Determining the Soil Water Characteristic Curve and Interfacial Contact Angle from Microstructural Analysis of X-Ray CT Images

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Abstract: The complex behavior of unsaturated soils can be partly attributed to the co-existence of networks of liquid bridges and saturated pockets in the soil void space. Past studies have examined how the water bridges and pockets behave when suction changes in soils. The study described here uses microfocused industrial X-ray computed tomography (X-ray μCT), to closely examine unsaturated geomaterials. In this study, an unsaturated glass bead sample was scanned in a suction-controlled setup. Images of the interphase microstructure were processed using image processing techniques. Water-air and solid-water interfaces were distinctly identified using phase-based segmentation. The soil water characteristic curve (SWCC) of the tested granular specimen was quantified by processing microstructural images that were obtained with X-ray computed tomography (CT) scanning. Values of interfacial contact angle were measured on orthogonally projected planes, and the associated results are presented and discussed. DOI: 10.1061/(ASCE)GT.1943-5606.0001677. © 2017 American Society of Civil Engineers.

Author keyword: Soil water characteristic curve; Suction; Saturation; Contact angle; Unsaturated soil.

Introduction

The complex behavior of unsaturated soils can be partly attributed to the co-existence of networks of liquid bridges and saturated pockets in the soil void space. In the past, studies have looked at how water bridges and pockets behave when suction changes in soils. However, historic limitations in the tools available for observation at the micro-level have hindered their efforts. Recent X-ray-based image acquisition developments such as microfocused X-ray computed tomography (X-ray μCT) have allowed for micro-scale investigation of geomaterials, and have the potential to improve our understanding regarding the behavior of unsaturated soils (Higo et al. 2011; Manahiloh 2013; Manahiloh and Muhunthan 2012; Willson et al. 2012).

Previous research has shown that degree of saturation, hydraulic conductivity, and capillary pressure dominantly influence unsaturated flow (e.g., Andrew et al. 2014). These bulk-scale parameters are in turn controlled by interphase interactions that govern interfacial contact, surface tension, and microscale topology (Chalbaud et al. 2009; Gaus 2010; Plug and Bruining 2007).

Proper understanding of the constitutive relationship between soil suction and saturation is of paramount importance for accurately modeling the engineering behavior of unsaturated soils (Lu and Likos 2004; Manahiloh 2013). A number of experimental setups and types of laboratory equipment have historically been used to determine the soil water characteristic curve (SWCC) (Bocking and Fredlund 1980; Cassel and Klute 1986; Fredlund and Wong 1989; Hilf 1956; Houston et al. 1994; Phene et al. 1971a, b; Stannard 1992). Saturation and/or drying is also inherently associated with the wettability behavior of the soil, which is governed by the contact angle made by the advancing or receding water-gas front (Andrew et al. 2014).

Three-dimensional (3D) information regarding the interior of objects can be captured with X-ray computed tomography (CT) (Denison et al. 1997; Masad et al. 1999). The imaging center at Washington State University (WSU) houses an X-tec 225 kV microfocused X-ray source for low-energy high-magnification imaging and a Pantak/Seifert 420 kV (East Haven, Connecticut) source for imaging tasks that require higher penetration energies (Fig. 1). The attenuation of X-rays is detected by a flat-panel Varian PaxScan 2520 (Palo Alto, California) with a Csl scintillator. Resolution close to 5 μm can be attained when scanning specimens with sizes on the order of a millimeter to a centimeter. The image characterization results that are presented here were from tests performed at WSU with a cone beam X-ray flat panel amorphous silicon high resolution computed tomography (FlashCT) machine. The imaging system shown in Fig. 1 could be used to scan objects up to a thickness of 20 cm (8 in.) and height of 46 cm (18 in.). This enables the integration and real time monitoring of tests, such as triaxial testing, that involve external hydro-mechanical loading. During scanning, the distribution of linear attenuation coefficients is calculated and used to generate 3D high-resolution digital images that represent density distribution throughout the scanned object. In the X-ray generated images, brighter voxels correspond to dense objects such as soil grains, and dark voxels represent objects with lower density such as voids or pore fluid.

X-ray μCT has been used for a variety of applications, including: 3D pore characterization (Brunke et al. 2007; Manahiloh et al. 2012; Sok et al. 2010; Weinekoetter 2008), 3D grain analysis (Ikeda et al. 2004; Jerram et al. 2009; Manahiloh and Muhunthan 2012; Masad et al. 2005), fracture analysis (Bertels et al. 2001;...

In this work, nondestructive microstructural characterization of unsaturated granular media was performed with an integrated X-ray μCT system (Fig. 1). A novel Tempe-type cell [Figs. 2(a and c)], developed by Manahiloh (2013), was used to control suction, wetting, and drying in a granular specimen housed inside an X-ray CT setup (Fig. 2). Figs. 2(b and d) show the general configuration regarding the X-ray setup including the specimen to be scanned. Subsequent sections describe the approach used to integrate microstructural image analysis with physical experiments. The associated image processing methodologies for quantifying the SWCC and interfacial angle of an unsaturated glass bead specimen.

![Fig. 1. X-ray μCT system: (a) X-ray chamber; (b) associated X-ray sources](image1)

![Fig. 2. (a) Schematic of specimen cell and saturation system; (b) schematic of the general X-ray CT cabin and specimen configuration used in the current study; (c) experimental setup at the specimen level; (d) specimen cell mounted within the X-ray μCT system [(c and d) modified from Manahiloh and Meehan 2015, © ASCE]](image2)
Experimental Setup and Specimen Preparation

The goal of imaging microstructural details in unsaturated granular media has been achieved following the advances made in X-ray μCT technology. This nondestructive testing advancement allowed for precise measurements that would not be otherwise achievable, which serve to further our understanding of the complex behavior of unsaturated soils. In particular, recent improvements that increased the attainable resolution have allowed effective determination of the SWCC and measurement of interfacial contact angles.

An X-Tec 225 keV X-ray micro-CT source was used to scan a specimen composed of microsphere glass beads varying from 0.25 to 0.60 mm in diameter. The grain size distribution [ASTM C136-06 (ASTM 2006)] of the material is shown in Fig. 3. The specific gravity of the glass beads was determined to be 2.50 [ASTM D854-14 (ASTM 2014)].

An integrated system composed of an X-ray CT scanner, a specimen cell, 3-D image processing software, and integrated imaging algorithms was used for data collection and nondestructive characterization. Laboratory testing was carried out by saturating and drying a specimen inside a specially designed suction-controlled cell with concurrent X-ray CT imaging. The integrated sample cell and X-ray CT system used for the study are shown in Fig. 2(d); a schematic of the imaging test setup is shown in Fig. 2(b).

During the scanning process, the position of the sample relative to the detector and the X-ray source governs the spatial imaging resolution. In the experiments reported here, the distances from the X-ray source to the sample and to the detector were measured to be 62 and 1,048 mm respectively. This setup produced a corresponding spatial resolution of 30 μm.

To acquire a good resolution image, it is important to find out the correct combination of X-ray energy and current (flux) for each sample type and size. The correct energy ensures the X-rays are strong enough to penetrate through the thickest portion of the specimen and reach the detector. X-ray energy dictates the contrast between components of images. Too high energy results in low contrast images. The current (flux) refers to the number of photons per second per unit area. It is controlled by adjusting the electron beam flux (mA). Information on the scan energy and flux used in the current study is given in Table 1. In the table, the first column contains information on the four stages that were used during the scanning process. In each stage, the specimen was equilibrated at different heads of water column to generate a range of suction data points. Details about each stage and the associated suction-saturation data will be provided in subsequent sections.

The glass bead specimen used in the current study was prepared by air pluviation (“raining”) the beads directly from a funnel attached to the top of the specimen chamber; this yielded a specimen with an average initial void ratio of 0.40. The height of the prepared specimen, the inside diameter of the sample cell, and the total mass of the glass beads used were measured to be 225 mm, 12.46 mm, and 49 grams, respectively. The pore-fluid was distilled water lightly doped with CsCl (3% by weight), to increase the attenuation of X-rays and ensure better contrast of the liquid phase with the air phase (Willson et al. 2012).

Image Acquisition and Processing

Digital image processing consists of algorithms for contrast enhancement, noise reduction, image sharpening, segmentation, object recognition, and many other qualitative analyses (Razavi 2006). Image processing has been used in a vast range of fields, and its applications are increasing every day. It plays a very important role in engineering, medicine, material sciences, agricultural, and other natural science studies. Recently, the application of digital image processing in geotechnical engineering has gained in popularity. In geotechnical engineering, digital images may be processed to study the flow (Yu 2010), deformation (Higo et al. 2013), and strength (Oda et al. 2004) related behaviors of geomaterials. For X-ray CT testing, digital image analysis can also be used to find the numbers, dimensions, and orientations of soil particles, investigate the distribution of pores, quantify porosity and anisotropy, and perform a variety of other microstructure-related analyses.

X-ray CT image acquisition was performed over 360 degrees to create a high-resolution three-dimensional tomographic dataset. This feature makes the cone beam X-ray CT scanner many times faster than other conventional linear detector array systems. With linear detector array systems, a fan of rays is emitted from the X-ray source. The images acquired with such beams will be single cross-sectional area images. For a complete scan, the user needs to move the sample up or down following each image acquisition. In the cone-type-beam however, the rays capture volumetric information, and the sample need not be moved, thus saving on imaging acquisition time.

A set of interactive software programs was used to control the data acquisition, image construction, and specimen visualization. To further refine or filter images to extract desired specimen properties and other information of interest, the collected images must be post-processed. During each test, scanning of samples was initiated using an application-specific FlashCT data acquisition system (DAQ). This program controls the hardware operation, calibration and image acquisition (HYTEC 2004). Using this DAQ, the datasets are saved as unified directory structure (UDS) files, which are text files containing data fields separated by linefeeds that can be

<table>
<thead>
<tr>
<th>Stage</th>
<th>Energy (keV)</th>
<th>Flux (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>155</td>
<td>145</td>
</tr>
<tr>
<td>2</td>
<td>155</td>
<td>145</td>
</tr>
<tr>
<td>3</td>
<td>165</td>
<td>145</td>
</tr>
<tr>
<td>4</td>
<td>170</td>
<td>145</td>
</tr>
</tbody>
</table>


![Fig. 3. Grain size distribution for the glass bead material](image-url)
later processed by the data processing system software (FlashCT DPS) to perform image construction. In the FlashCT DPS software package, the UDS header files are reconstructed into two-dimensional image slices. Calibration files are then used to correct pixel-to-pixel differences in the detector (i.e., to perform “bad pixel” correction). These calibration files contain radiographs taken with no object in the field of view. They range from completely dark images when an image is taken with no radiation exposure to light fields when an image is taken with full exposure (HYTEC 2004).

Physically centering the axis of rotation at the middle of the cropped region of the detector while aligning the system is one of the most challenging steps in the scanning process. A one-pixel offset of an image may result in a 50% loss of resolution (HYTEC 2004). Because perfect centering of the sample is difficult to attain, postcentering correction algorithms are employed to reconstruct an image with corrected slope and intercept (in which slope quantifies the deviation of the sample’s vertical edges from the true vertical and intercept refers to the difference between the sample center and the axis of rotation of the sample pedestal). These algorithms analyze image sinograms and correct the system’s center of rotation with respect to the entered data to yield reconstructions of the images with the centering problem rectified. Fig. 4 shows an example image of a porous concrete specimen before and after centering correction.

Reconstruction of three-dimensional images from a series of two-dimensional (2D) slices is performed as the last phase before the images are transferred to other post-image-processing software programs such as MATLAB and Image-Pro Plus (Media Cybernetics 2004). The software platform associated with the WSU X-ray CT system is FlashCT Visualizing (VIZ). A summary of the processes involved with X-ray CT scanning is shown in Fig. 5.

A digital image is a representation of a discrete function with integral (gray scale) or rational (red, green, blue) number ranges. The fundamental constituent element of a digital image is a pixel (1 x 1 square) in 2D and a voxel (1 x 1 x 1 cube) in 3D as shown in Fig. 6. The intensity of an image at a point is represented by the value of each pixel or voxel.

Computational resources play a significant role in digital image processing. Good performance typically requires the use of relatively fast parallel processing (i.e., 3.0 GHz/processor) with four hyper-threaded processors, and 4GB of RAM per core. The computational system used at WSU meets these requirements and consequently prevents memory-related shortcomings that can be encountered in the image preprocessing stages. In the data acquisition process, the data corresponding to voxel gray shades are stored as 16-bit integers ranging between 0 and 65,535. For image postprocessing, the unsigned 16-bit data demands relatively large amounts of memory.

To circumvent memory problems, the data was converted to 8-bit integers ranging from 0 to 255. For the glass bead images, this conversion showed negligible effects on image resolution but significantly reduced image size to a level that allowed relatively fast processing.

**Image Segmentation**

When numerical evaluation or quantification of features in images is performed, all images undergo a step called segmentation. In segmentation, the major aim is to split the image domain into distinct regions. The segmentation criteria used in this study targets intra-region uniformity, a criterion dictating regions to be uniform and homogenous, and interregion disparity, a criterion dictating that
adjacent regions should have a significant contrast. Most unsupervised segmentation methods use a combination of both interregion and intraregion metrics. A typical example of a global segmentation approach that uses these combinations is Otsu’s segmentation technique (Otsu 1979).

Otsu’s method tries to find a threshold value which minimizes the within-class variances (i.e., intraregion) of background and foreground voxel classes, which is equivalent to maximizing the variance between the means of the two clustered classes (i.e., interregion) (Gebreegi 2009; Sund and Eilertsen 2003; Wirjadi 2007). In Otsu’s thresholding technique, for an image taking on discrete voxel values \( k \), the optimal threshold, \( \theta \), is given as

\[
\theta_{\text{Otsu}} = \arg \max_{\theta} \left[ \sum_{k < \theta} p(k)(\mu_1 - \mu) + \sum_{k \geq \theta} p(k)(\mu_2 - \mu) \right]
\]

where \( p = \) normalized histogram; \( \mu = \text{mean}(f(x)) \); \( \mu_1 = \text{mean}(f(x) | f(x) \geq \theta) \); and \( \mu_0 = \text{mean}(f(x) | f(x) < \theta) \).

Otsu’s segmentation gives accurate results if there are no local inhomogeneities. Unfortunately, such inhomogeneities exist in the majority of geomaterials of interest, and the application of Otsu’s segmentation technique can return many misclassified voxels in a given segmented image. Even with extreme optimization of the acquisition parameters for better quality reconstructions, there is always noise when global thresholding techniques are applied for segmentation.

A solution to such instances is to use local adaptive thresholding techniques. These are region-based approaches that take into account the information in the direct neighborhood of each point of the domain. One example of a local adaptive segmentation technique is that of Li et al. (2008). Because Li’s approach uses an iterative minimization technique, an initial solution has to be provided to the method; to start with a good initial guess, initialization is usually performed using the results from Otsu’s segmentation.

The general process of segmentation followed in this study can be illustrated using a single X-ray CT slice (Fig. 7). The 8-bit raw X-ray CT slice obtained from a partially saturated glass-bead specimen [Fig. 7(a)] is investigated using a segmentation approach, and the gray values of pixels belonging to each phase are determined. These gray values can then be input into the image processing software program and the program can be instructed to render each phase in a different color. The result of this step is shown as Fig. 7(b), where the overall gray scale ranges shown in Fig. 7(a) are binned to three distinct black, gray, and white colors that signify the gas, liquid, and solid phases, respectively. Using masking techniques, an individual phase of interest can be segmented by masking others. The results from this technique, as applied to extracting the solid, liquid, and gas phases from Fig. 7(b), are shown in Figs. 7(c–e), respectively. For this specific image, the ranges of gray values for the gas, liquid, and solid phases were (0–30), (31–120), and (121–255), respectively. Any information sought on each phase can then be stored in arrays, with stored information later being used to calculate various engineering parameters. Example parameters that were calculated in this work include degree of saturation and interface angle.

### Soil Water Characteristic Curve from Microstructural Image Analysis

The SWCC provides a conceptual understanding between the mass (and/or volume) of pore-water and the energy state of the water phase (Fredlund et al. 2012; Pham 2005). It also provides a constitutive framework for combining the theory of unsaturated soil behavior and unsaturated soil properties, and plays a pivotal role in the solution of unsaturated soil problems (Fredlund et al. 2012). Common laboratory techniques used to apply matric suction and measure the equilibrium water content include tensiometers (Cassel and Klute 1986; Stammard 1992), axis translation techniques (Bocking and Fredlund 1980; Hilf 1956), electrical/thermal conductivity sensors (Fredlund and Wong 1989; Phene et al. 1971a, b), and contact filter paper methods (Houston et al. 1994). In this paper, a new approach for determining the SWCC is presented, in which the degree of saturation is obtained from digital image processing by means of thresholding and automated voxel-counting. Using this approach, the liquid and gas phase volumes in the specimen were determined using image-processing macros that counted voxels in the digital imagery (Media Cybernetics 2003). The resulting degree of saturation values were expressed as percentages by taking the ratios of the voxel counts corresponding to the liquid phase, \( V_L \), and void (gas plus liquid) phase, \( V_V \). To illustrate this process, consider the image shown in Fig. 7. For a uniform thickness slice, the volume ratio that is used in defining the degree of saturation [Eq. (2)] could be rewritten using the area ratio shown in Eq. (3). The area of the phases of interest, in turn, is equal to the number of dots (pixels) that make up the area. Therefore, from the images, the area is calculated as the total number of pixels that have gray values within a defined range

\[
S = \frac{V_w}{V_v} \times 100\%
\]

\[
S = \frac{A_w}{A_v} \times 100\% = \frac{A_{\text{liquid}}}{A_{\text{gas}} + A_{\text{liquid}}} \times 100\%
\]

For the defined area of interest shown in Fig. 7, the following pixel counts were obtained:
- Gas: 9,157;
- Liquid: 8,849; and
- Solid: 24,806.

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**Fig. 7.** Image segmentation: (a) raw image; (b) three-phase segmented image; (c) image segmented for solid phase only; (d) image segmented for liquid phase only; (e) image segmented for gas phase only
Using Eq. (3)

\[
S = \frac{A_{\text{liquid}}}{A_{\text{gas}} + A_{\text{liquid}}} \times 100\% = \frac{8,849}{9,157 + 8,849} \times 100\% = 49.17\%
\]

A partially saturated specimen was scanned in four stages, two along a drying path and two along a wetting path of the SWCC. This was to ensure that X-ray CT images of the granular and fluid microstructure were obtained over a sufficiently large enough range to infer the remainder of the SWCC. Matric suction was applied to the specimen by integrating a cellulose membrane at the base of the sample cell [Figs. 2(a and c)] and applying suction using a hanging column system [ASTM D6836-02 (ASTM 2008)]. For each of the test stages, the reference datum was fixed and the location of water inside the specimen was carefully marked and used in calibrating the variation of suction inside the cell. A small opening was provided at the top of the sample cell to ensure the air pressure was atmospheric, as shown in Fig. 2(c).

Fig. 8 provides a schematic of the water reservoir conditions under which the four scanning stages were implemented. Stage 1 represents the initiation of drying of the specimen from its fully saturated condition. In this stage, the suction head \((\Delta h_1)\) was set to 70 mm. Details regarding the scanned and suction measurement locations for Stage 1 are shown schematically in Fig. 9. The locations indicated within the specimen were all in reference to the base of the specimen column. In Stage 2 the water reservoir in the hanging column was lowered to cause a total head difference \((\Delta h_2)\) of 21.5 cm and further dry the sample column. Stage 3 represents initiation of rewetting of the specimen. This was achieved by raising the water reservoir such that the head difference at equilibrium \((\Delta h_3)\) was reduced to 12 cm. Finally, in Stage 4, the suction head \((\Delta h_4)\) was further reduced to 4 cm to continue the wetting path.

Data for the measured suction and calculated saturation are presented in Table 2. To obtain the numerical values for the degrees of saturation that are shown in Table 2, an image processing macro was developed and implemented.

Since Gardner’s (1958) work, a number of empirical equations have been suggested to best fit the SWCC data obtained from laboratory experiments (Brooks and Corey 1964; Fredlund and Xing 1994; McKee and Bumb 1984; Pham and Fredlund 2005; van Genuchten 1980). In this work, the experimental data collected for the SWCC from the integrated X-ray apparatus was fitted with Van Genuchten’s (1980) model, as shown in Fig. 10. Using the Van Genuchten model fit approach (for which the equation is provided Fig. 8. Schematic showing the experimentally controlled suction and wetting process.

<table>
<thead>
<tr>
<th>Stages</th>
<th>Measurement location (mm)</th>
<th>Suction (kPa)</th>
<th>Saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1 (drying)</td>
<td>155.0</td>
<td>0.000</td>
<td>97.34</td>
</tr>
<tr>
<td></td>
<td>162.0</td>
<td>0.069</td>
<td>97.18</td>
</tr>
<tr>
<td></td>
<td>175.5</td>
<td>0.201</td>
<td>97.04</td>
</tr>
<tr>
<td></td>
<td>189.0</td>
<td>0.333</td>
<td>95.70</td>
</tr>
<tr>
<td></td>
<td>202.5</td>
<td>0.466</td>
<td>85.50</td>
</tr>
<tr>
<td>Stage 2 (drying)</td>
<td>70.0</td>
<td>0.588</td>
<td>66.75</td>
</tr>
<tr>
<td></td>
<td>80.0</td>
<td>0.686</td>
<td>44.94</td>
</tr>
<tr>
<td></td>
<td>90.0</td>
<td>0.784</td>
<td>35.17</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>0.882</td>
<td>31.79</td>
</tr>
<tr>
<td></td>
<td>130.0</td>
<td>1.176</td>
<td>21.24</td>
</tr>
<tr>
<td></td>
<td>160.0</td>
<td>1.471</td>
<td>18.67</td>
</tr>
<tr>
<td></td>
<td>190.0</td>
<td>1.765</td>
<td>12.42</td>
</tr>
<tr>
<td></td>
<td>220.0</td>
<td>2.059</td>
<td>6.74</td>
</tr>
<tr>
<td>Stage 3 (wetting)</td>
<td>220.0</td>
<td>0.343</td>
<td>38.40</td>
</tr>
<tr>
<td></td>
<td>215.0</td>
<td>0.294</td>
<td>53.81</td>
</tr>
<tr>
<td></td>
<td>205.0</td>
<td>0.196</td>
<td>82.21</td>
</tr>
<tr>
<td></td>
<td>200.0</td>
<td>0.147</td>
<td>84.30</td>
</tr>
<tr>
<td></td>
<td>195.0</td>
<td>0.098</td>
<td>86.40</td>
</tr>
<tr>
<td>Stage 4 (wetting)</td>
<td>135.0</td>
<td>0.000</td>
<td>86.40</td>
</tr>
</tbody>
</table>


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in Fig. 10), $S_r$ and $S_w$ represent the saturated and residual saturations respectively, $\psi$ is the matric suction, $\alpha$ is a parameter related to the inverse of the air-entry suction, and $n$ is a nondimensional measure of the pore-size distribution. Relatively large $n$ values are indicative of uniform pore size distribution; $m$ is another fitting parameter that takes a role in controlling the symmetry of the SWCC. This parameter controls the slope of the characteristic curve in the relatively high suction range, where relatively small $m$ values result in a steeper slope at higher suctions.

**Interfacial Contact Angle from Microstructural Image Analysis**

The interfacial contact angle has been defined as the angle measured from the liquid-solid interface to the liquid-gas interface (Jury and Horton 2004), and it is believed to be an intrinsic property of any two contacting phases in a solid-liquid-gas system (Lu and Likos 2004). For unsaturated soil systems, the contact angle has been defined as the angle between a line tangent to the gas-water interface and a line defined by the liquid-solid interface. This definition is shown in Fig. 11. Generally speaking, contact angle is a widely used measure of wettability of surfaces (Anderson 1986).

Jury and Horton (2004) stated that a liquid is said to wet a solid if the liquid is preferentially attracted to the solid phase compared to its cohesive attraction to other liquid molecules. If the converse of this behavior is manifest (i.e., stronger cohesive force of the liquid than the adhesion to the solid), the liquid is said to repel the solid. In general, the wetting liquid-solid interfacial angle is larger than the drying interfacial angle. In a capillary tube filled with water, a wetting contact angle will lead to capillary rise. On the other hand, a similar capillary tube filled with mercury will exhibit a repellant contact angle, which leads to capillary depression (Lu and Likos 2004).

Multiple techniques of contact angle measurement have been reported. These include the dynamic sessile drop method (Dickson et al. 2006; Espinoza and Santamarina 2010), the captive bubble method (Chiquet et al. 2007), and techniques that involve micro-model studies (Chalbaud et al. 2009). These techniques could all be argued to be accurate. However, they are all only applicable to scenarios that involve flat solid surfaces. When the solid and/or the solid-liquid interface has nonplanar geometry, the applicability of the techniques listed becomes questionable. In unsaturated soil mechanics, phase interfaces are dominated by nonplanar geometries. That is where the need for direct interfacial angle measuring techniques that account for surface nonplanarity emanates.

The use of digital image processing to measure contact angle has been only lightly researched. Some studies tested the applicability of X-ray microtomography for contact angle measurement (e.g., Andrew et al. 2014). In these studies, phase curvature and surface roughness were not given enough attention. Very recently, a study by Andrew et al. (2014) used X-ray micro-CT and digital image processing to investigate the spatial variation of the interfacial boundary while measuring the contact angle in an unsaturated granular media.

This paper presents the results from a series of X-ray micro-CT imaging tests conducted under a suction controlled environment on a partially saturated granular specimen composed of a glass bead material. From the X-ray CT images, the three distinct phases (solid, liquid, and gas) can be clearly delineated using a range of X-ray attenuation coefficients to define each phase. As shown in Fig. 12(a), pixel coloring is correlated to X-ray attenuation, with the lightest colored pixels corresponding to the gas phase, the darkest colored pixels corresponding to the solid phase, and the intermediate (gray) pixels corresponding to the water phase.

For the X-ray CT equipment that was used in the current study, the base color level for each imaging scan is not constant; this means that a different pixel color range needs to be used to define the respective solid, liquid, and gas phases for each imaging scan. This phenomenon of varying base color can be clearly observed in Fig. 12(b), which shows a series of sequential scans that were performed along the length of the column. The whole length of the specimen was scanned in small segments to achieve good resolution of the three phases. The difference in the brightness of each segment can be attributed to the inconsistency in energy and flux emission as a function of the length of time the X-ray scanner was in continuous use. Visual differences in brightness do not negatively affect image analysis, provided each segment is analyzed independently and pixel color ranges are assigned accordingly, as was done in the current study.

To measure contact angle values directly within a given specimen, it is necessary to focus on the characteristics of a localized feature; such close analysis requires the use of high-definition X-ray CT images. In general, the scale at which a given feature must be assessed is a function of the solid particle sizes that are in contact and the resulting void space between the particles. For the current study, the relative size of a typical feature of interest is shown in Fig. 12(a).

The following section shows how the results from digital image processing can be used to measure individual interfacial contact angles for a given feature. The presented contact angle measurement approach is shown to be particularly beneficial, in that it can be applied to curved interfaces, not just the traditional flat interfaces that are used with glass plate testing approaches.

Fig. 13 shows a cubic image sample that contains an included air-ganglion feature of interest that can be used for interphase angle assessment; the image set shown corresponds to the sample...
Fig. 12. (a) Example X-Y image “slice” from the analyzed specimen; (b) a sub volume for which an analysis ganglion was defined; (c) sequential images along the height (X-Z) of the analyzed specimen.

Fig. 13. Typical coordinate axes system.

Fig. 14. Cross-sectional images taken in the z-direction [image centered at \((x, y) = (22, 22)\)]

Fig. 15. Cross-sectional images taken in the y-direction [image centered at \((x, z) = (22, 16)\)]
From these images, three orthogonal planes were chosen to measure the angles formed between the solid-liquid and liquid-gas interfaces (i.e., contact angle) for the tested specimen (Media Cybernetics 2003). The measured angles of interest for the three planes of characterization are provided in Figs. 18–20, along with the corresponding feature locations for each measured angle.

For the three images that were analyzed, the average contact angle values for the XY, XZ, and YZ planes were found to be 88.3°, 88.75°, and 88.1°, respectively, with an overall average of 88.4°. The standard deviations (SD) were found to be 0.64, 0.78, and 0.28, respectively. The number of measurements taken from each image varied depending on the presence of actual contacts between the liquid and solid phases. The relatively larger contact angles that were measured here indicate that the glass bead material is mildly hydrophobic. Performing contact angle measurements on the same material, but flat in this case, resulted in a contact angle of 87.3° when there is no fluid movement, and wetting and drying contact angles of 123.2° and 36.7° when the flat plane was inclined.

Fig. 16. Cross-sectional images taken in the x-direction [image centered at (y, z) = (22, 16)]

Fig. 17. (a) Three-dimensional volume resulting from the reconstruction of the 2D slices shown in Figs. 14–16; (b and c) 3D renderings showing the air-ganglion bounded by the liquid and solid phases [(a–c) reprinted from Manahiloh and Meehan 2015, © ASCE]

Fig. 18. Measurements on the XY plane located at Z = 11

Fig. 19. Measurements on the XZ plane located at Y = 26

Fig. 20. Measurements on the YZ plane located at X = 17
Fig. 21. Droplet prepared from a 3% CsCl-doped water solution: (a) no flow; (b) plane tilted by 30° to initiate flow to the right

at 30°. Figs. 21(a and b) show the images taken for contact angle measurement on a flat material. The curvature of the beads did not significantly change the measured contact angles. Under flow equilibrium conditions, the average angles measured for flat (87.3°) and spherical (88.4°) materials differ by only 1°.

Conclusions

A physical experimental approach integrated with digital image processing was shown to be useful for quantifying parameters of fundamental importance in unsaturated soil mechanics. A direct method that enabled identification of interfacial boundary surfaces, quantification of the SWCC, and the interfacial angle between the liquid-air and solid-liquid boundaries was presented. Theoretically, the technique described in this work has no use limitations. It could be used in studies that involve inherent surface roughness and curvature (e.g., unsaturated soil studies on granular media). The only necessary criterion is obtaining high-resolution microstructural images, for which the potential applicability of X-ray µCT scanners was demonstrated. An image-processing algorithm was developed and used for quantifying the degree of saturation of a partially saturated granular specimen in an automated manner. The use of a 3% by weight CsCl solution enabled separating the liquid phase from the gas phase that co-existed in the pore spaces. The average interfacial contact angles measured on the XY, XZ, and YZ planes were found to be 88.3°, 88.75°, and 88.1°, respectively. The overall average contact angle measured for the partially saturated glass bead material was 88.4°. The curvature of the glass beads didn’t significantly alter the magnitude of the measured interfacial contact angle. In general, the tested glass bead assembly exhibited a hydrophobic behavior, which is consistent with what was observed in the flat glass plate tests.

References


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