Comportement thermo-mécanique de l'interface sable-structure

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Thermo-mechanical behaviour of soil-structure interface

Comportement thermo-mécanique de l'interface sol-structure

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ABSTRACT: The mechanical behaviour of the soil-structure interface plays a major role in the shear characteristics and bearing capacity of foundations. In thermo-active structures, due to non-isothermal conditions, the interface behaviour becomes more complex. The objective of this study is to investigate the effects of temperature variations on the mechanical behaviour of soils and soil-structure interface. Constant normal load (CNL) and constant normal stiffness (CNS) tests were performed on soil and soil-structure interface in a direct shear device at temperatures of 22 and 60 °C. Fontainebleau sand was used. The results showed that the applied thermal variations have a negligible effect on the shear strength of the sand and sand-structure interface under CNL and CNS conditions, and the soil and soil-structure interface behaviour could be considered thermally independent.

RÉSUMÉ: Le comportement mécanique de l'interface sol-structure est d'une grande importance en raison du rôle de l'interface dans la résistance due au frottement et la capacité portante des structures. Dans les structures thermo-actives du fait de la variation de la température, le comportement de l'interface devient plus complexe. L'objectif de ce travail est d'étudier l'effet des variations de température sur le comportement mécanique de l'interface sol-structure. Des essais avec des conditions de charge normale constante (CNL) et de rigidité normale constante (CNS) ont été réalisés dans une boite de cisaillement direct à différentes températures, 22 et 60 °C sur des éprouvettes sol-sol et sol-structure. Le sable de Fontainebleau a été utilisés. Les résultats ont montré que les variations thermiques appliquées ont un effet négligeable sur la résistance au cisaillement des interfaces sable et sable-structure dans les conditions CNL et CNS et que le comportement du sable peut être considère comme étant indépendant de la température.

Keywords: Thermo-active structures, Temperature, Constant Normal Load, Shear Strength, Direct Shear test, Sand

1 INTRODUCTION

In energy geostructures, the thin layer of soil adjacent to the embedded structural elements composes a soil-structure interface that is subjected to mechanical loads and temperature changes. Different studies have been done to determine the mechanical parameters of soil-structure interface at isothermal conditions (Desai et al. 1985, Boulon 1989). The most important factors that have been mentioned in these studies affecting the interface behaviour are soil density, normal stress, structure roughness, shearing rate, and constant normal stiffness values.

An important concept to aid in understanding the interface behaviour is the constant normal stiffness (CNS) conditions, which explains the real shear behaviour of embedded foundations, as discussed in the following. The physical concept of constant normal stiffness (CNS) conditions at the soil-structure interface, was introduced by Wernick 1978 (Fig. 1). Depending on volumetric response of soil at interface (dilative or contractive) the surrounding soil stiffness limits the response of interface and acts as a virtual spring with a certain stiffness.

$$\Delta\sigma = -K.\Delta U \qquad (1)$$

where σ (kPa) is the normal stress, K(kPa/mm) is the stiffness of the adjacent soil (stiffness of the spring) and U(mm) is the normal displacement of the interface. Under CNS conditions, two general behaviours are observed in soils: dilative (dense or overconsolidated soils) and contractive (loose or normally consolidated soils). In the first case, with starting the shear the soil at the interface starts to contract slightly ($\Delta u>0$) at the beginning of the test, and the amount of normal stress decreases (due to the stiffness of the surrounding soil (virtual springs)) (Eq.1).

After this slight compression, the soil starts to dilate ($\Delta u<0$), and this dilation acts on the surrounding soil. Due to the compression of the surrounding soil, the amount of the normal stress increases ($\Delta\sigma>0$). This normal stress rise, consequently increases the shear strength of the soil at the interface. Conversely, in the second case (loose or normally consolidated soils), the soil at the interface contracts ($\Delta u>0$), and the normal stress decreases ($\Delta\sigma<0$) until the shear ceases.

The other important factor that was mentioned in different studies is the surface roughness of the interface (Kishida and Uesugi 1987, Porcino et al. 2003 and Hu and Pu 2004). Normalized roughness

(R_n), as reported by Kishida and Uesugi 1987, was defined by measuring Rmax (vertical distance between the highest peak and the lowest valley) along a profile length L equal to the mean grain size D_{50} and then normalized by D_{50}.

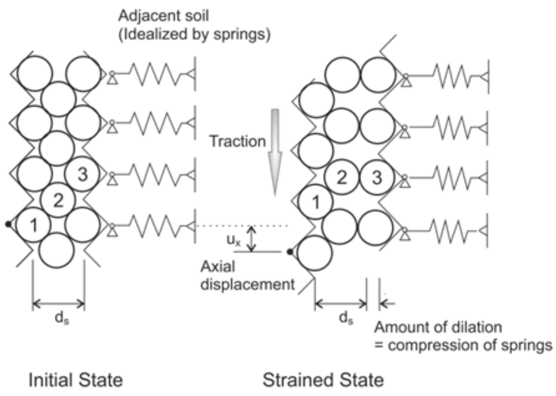

Figure 1. Behaviour of soil structure interface proposed by Wernick 1978 .

Different studies have been done on the effect of temperature on mechanical parameters of soils (Campanella and Mitchell 1968, Hueckel and Baldi 1990, Cekerevac and Laloui 2004, Abuel-Naga et al. 2006, Di Donna et al. 2015, Yavari et al. 2016). Among these studies Di Donna et al. 2015 and Yavari et al. 2016 have used temperature controlled direct shear device to investigate the mechanical behaviour of interface at non isothermal conditions.

Yavari et al. 2016 carried out soil structure interface shear tests on sand and clay samples at 5-20 and 40 ^oC, using a temperature controlled direct shear device. They showed that the shear stress behaviour of sand and clay shows a hardening behaviour while that of clay-concrete interface shows a softening one. They showed that, the effect of temperature (in the range of 5-40 ^oC) on the shear strength of sand, clay and clay-concrete interface was negligible.

Di Donna et al. (2015) performed direct shear tests at different temperatures (22, 60 ^{o}C) on clay-concrete and sand-concrete interfaces and revealed that the sand–concrete interface behaviour was not directly affected by the temperature changes but the clay-concrete interface showed higher shear strength at higher temperatures.

According to the literature, the effects of temperature on the friction angle and adhesion of the soil-structure interface, are poorly understood under both CNL and CNS conditions. In this study, a temperature-controlled direct shear device was used to perform interface tests on Fontainebleau sand on a rough surface under CNL and CNS conditions, to better understand the effect of temperature on mechanical parameters of interface.

2 EXPERIMENTAL PROGRAM AND MATERIAL PROPERTIES

In the following sections, the device which has been used, the material properties and the experimental program that have been chosen are presented.

2.1 Temperature-controlled direct shear device

A temperature controlled direct shear device was used in this study to perform constant normal load and constant normal stiffness conditions on the soil-structure interfaces (Fig. 2).The shear box dimensions was 60 x 60 x 35 mm, that box was placed inside another container and was filled with water in order to reach saturated condition. The heating system consisted of a heater that controlled the temperature of a circulating fluid, then this fluid circulated in the lower part of the container, so the water in the container and subsequently the sample, reached the desired temperature. Three thermocouples, one in the lower half of the shear box, one on the upper half of the shear box and the last one in the trunk controlled the temperature. The normal stress was applied with a loading frame and the vertical displacement was measured with a vertical displacement transducer (Fig. 2). The device was stress/deformation controlled one.

The lower half of the shear box moves and applies a shear stress to the sample. The parameters of soil structure interface were:

- Normal stress (σ_n (kPa))
- Vertical displacement (U (mm))
- Horizontal displacement (W (mm))
- Shear stress (τ (kPa))

2.2 Material properties

Fontainebleau sand was used in this study. The physical properties of this soil are presented in Table 1.

To perform soil-structure interface direct shear tests, a stainless steel plate (80 x 60 x 10 mm) with the desired roughness was designed and used as the structure. This steel plate is used to, avoid abrasion of the surface due to test repetition. The roughness of the steel plate was measured with a laser profilometer (Fig. 3).

Table 1. Fontainebleau properties (Pra-ai 2013)

D_{50} (mm)	0.23
G (Mg/m^3)	2.65
$\rho_{d\ max}$ (Mg/m^3)	1.72
$\rho_{d\ min}$ (Mg/m^3)	1.42
e_{max}	0.866

e_{min}	0.545
Cu = D_{60}/D_{10}	1.72

The measured profile is divided into the D_{50} of the Fontainebleau sand (0.23 mm) and at each segment the Rmax have been measured (R_{max}=0.073 mm, R_n=0.32). Due to the Uesugi and kishida (1986) classification (R_n>0.1-0.13 is rough) the interface can then be considered as a rough (Uesugi and Kishida 1986, Hu and Pu 2004).

2.3 Experimental program

To perform soil and soil-structure shear tests at different temperatures, the sand sample with a target density of 1.67 Mg/m^3 was poured and compacted in the shear box. This density corresponds to 90% of relative density and can be considered as a dense sample. The thermo-mechanical paths used in this study are presented in Fig. 4. For constant normal load (CNL) tests, the normal stress was applied on the samples (path 0-1, Fig.4), then for tests in elevated temperatures the temperature was increased (path 1-2) and at the end the shear displacement was applied with a rate of 0.1 mm/min (path 2-3).

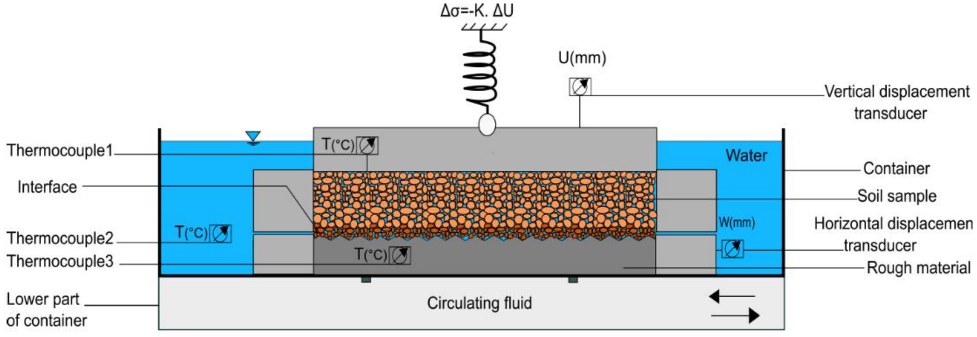

Figure 2. Soil-structure interface parameters

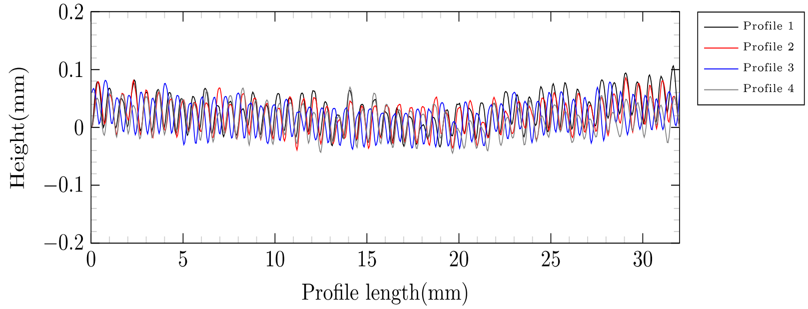

Figure 3. Laser profile of the steel surface

For constant normal stiffness tests the same consolidation path (path 0-1) was applied, then the temperature was imposed (path 1-2). In this step due to soil volumetric response in the contraction phase, the normal stress decreased (path 2-4) and with starting the dilation phase the normal stress increased (path 4-5). To apply the constant normal stiffness condition, the following steps have been followed:

1. The total horizontal displacement W (10 mm) was divided into "*n*"(100) segments (W/n = 0.1 mm).

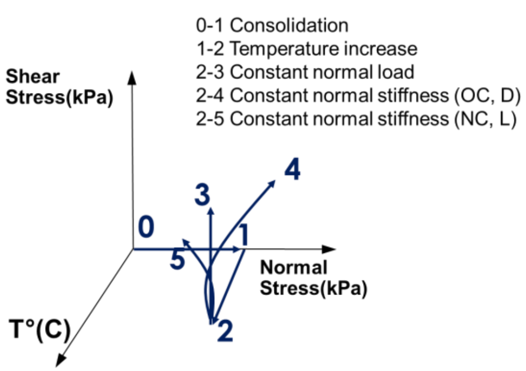

Figure 4. Thermo-mechanical paths in this study.

2. At the beginning of the test, the horizontal displacement was applied until reaching the first segment (0.1 mm).

3. In this step, the vertical displacement difference for this segment was measured.

4. This difference then was multiplied by the imposed value of stiffness and the normal stress difference ($\Delta\sigma$) that should be applied to the soil was calculated and applied (Eq.1).

5. This process was repeated for all segments until the total horizontal displacement was reached.

3 RESULTS AND DISCUSSION

3.1 Sand

Fig. 5a presents the results of sand constant normal load tests at 22 and 60 ^{o}C. The dense samples of sand showed a peak at small strains and then they reached a critical state. Fig. 5b shows the volumetric behaviour of sand, at the beginning of the shear process, the soil contracted (U>0) and then dilated (U<0) and then reached a constant value that corresponds to the critical state of the soil.

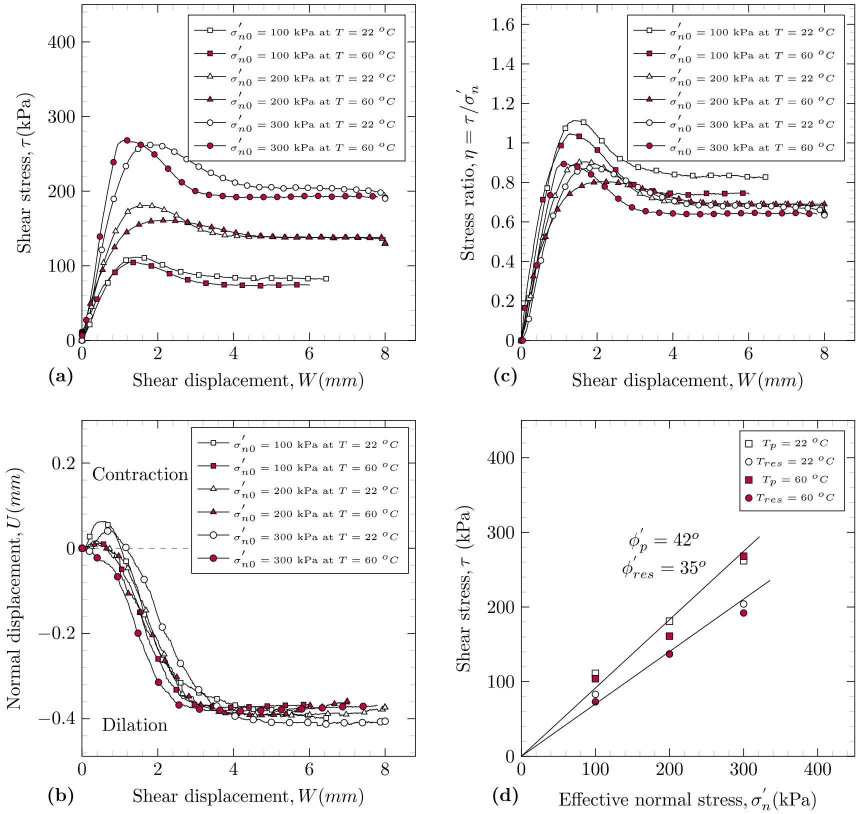

Figure 5. Sand constant normal load test results at 22 and 60 ^{o}C.

Fig. 5c shows the stress ratio ($\eta=\tau/\sigma_n$) variations with shear displacement. The peak shear strengths were reached for the same shear displacement. Fig. 5d shows the Mohr-coulomb plane for the sand samples. The peak friction angle is 42° while the residual friction angle is 35°. The same peak and residual friction angles at both temperatures show the negligible effect of thermal variations on the shearing behaviour of the studied sand.

3.2 Sand-structure

Fig. 6a shows the CNL results of the sand-structure tests with different initial effective normal stresses (σ'_{n0}=100, 200, 300 kPa) at 22 and 60 °C. The peak and residual values of the shear stress at different temperatures are almost the same. The contraction (0.01 mm) and dilation (-0.2 mm) amounts in the volumetric response are approximately half that of the sand-sand case due to the thickness of the soil sample in the sand-structure tests (Fig. 6b). In terms of the temperature effects on the volumetric response, at both 22 and 60 °C, the volumetric responses followed the same trend. The stress ratio curves for different temperatures vary between 0.8-1 (Fig. 6c). The Mohr-Coulomb plane of the sand-structure tests under the CNL condition is presented in Fig. 6d. The peak friction angle of the sand-structure interface is 37°. Fig. 7 shows the constant normal stiffness results for sand-structure samples at 22 and 60 ^{o}C. With increasing the stiffness of the surrounding soil the dilating behaviour of the sand at interface zone was more restricted compared to CNL case, and the normal stress acting on the interface increased, consequently the shear stress increased (Fig. 7a and Fig. 7c). The volumetric response of sand at interface controls the amount of normal stress increase (Eq. 1). Fig. 7b shows that at the beginning of shearing the interface contracted slightly which decreased the normal stress then with starting the dilation, the normal stress increased. Fig. 7b shows the volumetric response of interface at CNS condition for two values of temperature (22 and 60 ^{o}C). Fig. 7d shows the Mohr-coulomb plane of the sand-structure interface. The soil was consolidated under 100 kPa of normal stress at the beginning, then with starting the shear the normal stress first decreased then increased. The superposition of curves at 22 and 60 ^{o}C shows that temperature has a negligible effect on Fontainebleau sand shear behaviour.

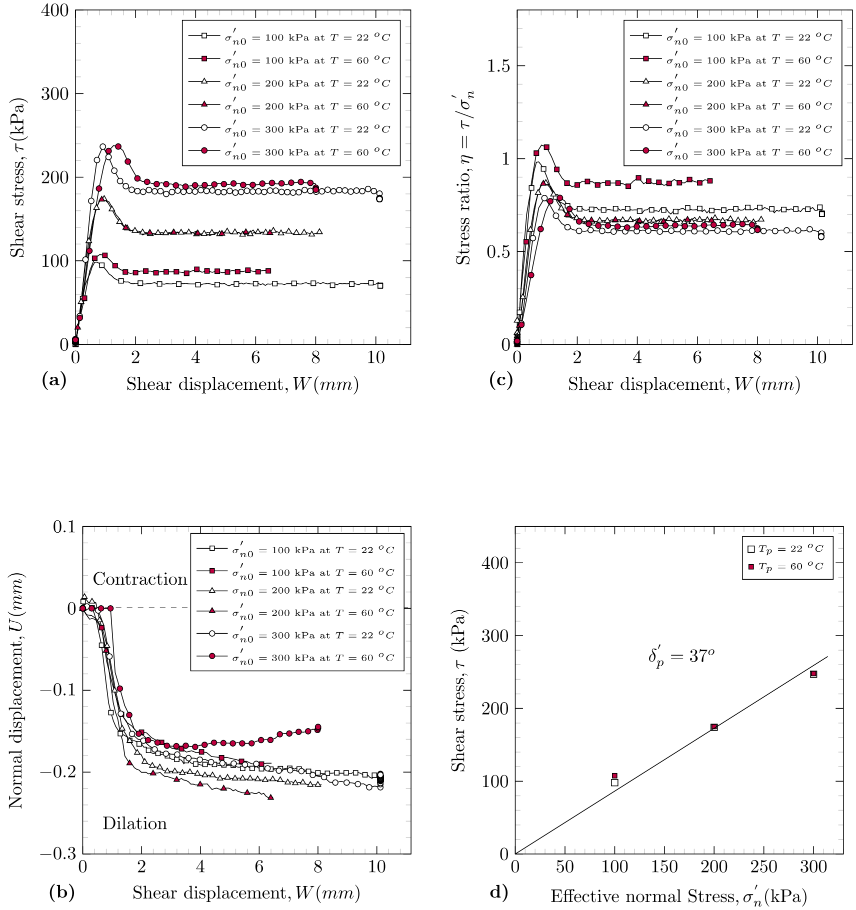

Figure 6. Sand-structure constant normal load test results at 22 ^{o}C and 60 ^{o}C.

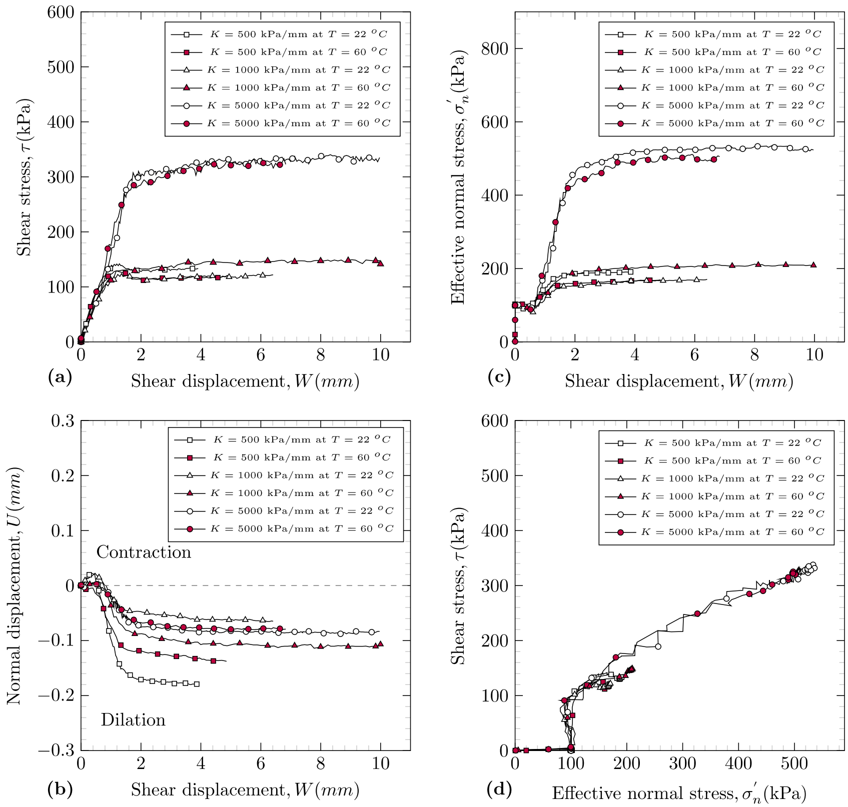

Figure 7. Sand-structure constant normal stiffness test results at 22 ^{o}C and 60 ^{o}C.

4 CONCLUSIONS

Constant normal load (CNL) and constant normal stiffness (CNS) tests were carried out on sand and sand-structure interface at different temperatures (22-60 ^{o}C). The CNL results of sand showed that the temperature have a negligible effect on the mechnical properties of Fontainebleau sand.

For sand-structure interface tests, the CNL results at different temperature confirms the same behaviour as sand and the lower value of friction angle assures that the shear have occured at the interface zone. In CNS tests of sand-structure different stiffness values were applied at different temperatures, and it was observed that with increasing the stiffness the normal and shear stresses acting on the interface increases subsequently. In CNS tests such as the CNL tests, the temperature does not change the interface behaviour.

Further work will be carried out to investigate the effects of monotonic and cyclic thermo-mechanical loadings on the shear characteristics of clay and clay-structure interface.

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