On the development of a new temperature-controlled triaxial apparatus for saturated soils

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In recent years, the study of the thermo-hydro-mechanical (THM) behaviour of soils has been a growing research area within the geotechnical community, due to its importance in a wide range of modern civil engineering and energy applications. One strand of the THM research has primarily focused on the potential use of clays as part of the multi-barrier concept in underground nuclear waste disposal facilities. Stiff clays have been considered as potential host rocks (Gens et al., 2007), while heavily compacted swelling clays have been considered for the use as engineered barriers (Delage et al., 2010). Another strand of the THM behaviour of soils focuses on the area of energy geostructures such as ground heat storage and their impact on the host soil (Moritz, 1995; Brandl, 2006; Bourne-Webb et al., 2009; Di Donna & Laloui, 2013). Laboratory testing is essential in order to gain an understanding of the THM behaviour of geomaterials, which conventional soil mechanics cannot explain. Standard laboratory equipment, such as the triaxial apparatus, can be modified to control temperature in addition to stresses. Since the first triaxial apparatus for saturated soils which allowed the control of both temperature and stress, developed by Campanella and Mitchell (1968), several researchers have also developed a range of temperature-controlled testing cells. These can be classified by the technique used for controlling the testing temperature: circulation of a temperature-controlled confining fluid (Campanella & Mitchell, 1968; Savvidou & Brito, 1995), external heating of the cell (Baldi et al., 1987; Lingnau, 1993), or internal heating of the cell (Demars & Charles, 1982; Kuntiwattanakul, 1991; Moritz, 1995, De Bruyn & Thimus, 1996; Cekerevac et al., 2005; Uchaipichat, 2005; Abuel-Naga et al., 2007).

The new temperature-controlled triaxial apparatus developed at Imperial College is schematically presented in Figure 1. It is capable of testing soil samples of up to 50 mm diameter at temperatures up to 85 °C and pressures up to 800 kPa. The apparatus consists of a stainless steel cell which uses de-aired water as confining fluid and incorporates six 150 W cartridge heaters evenly distributed in the top and bottom plates (three each) of the apparatus. Each of the heaters is associated with its own temperature sensor to allow computer controlled temperature regulation. An additional sensor is fitted within the tip of a brass element to monitor the cell fluid temperatures. Both cell and back pressures are controlled via air-water interfaces which incorporate 50 cm^3 volume gauges, with a sensitivity of 0.001 cm^3, to monitor water flowing in and out of the cell and sample respectively. As heat dissipates readily over the length of tubing between the sample and the point of measurement, the volume gauges are located at a significant distance from the cell to ensure that there is no significant transfer of temperature to the measuring devices. Deviatoric stresses are applied to the sample using a digital computer-controlled 50 kN loading frame and are monitored using a high-resolution (±1.5 N) internal 3 kN capacity load cell. The current set-up allows isotropic and triaxial compression tests to be performed and the axial deformations during shearing are monitored using an external LVDT.

Several calibration tests have been performed to understand the behaviour of the apparatus with temperature change and to validate its design. Initially, key aspects of the thermal performance of the cell have been thoroughly investigated: the relationship between the temperature at the monitoring point and the temperature inside the sample, the uniformity of temperature in the sample at steady state, the thermal losses and the effect of the heating rate. A test performed with three T-type thermocouple needles inserted at different heights in a soil sample consisting of a kaolin-based mixture, showed that at a steady state of 80 °C the temperature gradients within the soil are

insignificant, less than 0.2 °C, and the soil sample temperature can be considered to be uniform. In addition, it was shown that the maximum deviation from the measured temperature in the monitoring point of the cell water and at any point of the soil sample is 0.15 °C. This confirms that the temperature sensor within the cell water is a reliable, non-intrusive method of assessing the temperature of the soil sample, which can be assumed to be equal to the cell water temperature. Further tests highlighted that the recommended heating rate for testing is 0.5 °C/hr. This rate ensures that no significant gradients are induced within the cell during the transient state and has the additional benefit of allowing for dissipation of excess pore pressures under drained conditions during the heating and cooling tests. The rate of thermal loss of the cell, which describes the difference between the temperature of the heaters and of the water for different heater temperatures, was found to be of 0.09 °C per 1 °C increase in the heaters. This information is essential for the temperature control of the apparatus.

The second part of the calibration of the apparatus consisted of assessing the behaviour of the different components (steel cell, tubing, volume gauges) with temperature in order to account for system compliance when analysing the data. Two methods were initially proposed for the measurement of sample volume changes during THM tests: "direct" measurements from the cell volume gauge or applying the well-known formula of Campanella & Mitchell (1968), to add to the measured drained water (back volume gauge) the effects of the thermal expansion of the solid and water phases of the sample itself. An initial series of calibration tests performed using a steel dummy sample on top of a saturated porous stone under a confining pressure of 700 kPa and a back pressure of 300 kPa, heating and cooling from ambient to 80 °C, at a rate of 0.5 °C/hr, allowing for equalisation. Initially, a standard latex membrane and nitrile O-rings were used. It was seen that both the latex membrane and nitrile O-rings experienced significant degradation and the measured flow through the membranes were unacceptable. The next test was performed using a neoprene membrane and nitrile O-rings. The magnitude of the seepage through the membrane was reduced, but it was still significant (varying from 0.45 cm^3/day at 80 °C to 0.21 cm^3/day at 40 °C). Despite being relatively small rates, the extensive duration of the tests would result in unacceptable flow volumes. It is also worth noting that the nitrile O-rings suffered significant elongation after the prolonged exposure to high temperature, which may have contributed to the aforementioned flow. Finally, a test was performed using a double neoprene membrane, separated by a thin layer of vacuum grease, and Viton O-rings, which have a high temperature resistance. The flow through the membrane was reduced to less than 0.01 cm^3/day and was considered negligible. The flow of water into (positive) and out of the cell (negative) during the final calibration test is presented in Figure 2. It is non-linear, as the thermal coefficient of volumetric expansion of water is not constant with temperature. A significant amount of water leaves the cell during heating under controlled pressure and at the end of the temperature cycle there is an excess of 3 cm^3 of water that flowed into the cell. This suggests that during the applied temperature cycle the same volume of water is lost through absorption by the plastic top cap, connecting tubing, and membrane itself, in addition to the long-term drift of the volume gauge and the small volume of seepage through the membranes. The results of this calibration test demonstrate then that the cell volume gauge is not a suitable device for measuring sample volume changes since the changes of cell water are much greater than the expected thermal volume changes in the soil, which will be of a similar magnitude to the losses seen in this calibration. The implication of this is that, in the absence of internal instrumentation, only the Campanella & Mitchell (1968) approach can be taken to assess the thermal volumetric strains, which relies on the measurement of the drained water. The behaviour of the drainage (back pressure) system has also been examined in detail. It has been found that the initial set-up which consists of nylon tubing and volume gauge has a continuous drift (loss) of approximately 0.02 cm^3/day at ambient temperature. The calibration tests showed that this drift increases with increasing temperature (up to 0.12 cm^3/day at 80 °C), although without a clear trend which could be taken into account to correct the data. An alternative set-up for the drainage system was then implemented, consisting of steel tubing. The long-term drift of the system at room temperature was significantly reduced to 0.004 cm^3/day. This rate does not increase with increasing temperature as observed in the previous nylon set-up and it is possible to measure the thermal expansion of the drainage system (tubing, porous stone) during heating. A correction can then be made to the measured volumes of drained water.

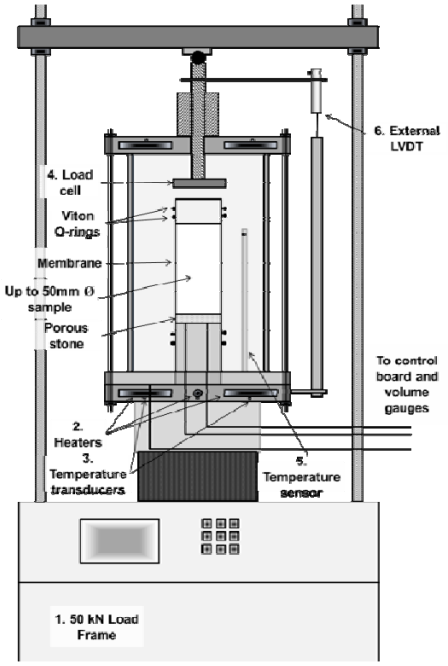

Figure 1. Schematic of the new apparatus

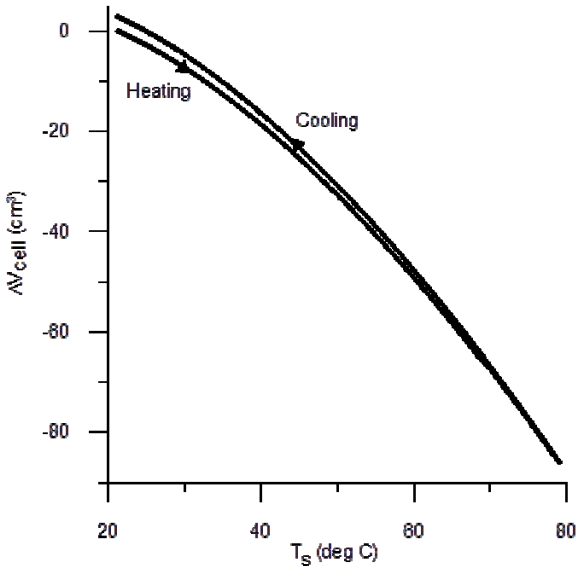

Figure 2. Cell water response to temperature changes

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