Influence of thermal cycles on the deformation of soil-pile interface in energy piles

Roxana Vasilescu[1,2,*], *Kexin* Yin[1], *Anne-Laure* Fauchille[1], *Panagiotis* Kotronis[1], *Christophe* Dano[3], *Richard* Manirakiza[2], and *Philippe* Gotteland[4]

[1]Institut de Recherche en Génie Civil et Mécanique (GeM), Ecole Centrale de Nantes, Université de Nantes, France
[2]PINTO SAS, 35300, France
[3]Université Grenoble Alpes, CNRS 38000 Grenoble, France
[4]Fédération Nationale des Travaux Publics, 75008 Paris, France

Abstract. Energy piles are double purpose foundation elements used both for transferring loads to the soil and temperature regulation in buildings. The response of the pile-soil interface is influenced by daily and seasonal temperature variations. In order to assess the impact of thermal cycles on the mobilization of shear strength in energy piles, a series of saturated soil-concrete interface direct shear tests were performed in the laboratory for different temperature gradients with a new interface direct shear device adapted for thermomechanical loading. As natural soils are very complex due to a high variability of mineralogy and anisotropy, silica and carbonate sands were chosen in this study. Those sands are considered as the main types of sandy soils commonly met in geotechnics. The experimental campaign is divided in two parts: (i) Concrete-soil direct shear tests at 13°C (constant temperature) to be used as a reference (ii) Concrete-soil direct shear tests after 10 temperature cycles with a gradient $\Delta T=10°C$, under submerged conditions. For these two types of soils, realistic temperature cycles applied between 8 and 18°C cause the overall low contraction of the samples. However the interface friction angles are not significantly modified before and after the temperature cycles. Even if the vertical strains of soils are cumulative along temperature cycles, soil's strains and friction angle changes are relatively negligible for the temperatures and water content tested, which support the low impact of temperature cycles on the deformation of soil concrete foundation under submerged conditions. These experimental results bring new features which will be implemented in numerical models to study the long-term use of energy piles.

1 Introduction

Energy piles are double purpose structures which consist in the integration of heat exchanger, within structural foundations [1]. The operation of the ground source system energy piles brings about temperature changes which can have an impact on the pile deformation [2-7] as well as on the soil-pile interface [8-10]. Although this solution has been used for some time in Europe, the information concerning the long term thermo-mechanical behavior of the foundation and of the surrounding soil is still limited.

Focusing on the response of the soil-pile interface, Xiao et al., Di Donna et al., and Yavari et al. performed direct shear tests to explore the effect of the temperature changes [11-14] and Xiao et al. [15] investigated the effect of temperature cycles on a disturbed natural soil-concrete interface for unsaturated conditions. For a saturated clay-concrete interface, Di Donna et al. showed an increase of the interface shear strength due to heating, which may be explained by thermal consolidation [12]. Yavari et al. showed that the temperature effects on the

friction angle and adhesion are minor [13-14] and the results of Xiao et al. [11] showed a slight decrease of adhesion of the soil-concrete interface when subjected to cooling and negligible effects on the friction angle for unsaturated soil conditions. Xiao et al. [15] also pointed out that after 10.5 temperature cycles an increase of the interface shear strength as well as an increase of adhesion (in the case of large heating cycles) was detected for sandy silty clay-concrete interface and it was mostly attributed to water migration due to the temperature changes.

Even though energy piles can be used regardless of the degree of saturation of the soil, the geothermal activation of the foundation is more efficient when the soil is saturated (i.e. the entire pile or part of it rests below the ground water level). In this case saturated conditions, or at least submerged conditions, are required to investigate the behaviour of soil-pile interfaces at the laboratory scale.

This study, further investigates the effect of temperature cycles on the soil-structure interface under submerged conditions in a direct shear box adapted for thermomechanical loading by using two of the most

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* Corresponding author: andreea-roxana.vasilescu@ec-nantes.fr

commonly encountered sand types: silica sand and carbonate sand.

2 Experimental setup

An interface direct shear test device adapted for thermo-mechanical loading was employed for performing the experiments (Fig. 1a). The shear box is divided in two parts, subsequently referred to as upper part and bottom (lower) part. This box is installed in a container which is filled with water for simulating saturated conditions. The upper part holds samples of 100 mm × 100 mm soil specimens with an initial height of 25 mm, while the bottom part contains a 140 mm × 100 mm × 11 mm concrete plate (Fig. 1c).

A temperature sensor (precision of ±0.2°C) is situated in the lower part, under the concrete plate. The thermal loading is applied through a closed loop circuit (Fig. 1b), that passes through a system installed under the container accommodating the shear box and that is connected to a refrigerated heating circulator bath with air-cooled cooling machine. The thermoregulation system is equipped with one Pt100 internal temperature sensor and one Pt100 temperature sensor external connection, in which the bottom temperature sensor is plugged-in. The temperature in the tested specimen is measured through the above mentioned Pt100 temperature sensor installed under the bottom part of the shear box which is also used for running the temperature tests.
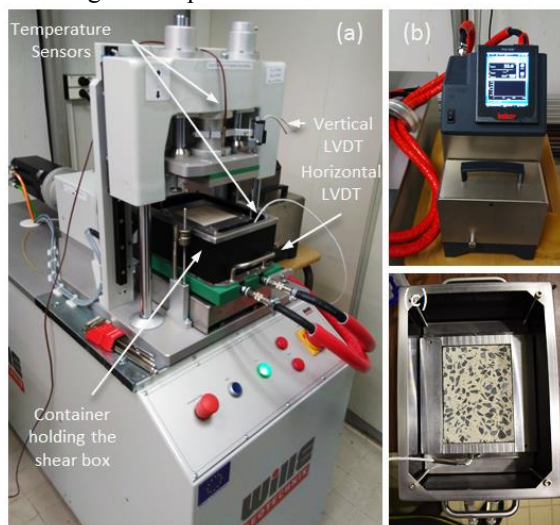

Fig. 1. Interface direct shear test device: (a) Mechanical loading frame; (b) refrigerated heating circulator bath; (c) concrete plate fixed in the lower box, installed in the container holding the shear box.

A load cell is installed on each actuator to measure the vertical and horizontal loads applied on the sample. Two linear variable differential transducers (LVDTs) are used to measure the horizontal and vertical displacements with a precision of ±10 μm.

3 Materials

3.1 Concrete

The concrete was prepared in the laboratory by mixing CEM I 52.5 N CE CP2 NF-23-01-12 cement, limestone filler, sand (0-4 mm) and aggregates (6-10 mm) according to a mix design based on Eurocode 2. Several pieces of concrete with the thickness of 11 mm were cut and fixed in the bottom box as shown in Fig. 1c.

The same concrete plate was used for all sand experiments. The value of the maximum vertical distance between the highest and the lowest peaks of the structure's asperities over a gage of fixed length (R_{max}) was 83 μm to 93 μm before and after the tests. Therefore no significant changes of concrete roughness after the direct shear tests were recorded in the study conditions.

3.2 Silica sand

Fontainebleau sand NE34 (Sibelco) was used in this study for its high quartz content (99% quartz). The limited temperature effect on the mechanical behaviour of Fontainebleau is well-characterised [12-13] and this sand was thus used as a reference sand to evaluate the performance of the testing device and the repetability of the testing procedure. The physical properties of Fontainebleau sand are presented in Table 1.

Table 1. Fontainebleau sand properties.

C_u (-)	D_{10} (mm)	D_{50} (mm)	ρ_s (g/cm^3)
1.70	0.13	0.21	2.65

where: C_u is the coefficient of uniformity, D_{10} and D_{50} are the sieve diameters corresponding to 10 and 50% of material passing and ρ_s is the grain density.

3.3 Carbonate sand

Carbonate sand from South China Sea was used to assess the effect of temperature cycles on the soil-structure interface. The available material is disturbed and uncemented. The tested sand was obtained by mixing segregated grain size samples ranging between 1.0 mm and 4.0 mm. The content of calcium carbonate exceeds 97% and the main mineral components are aragonite and magnesium calcite. Many of the carbonate grains are dendritic and crushable. The physical properties of carbonate sand are presented in Table 2.

Table 2. Carbonate sand properties.

C_u (-)	D_{10} (mm)	D_{50} (mm)	ρ_s (g/cm^3)
1.45	1.09	1.35	2.76

where: C_u is the coefficient of uniformity, D_{10} and D_{50} are the sieve diameters corresponding to 10 and 50% of material passing and ρ_s is the grain density.

4 Experimental procedure

For all the tests each sample was installed by pouring layers of sand and then compacting them by dry tamping. The sample was then placed in the loading frame and a vertical load of 50 kPa, 100 kPa or 150 kPa (corresponding to the effective lateral pressure at 5 m, 10 m and 15 m deep), was applied and kept constant during the entire test (CNL test). Distilled water was added in the container in order to perform the test in almost saturated conditions. Temperature was then set to 13°C, corresponding to a reference temperature bellow a ground depth of 5 m [16].

The experimental campaign is divided in two parts: (i) Concrete-soil direct shear tests at 13°C (constant temperature) to be used as a reference and (ii) Concrete-soil direct shear tests after 10 temperature cycles with a gradient ΔT=10°C. For the first part of the experimental campaign, after reaching the 13°C target temperature in the sample, a displacement controlled interface direct shear test was performed at a loading speed of 0.5 mm/min. For the second part of the experimental campaign a temperature variation between 8°C and 18°C was imposed before performing the displacement controlled interface direct shear test.

5 Results and discussion

5.1 Silica sand

For Fontainebleau sand samples, the volumetric strain ε_v shows cycles with a maximum amplitude of 0.25% (Fig. 2a, c, e) during temperature cycles (Fig. 2b, d, f). An accumulation of negative strains is recorded. These results may be explained by small grain rearrangement and gradual volume reduction. As expected, a dilating phase during heating is followed by a contracting phase during cooling for each cycle, leading to an overall contraction of the sample. It should be noted, that for each heating/cooling cycle, a delay may be observed in the sample response: during heating, while the temperature is increasing, the sample exhibits contractive behaviour and only after the target temperature is reached, it begins to expand. This may be explained by the thermal inertia of the concrete plate and of the sand. Fig 2a, c and e also suggest that the magnitude of the volumetric strain is dependent on the applied vertical load and the sample's density: the higher the applied load, the lower the recorded volumetric strain, and the lower the density, the higher the volumetric strain is (the sample in Fig 2a has the density of 1.76 g/cm³, the one in Fig 2b has the density of 1.73 g/cm³ and the one in Fig 2c has the density of 1.79 g/cm³).

The interface friction angle, calculated from the three displacement controlled interface direct shear test (for a vertical load of 50 kPa, 100 kPa and 150 kPa respectively) was found equal to 25° for the tests performed on Fontainebleau sand at 13°C and 25.3° for the cyclic tests 8-18°C. These values are lower than the soil internal friction angle (36°) which confirms that the shearing occurs at the interface rather than in the soil. The 0.3°

difference between the interface friction angles identified for the two types of test suggests that there is no influence of temperature cycles on the shear strength mobilization for the sand concrete interface.
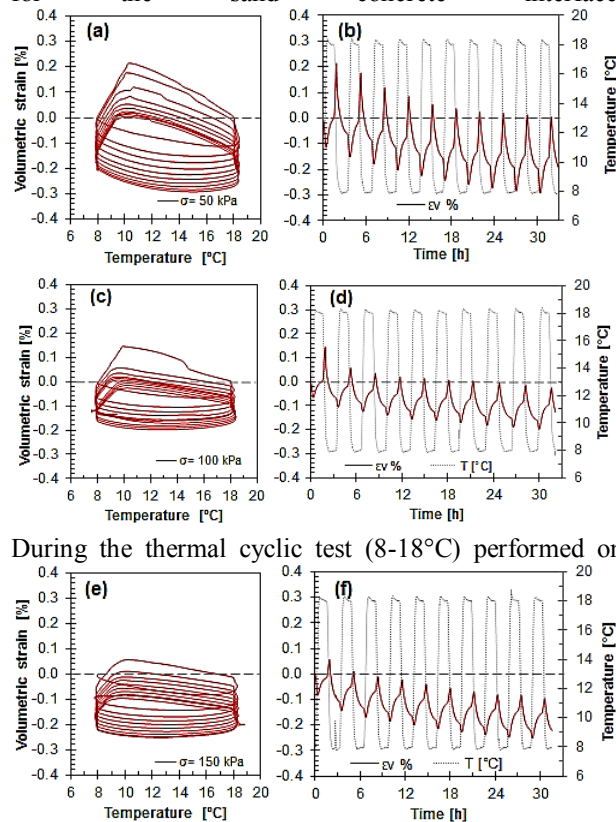

Fig. 2. Fontainebleau sand cyclic temperature test series: (a) Evolution of the volumetric strain and temperature at 50 kPa; (b) Time evolution of the volumetric strain and temperature at 50 kPa; (c) Evolution of the volumetric strain and temperature at 100 kPa; (d) Time evolution of the volumetric strain and temperature at 100 kPa; (e) Evolution of the volumetric strain and temperature at 150 kPa; (f) Time evolution of the volumetric strain and temperature at 150 kPa.

5.2 Carbonate sand

The carbonate sand cyclic temperature tests show similar results to those obtained for Fontainebleau sand: a dilating phase during heating is followed by a contracting phase during cooling for each cycle, leading to an overall contraction of the sample (Fig. 3). In the case of carbonate sand, though, the sample expansion is more pronounced. The maximum volumetric strain is also more important (35% during the first thermal cycle). An almost symmetric behaviour can be observed in the case of carbonate sand, hinting to its thermo-elastic behavior (Fig. 3a, c, e). The same offset between the sample response and the type of loading (heating/cooling), as in the case of Fontainebleau sand, can be observed for carbonate sand: the sample stars swelling only after the target temperature was reached, for heating. The carbonate sand test results also display more pronounced volumetric strain values for lower load levels and for lower densities.
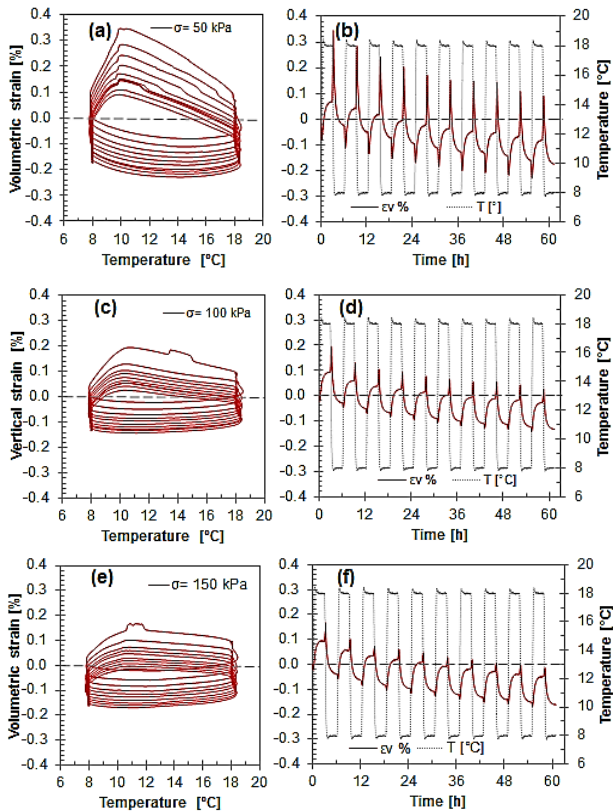
Fig. 3. Carbonate sand cyclic temperature test series: (a) Evolution of the volumetric strain and temperature at 50 kPa; (b) Time evolution of the volumetric strain and temperature at 50 kPa; (c) Evolution of the volumetric strain and temperature at 100 kPa; (d) Time evolution of the volumetric strain and temperature at 100 kPa; (e) Evolution of the volumetric strain and temperature at 150 kPa; (f) Time evolution of the volumetric strain and temperature at 150 kPa.

The interface friction angles, obtained from the displacement controlled interface direct shear test at 13°C and for the cyclic tests 8-18°C are 30.7° and 31.6° respectively. These values are lower than the soil internal friction angle (41°) which confirms that for the carbonate sand-concrete tests the shearing occurs at the interface rather than in the soil. The 0.9° difference between the interface friction angles identified for the two types of test (at constant temperature and after 10 temperature cycles) implies that there is no influence of temperature cycles on the shear strength mobilization for the sand concrete interface. This difference may be due to the slight sample densification after the temperature cycles.

6 Conclusions and perspectives

The effect of cyclic temperature changes on quartz sand-concrete and carbonate sand-concrete interface in conditions was studied in the laboratory using an interface direct shear device adapted for thermo-mechanical loading.

It was found that the effect of 10 temperature cycles with a gradient $\Delta T=10°C$ on the mobilization of the shear strength at the soil-concrete interface is negligible. Nevertheless, these temperature cycles lead to a slight sample densification for both types of sand. The preliminary conclusions of this work therefore confirm the limited effect of temperature cycles on sandy soil pile interface deformation below the level of groundwater table.

These results also provide quantitative information concerning the amplitude of the volumetric strain of sandy materials subjected to temperature cycles for further development of numerical models that simulate accurately the effect of temperature at the pile-soil interface.

Further interface direct shear tests will be conducted to explore the effect of a higher number of cycles (50 to 100 cycles) and higher temperature gradients on the soil-concrete interface. A series of clay concrete-interface tests will also be conducted in order to determine the effect of temperature cycles on the shear strength parameters. This new series of experiments will help understand the relationships between the temperature and shearing behaviour of a large panel of natural soils and will aid to improve the design of more efficient energy geostructures.

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