Modeling unsaturated soil behavior under multiaxial stress states

Modélisation de comportement des sols non saturés sous états multiaxiales de stress

L.R. Hoyos, A. Laikram, D. Pérez-Ruiz & A.J. Puppala
University of Texas at Arlington, Arlington, Texas 76019, USA

ABSTRACT

This paper presents the results from a preliminary series of conventional triaxial compression (CTC) and triaxial compression (TC) tests conducted on compacted silty sand (SM) under constant-suction states. The experiments were conducted by using a novel, servo-controlled, true triaxial (cubical) apparatus that is suitable to test 3-in (7.5-cm) per side, cubical specimens of unsaturated soil under controlled-suction states and 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 ceramic disk and between five flexible (latex) membranes on the remaining sides of the cube. The cell features two independent pore-air (u_a) and pore-water (u_w) pressure control systems via a PCP-5000-UNSAT pressure panel. Target suction levels are induced and kept constant during testing using the axis-translation technique. The technique is implemented by utilizing the $s = u_a$ testing concept ($u_w = 0$), which plays a fundamental role in characterizing unsaturated soil behavior under multiaxial stress paths that are likely to be experienced in the field. Results from suction-controlled tests under axisymmetric conditions ($\sigma_2 = \sigma_3$) were used for calibration and further fine-tuning of the original elasto-plastic, critical state based framework postulated by the Barcelona Model (Alonso et al. 1990). Matric suction was found to exert a noticeable influence on the soil's stress-strain-strength behavior under multiaxial stress states. Numerical predictions of experimental stress-strain response of silty sand under axisymmetric conditions, using the Barcelona Model, were proved to be reasonably accurate.

RÉSUMÉ

Ce document présente les résultats préliminaires d'une série de compression triaxiale conventionnelle (CTC) et triaxiaux de compression (TC) tests effectués sur le sable limoneux compacté (SM) en constante aspiration Etats. Les expérimentations ont été conduites à l'aide d'un roman, servo-contrôlé, la véritable triaxial (cubique) les appareils qui se prêtent à l'épreuve 3-in (7.5-cm) de chaque côté, cubiques spécimens de sol non saturé sous contrôle états-aspiration et d'un large éventail des chemins qui ne sont pas réalisables dans un appareil cylindrique classique. Le matériel est un mixte de frontière type d'appareil, le modèle assis au sommet d'une haute entrée d'air en céramique disque flexible et de cinq (latex) de membranes sur les autres faces du cube. La cellule dispose de deux indépendants pore-air (u_a) et l'eau des pores (u_w) de systèmes de contrôle de la pression par l'intermédiaire d'un PCP-5000-UNSAT groupe de pression. Cible d'aspiration sont induits et maintenue constante au cours des essais en utilisant l'axe de traduction technique. La technique est mis en oeuvre en utilisant les unités de test $s = u_a$ concept ($u_w = 0$), qui joue un rôle fondamental dans la caractérisation des sols non saturés comportement sous multiaxial chemins qui sont susceptibles d'être expérimenté dans le domaine. Les résultats de tests d'aspiration contrôlée sous axisymmetric conditions ont été utilisées pour l'étalonnage et le réglage fin de l'original élasto-plastique, état critique fondée cadre postulé par le modèle de Barcelone (Alonso et al. 1990). Matric aspiration a été trouvé à exercer une influence notable sur le sol du stress-strain-force comportement sous stress multiaxial Etats. Calcul des prévisions de contrainte-déformation expérimentales réponse de sable limoneux axisymmetric sous conditions, en utilisant le modèle de Barcelone, ont révélé être raisonnablement précis.

Keywords : unsaturated soils, matric suction, true triaxial test, constitutive modeling

1 BACKGROUND AND SCOPE

Description of the stress-strain-strength behavior of unsaturated soils has been closely linked with efforts to isolate the most relevant effective stress fields governing their mechanical response. The adoption of matric suction, $s = (u_a - u_w)$, and the excess of total stress over air pres-sure, $(\sigma - u_a)$, as 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, only allow for the application of loads along limited paths and/or modes of soil deformation, i.e., one-dimensional, hydrostatic or axisymmetric loading. In nature, pavement subgrades and shallow foundation soils well above the ground-water table are subjected 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 in Figure 1.

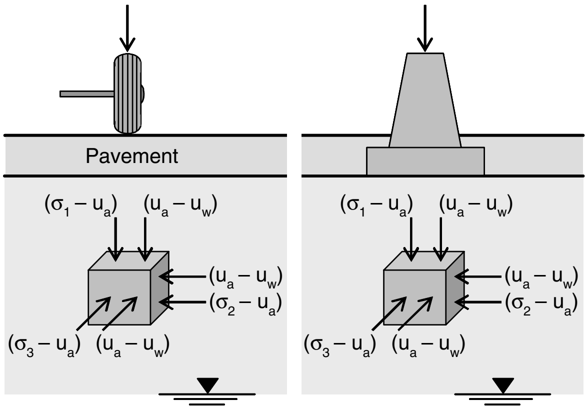

Figure 1. Unsaturated soil deposits under 3-D stress gradients.

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

It is in this context that a true triaxial (cubical) cell, capable of inducing a wide range of simple-to-complex multiaxial stress paths under controlled-suction states in the test specimens, plays a critical role in the stress-strain-strength characterization of this type of materials.

This paper summarizes the results from a preliminary series of conventional triaxial compression (CTC) tests and triaxial compression (TC) tests conducted on unsaturated silty sand (SM) under controlled-suction states. The experiments were conducted using a novel, fully servo-controlled, true triaxial apparatus that is suitable to test 3-in (7.5-cm) per side cubical specimens of unsaturated soil under controlled-suction states and for a wide range of stress paths that are not achievable in a conventional cylindrical apparatus.

Test results from suction-controlled tests under axisymmetric conditions ($\sigma_2 = \sigma_3$) were utilized for calibration and further validation of the original elasto-plastic framework postulated by the Barcelona Model (Alonso et al. 1990).

The following sections include the description of the main components of the novel true triaxial device, the analysis of key test results and numerical predictions with the Barcelona Model.

2 A NOVEL TRUE TRIAXIAL DEVICE

The cell described in this paper is an upgraded, more elaborate version of the one previously reported by Hoyos and Macari (2001), featuring two independent pore-air (u_a) and pore-water (u_w) pressure control systems via a PCP-5000-UNSAT pressure control panel from Geotechnical Consulting & Testing Systems (GCTS), Tempe, Arizona.

The cell consists mainly of a stainless steel frame featuring six pressure cavities to accommodate one top and four lateral flexible latex membranes, and a cubical base aluminum piece at the bottom to house one 5-bar ceramic and four symmetrically spaced coarse porous stones, as shown in Figures 2 and 3.

After setting the compacted specimen into the inner cavity of the frame, the remaining five walls are assembled to the frame. Three LVDTs per face (top and four lateral) are used to monitor soil deformations while de-aired water is used to pressurize the specimen via cubical latex membranes. The external pressure is transmitted to the water-filled latex membranes via pressure inlet/outlet connections on the walls.

Figure 4 shows the entire test layout, including the servo-controlled external pressure application system (on the left) and the fully assembled cubical cell interacting with the PCP-5000-UNSAT pressure control panel (on the right).

Pore-air pressure is supplied at the bottom of the specimen via a full set of air-pressurized manifolds and nylon tubing from the PCP-5000-UNSAT control panel. Pore-water pressure can be applied and/or controlled at the bottom of the soil specimen through the 5-bar ceramic disk. Water pressure is also supplied via nylon tubing from the PCP-5000-UNSAT pressure panel. The axis-translation technique is then implemented by utilizing the $s = u_a$ testing concept ($u_w = 0$).

The panel also features a flushing mechanism at the bottom assembly, as shown in Figure 5. All suction-controlled tests are entirely computer-driven via a data acquisition/process control system (DA/PCS). Sample preparation process and saturation of the ceramic disks are fully described by Hoyos et al. (2008).

Test soil consisted of poorly graded silty sand (SM). After saturation of the 5-bar disk, the bottom and the four lateral wall assemblies are then set into place. A typical 3-in (7.5-cm) side, cubical specimen is then prepared in-place using a combined pluviation-tamping compaction process (Hoyos et al. 2008).

The specimen is prepared in approximately eight pluviated layers, with each layer compacted at a target moisture content 4% greater than the Proctor optimum. Tamping corresponds to a compactive effort considerably less than that of standard Proctor compaction. The intention was to reproduce specimens with low preconsolidation stress values, so that it is relatively feasible to reconsolidate the soil to a virgin state.

The core system of the cell was manufactured and check-out tested at the University of Colorado, Boulder. The PCP-5000-UNSAT pressure control panel was then adapted to the cubical cell at the advanced Geomechanics Laboratory of the University of Texas at Arlington.

The PCP-5000-UNSAT panel has been successfully utilized in cylindrical triaxial cells and it also features a specific water volume change transducer for accurate measurement of changes in v_w (= $1 + eS_r$) with 0.01 cc resolution.

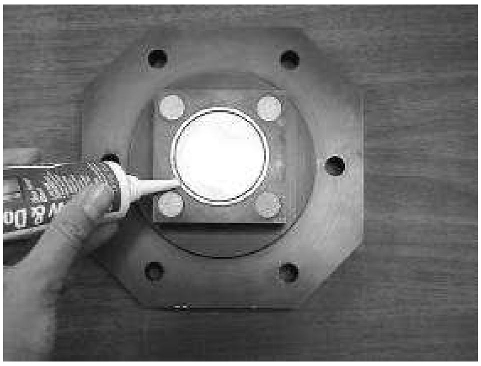

Figure 2. Sealing of 5-bar ceramic onto cubical base aluminum piece.

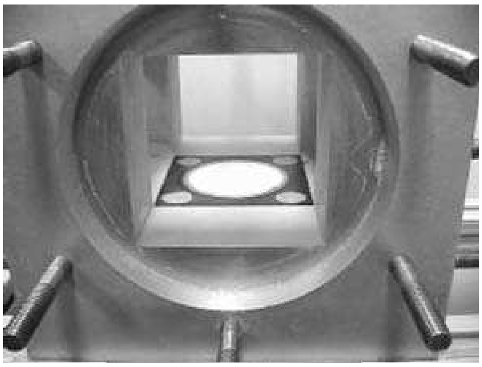

Figure 3. Cubical base aluminum piece fitted onto bottom assembly.

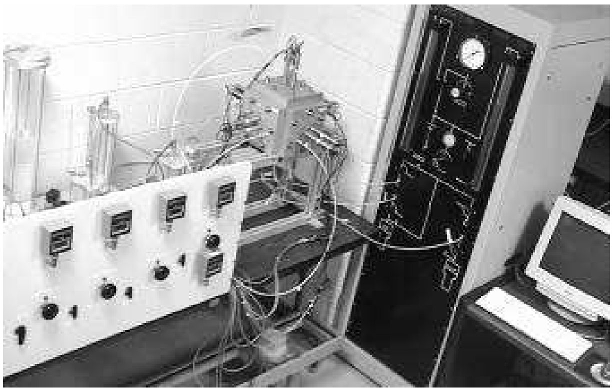

Figure 4. Entire cubical test layout, including external pressure control system (left) and PCP-5000-UNSAT pressure control panel (right).

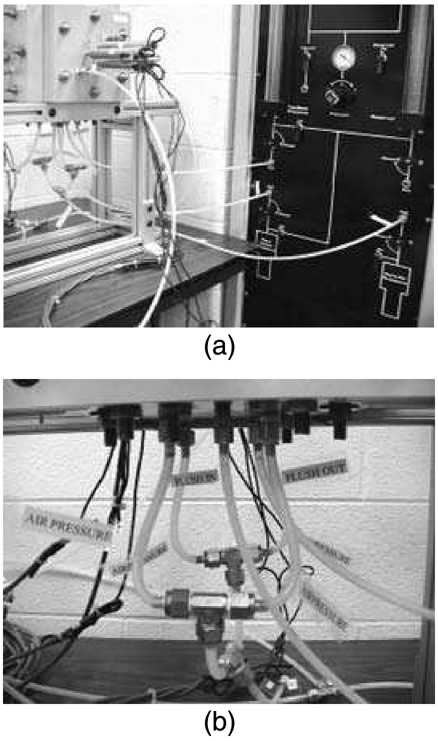

Figure 5. Suction-controlled and flushing mechanism: (a) cubical cell interacting with PCP-5000-UNSAT panel; (b) pore-air pressure, pore-water pressure, and flushing control lines.

3 SUCTION-CONTROLLED TEST SCHEME

In this work, identically prepared specimens of silty sand (80% sand and 20% silt) were subject to a multi-stage testing scheme in which suction was kept constant at 50, 100, 200, 300 or 400 kPa. A soil specimen was first brought under isotropic stress state and subsequently imposed a constant-suction, monotonic shearing until it was apparent the deviator stress had reached a peak value. The suction-controlled testing scheme is depicted schematically on a deviatoric plane in Figure 6.

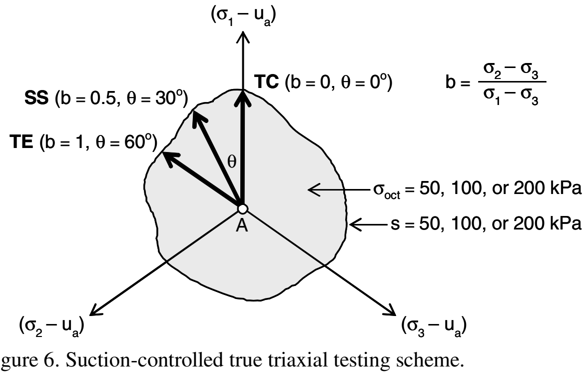

Figure 6. Suction-controlled true triaxial testing scheme.

In this work, the net octahedral stress σ_{oct} and deviator stress q are both defined in terms of the total principal stresses, σ_1, σ_2, and σ_3, and the pore-air pressure u_a, as follows:

$$\sigma_{oct} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} - u_a \tag{1}$$

$$q = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} \tag{2}$$

Figure 7 shows the typical deviator stress versus principal strain response of silty sand from suction-controlled TC tests. In this figure, suction is shown to exert an important influence on the shear resistance of compacted silty sand, with a noticeable increase for s = 400 kPa. However, a relatively small increase in strength is observed from 300 to 400-kPa suction, suggesting a nonlinear increase in strength, in accordance to typical trends observed in the unsaturated soil strength parameter ϕ^b at higher values of suction (Fredlund and Rahardjo 1993).

During TC testing, the major principal stress σ_1 is increased while both the intermediate σ_2 and minor σ_3 principal stresses are reduced, such that the net octahedral stress σ_{oct} remains constant. Therefore, the corresponding minor and intermediate principal strains were found to be expansive (–) while the major principal strain is compressive (+).

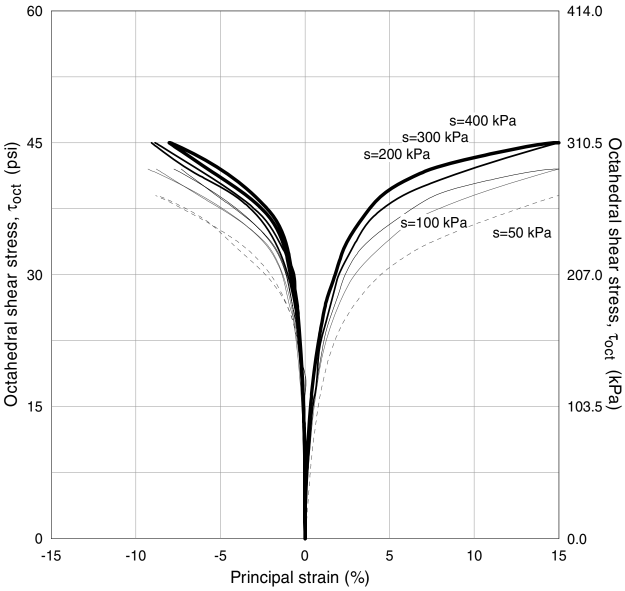

Figure 7. Silty sand response from suction-controlled TC tests under net octahedral normal stress σ_{oct} = 150 kPa.

4 BARCELONA MODEL PARAMETERS

Alonso et al. (1990) postulated a critical state based framework (Barcelona model) involving four state variables: the net mean stress, $p = (1/3)(\sigma_1 + 2\sigma_3) - u_a$, deviator stress, $q = (\sigma_1 - \sigma_3)$, matric suction, $s = (u_a - u_w)$, and specific volume, $v = (1 + e)$. The model rigorously respects the well-established framework of the Modified Cam-Clay model, featuring elastic strains when soil state lies inside a state boundary surface, and plastic strains when this surface is reached. Plastic behavior, as the soil state traverses the boundary surface, corresponds to an expansion of a yield surface in p:q:s space, as shown in Figure 8. A detailed description of model yield loci, flow rules, hardening laws, and elasto-plastic strain definitions is presented by Alonso et al. (1990) and Macari et al. (2003).

Best-fit values of the Barcelona model parameters used for numerical predictions in this work are summarized as follows: $\lambda(0)$ = 0.20, slope of normal compression line in v:p plane for saturated case; k = 0.012, elastic swell index; β = 18.1 $(\text{MPa})^{-1}$, parameter controlling rate of increase of $\lambda(s)$ with suction; r = 0.22, parameter defining maximum stiffness; p^c = 0.056 MPa, reference stress for which the LC locus becomes a straight line; G = 9.2 MPa, shear modulus; M = 1.42, slope of critical state line; *k* = 1.124, parameter controlling increase in cohesion with suction, $p_o(0)$ = 0.071 MPa, yield stress for saturated case; and s_o = maximum past suction defining SI locus (undetermined).

Model parameters were obtained from a series of suction-controlled isotropic and axisymmetric loading tests conducted by Laikram (2007) on similar compacted silty sand soil.

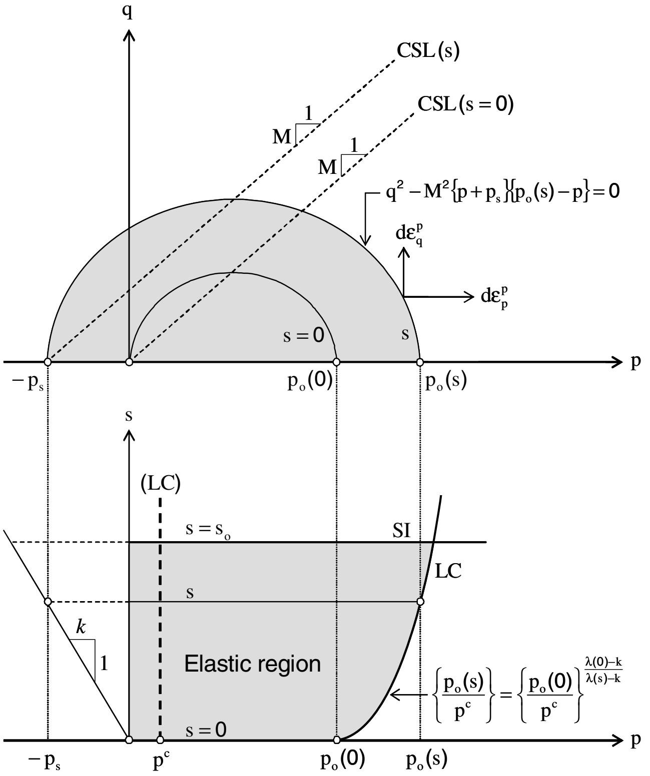

Figure 8. Original Barcelona model framework shown in p:q:s space.

5 BARCELONA MODEL PREDICTIONS

Barcelona model parameters (summarized above) were used for predicting unsaturated soil response under axissymmetric stress states. Figure 9 shows the experimental and predicted responses of compacted silty sand from a s-controlled CTC test conducted at σ_{oct} = 100 kPa and s = 50 kPa. Numerical predictions show reasonably good agreement with the observed experimental response. Likewise, Figure 10 shows the experimental and predicted responses of compacted silty sand from a s-controlled CTC test conducted at σ_{oct} = 100 kPa and s = 150 kPa. Numerical predictions also show reasonably good agreement with observed experimental response.

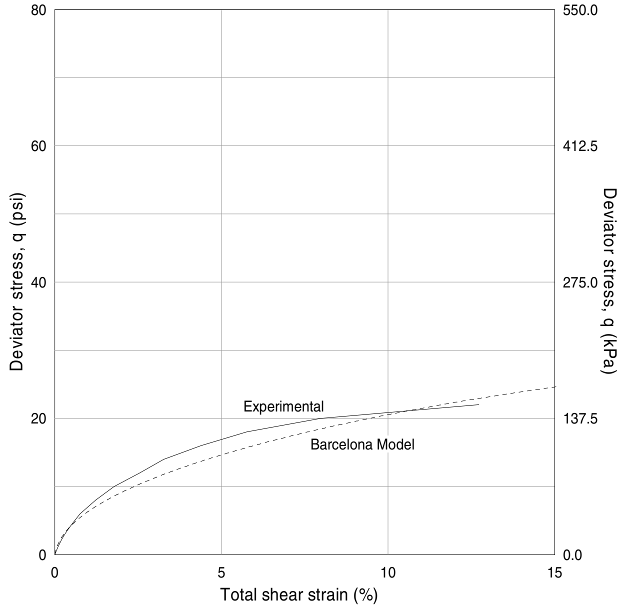

Figure 9. Silty sand response from suction-controlled CTC test under net octahedral stress σ_{oct} = 100 kPa and matric suction s = 50 kPa.

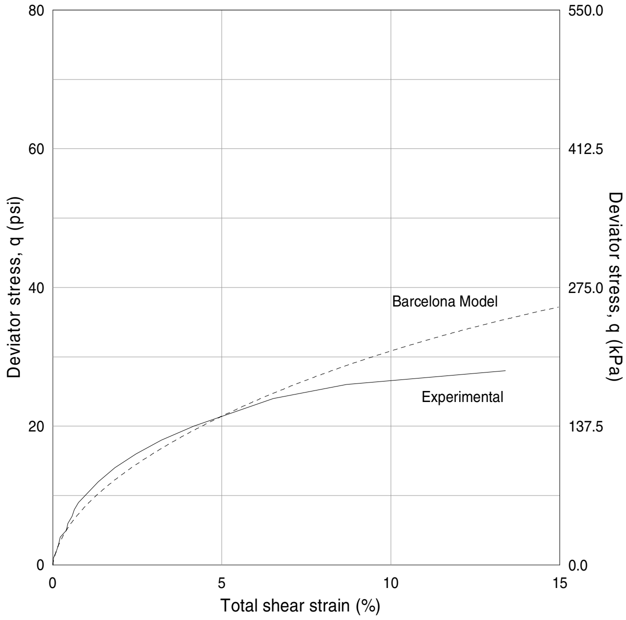

Figure 10. Silty sand response from suction-controlled CTC test under net octahedral stress σ_{oct} = 100 kPa and matric suction s = 150 kPa.

6 CONCLUDING REMARKS

Suction-controlled test results from compacted silty sand, as described herein, has shown that the newly developed apparatus is reasonably suitable for testing soils under suction-controlled conditions using axis-translation technique. On-going testing involves a wide range of stress paths that are not achievable in a cylindrical apparatus, including simple shear tests in deviatoric plane. Agreement between numerical predictions and observed response of unsaturated silty sand underscore the potential of the Barcelona Model for numerical analyses of geotechnical boundary-value problems involving soil deposits that remain partially saturated throughout the year and subject to 3-D stress states $(\sigma_{ij} - u_a\delta_{ij})$ and $(u_a - u_w)\delta_{ij}$.

ACKNOWLEDGEMENTS

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