Investigation of thermal effects on the saturated shear behaviour of a clayey sand-structure interface

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ABSTRACT

The mechanical behaviour of soil-structure interfaces at various temperatures plays a key role in predicting the performance of energy piles, such as their ultimate bearing capacity and settlement under heating and cooling. The experimental data was limited in the literature, and previous studies used clay and clean sand. In this study, a modified direct shear apparatus that can control temperature was developed. To control interface temperature, a refrigerated/heated circulating bath is connected to channels in the lower shear box and then heated/cooled water is circulated. The interface can be heated/cooled through heat exchange with circulating water. Three series of tests were conducted at various temperatures of 8, 20 and 42 °C and effective normal stress levels of 50, 150 and 300 kPa. The soil specimen was recompacted clayey sand with a 95% degree of compaction. The results indicate that the shear strength of saturated soil-structure interfaces decreases with increasing temperature. This is likely because temperature elevation results in a reduction of interface roughness and a partial increment of void ratio in the shear zone.

Keywords: Soil-structure interface, Temperature effects, Saturated shear behaviour, Cooling/heating condition.

1. Introduction

Energy piles are an environment-friendly technology for space heating and cooling in buildings. During winter and summer, they can extract geothermal energy from and dissipate heat into the ground, respectively, where the temperature below a certain depth stays fairly constant. Compared to conventional heating and cooling systems, the utilization of energy piles can reduce energy consumption and CO_2 emission by about 60% and 50%, respectively (Patel and Bull 2011). Hence, energy piles have received increasing attention during the past two decades (Brandl 2006; Laloui and Di Donna 2013; McCartney 2013).

Different from conventional piles, the circulation of heat-exchange fluid in energy piles subjects the piles, surrounding soils and their interfaces to heating and cooling. The variation of temperature would affect the engineering properties of soils and interfaces and hence alter the pile settlement and bearing capacity, as supported by some theoretical and experimental studies (Alsherif and McCartney 2015; Amatya et al. 2012; Laloui et al. 2006; Ng and Zhou 2014; Tang et al. 2008). To fully understand and properly analyze the performance of energy piles, including the thermally induced changes in bearing capacity and settlement, it is crucial to understand the thermo-mechanical behaviour of soils and soil-structure interfaces. Extensive researchers have investigated the influence of thermal cycles on the behaviour of saturated soils. So far, however, there are only a few investigations on the thermo-mechanical behaviour of soil-structure interfaces (Di Donna et al. 2016; Li et al. 2019; Maghsoodi et al. 2020; Xiao et al. 2019; Yavari et al. 2016). The results of these studies suggest that thermal effects on the sand-structure interfaces are negligible, while the behaviours of clay-structure interfaces are clearly affected by temperature. Di Donna et al. (2016) performed a series of direct shear tests on the interfaces between piles and normally consolidated (NC) illite clay at different temperatures (22, 50 and 60 °C). They found that the critical shear strength increased with temperature. However, Yavari et al. (2016) concluded that the effects of temperature on the shear strength were negligible, based on their direct shear tests on over-consolidated (OC) Kaolin clay-structure interface at 5, 20 and 40 °C. Li et al. (2019) investigated that the thermal effect on the critical shear strength of NC red clay-structure was also negligible under larger normal stress levels at 2, 15 and 38 °C. In the studies of Maghsoodi et al. (2020), the results of constant normal load (CNL) and constant normal stiffness (CNS) tests on NC kaolin clay-structure interface presented that temperature rise had less impact on the shear strength in the case of the clay–pile interface than in the clay specimens. However, compared to clay and clean sand, there is a lack of data for other soil types of interface behaviour under non-isothermal conditions.

In this study, a temperature-controlled direct shear apparatus was developed to study the thermo-mechanical behaviour of a clayey sand-steel interface. Eleven tests were conducted at various temperatures (8, 20 and 42 °C) and normal stress levels (50, 150 and 300 kPa). In the following sections, the test methods and results are discussed in detail.

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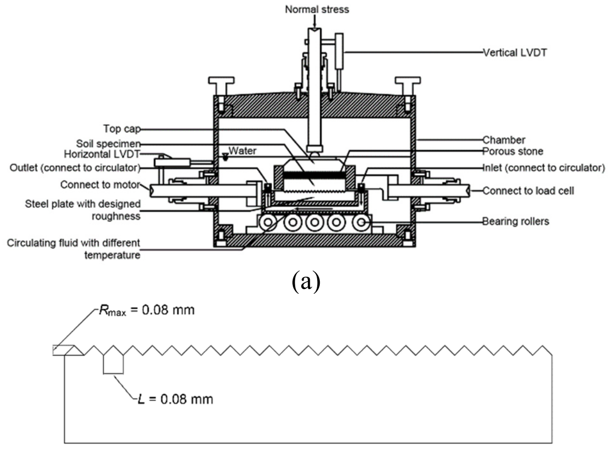
2. Methodology

2.1. Apparatus

To study the thermo-mechanical behaviour of soil-structure interfaces, a new temperature-controlled direct shear device was developed, as shown in Figure 1. The upper box accommodated a soil specimen with a surface area of 60 mm × 60 mm and a height of 20 mm, while the low shear box contained a steel interface with a surface area of 100 mm × 100 mm and a height of 20 mm. The maximum shearing displacement during the tests is 15 mm. Thus, the shearing area during the tests is constant. The whole shear box (including the upper and low parts) was placed inside a chamber filled with water to reach saturated conditions. The normal loads were applied by dead weight, while the shear loads were provided by the motor, which can control the shearing rate. A load cell from *Applied Measurement* (capacities: 0-2.45 kN; accuracy: 0.001 kN) is connected to the upper shear box through a loading ram to measure the shear load. Two linear variable differential transformers (LVDTs) manufactured by *VJ Tech* are used to measure both horizontal and vertical displacements. Horizontal and vertical LVDTs have a stroke length of 50 (accuracy: 0.01 mm) and 5 mm (accuracy: 0.001 mm), respectively. All sensors are connected to the *Clisp Studio* software through the datalogger *MiniSCANNER 2* provided by *VJ Tech*. To control temperature, a refrigerated circulator was used to provide a closed water flow with different temperatures through the channels inside the low-shear box.

To calibrate the temperature homogeneity in this chamber, a thermocouple was immersed in the chamber water, and two thermocouples were inserted inside the soil specimen: one was placed in the central location, and the other one was put in the side location. Two calibration tests were carried out, with a target soil temperature of 45 and 5 °C, respectively. Although some heat loss decreases the target temperature to the real temperature of 42 and 8 °C, the temperature at the equilibrium state is stable, as shown in Figure 2. Moreover, it can be seen that the temperatures inside the soil specimen are homogeneous at different locations. And the temperature difference between the soil specimen and chamber water is just 0.2 °C.

Furthermore, the load cell and LVDTs were also calibrated in this study. Particularly, the measurement of soil deformation during heating/cooling was affected by apparent deformation as a result of the thermal response of different equipment components. The apparent deformation was calibrated by conducting heating-cooling tests on a stainless-steel specimen with a linear thermal expansion coefficient of 10.4×10^{-6} °C^{-1}. Calibration tests were also conducted to check the friction between the lower and upper shear boxes and that between the loading rod and chamber at different temperatures in the chamber. The total friction is presented in Figure 3, in which the shear stress is the measured shear force due to device friction divided by the interface area during a test with soil. When relative displacement is larger than 1 mm, shear stress is always small (0.5 ± 0.25 kPa) under different temperature conditions.



(b)

Figure 1. (a) Schematic diagram of the temperature-controlled direct shear apparatus; (b) Interface roughness

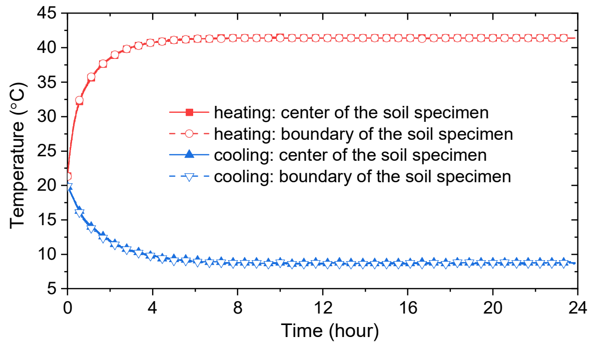


Figure 2. Typical temperature-time relation monitored at different locations of soil specimen subjected to heating/cooling.

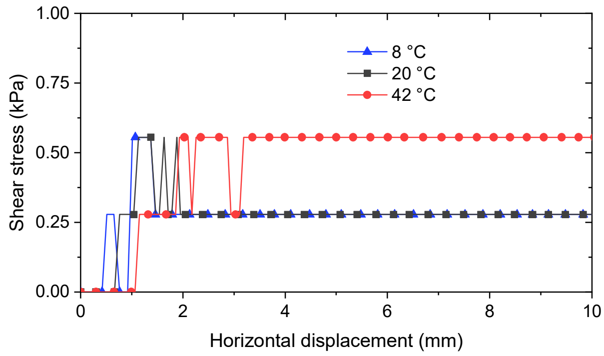


Figure 3. Calibration of the total frictional force, including the friction between lower and upper shear boxes and the friction between loading rod and chamber, at different temperatures.

A stainless-steel plate (100 mm × 100 mm × 20 mm) was used as the pile surface in this study. Compared to a concrete interface, the steel plate can provide a more uniform surface and avoid abrasion due to test repetition. The Industry Center of Hong Kong Polytechnic University manufactured the desired roughness. Its roughness was measured by the *Mitutoyo Surftest,* and the value of R_{max} is 80 µm. As defined in the previous studies (Uesugi and Kishida 1986), R_{max} is the maximum vertical distance between the highest peak and lowest trough on the steel surface along a profile equal to D_{50} that is the mean grain size. Thus, the normalized roughness R_n was proposed to determine the roughness of interface:

$$R_n = \frac{R_{max}}{D_{50}} \quad (1)$$

For the tested soil in this study, D_{50} is 0.08 mm. Thus, the normalized roughness R_n is 1. Based on previous research (Yoshimi and Kishida 1981), the value of R_{max} is within the typical range of pile surface roughness. Hence, the steel plate has reasonable roughness for simulating pile surfaces.

2.2. Soil properties and specimen preparation

The soil used in this study is a kind of clayey sand, which is a locally available completely decomposed granitic (CDG) soil in Hong Kong. The CDG soil tested in this study is the same as that in the previous study (Borana et al. 2018). Its basic properties are given in Table 1. Specifically, the liquid limit was measured by the fall-cone method following the procedures in Bs 1377-2 (1990). The particle size distribution is shown in Figure 4.

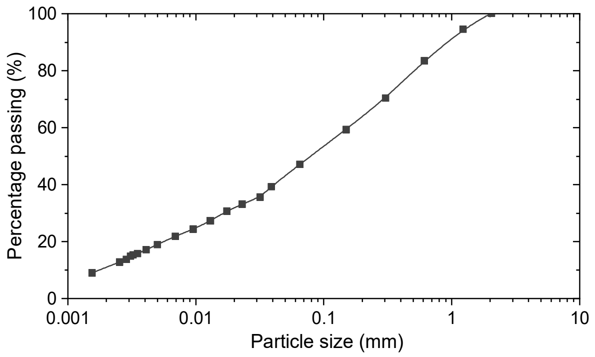


Figure 4. Schematic diagram of the temperature-controlled direct shear apparatus.

Table 1. Basic properties of the soil used in the study

Properties	Value
Unified soil classification system (ASTM D2487, 2017)	SC
Specific gravity	2.59
Clay content (<0.002 mm) (%)	13
Silt content (0.002-0.063 mm) (%)	34
Sand content (0.063-2.0 mm) (%)	55
Liquid limit (%)	31
Plastic limit (%)	21
Plasticity index (%)	10
Maximum dry density (kg/m^3)	1840
Optimum moisture content (%)	13.4
Internal effective friction angle ϕ' (°) (Zhang et al., 2008)	38-42

To prepare fully saturated and recompacted direct shear specimens, the CDG soil from the site was firstly dried at 105 °C in the oven and then broken up into small particles by a rubber hammer. The broken soil particles were sieved through 2 mm BS sieve and the soils passing through the sieve were put back to the 105 °C oven again for another 24 hours. After drying, these sieved soils were mixed with distilled water to reach the optimum water content and sieved by 2 mm BS sieve again to avoid the significant soil aggregation. Then the mixture was kept in a plastic bag for 24 hours to achieve uniform water distribution in the specimen (Cui and Zhou 2022). Following that, the moist specimen was statically compacted in the upper shear box by using a static compaction machine that could control the compaction rate and record the compaction pressure during the process. The degree of compaction was 95% in this study. It should be pointed out that during the specimen preparation, water loss may occur because some water evaporated or attached to the plastic bag. To accurately determine the compaction water content, some soil was collected from the plastic bag to measure its water content. The difference between this final water content and the initial water content was less than 0.2%. The recompacted specimen alone with the upper shear box and steel interface, was put inside the chamber and immersed in the water. Then the whole chamber was exposed to a vacuum of 10 kPa for 24 hours. This method was found able to remove air bubbles inside the specimen and hence saturate the specimen efficiently.

2.3. Testing program and testing procedure

In this study, eleven temperature-controller direct shear tests were conducted to investigate the thermal effects on the mechanical behaviour of the soil-structure interface under fully saturated conditions. Tests were conducted under constant temperatures (8, 20 and 42°C) to study the effects of temperature on the shear strength since the temperature range for energy piles in service conditions is commonly within 4~60°C (Knellwolf et al. 2011). At each temperature condition, the direct shear test was conducted at various normal stress levels (50, 150 and 300 kPa), with reference to energy piles.

Table 2. Test program

Test ID	Effective normal stress (kPa)	Temperature (°C)	Void ratio after shearing
N50T8	50	8	0.44
N50T20	50	20	0.45
N50T42*	50	42	0.45
N150T8*	150	8	0.41
N150T20	150	20	0.41
N150T42	150	42	0.41
N300T8	300	8	0.39
N300T20	300	20	0.39
N300T42	300	42	0.39

Note: * the tests were carried out twice to evaluate the repeatability of experimental results. The initial void ratio and water content after specimen preparation are 0.48±0.01 and 13.4±0.2%, respectively.

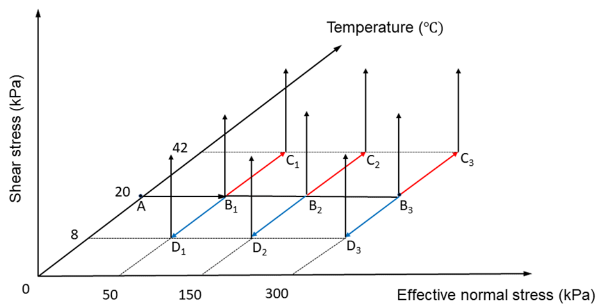
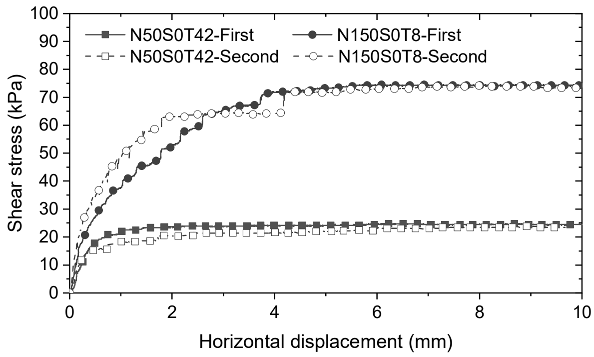


Figure 5. Thermo-hydro-mechanical path of the direct shear tests (Point A represents the initial state after soil saturation).

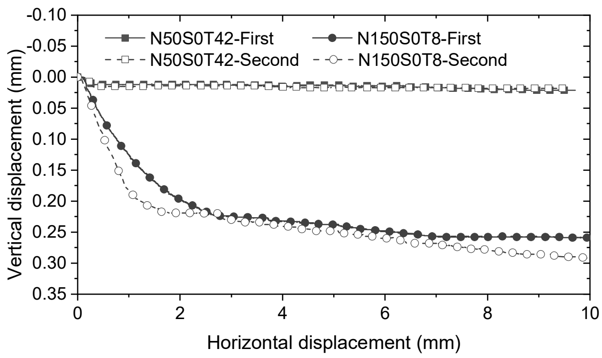
Figure 5 shows the thermo-mechanical paths of the temperature-controlled direct shear tests. It consists of the following stages: 1) applying the target normal stress to the specimen for 24 hours (i.e., path A–B, also called consolidation stage); 2) applying different thermal loadings to the specimen (i.e., path B–C and B-D). It should be mentioned that the specimen is maintained under the target temperature for additional 12 hours at least to allow the sufficient dissipation of thermally induced water pressure; 3) shearing the specimen at a constant rate (0.004 mm/min) and constant temperature (8, 20 and 42°C). The shearing rate is 0.004 mm/min, which can guarantee the shearing under drained conditions (Borana et al. 2018; Hossain and Yin 2010).

3. Repeatability of the test results

To assess the reproducibility of the test results, some tests were conducted twice, as shown in Table 2. It can be seen from Figure 6(a) that the shear stress-horizontal displacement relations at the same test condition almost coincide with each other. The shearing-induced vertical displacement shown in Figure 6(b) indicates that the deformations under the same conditions of temperature and normal stress are also identical. The differences in the critical shear strengths at the same test condition are smaller than 1 kPa, which is almost consistent with the friction of the device shown in Figure 3. The experimental errors in the vertical displacement at the same test condition are within 1% , These findings confirm the good reproductivity of the test results.



(a)



(b)

Figure 6. Repeatability of test results: (a) stress-horizontal displacement relation; (b) shearing induced vertical deformation (positive value means contraction).

In addition, there are some stair step shapes in the shear stress-displacement curves. This is probably related to the potentially developed thin water film at the interface (Bhushan 2003; Fountaine 1954), which increases the shear resistance at some locations of the interface.

4. Interpretations of the test results

4.1. Thermally-induced volumetric strain prior to the shearing

Figure 7 displays the thermally induced volume change behaviour of saturated CDG specimens before shearing. CDG is generally composed of plagioclase feldspar, orthoclase feldspar, quartz and mica. Similar to clay and sand in the literature, the thermally induced volumertic behaviour of CDG is mainly governed by the consolidated state rather than minerals (Ng et al. 2020). In Figure 7, for all saturated specimens, contractive deformation was observed during cooling from room temperature to 8 ºC because of elastic deformation. During heating from room temperature to 42 ºC, the specimens under effective normal stresses of 50 kPa were observed to have a slight expansion of 0.03%, while others contracted by about 0.15%. Heating-induced deformation is closely related to the overconsolidation ratio (OCR) of soil specimens. The pre-consolidation pressure of the specimens used in this study is around 75 kPa after static compaction and saturation, determined using the method of Casagrande (1936). The specimens under 50 kPa were slightly overconsolidated (OCR = 1.5), while others were normally consolidated (OCR = 1). According to previous studies (Cekerevac and Laloui 2004; Demars and Charles 1982; Plum and Esrig 1969; Zhou and Ng 2015), the specimens at normally and overconsolidated conditions generally show plastic contraction and elastic expansion during heating, respectively.

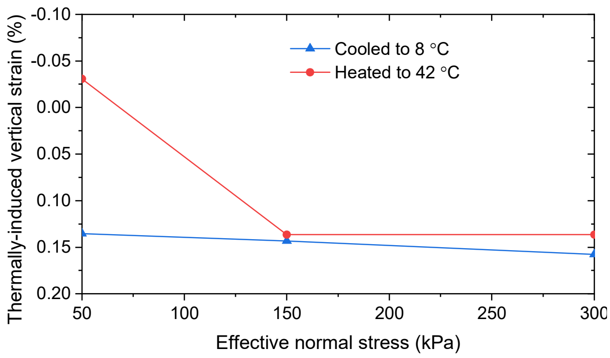


Figure 7. Thermal strain at various stresses and suctions (positive value means contraction).

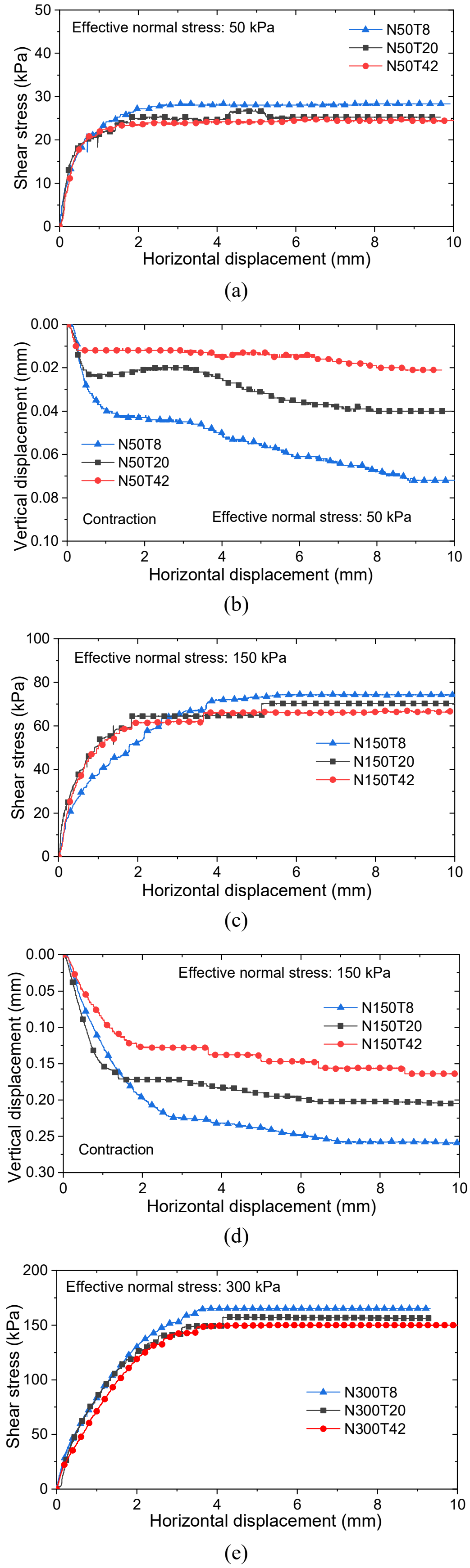
4.2. Temperature effect on the shear behaviour of saturated clayey sand-structure interface

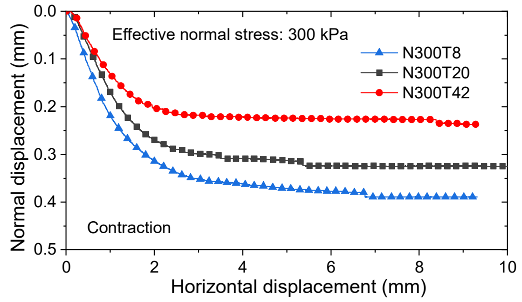
Figure 8 shows the results of direct shear tests under constant temperatures (8, 20 and 42°C). All the tests were conducted under fully saturated conditions. Three different effective normal stresses were considered. At each stress level, it is clear that the shear strength consistently decreases with increasing temperature, as shown in Figure 8 (a), (c) and (e). Taking the soil-structure interface under 50 kPa normal stress as one example, when temperature increases from 8°C to 42°C, the critical shear strength decreases by 12.7%. Similar results were observed at the other effective normal stresses. However, this significant decrement of shear strength induced by heating in this study is opposite to the results of the previous studies (Di Donna et al. 2016; Li et al. 2019; Maghsoodi et al. 2020), in which the interface shear strength increases with heating temperature. Only in the study of Yazdani et al. (2019), they found that the shear strength of OC kaolin clay-structure interface decreases with increasing temperature, which agrees well with the investigations in this study. Explanations to the thermal effects on shear strength are given later.

Figure 8(b) shows the shearing-induced volume change at effective normal stress of 50 kPa. It is clear that temperature elevation reduced the contraction. The accumulated contractions were approximately 0.065, 0.04 and 0.02 mm at 8, 20 and 42 °C, respectively. At effective normal stresses of 150 and 300 kPa, similar results were obtained, as presented in Figures 8(d) and 8(f). At all test conditions, the soil contracted during shearing, which is consistent with the strain-hardening behaviour shown in Figures 8(a), 8(c) and 8(e). The reduction of contraction with increasing temperature was also supported by experimental data about a variety of clay-structure interfaces by previous researchers (Di Donna et al. 2016; Maghsoodi et al. 2020) who attributed it to thermal strain before shearing. It seems that the postulation is inapplicable to the CDG-structure interface tested in this study because its thermal deformation is consistently less than 0.15% (see Figure 7), much smaller than that of clay-structure interfaces (Li et al. 2019). This comparison suggests that the temperature sensitivity of different soils has a significant influence on the interface shearing behaviour via thermal deformations prior shearing.

For CDG-steel interface, the above thermal effects on shear strength and contraction/dilatancy are at least partially related to the thermal expansion coefficients of the soil and counterface. The linear thermal expansion coefficients of the steel and CDG are about 1×10^{-5} and 4×10^{-5} per degree, respectively (Plevova et al. 2015). Thus, the normalised roughness of the test interface decreases upon heating. The reduction of roughness would reduce the thickness of the shear band, the shearing-induced volume change and the shear strength of interfaces, as revealed by extensive experimental data in the literature (Chen et al. 2015; Tsubakihara et al. 1993; Wang et al. 2020).

What's more, thermal effects on contraction/dilatancy were possibly related to the strength property of interfaces. At a given effective normal stress, shearing-induced contraction is larger at a lower temperature. Given a shear displacement, the void ratio in the shear zone of unheated specimens is smaller than that of heated specimens, leading to more significant inter-particle friction and larger shear strength.





(f)

Figure 8. Shear behaviour of saturated CDG-structure interface at various temperatures and effective normal stresses: (a), (c), (e) stress-horizontal displacement relation; (b), (d), (f) shearing induced vertical deformation.

4.3. Thermal effects on the failure envelope

From the results in Figure 8, the critical shear strengths at various net normal stresses and temperatures are determined and shown in Figure 9. The failure envelope at each temperature was fitted using a straight line in reference to the Mohr-Coulomb failure criterion with an assumption of zero adhesion, considering the use of saturated and compacted CDG. The obtained friction angles with respect to net stress (i.e., δ') are 27.3°, 26.1° and 25.1° at temperatures of 8, 20 and 42 °C, respectively. The slight reduction of friction angle upon heating is likely attributed to the decrease in interface roughness and the increase of the void ratio in the shear zone, as discussed above. Moreover, the interface friction angle is smaller than that of the pure CDG, which generally fell in the range of 38 and 42 degrees (Zhang et al. 2008). It implies that the failure was attributed to not only the shearing inside the soil but also the sliding at the interface (Littleton 1976; Lupini et al. 1981; Takada 1993).

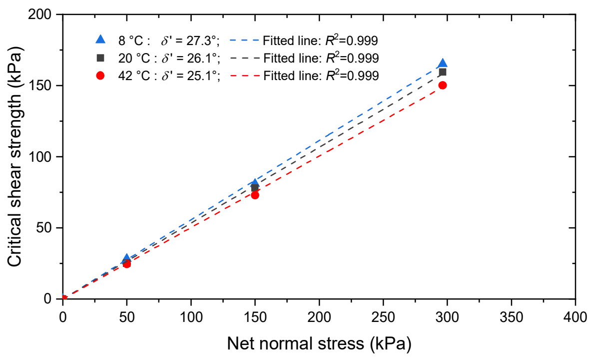


Figure 9. Critical shear strength of saturated CDG-structure interface at different temperatures.

5. Conclusions

In this study, a new direct shear apparatus was developed for testing soil-structure interfaces. With reference to energy piles, different effective normal stresses (50, 150 and 300 kPa) and temperatures (8, 20 and 42 °C) were considered in the test programme.

Based on the results, it is concluded that the shear strength of saturated CDG-structure interface decreases with increasing temperature, since temperature elevation results in a reduction of interface roughness and a partial increment of void ratio in the shear zone. The data are useful for developing constitutive models for soil-structure interfaces and analysing the performance of energy piles.

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