Introduction

All kinds of ground-embedded structures, such as tunnel anchors and linings, slabs, piles and diaphragm walls, can be used to exchange heat with the ground. A system of pipes installed within concrete structures, with a heat carrier fluid that circulates through it, can extract heat from the ground to satisfy the need for heat during the winter and can expel excess heat during the summer, based on the concept of shallow geothermics. Since energy geostructures are becoming more and more common, there is a need for improved scientific knowledge of their behaviour (Laloui and Di Donna, 2011). Several efforts have been devoted to the investigation and optimization of the energy performance of such structures (Pahud, 2002). With regards to their mechanical behaviour and geotechnical design, research has been devoted to the in-situ characterization (Amatya et al., 2012), numerical analysis (Laloui et al. (2006), Dupray et al. (2013), Di Donna et al. (2013)) and the development of design tools (Knellwolf et al., 2011), with the purpose to include the effects induced by the temperature changes in the design procedure. A part of the recent advancements related to this topic are illustrated in this work, including mainly the effects of seasonally cyclic thermal loading on the soil and pile-soil interface response, with the consequent effects in terms of stresses and displacements induced in an energy piles foundation.

Thermo-mechanical behaviour of soils: experimental and numerical results

When a thermal load is transmitted from a pile to the soil, this latter reacts by changing its volume, and eventually its response, depending on the type of soil. The main consequence of the thermal volume variation in the soil is to affect the foundation displacements, making it move upwards when the soil dilates and downwards when it contracts. The entity of this effect on the behaviour of the foundation depends on the volume of heated ground and the range of temperature variation. The thermal load imposed by energy piles in current applications is in the range of 2-30 °C, but future developments employing the injection of heat in the ground from other technologies, such as solar panels, will lead to higher temperature variations. Soils are porous materials made of a solid skeleton, represented by grains or aggregates, and pores that, in saturated conditions, are filled with water. Heating a granular soil (sand or gravel) in drained conditions results in an increase of volume directly related to the grains' thermal expansion coefficient. The response of clays is more complicated as it depends on the microstructure and the electrochemical equilibrium between clay particles (Hueckel, 1992). In particular, it has been largely demonstrated that the material contracts upon heating in NC conditions and a significant part of this deformation is irreversible, while highly OC materials experience a volume expansion during heating that is recovered during cooling. The first experimental results of this nature date back to the 1960s – 1980s (Campanella and Mitchell, 1968) and have been widely confirmed more recently (Burghignoli et al. (2000), Cekerevac and Laloui (2004)). Concerning the response under more than one heating-cooling cycle Campanella and Mitchell (1968) have shown that the first temperature cycle removes most of the irreversible volume change in NC clays and that subsequent cycles of the same magnitude and range produce small increments of irreversible deformation that decrease cycle after cycle, revealing an accommodation phenomenon. Similar results have been obtained by the different authors for a wide range of different clayey materials containing variable quantities of illite, kaolinite, chlorite and smectite (Figure 1a). Several constitutive models for describing this behaviour have been proposed in the last two decades and a comprehensive summary of their features, capabilities and limitations is presented by Hong et al. (2013). Among these, the ACMEG-T model proposed by Laloui and Francois (2009) has been validated and shown to be capable of reproducing the experimental results under different thermal-stress paths with good accuracy. One example is provided here, related to Boom clay (experimental data from Baldi et al. (1991)). The parameters were previously calibrated based on experimental data available in the literature (Laloui and Di Donna (2013)). The test includes three experiments (one NC and two OC) run by imposing one drained heating-cooling cycle from 20 to 95 °C under constant isotropic confinement. The confinement imposed for the NC conditions was 6 MPa, while in the two OC cases, the sample was first consolidated to 6 MPa and then unloaded to 3 (OCR=2) and 1 MPa (OCR=6).

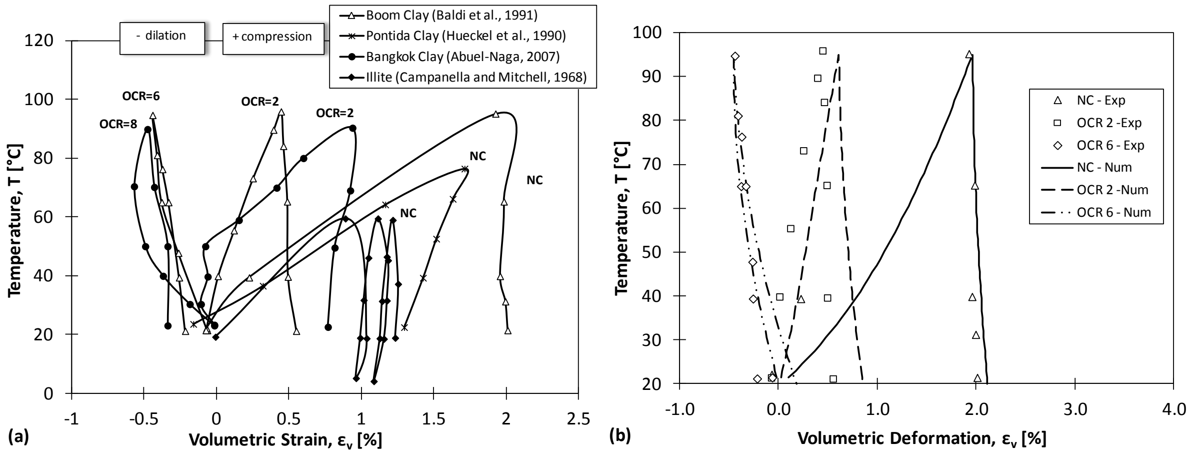

***Figure* 1** *Thermal deformation of clays: (a) experimental results (b) numerical simulations.*

Identical thermal-stress paths were numerically simulated with the ACMEG-T model, and the results, presented in Figure 1b, show the ability of the model to develop thermo-elastic or thermo-elastoplastic deformation depending on the material's initial OCR.

Thermal effects on the pile-soil interface

With the purpose to investigate the response of soil-concrete interface at high temperature a new direct shear box with temperature control was designed and calibrated. The geometry of the shear box allows running soil-concrete interface test keeping constant the contact area between the two materials. Besides, it was especially designed to accommodate also the heating system. This latter is innovative and based on an electrical heating tissue. Finally, the normal stiffness control, known to be essential to reproduce the real pile-soil interface conditions (Lehane et al., 1993), was implemented. Tests were run on sand-concrete and clay-concrete interfaces, employing quartz sand and illite clay respectively. Both constant normal load (CNL) and constant normal stiffness (CNS) conditions were investigated, at ambient (20 °C) and high (60 °C) temperature. The (initial in case of CNS tests) imposed normal load was 50, 100 and 150 kPa, as representative of the pile-soil interface conditions. The imposed normal stiffness (in CNS tests) was computed as (Wernick, 1978):

$$K = 2G/r \qquad (1)$$

where G is the shear modulus of the soil and r the radius of the considered pile. The first results show that the response of a sand-concrete interface is not affected by temperature while this is not the case for the one of a clay-concrete interface (Figure 2).

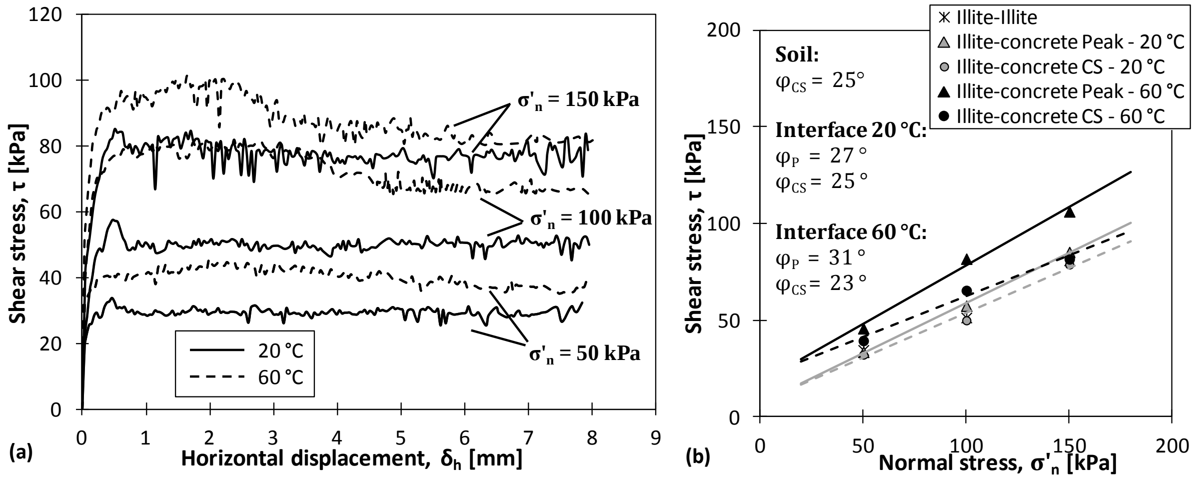

***Figure* 2** *Experimental results on clay-concrete interface at different temperature.*

In this latter case, the shear resistance increases at high temperature even if the friction angle remains constant (translation of the failure envelop). This is thought to be due to the thermal consolidation of the clay, but this observation needs more evidences to be confirmed.

Numerical simulations

After the implementation of the results presented in the two previous sections into a finite element code, several years of seasonally cyclic thermal loading on an energy pile foundation were studied numerically (Di Donna et al., 2013). The considered soil was NC and its behaviour, as well as the one on the pile-soil interface, was reproduced with the ACMEG-T model, which is also able to consider the cyclic accommodative thermal response of the soil. In the considered case, the additional irreversible settlement induced by the thermal loading was about 2.5 mm (10% of that induced by the mechanical load) while the amplitude of the elastic cyclic displacement of the piles was about 6 mm (see Figure 3a, where pile 1 is internal and pile 4 is external in the foundation). From a structural point of view, the heating and cooling phases result, respectively, in additional compressive and tensile stresses inside the piles (Figure 3b, where pile 2 is an internal pile). These are caused by the partial constraints imposed by the surrounding soil and the slab to the free thermal deformation of the foundation. The piles are more and more compressed after heating during the first 5cycles and then the internal stresses remain constant, when the thermal response of the soil becomes elastic (accommodation). During cooling the piles are less compressed with respect to the end of the heating but they never undergo tensile stresses. In conclusion, the thermally-induced effects in terms of piles' displacements and stresses are present but acceptable under normal working conditions.

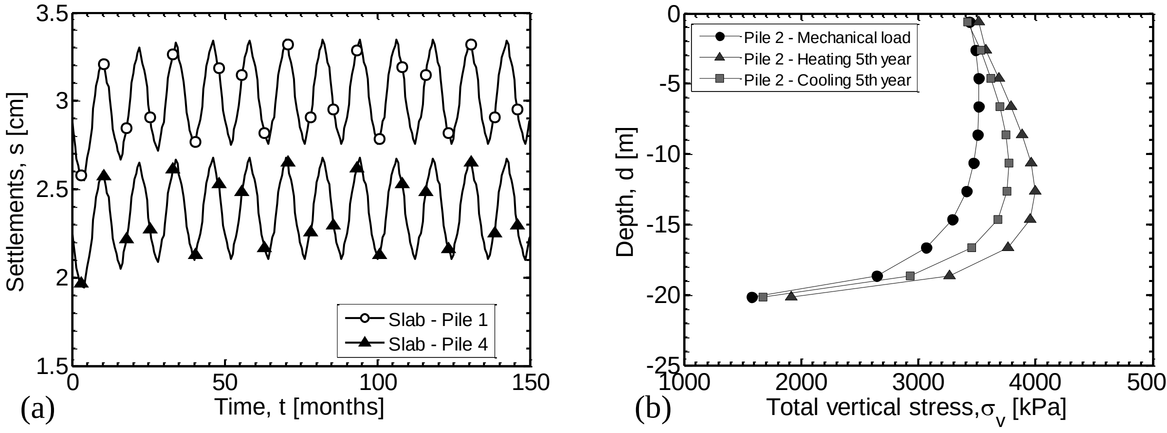

***Figure* 3** *FE simulations of an energy piles foundation: (a) piles' displacement and (b) piles' stresses during heating and cooling cycles (Di Donna et al., 2013).*

Conclusions

Besides the mechanical load coming from the building, energy piles transmit to the soil also a seasonally cyclic thermal load. The effects induced by this additional thermal load on the soil and pile-soil interface behaviour were studied experimentally and the thermoelastic-thermoplastic model ACMEG-T (Laloui and Francois, 2009) was shown to be able to reproduce the laboratory results. The implementation of this model into a finite element code allowed studying the mentioned effects on the response of an energy pile foundation, both in terms of piles' displacements and stresses. The results showed that the thermally-induced effects are present but acceptable under normal working conditions. In particular, the foundation showed thermal elastic displacements of 6 mm, an additional irreversible settlement of 2.5 mm at the long term and maximum additional stresses of 400 KPa.

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