Model test on bearing capacity characteristics of energy piles in saturated clay

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Abstract. Based on model tests, the load transfer mechanism of energy piles in saturated clay was studied, and the variation rules of pile and soil temperature, pile tip displacement, pile tip resistance, pile stress and lateral friction resistance were analyzed. The results show that the pile temperature decreases from top to bottom while the soil temperature decreases from the pile center to the radial direction. Under zero load, the pile expands by heat, and the pile top has a large upward displacement. Thermal consolidation of soil, settlement of soil surface and negative lateral friction occur under the alternating action of cooling and heating loads. Under working load, after applying cooling and heating load, the pile will produce unrecoverable accumulative settlement.

1. The introduction
Energy pile as a new type of buried pipe technology of pile foundation, the heat exchange pipe is directly placed in the concrete pile foundation of the building. Ground source heat pump technology is combined with building pile foundation to form energy pile. Energy pile can not only bear the load of the upper building, but also play the role of ground source heat pump heat exchanger. The energy pile technology was first proposed in the 1980s, and was soon popularized and applied in Austria, Germany, Japan and Switzerland[1-2].

In recent years, relevant scholars have carried out a series of studies on the thermal-mechanical properties of energy piles and achieved certain results. Gui S Q et al.[3] simulated actual engineering and studied the structural response of pile under thermal-mechanical action, and concluded that additional stress was generated at different temperatures while pile top settlement decreased during heating and increased during cooling; Huang Xu et al. [4] studied the bearing capacity and load transfer characteristics of PCC energy pile in saturated sand under the condition of alternate cooling and heating cycles, and analyzed the variation of soil temperature field around the pile; C Knellwolf et al.[5] put forward the design method of heat exchange pile by adding temperature strain into load transfer method, but did not consider the influence of temperature on soil around pile; Ehn Gashti et al.[6] studied the structure and geotechnical resistance of composite energy pile foundation by finite element numerical simulation, and reached the conclusion that additional compressive stress would be generated while colling; N Yavari et al.[7] used model piles to study the mechanical properties of energy piles in saturated clay under thermal-mechanical action, and reached the conclusion that piles would produce irreversible settlement after multiple thermal cycles; Stewart and McCartney[8] studied...
the interaction mechanism of the pile-soil interface of end-bearing energy piles in silty clay, and the results showed that the pile top would have a downward displacement in the continuous temperature cycle; based on the indoor model test method, Wang C L et al. [9] studied the pile bearing characteristics and heat transfer characteristics under thermal-mechanical coupling in saturated sand, and reached the conclusion that pile top settlement accumulates with the increase of temperature cycles; Kong G Q et al. [10], based on model test method, studied pile top displacement during multiple cooling and heating cycles and found that multiple temperature cycles would lead to continuous accumulation of pile settlement.

In this paper, the bearing capacity characteristics of energy pile in saturated clay were studied by model test. Under the condition of zero and working load, the temperature and displacement of energy pile and soil around the pile were compared and analyzed, in addition, the variation rules of pile tip resistance, pile stress and side friction resistance were explored.

2.  Model test overview
The model groove used for energy pile test is a 550mm diameter cylinder enclosed by acrylic plate and the soil height in the groove is H=500mm. The soil used in this test is pure clay, and the clay is yellowish brown and plastic. Based on the conventional physical and mechanical experiments of clay soil, the water content of saturated clay is 39%, the liquid limit is 41.88%, the plastic limit is 22.25%, the liquid index and plastic index are 0.37 and 19.6 respectively, and the soil compression modulus is 5.53 MPa. Length of model pile is L=500mm, diameter D=84mm, and the concrete strength grade is C30. The sensor layout of the model groove is shown in figure 1.

The tests are divided into temperature cycle test under zero load and working load. Through temperature cycle test, the bearing capacity and displacement characteristics of energy pile under different temperature loads of cooling and heating are analyzed. The temperature cycle was set as 5℃→70℃→5℃, and the changes of pile top displacement, pile stress, pile tip earth pressure and soil temperature under different temperature loads were recorded during the test.

3.  Test results and analysis
3.1.  Temperature variation rule of pile and soil under different working conditions
Temperature sensors on the horizontal plane 200mm below the soil surface and the vertical surface 42mm from the center line of the pile were taken to draw the curve of soil temperature along the radial and vertical directions with time. The curve of temperature of pile and soil over time is shown in figure 2. Figure 2(a) and (b) represent vertical and radial, respectively. In the process of heating, the pile heating rate slows down obviously after reaching the target temperature for 8h, and the pile temperature tends to be stable. The maximum temperatures at the measured points T1, T5 and T9 are
38.6°C, 34.6°C and 24.9°C, respectively. The temperature decreases with the increase of pile depth. Due to the thermal resistance of the soil, the soil temperature decreases with the increase of the radial distance, and the temperature fluctuation at T8 is basically unchanged. For the measuring point with greater depth and farther away from the pile, the temperature drop is lagging behind. For example, the temperature of the measuring point T7 begins to drop around 26h, while the temperature of T5 decreases immediately after it begins to drop at the 24th hour.

3.2. Displacement at pile top and soil surface

3.2.1. Displacement at pile top
The displacement distribution rule of pile top under zero load and working load is shown in figure 3. The pile expands due to heating, upward displacement occurred at the pile top. But the working load has a great influence on the pile top displacement. The pile shrinks while cooling, the horizontal earth pressure between the pile and the soil decreases, and the pile is prone to large settlement under the working load. While heating, the working load limits the upward displacement of pile top to a certain extent, and while cooling, the working load will cause a large settlement, and the settlement deformation can not be recovered.

3.2.2. Displacement at the soil surface
Time history curve of vertical displacement of soil surface is shown in figure 4. In the heating process, the soil at B3 and B4 shows a settlement trend due to the thermal consolidation phenomenon, and the settlement rate is small. The settlement rate increases rapidly after the beginning of cooling and gradually decreases after 4 hours. Considering that the dissipation of excess pore water pressure increases the degree of soil consolidation. At B5, due to the soil squeezing effect caused by the pile expansion during heating, the soil surface presents the phenomenon of uplift, and the pile shrinks during cooling, The downward trend is the same as that at B3 and B4.
3.3. Change of soil pressure at pile tip

The variation rule of soil pressure at pile tip under temperature load during a single temperature cycle is shown in figure 5. The change of pile tip resistance is manifested as the change of pile tip earth pressure. Under the zero load, the pile expands while heating, and the soil pressure at the pile tip increases, while the pile shrinks while cooling, and the soil pressure at the pile tip decreases gradually. Under the working load, the soil pressure increases first and then decreases when the pile is heated. While cooling, the soil pressure at pile tip decreases first and then increases. Under zero load and working load, the change trend of pile tip soil pressure is different. It is considered that the pile settlement is larger under the combined action of working load and cooling load, and the resistance of pile tip increases at the end of cooling.
### 3.4. Distribution rule of pile stress and pile lateral friction resistance

#### 3.4.1. Distribution rule of pile stress

The distribution curve of pile stress along the depth is shown in figure 6. \( Z \) represents the depth below the soil surface, \( L \) represents the effective length of the model pile in the soil, and \( Z/L=0 \) refers to the soil surface. When the expansion and contraction of pile are constrained, additional axial stress will be generated in the pile. At this point, the actual thermal strain of the pile \( \varepsilon_T \) is less than the free strain \( \varepsilon_{T,free} \), which causes thermal stress \( \sigma_T \) to occur:

\[
\sigma_T = E (\varepsilon_T - \alpha_c \Delta T)
\]  

(1)

In the formula, \( E \) expresses the elastic modulus of concrete, \( \alpha_c \) expresses the linear expansion coefficient of concrete, \( \Delta T \) expresses the temperature change. It is defined that the compressive stress produced by the pile is negative and the tensile stress is positive.

As shown in figure 6 (a), under zero load, after heating, compressive stress is produced in the pile due to the constraint by the soil around the pile, which increases with the increase of depth. The thermal stress near the bottom of the pile reaches the maximum, which indicates that the zero point of displacement is also near the bottom of the pile. During cooling, the stress to prevent shrinkage is generated inside the pile, and the stress increases first and then decreases along the depth. Due to the small constraint at the pile tip, the stress is larger near the middle part of the pile.

As shown in figure 6 (b), under working load, the thermal stress of the pile near the middle part of the pile is the largest, and the zero point of displacement moves up to the middle part of the pile due to the constraint of the pile top.

![Figure 6 Distribution of pile stress along depth](image)

#### 3.4.2. Distribution rule of pile’s lateral friction resistance

Under the temperature load, due to the difference of thermal expansion coefficient between pile and soil, the pile-soil contact surface will produce relative displacement, which leads to the change of pile lateral friction resistance. The calculation formula of pile lateral friction \( f_{s,mo},j \) at different depths is as follows:
\[ f_{s, \text{mob}, j} = \left( \sigma_{T,j} - \sigma_{T,j-1} \right) D / 4 \Delta l \]  \hspace{1cm} (2)

In the formula, \( D \) expresses the diameter of the pile, \( \Delta l \) expresses the spacing of adjacent strain gauges, and \( j = 1,2,3,4 \) expresses the number of strain gauges from the soil surface to the pile bottom. The lateral friction resistance is defined as positive upward and negative downward.

As can be seen from figure 7, when the pile is heated, its two ends move upward and downward respectively. Negative lateral friction resistance is produced at the upper part of the pile, while positive lateral friction resistance is produced at the lower part. Under zero load, the zero point of displacement is lower than the center of the pile, while the zero point of displacement moves to the upper position of the center of the pile under the working load. While cooling, the upper lateral friction resistance of the pile is positive, and the lower lateral friction resistance is negative. The total lateral friction resistance of the pile under working load is larger than that under zero load, which to some extent confirms the difference in the change rule of pile tip resistance. Under zero load, regardless of heating or cooling, the value of lateral friction near the pile tip is smaller than that of the upper part of the pile, which is considered that the relative displacement between pile and soil is small due to the restraint of pile tip soil.

![Figure 7 Pile lateral friction distribution along depth](image)

4. Conclusion

Based on the model test of bearing capacity characteristics of energy piles in saturated clay, the temperature, displacement and bearing capacity of pile foundation were obtained and analyzed, and the following conclusions were drawn:

(1) During the temperature cycle, the temperature of the pile and the soil around the pile changes obviously. While heating, the temperature of the upper part of the pile is higher and decreases with depth, and the soil temperature decreases with the increase of radial distance. In the cooling stage, the greater the depth and the farther the distance from the pile, the temperature change is lagging behind.

(2) While heating and cooling, upward displacement and settling displacement occurred respectively. Under zero load, the pile expands at the heating stage, larger upward displacement occurred at the pile top. Working load will limit the expansion displacement of pile top and further aggravate the settlement of pile while cooling. Thermal consolidation occurred in the soil due to the alternating cooling and heating loads, and sinking phenomenon appeared on the soil surface.

(3) The soil pressure at the pile tip increases while heating and decreases while cooling. The variation trend of soil pressure at the pile tip under zero load is significantly different from that under working load. The change rule of pile lateral friction under the influence of temperature is basically...
the same. While heating, the negative lateral friction occurred at the upper part of the pile, the positive lateral friction occurred at the lower part, however, it is just the opposite while cooling.

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