Experimental Studies on Thermo-mechanical Coupled Behavior of Pile-Clay Interface

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Abstract: The thermo-mechanical coupled behavior of pile-soil interface is very important for the mechanical performance of energy pile. It is studied in this paper by the thermo-mechanical coupled direct shear tests with a temperature controllable concrete specimen in the top shear box and a Kaolin clay specimen in the bottom shear box. The results show that the strength of pile-clay interface significantly depends on the temperature, the temperature cycle number and the over-consolidation ratios of clay. With the heating-cooling cycles, the interface strength can increase and decrease monotonically or non-monotonically depending on the stress state and history of clay, which is generally a thermo-elasto-plastic process. It is shown that the thermo-mechanical coupled pile-clay interface behavior is the net effect of the pore water transportation and the rearrangement of clay particles near the interface as well as the thermal consolidation/expansion of clay. Keywords: energy pile; temperature cycle; pile-clay interface; direct shear test

1. Introduction
Energy pile is a new technology which uses the heat exchanger of ground source heat pumps buried in the piles of building to obtain or store thermal energy from/into the strata surrounding the pile foundation [1-3]. It provides both the bearing capacity against the upper loads and the medium for the heat exchanges between ground and building space. In contrast to conventional piles, there are significant thermo-mechanical coupling effects on the behavior of energy piles. During the operation of energy pile, both the pile and the surrounding soil will be subjected to temperature variation cycles which changes periodically. As a result, the thermal deformation and water migration can be observed in the soil around the piles, leading to changes in soil mechanical behavior as well as the pile-soil interaction and the bearing capacity of pile foundation. Especially considering that the thermal effects may result in the disengaging/sliding of the pile-soil interface and a large thermal additional stress within the pile, carefully studies on the thermally coupled behavior of energy pile become critically important for safety concern.

At present, the existing researches on energy piles mainly focused on the pile-soil thermal transmission mechanism, the bearing capacity characteristics and the heat transfer efficiency [4-7]. As discussed above, the thermal effect of the pile-soil interaction is one of key problems underlying the thermo-mechanical behavior of energy pile. Related studies can be found in the investigation of soil-structure contact surface strength under freeze-thaw cycles [8-10]; however, the mechanical properties of the energy pile-soil interface subjected to cyclic thermal loads are still less studied. Some
researchers had performed laboratory non-isothermal experiments on soil or pile-soil interface using different methods. For instance, Li Chunhong [11] used water bath to heat the concrete block and, similarly, Neda Yavari [12] used a circulating device to change water’s temperature in order to heating the soil inside. In general, it is somehow hard to ensure the heat transfer efficiency and thus the uniform temperature distribution within the test samples using this kind of heating tests. Zhao Gang [13] installed a circular heating plate on the upper part of the direct shear box to change the temperature of soil samples which could be more effective in the temperature controlling and monitoring. Based on similar principles, Suguang Xiao [14] and Saeed Yazdani [15] modified the conventional direct shear device to study the non-isothermal behavior of pile-soil interface with replacing the lower shear box by a concrete plate. In their tests, tubes connected to a heat pump were embedded into the concrete plate to control the heating or cooling process.

However, the studies on the thermal effects of pile-soil interface under complex stress and temperature histories are still insufficient noting that many of the existing researches only considered the monotonic thermal loads and simple couplings between thermal and mechanical loads. The stress history of soil and the reversibility/irreversibility of the thermal effects are relatively seldom studied. Especially, the mechanisms of the cyclic thermo-plastic behavior of pile-soil interface are still not clear, which are important for the understanding of the long-term behavior of energy pile. In this study, a modified direct shear test device is utilized to analyze factors affecting the shear strength of energy pile-soil interface and to interpret the underlying mechanisms mentioned above.

2. Experimental methods

2.1. Experiment Device

The tests were carried out using a strain-controlled direct shear device modified according to the demands of pile-soil interface test and temperature controlling. As shown in figure 1, the pile-soil interface was modeled by a soil specimen and a concrete specimen installed in the bottom shear box and the top shear box, respectively. The temperature-controlled cast aluminum circular heating block (diameter 60 mm; height 20 mm) was placed above the concrete specimen in order to change the temperature and simulate the heat transfer from the pile to the surrounding soil. A hole with a diameter of 3 mm was drilled in the side wall of top shear box slightly above the interface. A Pt100 temperature sensor was fitted through the hole to the interface position and connected to the paperless recorder to monitor the real-time temperature in the interface region. The borehole was very close to the shear plane, so the temperature recorded can be considered to be equal to interface temperature. In the tests, the side walls of the shear boxes were covered by thermal insulating material to avoid the horizontal heat exchanger between the test sample and the air environment and to ensure the uniform temperature distribution.
Figure 1. Pictures of experiment device used: (a) temperature-controlled heating device; (b) Pt100 temperature sensor and paperless recorder; (c) profile of direct shear test apparatus.

2.2. Experiment Material and Sample Preparation
The clay specimen was prepared by reconstituted kaolin clay. Its physical properties are shown in table 1. The concrete specimen was made of high-grade cement mortar, with a diameter of 61.8 mm and a height of 20 mm. After standardized maintenance, the surface of concrete specimen was sanded with sandpaper to ensure a certain roughness at the interface. The same concrete specimen was used throughout the tests, ignoring the effect of surface roughness change, and its surface was cleaned after each test.

Table 1. Physical indexes of the kaolinite used for the test.

| Parameter                      | Value |
|-------------------------------|-------|
| Gs                             | 2.67  |
| Plastic Limit ($w_p$) / %      | 26    |
| Liquid Limit ($w_L$) / %       | 48    |
| Platic Index ($I_p$)           | 22    |
| grain size d<2μm grain content / % | 82.2  |
Figure 2. Kaolin clay and concrete specimen used in tests.

The soil specimen was prepared from the reconstituted kaolin clay. The kaolin powder was first mixed with a water content of 1.5 times the liquid limit (1.5 \( w_L \)), and the slurry set aside for 24 hours to ensure soil particles fully wetted. It was then consolidated under different pre-consolidation pressures using an odometer to obtain clay specimens with different stress histories for the pile-soil interface tests (see below for the detailed information of the consolidation).

2.3. Experiment Procedure

Up to 60 sets of tests were carried out in this study and the detailed experiment conditions are shown in table 2. In each test, the pile-soil interface samples were first loaded under certain normal stresses and then subjected to several heating-cooling cycles under constant normal stresses. The interface shear tests under different constant temperatures were performed after the end of the heating-cooling process. By controlling the pre-consolidation stress and the present normal stress, pile-soil interfaces with clay specimens under different stress states and over-consolidation states can be studied. The ambient temperature was about 15°C. In each heating-cooling cycle, the samples were heated to a certain target maximum temperature and then the heater was shut off to allow the cooling. In order to study the thermo-elasto-plastic features of pile-soil interface, one batch of interface shear tests were performed at the target maximum temperature (with cycle numbers denoted as *5) and another batch were performed after the samples were cooled to the initial room temperature (with cycle numbers denoted as integers).

Before shearing, the samples were heated at a relatively slow rate of about 0.33°C/min to decrease the non-uniformity of temperature distribution and the temperature was kept for a certain period of time after the temperature reached the target values to allow the full dissipation of pore water pressure caused by the temperature change. With reference to experimental study on the thermal consolidation and temperature controlled triaxial shear tests [15], the thermally induced pore water pressure can be estimated to dissipate within 2 hours in the direct shear test.

3. Test Results and Discussions

For energy piles, the pile-soil interaction can be remarkably dependent on the thermal loading history. Its performance may change accumulatively with the increase in the heating-cooling cycle number, which also depends on the stress states and stress histories of the interface and the soil. In this section, the effects of temperature variation amplitude, temperature cycle number, soil stress state and stress history on the thermo-mechanical coupled elasto-plastic behavior of energy pile-soil interaction are analyzed based on experimental results obtained in this study.
which can be attributed to the adopted low coarseness, while a slight shear softening is shown in the shear tests for those with interfaces with normally consolidated soils. Table 2 shows the experimental results of the shear stress-displacement relationships for pile-soil interfaces sheared at room temperature (15 °C) and 25 °C (figure 3a) as well as those sheared at room temperature after undergoing 5 heating-cooling cycles with two different maximum temperatures of 25 °C and 40 °C (figure 3b). Plastic shear hardening without softening is observed in all isothermal tests regardless of the OCR values of the clay, which can be attributed to the adopted low coarseness of the concreted surface at the interface, while a slight shear softening is shown in the shear tests coupled with heating or heating-cooling histories, especially for the ones with clay OCR values of 2 and 4. In contrast, the interface heated to 25 °C with a clay OCR of 8 even shows more shear hardening than the one sheared at room temperature. Such thermal effects could be more remarkable when the interface surface is coarser. It can be then deduced that the heating may stiffen or weaken the pile-soil interface, depending on the stress state and history of the clay. This can also be supported by the significant clay OCR dependency of the pile-soil interface behavior shown in Figure 4. In general, both the initial shear stiffness and the shear strength increase at elevated temperatures for the interfaces with normally consolidated (NC) and slightly over-consolidated (OC) clays, while decrease for those with highly over-consolidated clays. Further discussions regarding such OCR dependency will be presented in the subsequent section.

| Test # | Pre-consolidation stress (kPa) | Thermal loading | Normal stress (σn/ kPa) | OCR |
|--------|--------------------------------|-----------------|------------------------|-----|
| 1,2,3,4 | 50,100,200,400                  | 15°C            | 50,100,200,400         | 1   |
| 5,6,7,8 | 100,200,400,800                 | 15°C            | 50,100,200,400         | 2   |
| 9,10,11,12 | 200,400,800,1600          | 15°C            | 50,100,200,400         | 4   |
| 13,14,15,16 | 400,800,1600,3200    | 15°C            | 50,100,200,400         | 8   |
| 17,18,19,20 | 50,100,200,400         | (15-25-15°C)-5 cycles | 50,100,200,400         | 1   |
| 21,22,23,24 | 100,200,400,800        | (15-25-15°C)-5 cycles | 50,100,200,400         | 2   |
| 25,26,27,28 | 200,400,800,1600       | (15-25-15°C)-5 cycles | 50,100,200,400         | 4   |
| 29,30,31,32 | 400,800,1600,3200     | (15-25-15°C)-5 cycles | 50,100,200,400         | 8   |
| 33,34,35,36 | 400                  | 15-25°C         | 50,100,200,400         | 8,4,2,1 |
| 37,38,39,40 | 400                  | (15-25-15°C)-1 cycle | 50,100,200,400         | 8,4,2,1 |
| 41,42,43,44 | 400                  | (15-25-15°C)-5 cycles-25°C | 50,100,200,400         | 8,4,2,1 |
| 45,46,47,48 | 400                  | (15-25-15°C)-10 cycles | 50,100,200,400         | 8,4,2,1 |
| 49,50,51,52 | 400                  | 15-40°C         | 50,100,200,400         | 8,4,2,1 |
| 53,54,55,56 | 400                  | (15-40-15°C)-5 cycles | 50,100,200,400         | 8,4,2,1 |
| 57,58,59,60 | 400                  | (15-40-15°C)-5 cycles-40°C | 50,100,200,400         | 8,4,2,1 |

3.1. Interface Shearing at Different Temperatures

The thermal effects of pile-soil interaction can be first examined by analyzing the shearing behavior of interface at different temperatures. In the tests, four groups of tests were conducted for interface samples sheared under four different normal stresses of 50 kPa, 100 kPa, 200 kPa and 400 kPa with a same pre-consolidation pressure of 400 kPa. The clay specimens thus had different OCR values of 8, 4, 2 and 1, respectively. The samples were subjected to different temperature histories before shearing.

Figure 3 shows the experimental results of the shear stress-displacement relationships for pile-soil interfaces sheared at room temperature (15 °C) and 25 °C (figure 3a) as well as those sheared at room temperature after undergoing 5 heating-cooling cycles with two different maximum temperatures of 25 °C and 40 °C (figure 3b). Plastic shear hardening without softening is observed in all isothermal tests regardless of the OCR values of the clay, which can be attributed to the adopted low coarseness of the concreted surface at the interface, while a slight shear softening is shown in the shear tests coupled with heating or heating-cooling histories, especially for the ones with clay OCR values of 2 and 4. In contrast, the interface heated to 25 °C with a clay OCR of 8 even shows more shear hardening than the one sheared at room temperature. Such thermal effects could be more remarkable when the interface surface is coarser. It can be then deduced that the heating may stiffen or weaken the pile-soil interface, depending on the stress state and history of the clay. This can also be supported by the significant clay OCR dependency of the pile-soil interface behavior shown in Figure 4. In general, both the initial shear stiffness and the shear strength increase at elevated temperatures for the interfaces with normally consolidated (NC) and slightly over-consolidated (OC) clays, while decrease for those with highly over-consolidated clays. Further discussions regarding such OCR dependency will be presented in the subsequent section.
Figure 3. Curves of shear displacement versus shear strength (a) at different temperatures and (b) at room temperature with different heating-cooling cycles.

The shear stress-displacement relations at the same room temperature are also remarkably dependent on the temperature history. As shown in figure 3b, similarly to the tests at different temperatures (figure 3a), a higher maximum historical temperature results in a larger stiffness and strength of pile-clay interface (OCR=1, 2 and 4). It can be then indicated that the thermally induced changes in the mechanical interface behavior should not be pure elastic. The elasto-plastic features of interface behavior can be further analyzed by comparing the shear strengths at room temperature with and without heating-cooling histories shown in figure 4b. Obviously, both the thermally induced stiffening and weakening of pile-soil interface are partially irreversible, and a higher maximum historical temperature leads to more significant thermo-plasticity. It is worth noting that in some existing studies the thermo-mechanical coupled behavior of highly over-consolidated clays is considered to be pure elastic. However, this may be inappropriate for pile-clay interface according to the results presented here. These elasto-plastic features of the thermo-mechanical coupled behavior of interface are very important for the modeling of energy pile, especially when thermal/mechanical unloading or cyclic loading problems are concerned.

Figure 4. Failure envelopes: (a) sheared at different temperatures; (b) sheared at room temperature with different heating-cooling cycles.

3.2. Effects of Temperature Cycle Number
Due to the thermo-elasto-plastic coupling in pile-soil interaction discussed above, the thermal-mechanical coupled interface response should also depend on the temperature cycle number. Figures 5a and 5b show the relationships between shear strengths and heating-cooling cycle numbers for interfaces sheared at the maximum temperature of the cycle (25 ℃; cycle number = 0.5, 5.5) and at the room temperature recovered (15 ℃; cycle number = 0, 1, 5, 10), respectively. All samples had the same pre-consolidation pressure and were sheared under 4 different vertical stresses after subjected to corresponding temperature cycles.
Figure 5. Curves of shear strength under different cycles: (a) sheared at maximum temperature (25 °C); (b) sheared at room temperature.

As shown in figure 5, both for the shear tests at 25 °C and at room temperature, the shear strength of pile-NC clay interface always increases with the temperature cycle number. It increases by 1% at the 5th cycle and almost 4% at the 10th cycle compared with the isothermal case. However, those of pile-highly OC clay interfaces (OCR=8) always decrease with the cycle number. This can be attributed to the thermal hardening of NC clay and thermal softening of highly OC clay broadly reported in literatures [16]. However, the thermal-mechanical coupled behavior of clay seems to be insufficient to support the thermally induced variations of pile-soil interface strength in thermal hardening lowly and moderately OC clays, which first increase after a monotonic heating to 25°C and slowly decrease after more heating-cooling cycles to the same temperature (OCR=2 and 4 in figure 5a). As a result, the corresponding shear strengths at room temperature after several temperature cycles (figure 5b) also decrease with the cycle number.

The non-monotonic change mentioned above may be interpreted from the following three aspects:

1. The thermal hardening of lowly or moderately OC clay subjected to cyclic temperature loads;
2. The migration of pore water from the clay to the interface induced by the temperature-gradient resulted density flow of pore water during the temperature cycling;
3. The break of biting between soil and concrete surface because of the rearrangement of clay particles near by the interface to adapt the thermal expansions of two different materials [17]. The first aspect increases the interface shear strength, which can be dominant in the first temperature cycle and leads to the strength increase; while the later two accumulate with the temperature cycling and may finally result in the strength decrease. It can be expected that the thermo-mechanical coupled behavior of pile-soil interface is the net effect of these three aspects, not only depending on the temperature cycle number but also on the stress history and the temperature cycling amplitude. On the other hand, in all cases the increase or decrease in interface shear strength seems to mainly occur in the early several temperature cycles under the given conditions. However, it may be not true in some cases with in situ soft clays subjected to periodic long-term temperature variations, which should be further studied in future.

3.3. Effects of OCR State

As discussed above, the stress history of clay has an important influence on the thermal effects of pile-clay interaction. In this section, the effects of OCR state will be further analyzed. It is known that an elevated temperature will result in the thermal consolidation of NC or slightly OC clay and the thermal expansion of highly OC clay [18], leading to the thermal hardening and softening of clay, respectively. This should be one of the main mechanisms underlying the OCR dependent thermo-mechanical coupled pile-clay interface behavior presented in Sections 3.1 and 3.2. As had been shown in Figure 3a, under a temperature elevation of 10°C, there is a critical value of OCR between 4 and 8 at which the interface shear strength variation is transited from increasing to decreasing.
In many other existing studies on the thermo-mechanical effects of clay or pile-clay interface, the OCR effects are analyzed from the experimental results for samples with the same pre-consolidation pressure and different current confining pressures. In this study, we further study the OCR effects for pile-clay interfaces under the same current normal stresses, as shown in Figure 6. It is shown that after 5 heating-cooling cycles, the critical OCR value decreases to between 1 and 2 under all normal stresses, which can be attributed to the mechanisms (2) and (3) interpreted in Section 3.2. It indicates that the shear strength of interfaces may be weakening under temperature cycles even if the thermal hardening occurs in the first cycle (also see the discussion in Section 3.2). Moreover, the lower the OCR of the clay, the larger the reduction in the shear strength observed with the temperature cycling, which is consistent with some other experimental studies [15].

![Figure 6](image.png)

**Figure 6.** OCR dependency of interface shear strength at room temperature with and without heating-cooling cycling histories.

### 4. Conclusion

In this paper, the direct shear test is used to explore the factors affecting the shear strength of pile-clay interface under the effect of temperature cycling, and the irreversible and cumulative effects of the temperature cycling process on the interface mechanical behavior are investigated. In the tests, the effects of temperature, temperature cycle number and OCR of clay are considered. The following conclusions could be concluded from the test results:

1. The shear strength and stiffness of pile-clay interfaces heated monotonically depend on the OCR value of the clay. They increase for NC and lowly to moderately OC clays, while decrease for highly OC clay. Generally speaking, the thermally induced changes in the mechanical behavior of pile-clay interface are irreversible so that the thermo-elasto-plasticity should be considered especially when the unloading or cyclic thermal/mechanical problems are concerned. Moreover, a larger temperature rise will result in a larger increase or decrease in the interface strength.

2. The variations of pile-clay interface strength subjected to heating-cooling cycles seem to be more complex than those under monotonic heating. With the increasing of temperature cycles, the interface strength monotonically increases and decreases for the cases with NC clays and highly OC clays, respectively. However, non-monotonic variations of the interface strength, which increases in the first temperature cycle and decreases with more cycles, can be found in the tests using lowly to moderately OC clays. It can be attributed to the temperature-gradient induced transportation of pore water from clay to the interface and the break of biting between clay and concrete surface as a result of the rearrangement of thermally expanded clay particles near the interface. The thermo-mechanical coupled behavior of pile-clay surface is just the net effect of these factors.

3. The thermal consolidation or expansion of clay which depends on the stress state and history is one of the main mechanisms underlying the OCR dependency of pile-clay interface behavior under non-isothermal conditions. There is a critical OCR value for the clay at which the variation of interface...
strength under temperature cycles is transited from strengthening to weakening, and this value can decrease with the temperature cycle numbers. In general, the OCR dependency for pile-clay interface seems to be more complex than that for clay itself and needs to be studied more carefully.

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