Measurement of Suction-Stress Characteristic Curve Under Drying and Wetting Conditions
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Reference

ABSTRACT
Suction-stress characteristic curve (SSCC) is an important constitutive relation defining variation of effective stress because of changes in soil water content. It can be intrinsically related to soil–water-retention curve. SSCC reflects the amount of mechanical work done to a unit volume of soil by its pore water at a particular state of matric potential or water content. A new testing system, based on a drying cake method was established to measure SSCC under both drying and wetting conditions. A previously developed theory of incremental linear elasticity allows the determination of suction stress by monitoring elastic modulus and deformation of a soil cake under varying water contents. Changes in suction stress and elastic modulus result in radial displacement field of a soil cake. A twin-cake testing procedure was established to independently measure: the elastic modulus change with water content on one cake by using a miniature-loading system, and the displacement field on the other cake by using a digital still camera throughout the drying and wetting processes. A particle image velocimetry technique was used to analyze a series of sequential images to calculate the evolution of radial displacement field and its center. The test results on four different soils, covering from sand to silt and clay, were compared and validated with the results obtained independently by a transient water release and imbibition method. It is demonstrated that this new testing system provides a simple, fast, and non-destructive way to measure SSCC under varying drying and wetting conditions.

Keywords
Young’s modulus, unsaturated soils, hysteresis, soil–water retention, suction stress, particle image velocimetry, soil drying and wetting
Introduction

Soils are complex engineering materials in terms of their particulate structure and multiphase composition under various saturated conditions. However, the mechanical behavior of soil can be treated at continuum level in geotechnical engineering practice when the local particle interactions are overwhelmed by global responses in the particle-continuum duality of soils (Wood 2008). Such occasions include stiffness at "zero" or small strains, crack-free or non-grain-crushing loading conditions, cohesive or cemented soils, etc. In unsaturated soils, there exist inter-particle forces holding the soil particles and the pore water together as a continuum medium like cement or a concrete material. Suction stress, systematically established by Lu and Likos (2004, 2006) and Lu et al. (2010), is a mechanical representation of inter-particle forces. It is built on the molecular-force interactions among solid, air, and liquid phases, mainly including adsorptive forces of electrical double layer interaction and van der Waals attraction, and the capillary force of curved air-water interface. Because these forces exist at or near the inter-particle contacts, suction stress does not depend on external forces. Rather, it is governed by soil constituents and prevailing energy states of pore water or environmental conditions in terms of matric potential. Therefore, suction stress is coined as the suction-stress characteristic curve (SSCC) (Lu and Likos 2004, 2006) depending on soil moisture and soil type. Recently, it was demonstrated (e.g., Lu et al.) that SSCC can be intrinsically correlated to soil–water-retention curve (SWRC) (Lu et al. 2014), and together they govern the hydrological and mechanical behaviors of unsaturated soils (Lu and Likos 2004).

Suction-stress characteristic curves provide a convenient and effective way to describe the state of stress of unsaturated soils. Following the effective stress theory by Terzaghi (1943), SSCC extends the effective stress concept to unsaturated soils by identifying two parts of skeleton stresses: Terzaghi’s effective stress and self-balanced inter-particle stresses. Terzaghi’s effective stress propagates as the “active” skeleton stress through soil grains from one to another. The internal ”local” stresses, which are usually not explicitly considered, are self-balanced by Born’s repulsion. The suction-stress-based effective stress principle goes beyond the Bishop’s effective stress framework (Bishop 1959) by including contributions of both adsorptive and capillary water to effective stress.

Currently, the common methods to experimentally measure SSCC include destructive methods such as triaxial, direct shear, and uniaxial tensile strength tests (e.g., Donald 1956; Bishop 1961; Lu et al. 2007; Khalili and Zargarbashi 2010; Khosravi et al. 2012), and non-destructive methods such as triaxial K0 (Oh et al. 2013) and drying cake tests (Lu and Kaya 2013). The macroscopic continuum manifestation of SSCC is the tensile strength in unsaturated soils. By assuming that the internal friction angle to be constant under different confining stress and matric suction, the suction stress can be determined by back-extrapolating the cohesion from the shear strength failure envelopes to zero shear stress on the total normal stress axis. Alshef and McCartney (2014) tested the shear strength from consolidated-drained triaxial tests on unsaturated specimens and calculated the suction stress directly using \( \sigma' = c/\tan(\phi') \) by giving the apparent cohesion \( c \) and the effective friction angle \( \phi' \). Akin and Likos (2015) used the same concept and conducted the Brazilian tension test to obtain the tensile strength, then converted it to suction stress. Those methods require either complex instrumentation or a long time for soil specimens to reach the equilibrium under certain matric suction levels. Additionally, they are all constrained by a limited access of a small suction range, and a loading condition when soil fails. Lu and Kaya (2013) invented a simple, fast, non-destructive, and non-invasive technique to directly measure SSCCs using a drying cake (DC) method. This approach employs a linear elasticity theory to determine the suction stress by measuring the elastic modulus and monitoring the deformation during the drying process. The particle image velocimetry (PIV) technique (White et al. 2003) was used to acquire the radial displacement field of a disc-shaped soil specimen and then convert the displacement to strain of the soil sample throughout drying. The DC method has provided an effective and accurate measurement of SSCC applicable to all types of soils over wide range of matric suction.

In this work, we followed the non-failure and elastic-deformation-based methodology, and redesigned the instrument to allow a complete measurement of SSCC for unsaturated soils under both drying and wetting processes. Several innovative features are described as follows. A miniature-loading module was incorporated into the entire system to facilitate an in situ measurement of the Young’s modulus of the soil cake sample under the same relative humidity environment with the other identical soil cake for the deformation measurement. A vapor-diffusing unit was deployed to provide water mist for the wetting process. Last, the results of SSCCs for both drying and wetting were compared with SSCCs obtained by the previously defined transient water release and imbibition method (TRIM method; Wayllace and Lu 2012).

Experimental Program

APPARATUS

The experimental setup for suction-stress measurement is shown in Fig. 1. The entire measuring system consists of three components: an environmental chamber providing controlled drying or wetting conditions for soil specimens; a miniature loading module measuring the Young’s modulus on one of the twin soil-cake specimens; and a monitoring unit with a digital camera and balance recording the deformation and weight of the other soil-cake specimens during the drying and wetting
processes. The full capacity of this instrumentation allows concurrent tests for two pairs of soil cakes. For simplicity, the scheme only shows half of the loading and monitoring configurations.

A top view of the axial symmetric conformation of this device is shown in Fig. 1a. A transparent acrylic cylinder with a removable top plate (as a lid) is seated on the bottom plate, and the bottom plate is firmly clamped at a lifted height off the base on four stainless-steel supporting bars. There are four circular openings on the bottom plate for the placement of two pairs of soil-cake samples: two are located at section A-A, and the other two at section B-B. The openings are slightly larger than the size of the sample holder, so that the environmental chamber is not completely sealed to avoid water vapor condensation during the wetting process. The arrangement of the four-sample configuration was made to accommodate the positions of loading actuators and digital balances. A small vapor-diffuse hole connecting to an adjustable humidifier is at the center of the bottom plate to provide water mist for wetting.

Two other side views portray the setups of the loading module and monitoring unit. Fig. 1b shows a vertical view of section A-A for the illustration of the loading module. An A-LAR200ALC-E01 model actuator (540-N thrust, 200-mm travel distance, 0.121-μm/s minimum speeds, from Zaber Technologies) is mounted on a cross-cylinder aluminum loading frame for applying vertical stress up to 100 kPa on a 3-in.-diameter soil sample. Underneath the sample holding plate, a high accuracy S-beam load cell (0.037 % accuracy, Omega Engineering) connected to a data logger (NI USB-6008) is used to measure and store the force applied on soil cake. Fig. 1c presents a section view of B-B for the demonstration of the monitoring unit. A digital camera (Nikon D3000) is fixed on a holding arm steadily clamped on the base. The other identical soil cake on a holding plate is seated on a digital balance (Ohaus SP602, 600 g in capacity and 0.01 g in accuracy) to monitor the weight change of the soil cake during drying or wetting.

The loading and monitoring components are independent with each other, but they are integrated into one platform to facilitate synchronized and in situ measurements for both elastic modulus and deformation. The digital camera, digital balance, and actuator are all connected to a computer for storage of the images, record of the moisture variations, and control of the
applied vertical force for modulus measurements. Compared to its predecessor (DC method), these improvements offer more precision and a complete drying–wetting cycle for the suction–stress measurement.

SAMPLE PREPARATION

To test the methodology, a total of four types of soil representing sand, silt, and clay were selected to verify the testing procedure. Table 1 lists the soil classifications and initial porosities of the soil cakes prepared. All soils were initially pulverized and oven-dried. Two identical soil cakes or twin-cake soil samples were made by putting the same amount of soil into a cylindrical mold: one for elastic modulus measuring and the other for deformation and weight monitoring. The dimension of the cake was 76.2 mm (3 in.) in diameter and about 20 mm in thickness. First, samples were carefully pre-compacted using a GeoJac loading system (Lu and Kaya 2013) to make homogeneous soil cakes and make equally distributed thicknesses throughout the cake. Next, the dry soil samples with mold were moved into a triaxial cell. A vacuum was applied for 2 h, and then de-aired water was sucked into the triaxial cell to saturate the samples for another 48–72 h. After saturation, the soil cakes were consolidated using a GeoJac loading system under ~900 kPa of the vertical stress to ensure that the initial stress condition of soil cakes was under the over-consolidated state. This treatment eliminated unnecessary plastic deformations of the soil samples under both drying and wetting and was applied to the linear elasticity theory. After consolidation for an additional 2–4 days, the soil cake samples were carefully extruded out of the cylinder mold, and were transferred onto two circular sample-holding plates or sample holder, which were made of acrylic plastic the same size as the specimen. A thin grease film was spread on the surface of each sample holder to reduce the friction between soil cake and plate. The purpose of such treatment was to remove any constraint on the boundary of the soil sample, so that soil can freely deform under various environmental loadings of drying or wetting. Finally, two cake samples with holding plates were placed in the chamber ready for testing: one on the load-cell in the A-A section through one opening, and the other on the digital balance in the B-B section through the next opening. The actuator and digital camera were previously center-aligned with the center positions of the corresponding soil cakes.

### TABLE 1
Properties of examined soils and fitting parameters of SWRC, based on the van Genuchten SWRC model.

<table>
<thead>
<tr>
<th>Soil</th>
<th>USCS</th>
<th>Porosity</th>
<th>$\theta_s$</th>
<th>$\alpha$ (1/kPa)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Esperance sand</td>
<td>SP</td>
<td>0.37</td>
<td>0.018</td>
<td>0.130/0.184</td>
<td>2.69/2.15</td>
</tr>
<tr>
<td>Bonny silt</td>
<td>ML</td>
<td>0.42</td>
<td>0.048</td>
<td>0.004/0.004</td>
<td>1.58/1.59</td>
</tr>
<tr>
<td>Georgia kaolinite</td>
<td>CL</td>
<td>0.52</td>
<td>0.038</td>
<td>0.0005/0.0005</td>
<td>2.03/2.05</td>
</tr>
<tr>
<td>Denver claystone</td>
<td>CL</td>
<td>0.47</td>
<td>0.149</td>
<td>0.002/0.003</td>
<td>1.55/1.43</td>
</tr>
</tbody>
</table>

TESTING PROCEDURES

The general methodology followed the same working principle as described in Lu and Kaya (2013). A complete test began with the drying process from fully saturated soils, and then wetting proceeded afterward. For drying, we took advantage of the low relative humidity in the Denver area, around 30 % (±10 %) at room temperature 25°C (±2°C), which is equivalent to 123–215 MPa of matric suction based on Kelvin’s equation (e.g., Lu and Likos 2004). The digital balance read the weight change throughout the test, and therefore the degree of saturation or water content of soil specimen can be calculated. A small amount of ponded water was on the bottom plate inside the chamber to reduce the initial gradient of relative humidity between the environment outside of the chamber and the moist air surrounding the soil cakes. A number of small holes on the top plate were also used to control the evaporation rate of soil water. These two practices were meant to reduce the speed of drying, and hence to prevent inhomogeneous moisture distribution and to avoid crack development. The drying process continued until a very small change of specimen weight was observed. An evaporation rate less than 0.1 % of the initial evaporation rate was used as the cutoff point to terminate the drying process. After drying, the wetting process followed by gradual increase of the relative humidity inside the chamber using the adjustable humidifier. A mild water-mist plume was injected through the vapor diffuser at the center of the bottom plate. An upward plume injection was deployed without bending the hose to prevent clogging induced by water condensation. The water-mist plume is made of micron-size droplets. Thus, the intensity of the water mist was adjusted to maintain a gentle relative humidity gradient between soil specimen and surrounding air. It is significantly important to provide an environment with a temperate relative humidity gradient for a homogeneous wetting and also to impede the crack occurrence. This has been achieved by a couple of trials before testing. The soil specimen slowly absorbed water from the ambient mist. Finally, the wetting process terminated either when the specimen gained weight back to the initial total weight at a saturated condition or when there was visible condensed water appearing on the cake surface.

During both the drying and wetting processes, the still digital camera took images of the soil cake specimen. The camera...
shot photographs automatically at designated intervals by computer. All images were stored on the hard drive for subsequent image processing and PIV analysis to determine the radial strain. At the same time of picturing, the automatic loading actuator was controlled by software to conduct uniaxial unconfined compression tests for fine-grained soils or uniaxial $K_0$ compression test for coarse-grained soil to determine the Young’s modulus (Lu and Kaya 2013). The loading plate was lowered at a normal speed until barely touching the top surface of the specimen. Then the vertical loading was applied at a traveling speed of 0.015 mm/min with a stop criterion of 1.5 % maximum vertical strain or maximum 100 kPa of vertical stress. For each loading, the linear portion of the stress–strain curve was used to calculate the elastic modulus from its slopes. In most cases, the tested soils showed a linear portion of stress–strain behavior before reaching ~1 % vertical strain or a vertical stress less than ~50 kPa. A full unloading was completed soon after, and the soil cake continued drying or wetting. The point where load cell reads greater than 1 kPa was considered as the loading plate fully touched the top surface of the specimen and as the starting point of loading. Therefore, positions of the loading plate were also recorded to calculate the change of the soil-cake thickness during the tests.

SUCTION-STRESS CALCULATION

After drying and wetting processes and the collection of all images and stress-strain behaviors of soil cake at each interval steps, the PIV analysis was performed to determine the strain, and then an elastic deformation theory was applied to determine the suction stress. The PIV technique is an optical method that visualizes the particle movement by operating sequential image processing. The soil texture on the image has been meshed into a grid of patches. The patches with best “degree of match” to the corresponding patches on the previous image in a predefined searching zone are identified by locating the peak of the auto-correlation function for each patch (Whittle et al. 2003). The correlation function uses the intensity or brightness matrix: integer 0–255 on the coordinate of patch center. The displacement vector of each patch can be determined by the correlation offset (White et al. 2003). A 48 × 48-pixel² PIV patch size was chosen considering the balance between patch number and patch size: a sufficient number of patches for better statistical averaging and a sufficient size of patches for high resolution of vector detection (<0.0007 pixels of standard error; Whittle et al. 2003). After the PIV analysis, we obtained the information of the displacements and coordinates of all patch centers at each interval of camera flashes, e.g., $u_{i,j}(x, y)$, where $u_{i,j}$ is the distance in pixels of the patch center traveled from frame $i$ to $j$, $x_i$ and $y_i$ are the coordinates in pixels of the patch center at frame $i$.

Using a predefined calibration factor between pixel and real dimension, the numbers of displacements and coordinates were converted into actual length unit (e.g., millimeters). Fig. 2 demonstrates the procedure of the suction-stress calculation. The displacements of all patches on each frame composed a displacement vector field. Ideally, the displacement field shows a

**FIG. 2**

Illustration of the experimental procedure to determine the suction stress of a soil for both drying and wetting process.
negative divergence vector field where all vectors pointing to the center of the circle when soil is under drying or shrinking. Likewise, the displacement field shows a positive divergence vector field when soil is under wetting or swelling. From the information of displacement field and coordinates, two sets of quantities at each frame or at different water contents can be determined: (1) radial displacement \( u_r \), and the change of radial displacement between intervals \( \Delta u_r \); and (2) the distance of each patch center to the displacement field center \( r \), and the change of \( r \) between intervals \( \Delta r \). All four quantities are functions of the coordinates of patch centers \((x_i, y_i)\) and degree of saturation \( S \).

From the elastic modulus measurements, the Young’s modulus is known as a function of water saturation \( E(S) \), assuming the Poisson ratio \( \nu = 0.25 \).

Given the water content or time-dependent functions of displacement vector fields, elastic moduli, and center locations of the displacement fields, the suction stress can be calculated by an analytical solution derived from a linear elasticity theory formulated as \( (Lu \ and \ Kaya \ 2013) \):

\[
\sigma^s(S) = -\frac{E(S) \cdot u_r(r, S)}{(1 - \nu) \cdot r(S)}
\]  

\( (1) \)
Considering that, in general, the elastic modulus of the soils has non-linearly depended on soil moisture, the differential or incremental form of the elastic solution was used in the form as:

\[
\Delta \sigma^i(S) = -\frac{u_r(r,S)}{(1 - \nu) \cdot r(S)} \Delta E(S) - \frac{E(S)}{(1 - \nu) \cdot r(S)} \Delta u_t(r,S) + \frac{E(S) \cdot u_t(r,S)}{(1 - \nu) \cdot r(S)} \Delta r
\]

This equation indicates that the contributions to the change in suction stress consist of three parts: first, the change of suction stress caused by the change in elastic modulus because of moisture variation; second, the change of suction stress caused by the particle displacement or soil cake deformation because of drying or wetting; and third, the change of suction stress caused by the drifting of the radial displacement field center. Recall that this incremental suction stress is calculated on each patch; the average change of suction stress throughout the sample is the mean value over the patch population of the soil cake:

\[
\Delta \sigma^a(S) = \frac{1}{N} \sum_{k=1}^{N} \Delta \sigma^a_k(S)
\]

where:
- \( k \) = the \( k \)th patch,
- \( N \) = the total number of the patches.

Once the incremental change of suction stress is calculated, the cumulative suction stress can be added up from the zero suction stress at full saturation state to the current state of degree of saturation \( S \):

\[
\sigma '(S) = \sum_{m=1}^{M} \Delta \sigma^m
\]

For a 3-in.-diameter soil cake, 3872 x 2592 pixels\(^2\) of the picture size and the 48 x 48 patch size, there were about 500 to 1000 patches generated on each step for sufficient accuracy of the suction-stress averaging. Typically, an increment of 0.05–0.10 of degree of saturation was selected as the interval of the measurement. As such, the increment was not too small, resulting in insufficient deformation and was not too large, causing inadequate smoothness and precision of the cumulative suction-stress curve.

**Results**

An example of drying and wetting progressing curves with time for a silty soil tested is shown in **Fig. 3**. For a typical sandy silt, the drying process took about 4–5 days and wetting about 9–12 days under the local room environment. For clayey soil, the
drying and wetting processes were intentionally slowed down further to ensure the homogeneous distribution of water content at local points in the soil cake considering the low permeability of clay. Therefore, the time for drying and wetting may be doubled (e.g., Denver claystone ~8 days for drying and ~15 days for wetting). The water mist from the adjustable humidifier was gently released into the chamber to ensure that the wetting rate is no higher than drying rate. This also reduces the possibility of soil cracking and condensation of water droplets on the soil cake surface. For each process, about 10–15 measurements of deformation and elastic modulus were conducted.

Soil deformation under drying and wetting can be quantified as the radial strain and porosity variation with saturation. The results of total radial strain averaged over all patches from PIV analysis for four tested soils are shown in Fig. 4. When soils are at a low degree of saturation, the radial strain change follows almost the same trajectory of drying and wetting, whereas at high degrees of saturation the radial strain of wetting is slightly smaller than that of drying. The total averaged radial strain varies one order of magnitude as soil dries depending on soil type, from ~0.01 for sand to ~0.1 for clay. It is known that the change of the thickness and diameter of the soil cakes from actuator loading position and PIV image processing and the calculated porosity change during drying and wetting can be computed as shown in Fig. 5. Porosity variations behave similarly to radial strains, indicating that, after wetting, the soil samples did not fully return to the original size before drying. All soils, except Georgia kaolinite, shrink under drying and swell under wetting. The total porosity change from full saturation to the end of drying also varies widely depending on soil type (e.g., as small as ~0.015 for sand, and can be as large as ~0.18 for clay). Georgia kaolinite has a non-monotonic behavior of volume change during both drying and wetting. The porosity first decreases as the soil water reduces from full saturation, then keeps constant and slightly increases as the degree of saturation further reduces. There is some hysteresis observed in Esperance sand and Bonny silt, but Georgia kaolinite and Denver claystone almost show the same path for drying and wetting. As previously described, the soil cakes were seated on a frictionless plate with no external loading applied. The designed boundary condition excludes the affecting factors of boundary constraint and external confinement. This suggests that the environmental loading or moisture-induced suction stress is the sole driving force causing the soil cake deformation. As formulated in Eq 2,
the deformations of soil cakes caused by the change of water content contribute a large portion of the change in suction stress.

Changes of elastic moduli measured with varying degrees of saturation are shown in Fig. 6. As soil dries, the magnitude of Young's modulus gradually increases from tens of kPa up to over 800 kPa for Esperance sand, and up to two or three thousands of kPa for silts and clays. The variation of elastic modulus is greater in the range of medium and high degree of saturation than in the range of low degrees of saturation. The $E$ value increases very little in the range of saturation less than 0.1. The hysteresis is observed when soil cakes have a high soil moisture level. The elastic modulus of wetting is almost the same as that of drying at a low degree of saturation (e.g., the saturation range less than 0.15 for Esperance sand, less than 0.50 for Bonny silt and Georgia kaolinite, and less than 0.20 for Denver claystone). Beyond those ranges, the elastic moduli of wetting are smaller than the moduli of drying. Comparing the elastic modulus development over the whole range of saturation, the change of Young's modulus can be several hundreds of times, depending on soil type. Therefore, as indicated in Eq 2, the variation of elastic modulus is another major contribution to the change of suction stress.

The third part of the suction-stress contribution can be obtained by determining the locations of the displacement field centers, following the same procedure of PIV analysis as described in Lu and Kaya (2013). This part, caused by field center drifting, has been identified to be a relatively small quantity compared with the other two counterparts. In other words, the change of suction stress is found to be insensitive to the variation of the displacement field center locations.

FIG. 7
Calculated suction-stress characteristic curves of tested soil samples for drying and wetting.

The suction stress at each point on the curves was statistically averaged over all local points throughout the soil cake. The standard deviation of the mean suction-stress value of each point was also plotted as the error bar shown in Fig. 7. The small length of the error bar indicates uniform suction stress from patch to patch throughout the soil sample, which verifies our assumption that the water content distribution is uniform.
and the suction stress at every local position is the same throughout the soil cake. Starting with drying from full saturation, the suction stress has a large increase from zero to 2–4 kPa for Esperance sand and to ~10 kPa for other soils, in the air-entry range of 0.9–1.0 saturation. Then, as the water content decreases, the suction stress gradually increases. For Esperance sand in Fig. 7a, the suction stress slightly increases from 5 kPa to 7 kPa as the saturation decreases from 0.85 to 0.15. As the sand continues to dry, suction stress has a small sudden jump from 8 kPa to 10 kPa. As for wetting, suction stress also has a small sudden drop from 10 kPa to 5 kPa as the saturation increases from 0.01 to 0.15. Such variation is considered as the snap-off effect of the pendular liquid bridge as the water content crossover the residual saturation where the water film becomes discontinuous. For Bonny silt and Denver claystone (Fig. 7b and 7d), these two soils show similar evolution of suction stress of drying and wetting. As the soils dry to 0.01–0.03 of saturation, the suction stress can be built up to ~100 kPa for Bonny silt and ~350 kPa for claystone.

Over the entire drying and wetting saturation range, the suction stress of drying is always equal or higher than suction stress of wetting. No obvious hysteresis can be observed at low soil moisture range: 0.03 to 0.55 for Bonny silt and 0.01 to 0.3 for claystone in degree of saturation. Georgia kaolinite in Fig. 7c shows similar suction-stress development with sandy soil, because of the small particle size and low inter-particle exchangeable cations (e.g., Lu and Khorshidi 2015). As the saturation decreases from 1.0 to 0.5, the suction stress gradually increases from 0 to ~200 kPa. Then the suction stress is maintained at the same magnitude and even slightly decreases as the soil moisture decreases to ~0.05. The suction stress on the wetting path overlaps with the suction stress of drying as the saturation increases from 0.05 to 0.5, and then the suction stress of wetting starts to be smaller than the suction stress of drying as the saturation continues to increase up to 0.9. From the results of four tested soils, the soil cake deformation method is able to obtain reasonable SSCCs. The hysteresis of suction stress between drying and wetting mainly exists in the high saturation induced by capillary hysteresis of SWRC because of the well-known ink-bottle pore neck mechanism and contact angle hysteresis mechanism (Lu and Khorshidi 2015), whereas in low-saturation or high-suction range, the hysteresis mechanism of suction stress is dominated by hydration hysteresis on particle surface and cation hydration because of soil mineralogy (Lu

**FIG. 8**
Calculated soil–water-retention curves of tested soil samples for drying and wetting.
and Khorshidi 2015). However, in the complete SSCC contour as observed in Fig. 7, hydration hysteresis is less prominent than capillary hysteresis.

Once SSCC has been identified, we used the same concept of effective degree of saturation $S_e$ in Lu and Likos (2006) to back-calculate the SRWC by assuming that the residual water content is zero ($S_e = S$). Thus, matric suction can be directly calculated as:

$$\psi(S) = \sigma^i(S)/S$$

(5)

All calculated SWRCs under drying and wetting are shown in Fig. 8. SWRC is one of the most important constitutive relations for unsaturated soils. It reflects the soil’s capability of retaining water and implies the energy state of the pore water maintained within the soil. The results in Fig. 8 show that the measured matric suction can cover a wide range of suction, up to tens of thousands of kPa.

Validation Against TRIM Method

The results of measured suction stress using the soil cake deformation method and calculated matric suction were compared with the results independently obtained using the TRIM technique for validation. Specimens prepared from the same batch of soil samples with the same procedure for each type of soil was used for TRIM test validation. TRIM is an indirect method that can be performed also under both drying and wetting conditions. This approach consists of physical water-flow experiments and inverse numerical modeling. It measures the transient water flow released or drained out of soil samples under a two-step of matric suctions applied for drying, and followed by measuring water imbibition flow into the soil under zero suction for wetting. The diffusion-type transient water flows under both drying and wetting conditions serve as objective functions. The subsequent numerical modeling uses the van Genuchten (VG) SWRC model and hydraulic conductivity function (van Genuchten 1980) to solve the Richards’ flow equation (Richards and Weeks 1953) and fit with those objective flow functions. At the same time, it iteratively identifies the VG model parameters of SWRC. The detailed principle and procedures can be found in Wayllace and Lu (2012) and Dong et al. (2014). As such, the SSCC and SWRC obtained by TRIM can be expressed by:

$$\sigma^i(S_e) = \psi(S_e) \cdot S_e$$

(6)

$$\psi(S_e) = -\frac{1}{\alpha} \cdot \left(\frac{S_e}{S_e^{\alpha} - 1}\right)^{1/n}$$

(7)

$$S_e = \frac{\theta - \theta_i}{\theta_i - \theta_f}$$

(8)

**FIG. 9**

Measured and HYDRUS fitted water-flow results of drying and wetting for tested soils.
where:

- \( \psi \) = matric suction in kPa,
- \( x \) and \( n \) = empirical fitted SWRC parameters of VG model, with \( x \) (kPa \(^{-1}\)) being related to the inverse of the air entry suction,
- \( n \) = the pore-size distribution,
- \( S_e \) = the effective degree of saturation,
- \( \theta \) = the volumetric water content, and
- \( \theta_s \) and \( \theta_r \) = the saturated and residual volumetric water contents, respectively.

The results of comparisons between experimentally measured and simulated water flow under a two-step drying and one-step wetting, as shown in Fig. 9, suggest a good fitting obtained by HYDRUS 1D modeling (ˇSimůnek et al. 1999) for all tested soils. Table 1 also lists the fitted SWRC parameters of both drying and wetting for each tested soil. Using those parameters, the SSCCs using the VG model and, accordingly, the SWRCs can be calculated as presented in Figs. 10 and 11. Notice that, in Fig. 10, the SSCCs from TRIM test generally fit well with the soil cake measurements in most part of the saturation range except at low degrees of saturation. For example, the Esperance sand develops small suction stress from 0 to 6 kPa with respect to the water content varying from full saturation to \(~0.2\) in Fig. 10a. The TRIM test results of drying and wetting are reasonably comparable with the soil cake measurements. Below saturation 0.2, the calculated suction stress by Eq 6 shows a deviation from the measured data points and decreases to zero rather than some finite values \(~10\) kPa as measured. Similar observations can be found in Bonny silt and Denver claystone in Fig. 10b and 10d. The initial rise of suction stress caused by the formation of air–water interfaces at the air-entry was captured well by the TRIM curves, from full saturation 1.0 to 0.8 \(~0.9\). As the saturation continues to change from the air entry (0.8 \(~0.9\)) to 0.3 saturation, the suction stress gradually increases from \(~10\) kPa to \(~80\) kPa for Bonny silt and to \(~200\) kPa for Denver claystone. The SSCCs from the TRIM tests also simulate well on developing curve shapes. As approaching the residual saturation, the TRIM test results in this case show higher suction-stress values with a steeper slope, which is somehow misleading and incorrect comparing to measured data points. For Georgia kaolinite in Fig. 10c, the TRIM test results can simulate very well to the measured data from saturation 0.7 to the dry end of saturation \(~0.05\) with the suction stress almost constant at \(~150\) kPa, whereas at the air-entry range (saturation 0.7–1.0) the curves vary with higher slopes but have a still reasonable error range of tens of kPa.

FIG. 10
Comparison of SCC obtained by soil cake method and TRIM method for drying and wetting.
Similar observations can also be identified in Fig. 11 for the comparisons of inferred SWRCs. All SWRCs derived based on the TRIM tests can simulate well to the inferred SWRC based on soil cake measurements by Eq 5, from full saturation 1.0 to the range near the residual saturation (e.g., 0.03 for Esperance sand, 0.15 for Bonny silt, 0.05 for Georgia kaolinite, and 0.3 for Denver claystone). Around the residual saturation, the SWRCs derived from the TRIM tests continue to increase toward the infinity, whereas the inferred SWRCs using Eq 5 are approaching some finite values.

Based on the above findings, we can conclude that the soil cake deformation method can be compared well and be proved valid in the capillary regime with well-established TRIM method for suction-stress and matric suction assessment under both drying and wetting conditions. The mismatch of SSCC and SWRC between TRIM method and soil cake deformation method in low saturation range or adsorption water regime is considered because of the incapability of VG model for adsorption water and the limitation by using the concept of residual water content. Recent studies have revealed the roles that adsorption water played in the soil–water interaction in high suction range (e.g., Frydman and Baker 2009; Revil and Lu 2013; Lu and Khorshidi 2015). The adsorption and capillary water can coexist in soil at certain energy levels of the soil water. As the soil dries under high suction range, capillary water will eventually vanish as the water content decreases to zero because of the soil–water cavitation (Herbert et al. 2006). Therefore, the adsorption water dominates in low soil moisture and contributes the major portion to the matric potential. Lu (2016) proposed a new generalized SWR model, which fully defines the regimes of adsorption water and capillary water. There are several controlling points in a complete SRWC model: the air-entry suction, completion of adsorption, cavitation of capillary, and highest matric suction. When fitting the VG model to a comprehensive set of SWRC data, the model permits the air entry value and curvature of the capillary regime to be well-captured, but does not capture changes in curvature at high suction because of other water-retention mechanisms. On the other hand, considering the fact that there is no complete suction-stress model that defines the suction stress because of adsorption water, the soil cake deformation method provides an excellent pathway to measure the SSCC over a wide suction range (up to hundreds of MPa and especially in high suction range). The measured suction stress in low water saturation,
which deviates from the TRIM test results, indicates that adsorption water also affects suction stress in the high suction range. This suggests the necessity of a complete model of suction stress, which fully defines the suction-stress component caused by capillary water and adsorption water.

Conclusions

A soil cake deformation method was introduced, for the first time, for measuring a complete cycle of suction-stress characteristic curve under drying and wetting conditions. The newly developed instrumentation integrated three components: an environmental chamber provides a controlled drying and wetting rate, a loading module to measure the moisture-dependent elastic modulus, and a deformation and water content monitoring unit to record the volume and weight change, the particle displacement, and radial strain of the soil cake. A detailed sample preparation and testing procedure has been established to conduct the drying and wetting processes. A twin-cake design with in situ testing of elastic modulus allowed synchronized suction-stress development and precise measurement. A linear elastic theory was employed to determine the suction stress developed at different degrees of saturation along drying and wetting processes. The change of elastic modulus and the deformation induced by varying soil moisture consist of two major contributions to the suction-stress development. The change of suction stress has been found not sensitive to the drifting of the center locations of displacement field.

The new technique can yield variations of porosity, elastic modulus, and SSCC and SWRC under both drying and wetting conditions. The results from various types of soils were found to be comparable with the independent results obtained from the well-established TRIM technique in the capillary water-retention regime. This new technique has been demonstrated to satisfactorily: (1) provide a simple fast and accurate measurement without damaging the soil sample, (2) cover a wide range of water content or matric suction (especially high suction range), and (3) measure the suction stress with a full capability of drying and wetting.

The need for further research improvements are also identified. The mismatch of SSCCs and SWRCs in the high suction range suggests the necessity of further investigation on the effects of adsorption water on the suction-stress development. Uncertainties still remain in the accurate control of relative humidity because of the absence of direct measurement of matric suction. These uncertainties can be addressed in the future by including a finely controlled environment chamber with precise relative humidity or suction measurement.

ACKNOWLEDGMENTS

This research is supported by a grant from the National Science Foundation (NSF CMMI-1230544) to N.L.

References


