Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-387

A novel true triaxial apparatus for testing unsaturated soils under suction-controlled multi-axial stress states

Un nouvel appareil cubique pour l'essai des sols insaturés sous l'aspiration commandée et les états multi-axiaux d'effort

Laureano R. Hoyos, Arthit Laikram & Anand J. Puppala
The University of Texas at Arlington, Arlington, Texas, USA

ABSTRACT
This paper describes a novel servo-controlled true triaxial apparatus that has been developed to test 3-in (7.5-cm) per side, cubical specimens of unsaturated soil under controlled-suction states for a wide range of stress paths that are not achievable in a conventional cylindrical apparatus. The cell is a mixed-boundary type of device, with the specimen seated on top of a high-air-entry disk(s) and between five flexible (latex) membranes on the remaining sides of the cube. The new cell is an upgraded, more elaborate version of the one recently implemented by Hoyos (1998), featuring two independent pore-air and pore-water pressure control systems via a PCP-5000-UNSAT pressure panel. Matric suction states in the cubical specimens are induced during testing using axis-translation technique. The paper outlines the importance and development of the new cell, including a brief overview of its main components and the initial validation of its suitability for testing unsaturated soils utilizing the $s = u_a$ testing concept ($u_w = 0$).

RÉSUMÉ
Cet article décrit un nouvel appareil cubique pour l'essai des spécimens cubiques du sol insaturé sous l'aspiration commandée et pour un éventail de trajectoire d'effort qui ne sont pas réalisables dans un appareil cylindrique conventionnel. Le dispositif est un type mélangé de frontière de dispositif, avec le spécimen posé sur un disk(s) d'haut-air-entrée et entre cinq membranes flexibles (de latex) des côtés restants du cube. L'appareil est une version améliorée et plus raffinée de celui récemment mise en application par Hoyos (1998), comportant deux les systèmes de commande indépendants de pression d'pore-air et de l'pore-eau. Des états d'aspiration dans les spécimens sont induits pendant la technique employante d'essai d'axe-transfer. Le papier décrit l'importance et le développement du nouvel appareil, y compris une brève vue d'ensemble de ses composants principaux et de la validation initiale de sa convenance à d'essai de sols insaturée employer le concept d'essai $s = u_a$ ($u_w = 0$).

1 INTRODUCTION

Over the last few decades, the description of the stress-strain-strength behavior of unsaturated soils has been closely linked with efforts to isolate the relevant effective stress fields governing the soil's mechanical response. The adoption of matric suction, $s = (u_a - u_w)$, and the excess of total stress over air pressure, $(\sigma - u_a)$, as the relevant stress state variables, have allowed the modeling of various key features of unsaturated soil behavior via suction-controlled oedometer, triaxial, and direct shear testing (Alonso et al. 1990, Wheeler and Sivakumar 1992, Fredlund and Rahardjo 1993).

The majority of these devices, however, allow for the application of loads along limited paths and modes of deformation, such as one-dimensional, hydrostatic, or axisymmetric loading. In nature, subgrade and shallow foundation soils above the ground-water table are subject to three-dimensional stress gradients due to changes in the stress state variables $(\sigma_{ij} - u_a\delta_{ij})$ and $(u_a - u_w)\delta_{ij}$, as depicted schematically in Fig. 1.

Therefore, the accurate prediction of the stress-strain response of geosystems involving unsaturated soils requires that all constitutive relations be valid for all major stress paths likely to be experienced in the field.

It is in this context where a true triaxial (cubical) cell, capable of inducing a wide range of suction states in the test specimens, plays a fundamental role in the complete stress-strain-strength characterization of this type of materials.

This paper describes a novel servo-controlled true triaxial apparatus that has been developed to test 3-in (7.5-cm) per side, cubical specimens of unsaturated soil under controlled-suction states for a wide range of stress paths that are not achievable in a conventional cylindrical apparatus. The equipment is a mixed-boundary type of device, with the specimen seated on top of a high-air-entry disk(s) and between five flexible (latex) membranes on the remaining sides of the cube. The new cell is an upgraded, more elaborate version of the one recently implemented by Hoyos (1998), featuring two independent pore-air pressure (u_a) and pore-water pressure (u_w) control systems via a PCP-5000-UNSAT pressure control panel. Suction states in the cubical specimens during suction-controlled testing are induced via axis-translation technique.

The paper also outlines the importance and development of the new cell, including brief details of its main components, design and assembling, and the initial validation of its suitability for testing unsaturated soils under controlled suction states utilizing the $s = u_a$ testing concept ($u_w = 0$).

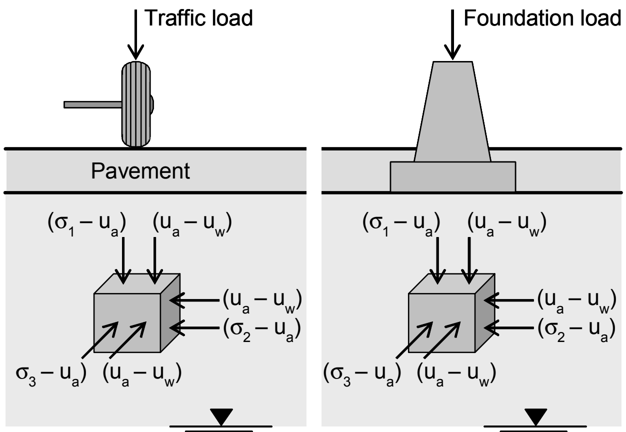

Figure 1. Unsaturated soil deposits under true triaxial stress states.

2 IMPORTANCE

Several researchers, including Ko and Scott (1968), Atkinson (1972), Lade and Duncan (1973), Sture (1979), Sture and Desai (1979), Egging (1981), Mageli (1982), Janoo (1986), Arthur (1988), Reddy et al. (1992), and Callisto and Calabresi (1998), have conducted studies on the use of true triaxial devices for characterization of soil, rock, and cemented materials. These studies have outlined the benefits of the cubical apparatus over the cylindrical triaxial cell for testing stress-strain-strength behavior of soils. However, none of these have dealt with behavior of unsaturated soils under suction-controlled conditions.

Matric suction plays a paramount role in unsaturated soil response under 1-D, isotropic, and axisymmetric loading conditions. Therefore, suction is expected to play as critical a role in unsaturated soil response under multiaxial stress states (Fig. 1). The present work is largely motivated by the lack of experimental evidence of this kind.

3 PREVIOUS WORK

In a recent attempt by Hoyos (1998) to test unsaturated soils under multiaxial loading, a 30-year-old cubical apparatus was modified to test 4-in (10-cm) side, cubical specimens of silty sand under suction-controlled conditions. The original development of the apparatus was presented by Atkinson (1972) for multiaxial testing of rock materials. Pore-water pressure (u_w) was applied to the bottom of the specimen through a 5-bar HAE ceramic disk. Pore-air pressure (u_a) was applied to the top and four lateral faces of the specimen via an air-pressurized manifold. Test results have been reported by Hoyos (1998).

Nevertheless, this existing device presented some equipment and testing related limitations: (1) The steel frame is highly corrosive, which results in occasional clogging of the 5-bar disk, (2) Hydraulic oil is used to pressurize latex membranes in contact with soil, with oil temperatures ranging from 28 ^{o}C to 38^{o}C, (3) Latex membranes have low durability when exposed to hydraulic oil for an extended period of time, (4) Pore-water temperature cannot be controlled, delaying equalization of pore fluids, and (5) Device allows only stress-controlled testing.

4 A NOVEL UNSAT TRUE TRIAXIAL APPARATUS

The true triaxial apparatus described herein is aimed at overcoming all of the above limitations, yielding a considerably enhanced performance, which includes: (1) More testing accuracy and reliability, (2) More flexibility of operation and breadth of application, (3) More refined data acquisition and process control systems, and (4) Increased amount and quality of testing variables monitored during suction-controlled testing.

True triaxial devices can be classified into three categories: rigid-boundary, flexible-boundary, and mixed-boundary (Sture 1979, Arthur 1988). The apparatus presented in this paper is a mixed-boundary type of cell, with the specimen seated on top of an arrangement of nine equally spaced, 0.75-in diameter 5-bar ceramic disks and between five flexible membranes on the remaining sides of the cube, as depicted schematically in Fig. 2.

The cell (Fig. 2) consists mainly of a stainless steel frame **(1)** featuring six pressure cavities to accommodate one top and four lateral flexible latex membranes **(2)**, and a cubical base aluminum piece **(3)** at the bottom to house nine equally spaced, 0.75-in diameter, 5-bar ceramic disks **(4)**. Once the ceramic disks have been fully saturated in-place, the specimen **(5)** is prepared in-place via tamping compaction. After compaction, the remaining five walls **(6)** are assembled to the frame. Three LVDTs **(7)** per face monitor soil deformations. De-aired water pressurizes the specimen via the latex membranes. The water-based hydraulic pressure will be transmitted to the water-filled latex via pressure inlet/outlet connections **(8)** on the walls.

Pore-air pressure (u_a) is applied along the borderlines of the top and lateral faces of the specimen via 0.1-in diameter channels drilled through the corners and along the edges of the main frame **(9)**. Air pressure is supplied via a set of air-pressurized manifolds with nylon tubing **(10)** from an external PCP-5000-UNSAT pressure control panel. Pore-water pressure (u_w) is applied to the bottom of the specimen through the arrangement of nine equally spaced, 0.75-in diameter, 5-bar ceramic disks **(4)**. Water pressure is supplied via nylon tubing **(11)** from the PCP-5000-UNSAT pressure control panel. A grooved compartment uniformly distributes the water underneath the 5-bar disks.

Fig. 3 shows a plan view of the arrangement of all 5-bar ceramic disks at the bottom assembly. A flushing mechanism **(12)** is added to the bottom assembly. Tests are entirely computer-driven via a data acquisition/process control system (DA/PCS).

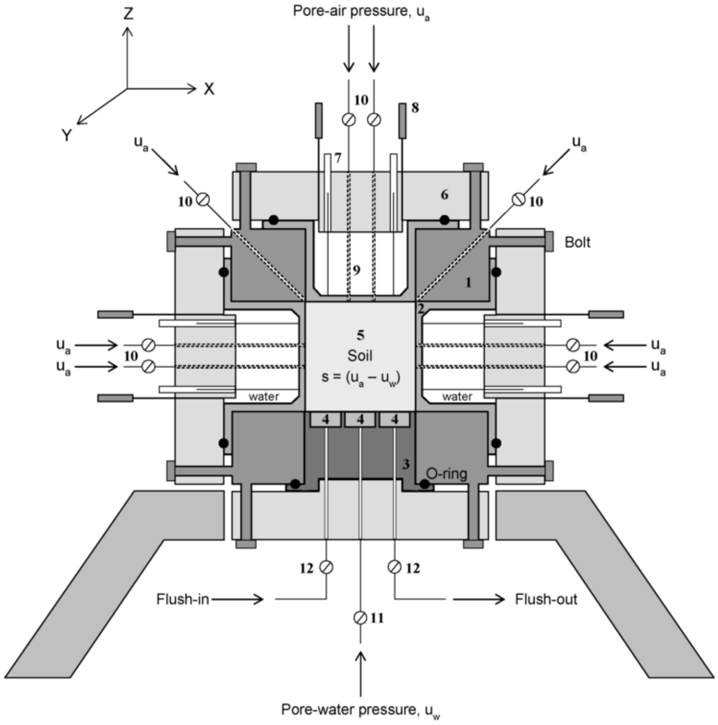

Figure 2. Cross-sectional view of suction-controlled cell (no scale)

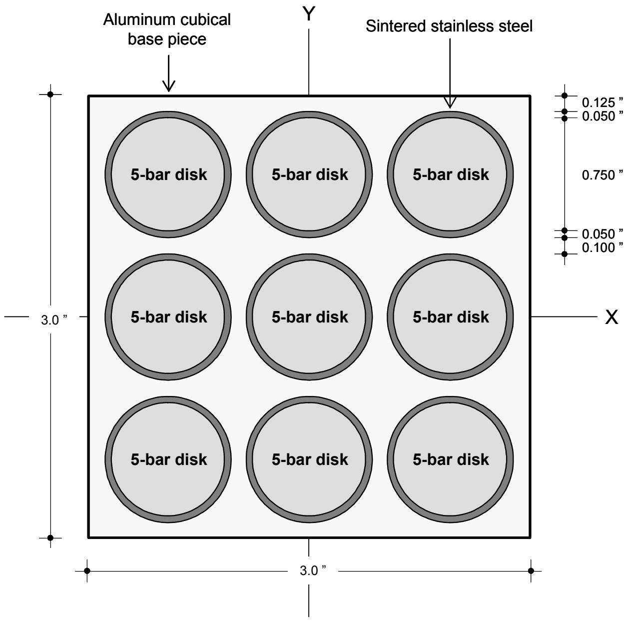

Figure 3. Plan view of bottom cubical base with 5-bar ceramic disks.

The core of the cubical cell (Fig. 2) was manufactured at the University of Colorado, Boulder. The PCP-5000-UNSAT pressure control panel from Geotechnical Consulting and Testing Systems (GCTS) is adapted to the cubical setup to control pore-air pressure (u_a) and pore-water pressure (u_w). This novel system has been successfully utilized in cylindrical cells, and it features pressure/volume control cell pressure, pore/back pressure, pore-air pressure (u_a) with 2 MPa (300 psi) pressure range, and 300 cc (18 in^3) volume capacity. It also includes hydraulic servo valves, electro-hydraulic pump, pressure transducers with 0.1 kPa (0.02 psi) resolution, and specific water volume ($v_w = 1 + eS_r$) change transducer with 0.01 cc resolution. Fig. 4 shows a photograph of the entire test setup.

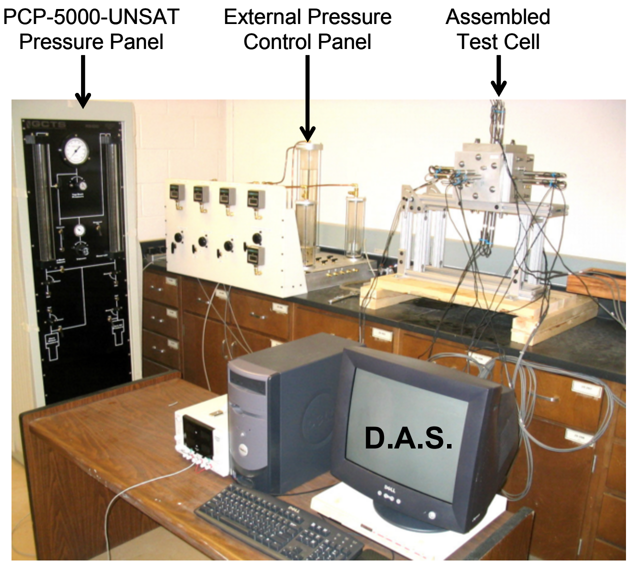

Figure 4. Photograph of entire cubical test setup.

5 INITIAL AXIS-TRANSLATION VERIFICATION TEST

Poorly graded silty sand (SM) was used for initial verification of the suitability of axis-translation technique for the newly developed device. Upon saturation of the 5-bar disks, the 7.5-cm side, cubical soil specimen was prepared using in-place tamping compaction (Reddy et al. 1992). Each soil layer is compacted at a moisture content 4% greater than standard Proctor optimum. Tamping corresponds to a compactive effort considerably less than that of standard Proctor compaction. The intention is to reproduce specimens with low preconsolidation stress values, so that, subsequently, it is relatively easy to re-consolidate the soil to a virgin state.

A procedure similar to that suggested by Fredlund (1973), to ensure full, in-place saturation of a high-air-entry disk, is used herein. The procedure is adapted to the working conditions of the 5-bar disks in the bottom assembly (Fig. 2).

The suitability of the axis-translation technique in the newly developed apparatus was then experimentally validated by conducting two constant-suction (drained) tests, both involving isotropic loading and axisymmetric shearing stages, on two identically prepared specimens of silty sand. Tests were performed at same constant matric suction, s = 200 kPa, and loading rate of 10 kPa/hr.

In each test, as depicted in Fig. 5, pore-fluid (air and water) equalization stage is followed by a ramped consolidation stage (path AB) and a final shearing stage (path BC). The first specimen, however, was subjected to $s = u_a = 200$ kPa ($u_w = 0$), while the second specimen was subjected to $u_a = 300$ kPa and $u_w = 100$ kPa (s = 200 kPa).

Soil response in Fig. 6(a) is presented in terms of specific volume (v = 1 + e) versus mean net stress (p) for ramped consolidation stage (path AB). Likewise, soil response in Fig. 6(b) is presented in terms of deviator stress (q) versus axial strain for axisymmetric shearing stage (path BC).

Test results in Figs. 6(a) and 6(b) shows no significant difference in soil response under both test conditions, hence validating the technique.

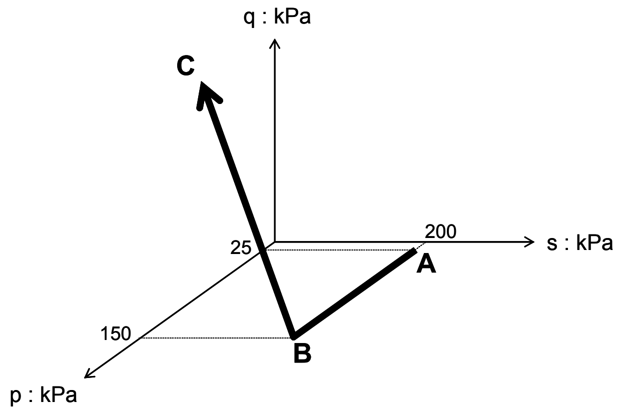

Figure 5. Stress paths in p:q:s space for axis-translation validation.

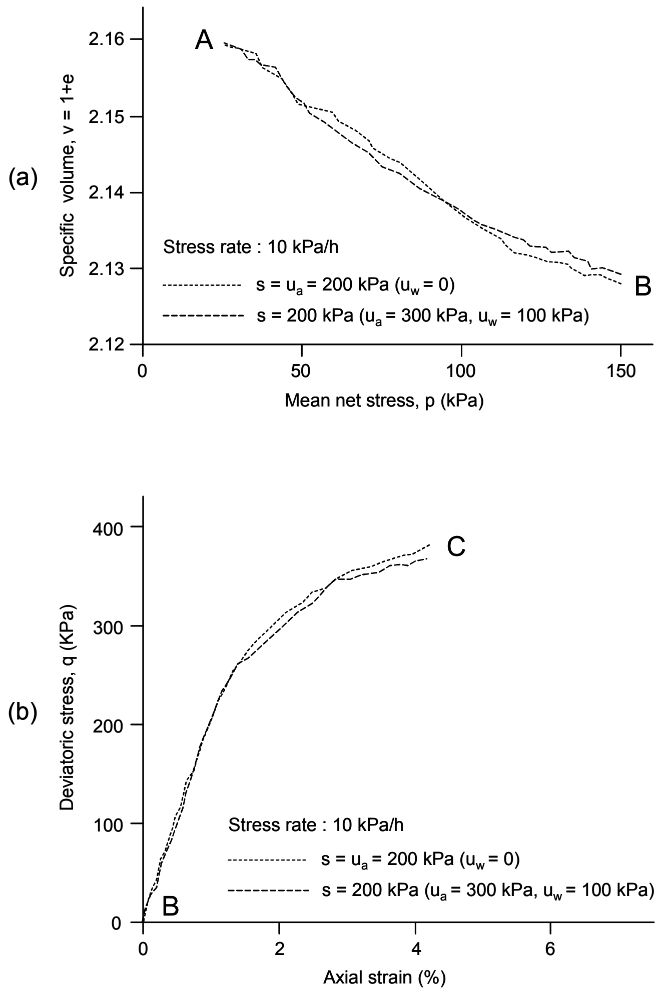

Figure 6. Axis-translation validation: (a) Isotropic loading; (b) Shearing.

6 CONCLUSIONS

Preliminary testing on silty sand, as described herein, has shown that the newly developed apparatus is suitable for testing soils under suction-controlled conditions using the axis-translation technique. On-going testing involves a wide range of stress paths that are not achievable in a conventional cylindrical apparatus, including simple shear (SS) in a deviatoric stress plane (π-plane). Further refinement contemplated in the near future includes control of temperature in pore fluids (air and water).

ACKNOWLEDGEMENTS

This on-going research is funded by the U.S. National Science Foundation (NSF), Award # 0216545. This support is gratefully acknowledged.

REFERENCES

Alonso, E.E., Gens, A. and Josa, A. 1990. A constitutive model for partially saturated soils. Géotechnique, 40(3), 405-430.

Arthur, J.R.F. 1988. Cubical devices: versatility and constraints. Advanced Triaxial Testing of Soil And Rock, STP 977, ASTM, Philadelphia, PA, 743-765.

Atkinson, R.H. 1972. A cubical test cell for multiaxial testing of materials. Ph.D. Dissertation, University of Colorado at Boulder, Boulder, CO.

Callisto, L. and Calabresi, G. 1998. Mechanical behaviour of natural soft clay. Géotechnique, 48(4), 495-513.

Egging, D. 1981. Constitutive relations of randomly oriented steel fiber reinforced concrete under multiaxial compressive loadings. Ph.D. Dissertation, University of Colorado, Boulder, CO.

Fredlund, D.G. 1973. Volume change behavior of unsaturated soils. Ph.D. Dissertation, University Of Alberta, Edmonton, Alta., Canada.

Fredlund, D.G. and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John Wiley and Sons, Inc., NY.

Hoyos, L.R. 1998. Experimental and computational modeling of unsaturated soil behavior under true triaxial stress states. Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA, 352 p.

Janoo, V.C. 1986. Drained and undrained behavior of sand under high pressures. Ph.D. Dissertation, University of Colorado at Boulder, Boulder, CO.

Ko, H.Y. and Scott, R.F. 1968. Deformation of sand at failure. ASCE J. Soil Mech. Found. Engrg. Div., 94(SM4), 883-898.

Lade, P.V. and Duncan, J.M. 1973. Cubical triaxial tests on cohesionless soil. ASCE J. Soil Mech. Found. Div., 99(SM10), 793-812.

Mageli, T.S. 1982. Development of a servo-controlled true-triaxial cell and cyclic loading of clays. M.Sc. Thesis, University of Colorado at Boulder, Boulder, CO.

Reddy, K.R., Saxena, S.K. and Budiman, J.S. 1992. Development of a true triaxial testing apparatus. ASTM Geotech. Test. J., 15(2), 89-105.

Sture, S. 1979. Development of multiaxial cubical test device with pore-water pressure monitoring facilities. Rep. VPI-E-79.18, Dept. Civil Eng., Virginia Poly. Inst. & State U., Blacksburg, VA.

Sture, S. and Desai, C.S. 1979. A fluid cushion truly triaxial or multiaxial testing device. ASTM Geotech. Test. J., 2(1), 20-33.

Wheeler, S.J. and Sivakumar, V. 1992. Development and application of a critical state model for unsaturated soils. Predictive Soil Mech., eds: G.T. Houlsby & A.N. Schofield, 709-728, London.