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Reference

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ABSTRACT

A fully automated relative-humidity (auto-RH) control unit has been adapted to a newly implemented double-walled triaxial cell to test unsaturated soils under higher total suction states via the vapor-pressure technique, allowing for direct measurement and control of the relative humidity inside the pores of the test soil. The triaxial system is also suitable for implementing the axis-translation technique. With the operational and fully integrated servo-controlled triaxial system, a series of conventional triaxial compression (CTC) tests were conducted on identically prepared specimens of compacted silty sand under constant total suction states of 20 MPa and 300 MPa, induced and controlled via the automated auto-RH control unit. The suitability and reliability of the integrated system was demonstrated by closely repeatable results obtained from the series of suction-controlled CTC tests. Suitable shearing rates for suction-controlled testing of compacted silty sand, via both axis-translation and relative-humidity-based techniques, were also empirically assessed through a series of strain-/suction-controlled tests. The latter were conducted at different axial loading rates (% axial strain per unit time) under either constant matric suction (0.5 MPa) or constant total suction (300 MPa). In both cases, the most suitable shearing rate was identified as the maximum rate for which the test soil continued to be subjected to a constant matric or total suction throughout the entire shearing stage.

Keywords

unsaturated soils, matric suction, total suction, triaxial testing, strength and compressibility of soils

Introduction

The adoption of matric suction ($u_a - u_w$) and the excess of total stress over air pressure, that is, net normal stress ($\sigma - u_a$), as the relevant stress state variables, has facilitated the investigation of essential features of unsaturated soil behavior via the axis-translation technique (Hilf 1956; Matyas and Radhakrishna 1968; Fredlund and Morgenstern 1977). On the other hand, triaxial testing continues to be the most universally used technique to characterize the shear strength and volume-change behavior of saturated and unsaturated geomaterials under axisymmetric stress sates. The suitability of the axis-translation technique for imposing considerably higher values of suction during triaxial testing, however, is limited to the nominal air-entry value (AEV) of the ceramic disk that the soil specimen is typically resting on. This limitation normally constrains the testing capability of most suction-controlled triaxial devices to a suction state less than 1500 kPa.

It is well known that some of the most critical geotechnical infrastructure, including earth slopes in tropical regions and nuclear waste disposal clay liners, involve the use of naturally occurring or compacted geomaterials subjected to a much wider range of moderate-to-high suction values, throughout any given year. It is in this context that the vapor-pressure-based techniques have proved suitable for controlling the relative humidity present in the pore-air phase of the test soil, thus allowing for the imposition of multi-stage stress paths, including controlled wetting–drying, at considerably higher suction values (e.g., Mahalinga-Iyer and Williams 1985; Vanapalli and Fredlund 2000; Blatz et al. 2002, 2008; Nishimura and Fredlund 2003; Lu and Likos 2004; Nishimura and Vanapalli 2005; Nishimura et al. 2008).

In the present work, a novel fully automated relative-humidity (auto-RH) control unit has been adapted to a newly implemented double-walled triaxial cell to test unsaturated soils under higher total suction states via the vapor-pressure technique, thus facilitating the direct measurement and control of the relative humidity inside the pores of the test soil. (Essential modifications to the core cell for implementing the axis-translation technique are briefly discussed in parallel.) The "forced" streaming of RH-controlling vapor gas through the soil pores, and the direct measurement of RH of the influent and effluent streams, constitute some of the novel features of the current system. Previously reported arrangements, for the most part, only measure the induced RH of the influent gas stream (e.g., Nishimura and Fredlund 2003).

With the operational and fully integrated servo-controlled triaxial system, a series of conventional triaxial compression (CTC) tests were conducted on identically prepared specimens of compacted silty sand under constant total suction states of 20 MPa and 300 MPa, induced and controlled via the automated auto-RH control unit. The suitability and reliability of the integrated system was demonstrated by closely repeatable results obtained from the series of suction-controlled CTC tests. Suitable shearing rates for suction-controlled testing of compacted silty sand, via both axis-translation- and relative-humidity-based techniques, were also empirically assessed through a series of strain-/suction-controlled tests.

By selecting compacted silty sand as the test material, the present experimental effort aimed to focus on suction-controlled testing of a relatively dense soil with a natural tendency to experience dilatancy and post-peak softening as it approaches critical state under unsaturated conditions. The main intent was to gain critical insight into some of the most essential hydro-mechanical features of densely compacted intermediate geomaterials, including apparent cohesion, post-peak softening, and strain-induced dilatancy under suction-controlled monotonic shearing.

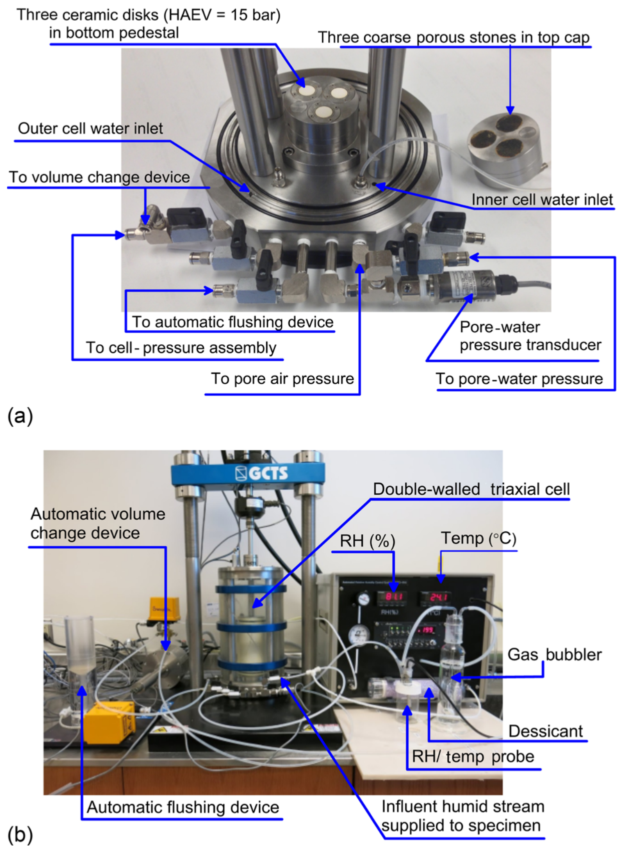
Despite recent and valuable efforts to characterize and model some of the key mechanical features of this type of materials, including Estabragh et al. (2004), Zhang and Li (2011), Liu and Muraleetharan (2012), Usmani et al. (2012), and Estabragh and Javadi (2014), conclusive experimental evidence of all these phenomena at relatively high suction states, particularly beyond residual suction value (desiccation), remains rather limited. This has been a chief motivation for the present research work.

Auto-RH/Triaxial System: Main Features

In the present work, statically compacted specimens of silty sand were tested in the low-to-medium suction range (50–750 kPa), via the axis-translation technique, as well as in the higher suction range (20–300 MPa), via the vapor-pressure technique. It is well known that the axis-translation technique consists of elevating both the pore-air pressure u_a and the pore-water pressure u_w above reference atmospheric pressure to prevent cavitation in the pore-water phase, thus rendering the desired matric suction relatively feasible to impose, measure, and control. Main features of the bottom assembly of the present suction-controlled, double-walled triaxial cell are shown in **Fig. 1(a)**, including all of the following key items: (1) bottom pedestal with three exchangeable 15-bar ceramics or porous stones; (2) top cap with three porous stones; (3) outer-cell water inlet; (4) inner-cell water inlet; (5) pore-water pressure inlet; (5) pore-water-pressure transducer; (6) pore-air-pressure inlet; (7) flushing inlet; (8) flushing outlet; (9) outer-cell water outlet; and (10) volume-change outlet (connected to a volume-change device).

As previously mentioned, the triaxial cell has been upgraded to extend its suction-controlled testing capabilities to a considerably higher total suction range by combining its core system with a fully automated relative-humidity (auto-RH) control unit, as shown in **Fig. 1(b)**. A similar auto-RH unit was used

FIG. 1 (a) Bottom assembly with suitable features for either axis-translation or vapor-pressure technique, and (b) core triaxial system with fully automated relative-humidity (auto-RH) control unit.



by Likos and Lu (2003) for assessing soil-water retention properties of relatively small specimens of clayey soils. The present work constitutes one of the first attempts at adapting this particular auto-RH unit to the main modules of a double-walled triaxial cell. 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.

A complete schematic layout of the fully integrated system is shown in **Fig. 2**. The double-walled chamber features 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/volume controller. The total change in volume experienced by the soil specimen seating inside the inner cell 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 (Patil 2014).

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 (Likos and Lu 2006). The thermodynamic relationship between relative humidity of pore-water vapor (RH) and total suction Ψ_t (kPa) can be readily established via Kelvin's Law:

$$\psi_t = -\frac{RT}{v_{w0}\omega_v}\ln\left(\frac{u_v}{u_{v0}}\right) = -\frac{RT}{v_{w0}\omega_v}\ln(\mathrm{RH}) \qquad (1)$$

where:

u_v = partial pressure of water (e.g., soil pore-water) vapor (kPa),

u_{v0} = saturation pressure of pure water vapor (kPa),

R = universal gas constant (8.31432 J mol^{-1} K^{-1}),

T = absolute temperature (K),

v_{w0} = specific volume of water (i.e., reciprocal of density, m^3/kg), and

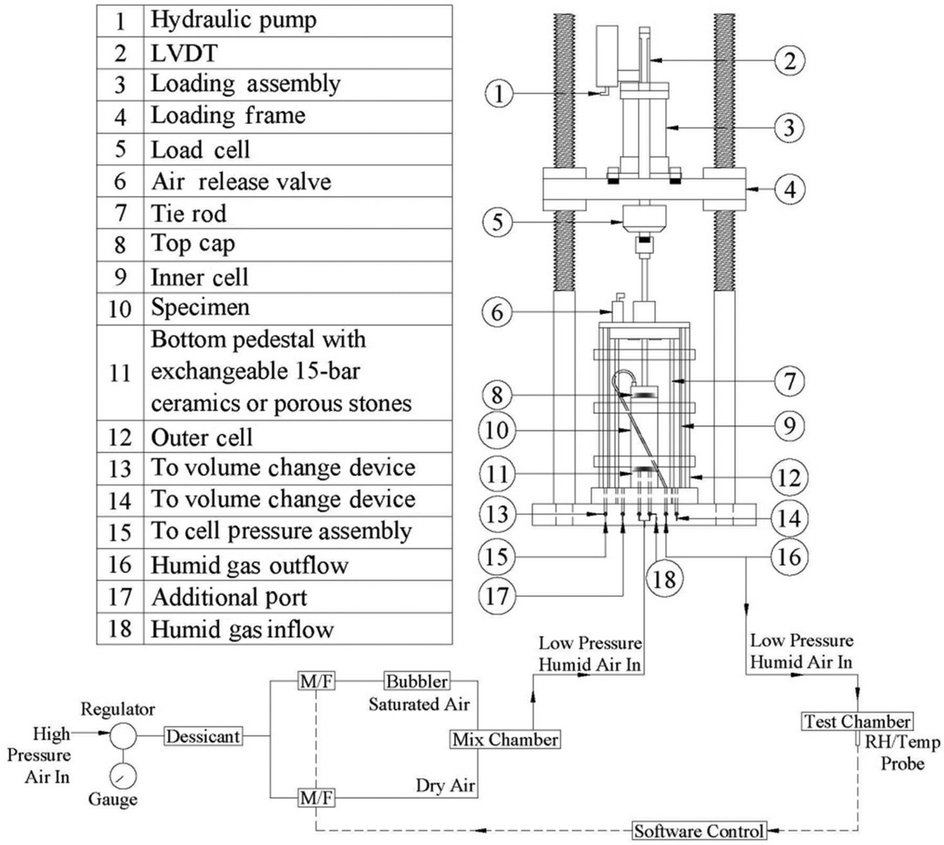
ω_v = molecular mass of water vapor (18.016 kg/kmol).

The auto-RH control unit relies on computer-proportioned mixing of vapor-saturated air ("wet") and desiccated air ("dry") in a closed environmental (mix) chamber to generate a steady stream of low-pressure humid air toward the pores of the test soil, thus inducing a desired state of total suction in the air–water interphase by ultimately controlling the relative humidity in the pore–air phase. Key components of the auto-RH unit's hardware are schematically outlined in **Fig. 2**. Originally, high-pressure air from an in-house source is gradually regulated, via dial gauging, down to a relatively low pressure of ~5 psi. It is then sent through a column of granular drying agent (desiccant) that can be recharged if required, as shown in **Fig. 1(b)**. The low-pressure air stream is then split through two computer-controlled mass/flow (M/F) valves to independently regulate the flow rate of the two resulting air/gas streams, between 0 and 500 cm^3/min, based on an electronic signal from the control PC, as shown in **Fig. 2**.

One of the air streams is vapor saturated (~100 % RH) by bubbling it through a gas-washing bottle filled with distilled water, as shown in **Fig. 1(b)**. The gas bubbler is refilled periodically during long testing times. The "wet" and "dry" air streams are then reintroduced in a mixing chamber at a user-defined, combined (total) flow rate of 200 cm^3/min, as shown in **Fig. 2**. The effluent air stream has a relative humidity that is a direct function of the "wet" to "dry" (w/d) gas flow ratio, or "wet" to "total" (w/t) flow ratio, maintained by the control PC. The low-pressure, humid gas stream is finally routed, via a 1/4-in. nylon tubing, into the pores of the soil specimen through small

FIG. 2

Complete schematic layout of fully integrated auto-RH/triaxial testing system.



openings beneath a porous, low-AEV stone housed by the bottom pedestal.

The vapor-saturated gas flow comes out of the soil specimen through the coarse stone housed by the top cap, and then via 1/8″ semi-rigid nylon tubing is routed back into a small, acrylic "test chamber," which also features a capacitance-film relative humidity/temperature probe (RH/temp probe) affixed to its lid, as shown in **Figs. 1(b)** and **2**, thus allowing for direct measurements of the outflow RH. Signals from the RH/temp probe form a feedback loop with a control PC for automated regulation of the two mass-flow (M/F) controllers. The measured RH and temperature correspond to the target value of total suction calculated via Kelvin's equation (Eq 1). As previously mentioned, the "forced" streaming of RH-controlling vapor gas through the soil pores, and the "direct" measurement of RH of the influent and effluent streams, constitute some of the novel features of the current auto-RH/triaxial system. Previously reported arrangements, for the most part, including Nishimura and Fredlund (2003), only measure the induced RH of the influent gas stream.

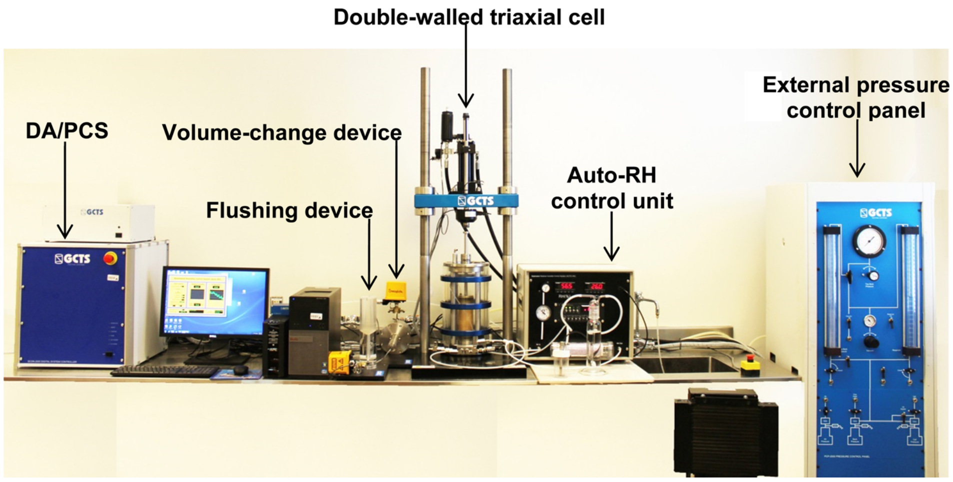
The RH/temp probe was calibrated separately, on a regular basis and prior to triaxial testing, via the same small "test chamber" adapted to the system. The test chamber, housing the RH/temp probe and half-filled with salt solutions of known concentrations (known RH), along with the auto-RH control unit, forms a closed-loop system essential for accurate calibration of the RH/temp probe (Likos 2012; Patil 2014). Likos and Lu (2003) also demonstrated the virtual insensitivity of the auto-RH control unit to temperature fluctuations in the surrounding environment.

Continuous data acquisition and process control is possible through an executable (.exe) file, along with associated drivers. The control panel features inputs such as total flow rate, target RH (%), RH increments (%), increment time step (h), and data logging interval (min). It also includes automatic outputs such as RH (%), temperature (°C), and total suction (kPa) calculated based on RH/temperature readouts. **Fig. 3** shows a panoramic view of the fully integrated double-walled triaxial system, including the auto-RH control unit.

It is well known that different calibration methods may lead to varying relationships between osmotic pressure and concentration of PEG solutions (Ng et al. 2007). The current auto-RH/triaxial system does not require the use of salt solutions or even semi-permeable membranes. On the other hand, the osmotic technique has proved suitable for a maximum value of applied osmotic pressure of just above 10 MPa (Delage et al.

FIG. 3

Panoramic view of fully integrated auto-RH/triaxial system and testing setup.



1998). With the current auto-RH/triaxial system, total suction states as large as 600 MPa can be attained and subsequently sustained throughout the consolidation and shearing stages of suction-controlled triaxial testing. (Suitable pore-fluid equalization times are addressed in the following sections.)

Auto-RH/Triaxial System: Performance Verification

TEST SOIL: BASIC PROPERTIES

The test soil used in this work classifies as silty sand (SM) according to the USCS, with 55 % sand, 37 % silt, 8 % clay, and particle-size distribution as shown in Fig. 4a; specific gravity, $G_s = 2.67$; standard Proctor maximum dry unit weight, $\gamma_{d\text{-max}} = 1.87\ \text{g/cm}^3$; and optimum moisture content, OMC = 12.2 %. The soil-water retention curve (SWRC) was obtained via both pressure-plate- and relative-humidity-based techniques, as shown in **Fig. 4(b)**, featuring an air-entry value of 8 kPa, a residual total suction of 2000 kPa (2 MPa), and test moisture contents of approximately 1.25 % and 0.3 % corresponding to total suction values of 20 MPa and 300 MPa, respectively. **Fig. 4(b)** also shows best-fitting SWRC model parameters, as per van Genuchten (1980) and Fredlund and Xing (1994). In this work, relative-humidity-based conditioning, using the very auto-RH unit, was used to assess the soil-water-retention properties in the higher suction range, as explained later in this section.

TRIAXIAL SPECIMENS: COMPACTION PROTOCOL

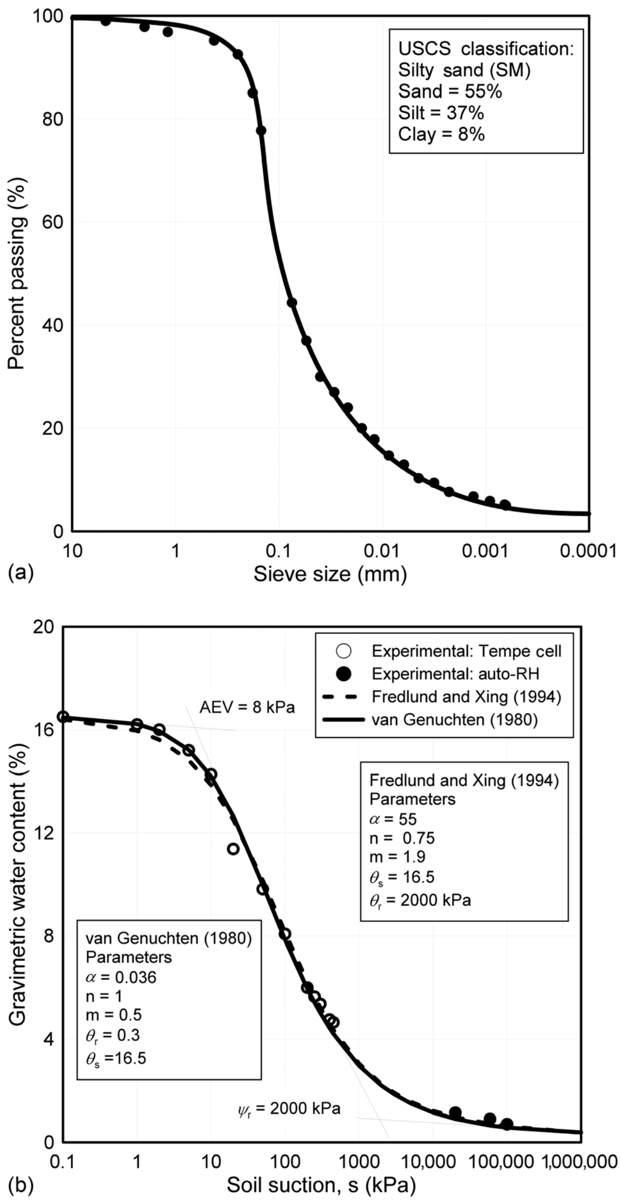
The dry soil was first thoroughly mixed with distilled water at a moisture content of 14.2 % (2 % more than OMC). The moist soil was then sealed in nine airtight ziplock bags in approximately equal proportions. The sealed bags were then placed and sealed into a plastic container that was kept in a 100 %-humidity environmental chamber for at least 24 h. Several attempts were made to reproduce reasonably identical specimens with target dry density, $\gamma_{d\text{-max}} = 1.87\ \text{g/cm}^3$, by statically compacting one, three, eight or nine equal layers/lifts into a 70-mm diameter, 130-mm height split mold via a 50-kN-capacity load frame, as shown in **Fig. 5**. Compaction displacement rates of 1.0 or 1.5 mm/min were used while subjecting each layer/lift to a maximum vertical stress of 1200, 1400, or 1600 kPa. Significant variability was observed in terms of final induced displacement as additional layers/lifts were being added into the mold.

Results showed that the target dry density, $\gamma_{d\text{-max}} = 1.87\ \text{g/cm}^3$, was closely achieved when the specimen was prepared in nine equal layers/lifts, with each layer/lift subjected to a maximum vertical stress of 1600 kPa at a constant displacement rate of 1.0 mm/min. **Fig. 6** shows the compression (vertical stress versus axial displacement) curves for each of the nine layers as they were subjected to static compaction under these particular conditions. Routine and thorough visual inspection of typical specimens, as the one embedded in **Fig. 6**, revealed no conspicuous fissures, voids, or horizontal interfaces between any two consecutive layers/lifts. Test specimens for all subsequent testing in the auto-RH/triaxial system were, hence, prepared by following this same protocol, yielding an average void ratio, $e = 0.46$–0.49; average initial water content, $w = 14.2$ %; initial degree of saturation, $S = 81$ %; and initial soil suction, $s = 10$ kPa, just above the AEV (**Fig. 4**).

SATURATED SOIL TESTING: DISCARDING MEMBRANE PENETRATION EFFECTS

During conventional triaxial compression (CTC) testing, where the cell pressure is normally kept constant, the effects of latex membrane penetration, which is largely dependent on cell pressure, have generally proved virtually negligible, particularly in

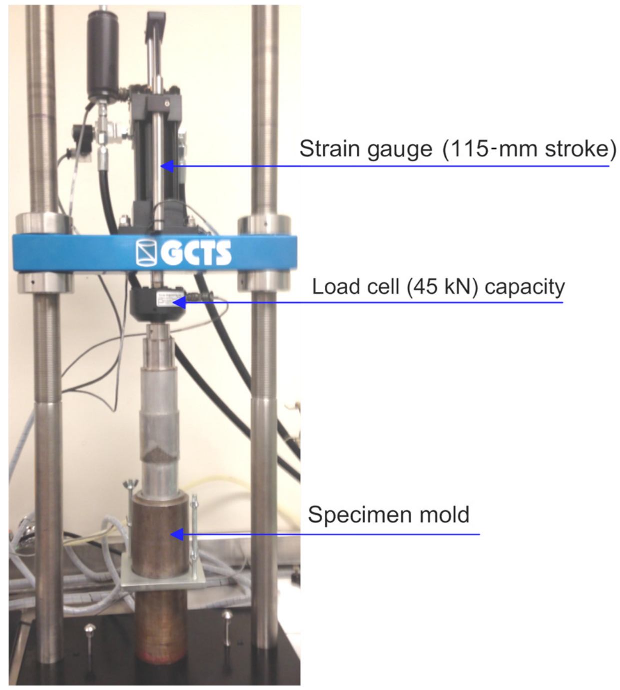
FIG. 4 (a) Particle-size distribution of SM soil and (b) soil–water characteristic curve (SWCC) from compacted SM soil.



terms of volume change measurements. However, membrane penetration may have a significant influence on these measurements during triaxial testing under varying radial stresses, particularly on coarse-grained soils (Ali et al. 1995; Garga and Zhang 1997), whereas a few analytical solutions have been proposed to accurately assess the corrected volume (Molenkamp and Luger 1981; Baldi and Nova 1984; Kramer et al. 1990; Ali et al. 1995; ASTM D7181-11).

In this work, potentially misleading effects of membrane penetration was experimentally and, thus, directly assessed by measuring the difference between the total pore-water volume expelled out of a saturated soil specimen and the total (overall)

FIG. 5 Illustration of multi-layer/lift static compaction protocol.



volume change of the specimen under constant confining pressure (isotropic consolidation stage). The triaxial cell is first filled with distilled water and subjected to a 10-kPa pressure. The pore-water pressure line is then saturated and a 5-kPa back pressure is applied at the bottom of the specimen while the cell pressure is simultaneously increased to 15 kPa. From this point

FIG. 6 Compressibility of each of the nine layers/lifts subjected to static compaction (1.0 mm/min).

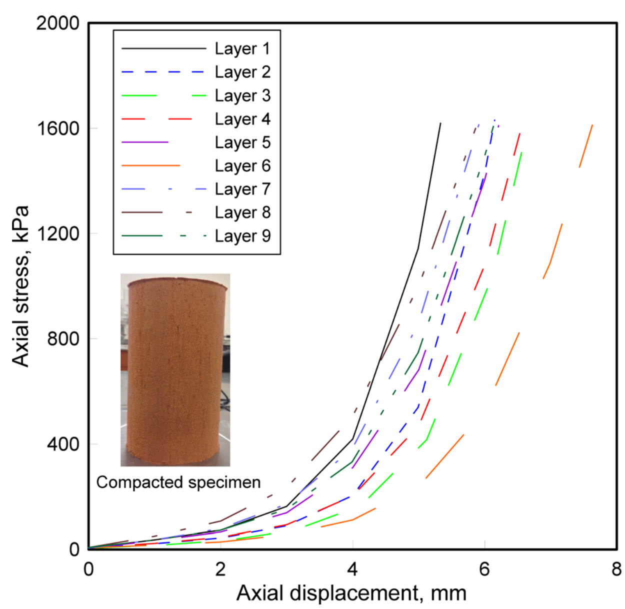


FIG. 7 Total (overall) and pore-water-volume changes during isotropic consolidation of fully saturated SM soil specimen.

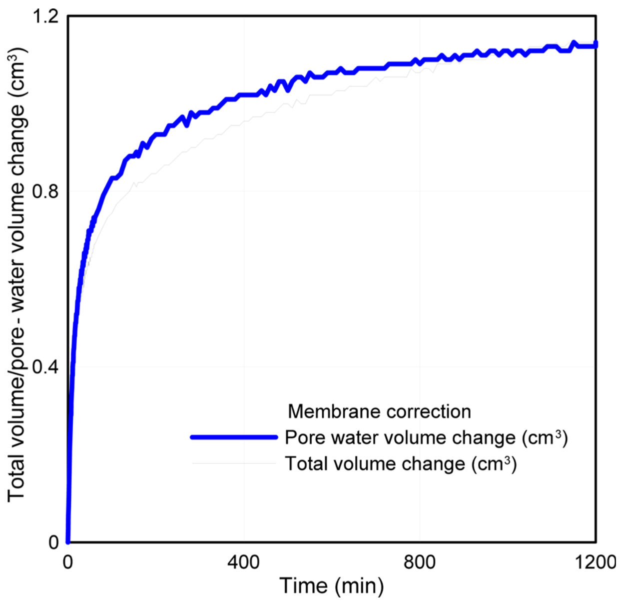
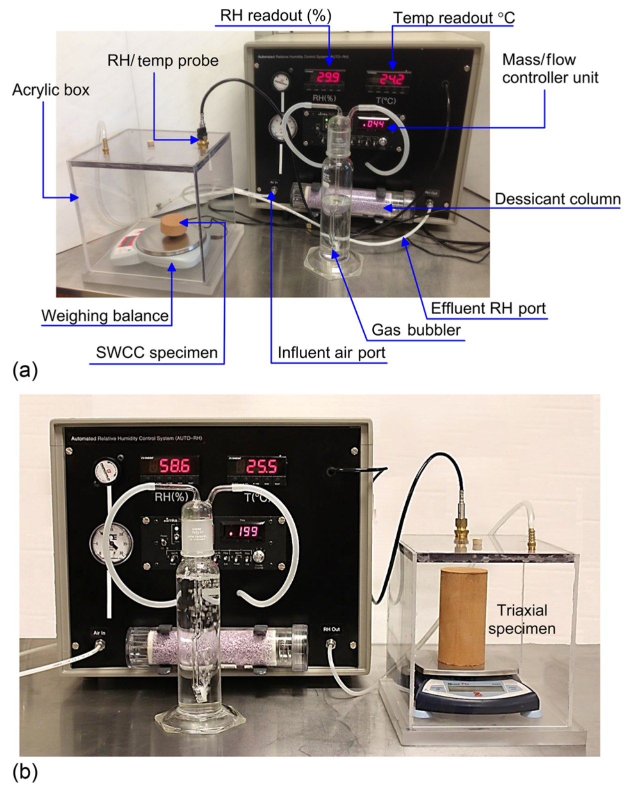


FIG. 8 Calibration chamber adapted to auto-RH control unit for specimen conditioning: (a) SWCC specimen and (b) triaxial specimen.



on, the back pressure is gradually raised, with simultaneous and equal increases in cell pressure, so as to maintain a constant effective stress of 10 kPa, until full saturation is attained with a reasonably acceptable Bishop's parameter, $B = 0.98$–1.0.

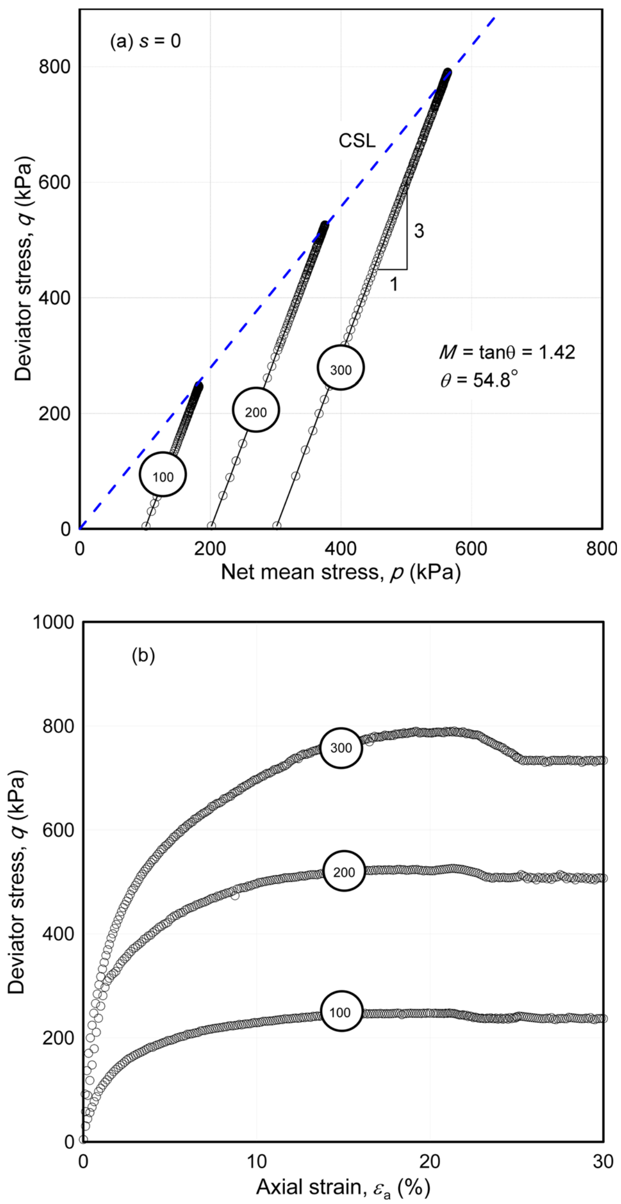
Following complete saturation, the specimen is isotropically consolidated by keeping the back pressure constant and raising the cell pressure until a target value of effective confining pressure is achieved. **Fig. 7** shows the change in both total (overall) and pore-water volumes, with elapsed time, during isotropic consolidation stage under constant cell pressure of 910 kPa and back pressure of 610 kPa, i.e., effective stress of 300 kPa, with the primary consolidation stage accomplished in less than 24 h. It can be readily noticed that changes in total and pore-water volumes are virtually same, particularly at the end of the consolidation stage; hence, no further studies on membrane penetration effects were pursued in this current work, nor were vertical filter paper strips deemed necessary to expedite pore-water drainage during saturated or unsaturated testing.

UNSATURATED SOIL TESTING: SPECIMEN CONDITIONING VIA AUTO-RH UNIT

In this work, as previously noted, relative-humidity-based conditioning of the SM soil, using the automated auto-RH unit, was used to assess its water retention properties in the higher suction range (**Fig. 4**), as well as to attain desired total suction states (20–300 MPa) in freshly compacted triaxial specimens prior to suction-controlled shearing in the triaxial cell. A custom-made calibration chamber, adapted to the working conditions of the auto-RH control unit, was used for either purpose, as shown in **Fig. 8**. The chamber consists of a $10 \times 10 \times 18$ cm acrylic box featuring an inside digital balance to record the specimen weight. The chamber is sealed with a rubber gasket at the bottom to prevent moisture leakage. An inlet is provided for circulation of saturated air from the auto-RH unit into the chamber, whereas an effluent-air outlet is provided at the top. A relative humidity/temperature probe (RH/temp probe) is also affixed onto the top of the chamber via steel fittings.

Target total suction states, in either SWRC samples or triaxial specimens, were automatically attained by supplying vapor-saturated air from the auto-RH unit into the chamber via 1/4-in. nylon tubing. 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, through a process virtually identical to that shown in **Fig. 2**. The soil water content was continuously monitored by the digital balance as water vapor was being adsorbed or desorbed by the specimen. Final water content was recorded when equilibrium (constant soil mass) was reached between the RH in the soil pores and the RH inside the calibration chamber. Additional SWRC points in the higher suction range (**Fig. 4**) can then be assessed through ∼10 % RH step increments. The same protocol was used for pre-conditioning triaxial specimens to target total suction values of up to 300 MPa.

FIG. 9 Typical response of saturated SM soil from CTC testing: (a) stress paths and (b) stress–strain response.



SATURATED SOIL TESTING: VERIFYING TYPICAL SM RESPONSE

Three additional specimens of saturated SM soil were tested under consolidated-drained (CD) conditions for initial confining pressures of 100, 200, or 300 kPa. The stress paths and soil responses, presented in terms of deviator stress versus axial-strain response, are shown in **Fig. 9**. Each specimen was sheared by following a CTC stress path at a constant shearing strain rate of 0.2 %/min, until it was readily apparent that 30 % axial strain had been reached. The tests confirmed that no excess pore-water pressure was generated during shearing at this specific rate (Patil 2014). All three specimens failed by bulging, without any distinct shear planes, also featuring hardening-type failure, as shown in **Fig. 9**. Mohr–Coulomb analysis yielded a cohesion intercept, $c' = 0$; effective friction angles, $\phi'_p = 39°$ and $\phi'_{cs} = 35°$, at peak failure and critical state conditions, respectively; and slopes of critical state lines, $M_p = 1.6$ and $M_{cs} = 1.42$, at peak failure and critical state conditions, respectively. (Although the fully saturated tests resulted in ϕ'_p between 37–38°, these same results, when plotted together with results from tests at different suction values, yielded an average value of $\phi'_p = 39°$.)

These behavioral patterns and parameters are typical of saturated silty soils, which confirm the suitability of the core triaxial system to reproduce typical behavior long observed in densely compacted intermediate geomaterials under saturated conditions (Bishop and Henkel 1962). Results from this preliminary set of saturated tests ($s = 0$) were also crucial to understand, by comparison, the effect of suction ($s \neq 0$) on some of the essential hydro-mechanical features of densely compacted soils, including apparent cohesion, post-peak softening, and strain-induced dilatancy under suction-controlled shearing, which was previously stated as one of the main purposes of the present work.

UNSATURATED SOIL TESTING: SUITABLE EQUALIZATION TIMES

Statically compacted specimens prepared for triaxial testing were first air-dried under laboratory environment (24°C) until the monitored water content came reasonably close to that corresponding to the desired total suction state (**Fig. 4**), a process that took between 4–5 days. The specimen was then transferred to the calibration chamber (**Fig. 8**) for preconditioning of the pore-fluids prior to triaxial testing, as explained immediately above. 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). **Fig. 8(b)** shows a typical desiccated specimen of compacted SM soil after its preconditioning under total suction of 300 MPa, featuring no visible cracks and/or excessive shrinkage. The preconditioned specimen was then immediately mounted onto the bottom pedestal of the cell and O-ring sealed with a latex membrane. The mounted specimen was finally allowed to equilibrate under target RH value for at least 15 additional days, as previously explained and shown in **Fig. 2**.

Complete assembling of the triaxial system was then finalized. The double-walled confining cell was set into place, slowly filled with distilled water, and the specimen subjected to a 10-kPa confinement, whereas RH, temperature, and, hence, total suction inside the specimen were continuously monitored. Volume changes experienced by the soil during water filling of the cell were recorded via an automatic volume-change device, which allowed for accurate dimensions of the specimens to be accounted for prior to initiating the consolidation stage. As the cell was filled with water, the initially induced total suction was also observed to be slightly altered as the latex membrane came into contact with the water filling the cell. For instance, during a typical CD test under total suction of 300 MPa, the initial ~10.9 % RH was suddenly increased to ~12 % RH, after the cell was completely filled with water (a process that takes 45 min), which corresponds to a total suction value of 286 MPa. Therefore, a typical specimen was simultaneously allowed to regain equilibrium under target total suction of 300 MPa, and to experience volume change under constant 10-kPa confinement, a process that typically took 1–2 h.

The next stage consisted of isotropic consolidation under controlled suction. This was done by increasing the cell pressure at the rate of 5 kPa/h, 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. 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, and 300 kPa), the application of desired isotropic consolidation pressure took 18, 38, and 58 h, respectively. Each specimen was kept for at least 24 h after the consolidation pressure was applied to ensure complete dissipation of pore air pressure (no change in volume of specimen).

UNSATURATED SOIL TESTING: SUITABLE SHEARING RATES

In this work, as previously mentioned, suitable shearing rates for suction-controlled testing of compacted silty sand, via both axis-translation and relative-humidity-based techniques, were also empirically assessed through a series of strain-/suction-controlled tests. The latter were conducted at different axial loading rates (% axial strain per unit time) under either constant matric suction (0.5 MPa) or constant total suction (300 MPa). In both cases, the most suitable shearing rate was identified as the maximum rate for which the test soil continued to be subjected to a constant matric or total suction throughout the entire shearing stage.

A total of three drained, suction-controlled CTC tests were conducted on three identically prepared specimens of SM soil via the axis-translation technique. All specimens were first brought to the same initial condition ($\sigma_3 - u_a) = 300$ kPa and $s = 500$ kPa, and then sheared at different shearing rates, i.e., 0.0029 %/min (lowest), 0.0086 %/min (medium), and 0.014 %/min (fastest). **Fig. 10(a)** shows a significant influence of suction-controlled shearing rate on peak deviator stress. Relatively low and medium shearing rates yielded virtually the same deviatoric stresses at critical state, with minimal variation at peak. Peak deviator stress induced by fastest shearing rate is about 16 % greater than that induced by the lowest rate, which is strongly indicative of inadequate dissipation of pore pressures. Likewise, **Fig. 10(b)** shows that low and medium shearing rates yielded similar responses in terms of volumetric strains induced by suction-controlled shearing. A shearing rate of 0.0086 %/min, with minimal effects on volume change and peak/critical stresses, was then selected as most feasible for testing in the low-to-medium matric suction range via the axis-translation technique (Patil et al. 2014).

FIG. 10 Effect of suction-controlled shearing rate on compacted SM soil response via axis-translation technique ($s = 0.5$ MPa): (a) stress–strain response and (b) volumetric-strain response.

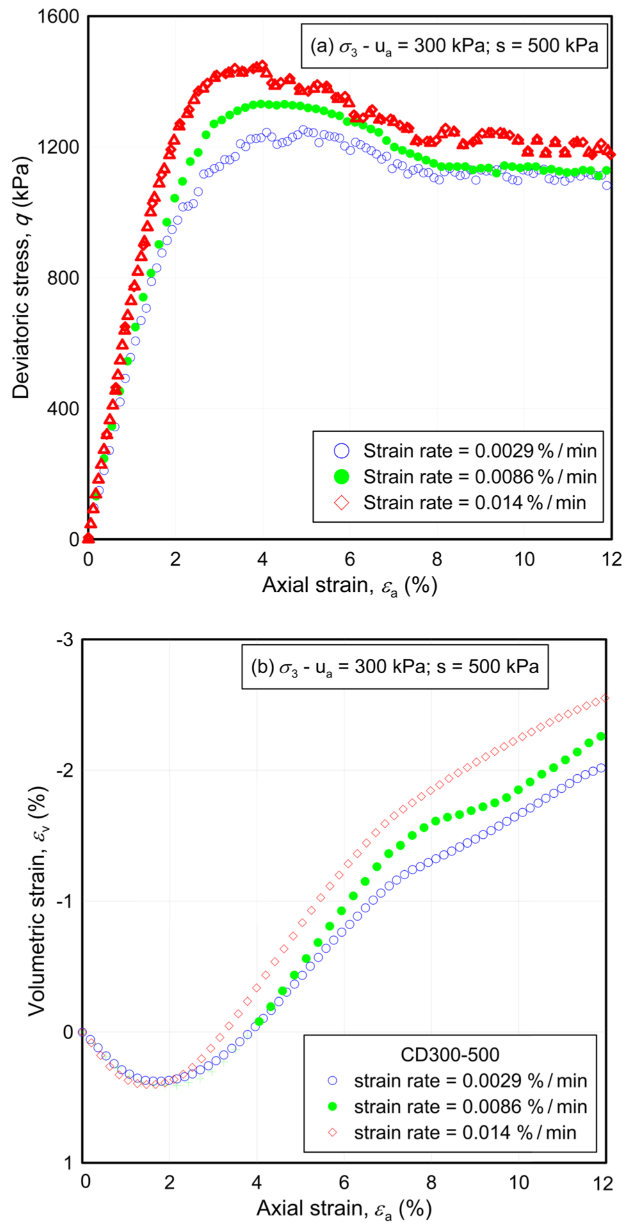
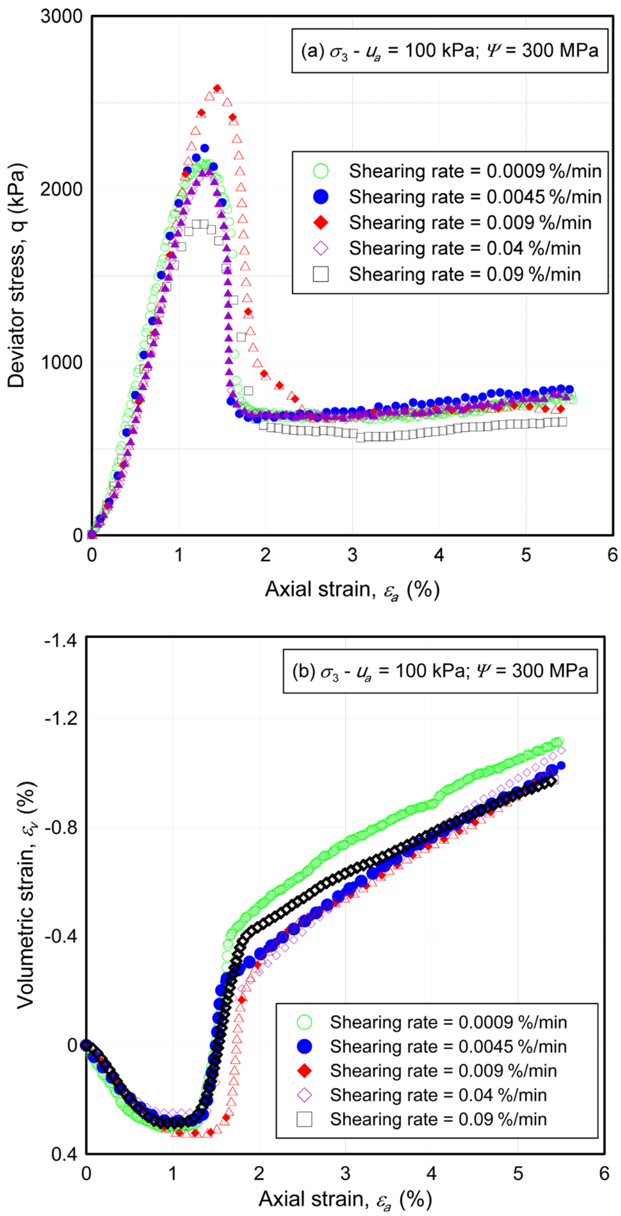
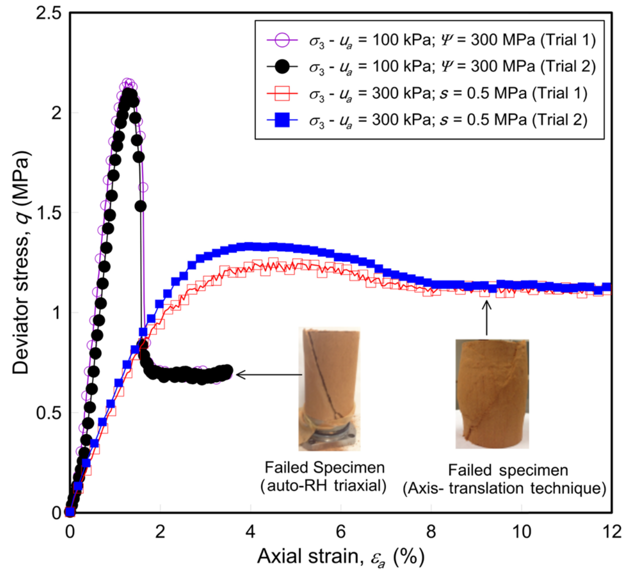


FIG. 11 Effect of suction-controlled shearing rate on compacted SM soil response via vapor-pressure technique ($\psi = 300$ MPa): (a) stress–strain response and (b) volumetric-strain response.



An additional set of five drained, suction-controlled CTC tests were conducted on five identically prepared specimens of SM soil via the vapor-pressure technique. All specimens were first brought to the same initial conditioning, $(\sigma_3 - u_a) = 100$ kPa and $\psi = 300$ MPa, via the auto-RH control unit, and then sheared at different shearing rates, i.e., 0.0009 %/min, 0.0045 %/min, 0.009 %/min, 0.04 %/min, and 0.09 %/min. **Fig. 11** shows that the lowest shearing rate of 0.0009 %/min proved most feasible for testing in the high total suction range via the vapor-pressure technique, maintaining constant total suction, allowing the soil to dilate to a maximum, and having minimal effects on peak deviator stress (Patil 2014).

FIG. 12 Assessing repeatability of test results in compacted SM soil via axis-translation ($s = 0.5$ MPa) and vapor-pressure ($\psi = 300$ MPa) techniques.



UNSATURATED SOIL TESTING: REPEATABILITY OF TEST RESULTS

The performance reliability of the integrated auto-RH/triaxial system was finally demonstrated by assessing how suitable the system was to produce closely repeatable results, in terms of compacted SM soil behavior, from suction-controlled CTC testing, via either axis-translation (constant matric suction of 0.5 MPa) or vapor-pressure (constant total suction of 300 MPa) technique. Two identically prepared specimens were sheared at the corresponding shearing-strain rate previously found as most suitable for each technique. Specimens were tested under initial net confinements of 300 kPa and 100 kPa, respectively. The soil responses, presented in terms of deviator stress versus axial-strain response are shown in **Fig. 12**.

It can be readily observed that the SM soil response is closely replicated when tested by either technique, particularly in terms of peak and critical state deviator stresses. As expected, however, the level of induced suction in the soil specimen, matric or total, plays a definitive role in its mechanical response, with highest strength and exacerbated post-peak softening observed for highest suction of 300 MPa. It can also be noticed that the soil progresses from a bulging-type failure, with more than one visible shear band, under relatively low matric suction (0.5 MPa), to a more brittle-type failure, with just one distinct shear band, under much higher total suction of 300 MPa, as shown by the photos of typically failed specimens embedded in **Fig. 12**. A more thorough analysis of this hydro-mechanical behavior, including volumetric response, is presented in the following section.

TABLE 1 Sequential summary of accomplished suction-controlled CD triaxial testing program.

Test Set	Purpose of Tests	Net Initial Confinement ($\sigma_3 - u_a$) (kPa)	Suction State (MPa)	Shearing Rate (%/min)	Number of Tests
I	Assessment of suitable shearing rate (axis translation)	300	0.5	0.0029 0.0086[a] 0.0140	3
II	Assessment of suitable shearing rate (relative humidity)	100	300	0.0009[b] 0.0045 0.0090 0.0400 0.0900	5
III	Assessment of repeatability of test results[c]	300	0.5	0.0086	2
		100	300	0.0009	2
IV	Assessment of compacted silty sand behavior	100, 200, 300	0.0	0.2000	3
		100, 200, 300	0.5	0.0086	3
		100, 200, 300	20	0.0009	3
		100, 200, 300	300	0.0009	3

[a]Suitable shearing rate (axis-translation).
[b]Suitable shearing rate (relative-humidity).
[c]Duplicate tests for each set of initial net stress and suction states.

Soil Response from Suction-Controlled Triaxial Testing

EFFECT OF TOTAL SUCTION (CONSTANT NET CONFINEMENT)

Table 1 presents a sequential summary of the entire suction-controlled CD triaxial testing program accomplished in this research work, including the specific purpose of each test and the corresponding test variables. With the fully operational and thoroughly verified auto-RH/triaxial system, a series of consolidated-drained CTC tests were finally conducted 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: Test Set IV (**Table 1**). Specimens were sheared under initial net-confining pressures of 100, 200, or 300 kPa. **Figs. 13** and **14** show the stress–strain and volume-change response of compacted SM soil from suction-controlled CTC tests conducted at initial net confinements, $\sigma_3 - u_a = 100$ kPa and 300 kPa, respectively. These figures are clearly indicative of increasing 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 the critical state is apparently reached. Thereby strain-hardening type response, observed in saturated specimens, progressed toward 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 the highest total suction of 300 MPa, then featuring a sudden drop in deviator stress, until eventually reaching the critical state with a relatively small change in strain. Peak and critical-state strengths were 5 and 3 times larger, respectively, when total suction was increased from 0 (saturated) to 20 MPa. Likewise, peak and critical-state strengths were 1.2 and 1.6 times larger, respectively, when total suction was increased from 20 MPa to 300 MPa.

On the other hand, **Figs. 13–14** clearly show 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. Such a response is typical of relatively dense or overconsolidated soils. The controlled-suction shearing continued until the soil softened back to critical state, at which point the soil is expected to exhibit only shear deformations (plastic flow), with no further change in shear strength or volume. All the specimens showed brittle type failure, without any bulging. Similar observations were made from testing SM soil at net confinement, $\sigma_3 - u_a = 200$ kPa (Patil 2014).

All of these observations serve as further substantiation of some of the key findings reported from previous works on this type of material (Estabragh et al. 2004; Zhang and Li 2011; Liu and Muraleetharan 2012; Usmani et al. 2012; Estabragh and Javadi 2014). Experimental evidence at considerably higher suction states, however, particularly beyond residual suction value (desiccation), as considered in the present work, had remained rather limited.

EFFECT OF NET CONFINEMENT (CONSTANT TOTAL SUCTION)

The effect of initial net confinement can be more readily analyzed by plotting the results on the basis of the three net

FIG. 13 Response of compacted SM soil from CTC tests under initial net confinement of 100 kPa and constant total suctions of 0, 20, and 300 MPa: (a) stress–strain response and (b) volumetric-strain response.

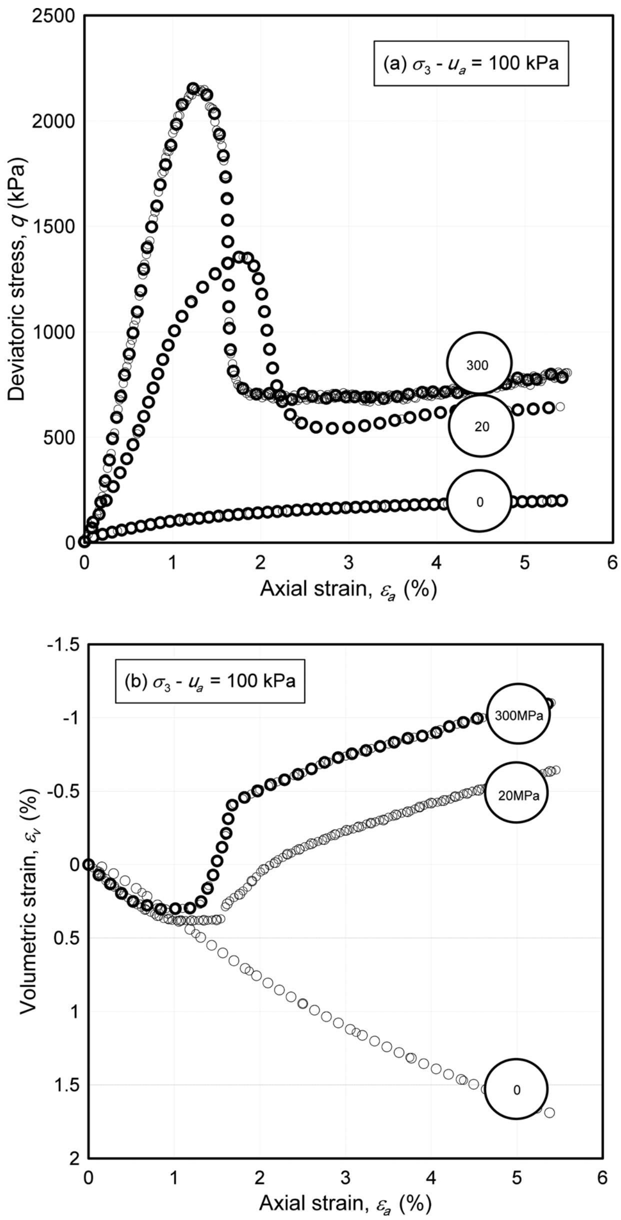
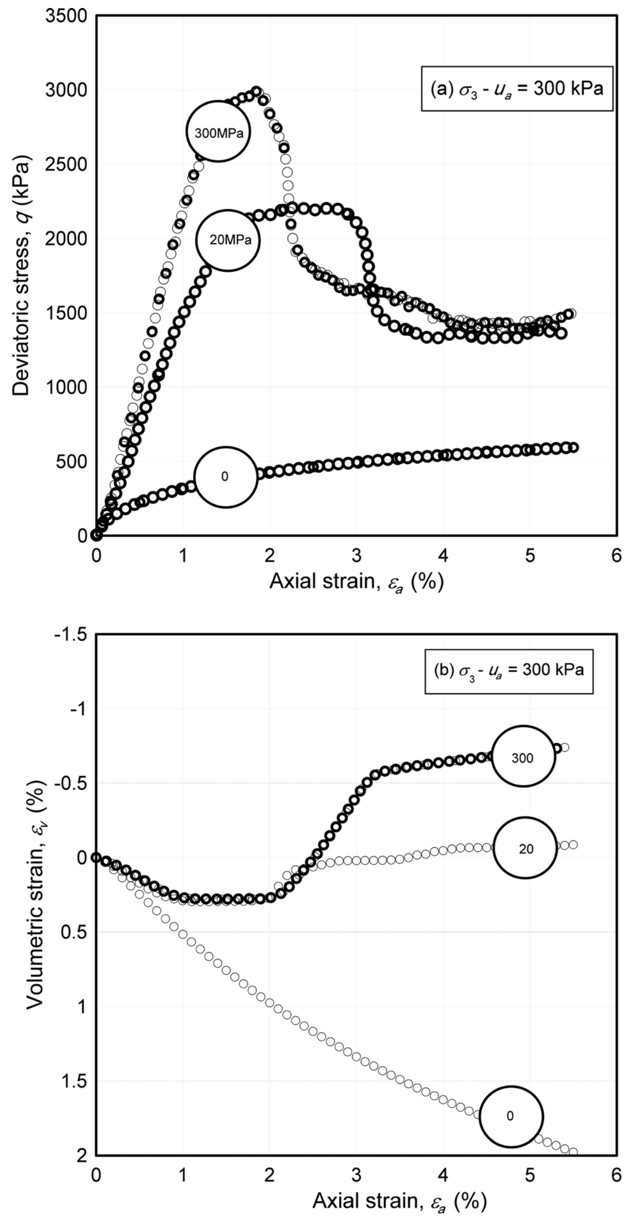


FIG. 14 Response of compacted SM soil from CTC tests under initial net confinement of 300 kPa and constant total suctions of 0, 20, and 300 MPa: (a) stress–strain response and (b) volumetric-strain response.



confinements considered, $\sigma_3 - u_a = 100$, 200, and 300 kPa; for a given value of total suction of 0, 20, or 300 MPa, as shown in **Figs.** 15 and 16. As expected, these figures are clearly indicative of increasing soil stiffness (tangent modulus), peak strength, and soil brittleness with increasing net confinement. The effect of net confinement, however, appears to be less pronounced, particularly in terms of initial stiffness and critical-state strength, at highest total suction of 300 MPa.

On the other hand, a considerable increase in the initial net confinement, from 100 kPa to 300 kPa, appears to have inhibited the relatively large amount of shear-induced dilation that is expected from SM soil tested under higher total suction (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. Particle-size distribution curves of tested SM soil materials were assessed prior to and after suction-controlled triaxial testing, which showed a slight rightward shift of the curve after testing under higher confinements. (A more thorough analysis of this finding is far beyond the intended scope of the present work.)

FIG. 15 Response of compacted SM soil from CTC tests under constant total suction of 20 MPa and initial net confinements of 100, 200, and 300 kPa: (a) stress–strain response and (b) volumetric-strain response.

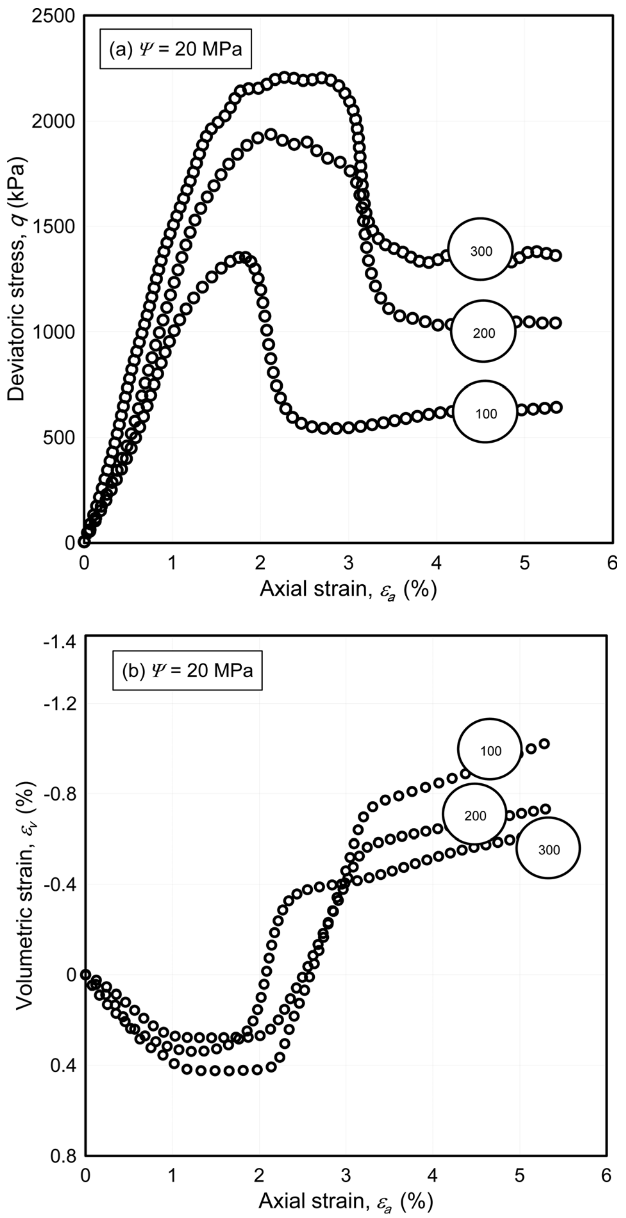
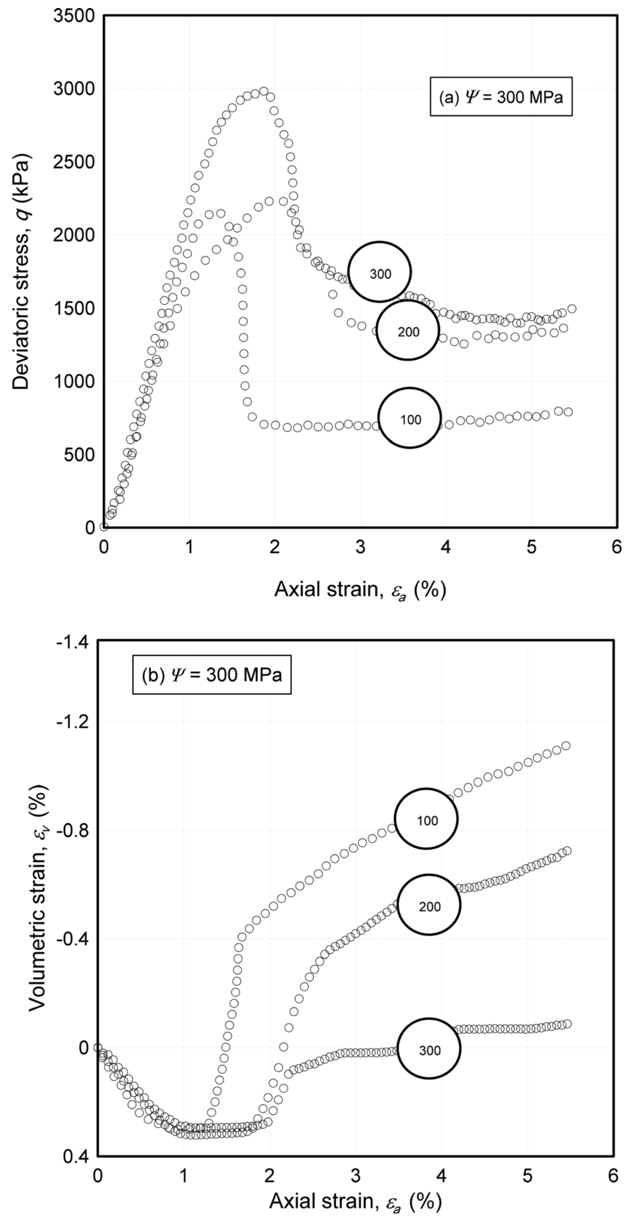


FIG. 16 Response of compacted SM soil from CTC tests under constant total suction of 300 MPa and initial net confinements of 100, 200, and 300 kPa: (a) stress–strain response and (b) volumetric-strain response.



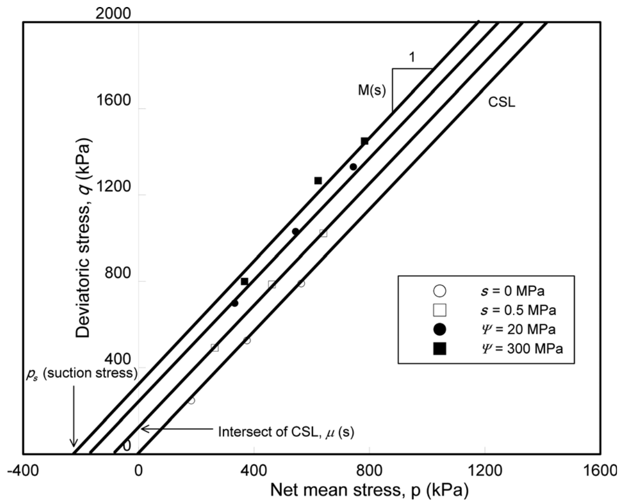
CRITICAL STATE LINES

Figs. 17 shows the best-fit critical state lines (CSLs) obtained from triaxial testing in the low-to-medium matric suction range (0.5 MPa), via axis-translation technique, as well as higher total suction range (20–300 MPa), via vapor-pressure technique. Suction is observed to exert a significant influence on the final positioning of the CSL. The slope of all critical state lines, however, remains virtually constant, in close agreement with the constitutive, critical-state-based framework postulated by Alonso et al. (1990).

Concluding Remarks

A fully automated relative-humidity (auto-RH) control unit was adapted to a newly implemented double-walled triaxial cell to test unsaturated soils under considerably higher total suction states via the vapor-pressure technique. The fully integrated auto-RH/triaxial system is also suitable for implementing the axis-translation technique. The "forced" streaming of RH-controlling vapor gas through the soil pores, and the direct measurement of RH of the influent/effluent streams, constitute

FIG. 17 Critical state lines from suction-controlled triaxial testing via axis-translation ($s = 0–0.5$ MPa) and vapor-pressure ($\psi = 20–300$ MPa) techniques.



some of the novel features of the current auto-RH/triaxial system.

The chief intent of the present work was to gain critical insight into some of the essential hydro-mechanical features of densely compacted intermediate geomaterials, including post-peak softening and strain-induced dilatancy under suction-controlled monotonic shearing. The reliability of the system was demonstrated by closely repeatable results obtained from a short series of suction-controlled CTC tests on compacted silty sand. Suitable shearing rates via axis-translation technique (0.0086 %/min) and vapor-pressure technique (0.0009 %/min) were also empirically assessed.

With the fully operational auto-RH/triaxial system, a series of consolidated-drained CTC tests were conducted 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. 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.

On the other hand, results clearly showed a marked change in shear-induced volumetric response from initially compressive to purely dilational when total suction was increased from 0 (saturated) to 20 or 300 MPa. A considerable increase in net confinement, however, from 100 kPa to 300 kPa, appears to inhibit the relatively large amount of shear-induced dilation of SM soil under highest total suction (300 MPa). The slope of all critical state lines (CSLs) obtained via either axis-translation or vapor-pressure technique remains virtually constant, in close agreement with the constitutive, critical-state-based framework originally postulated by Alonso et al. (1990).

Additional suction-controlled testing along more complex stress paths are currently being undertaken at the University of Texas at Arlington. Results from the present and future experimental works will prove crucial in the calibration, verification, and fine-tuning of constitutive models for densely compacted geomaterials that are prone to shear-induced post-peak softening and strain-induced dilatancy under suction-controlled conditions.

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