Influence of Soil Cracking on the Soil-Water Characteristic Curve of Clay Soil

M.M. Abbaszadeh, S.L. Houston, C.E. Zapata

Abstract. The hydraulic conductivity for unsaturated soil conditions is more difficult to estimate than for the saturated condition. In addition, as the soil transitions from intact to cracked, the difficulty in estimating the unsaturated hydraulic conductivity increases. One critical step in the determination of unsaturated flow hydraulic conductivity is the evaluation of the Soil-Water Characteristic Curve (SWCC). In this paper, a series of laboratory studies of direct measurements of cracked soil SWCCs is presented, including challenges associated with the control of very low suction levels associated with crack dewatering. An oedometer-type SWCC apparatus, capable of suction and net normal stress control, and volume change measurement, was used in these experimental studies. It is common that SWCCs are comprised of matric suction values below about 1500 kPa, and total suction values for suctions higher than about 1500 kPa (Fredlund et al., 2012). In this study, all measured or controlled suction values were less than 1500 kPa and obtained using the axis translation change measurement, was used in these experimental studies. It is common that SWCCs are comprised of matric suction values below about 1500 kPa, and total suction values for suctions higher than about 1500 kPa (Fredlund et al., 2012). In this study, all measured or controlled suction values were less than 1500 kPa and obtained using the axis translation method, and the curve in the higher suction range was projected by forcing the SWCC through 10^6 kPa for completely dried conditions (Fredlund et al., 2012). Volume change corrections were made to the reported volumetric water contents, which is of particular importance when the soil under consideration undergoes volume change in response to wetting or drying. A technique for the determination of the SWCC for cracked clay soils is presented. Test results validated the fact that the SWCC of a cracked soil can be represented by a bimodal function due to the Air Entry Value (AEV) of the cracks being much lower than the AEV of the soil matrix. It was also found that differences between the SWCC for cracked and intact soil appears only in the very low suction range.

Keywords: SWCC, cracked soil, unsaturated soil mechanics, air entry value, bimodal behavior, laboratory testing.

1. Introduction

The problem of estimating ground surface flux is one of great interdisciplinary interest, and the literature is replete with related articles from disciplines including soil science, geotechnical engineering, environmental ecology, hydrology, water resources, forestry, landscape architecture, geology, and environmental engineering. Surface flux is related to complex interrelationships between the soil and atmosphere, and soil anomalies such as cracks must be appropriately considered in any surface flux modeling process. However, there is little data available for the assessment of the effect of cracks on unsaturated flow related properties, such as the Soil-Water Characteristic Curve (SWCC) and the hydraulic conductivity function.

The properties and behavior of unsaturated cracked soil are potentially different from those of intact soil, and the absence of direct test data on cracked soil properties leads to uncertainty in the evaluation of surface flux conditions. It is important to develop an improved understanding of cracked soil properties because seasonal cracking of soil results in poor estimates of runoff and infiltration due to the changing soil storage conditions (Arnold et al., 2005).

The primary focus of this paper is to present laboratory data for cracked and intact clay SWCCs. An oedometer pressure plate device was used so that the overall volume change of the soil specimens could be tracked during the experiment. The laboratory SWCC data presented in this paper also contributes to the previously proposed idea of use of bimodal characteristic of fractured soils and gap graded granular soils (Zhang & Fredlund, 2004; Zhang & Chen, 2005; Fredlund et al., 2010a; Booth et al., 2013). In this study, a bimodal SWCC is obtained for a cracked expansive clay. Previously developed models for bimodal SWCCs were for gap-graded granular soils and for fractured rock (Zhang & Fredlund, 2004; Zhang & Chen, 2005). For gap graded granular soils the assumption in modeling is that the volume of the soil (including the relative porosity of both the finer and coarser fractions) does not change. Similarly, in the study of fractured rock, the volume of the fractures and the volume of the intact rock matrix can reasonably be assumed to remain constant. Booth et al., 2013, applied similar no-volume-change assumptions to London clay and showed promising results. However, the laboratory results of this study are for a moderately expansive clay, and provide much needed data for consideration of the effect of soil cracks on unsaturated soil property models for the case where the volume change in the cracks, and the soil matrix itself, may not be negligible.
2. Background

A soil water characteristic curve (SWCC), also known as water retention curve, represents the relationship between soil suction and the amount of water that the soil can hold at that particular suction, which can be expressed in terms of moisture content or degree of saturation. Relationships for estimating the hydraulic conductivity function for unsaturated soils based on the SWCC are commonly used, but have not been thoroughly evaluated for cracked soils through laboratory testing. The measurement of the hydraulic conductivity for an unsaturated soil is extremely difficult, and the existence of cracks further complicates the measurement. For this reason, the SWCC has been used to predict the hydraulic conductivity of a cracked material (Peters & Klavetter, 1988; Mallant et al., 1997; Köhne et al., 2002; Liu et al., 2004; Zhang & Fredlund, 2004; Li et al., 2011). Thus, one challenge for predicting the hydraulic conductivity of cracked soil is determining the SWCC for such soils. Once the SWCC is established, it is likely that one of several existing predictive models can be used to estimate the unsaturated hydraulic conductivity function for a cracked soil.

Few researchers have attempted to directly measure the SWCC for cracked materials, although some researchers have studied cracked clay SWCCs. Among those, Chertkov & Ravina (2000) studied the shrinking–swelling behavior of clay including a network of capillaries to represent cracks in the soil. The SWCC for the cracked soil was determined by modeling, rather than through laboratory testing; the models used incorporated the total crack volume and the volume of water-filled cracks, and the van Genuchten-Mualem model for estimating the unsaturated hydraulic conductivity function (van Genuchten, 1980). In other modeling efforts, Liu & Bodvarsson (2001) studied the use of the van Genuchten (1980) and Brooks & Cory (1964) SWCC models for the hydraulic conductivity of a fractured rock.

Zhang & Fredlund (2004) discussed that a fractured rock will produce a bimodal SWCC with a matrix phase and a fracture phase. The Soil-Water Characteristic Curve of the fractured rock was presented as the sum of the effects of the two phases, weighted according to their respective porosities. The combined matrix and fracture medium was treated as a continuum, with the same suction applied to the combined material and to the individual fracture and matrix phases. A computed Soil-Water Characteristic Curve for the rock matrix, the fractures, and the entire fractured rock mass is shown in Fig. 1 (Modified from Zhang & Fredlund, 2004). The first AEV belongs to the fractured media and the second AEV belongs to the intact (non-fractured) media. Taking a similar continuum approach to cracked soils, the Soil-Water Characteristic Curve of a cracked clay might be expected to take on a bimodal character. Several mathematical models for the SWCC are available that allow for a bi-modal SWCC representation of the SWCC (Durner, 1994; Burger & Shackelford, 2001; Gitirana & Fredlund, 2004; Zhang & Chen, 2005), however none of these take into consideration volume change of the cracks and the intact matrix.

Fredlund et al. (2010b) provided numerical modeling results for a slab on ground foundation on expansive soils, with the cracked clays near the ground surface modeled using a bimodal SWCC, such as that shown in Fig. 1. Booth et al. (2013) showed that using bimodal SWCC and hydraulic conductivity function in numerical modeling of the hydrology of a cracked soil results in more accurate predictions of the matric suction. However, no supporting laboratory data was available for validation of the bimodal SWCC models used, and as previously discussed, available bimodal models do not consider volume change, either quantitatively or through direct measurement.

A capillary model, based on crack geometry, has been used to determine the air-entry value corresponding to the desaturation of the cracks in clays, along with supporting laboratory data (Abbaszadeh et al., 2010). Li et al. (2011) employed the same theoretical capillary-model based relationship proposed by Abbaszadeh et al. (2010), and reported 11.8-millimeters (mm) as the maximum crack size for which the capillary model is applicable. Li et al. (2011) also suggested a method to predict the SWCC and permeability function for cracked soil considering crack volume change during drying-wetting cycles. The authors argued that the crack development can be explained by a relationship between the matric suction and crack porosity differences. Li et al. (2011) present a three-dimensional SWCC model wherein the bimodal behavior of the cracked soil appears as the crack porosity increases. The method used by Li et al. requires that the relationship between the crack porosity and suction be established. The authors suggest the use of a linear relationship, which has not been demonstrated across a wide range of soil types and suction values or through direct measurement. Clearly, there is a need for

![Figure 1 - Typical Bimodal SWCC for Cracked Soil (Modified from Zhang & Fredlund, 2004).](image)
further research on the behavior of cracked clays for which the matrix and the crack volume change with change in soil suction. The data presented in this paper represents a start on development of a database required for refinement of SWCC models for cracked expansive clays.

3. Material and Laboratory Testing Program

Five SWCC tests were conducted for intact soil entailing both drying (3 tests) and wetting (2 tests) paths. Replicate tests were performed so that average curves could be developed for comparison of cracked to intact soils. The averaging of data helps to remove some of the effects of natural sample variability. In addition, six SWCC tests were conducted for cracked soil, four of which followed the drying path and two followed the wetting path. These experiments were conducted under two confining stress levels: (1) essentially zero, and (2) 20 kPa net normal stresses. When zero normal stress was desired, a token load of about 1 to 3 kPa was applied in order to maintain the specimen in contact with the ceramic stone. The net normal stress was varied to simulate very near-surface soils and soils of depth of approximately 1-meter which is a common depth of mitigation for expansive clay profiles. An oedometer-type pressure plate device (Perez-Garcia et al., 2008) was used to obtain the SWCC and the hanging manometer technique was used to apply very low matric suctions required to capture the AEV of the crack. The oedometer-type pressure plate device is essentially a pressure plate cell that is outfitted with a loading piston to apply a net normal stress to a specimen that is restrained from radial deformation by a confining ring. A Linear Variable Displacement Transducer (LVDT) can be attached to the loading piston so that vertical deformations are measured as suction is changed. Suction values are controlled by the axis translation method. The hanging manometer was required to apply a very low suction value to the specimen because pressures lower than about 5 kPa cannot be consistently maintained with traditional pressure regulators.

3.1. Soil characteristics

The soil used in this study was obtained from a site near San Diego, California, and is named San Diego Soil in this paper. The index properties of the test soil are presented in Table 1.

3.2. Sample preparation

Identical companion specimens were compacted in three equal layers inside brass rings of 25-mm in height and 61-mm in diameter. The compaction condition corresponded to 98% of Standard Proctor maximum dry density (1.74 g/cm³) and optimum water content (18%). Prior to sample preparation, the soil was first passed through a U.S. #4 sieve (4.76-mm), and then enough water was added to reach to the optimum water content of 18%. The soil was then sealed in plastic bags for at least 48 h before starting the sample compaction. This process allowed the water to equilibrate throughout the soil so that the moisture would be distributed more uniformly in the test specimen. After compaction of each layer was completed and just before compacting the next layer, the top surface of the preceding layer was scarified using a sharp tool. The scarification created a better contact between the two layers and produced a more uniform compacted specimen. During the compaction of the last (third) layer, care was taken not to overcompact the specimen. Any minor adjustments required in the computation of specimen dry density were made. In spite of careful control of the method of specimen preparation, some sample variability will exist. For this reason, duplicate tests were performed so that average SWCC curves of cracked and intact specimens could be compared.

To manufacture the cracked specimens, after the sample was compacted inside the brass ring, soil cracks were introduced into the soil matrix using an aluminum shim.

Table 1 - Characteristics for San Diego soil.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity (ASTM D854-06)</td>
<td>2.72</td>
</tr>
<tr>
<td>Particle Size Analysis (ASTM D422-63 (Reapproved 2007))</td>
<td>% Sand 63</td>
</tr>
<tr>
<td>% Silt 30</td>
<td></td>
</tr>
<tr>
<td>% Clay 7</td>
<td></td>
</tr>
<tr>
<td>Unified Soil Classification System (ASTM D2487-06)</td>
<td>SC</td>
</tr>
<tr>
<td>Atterberg Limits (ASTM D4318-05)</td>
<td>LL 41</td>
</tr>
<tr>
<td>PL 17</td>
<td></td>
</tr>
<tr>
<td>PI 24</td>
<td></td>
</tr>
<tr>
<td>Standard Proctor Test (ASTM D698-07)</td>
<td>Optimum water content 18%</td>
</tr>
<tr>
<td>Maximum Dry Density (g/cm³)</td>
<td>1.74</td>
</tr>
<tr>
<td>Expansion Index (ASTM D4829-08)</td>
<td>114</td>
</tr>
</tbody>
</table>
The cracks were approximately 1-mm wide and 10-mm deep. The total volume of cracks was measured, as a percentage of the overall specimen volume, to be about 3 to 5%. The volume of cracks was decided based on the results of a companion study that was conducted with the same soil to evaluate the extent of natural crack formation due to the drying and wetting cycles. From this study, it was concluded that the total volume of cracks in the field was about 3-5% of the overall volume of the clay (Abbaszadeh, 2011).

Based on a thorough literature review, a crack pattern consistent with field crack observations was selected. Due to the extremely complex process of soil cracking, it is almost impossible to generalize or choose one crack pattern which forms in all desiccated soils. However, it was concluded that a hexagon pattern was the most appropriate pattern because it was relatively consistent with actual crack patterns observed in near-surface clays. This finding is also consistent with the conclusion of Konrad & Ayad (1997), who suggested a polygon crack pattern develops during different stages of cracking (Fig. 2), as well as the observed field cracks reported by Longwell (1928) as shown in Fig. 3.

There are several uncertainties associated with crack behavior in response to wetting and drying (i.e. suction change). For example, the extent of crack healing during wetting and the opening of cracks during drying are not entirely predictable. To exhibit the SWCC bimodal behavior, the cracks must be initially fully saturated, but must be wide enough so they will not heal completely, due to swelling of the soil, upon saturation. Further, the cracks must be small enough in width to prevent desaturation by gravity drainage. The size of cracks selected for laboratory study must also be consistent with cracks that form in the field. Based on laboratory observations on the test soil of this study, and also based on literature review related to the size of cracks in the field, an appropriate crack width for this study was determined to be about 1 to 1.5-mm. This range of crack width falls within the range of crack widths observed in the field (Ruy et al., 1999), and corresponds to a crack size that does not drain under gravity alone or fully close due to swelling upon wetting. For the test soil, cracks of 1.1 to 1.3-mm width were observed to shrink to about 0.7 to 0.8-mm width after specimen saturation. Figure 4 shows an example of a cracked sample at the end of the specimen preparation process. The crack widths varied from 1.1 to 1.3-mm in this study due to difficulties in making exactly identical cracks in the soil specimens.

3.3. Test procedure

To obtain the drying path SWCC, the sample was saturated by submerging the specimen inside a water tray, and both ends of the soil sample were covered by one filter paper directly in contact with the soil surface, followed by a porous stone in contact with the filter paper. This process prevented loss of soil during the swelling and saturation phase and also facilitated the infiltration of water through the porous stones. For the wetting path SWCC, the specimen was air-dried until it reached the water content range corresponding to the desired initial suction for the test; equilibration time was allowed after the specimen reached the initial (starting) value of soil suction for the test.
The axis translation technique was used to apply various levels of matric suction for SWCC determination. The hanging manometer technique was used, in accordance with ASTM D6836-02, to apply very low suction pressures. The hanging manometer technique involves creating a negative pore water pressure \((u_w)\) at the base of the specimen, while keeping the pore air pressure \((u_a)\) constant and equal to atmospheric pressure inside of the oedometer pressure plate device. This will result in an applied matric suction equal to the value of the negative pore water pressure imposed by the hanging manometer by positioning the water level in the tube at a lower elevation than the based on the specimen. For example, to apply 0.1 kPa matric suction, the elevation difference between the water level in the tubes and the cell base (where the sample rests) should be equal to 1.0 cm. Figure 5 schematically illustrates the hanging manometer technique.

One of the major difficulties associated with setting a fixed low suction value is the continuous elevation change of the water that occurs inside the tube as the specimen seeks equilibration with the target applied suction. Thus, the applied suction changes as the water elevation in the tube is allowed to change. To maintain the small target applied suction constant, close monitoring is required (if overflow of excess water from the tube is not allowed or if water tends to move into the specimen). This monitoring can be tedious in consideration of the lengthy test times required for equilibration for highly plastic soils.

Another issue which makes testing at very low suctions challenging is that it is not possible to fully saturate the intact portion of the specimen because back-pressure saturation techniques are not easily employed in pressure plate testing. In the laboratory tests of this study, it was observed that although initial crack dewatering typically occurred rather quickly, under very low suctions some samples started to absorb water after the initial crack dewatering process. It is believed that water uptake by the specimen at very low suctions and after crack dewatering, is a result of the incomplete saturation of the intact matrix of the soil, in spite of the cracks having been filled with water and the specimen having been submerged for an extensive time during the pre-test saturation of the specimen. In other words, at early stages of the test under very low applied matric suction, when the cracks are still full of water, the cracks in the soil dominate the behavior; however, at values of suction greater than that required for crack dewatering, the intact soil matrix (not 100% saturated, and having some remaining matric suction) dominates the response. Table 2 summarizes conditions for the SWCC tests that were conducted for cracked specimens.

Although volume change measurements were made in the course of SWCC measurements for this study, the volume change behavior of the soil was not explicitly ad-

**Table 2** - Test characteristics for cracked and intact specimens – San Diego soil.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test type</th>
<th>Applied suction* (kPa)</th>
<th>Applied normal stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact-01</td>
<td>Drying</td>
<td>10, 90, 200, 450, 1240</td>
<td>0</td>
</tr>
<tr>
<td>Intact-02</td>
<td>Drying</td>
<td>25, 100, 200, 450, 1240</td>
<td>0</td>
</tr>
<tr>
<td>Intact-03</td>
<td>Drying</td>
<td>8, 50, 265, 480, 1240</td>
<td>0</td>
</tr>
<tr>
<td>Intact-04</td>
<td>Wetting</td>
<td>1320, 320, 140, 35</td>
<td>0</td>
</tr>
<tr>
<td>Intact-05</td>
<td>Wetting</td>
<td>1320, 320, 140, 35</td>
<td>20</td>
</tr>
<tr>
<td>Cracked-01</td>
<td>Drying</td>
<td>0.1, 1.0, 25, 90, 200, 485, 1240</td>
<td>0</td>
</tr>
<tr>
<td>Cracked-02</td>
<td>Drying</td>
<td>0.075, 1.035, 8.0, 30, 90, 345, 1240</td>
<td>0</td>
</tr>
<tr>
<td>Cracked-03</td>
<td>Drying</td>
<td>0.075, 0.555, 1.46, 10, 25, 90, 565, 1240</td>
<td>0</td>
</tr>
<tr>
<td>Cracked-04</td>
<td>Drying</td>
<td>0.09, 0.78, 10, 45, 100, 200, 425, 1260</td>
<td>0</td>
</tr>
<tr>
<td>Cracked-05</td>
<td>Wetting</td>
<td>1255, 290, 100, 35</td>
<td>0</td>
</tr>
<tr>
<td>Cracked-06</td>
<td>Wetting</td>
<td>1255, 290, 100, 36</td>
<td>20</td>
</tr>
</tbody>
</table>

* Suction values less than 5 kPa were obtained using a hanging manometer device.
dressed here; nonetheless, volume change of the cracks did occur during both wetting and drying, and volume change of the clay matrix also occurred, and the impact of volume change was captured phenomenologically in the test data. Hence, the cracks did not have a constant porosity throughout the test and the soil matrix did not have a constant porosity, but the volume changes of the specimen matrix and cracks are reflected in the directly measured SWCC data (and associated directly measured AEV). In general, volume change should be expected when soil suction is changed, particularly for swelling, high plasticity soils. In expansive clays, the presence of cracks provides a cavity for expansion that reduces vertical heave and swell pressure. Abbaszadeh (2011), provides data, including data on the clay of this present study, showing that cracks decrease swell pressure and heave of expansive clays.

4. Results

A total of five SWCC experiments were conducted for intact specimens. Three of these tests followed drying paths and the other two followed wetting paths. The SWCC results for the drying and wetting tests on intact specimens of San Diego soil are presented in Fig. 6. The values of volumetric water content at the lowest plotted suction value (0.01 kPa) were estimated to be equal to the directly calculated values for the specimens at zero suction. This was done due to the necessity of plotting suction on a log scale.

A total of six SWCC tests were conducted on cracked specimens prepared by compaction of San Diego soil. Four of these tests followed drying paths and the other two followed wetting paths. The SWCC test results of the cracked specimens are presented in Fig. 7, including both wetting and drying paths. Although it is difficult to draw a single curve representing the entire data set, the data shown in Fig. 7 demonstrates the bimodal behavior of the SWCC for the cracked samples.

Quantification of a bimodal SWCC for cracked soil is difficult to accomplish for a variety of reasons, not the least of which is the difficulty in controlling the required extremely small suctions for observing the AEV associated with crack dewatering. Nevertheless, it was possible to bracket the AEV on a test specimen. The specimen was prepared with cracks of an initial width, \( w_c \), of about 1.1 to 1.3-mm and a depth, \( h_c \), of about 10-mm. After wetting the specimen to essentially saturation, a slight closing of the cracks to a width of about 0.75-mm was observed. A value of \( u_a - u_w \) of 0.075 kPa was applied in the oedometer-type SWCC cell and the specimen was allowed to equilibrate. It was directly observed, by disassembly of the pressure plate cell, that a few of the cracks showed signs of starting to

![Figure 6](image_url)
dewater at 0.075 kPa suction (Cracked-02 and Cracked-03 specimens). Direct examination of the cracks was also performed after equilibration at 0.09 to 0.1 kPa suction (Cracked-01 and Cracked-04 specimens), and the cracks were found to be more or less completely dewatered. Thus, the $u_a - u_w$ causing initiation of dewatering was somewhere between 0.075 kPa and 0.1 kPa, experimentally, and perhaps closer to 0.07 kPa. This is consistent with the theoretical calculations of Abbaszadeh et al. (2010) wherein a capillary model was used to estimate the air entry value of cracks, and cracks of 0.75-mm width were found to dewater at a value of $u_a - u_w$ of about 0.07 kPa.

4.1. Effect of overburden pressure

The effect of overburden stress, for the limited stress range considered in this study, was negligible. An overburden stress of 20 kPa, the highest stress considered in this study, corresponds to approximately 1-meter depth. Many field cracks are observed to be of limited depth, such that an overburden stress of 20 kPa is reasonable for the SC soil of this study. However, field cracking and weathering of high plasticity clays has been observed to depths of approximately 10-meter. The tests in this study were performed using hanging dead weights to achieve net normal stress, and therefore higher values of net normal stress were not practical. Therefore, further testing at higher overburden stress is required to make definitive statements concerning the impact of net normal stress on the SWCC of cracked clay.

4.2. Comparing SWCCs for intact and cracked specimens

The purpose of performing SWCC tests for intact and cracked specimens was to evaluate the effect of soil cracking on the water retention properties of the expansive soil of this study. Figure 8 compares the best-fit (using all test results) SWCCs for intact and cracked specimens for the drying path. Averaged curves (i.e. curves obtained using all test specimen data) were used for making a better comparison between intact and cracked specimens due to the inevitable sample variability that occurs in specimen compaction and crack creation, as well as all other variables associated with the SWCC test procedure itself.

From Fig. 8, it can be concluded that the significant difference between the SWCC for cracked and intact soil is only at very low suction range. The cracked soil exhibits bimodal behavior which can be explained by the pore space disparity that the cracks create in the matrix structure of the soil. In other words, at very low suctions the cracks will dewater, but the much smaller voids in the intact soil matrix will not dewater. However, at higher suctions the SWCC of
the cracked soil is controlled by the intact matrix. Thus, after a certain matric suction range, the water storage capacity of the intact and cracked soils tend to merge.

The suction range at which the cracked and intact SWCC curves merge depends entirely on the crack dimensions. The fact that the cracked and intact clay SWCCs merge at very low values of matric suction (associated with the width of the crack), represents a significant finding for geotechnical engineering field applications because many unsaturated soils problems of a practical nature involve unsaturated conditions where the soil suction is much higher than the AEV of cracks typical of field conditions.

5. Summary and Conclusion

The effect of soil cracking on the SWCC of soil was investigated through laboratory testing. Both wetting and drying paths were studied. The effect of net normal stress on the SWCC test results was also considered. A hexagonal crack pattern was adopted for the cracked clay specimens as being a reasonable pattern for field conditions based on literature review.

The hanging manometer technique was implemented in order to apply and maintain very low matric suction required for capturing the AEV of the cracked samples. Experimental results showed that the SWCC for a cracked soil can be represented by a bimodal curve. However, the AEV of the cracks is very low, even for the relatively small crack widths considered in this laboratory study. Dewatering of larger field cracks would be expected to occur at extremely low suction values, and larger cracks may dewater under gravity alone. Because cracks dewatered at a very low AEV, the SWCCs of intact and cracked clays at suctions greater than the AEV of the cracks were found to be very similar (i.e. were found to essentially merge).

The net normal stress values applied during the measurement of SWCCs in this study corresponded to soil depths of 0 to 1-meter, and some additional testing at higher net normal stress values is recommended for future study. Further, the crack sizes studied in this research represent the lower range of crack width dimensions found in the field. Consequently, for field applications where the soil remains unsaturated, a cracked soil could rationally be modeled using the properties of the intact matrix, and ignoring the bimodal behavior at very low suction values. However, for field applications where the ground surface becomes saturated and extremely low suction to positive pore water pressures develop, the impact of cracks can, of course, be dramatic with regard to the amount of water entering the subsurface. Thus, it is critical to keep in mind that although the unsaturated soil SWCC for cracked and intact specimens is essentially the same over a wide range of suction values of interest for unsaturated soil mechanics problems, saturated flow properties of cracked and intact specimens are quite different.

The findings of this study provide support treating cracked soil as a continuum for unsaturated flow conditions, using lumped parameters for the cracked soil mass. This is because when the soil remains in an unsaturated state, the dominant flow of water is through the soil matrix, rather than through the cracks, which have been shown to dewater at very low suction values. However, for saturated-unsaturated flow problems, such as when the ground

![Figure 8 - Comparison between cracked and intact averaged SWCCs for San Diego soils.](image-url)
surface becomes saturated and positive pore water pressures develop, it is possible that the cracks within the soil are best modeled as discrete elements to avoid sharp discontinuities in the unsaturated soil property functions at the AEV of the cracks. Additional research on numerical modeling of flow through cracked soils is needed.

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References


