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Response of intermediate unsaturated soils under suction-controlled plane strain conditions: A preliminary investigation

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ABSTRACT: The engineering performance of a vast majority of geotechnical infrastructure, including earth slopes, embankments, pavements, tunnels, and earth retaining systems, may be more suitably modeled using plane strain analyses, given the particular geometries, stress paths, and boundary conditions such geosystems normally feature or experience in the field. Biaxial devices allow for direct and reliable testing of soils under truly plane strain conditions, facilitating accurate assessments of shear banding phenomena and stress-strain-strength parameters under these conditions. The majority of biaxial devices developed to date, however, allow for soil testing mostly under dried or fully saturated conditions. This paper introduces a suction-controlled biaxial apparatus that is suitable for soil testing under controlled-suction states via the axis-translation technique. The design of its core system is based upon the original Vardoulakis type of biaxial apparatus. In this work, biaxial specimens are prepared by uniaxial consolidation of a slurry mixture, made of 75% silty sand and 25% kaolin, into a custom-made biaxial consolidation mold. A thorough performance verification of the newly implemented apparatus was first accomplished, followed by a preliminary series of constant-suction plane strain tests. Results reflect the important role played by matric suction in the stress-strain-strength response of intermediate unsaturated soils under plane strain conditions.

Keywords: unsaturated soil; matric suction; axis-translation; plane strain; biaxial apparatus

1 INTRODUCTION

The engineering performance of a vast majority of geotechnical infrastructure, including earth slopes, embankments, pavements, tunnels, and earth retaining systems, may be more suitably modeled using plane strain analysis, given the particular geometries, boundary conditions, and stress paths such geosystems normally feature or experience in the field, as illustrated in Figure 1. Biaxial devices

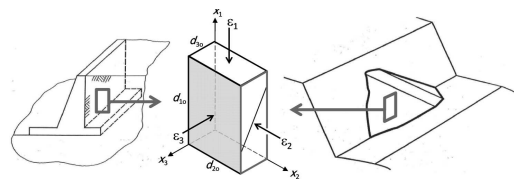


Figure 1. Typical geosystems subject to plane strain conditions.

allow for direct and reliable testing of soil materials under truly plane strain conditions, facilitating accurate assessments of shear banding phenomena and stress-strain-strength parameters under these conditions.

The majority of biaxial devices developed to date, however, allow for soil testing mostly under dried or fully saturated conditions (Wood 1958, Vardoulakis and Goldscheider 1981, Vardoulakis and Graf 1985, Drescher et al. 1990, Alshibli et al. 2004). Only until very recently, limited attempts have been reported to test unsaturated soils under plane strain shearing and controlled suction conditions (Schanz and Alabdullah 2007, Nikraz and Fauziha 2008). These results, however, are far from conclusive, as they are mostly limited to suction values of 20 kPa, while the biaxial devices used offer ample room for refinement and development.

This paper introduces a suction-controlled biaxial apparatus suitable for soil testing under controlled matric suction states induced via the axis-translation

technique. The design of its core system is based upon the original Vardoulakis type of biaxial apparatus (Vardoulakis and Goldscheider 1981). The apparatus allows for direct measurements of normal stresses generated between the soil specimen and two lateral rigid walls, as well as soil volumetric changes during suction-controlled biaxial shearing.

A thorough performance verification of the newly implemented apparatus was first accomplished, followed by a preliminary series of suction-controlled plane strain tests conducted on compacted silty sand under constant matric suction states, $s = 75$ kPa and 100 kPa. Results reflect the important role played by matric suction in the stress-strain response of intermediate unsaturated soils under plane strain conditions.

2 ASSEMBLING OF BIAXIAL APPARATUS

The core system of the apparatus was originally designed and manufactured at the geotechnical laboratories of the Universidad de los Andes, Colombia, and recently upgraded for suction-controlled testing at the Advanced Geomechanics Laboratory (AGL) of the University of Texas at Arlington. Details of the original design, main components, and preliminary performance verification, including calibration with prismatic samples of neoprene rubber of known stiffness, are given by Ruiz et al. (2003) and Cruz et al. (2011, 2012).

Plane strain condition is imposed on the specimen by means of two 8 mm thick rigid walls made of type 304 stainless steel. These walls prevent the specimen from deforming along the intermediate principal axis X_2 (Fig. 1). An orderly step-by-step assembling process of the apparatus is illustrated in Figure 2, and can be summarized as follows:

Step 1. The base plate supporting the apparatus is fitted with three Sensotec type miniature load cells (A, B, C) located right underneath the bottom pedestal. Applied normal stresses can then be simultaneously measured in the upper and lower sides of the prismatic specimen, thus allowing for assessment of the level of frictional resistance generated between the lateral walls and the soil specimen during plane strain shearing.

Step 2. The bottom pedestal, made of stainless steel, receives a 3-bar HAEV ceramic disk for control and measurement of pore-water pressure u_w during suction-controlled testing. The pedestal rests on a U-shaped base frame, also made of stainless steel, which couples both the pedestal and the rigid lateral walls to a sliding table.

Step 3. The Schneeberger type sliding table, model NKL 6-110, which provides an additional degree of freedom to expedite the formation of the failure surface during shearing, is fitted with an horizontal

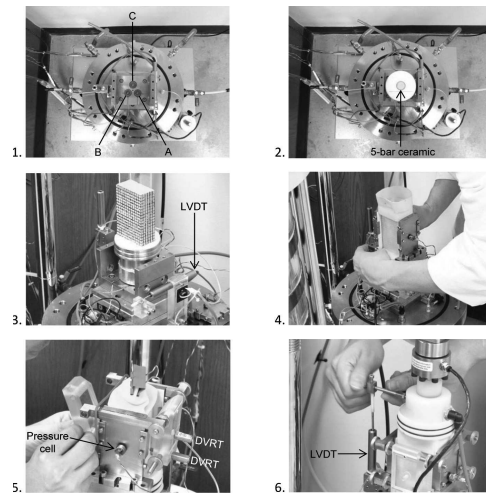


Figure 2. Step-by-step assembling process of BX apparatus.

LVDT (Linear Variable Differential Transformer) affixed to the base plate of the apparatus. The eventual formation of a failure surface or a shear band(s), perpendicular to the minor principal axis X_3 (Fig. 1), can be readily detected by sensing the start of motion of the sliding table with the LDVT. *Step 4.* A latex membrane is gently placed around the compacted specimen and tightly O-ring-secured onto the bottom pedestal. The rigid walls are then set into place. Four stainless steel tie rods are then tightly secured onto each of the rigid walls to prevent the walls from bending during shearing.

Step 5. Lateral displacements experienced by the specimen in the minor principal axis X_3 during plane strain shearing is measured by four Microstrain type DVRTs (Differential Variable Reluctance Transducers) securely attached to the tie rods with an acrylic plate. The intermediate principal stress along axis X_2 (Fig. 1) is measured via Sensotec type pressure cells, one installed at each of the rigid lateral walls. Readings from the cells, along with the measurements of displacement in the remaining principal axes, allow for a complete definition of stress and strain tensors during suction-controlled plane strain testing.

Step 6. Vertical displacement of the soil specimen in the major principal axis X_1 (Fig. 1) during plane strain shearing is measured by a vertically positioned LVDT. An Omega type load cell, model LCM203-50 kN, is used for readings of applied vertical load. The top loading cap is made of light Nylon 66 type material to minimize the initial seating load acting on the specimen. Pore-air pressure is controlled and supplied to the soil pores through the top loading cap via a coarse porous stone, which



Figure 3. Servo/suction-controlled plane strain testing system.

enables implementation of the axis-translation technique using the $s = u_a$ ($u_w = 0$) testing approach.

A panoramic view of the servo/suction-controlled plane strain testing system is shown in Figure 3, including its four main modules: (1) Core cell of fully assembled system, (2) Data acquisition and process control system, (3) Model PCP-UNSAT panel for external control of pore-air pressure and implementation of the axis-translation technique, and (4) graduated standpipe to aid with the adequate assessment of pore-fluids equalization.

The core assembly of the biaxial device, as shown in Figure 3, is ultimately placed inside a Wykeham Farrance type pressure cell, in which specimens can be subjected to cell pressures of up to 1.7 MPa. The axial stress is applied by means of a type MTS Universal Machine with 1 MN capacity. The machine can be used for plane strain testing under both stress- or strain-controlled schemes.

The procedure followed for the preparation of soil specimens is summarized in the following section.

3 PREPARATION OF TEST SPECIMENS

A typical soil specimen is prepared via uniaxial consolidation of a slurry mixture, made of 75% silty sand and 25% kaolinite, into an acrylic biaxial mold (Cruz et al. 2011, 2012). The slurry is prepared with water content about twice its liquid limit of 25.3%. The slurry mixture is consolidated to dimensions of 80 mm $\times$ 80 mm $\times$ 135 mm. Load increments of 12.5, 25, 50, 100, 200, and 400 kPa are applied, resulting in a saturated unit weight of 20.1 kN/m³. The sample is removed from the consolidation mold, from which two specimens are trimmed for plane strain testing in the biaxial apparatus. All specimens are trimmed to final dimensions of 90 mm $\times$ 60 mm $\times$ 30 mm (Fig. 2). The soil classifies as SM as per the USCS.

Figure 4 shows a typical set of negative digital radiographs taken from a freshly prepared

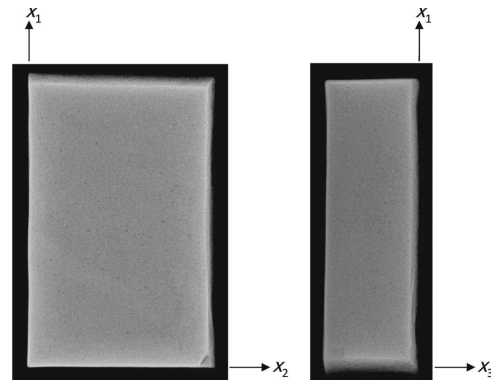


Figure 4. Verifying specimen homogeneity via X-Ray imaging.

specimen in order to qualitatively verify the suitability of the consolidation process to produce reasonably homogenous specimens. X-ray radiography is a nondestructive method used to assess density, size and composition of materials in branches of medicine, sciences, and the materials industry. The method is based upon the physics of the phenomenon of absorption of radiation. When an X-ray strikes the exposed material, a percent of this radiation is absorbed by atoms while the rest is detected by a digital sensor or photographic film, hence highlighting the anomalies and disturbances present in the test material (ASTM D 4452-06).

Compacted SM soil specimens are covered with a thin layer of paraffin prior to X-ray testing. Negative radiographs are typically greyscale digital images of 8 bits, allowing for up to 256 different intensities of grey. Concentrations of color black represent areas with low density, while whiter colors represent higher densities. Figure 4 shows a specimen of SM soil with reasonably homogenous structure and virtually no conspicuously large voids, defects, or heterogeneous densification induced during consolidation of the slurry mixture (Edges of a specimen prepared for X-ray testing are expected to be somewhat irregular after application of paraffin coating).

4 FURTHER PERFORMANCE VERIFICATION

As previously mentioned, preliminary calibration of the apparatus using neoprene rubber blocks replicating the typical size and shape of a soil specimen was reported by Cruz et al. (2011). In this work, further verification of the suitability of the biaxial apparatus was accomplished by monitoring the response of the three miniature load cells A,

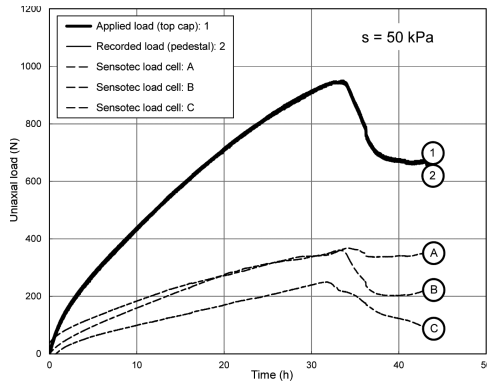


Figure 5. Response of Sensotec miniature load cells.

B, and C (Fig. 2), located right underneath the bottom pedestal, under actual suction-controlled monotonic loading of a compacted soil specimen.

Figure 5 shows the response of Sensotec miniature load cells A, B, and C from suction-controlled monotonic loading of a compacted SM soil specimen under 100 kPa net mean stress and constant 50 kPa matrix suction. In order to assess the amount of friction generated between the soil specimen and the rigid walls (Fig. 2), the monotonic load applied via the top loading cap is compared with the sum of forces individually recorded by each miniature load cell (Rhee 1991, Harris 1994).

Curve 1 represents the applied load directly measured by the Omega type load cell. Curve 2 represents the sum of forces individually recorded by the three Sensotec miniature load cells. Individual responses from each load cell are also included. The observed trends from curves 1 and 2 are virtually identical, which is highly indicative of negligible friction actually being generated between the specimen and the rigid walls throughout the entire test.

5 RESPONSE OF COMPACTED SM SOIL

A short series of 6 suction-controlled tests were performed on an equal number of identically prepared specimens of SM soil. Specimens were tested under initial net confining pressures, $p = (\sigma_3 - u_a) = 75$ kPa or 100 kPa, and constant matrix suction, $s = 50, 75$ or 100 kPa. The procedure is similar to conventional CD testing with axial strain control (Vardoulakis and Goldscheider 1981, Drescher et al. 1990, Alshibli, et al. 2004).

Suitable time for pore-fluids equalization under a sustained suction state is assessed from the amount of water expelled from within the soil (drying path) as the corresponding pore-air pressure u_a is increased to 50, 75, or 100 kPa.

Results showed suitable pore-fluids equalization times of 48 hours (3 days), 144 hours (7 days), and 240 hours (11 days) for matric suctions of 50, 75, and 100 kPa, respectively. In all cases, thorough flushing of diffused air underneath the 3-bar ceramic was performed daily as per guidelines recommended by Padilla et al. (2006).

After completion of pore-fluids equalization stage, the soil was sheared at a constant vertical strain rate of 0.004 mm/min ($4.44 \times 10^{-5}\%$ vertical deformation per minute), which is considered to be low enough to prevent sudden increases in pore pressure during suction-controlled shearing in this type of materials (Fredlund and Rahardjo 1993).

Figure 6 shows the stress paths in $q:p$ plane, and the corresponding stress-strain response of SM soil, from three tests conducted under suction, $s = 75$ kPa.

MIT notation for net mean stress, $p = (\sigma_1 + \sigma_3)/2 - u_a$, and shear stress, $q = (\sigma_1 - \sigma_3)/2$, was adopted. As expected, soil strength is greatly influenced by the level of initial confinement, with higher strength at $p = 100$ kPa under constant suction, $s = 75$ kPa. In all cases, peak strength is followed by softening behavior until an apparent residual state is finally attained. The initial void ratio of all test specimens was approximately, $e = 0.65$.

The effect of initial net mean stress, $p = (\sigma_3 - u_a)$, on the slope and positioning of the plane-strain failure envelopes obtained for compacted SM soil in $q:s$ plane is illustrated in Figure 7. These preliminary results hint to a peak strength framework under plane-strain conditions conceptually similar to that postulated for peak shear strength of unsaturated soils under axisymmetric stress states (Fredlund et al. 1978):

$$\tau_{ff} = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (1)$$

where, ϕ' = friction angle with respect to net mean stress, and ϕ^b = friction angle with respect to matric suction. Fredlund et al. (1978) postulated a constant slope for peak shear strength envelopes of unsaturated soils, independent of matric suction, $s = (u_a - u_w)$, as observed in Figure 7.

Figure 8 shows typical features of a failure surface induced by suction-controlled plane-strain shearing on a compacted specimen of SM soil. The specimen corresponds to test conditions, $p = 75$ kPa and $s = 50$ kPa. The final mesh-tracked geometry of the failed specimen shows a relatively uniform deformation in minor principal axis X_3 throughout the height of the specimen, as measured by the three DVRTs. A fully developed failure surface, making a 62° angle with respect to the horizontal, can be readily identified. A similar failure surface, making a 65° angle with the horizontal,

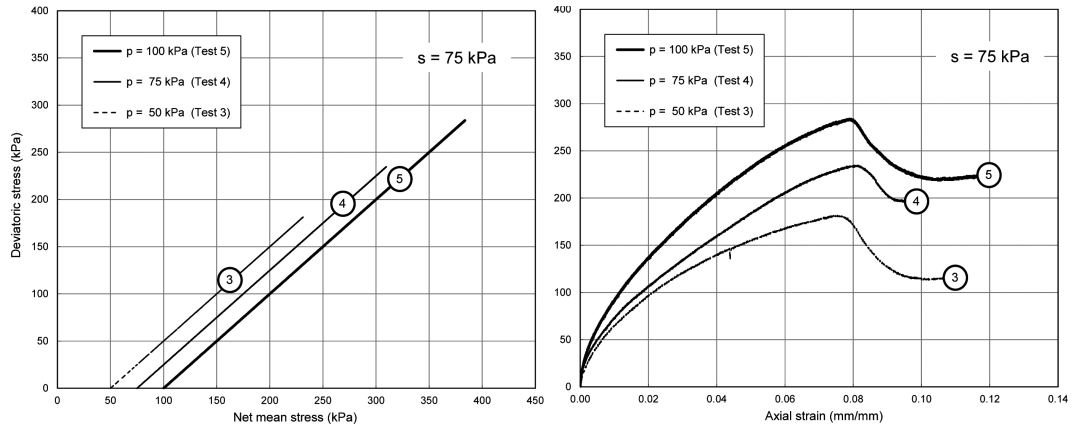


Figure 6. Stress-strain response of SM soil from suction-controlled plane-strain shearing under matric suction, $s = 75$ kPa.

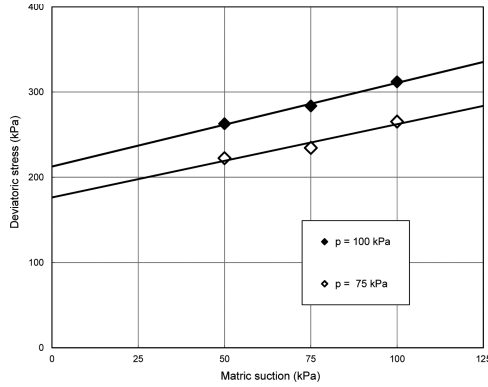


Figure 7. Plane-strain shear failure envelopes from SM soil.

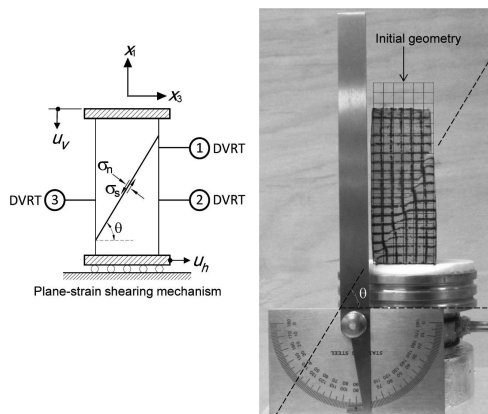


Figure 8. Typical plane-strain failure surface through SM soil.

was identified for a soil specimen failed under matric suction, $s = 100$ kPa, further substantiating the results shown in Figures 6 and 7.

6 CONCLUDING REMARKS

A fully servo/suction-controlled biaxial apparatus for testing unsaturated soils under plane strain conditions has been introduced. Results from performance verification tests show that the apparatus is suitable for testing soils under controlled suction states via axis-translation technique, with virtually no friction developed between the specimens and the rigid walls during suction-controlled plane strain shearing. Identically prepared samples of SM soil were tested under initial net confining pressures varying from 75 kPa to 100 kPa, and constant matric suctions varying from 50 kPa to 100 kPa. Test results reflect the important role played by matric suction in the stress-strain-strength response of intermediate unsaturated soils under plane strain conditions. The apparatus will be instrumental in future research efforts related to the experimental calibration and validation of constitutive frameworks postulated for unsaturated soils under plane strain conditions, as well as the assessment of suction effects on stress localization phenomenon in compacted soils subjected to plane strain shearing.

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