Construction and application of a PCC energy pile model test system

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Abstract: PCC energy piles represent a new type of energy pile technology. At present, research on the bearing characteristics of PCC energy piles is relatively limited. This study designs and builds a PCC energy pile model test system, including a model pile, optical fiber sensors, and heat transfer, loading, and data acquisition devices. The system is used to study the bearing characteristics of PCC energy piles under different temperatures. Results show that the temperature of the pile is transferred to the soil along the radial direction under the action of a circulating temperature and the moisture in the soil around the pile migrates along the direction of heat transfer. The migration speed increases when the temperature gradient is large. At the end of circulation, the displacement of the pile top increases by 0.6% D, the resistance at the pile end increases by 1.28 times, and the maximum strain point of the pile body is 70%L from the pile top. The PCC energy pile test system proposed in this work is feasible and applicable.

Key words: PCC energy pile; single pile; model test; bearing characteristics; temperature effect;

1 Introduction

Energy pile technology combines the advantages of ground source heat pump technology and building pile foundation technology to produce numerous economic, environmental, and social benefits [1-3]. Scholars at home and abroad have conducted numerous studies on energy pile technology. Kong G Q et al. [4], for example, conducted research on the heat transfer and bearing characteristics of embedded steel pipe single U-shaped energy piles under multiple cooling/heating cycles with a working load. Liu H L et al. [5] studied the thermodynamic effect and bearing characteristics of energy piles under different degrees of compaction. Research results showed that, when heated, the soil around the pile experiences increases in horizontal earth pressure, a pressure stress is generated inside the pile body, and the pile top is displaced upward. Moreover, as the temperature increases, the degree of compaction, horizontal earth pressure around the pile, and stress of the pile body increase, whereas the displacement of the pile top decreases. Gui S Q et al. [6] conducted field tests of energy piles. Wang C L et al. [7] studied and analyzed the displacement and thermal stress of two types of buried pipe forms (i.e., single U and W type) under different constraint conditions of the pile top and bottom. Peng et al. [8] studied the thermomechanical characteristics of friction-type energy pile groups in dry sand under the action of temperature by conducting a model test; the group then analyzed the vertical displacement of energy pile groups and the thermal stress distribution of the piles under the conditions of partial and full energy pile heating. Fei K et al. [9] studied the mechanical characteristics of a single energy pile in a normal consolidated clay foundation considering different working load levels of the pile top and analyzed the influence of temperature cycle on the top settlement, side friction, and axial force of the pile. Using the numerical simulation method, Olgun [10], Abdelaziz [11], Caulk [12], and Hao Y H [13] studied the radial expansion behavior of single energy piles, the change in normal stress on the contact surface of the pile and soil, the nonuniform distribution of stress and strain in energy piles under the action of temperature, and the influence of different constraint elements on the thermodynamic responses of single energy piles. Most theoretical methods are based on the load transfer method, which combines different thermal models to obtain a calculation method of the bearing characteristics of single energy piles [14]. Gao et al. [15] applied Brillouin optical frequency domain analysis technology (BOFDA) to measure the...
temperature of PCC energy piles and found that this technology could effectively monitor the temperature of the piles under different working conditions. Thus, the group provided a new means for monitoring the thermodynamic characteristics of PCC energy piles. Huang X et al. [16-17] studied the thermodynamic characteristics of PCC energy piles under the action of cyclic temperature fields on the basis of a model test and numerical simulation method. The authors showed that the thermal stress of the pile is greatly affected by the temperature, and its change value differs under different constraint conditions; in particular, the pile bottom produces a large tensile stress under the refrigeration cycle.

At present, research on the bearing characteristics of PCC energy pile is relatively scarce. This work designs and builds a PCC energy pile model test system that includes a heat transfer module, a loading module, and a data acquisition module to study the bearing characteristics of PCC energy piles under different working conditions. A model test of a PCC energy pile is conducted using the developed test system to understand the distribution characteristics of soil temperature and moisture field around PCC energy piles under the action of temperature. The change law of these characteristics is then established.

2 Construction of the model test system

The model trough measures 2.65 m in length, 2.00 m in width, and 2.30 m in height and is made of C30 concrete. The vertical steel column and model groove are poured as a whole, and the middle cross bar is connected to the steel column with high-strength bolts; together, these structures make up the reaction device of the model groove.

The actual fabrication and embedding of the model pile were realized according to the size of the model groove and reducing boundary effects. The pile diameter D of the model pile is 0.11 m, the design model pile length L is 1.65 m, and the model pile wall thickness is 0.03 m. The upper part of the pile is located 0.1 m above the soil surface. The model piles are arranged in a square plane, the distance between adjacent pile axes is 0.55 m, and the minimum distance between the pile axis and the inner wall of the model groove is 0.725 m. The layout of the model piles is shown in Figure 1.

![Figure 1. Layout of the model piles.](image)

The test system adopts two types of soil to simulate the soil layer of the PCC energy pile in practical engineering. The soil layer distribution is shown in Figure 2. The clay layer is 0.85-m thick, and the sand layer is 1.35-m thick. The clay is filled in layers and compacted manually every 0.20 m. Sand is filled via the sand rain method, and the dropping distance of the funnel is controlled to 0.40 m to ensure the uniformity of sand filling. The physical and mechanical parameters of the soil are given in Table 1.
### Table 1. Physical and mechanical parameters of soil.

| Parameter                     | Value |
|-------------------------------|-------|
| **Clay**                      |       |
| Density, $\rho$/(kg/m³)       | 1.93  |
| Elastic modulus, $E$/(MPa)    | 24    |
| Poisson's ratio, $\nu$        | 0.3   |
| Cohesion, $c$/(kPa)           | 28.6  |
| Internal friction angle, $\phi$/(°) | 23.1  |
| **Sandy soil**                |       |
| Density, $\rho$/(kg/m³)       | 1.70  |
| Elastic modulus, $E$/(MPa)    | 15    |
| Poisson's ratio, $\nu$        | 0.3   |
| Internal friction angle, $\phi$/(°) | 29.7  |

Figure 2. Schematic of the soil layer distribution (unit: m).

The PCC energy pile model is prefabricated via the mold casting method, and the mold is shown in Figure 3. The mold used in the test system includes two concentric PVC pipes. The inner diameter of the larger PVC pipe is 11 cm, its wall thickness is 2 mm, and its length is 170 cm. The outer diameter of the smaller PVC pipe is 5 cm, its wall thickness is 1 mm, and its length is 200 cm. A layer of fresh-keeping film is wrapped around the smaller PVC pipe to facilitate the removal of the mold, and the mold is installed after the application of a release agent. The bottom of the internal and external molds is fixed with a ring-shaped white heat preservation plate with a thickness of 5 cm (Figure 3 (a)). This preservation plate can effectively prevent the leakage of bottom concrete while maintaining a fixed distance between the internal and external molds. At the top of the mold, the spacing between the internal and external molds with three insulation boards of the same size is fixed (Figure 3 (b)) to maintain the wall thickness of the model pile and facilitate subsequent concrete pouring. The bottom of the mold is placed in a 30-cm-high protective tube, and the space between this tube and the mold is filled with sand. Concrete blocks are established around the protective tube to keep it stable, prevent the model pile from shaking during pouring, and maintain pile quality.

Figure 3. Pile-making mold: (a) Bottom of mold; (b) Top of mold.

The model pile is made of C30 concrete with the corresponding mixture proportion: water:cement:sand:stone = 0.47:1:1.342:3.129. The pouring process of the model is as follows. The aggregate was weighed according to the designed mixture proportion and then evenly mixed with water. The concrete was subsequently poured and vibrated to improve its compaction. In this work, the model pile was vibrated by knocking the external mold with a rubber hammer. The model pile was formed and allowed to stand for 5 hours. Thereafter, the internal formwork was removed and rotated once every 20 minutes. The concrete was cured for the desired length of time. Elastic lines were made on the surface of the external mold with ink cartridges, and the mold was cut along these lines. The external mold was completely removed and the required PCC energy pile model was obtained, as shown in Figure 4.
Figure 4. PCC energy pile model.

Four FBG sensors are arranged on the surface of each pile to monitor the strain of the PCC energy pile. The arrangement process of the FBG sensors is shown in Figure 5. First, a cutter is used for slotting along the cutting mark left on the surface of the pile during the removal of the outer formwork (Figure 5(a)). During slotting, the depth of the slot is controlled to 2–3 mm. After slotting, a blower is used to clean the slot. The sensor is laid, and quick-drying glue is used to fix this sensor on both sides (Figure 5(b)). The transmission fiber is spread along the pile, and quick-drying glue is used to fix it at a distance (Figure 5(c)). The model pile can be moved after the glue is completely dried (Figure 5(d)). After encapsulation of the FBG sensor on the pile surface, the bare fiber exposed to the pile head is protected with a special casing and the optical fiber is coiled and bound to prevent damage during the test.

Figure 5. Fiber Bragg grating sensor layout process: (a) Slotting; (b) Point adhesion; (c) Full adhesion; (d) Solidification.

Figure 6 shows a schematic of the fiber Bragg grating sensors on the surface of pile 1. F1 is installed 15 cm from the pile top, F4 is installed 15 cm from the pile end, and the interval between the four sensors is 45 cm. The layout of the three other piles is identical to that of pile 1.
The pile end resistance is monitored using micro strain-type earth pressure gauges suitable for the model test. The arrangement of the earth pressure gauges is shown in Figure 7. The small PVC pipe embedded in the soil in the figure is the positioning device of the model pile. One earth pressure gauge is placed on both sides of the PVC pipe, and two earth pressure gauges are placed at the bottom of each pile to prevent movement and displacement during pile embedment.

The distribution characteristics of soil temperature and moisture field around the PCC energy pile are analyzed. To this end, temperature sensors are arranged along the axial and radial direction of the pile to monitor changes in soil temperature around the pile, and moisture sensors are arranged in the upper clay to monitor the migration of soil moisture during the temperature cycle. The layout of the temperature and moisture sensors is shown in Figure 8. The axial spacing of the temperature sensors is identical to that of the fiber grating sensors, and the moisture sensors are arranged only in the clay layer.
Figure 8. Schematic of the temperature and moisture sensor layout: (a) Front view; (b) Vertical view (unit: cm).

The displacement meter is fixed to the counterforce frame through the magnetic seat, and the end of the displacement meter is in contact with the load on the pile top, as shown in Figure 9. The opposite end of the sensor is connected to the static strain acquisition instrument, the sensor mode is selected via the acquisition instrument, and the relevant parameters are inputted.

Figure 9. Layout of the displacement meter.

The temperature effect is achieved by the heat transfer module, which is mainly composed of a constant-temperature water bath, water pump, heat conducting liquid, and heat conducting pipe, as shown in Figure 10. The heat conducting liquid used in this test is pure water, and the heat conducting pipe is a plastic hose with an outer diameter of 10 mm and an inner diameter of 8 mm. The constant-temperature water bath is used to control the circulating water temperature, and the water pump is used to provide the water circulation and control the flow rate. Because of the limitation of the inner diameter of the model pile, a single U-type heat source is used in this test.

Figure 10. Heat transfer module: (a) Heat pipe arrangement; (b) Water pump; (c) Heat pipe arrangement.
The load is realized by the loading module. Because the upper space of the model groove is limited, the mechanical loading method is selected. The composition of the loading module is shown in Figure 11. An I-shaped steel is placed horizontally on the upper part of the model groove as the reaction device of the jack to apply the load to the center of the pile group.

![Figure 11](image)

A static strain tester is used to collect data from the earth pressure gauge, displacement gauge, and pressure sensor. Soil moisture monitoring stations are mainly used to monitor soil temperature and moisture. An FBG demodulator is used to obtain the FBG data. Data of the earth pressure gauge, displacement gauge, and pressure sensor are automatically acquired. The collection frequency of static strain tester is set to once per 1 second to collect a large amount of test data. The soil temperature and moisture are automatically read by the software, and the acquisition frequency is controlled to once every 2 hours according to the test process. The data of FBG demodulator are read and recorded manually, and the acquisition frequency is once every 2 hours.

3 Model test of the PCC energy pile

A model test of the PCC energy pile under the action of temperature is conducted using the fabricated pile test system, and the bearing characteristics of the energy pile are analyzed. The specific operation of the test is as follows: the temperature cycle of pile 2 is conducted, the cycle temperature is 40 °C, and the cycle time is 8 h. During circulation, the soil temperature and moisture around the pile, the displacement of the pile top, the strain of the pile body, and the resistance of the pile end are monitored.

Figure 12 shows the change in temperature at measurement points T₁, T₂, and T₃ as a function of time. T₁, T₂, and T₃ are arranged 150 cm from the pile top and D, 2D, and 3D, respectively, from the central axis of pile 2. As the cycle time increases, the temperatures of T₁, T₂, and T₃ gradually increase, thereby indicating that the temperature of the energy pile has obvious time effects when transferred to the soil. Before the cycle is not stable, the soil temperature increases with increasing cycle time. The temperature of T₁ increases by 0.3 °C in the period of 0–2 hours and 0.2 °C in the period 6–8 hours. These findings demonstrate that the heat transfer efficiency of the energy pile decreases gradually with the circulation because the temperature difference between the pile and the soil decreases gradually with increasing soil temperature, thereby resulting in slow temperature transfer. The temperature of T₃ does not change over the first four hours of the cycle but begins to rise at approximately 6 hours. This result shows that the influence range of the energy pile on the soil is related to the cycle time. Specifically, the longer the cycle time, the greater the influence range. At the end of the cycle, the T₁ temperature increases by 0.7 °C, the T₂ temperature increases by 0.2 °C, and the T₃ temperature increases by 0.1 °C. Differences in temperature increments may be attributed to differences in the distance between the three points and the pile. As the distance between the measurement point and the pile increases, the impact of the pile on the soil temperature gradually decreases.
Figure 12. Changes in soil temperature with time along the radial direction.
Figure 13 shows the change in soil temperature around the pile as a function of depth. Here the temperature at the measurement point at the end of the cycle is selected, the 1D curve shows the temperature data of measurement points T₁, T₇, and T₁₀ (distance from the central axis of pile 2 is D), the 2D curve shows the temperature data of measurement points T₂, T₈, and T₁₁ (distance from the central axis of pile 2 is 2D), and the 3D curve shows the temperature data of measurement points T₃, T₉, and T₁₂ (distance from the central axis of pile 2 is 3D). Because the temperatures of T₁₆, T₁₇, and T₁₈ are greatly affected by the environment and, thus, cannot reflect the real temperature distribution and change characteristics of the soil, the data of these measurement points are not included in the figure. Figure 13 reveals that the temperature variation of the soil at different distances from the pile is consistent, and the curve shape is large in the middle and small at both ends. The highest temperature measured by the test system occurs at a depth of 95 cm or 70% L from the pile top.

Figure 13. Changes in soil temperature with time along the axial direction.
Figure 14 shows the change in moisture at measurement points H₁–H₄ as a function of time. H₁, H₂, H₃, and H₄ are arranged 80 cm from the top of the pile and D, 2D, 3D, and 4D, respectively, from the central axis of pile 2. As the cycle time increases, the moisture of H₁, H₂, H₃, and H₄ gradually decreases, thereby indicating that the decrease in soil moisture around the energy pile has obvious time effects. Specifically, the longer the cycle time, the greater the decrease in soil moisture. The moisture of H₁ decreases by 2.5% m³/m³ over the period of 0–2 hours and 1.8% m³/m³ over the period of 6–8 hours, which indicates that the decrease rate of soil moisture gradually slows down with increasing circulation. The moisture of H₁ does not change within the first 4 hours of the cycle but decreases in the sixth hour, which shows that the influence range of the energy pile on soil moisture is related to the cycle time. Specifically, the longer the cycle time, the larger the influence range. At the end of the cycle, the moisture of H₁ decreases by 5.3% m³/m³, that of H₂ decreases by 4.5% m³/m³, that of H₃ decreases by 3.6% m³/m³, and that of H₄ decreases by 2.5% m³/m³. Significant differences in the moisture changes of different measurement points could be attributed to differences in the distance between the four measurement points and the pile. As the distance between these points and the pile increases, the affected degree of the moisture gradually decreases.

Figure 14. Changes in soil moisture with time along the radial direction.
Figure 15 shows the change in soil moisture around the pile with increasing depth. Here, data obtained at measurement points H₁₀, H₉, and H₅ (the distance from the central axis of pile 2 is D) at different times are depicted in the figure. The increment in soil moisture around the pile at different depths remains relatively constant at different cycle times because the change in moisture is caused by temperature. The influence of the pile on the soil temperature within the depth range of 30–70 cm is fairly constant, which means the pile temperature is basically constant within this depth.

![Figure 15](image1)

**Figure 15.** Changes in soil moisture with time along the axial direction.

Figure 16 shows the change in displacement of the pile top as a function of time. In this paper, the positive and negative values of displacement are defined as positive upward and negative downward. Figure 16 shows that under the thermal cycle, the displacement of the pile top is positive, that is, the pile top moves upward because of the expansion of the pile after heating. The upward displacement of pile top is due to the small constraint. As the circulation time increases, the displacement of pile top increases gradually because of the gradual increase in the temperature of pile and its thermal expansion. In the periods of 0–2, 2–4, 4–6, and 6–8 hours, the displacement of the pile top changes by 0.42, 0.11, 0.03, and 0.03 mm, respectively. This result indicates that the rate of change decreases with increasing cycle time. As the pile temperature increases, the temperature difference between the pile and the heat pipe and the heat absorbed by the pile per unit time gradually decrease, thereby resulting in gradual decreases in the rate of thermal expansion and rate of change of the pile top displacement.

![Figure 16](image2)

**Figure 16.** Variation in pile top displacement with time.

Figure 17 shows the change in the pile end resistance as a function of time. In the period of 0–2 hours, the pile end resistance decreases slightly, likely because of the intense heat exchange at the initial stage of the cycle. In the period of 2–8 hours, the resistance at the pile end increases gradually as the temperature of the pile increases, the thermal stress of the pile increases gradually. The thermal strain of the pile is limited by the large restriction of the soil at the pile end, which results in an increase in the resistance of the soil to the pile upward. In the period of 4–8 hours, the pile end resistance and circulation time change nearly linearly. When the circulation stabilizes, the heat absorbed by the pile per unit time is equal. The thermal expansion generated is also equal, which is consistent with the change rule of the pile top displacement in the 4–8-hour period depicted in Figure 16. The increase in pile top displacement and pile end resistance are similarly due to the increase in pile temperature.

![Figure 17](image3)
Figure 17. Variation in pile top resistance with time. Figure 18 shows the change in pile strain with increasing depth. The highest measurement point of the pile is only 5 cm away from the filling surface and greatly affected by the temperature; thus, its data cannot truly reflect the thermal strain of the pile body, and the data of this measuring point are not included in the figure. Under a constant cycle time, the strain at different positions of the pile first increases and then decreases with the depth. The strain peaks at the point located 95 cm from the filling surface, that is, 70% L from the pile top, which is consistent with the change rule of the pile temperature. As the cycle time increases, the strain of the pile at different depths gradually increases but the increase range gradually slows down. Taking the strain at a depth of 95 cm as an example, the cycle time increases for 2 hours, and the strain increases by 75.6%, 8.6% and 8.4%. This result shows that the temperature of the pile gradually increases and the heat exchange efficiency of the energy pile gradually decreases with increasing cycle time. The strain of the measurement point located 50 cm from the filling surface in the figure is obviously small because the temperature of the pile is affected by the environment. In addition, the strain and temperature of the pile cause wavelength changes in FBG. No temperature compensation is adopted in this test, but the wavelength change caused by temperature could be theoretically calculated according to the temperature sensitivity coefficient of FBG and the soil temperature 1D away from the pile axis and reduced in the monitoring results. The strain data of the pile shown in this paper are all the removal temperature impact.

Figure 18. Distribution of strain distribution on the pile as a function of depth.

4 Conclusions
This paper introduces the construction process of a PCC energy pile test system, including model pile fabrication, sensor arrangement, and device configuration, in detail and applies the obtained system to PCC energy pile tests. The main conclusions are as follows:

(1) The fabricated PCC energy pile test system could carry out model tests of the bearing characteristics of PCC energy piles under various working conditions, thereby demonstrating its feasibility and applicability.

(2) The temperature of the PCC energy pile is transmitted to the soil along the radial direction, and soil temperatures at the same distance from the pile are affected to the same extent. Temperature transfer
between the pile and soil shows obvious time effects. As the cycle time increases, the soil temperature and temperature influence range of the energy pile gradually increase. At the end of the cycle, the influence range of the energy pile is 4D but the heat transfer efficiency of this pile gradually decreases. The highest temperature point of the pile body occurs near the middle of the structure (70% L from the top of the pile).

(3) The soil moisture around the pile moves along the direction of heat transfer, the temperature gradient is large, the moisture migration speed is high, and the change in soil moisture has obvious time effects. The longer the cycle time, the lower the soil moisture. At the end of the cycle, the influence range of soil moisture is identical to that of temperature.

(4) Under thermal cycling, the top of the energy pile produces upward displacement, and the increase rate is initially high but then decreases. At the end of the cycle, the displacement of the pile top is 0.6% D and the pile end resistance increases by 1.28 times relative to the original value. The strain of the pile first increases and then decreases along the depth direction, and the maximum strain point is located 70% L from the pile top.

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