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Apparatus development for contact mechanics of energy pile-soil interface

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Abstract. An Energy Pile-Soil Interface Characteristic Apparatus (EPSICA) was developed to investigate the contact mechanics of the pile-soil interface. In the center of the apparatus, there is an energy pile model, around which different soil can be filled to simulate pile in different subsoil. The soil can be saturated. By applying loads on the top of the soil, the different depths were simulated. The temperature of energy piles was controlled by the cycling fluid with a water bath. The Pt100 sensors were installed in the pile and soil to measure the temperature changes. The miniature earth pressure cells were installed on the pile surface to measure the normal stress of the pile-soil interface. The FBG quasi-distributed optical fiber technology was used to measure the hoop strain to evaluate the circumferential deformation of the pile model. Taking the sand foundation as an example, the mechanical behavior of pile-soil contact behavior during the heating and cooling cycle was studied based on the temperature of pile and soil, normal stress of pile-soil interface and hoop strain of pile. The developed apparatus provides a new method for the study of thermos-mechanical behavior of energy pile.

1 Introduction

For energy piles, the temperature of the pile and the surrounding soil will change significantly, which will change the interaction between the pile and the soil. The deformation of the pile and the soil and the bearing capacity of the pile changes accordingly. The researches on energy piles mostly focus on the axial stress and deformation of energy piles, as well as the friction characteristics of the pile-soil interface. The research on the interaction between piles and soils under the conditions of heating and cooling cycle is also very important.

McCartney and Murphy obtained the distribution of the side frictional resistance of the energy piles by field tests [1]. A centrifuge test was conducted to study the change of the side frictional resistance of the pile at different temperatures. It was found that the side frictional resistance of the pile increased in the case of temperature changes [2]. Di Donna et al. investigated the effects of different temperature conditions on the pile-soil interface and found that the temperature had little effect on the sand-concrete interface [3]. Olgun et al. found that the increase of pile-soil contact pressure caused by radial thermal expansion is small for saturated clay [4]. Xiao et al. found that the shear strength of the soil-concrete interface will change significantly because of the temperature and the radial displacement of the pile caused by temperature for the consolidated clay [5]. Obviously, interfacial behavior needs to be studied further because of its complexity.

2 Energy pile-soil interface characteristics apparatus

During the cooling and heating cycles of energy pile, the stiffness of the pile-soil interface and the radial stress of the surrounding soil will be affected because of the thermal expansion and contraction of the pile and surrounding soil, which finally results in the bearing capacity changes of the friction pile. In order to study the interaction between pile and soil as well as the changes of the bearing capacity, an Energy Pile-Soil Interface Characteristics Apparatus (EPSICA) was developed. The temperature of the soil and pile, as well as the normal stress of the pile-soil interface, were measured by installing the sensors in the model. The changing mode and mechanism of the normal stress caused by the heating and cooling cycle were studied.

The EPSICA mainly consists of five parts: the cylindrical pressure chamber, confining pressure controller, displacement controller, temperature controller, and data acquisition unit, as shown in Fig.1.

The confining pressure controller was used to apply vertical pressure to the soil filled in the cylindrical pressure chamber to simulate the depth of the soil. The confining pressure controller includes the load cell, pressure source, and pressure tube. The cylindrical pressure chamber is made of Plexiglas with a thickness

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of 7 mm, an outer diameter of 250 mm and a height of 200 mm. The energy pile model with a diameter of 100 mm is installed in the center of the pressure chamber. The pile model was made of concrete with steel tubes on both ends, which are used for water seal. Different kinds of soil can be filled between the pile and the chamber. A stepper motor and a guiding device constitute the displacement controller, which was used to control the displacement, direction, and speed of the pile body. The temperature controller consists of two low-temperature water baths and a circulating tube. The temperature of the energy pile model can be controlled by water circulating with the water bath I to simulate the heat exchange. The water bath II was utilized to control the environmental temperature outside the pressure chamber. The data acquisition unit includes the temperature sensors, miniaturized earth pressure cells, FBG strain sensors, displacement sensors and data logger.

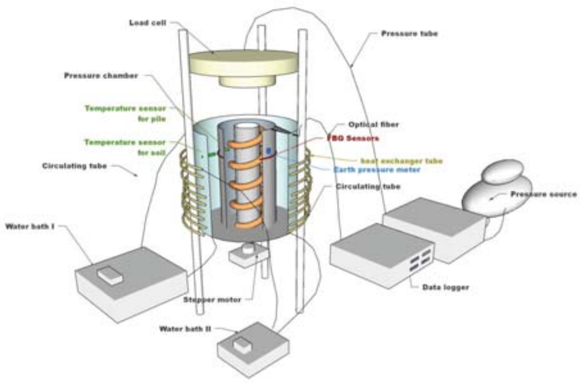

Fig.1 Components of Energy Pile-Soil Interface Characteristics Apparatus (EPSICA)

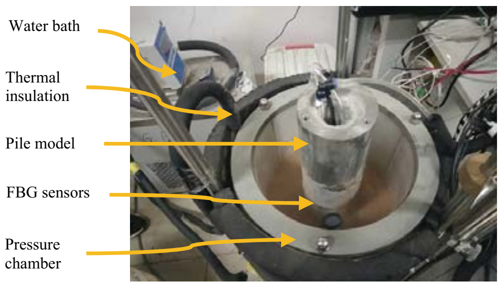

Fig. 2 Photo of the pile model and pressure chamber

The energy pile model is a hollow concrete cylinder so that the cables of the sensors can be connected to the data acquisition unit through the hollow center. In the pile model, there is a spiral copper tube that was connected to the water bath I to control the pile temperature by water circulating. The temperature sensors and miniature earth pressure cells were installed on the surface of the pile to measure the temperature and normal stress of the pile-soil interface. An optical sensing cable with FBGs was attached to the pile surface to measure the hoop strain. The accuracy of the temperature sensor is 0.1 °C. The accuracy of FBG is 1 με. The installation of the sensors is shown in Fig.1.

A temperature sensor for soil was installed in soil between the pile and the chamber. The height of the temperature sensor is the same as the miniature earth pressure cell. The outer surface of the pressure chamber was covered with the circulation tube and thermal insulation foam to prevent the influence of the environmental temperature.

3 Process of experiments

After the pile model was installed and the chamber was filled with soil, a loading plate was placed on the upper surface of the soil. In this experiment, the surrounding soil was dry sand. The density of the sand was 1.44g/cm^3. Constant vertical pressure was applied to the soil through the loading plate. The vertical pressure can be adjusted according to the simulated depth. The axial displacement of the soil was measured by displacement meter installed on the top of the loading plate. Water bath I was used to control the temperature of the pile model. The water bath II was used to keep a constant temperature on the outer surface of the chamber to avoid the influences of the air temperature changes during the whole experiment. Initially, the temperature of the two water bath was 20 °C and the circulation was conducted until the temperature of the pile and soil had no more changes. The operation of the energy pile was simulated by changing the temperature of the water bath I, during which the temperature of pile and soil, the contact pressure of the pile-soil interface and the hoop strain of the pile were recorded. After the monitored data reached a stable state, the temperature of the water bath I was adjusted to conduct the next stage experiment.

3. Experimental results and analysis

3.1 Temperature of the pile and sand

A temperature cycle of 20-40-20-5-20 °C was controlled by the water bath I to change the pile temperature. The outer temperature of the chamber was kept at 20 °C by cycling with the water bath II as there is a circulation tube wrapped around the chamber. The temperature of the energy pile and the sand are shown in Fig.3.

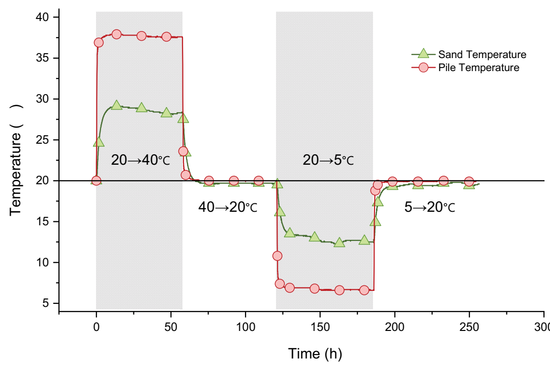

Fig. 3 Temperature of pile and sand in one cycle

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During the cycling, the changes of the pile temperature were different from that of the sand as the soil temperature sensor was installed in the sand between the pile and the chamber. The pile temperature stabilized quickly because the concrete pile model has good thermal conductivity whether in the heating or cooling stage. It took more time for the soil to reach stability. That is to say that the temperature of the pile and the soil can not changes synchronously at the beginning of heat exchange. Meanwhile, the thermal and mechanical performance of the concrete and sand are different. These may lead to the changes of the contact mechanics. The temperature of the pile model and soil simulated by the EPSICA is helpful to investigate the behaviour of the real energy pile.

3.2 The hoop strain of the pile

As shown in Fig.4, the hoop strain and temperature of the pile have a positive correlation. The hoop strain was obtained by FBG strain sensors, which were attached on the surface of the pile model. The ratio between the strain and temperature was about 1.75-2.0 με/°C whether in the heating or cooling stage. The pile temperature changed quickly. Meanwhil, the strain reached the extreme value and then recovered partially in each stage because of the interaction between the pile and surrounding soil, which should be owing to the increase of the soil temperature. The interaction is related to the temperature changes as well as the thermal-mechanical properties of the pile and the sand. An unrecoverable compressive strain can be observed at the end of the cycle, which was the result of the normal stress increase. It should be noticed that the hoop strain changed dramatically at the beginning of heat exchange, which indicates that the diameter of the pile will change significantly. The surrounding soil of the energy pile will be compressed in the heating stage. The normal stress of the pile-soil interface will increase. On the contrary, the pile will shrink radially in the cooling stage, which may lead to a dramatical deduce of the normal stress of the pile-soil interface. Of course, the normal stress will recover markedly with the increase of the soil temperature.

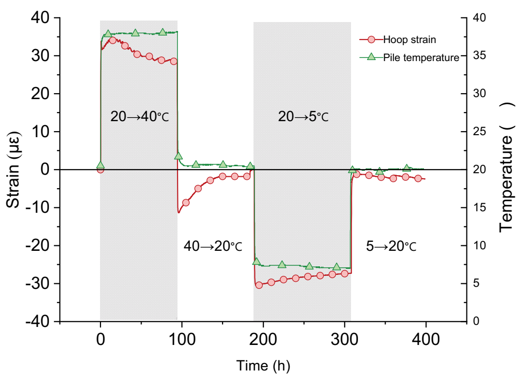

Fig.4 Hoop strain of the pile in one cycle

3.3 Contact behavior of the pile-soil interface

When the temperature of the cycling water increased from 20 to 40 °C, the pile temperature quickly peaked to 40 °C in 5 hours and then got stabilized. The increased rate of the sand temperature was smaller than that of the pile. The temperature of water bath II was kept constant to prevent the influence of the air temperature, which fluctuated during the cycle. The normal stress on the pile side increased 40 kPa at an increasing rate of 2 kPa/°C and then decreased. The stable normal stress was larger than the initial value at the temperature of 20°C, which indicates that the normal stress increases with the temperature. The stable contact pressure is higher than the initial value at a rate of 0.5 kPa/°C. It can be inferred that the thermal expansion of the pile and sand lead to the increase of the normal stress. The expansion of the soil can be verified by the soil displacement, which is increased about -0.07 mm (negative means upward displacement). However, the upward displacement of the sand was partially restrained by the constant vertical pressure, which results in the stress adjustment of the soil and the movement of the sand particals. The density of the soil increased accordingly. The behavior of the sand and pile in the heating stage is shown in Fig. 5.

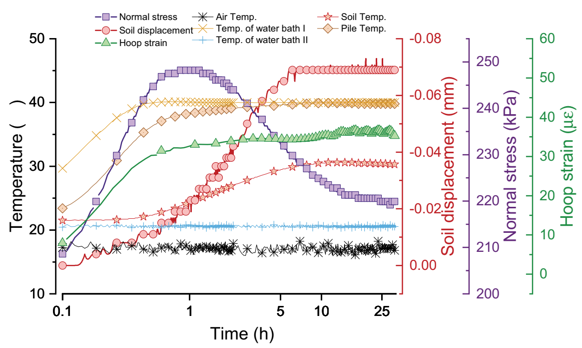

Fig. 5 Contact behavior when the temperature increases from 20 °C to 40 °C

During the cooling process, the normal stress decreased because of the cold shrink of the pile and sand in the first hour. The normal stress on the pile side decreased about 40 kPa at a rate of 2 kPa/°C. Attention should be paid for the design of the energy pile as the bearing capacity of the pile may decreases because of the reduce of the normal stress. Addition subsidence of the pile may occur at the early stage of the thermal exchange as well.

After the pile temperature peaked and kept stable, the soil temperature and settlement decreased gradually. The normal stress on the pile-soil interface recovered and the stable normal stress at 20 °C was less than the normal stress at 40 °C. The behavior of the soil and pile in the cooling stage is shown in Fig. 6.

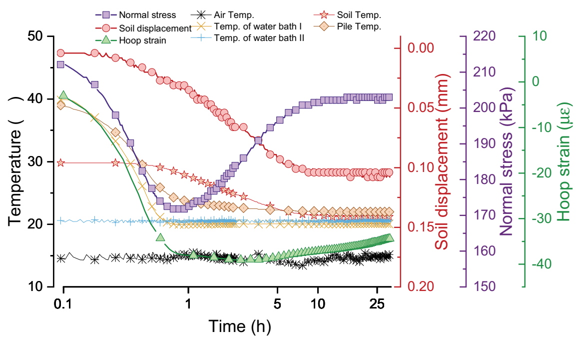

Fig. 6 Contact behavior when the temperature decreases from 40 °C to 20 °C

4 Conclusion

In order to investigate the contact behavior of the pile-soil interface during the heat exchange of the energy pile, an energy pile-soil interface characteristic apparatus (EPSICA) was developed. The temperature of the pile and soil, the hoop strain of the pile, the displacement of the soil, as well as the normal stress at the pile-soil interface were measured. The contact behavior of the pile-soil interface was discussed during the pile heating and cooling process respectively. It was found that normal stress increased sharply at the beginning of the pile heating. When the temperature the pile reached a constant state, the normal stress decreased slowly and come to a steady-state finally. For the pile cooling, the normal stress decreased sharply and recovered gradually to a constant value. The normal stress of the pile-soil interface increased with the cycle times. It can be concluded that EPSICA revealled the thermal-mechanical behavior of the pile-soil interface. This apparatus will be a usefull tool in the study of the energy pile.

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