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Mechanical behaviour of unsaturated expansive clay under K_0 conditions

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ABSTRACT

The mechanical response of unsaturated soils with significant amounts of active clay minerals can be highly stress path dependent. Traditionally, the Axis Translation Procedure has been used to study these materials in the laboratory. This technique, however, does not fully replicate conditions in the field, nor is it able to test soils during the important process of desaturation and resaturation. A novel osmotic oedometer has been developed at Imperial College London to test unsaturated soils under atmospheric pressure. With this equipment, it has been possible to continuously record changes in vertical and radial stress, gravimetric water content, degree of saturation, matrix suction, and void ratio, throughout a test. The Paper presents results from tests carried on samples of compacted London clay using the new oedometer and standard oedometers. The full data set gives an insight into the mechanical response of unsaturated expansive clay along complex stress paths. Results are interpreted using an existing framework for unsaturated expansive clays. Because of inherent limitations in the method of testing, some of the data needs to be interpreted with care. Nevertheless, the response recorded along different stress paths was found to be consistent and in agreement with framework predictions.

1. Introduction

The mechanical response of unsaturated expansive clays can be very complex. This is not only due to mineralogical composition and associated mechanical and physicochemical phenomena taking place at the particle level, but it is also closely related to interactions between microstructural volume changes and macrostructural rearrangements of the soil skeleton (Alonso et al., 1987, 1999; Gens and Alonso, 1992; Alonso, 1998; Lloret et al., 2003). Because of this, the behaviour of soils containing a significant amount of active clay minerals can be highly stress path dependent. In order to make accurate predictions of field response it is, therefore, necessary to be able to reproduce changes in applied stress and soil–water potential in the correct sequence.

The evaluation of the state of saturation in a soil can be based on either volumetric or pore-water potential considerations. A soil can be thought to be unsaturated if it contains three phases: solid particles, pore-water, and pore-air. In this case, the degree of saturation serves to differentiate between the saturated and unsaturated states. It is also possible to consider the stress recorded within the pore-water. If this is considerably negative with respect to atmospheric pressure, even if the degree of saturation is one, the soil can be thought to be in an unsaturated state (Blight, 2013). Although this second definition is not commonly used, nor is it universally accepted, it nevertheless follows that any apparatus designed to test unsaturated soils must be able to accommodate varying degrees of saturation, including the fully saturated state. Moreover, any such device should be able to test soils during the important process of desaturation and re-saturation.

The bulk of experimental work on unsaturated soils has been carried out using the axis-translation procedure (ATP). With this technique, it is possible to measure pore-water stresses in a sample by artificially increasing the surrounding pore-air pressure. However, since first introduced by Hilf (1956), the use of the ATP has been criticised. A summary of major difficulties associated with the experimental procedure and interpretation of results can be found, for example, in Delage et al. (2008).

As an alternative to the use of the ATP, unsaturated soils can be tested under ambient atmospheric pressure. In practice it has only been possible to do so with some degree of confidence after the introduction of high capacity tensiometers in the 1990s, capable of sustaining water tensions as high as 1.5 MPa. The modification of existing laboratory equipment to accommodate miniature tensiometers has allowed unsaturated soils to be tested under conditions more akin to those prevailing in the field. However, high capacity tensiometers can only measure, and not control, soil-water potential.

An elegant method of controlling pore-water potential under atmospheric pressure consists of using a solution and a semi-permeable membrane to generate an osmotic potential. Initially developed by biologists, this experimental technique was subsequently adopted by soil scientists and geotechnical engineers, the latter with mixed degrees

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of success (the reader is referred to Juca and Frydman, 1996; Ng et al., 2007; Delage et al., 2008 for a wider discussion on the subject).

Researchers at Imperial College London have been studying the behaviour of unsaturated soils since the late 1950s (Standing, 2012). In recent years, efforts have focused on the development of experimental techniques that do not require the use elevated air pressures. One of the main outcomes of such efforts has been the development of an osmotic oedometer capable of controlling and measuring matrix potential continuously and independently throughout a test. This Paper presents an outline of the main features of this osmotic oedometer — hereafter referred as the IC (Imperial College) oedometer. It also includes a summary of significant experimental results derived from a number of tests carried out on samples of compacted clay. The mechanical response recorded with IC oedometers and conventional oedometers is compared. The combined data set gives an insight into the behaviour of unsaturated expansive clay along stress paths where external stress and matrix potential were varied under ambient air pressure. In order to aid the discussion, results are interpreted, qualitatively, in terms of an existing elasto-plastic model for unsaturated expansive clays.

Samples of London clay were statically compacted to the same initial conditions, dry of optimum water content, and taken along a number of complex stress paths. These included hydration under constant vertical load or constant volume, loading and unloading at constant matrix potential, and wetting and drying under constant vertical stress. Because of inherent difficulties associated with the control of potential with an osmotic system, as well as due to limitations imposed by the oedometer itself, some of the paths were less than ideal. Testing times also played an important role in determining the extent of each test.

2. Equipment

2.1. IC oedometer

The IC oedometer was developed incrementally (Standing, 2012), starting with the work described in Dineen (1997). In its final configuration, the apparatus was designed to be able to (i) control matrix potential under ambient air pressure; (ii) measure matrix potential continuously and independently of any control mechanism; (iii) measure changes in sample volume accurately; (iv) measure changes in water content accurately and independently of any volume change readings; (v) measure both axial and radial stresses; (vi) follow complex stress paths involving loading, unloading, wetting, and drying; and (vii) apply vertical stresses in a continuous manner. In addition, data logging and stress path control were fully automated.

A diagram of the equipment is presented in Fig. 1. Matrix potential was controlled by circulating an osmotic solution of polyethylene glycol (PEG) under a polyether sulfonate ultra-filtration (PEF-US) semi-permeable membrane (marked as number 8 in Fig. 1). As the sample (1) rested directly over the semi-permeable membrane, it was possible to control matrix potential by modifying the concentration of the osmotic solution. The solution was kept inside a reservoir (13), placed over an electronic balance (14), and was circulated continuously with the aid of flexible tubing (10) and a peristaltic pump (11). The current system represents a development in the use of the osmotic technique to control pore-water potential in the laboratory (Low and Anderson, 1958; Lagerwerff et al., 1961; Peck and Rabbidge, 1966, 1969; Zur, 1966; Kassiff and Shalom, 1970, 1971; Delage et al., 1987, 1992; Slatter et al., 2000; Tarantino and Mongiovi, 2000, amongst others). The novelty resides in its ability, product of a fortunate choice of synthetic membrane and high molecular weight solute, to do so for long periods of time (the longest tests extended for 146 days). Details on the development, operation, and performance of the system can be found in Dineen and Burland (1996), Dineen (1997), Monroy (2006) and Monroy et al. (2007).

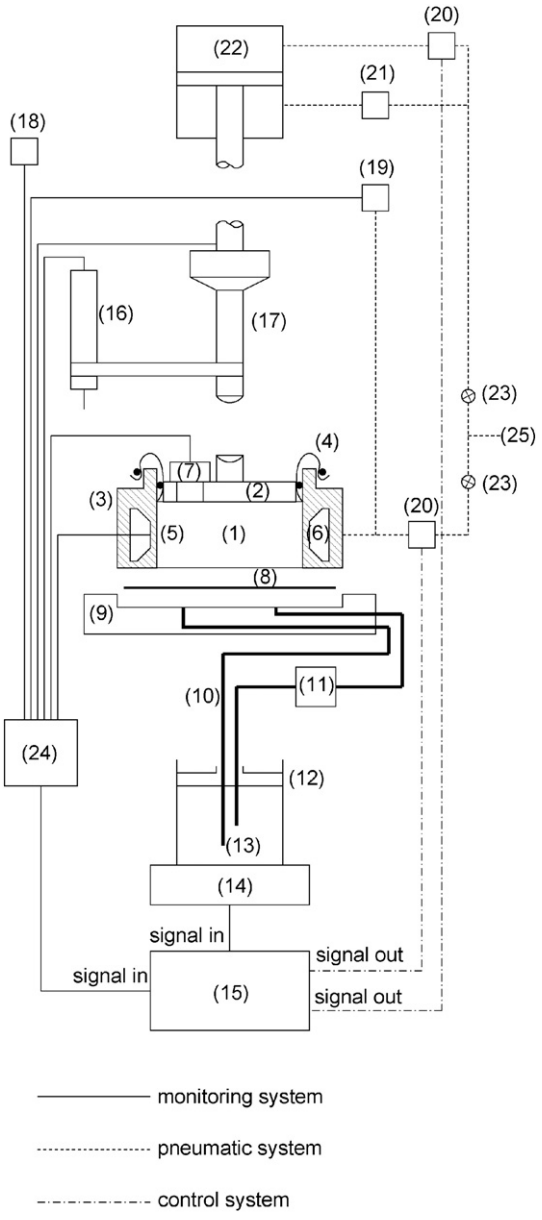

Fig. 1. Schematic view of the IC oedometer: (1) soil sample, (2) top cap, (3) oedometer ring, (4) latex membrane and o-rings, (5) strain-gauged diaphragms, (6) pressurised space behind diaphragms, (7) IC suction probe (miniature tensiometer), (8) semi-permeable membrane, (9) oedometer base, (10) PVC tubing, (11) peristaltic pump, (12) silicone oil and culture dish, (13) Pyrex beaker with osmotic solution, (14) electronic balance, (15) PC, (16) LVDT, (17) load cell, (18) temperature transducer, (19) pressure transducer, (20) variable manostat, (21) fixed manostat, (22) pneumatic piston, (23) valve, (24) analogue to digital converter and (25) 800 kPa air supply from the main/back-up compressor.

Variations in water content were derived from measurements of change in weight of the osmotic solution reservoir (13), as recorded with the balance (14). This approach assumes that only water can diffuse across the semi-permeable membrane (Dineen and Burland, 1996). The arrangement required evaporation losses to be kept to a minimum and this was achieved by fixing a latex membrane (4) between the top cap (2) and the oedometer ring (3), as well as by covering the osmotic solution with a layer of silicone oil and a culture dish (12).

Matrix potential was measured by placing one or two Imperial College (IC) suction probes (Ridley and Burland, 1996) (7) in contact with the sample's top face. A top cap (2) was designed to accommodate the probes (7) and hold the latex membrane (4) in place.