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Response of soil subjected to thermal cyclic loading: Experimental and constitutive study

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ABSTRACT

The response of soil subjected to thermal cyclic loading plays an important role in certain engineering applications, such as high-level nuclear waste disposal, heat storage systems, CO_2 sequestration plant and energy geostructures. For instance, energy geostructures impose temperature variations that are daily and seasonally cyclic to the soil and might have consequences of engineering relevancy, mainly in terms of foundation displacements. This paper aims to experimentally investigate the response of a natural silty clay soil to thermal cyclic loading in drained conditions. The experimental programme includes: (i) oedometric tests at various constant temperatures aimed at studying the sensibility of the material to temperature and (ii) thermal cyclic tests under constant vertical effective stress in oedometric conditions, with temperature ranging between 5 and 60 °C. As expected, the silty clay tested under normal consolidation conditions (NC) undergoes thermo-plasticity, and the results indicate that most of the irreversible deformation occurs during the first heating–cooling cycle, exhibiting an accommodative behaviour during the subsequent cycles. In other words, increments of irreversible deformation are observed in the thermal cycles successive to the first one, which generally become smaller and smaller cycle after cycle until stabilisation. In the end, the material tends to remain inside the elastic domain, exhibiting thermo-elastic expansion and contraction during heating and cooling. In the second part of the paper, an extension of an existing thermoelastic–thermoplastic constitutive model that aims to tackle the accommodative response is proposed. The extended model is able to reproduce the accommodation phenomenon thanks to an additional parameter called the cyclic plastic radius. The experimental results obtained are innovative in clarifying the response of soils subjected to drained thermal cyclic loading, and the constitutive model presented allows this aspect to be considered in the numerical analysis of the engineering applications where it is of concern.

1. Introduction

The study of the thermal effects on the behaviour of soils has always been a challenge for geotechnical engineers because there are many practical applications in which the response of soils to a thermal loading plays a crucial role. Examples include high-level nuclear waste disposal (Dupray et al., 2013), heat storage systems (Burger et al., 1985), energy geostructures (Laloui and Di Donna, 2013), buried high-voltage cables (Boggs, 1982) and CO_2 sequestration plant (Ochsner, 2008). Several efforts have been made recently to experimentally investigate the behaviour of soils in non-isothermal conditions at the laboratory scale (Abuel-Naga et al., 2007; Baldi et al., 1991; Boudali et al., 1994; Burghignoli et al., 2000; Cekerevac and Laloui, 2004; Hueckel and Baldi, 1990). Contemporaneously, efforts have also been devoted to the development of constitutive models that consider the thermal aspects. A state-of-the-art on this topic including a comparison between some of the available models was recently provided by Hong et al. (2013). Focusing on the consequences of the thermo-mechanical behaviour of soils on the engineering aspects related to energy geostructures (Di Donna and Laloui, 2013), it appears that: (i) the soil volumetric behaviour, which is responsible for the eventual additional displacements of the over-structure, is of primary importance; (ii) low temperatures are also involved in the process, up to approximately 5 °C; and (iii) an important role is played by the fact that the temperature variations are daily and seasonally cyclic, rather than monotonic, and occur in drained conditions. Only a few experimental results are currently available in such conditions (Campanella and Mitchell, 1968; Hueckel et al., 1998), and the physical mechanisms that control this behaviour have not yet been fully identified. In this framework, the goals of this paper are to experimentally investigate the volumetric response of a silty soil subjected to drained thermal cycles between 5 and 60 °C and to propose a constitutive model that is able to reproduce the observed behaviour.

2. Experimental investigation

The experimental setup developed ad-hoc for the purposes of this paper, the characterisation of the tested material and details about the

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followed stress–temperature paths are first described. Then, the attention focuses on the obtained results. The response of the material to mechanical loading under oedometric conditions at various constant temperatures is analysed to gain insight into its sensitivity to temperature and characterise its behaviour from the thermal viewpoint. The response under constant vertical effective stress during cyclic temperature changes is then studied and represents the main topic of this paper.

2.1. Experimental setup

The devices employed for the experiments are four oedometric cells that have been adapted to include the control of temperature (Fig. 1). The vertical stress is imposed through calibrated dead weights, and the vertical displacements are measured by four LVDTs (operating scale OS ±2.5 mm, sensitivity 0.099 mm/mV, accuracy ±0.21% OS). The thermal load is provided by spiral tubes positioned around the specimens and connected to a heater. The latter consists of a thermostat through which the temperature of the bath is imposed. A pump circulates the water at the desired temperature inside the spiral tubes, from the thermo-controlled bath to the cells. Both heating and cooling are possible, and the range of temperature considered is 5 to 60 °C. During the tests, the temperature is constantly monitored inside each cell using four thermocouples (type-K, accuracy of 0.1 °C). The cells are insulated with a polystyrene box to minimise the thermal losses. Oedometric rings made of invar (coefficient of thermal expansion of $5.5 \cdot 10^{-7}\ °C^{-1}$) are used to minimise the thermal radial deformation and guarantee the oedometric conditions during temperature changes. A system for water supply is installed to face the water evaporation during heating and maintain constantly saturated conditions. The entire apparatus was carefully calibrated for temperature.

2.2. Tested materials

Four soil samples (hereafter referred to S1, S3, S4 and S4b) were collected near Geneva, in Switzerland, in the framework of a project involving the construction of a new building and a large number of geothermal boreholes to be installed below it. Due to the poor quality of the ground in that area, the building lies on deep foundations. The latter are not equipped as energy piles, but will be equally subjected to the temperature variations induced by the geothermal boreholes, the foreseen maximum temperature for the project being 40 °C. The configuration is thus similar to the one of energy pile foundations and the thermal characterisation of the involved soil was needed for design purposes. The in-situ soil conditions were normally consolidated (NC) and the in-situ state of stress of the collected samples is presented in Table 1. The sample identification properties are collected in Table 2 and their position on the Casagrande chart is plotted in Fig. 2a. Accordingly, despite the differences in terms of liquid limit and plasticity index among the samples, they are all classified as inorganic clay with medium plasticity. According to the USCS classification, the tested material is a natural silty-clay. The four samples can be considered saturated, with natural water content in the range of 22 to 28%. The grain-size distribution is similar for the four samples, with fine fraction (diameter < 0.06 mm) between 94.7 and 97% (Fig. 2b). The samples were conserved in a humid chamber to keep the natural conditions. For each test, the specimen was cut from the in-situ collected samples and positioned in the oedometric cell, which was then filled with demineralised water. The specimens were cylindrical with a diameter of 60 mm and height of 20 mm.

2.3. Stress and thermal paths

As already mentioned, the whole experimental programme is divided into two parts, one devoted to characterise the material from a thermal point of view and the other to study the effects of thermal cyclic loading. This corresponds to two different stress–temperature paths: (i) oedometric tests at different constant temperatures (20, 40 and 60 °C) and (ii) thermal cycles under constant vertical effective stress (Fig. 3). The value of stress at which the thermal cycles are applied indicated in Fig. 3 corresponds to one of the experiments presented in the following; the details of the whole experimental programme are provided in Table 3. For the first stress–temperature path, the desired temperature was imposed to the sample under no vertical stress (except the weight of the top cap of 1 kPa) and, once the temperature and the related deformation stabilised, a complete oedometric test was performed. In this way, the first heating phase occurs in elastic conditions (applied stress lower than in-situ stress). The considered steps of vertical stress were 15, 60, 125, 250, 500, 1000 kPa and unloading to 60 kPa. Two tests were performed at 20 °C, two at 40 °C and two at 60 °C. For each of these temperatures, one test was run on a S3 specimen and the other was run on a S4 specimen (tests 1 to 6 in Table 3). The two specimens tested at 60 °C (tests 3 and 6 in Table 3), after unloading to 60 kPa, were cooled back to ambient temperature and finally subjected to thermal cyclic loading. This provided additional information about

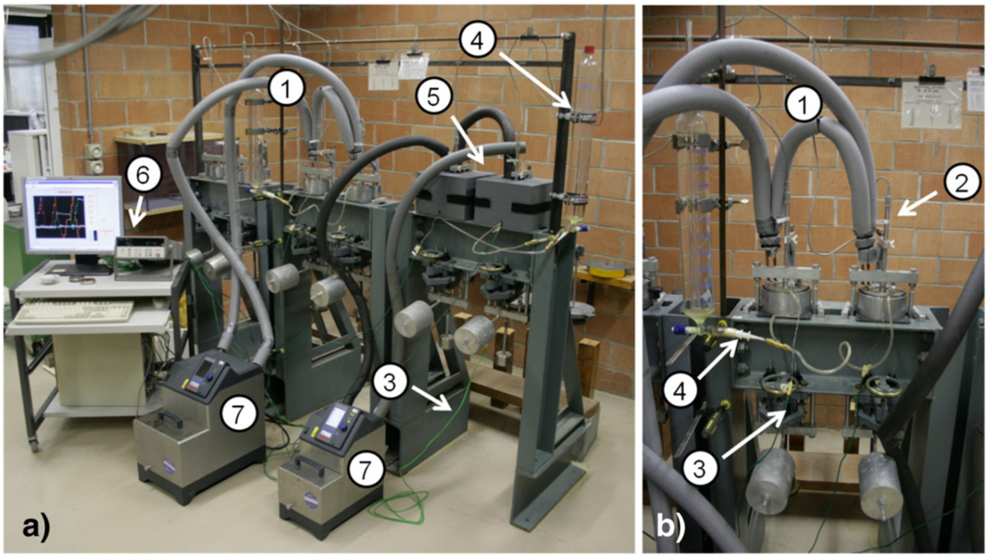

Fig. 1. Experimental setup: (a) global view and (b) detail (1: tubes with circulating water at the desired temperature, 2: LVDTs, 3: thermocouples, 4: water supplier, 5: insulation, 6: acquisition system, 7: heaters).