Characterization of compacted silty sand via relative humidity-controlled triaxial testing

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Abstract. Rather limited experimental evidence is available of triaxial shear-induced response of unsaturated soils at suction states far beyond residual suction. In this work, a fully automated, relative-humidity (Auto-RH) control unit is adapted to a newly implemented double-walled triaxial cell to test compacted silty sand specimens under considerably high total suction states via the vapor-pressure technique. The work is intended to gain critical insight into some of the most essential hydro-mechanical features of densely compacted intermediate geomaterials, such as post-peak softening and strain-induced dilatancy, under suction-controlled monotonic shearing. In general, peak strength is followed by large strain-induced softening until critical state is apparently reached. Strain-softening is observed to become considerably more pronounced with increasing total suction. The slope of critical state lines, however, remains virtually constant, regardless of induced total suction, in agreement with critical state-based constitutive frameworks previously postulated for unsaturated soils.

Key words: Unsaturated soils, vapor-pressure technique, double-wall triaxial cell, critical state line.

1 Introduction

Recently, researchers have shown growing interest in assessment of soil shear strength and stiffness behaviors in the high suction range ([8], [17], [2], and [9]). However, use of the axis-translation technique to impose high soil suction is limited (to about 1500 kPa) by the air-entry value of the ceramic disk. Changes in moisture content in unsaturated soil specimens at suction greater than approximately 3,000 kPa can be controlled using vapor phase equilibrium [9]. This method has been used to measure triaxial shear strength and volume change behavior of a non-plastic silty soil at high suction range, under controlled relative humidity environment, by regulating the inflow rate of air ([11] and [10]).

Although, the oedometer and direct shear tests are comparatively simple to be conduct, the triaxial testing facilitates soil testing along a wide variety of stress paths, thereby simulating different field conditions encountered in the geotechnical practice [2]. A substantial portion of the data available on unsaturated soil behavior has been obtained using the axis-translation technique (i.e. low-to-medium suction range). However, research using osmotic or vapor pressure based techniques in the higher suction range (i.e. above residual suction range), is very limited. This study is one of the few attempts made on high suction-based soil strength tests as it pertains to intermediate geomaterials.

An attempt has been made at Geomechanics laboratory of University of Texas at Arlington to develop a new apparatus by accommodating the RH triaxial equipment, in conjunction with the triaxial device, to directly control the relative humidity inside the specimen. Shear induced strength/volume change behavior in high total suction range is studied in current research. Same equipment was previously used to accommodate axis-translation technique to test soil specimen up to matric suction of 1500 kPa [13]. Present modifications have enhanced the capabilities of this triaxial equipment to test soil specimen up to total suction as high as 300 MPa. Efficacy of this equipment to reproduce similar test results at low, medium and high suction range has been performed and documented by [14].

2 Test material

The test soil comprised of 55% sand, 37% silt and 8% clay and is classified as silty sand (SM) according to the Unified Soil Classification system (USCS). Properties of compacted test soil specimen prepared by static compaction method are summarized in Table 1.

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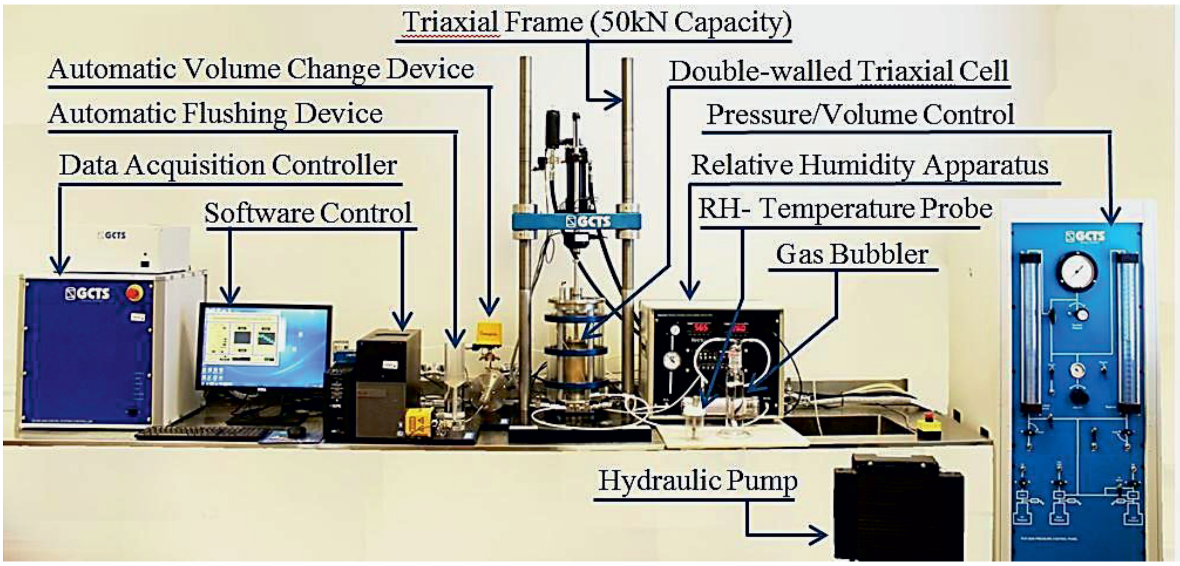

Figure 1. Panoramic view of entire Auto-RH/Triaxial test setup.

Table 1. As-compacted soil specimen properties.

Dry unit weight, ρ_d	1.8 g/cm^3
Moisture content, w	14.2 %
Air entry value (AEV)	10 kPa
Initial voids ratio ($e_{initial}$)	0.46-0.49
Diameter	2.8 in
Height	5.6 in

3 Specimen preparation(s)

Each specimen was statically compacted in nine equal layers. Each layer was compacted at a constant rate of 1 mm/min to a total vertical stress of 1600 kPa to produce overall homogenous specimen [14]. The convention used to designate the specimen is $CD_{x\text{-}y}$ where "CD" denotes the consolidated drained test; "x" represents the net confining pressure (σ_3-u_a), while "y" represents the imposed constant matric suction (u_a-u_w).

4 Auto-RH triaxial setup

The Auto-RH system [6] and [7], designed is capable of automatic control of relative humidity (RH) between ~ 1% RH and ~ 99% RH. This corresponds to a total suction range of 600 MPa to 1.4 MPa. The thermodynamic relationship between relative humidity of pore water vapor and total suction Ψ_t (kPa) is given by Kelvin's equation (1):

$$\psi_t = -\frac{RT}{v_{wo}\,\omega_v}\ln\left(\frac{u_v}{u_{vo}}\right) = -\frac{RT}{v_{wo}\,\omega_v}\ln(\mathrm{RH}) \qquad (1)$$

where u_v is partial pressure of water (e.g., soil pore-water) vapor (kPa); u_{vo} = saturation pressure of pure water vapor (kPa); R = universal gas constant (8.31432 J mol^{-1} K^{-1}); T = absolute temperature (K); v_{wo} = specific volume of water (reciprocal of density, m^3/kg); and, ω_v = molecular mass of water vapor (18.016 kg/kmol).

Main features of the fully integrated system, also referred to as the Auto-RH/Triaxial system in this work, include: (1) Auto-RH control unit; (2) Gas bubbler, desiccant, and temperature probe; (3) Double-walled triaxial cell; (4) Automated volume-change device; and (5) Automated flushing device. Figure 1 shows a panoramic view of entire RH-Triaxial setup.

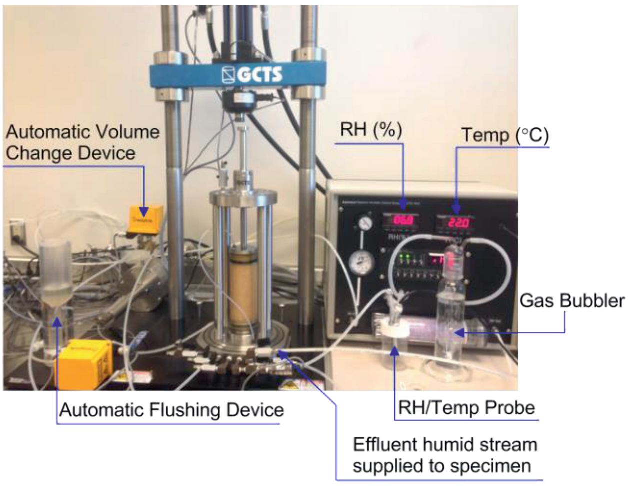

Figure 2. Triaxial setup with adapted Auto-RH control unit.

The double-walled chamber includes an inner cell subjected to same internal and external pressures, thus avoiding differential pressures and hence minimizing cell expansion and/or water leakage. The pressure and flow of water into the inner cell is controlled by a pressure and volume controller. The total change in volume experienced by the soil is equivalent to the amount of water flowing from (or into) the inner cell and into (or from) the outer cell. The total soil volume change was monitored by a volume-change device with a rolling diaphragm to minimize the sliding friction that normally occurs in conventional volume-change devices [14].

Humidity in the pore-air phase of the test soil can be ramped along paths of increasing or decreasing relative humidity, ranging from ~2% RH to ~95% RH, which corresponds to total suction states of ~500,000 kPa (500 MPa) to ~10,000 kPa (10 MPa); and is typically accomplished in step increments of ~10% RH. The "forced-flow" nature of the mixed-flow system significantly reduces the required pore-fluid equalization time [7].

5 Test procedure

5.1 Suction equalization

Statically compacted specimens prepared for triaxial testing were first air-dried under laboratory environment (24^{o}C) until the monitored water content came reasonably close to that corresponding to the desired total suction state, a process that took between 4-5 days. The specimen was then transferred to the calibration chamber connected to RH-apparatus for preconditioning of the pore-fluids prior to triaxial testing. The RH was incrementally stepped up/down to a desired value by proportioning the "wet" to "dry" gas flows, under constant feedback from the RH/Temp probe. It took between 8-10 days for the desiccated specimens to attain equilibrium (pore-fluid equalization under constant soil mass), irrespective of the magnitude of the total suction to be induced (20-300 MPa).

The preconditioned specimen was then immediately mounted onto the bottom pedestal of the cell and O-ring-sealed with a latex membrane. Target total suction states in triaxial specimens, were automatically attained by supplying vapor-saturated air from the Auto-RH unit into the specimen through bottom pedestal via ¼ in nylon tubing. The mounted specimen was finally allowed to equilibrate under target RH value for at least 15 additional days [14].

5.2 Isotropic consolidation

Upon reaching equilibrium, the triaxial double-walled cell was assembled and filled with water under a water pressure of 10 kPa. The RH/Temp and the related total suction was continuously monitored from the suction equalization stage till shearing. This monitoring provided an indirect knowledge of total suction inside specimen. Volume changes experienced by the soil throughout testing stages were recorded via an automatic volume-change device, which allowed for accurate dimensions of the specimens to be accounted for prior to initiating each stage.

The next stage consisted of isotropic consolidation under controlled suction. This was done by increasing the cell pressure at the rate of 5 kPa/hr., while keeping the circulation of relative humidity from bottom to top of the specimen. It should be noted that the bottom of the specimen was connected to the RH equipment; hence, no water back pressure was applied. The top of specimen was connected to the chamber with a RH probe that had a vent open to the atmosphere for the effluent (Fig. 2). Thus, the air pressure in the specimen was at atmospheric pressure (or reference zero). Depending upon the final consolidation pressure, $(\sigma_3 - u_a)$ = 100, 200, or 300 kPa, the application of desired isotropic consolidation pressure took 18, 38, and 58 hrs, respectively. Each specimen was kept for at least 24 hours after the consolidation pressure was applied to ensure complete dissipation of pore air pressure (no change in volume of specimen).

5.3 Shearing under constant suction

Once the isotropic consolidation process was complete, the total suction inside the specimen and the net confining pressure, $(\sigma_3 - u_a)$ = 100, 200, or 300 kPa, was kept constant and the specimen was sheared at a constant shearing rate of 0.0009%/min. Independent studies were conducted to determine appropriate shearing rate of 0.0009%/min [12].

6 Shear-induced soil response

The newly developed Auto-RH equipment was used to conduct a series of consolidated-drained CTC tests on nine identically prepared specimens of compacted SM soil under either saturated (s = 0) or constant total suction states of 20 MPa or 300 MPa. Specimens were sheared under initial net confining pressures of 100, 200, or 300 kPa. Figure 3a and 3b show the stress-strain and volume-change response of compacted SM soil from suction-controlled CTC tests conducted at initial net confinement, $(\sigma_3 - u_a)$ = 100 kPa. Similar tests were conducted at initial net confinement, $(\sigma_3 - u_a)$ = 200 kPa and 300 kPa with total suction, s = 0, 20, and 300 MPa.

Fig 3a clearly indicates an increase in soil stiffness (tangent modulus), peak strength, and soil brittleness with increasing total suction. In general, peak strength is followed by large strain-induced softening, until critical state is apparently reached. Thereby strain-hardening type response, observed in saturated specimens, progressed towards strain-softening type response with the introduction of higher soil suction. This strain-softening, in turn, is observed to become considerably more pronounced with increasing total suction: The specimens failed at lower strains under highest total suction of 300 MPa, then featuring a sudden drop in deviator stress, until eventually reaching critical state with a relatively small change in strain.

Figure 3b clearly manifests the change in shear-induced volumetric response from initial compressive to dilational type when the soil saturation state changed from saturated to unsaturated state with the introduction of total suction of magnitude 20 and 300 MPa.

All the specimens showed initial compression, followed by a stress-induced dilatancy-type response that increased with an increase in the suction induced. Such types of stress-strain and volumetric response are typical of dense or overconsolidated soils. All the specimens showed brittle type failure, without any bulging (Fig. 4b). Similar observations were made from testing SM soil at net confining pressure, $(\sigma_3 - u_a)$ = 200 kPa [14]. Figure 4a shows the homogenous compacted specimen with no visible cracks prior to testing while Figure 4b shows failed specimen at the end of test.

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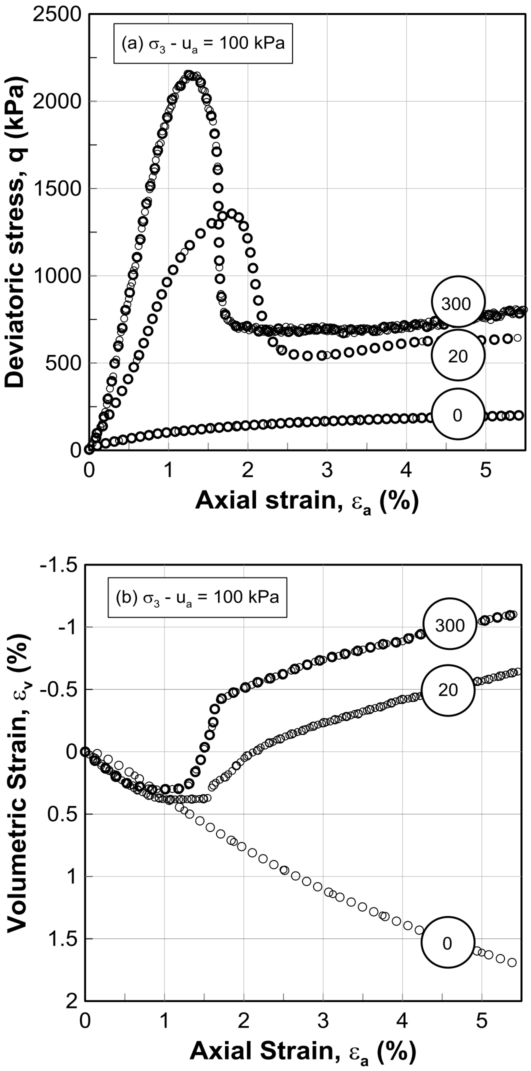

Figure 3. Response of compacted silty sand at net confining pressure, (σ_3 - u_a) = 100 kPa, and total suctions of 0, 20, and 300 MPa: (a) stress-strain response, (b) volume change.

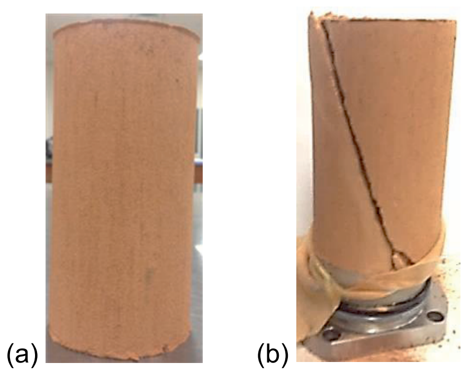

Figure 4. Typical features of as-compacted and failed silty sand specimens: (a) Desiccated specimen before testing, (b) Brittle type failure after CDRH300-300MPa triaxial test.

On the other hand, a considerable increase in net confining pressure, from 100 to 300 kPa, appears to have inhibited the relatively large amount of shear-induced dilation that is expected from SM soil when tested under higher total suction (300 MPa).

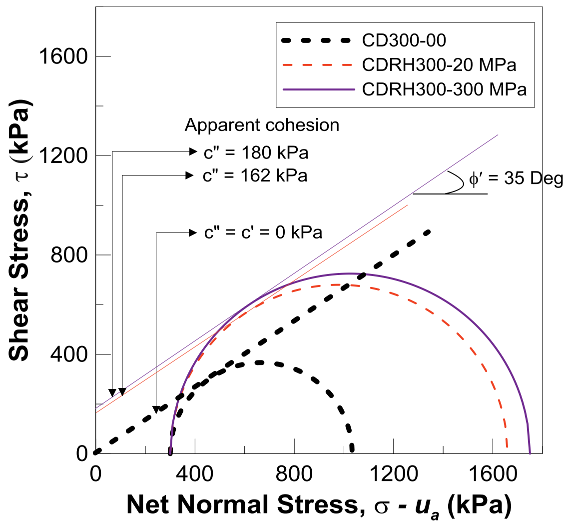

Figure 5. Mohr circles at critical state condition under net confining pressure, (σ_3 - u_a) = 300 kPa, and total suctions of 0, 20, and 300 MPa.

This can be attributed to large particle crushing under such high net confinements, which yields a particle gradation that renders a soil less dilational in nature. These observations substantiate some of the key findings reported from previous works on similar types of intermediate geomaterials [3] and [18].

Figure 5 shows Mohr's stress circles drawn at critical state failure. The angle of internal friction φ' = 35 deg. remains unchanged with increase in total suction up to 300 MPa. In fact, the failure envelope obtained at s = 300 MPa appeared to be very similar to that obtained by [5]. Clearly, there is no effect of change in soil suction on angle of internal friction. Figure 6 manifests an upward shift in critical state lines (CSL) with increase in soil suction. It also illustrates that slope of CSL is independent of increase in suction inside the specimen.

7 Effect of suction on critical state lines

Figures 6 shows the best-fit critical state lines (CSLs) obtained from triaxial testing at soil suction s = 0, 20 and 300 MPa via vapor-pressure technique. The critical state line is shifted upward with an increase in total suction, thereby, causing an increase in suction stress. The slope of all critical state lines, however, remains virtually constant, in close agreement with the constitutive, critical state based framework postulated by [1] and similar to [15 and 16].

8 Concluding remarks

A newly developed Auto-RH/Triaxial system was used to conduct Consolidated-drained CTC tests on specimens of compacted SM soil under total suctions of 0-300 MPa. In general, shear strength at peak and critical state increased with increasing total suction. Peak strength is followed by large strain-induced softening, until critical state is apparently reached. Strain-softening is also observed to be considerably more pronounced with increasing suction.

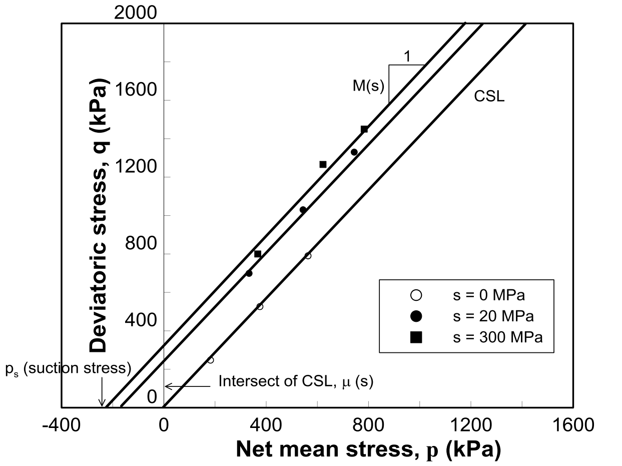

Figure 6. Critical state lines (CSLs) under net confining pressures, (σ_3 - u_a) = 100, 200, and 300 kPa, and total suctions of 0, 20, and 300 MPa.

Test results clearly showed a marked change in shear-induced volumetric response from initially compressive to purely dilational type when total suction was increased from 0 (saturated) to 20 or 300 MPa. An increase in net confinement from 100 kPa to 300 kPa tends to inhibit the shear-induced dilation of SM soil under constant total suction. The slope of all critical state lines (CSLs) obtained via vapor-pressure technique remains virtually constant, in close agreement with the constitutive, critical state based framework originally postulated by [1].

Experimental results such as the one obtained by testing densely compacted geomaterials at low, medium and high suction will help in the calibration, verification and fine-tuning of constitutive models. Modeling such shear-induced continuous stress-strain response along entire suction range (0 to 300 MPa) is currently being studied at The University of Texas at Arlington.

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