X-ray Computed Tomography Method for Measuring Matric Suction of Micro-Sheet Materials Mixed Cs$_2$SO$_4$

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Abstract. In this paper, the X-ray computed tomography method was applied to measure the matric suctions of the glass-sheet samples. With the contributions of Cs$_2$SO$_4$ solution, the distributions of water among glass sheets were distinctly observed. The shape of the liquid bridges between the glass sheets are not simple circular ring, but rings with the triangular or quadrangular projective planes. Cs$_2$SO$_4$ resulted in the coefficient surface tension of the solution decreasing, which is the main reason that the tested values of matric suction were slightly higher than calculated. Overall, the differences between tested and calculated values are less than 3%, which testified that X-ray computed tomography method for measuring matric suction is feasible. The significance of this work is X-ray computed tomography method could be applied in unsaturated clay soil constituted by sheet particles.

Keywords: X-ray computed tomography; Matric suction; Micro-sheet; Cesium sulfate

1. Introduction

The matric suction between particles is an important physical parameter to analyze the mechanical properties of the wet granular material, especially for unsaturated soil [1]. Therefore, various of particle hypothesis and contacts are proposed, i.e., spherical hypothesis [2, 3], ellipsoid hypothesis [4], sphere-sphere [5] and sphere-plate contact [6, 7], etc. And a number of studies have considered matric suction development in sandy soil [5, 8, 9]. The glories of studying on matric suction in sandy soil don’t represent the development in unsaturated soil. The main reasons are that two challenges exist for a long time. (1) The soil particles assumed as spheres are not reasonable, however, the clay are composed with sheet particles. (2) The 3D distributions of water were always assumed as ideal circular-ring and difficultly observed. Due to the restriction of the observational technique and complexity of the structures, the development of matric suction in clay lags behind sandy soil. Overall, the matric suction between the sheet particles is necessary to study further on.

As a non-destructive technique, X-ray computed tomography ($\mu$-CT) method has been applied in most fields, i.e. biology, medicine, geology [10-13]. Especially for studying the structures and properties of the objectives [14-17]. In this work, a method based on X-ray computed tomography for investigating the three-dimension distribution of the water mixed with Cs$_2$SO$_4$ among the glass sheets. Through the contrastive analysis of the testing and calculated results of matric suctions, the feasibility of the method to measure the matric suction with $\mu$-CT method is verified.
2. Materials and Methods

2.1. Materials and Scanning Method
The glass sheets were collected as the study materials. The size of the sheet was 3mm x 2mm x 0.5mm. The density of the glass was 2.60 g/cm³. After fat-soluble compounds dissolved with alcohol and air-drying, the glasses were randomly filled in the cylindrical Peek tube (diameter was 20mm) and both ends of the tube were plugged with plastic plug reserved small holes. The glasses were wet with the cesium chloride solution which was helpful to scan the water distribution (figure 1). After the samples were stored in the humidity-controlled room to allow equilibration of the water content within the samples for at least 24 h. Through testing the weight before and after wetting experiment, the water contents were respectively 7.1%, 11.4%, 15.3%, and 18.7%. And the matric suction of the wetted glassed was measured with the temperature and humidity sensor [18] (figure 1).

![Figure 1](image.png)

**Figure 1.** Materials and methods. (a) The sampling method and the particle sizes. (b) Test of the matric suction. (c) X-ray scanning.

The μ-CT scanning experiments were completed in the X-ray imaging and biomedical application beam line (BL13W1) of the Shanghai Synchrotron Radiation Facility (SSRF) in China. The photon energy was set as 40 keV with an exposure time of 0.5s; the distance between the sample and the lens was 65 cm; the resolution of the lens was 9μm. The Peek tube was mounted on a rotary stage and rotated from 0° to 180° at the same interval (0.25°), shown in figure 1. About 720 slices with a size of 3992x537 pixels were reconstructed for the glass-sheet sample. The slices were first pre-processed with the Pitre software including image cropping, phase retrieval and slice reconstructing [19]. Then the images visualization and quantification were completed with the Avizo software package (version 8.0, VSG, 19 France) [20].

2.2. Calculation Method
According to the characteristic of the cuboid structure, the contacts between the sheet particles include face-face, face-edge, face-angle, angle-angle, angle-edge, edge-edge, etc. Indeed, two faces constitute an edge and three faces constitutes an angle. From the perspective of mesoscopic, the contacts could
be generalized into face-face (figure 2).

**Figure 2.** 3D and 2D diagrams of the particle contacts. (a) All the contacts between sheet particles. (b) 3D diagram of generalized contact. (c) 2D calculation diagram.

With the tools in Avizo software, the dimensions, volume and contact angles of the fluid bridge were measured. The 2D calculation diagram is shown in figure 2. Based on Young–Laplace equation [21],

\[ P_c = u_a - u_w = T_s \left( \frac{1}{r} - \frac{1}{l} \right) \]  

(1)

where \( r \) is the curvature radius of the meniscuses along the air side, \( l \) is the curvature radius of the meniscuses along the water side,

\[ r = \frac{b / \tan \beta + h}{\cos \theta + \sin (\beta - \theta)} \]  

(2)

\[ l = b - r \left[ 1 - \cos (\beta - \theta) \right] \]  

(3)

where \( b \) is the distance from the edge of the shrink film and cuboid particle to the axis of the particles. \( \theta \) is the contact angle between shrink film and cuboid particle, \( 2\beta \) is the filling angle of the cuboid particle.

Substituting Eq. (2) and (3) into Eq. (1), the matric suction can be obtained,

\[ P_c = T_s \left\{ \frac{\cos \theta + \sin (\beta - \theta)}{b / \tan \beta + h} - \frac{1}{b - r \left[ 1 - \cos (\beta - \theta) \right]} \right\} \]  

(4)

3. Results and Discussion

Figure 3 shows the horizontal and vertical cross sections obtained with X-ray computed tomography performed on the sample. Grey parts, black parts and bright white parts are respectively corresponding to glass sheets, voids and Cs\textsubscript{2}SO\textsubscript{4} solution (representing water). Especially, Cs\textsubscript{2}SO\textsubscript{4} solution is unexpectedly distinct from other parts. The 2D and 3D images obtained with the X-ray computed tomography method clearly describe the water distributions between the glass sheets (figure 3), which indicates that Cs\textsubscript{2}SO\textsubscript{4} supplies adequate contributions to this experiment. Indeed, Cs\textsubscript{2}SO\textsubscript{4} is easily soluble in water and the density is 4.234g/mL(25°C), which absorbs higher energy of X-ray comparing with water during the scanning process.
Figure 3. The horizontal and vertical cross sections obtained by X-ray computed tomography.

The 2D images in grey levels extracted from the 3D image show different particle contacts (including face-face, face-edge, face-angle, angle-angle, angle-edge, edge-edge, etc.) and liquid bridges between the glass sheets (figure 3). Figure 3(b) shows that the thicknesses of liquid bridge range from 0.03 to 0.7mm. And the contact angles range from 30 to 40 °. Interestingly, the shapes of the liquid bridges between the glass sheets are not simple circular-rings, but present rings with the triangular or quadrangular projective planes, which indicate the reasonability of generalizing the contacts between glass sheets into face to face.

Figure 4. Matric suction versus water content.

Figure 4 shows the results respectively obtained with calculated model and tests. The maximum measured matric suction values obtained from the tests and calculation performed on the glass sample
were respectively 1143 kPa and 1187 kPa. With the water contents increasing, the matric suctions trend to decreasing. Figure 4 highlights the fact that the rate of increase in matric suction on the side of low water content was substantially higher than the rate of decrease in matric suction on the side of high water content. This trend is similar to that observed in the results of Marinho and Stuermer (2000) [22]. Figure 4 shows that the tested values are slightly higher than the calculated values. The main reason is that the water was mixed Cs$_2$SO$_4$, which increase the density of the solution. In this work, the coefficient of surface tension of the Cs$_2$SO$_4$ is 53.7 dyn/cm (20°C) less than 72.7 dyn/cm (20°C) of water. The decrease of the coefficient results in the tested values with temperature and humidity sensor (specific to water) are slightly higher than calculated. In addition, during the process of 3D visualization, a slight error of threshold adjustment also leads to the calculated values less than tested. Overall, the differences between tested and calculated values are less than 3%, which testified that X-ray computed tomography method for measuring matric suction is feasible.

What is the significance of this work? Indeed, the aim of this study is applying the X-ray computed tomography method to analyze the mechanical property of unsaturated clay soil. The clay soils are constituted by lots of typical sheet particles. However, the complexity of the structures and visualization of water limit the development of unsaturated clay soil.

4. Conclusions
In this work, the X-ray computed tomography method was proposed to measure the matric suctions of the glass-sheet samples. Due to Cs$_2$SO$_4$, the distributions of water among glass sheets were distinctly observed. The shape of the liquid bridges between the glass sheets are not simple circular ring, but rings with the triangular or quadrangular projective planes.

Cs$_2$SO$_4$ resulted in the coefficient surface tension of the solution decreasing, which is the main reason that the tested values of matric suction were slightly higher than calculated. Overall, the differences between tested and calculated values are less than 3%, which testified that X-ray computed tomography method for measuring matric suction is feasible. The significance of this work is X-ray computed tomography method could be applied in unsaturated clay soil constituted by typical sheet particles.

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References
[1] Lim T T, et al. 1996 CAN. GEOTECH. J. 33: 618.
[2] Megias-Alguacil D and Gauckler L J 2009 AICHE. J. 55: 1103.
[3] Tang L 2001 Chinese Journal of Geotechnical Engineering 23: 412.
[4] Kim D O, et al. 2016 LANGMUIR 32: 11899.
[5] Anandarajah A and Amarasinghe P M 2011 Journal of Geotechnical & Geoenvironmental Engineering 138: 3906.
[6] Ardito R, et al. 2014 European Journal of Mechanics - A/Solids 47: 298.
[7] Yang L, Hu J H and Qin J 2014 GRANUL MATTER 16: 903.
[8] He W and Dinsmore A D 2015 SOFT MATTER 11: 5087.
[9] Yang S, Wu J H and Wang X 2013 Advanced Materials Research 634-638: 2945.
[10] Wildenschild D, et al. 2002 J. HYDROL. 267: 285.
[11] Ketcham R A and Carlson W D 2001 COMPUT GEOSCI-UK 27: 381.
[12] Paulus M J, et al. 2000 NEOPLASIA 2: 62.
[13] Luxenberg J S, et al. 1988 *AM J PSYCHIAT* **145**: 1089.
[14] Dhondt S, et al. 2010 *TRENDS PLANT SCI.* **15**: 419.
[15] Sander T, Gerke H H and Rogasik H 2008 *GEODERMA* **145**: 303.
[16] Stuppy W H, et al. 2003 *TRENDS PLANT SCI.* **8**: 2.
[17] Rogasik H, et al. 2003 Geological Society London Special Publications **215**: 151.
[18] Zhang P, et al. 2013 *Chinese Journal of Rock Mechanics and Engineering* **31**: 2792.
[19] Chen R C, et al. 2012 *J. SYNCHROTRON RADIAT* **19**: 836.
[20] Liu J, Pereira G G and Regenauer-Lieb K 2014 *J. GEOCHEM EXPLOR* **144**: 84.
[21] Rey A D 2000 *J. CHEM PHYS* **113**: 10820.
[22] Marinho F A M and Stuermer M M 2000 *Proceedings of Geo-Denver*: 125.