Unsaturated Soil Response under Plane Strain Conditions Using a Servo/Suction-Controlled Biaxial Apparatus

José A. Cruz, Laureano R. Hoyos, and Arcesio Lizcano

Abstract. The engineering response of a vast majority of geotechnical infrastructure, including earth slopes, embankments, tunnels and pavements, may be most accurately modelled using plane strain analyses, given the particular geometries, stress paths and boundary conditions that such geosystems normally feature or undergo in the field. Biaxial devices allow for direct testing of soils under truly plane strain conditions, facilitating a more accurate assessment of shear banding phenomena and stress-strain-strength parameters under these conditions. However, most conventional biaxial devices reported to date only allow for soil testing under dried or saturated conditions. This paper introduces a suction-controlled biaxial apparatus that is suitable for soil testing under controlled-suction states via 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 clay, into an acrylic custom-made biaxial consolidation mold. The results from a short series of constant-suction tests reflect the important role played by matric suction in the stress-strain response of unsaturated soils under plane strain conditions.

Keywords: unsaturated soil, matric suction, axis-translation, plane strain analysis, biaxial apparatus.

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1 Introduction

The engineering response of a vast majority of geotechnical infrastructure, including earth slopes, embankments, tunnels and pavements, may be most accurately modelled using plane strain analyses, given the particular geometries, stress paths and boundary conditions that such geosystems normally feature or undergo in the field. Biaxial devices allow for direct testing of soils under truly plane strain conditions, facilitating a more accurate assessment of shear banding phenomena and stress-strain-strength parameters under these conditions. However, most conventional biaxial devices reported to date only allow for soil testing under dried or saturated conditions, including Wood (1958), Vardoulakis & Goldscheider (1981), Vardoulakis & Graf (1985), Dresher et al. (1990), Lizcano et al. (1997), and Alshibli et al. (2004). Recently, few attempts have been made at testing unsaturated soils under both plane strain shearing and controlled-suction states, including the works by Schanz & Alabdullah (2007) and Fauziah & Nikraz and (2008). These results, however, are far from conclusive and the corresponding devices offer ample room for further development, refinement and elaboration.

This paper introduces a suction-controlled biaxial apparatus that is suitable for soil testing under controlled-suction states via the axis-translation technique (Hilf 1956). The design of its core system is based on the original Vardoulakis type of biaxial apparatus (Vardoulakis & Goldscheider 1981). In the present work, biaxial specimens are prepared via uniaxial consolidation of a slurry mixture, made of 75% silty sand and 25% kaolin clay, into a custom-made biaxial consolidation mold. The range of induced matric suction states (50-100 kPa) from a short series of tests is shown to have a critical influence on the stress-strain-strength response of unsaturated soils under plane strain conditions.

2 Servo/Suction-Controlled Biaxial Apparatus: Key Features

The core system of the biaxial apparatus introduced in this work was designed and manufactured at the geotechnical laboratories of the University of the Andes, Bogotá, Colombia (Ruiz 2003), and was adapted for suction-controlled testing at the University of Texas at Arlington. The apparatus allows for the assessment of all of the following: (1) Pre/post-failure soil behavior; (2) Peak strength and evolution of strength parameters with time; (3) Soil response under combined direct and biaxial shearing; (4) Angle of dilatancy; and (5) Orientation of failure plane and formation of spontaneous shear bands.

Fig. 1 shows a detailed schematic of the fully assembled apparatus, including a numbered outline of all its main components. Fig. 2 shows actual photographs of the core system and the partly assembled apparatus. The device allows measurements of normal stresses between the soil sample and two lateral rigid walls, as well as soil volumetric changes during shearing. A detailed description of its calibration, using a neoprene spring rubber block, is given by Cruz et al. (2011).

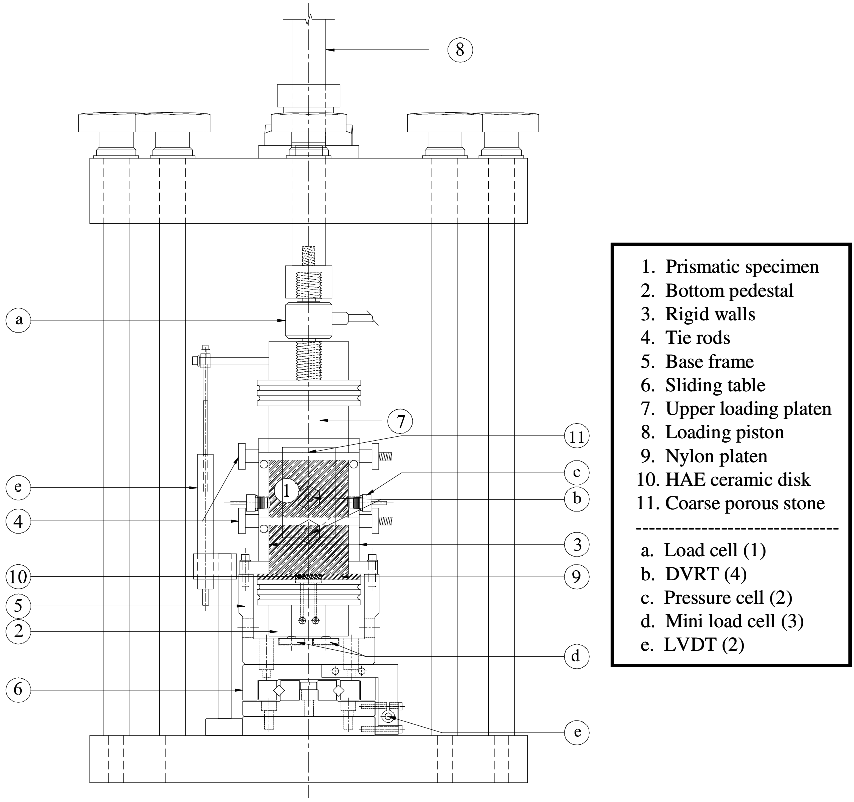

Fig. 1. Schematic of fully assembled suction-controlled biaxial apparatus and main components.

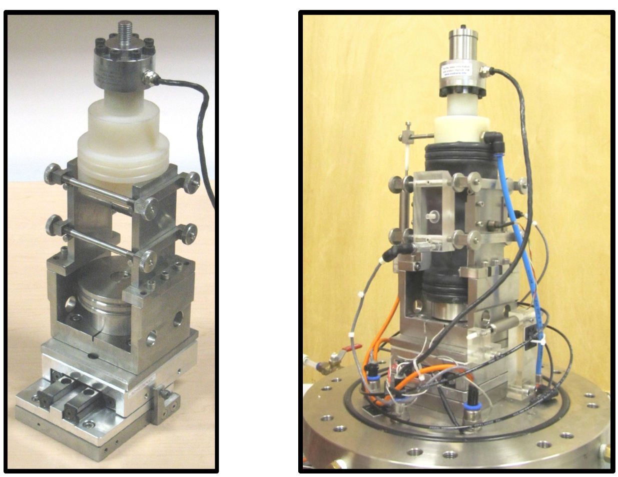

Fig. 2. Photographs of core system and partly assembled suction-controlled biaxial apparatus.

3 Test Soil and Sample Preparation

The soil material tested in this work is an artificially mixed soil made of silty sand (SM) and kaolin clay (CH). The silty sand soil yields a specific gravity, G_s = 2.63; while the kaolin clay yields a specific gravity, G_s = 2.58. Atterberg limits tests on kaolin clay yield liquid limit, LL = 57.1%, and plastic limit, PL = 45.8%. The soil-water characteristic curve (SWCC) of the artificially mixed soil is shown in Fig. 3, including data from pressure plate extractor, Tempe cell, and chilled mirror based techniques, and best-fitting model curves by van Genuchten (1980) and Fredlund & Xing (1994). The mixed soil still classifies as SM according to the USCS.

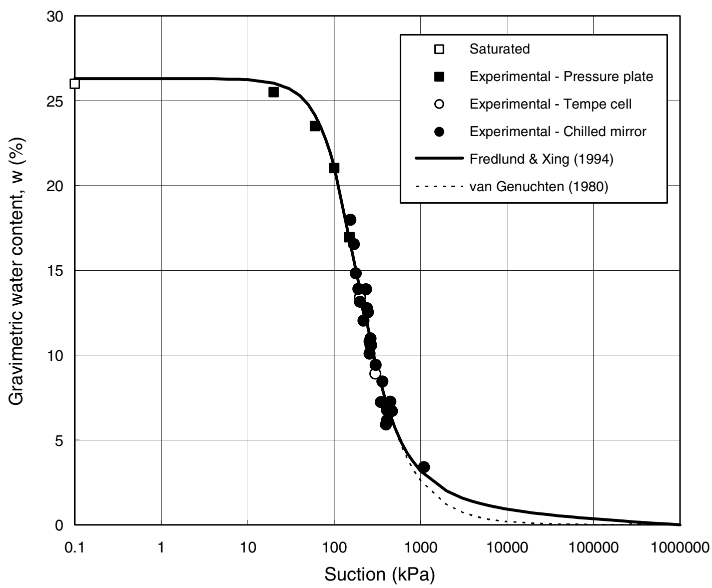

Fig. 3. Soil-water characteristic curve of SM soil using data from various techniques.

As previously mentioned, a typical biaxial specimen in this work is prepared by uniaxial consolidation of a slurry mixture (75% silty sand and 25% kaolin) into an acrylic custom-made biaxial mold, as shown in Fig. 4(a). The slurry is prepared with an initial water content that is about twice that corresponding to its liquid limit, LL = 25.3% (i.e., 1500 g of dry sand-kaolin thoroughly mixed with deaired-deionized water). The biaxial mold has an 80 x 80 mm square section and a 200 mm height. An incremental vertical load is applied to the slurry mixture through a squared acrylic plate featuring an affixed coarse porous stone at its bottom surface. The load is applied via a pneumatic actuator: Fig. 4 (a).

During uniaxial consolidation, the axial deformations are measured with a dial gauge while the expelled water, from within the slurry, is collected in a graduated cylinder: Fig. 4(a). The initial height of the slurry mix is 190 mm, and it is consolidated to final target dimensions of 80 mm x 80 mm x 135 mm. Load increments of 12.5, 25, 50, 100, 200, and 400 kPa are typically applied, with each load increment acting on the slurry mix until no further vertical deformation or change in expelled water volume, whichever is achieved last, is observed (normally after 90% of primary consolidation, t_{90}). This consolidation process yields an average saturated unit weight of about 20 kN/m^3.

The compacted 80 x 80 x 135 mm sample is then gently removed from the consolidation mold, from which two soil specimens can be trimmed for plane-strain testing in the biaxial apparatus, as shown in Fig. 4(b). Prior to plane strain testing, two specimens, having a final average mass of about 323.3 g, are trimmed to final dimensions, d_{10} = 90 mm, d_{20} = 60 mm and d_{30} = 30 mm, as shown in Fig. 5.

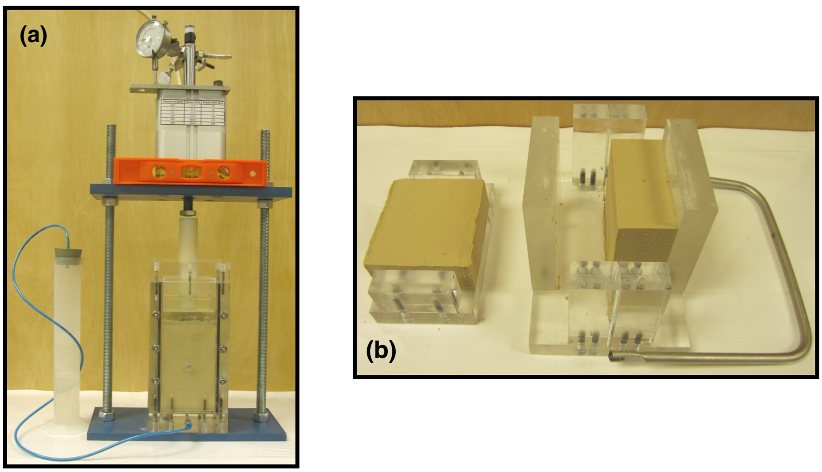

Fig. 4. Biaxial sample preparation: (a) consolidation of slurry mixture, (b) split sample trimming.

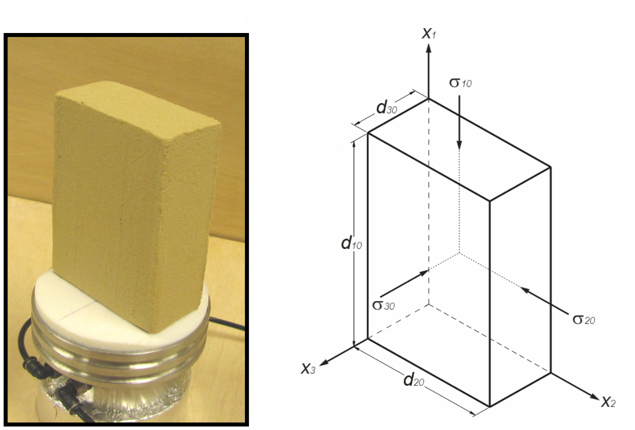

Fig. 5. Fully trimmed 90 mm x 60 mm x 30 mm sample for testing in the biaxial apparatus.

4 Results from Suction-Controlled Plane-Strain Tests on SM Soil

In this work, two identically prepared samples of compacted SM soil were tested in the fully assembled biaxial apparatus (Fig. 1) under net confining pressure, p = (σ_3 – u_a) = 50 kPa; and matric suction states, s = u_a = 50 kPa and 100 kPa, respectively. The axis-translation technique was implemented via a 15.87 mm diameter, 3-bar ceramic disk (i.e., HAEV = 300 kPa) located at the bottom pedestal, as illustrated in Fig. 1.

The suitable pore-fluid equalization time, for the typical biaxial specimen used in this work, was found to be about 144 hrs (6 days). Upon completion of pore-fluid equalization stage, the sample was sheared at a constant vertical deformation rate of 0.004 mm/min (i.e., $4.44\text{x}10^{-5}$% strain/min), which is considered to be low enough to prevent sudden increases in pore pressure during shearing (Fredlund & Rahardjo 1993). Thorough flushing of diffused-air underneath the 3-bar ceramic disk was performed every 24 hrs.

The applied axial stress vs. axial strain response of SM soil from both suction-controlled tests is shown in Fig. 6. Peak stress values of 724.8 kPa and 309 kPa, corresponding to axial strain values of 6.16% and 6.42%, were attained under matric suction states, s = 100 kPa and 50 kPa, respectively. Peak strength is followed by a sharp drop in stress until an apparent residual state is achieved at maximum axial strain values of 8.32% and 8.83%, respectively. The results reflect the important role played by matric suction in the stress-strain-strength response of unsaturated soils under plane strain conditions.

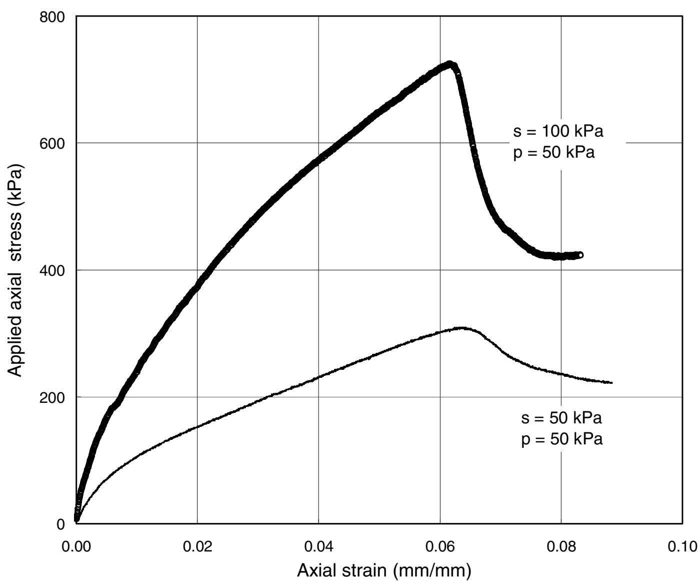

Fig. 6. SM soil response from biaxial tests under constant matric suction s = 50 kPa and 100 kPa.

Fig. 7 shows actual photographs of soil samples failed under plane strain shearing at constant matric suction states, s = 100 kPa (left photo) and s = 50 kPa (right photo). A fully developed failure surface, making a 65^{o} angle with the horizontal, can be readily identified for the sample failed at s = 100 kPa. Likewise, a failure surface, making a 61^{o} angle with the horizontal, can be identified for the sample failed at s = 50 kPa, which further substantiates the results observed in Fig. 6.

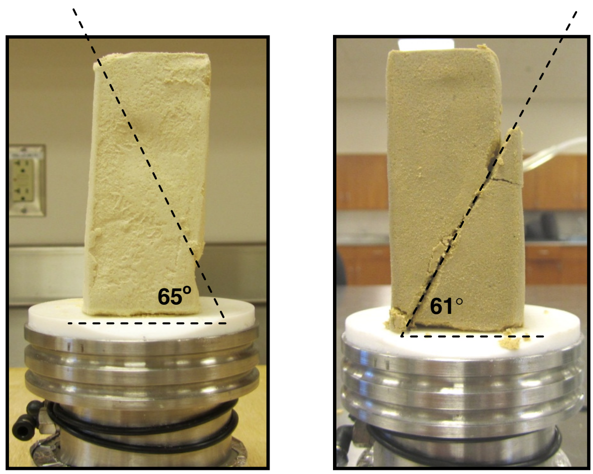

Fig. 7. SM soil specimens failed under biaxial shearing at s = 100 kPa (left) and 50 kPa (right).

5 Concluding Remarks

A suction-controlled biaxial apparatus for soil testing under controlled-suction states has been introduced. Results show that the apparatus is suitable for testing soils under controlled-suction states via the axis-translation technique. Two identically prepared samples of SM soil were tested in the biaxial apparatus under net confining pressure of 50 kPa and matric suction states of 50 and 100 kPa, respectively. Test results reflect the important role played by matric suction in the stress-strain-strength response of unsaturated soils under plane strain conditions. The operational apparatus will continue to play a fundamental role in future research related to the calibration and validation of constitutive models postulated for unsaturated soils under plane strain conditions, as well as the effects of suction on stress localization phenomenon in compacted soils subjected to plane-strain stress states.

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