27], based on the ideal elastoplastic model and the hyperbolic model, proposed a new pile–soil load transfer model, considering Masing’s rule.

At present, the experimental research of energy pile is mainly focused on the cast-in-place pile in the summer, and nearly without in-situ experimental researches on the PHC energy pile under dual working conditions and temperature cycling conditions. The PHC pipe pile has the characteristics of convenient construction, low cost, strong ability to penetrate the soil, and wide applications. It can be applied to the foundation treatment, industrial workshops, and multi-story and high-rise buildings.

2. Experimental Study of Thermal Response of Vertically Loaded Energy Pipe Pile

Based on the in situ thermal response test of the PHC energy pile, the variation in temperature and thermal stress were monitored and analyzed, and the following conclusions can be drawn:

(1) During the operation of the PHC energy pile in the summer and winter, the temperature of the pile gradually changed. The temperature in the initial stage changed rapidly; as the test progressed, the temperature increment gradually decreased. In short, the temperature was low at the two ends and high in the middle;

(2) Under both the summer and winter conditions, the thermal stress gradually increased with the pile's temperature, due to the joint constraints of the soil around the pile and the soil at the pile top; the thermal stress was small at both ends and large in the middle, and this is probably because the pile top is located at the dense sand layer and the restraint rigidity is relatively large. At the end of the summer test, the maximum compressive stress at 8 m of the pile was 3.446 MPa; in the winter, the maximum tensile stress at 8 m of the pile was 2.69 MPa. The thermal stress has a linear relationship with the temperature increment. The relationship between the maximum compressive stress and the temperature difference is $\sigma T=0.216\Delta T$; the relationship between the maximum temperature tensile stress and the temperature difference is $\sigma T=0.3\Delta T$. The results showed that the temperature stress generated under the dual temperature cycle conditions would not affect the safety of the pile foundation and the superstructure;

(3) The pile is constrained by the soil around during the temperature cycle and cannot be deformed freely, leading to side friction resistance. In the summer, the soil around the upper part of the pile produced negative side friction resistance, and the soil around the lower part of the pile produced positive side friction resistance; the situation is the opposite in the winter. The neutral point is about 10.75 m away from the pile top, and it did not move during the whole test, indicating that the neutral point of the pile is close to the end of the pile with a higher degree of restraint. The side friction resistance of the pile increased with the increase in the temperature difference and increased along with the neutral point to the two ends of the pile, and the absolute value of the soil friction resistance of the upper part of the pile was larger than the that of the lower part. Under the winter condition, the side friction resistance degraded from 4.5 to 11.5 m during the test. In addition, the results show that the position of the neutral point of the pile is affected by the pile end restraint condition, and it is always close to the end of the pile with stronger restraint;

(4) During the test, the displacement of the pile top and other measuring points had been increasing, and the displacement of the point above the neutral point was greater than the displacement of the point below the neutral point. The test results show that at the end of the summer test, the displacement of the pile top was 0.7 mm, about 0.175%D. In the winter, as the temperature of the pile gradually decreased, the displacement of the pile top gradually increased. At the end of the test, the displacement of pile top gradually increased, and the maximum displacement was 0.4 mm, about 0.1%D.

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