A new suction and temperature controlled triaxial apparatus

Un nouvel appareil triaxial à contrôle de succion et de température

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ABSTRACT: In this paper a new hydraulically controlled triaxial apparatus, designed specifically for testing unsaturated soils under non-isothermal conditions, is described. Novel features of the equipment are the use of a laser-based system to measure radial deformation throughout the specimen height, the simultaneous application to both ends of the sample of the air and water pressures required for matric suction control and the incorporation of an external heating system to perform non-isothermal paths. The paper also contains selected results of isotropic suction controlled wetting paths on clay specimens under isothermal conditions, showing the time evolution of axial and radial strains as well as the progressive development of the lateral profiles of the sample. Some results of non-isothermal paths under constant matric suction are also presented.

RÉSUMÉ: Dans cet article, un nouvel appareil triaxial contrôlé hydrauliquement et conçu spécifiquement pour tester des sols non saturés dans des conditions non isothermes est décrit. Les nouvelles caractéristiques comportent l'utilisation d'un système à base de laser pour mesurer la déformation radiale sur toute la hauteur de l'échantillon, l'application simultanée sur le haut et le bas de l'échantillon d'une pression d'air et d'une pression d'eau afin d'imposer la suction matricielle et l'incorporation d'un système de chauffage externe pour effectuer les chemins non isothermes. L'article contient de plus une sélection de résultats de chemins de mouillage isotropes à suction contrôlée sur des échantillons d'argile sous conditions isothermes. L'évolution temporelle des déformations axiales et radiales ainsi que le développement progressif des profils latéraux de l'échantillon sont montrés. Quelques résultats de chemins non isothermes à suction matricielle constante sont de plus présentés.

1 INTRODUCTION

The adequate experimental observation of thermo-hydro-mechanical coupled phenomena affecting partially saturated soils, requires the development of special equipment, providing a reliable phenomenological description of the stress-strain and strength behaviour of the soil. For instance, the disposal of HLW containers in a repository surrounded by compacted clay backfill, will cause temperature variations in the near field of the repository as well as the development of an hydration front when the ground water enters the clay barrier. The backfill will experience heating-cooling and wetting-drying paths, which may cause swelling-collapse and shrinkage response on the clay. To gain insight into these complex phenomena, a new triaxial cell has been built, which also permits the quantitative validation of the theoretical constitutive models and the determination of soil parameters used in numerical analysis.

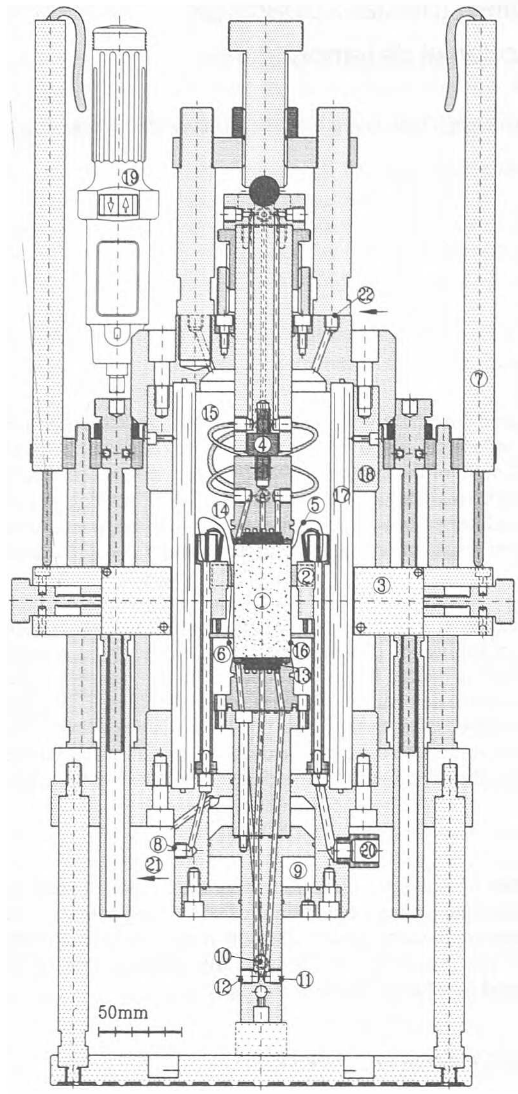
The design of a new thermal triaxial apparatus to test unsaturated soils requires the adoption of a reliable method for controlling matric suction, the development of an accurate procedure to monitor the volume change of the specimen and an adequate heating system to allow for temperature paths. In the past, suction control has been achieved by means of different techniques: osmotic (Delage *et al.* 1987; Cui, 1993), axis translation (Sivakumar, 1993) and controlled relative humidity of the atmosphere that sorrounds the soil (Lagny, 1996). Monitoring of cell fluid in double-walled cells (Bishop and Donald, 1961; Wheeler, 1986; Josa *et al.*, 1987) volume-pressure controllers for air and water volume change measurements and the use of internal local transducers (Maswoswe, 1985; Hird and Yung, 1989; Kolymbas and Wu, 1989; Drumright, 1989) have been used for the measurement of the volumetric deformation of the sample. With regard to the heating system several methods to impose a uniform temperature field in triaxial cells are described in the literature. Heating is provided either by circulation of a fluid, usually water (Savvidou and Britto, 1995; De Bruyn and Thimus, 1996), or by installing internal heaters with a propeller (Towhata and Kuntiwattanakul, 1994), or by surrounding the cell with lateral heaters (Baldi *et al.*, 1986; Saix and Jouanna, 1990; Lingnau, 1993).

This paper describes a new hydraulically loaded triaxial apparatus specifically designed for testing of unsaturated soils with simultaneous control of stress, suction and temperature. Some typical test results of isotropic loaded suction controlled wetting paths, as well as non-isothermal paths under constant matric suction on clay specimens are presented to illustrate the performance of the apparatus and measuring systems.

2 DESCRIPTION OF THE APPARATUS

A triaxial equipment designed to apply arbitrary stress, suction and temperature paths has been built according to the cross-section scheme shown in Figure 1. The basic design of the cell is based on the Bishop and Wesley (1975) hydraulic triaxial apparatus for controlled stress path testing, with a moving pedestal which pushes the soil sample against a stationary internal load cell. The apparatus is designed to test unsaturated samples of 38 mm diameter in both axial compression and axial extension under either controlled rate of loading or controlled rate of strain.

Matric suction is applied via axis translation technique, controlling positive air and water gauge-pressures that maintain a difference equal to the prescribed suction. A novel feature of the system is the possibility of independent or simultaneous application of air and water pressures required for suction control to both ends of the sample. In this case both top and bottom platens include a combination of two different porous stones: a peripheral annular coarse one (3 mm thick porous stainless steel, 10 μm pore size) connected to air pressure and an internal fine pore one (6 mm thick and 30 mm diameter) with a high air entry value (1.5 MPa at 22°C and 1.2 MPa at 80°C). In this way both fluid pressures can be applied to the caps at the same time ensuring a significantly shorter equalization stage, an important advantage when testing low permeability unsaturated soils. A perforated loading ram and top cap take the drainage and pore pressure leads inside to the sample ends. Water changes in the soil are calculated measuring the water volume by means of burettes with 10 mm^3 resolution, that crosses both high entry discs. This value is corrected taking into account the water evaporated from the specimen, specially under high temperatures, and the amount of air diffusing through the ceramic discs. A diffused air flushing system is used in conjunction with the water volume change indicators in order to flush and measure the



1) Specimen; 2) LVDT (axial strain); 3) Laser displacement sensor (radial strain); 4) Load cell or alignment device (isotropic test); 5) Top thermocouple (external heater control); 6) Bottom thermocouple (gear pump control); 7) LVDT (vertical displacement of laser sliding subjection); 8) Confining pressure; 9) Load pressure chamber (vertical stress); 10) Air pressure; 11) Water pressure (volume change measuring system); 12) Water pressure (diffused air flushing system); 13) High air entry ceramic disc; 14) Coarse porous ring; 15) Confining fluid (air or silicone oil); 16) Silicone/latex membrane; 17) Perspex wall; 18) Steel wall; 19) Vertical displacement electric motor; 20) Electrical connections to transducers and data acquisition system; 21) Connection to forced convection system (gear pump); 22) Connection from forced convection system (heater).

Figure 1. Layout of the triaxial cell.

volume of diffused air.

Both air and silicone oil of low viscosity (100 mm^2/s at 22°C and 35 mm^2/s at 80°C) can be used as confining fluids. The latter one has been chosen because of its low electrical conductivity (no electrical interference with internal transducers), some buoyancy effect in reducing the weight of the internal LVDTs and small rates of flow through the membrane reducing the fluid exchanges to a minimum in long-term tests (Leroueil *et al.*, 1988). Silicone rubber membranes were also developed for use at elevated temperature (higher than 60°C). Confining pressure is imposed by means of compressed air (up to 4.0 MPa), which acts over a free interface of silicone oil in an expansion chamber that compensates the thermal volumetric variations of the confining fluid (approximately an increase of 5.5% of the initial volume upon heating from 22°C to 80°C). A 15 mm thick perspex wall cell is externally enclosed by another stainless steel cylinder, also 15 mm thick, where four windows (30 mm wide) have been provided: two for observing the internal transducers and two for the laser beam to reach the specimen.

Axial load is applied by means of compressed air or another fluid pushing a piston in the loading pressure chamber that acts on the lower base of the specimen. The top cap, screwed to an internal pressure and temperature compensated load cell of 15 kN capacity, is maintained fixed in position by an adjustable rod passing through the top of the pressure chamber. This arrangement permits to attain a triaxial extension condition, to prevent cap rotation and to maintain the alignment between the loading piston and sample cap. The loading ram, with the same diameter as the specimen throughout its height, provides the vertical stress independently from the cell pressure. The internal load cell, free of piston seal interference, is used as a redundant system in monitoring ram friction from the loading pedestal and controlling the deviator stress. Alternatively, a non-contact alignment device for specimen tilting control, which replaces the load cell, can be used to carry out isotropic compression tests. Strain controlled tests can be run by connecting the loading pressure chamber to a volume controller speed adjustable motor in conjunction with another fluid system.

Axial displacements are measured internally using two miniature LVDT transducers (±3 mm stroke) adhered to the membrane, mounted on two opposite sides of the sample and covering the central part of the specimen. These local devices present a wide range of strain measurement between 10^{-5} and 10^{-1}, excluding bedding and compliance in loading system errors. The transducers are designed to operate in a temperature range of -40°C to 85°C. LVDT transducers were carefully calibrated for pressure and temperature effects (0.005% of 3 mm/°C zero and sensitivity drift).

Radial deformations on two diametrically opposite sides of the specimen are measured by means of a non-contact, long-range, electro-optical laser system mounted outside the chamber on rigid supports attached to the cell base. The laser emitting portion of the sensor head, with a measurement range of ±10 mm, is positioned at a stand-off distance of aproximatelly 45 mm from the target surface by means of micrometer screws and an operating indicator that helps reaching the center of the range. The laser transmitter and receiver displacement sensor ensures a resolution of 2 μm (strain resolution of $5x10^{-5}$) with a high response speed of 60 ms. The surface of the rubber membrane is iluminated (spot diameter of 1.0 mm) by the coherent laser light, which crosses 15 mm transparent perspex wall and 25 mm of confining fluid. For better reflection a thin layer of white acrylic painting was coated on a part of the rubber membrane. Cyclic calibration curves at different temperatures have been obtained for the laser system in combination with the two suggested cell fluids. The dependence of the temperature on the sensitivity shift of the sensor, due to the physico-chemical changes of the optical properties of the silicone oil, is of minor importance (approximately $5.5x10^{-4}$%FS/°C). The influence of temperature on zero shift of the sensor (approximately 0.023%FS/°C) is caused by the lateral displacement of the rigid supports attached to the base cell (thermal dilatation) and the temperature effect on the sensor head. Careful cyclic calibrations have been done to take into account this latter effect at constant stand-off distance of the sensor head and monitoring its temperature in a constant laboratory environment. A novelty of the apparatus is that the lateral measuring system can be moved up and down by means of an electric motor, which acts on the vertical displacement of the sensor at a rate of 2.6 mm/s. In this way the whole profile of the sample from pedestal to cap can be measured with the same strain resolution. The volume change determination is more representative of the whole specimen than that obtained from local local measurements.Additionally, some non-uniformity of the sample and uncertainties such as specimen tilting, restraints from end platens, deformation modes (bulging, convex or concave shapes) and local irregularities of the membrane surface, can be easily detected.

The heating system, which imposes a uniform temperature field around the specimen, consists in an external heating chamber with a thermostatically controlled 1000 W heater housed inside. A silicone oil forced convection circulation system, driven by a high pressure gear pump, is able to provide soil temperatures ranging from ambient to 80°C. The amount of power supplied to the heater is electrically controlled (both voltage and intensity) in order to balance the heat transfer from the triaxial cell to the surrounding environment. A temperature control unit triggers and adjustes the velocity of the pump motor (up to a maximum of 800 mm^3/rev with oil at 50°C), permitting the selection of the optimum flow that ensures a constant and uniform temperature field within the cell. Two type K thermocouples located close to both ends of the sample are used as feedback signals acting on a programmable thermostat, which controls independently the external heater and the pump and permits the automatic data logging of the soil temperature. Temperature rise to the target value can be modified during the heating path, a typical rate being 5.0 °C/h. The 15 mm perspex wall acts as an insulator to minimize the heat transfer from the inner cell (thermal conductivity and heat capacity of 0.23 W/(m.K) and 1.67 J/(g.K) respectively). All the heating system is adequately isolated to prevent heat loss, with the exception of a coil that it does not go through the heating chamber and is used as a controlled cooling circuit. The whole system is located in a temperature controlled room where the maximum temperature variation is ±1°C.

Data logging from the 13 transducers (two miniature internal LVDTs, two laser displacement sensors, an internal load cell, two internal thermocouples, two external LVDTs for vertical displacement monitoring of laser subjections and four pressure transducers) is controlled by a personal computer. The system provides test control with on-line presentation of geotechnical parameters.

3 EXPERIMENTAL RESULTS

The moderately swelling soil used in the experiments is Boom clay from the HADES underground laboratory in Mol, Belgium. This clay has a liquid limit of w_L=55.9%, a plastic limit of w_P=29.2% and 49.7% of particles less than 2μm. In preparing specimens, the required quantity of deaired water to achieve a predetermined water content of (15.0±0.3)% was added to the powder. It approximately corresponds to an initial total suction of 2.5 MPa. A 5-day curing time in sealed bags was adopted to ensure equalization of moisture content. Specimens 38 mm in diameter and 76 mm high were compacted in a rigid mold in three lifts at a dry unit weight of (13.7±0.1) kN/m^3 using static one-dimensional compression and resulting in a departure saturation of (43.5±1.5)%.

Several types of suction, stress and temperature paths have been followed. Wetting and drying cycles, under constant isotropic stress and temperature, have been imposed by varying matric suction. The sample was isotropically loaded at constant water content until the desired net mean stress was reached. Afterwards, the suction paths were imposed step by step by applying a constant air pressure to the coarse porous rings and controlling the water pressure acting on the high air entry value ceramic discs. Figure 2 shows the time evolution of axial and radial strains, as well as the water volume change, that undergoes the soil sample upon imposing a suction change starting from the initial condition to a final matric suction of 0.45 MPa under a constant isotropic net mean stress of (σ_m-u_a)=0.60 MPa and a constant temperature of T=22°C. Radial strain evolution corresponds to the intermediate part of the specimen. The volumetric behaviour exhibits collapse as a result of the progressive wetting under constant net stress of the partly saturated and metastable soil fabric. At the beginnig of the test some small swelling is recorded by the vertical LVDT transducers, before the macroscale contacts between peds become weaker and fail under local shear causing a macroestructural collapse. Shear strain development shows some distorsion of the sample upon wetting, due to the anisotropic loading condition imposed to the specimen during static compaction. Of special interest is the progressive development of the lateral profiles of the sample (shown in Figure 3) at the different stages indicated in the previous figure. It is observed an inhomogeneous collapse deformation development along the specimen height as the wetting front advances, partly affected by the ends restraint of the porous stone platens. The volume change determination taking into account the non-uniformity of the sample deformation is more representative of the whole specimen, specially when calculating degrees of saturation. Figure 4 shows the difference between measured mid-height radial strains and calculated mean value radial strains obtained from

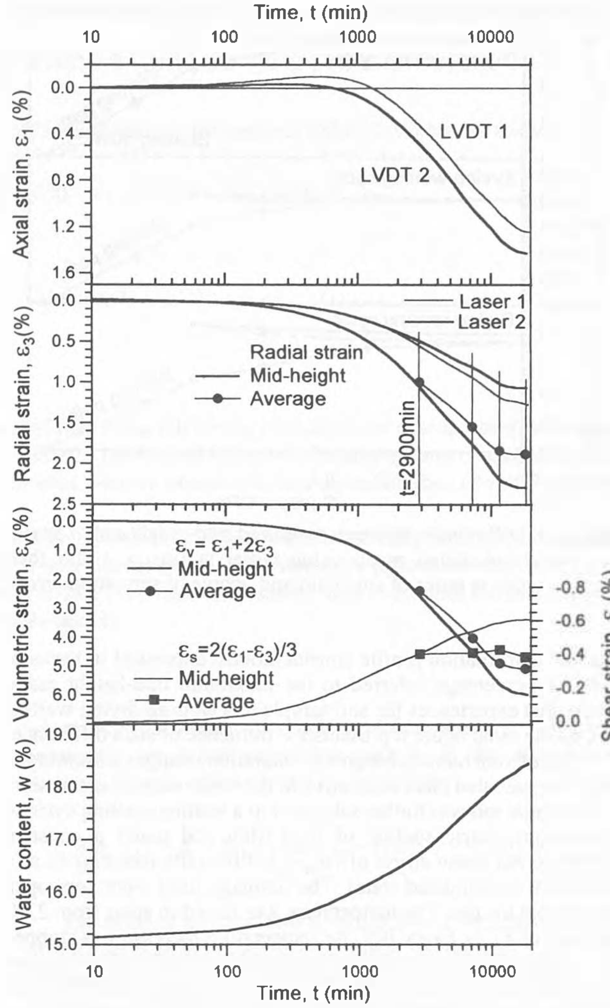


Figure 2. Time evolution of axial, radial, volumetric and shear strains and water volume change in a wetting path (ψ_o=2.5 MPa to s=0.45 MPa) under a constant isotropic net mean stress of (σ_m-u_a)=0.60 MPa.

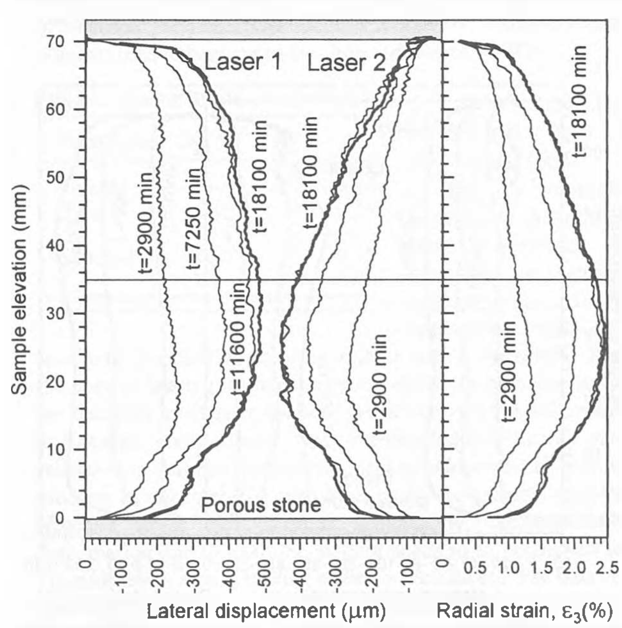


Figure 3. Progressive development of the lateral profiles of the specimen in a wetting path (ψ_o=2.5 MPa to s=0.45 MPa) under a constant isotropic net mean stress of (σ_m-u_a)=0.60 MPa.

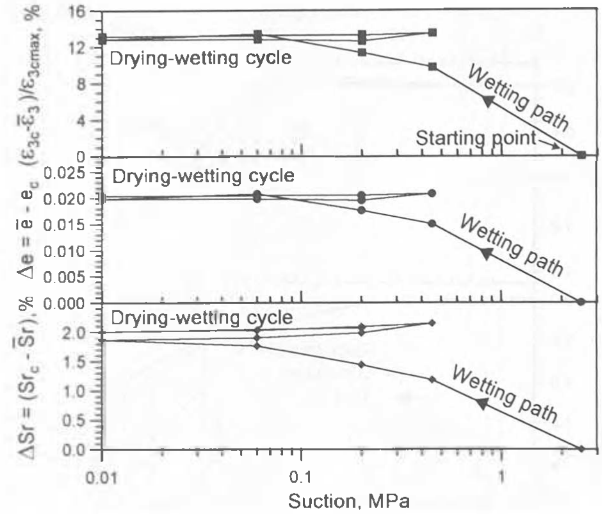


Figure 4. Differences between measured mid-height radial strains (ϵ_{3c}) and calculated mean value radial strains ($\bar{\epsilon}_3$) and their consequences in terms of void ratio and degree of saturation errors.

sample deformation profile considerations, expressed in terms of relative percentage referred to the maximum mid-height radial strain, that experiences the soil sample in a wetting-drying-wetting cycle. The same figure represents the influence of such differences in terms of void ratio and degree of saturation changes, assuming in the latter case that there is no error in the water content estimation.

The same soil was further subjected to a heating-cooling cycle at a constant matric suction of 0.20 MPa and under a constant isotropic net mean stress of $(\sigma_m-u_a)=1.00$ MPa (the clay is at a normally consolidated state). The drainage lines were kept open throughout the test. The temperature was raised in steps from 22°C at a rate of 5°C/h. Every 10°C the temperature increase was stopped to allow for full equilibration of pore pressure generated by heating. This pore pressure results from the higher expansion coefficient of water compared to that of soil. Hence, at every temperature rise, the sample initially dilates but, afterwards, a net compression is observed due to collapse phenomena associated with the loss of shearing strength of the contacts between peds. Figure 5 shows the development of sample profiles with increasing temperature. They correspond to the fully equilibrated state at the end of every 10°C temperature increase. The increasing compressive lateral strains associated with increasing temperature can be readily observed.

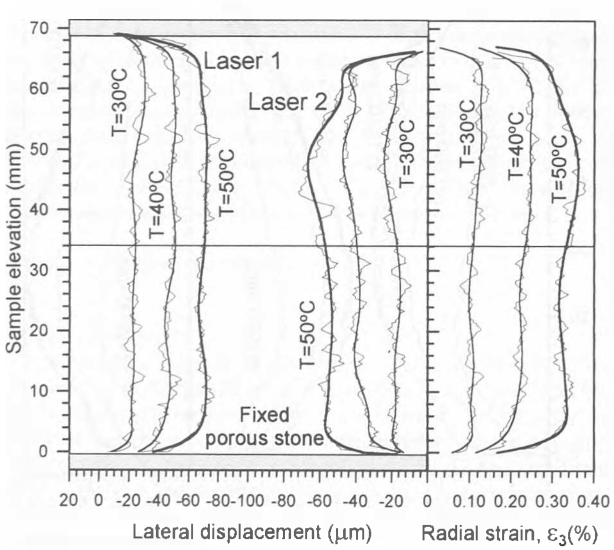


Figure 5. Progressive development of the lateral profiles of the specimen in a heating path (T_o=22°C to T_f=50°C) under a constant suction of s=0.20 MPa and an isotropic net mean stress of $(\sigma_m-u_a)=1.00$ MPa.

4 CONCLUSIONS

The apparatus described in the present paper is a suitable equipment for testing unsaturated soils under suction-(up to 1.5 MPa) and temperature (up to 80°C)-controlled paths in a wide range of stress conditions. The proposed electro-optical laser measuring system has produced reliable readings of lateral deformations throughout the specimen (strain resolution in the range of $5x10^{-5}$), which can be converted to an overall volume change determination more representative of the whole sample. Non-uniformity of the sample deformation pattern is more easily detected as well. The simultaneous application of suction control to both ends of the sample ensures a significant shorter testing time.

Collapse behaviour due to wetting under constant isotropic net mean stress, as well as thermal contraction due to temperature increase under constant matric suction and isotropic stress, have been observed through the progressive development of the lateral profiles of the specimen.

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