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Influence of cracks on soil water characteristic curve

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ABSTRACT: The soil water characteristic curve was determined for two cracked soils of Saskatchewan, Canada. Using high quality undisturbed field samples, both soils indicated bimodal curves comprising of two air entry values. The fissure AEV (associated with drainage through cracks) and the matrix AEV (related to seepage through soil matrix) were found to be 10 kPa and 300 kPa for the expansive clay in Regina and 5 kPa and 100 kPa for the cemented sandstone at Avonlea. The appropriate parameter on the ordinate for presenting the curve is water content for expansive soils and degree of saturation for erodible soils.

1 INTRODUCTION

The soil water characteristic curve (SWCC) is a continuous sigmoid function that correlates the presence of water with suction. This curve describes important features of soils when their saturation state is altered. Soils remain fully saturated with increasing suction up to the air entry value (AEV) when air starts to enter into pore spaces under capillarity. Thereafter, soils continuously lose water with increasing suction until the residual state. The remaining water is difficult to force out and complete soil desiccation requires a suction of 10^6 kPa. The curve comprises of three straight-line portions: a horizontal line from saturation to the AEV; a steep downward slope from the AEV to the residual state; and a flat downward slope from the residual state to the completely dry state. The curve shape is affected by the following soil properties: (i) grain sizes and soil microstructure that influences pore tortuousity; (ii) dry unit weight that is related to the total void space in a soil; and (iii) clay mineral types and amounts that dictate the amount of adsorbed water.

The above-mentioned SWCC works well for compacted clays and well-graded sandy soils. However, natural soils deviate from this conventional behavior owing to the presence of cracks that are primarily derived from over-consolidation and desiccation. This is particularly the case for surface soils where most construction activities take place. Theoretically, soil discontinuities affect the water flow pattern by encouraging the initial water migration through the cracks before the commencement of water movement through the pore system within the soil (Fredlund et al., 2010).

The surface sediments in southern Saskatchewan, Canada, are derived from extensive physical weathering (scraping, deposition, overburdening, and reworking of materials) by up to seven glacial advances and retreats (Christiansen & Sauer 2002). The last glaciation known as the Wisconsinan (23,000 years BP to 17,000 years BP) extended throughout the entire province. The up to 1000 m thick ice sheet started to retreat in the north-eastwardly direction around 17,000 years BP. According to Mollard et al. (1998), this process was completed around 8000 years BP when the essential features of the present landform emerged including moraines and eskers. Two local soils are of particular concern because of their problematic engineering features. The expansive clay in Regina shows large swell-shrink deformations whereas the cemented sandstone at Avonlea exhibits extensive slope stability issues. Both of these soil responses are due to changes in water availability that, in turn, are derived from periodic weather variations in a predominantly semi-arid climate. Because of the glacial overburden removal, both of these soils show hair-line discontinuities within the surface layer. Clearly, a glacial geology and a semi-arid climate govern the behavior of natural soils in this part of the Canadian prairies.

The main objective of this paper was to understand the water retention behavior of two natural soils possessing cracks, namely; Regina clay and Avonlea sandstone. The geotechnical index properties of the materials were determined for preliminary soil assessment. Likewise, the soil water characteristic curves were determined using high quality undisturbed samples collected as part of separate site investigation programs.

2 GEOTECHNICAL INDEX PROPERTIES

The geotechnical index properties were determined according to the ASTM test methods as follows: (i) field water content (w) by the Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D2216-05); (ii) field dry unit weight (γ_d) by the Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (D2937-10); (iii) specific gravity (G_s) by the Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (D854-10); (iv) liquid limit (w_l), plastic limit (w_p) and plasticity index (I_p) by the Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (D4318-10); and (v) grain size distribution by the Standard Test Method for Particle-Size Analysis of Soils (D422-63(2007)). The entire grain size distribution data is not given in this paper.

Table 1 provides a summary of the geotechnical index properties of the investigated soils. Despite a closely matching specific gravity, the Regina clay had a dry unit of 1.34 g/cm^3 and a void ratio of 1.05 whereas the Avonlea sandstone had a dry unit of 1.61 g/cm^3 and a void ratio of 0.7. This indicates the finer and fissured nature of the former deposit and the coarser and dense nature of the latter sediment. Furthermore, the two materials were found to be quite different from one another in terms of their water adsorption capacity. The Regina clay was characterized by a high liquid limit (83%) and plasticity index (53%) that is attributed to the presence of expansive clay minerals in the soil (Ito & Azam 2009). In contrast, the Avonlea sandstone exhibited a lower liquid limit (39%) and plasticity index (8%) because of the predominance of non-clay minerals such as quartz, calcite, and feldspar (Imumorin & Azam 2011). These observations correlated well with the clay size fraction that measured 66% and 13% for the two sediments, respectively. Based on the Unified Soil Classification System (USCS), the Regina clay was classified as CH (clay with high plasticity) whereas the Avonlea sandstone was classified as SM (silty sand).

Table 1. Summary of geotechnical index properties.

Property	Regina clay	Avonlea sandstone
Field Water Content, w (%)	31	5
Field Dry Unit Weight, γ_d (g/cm^3)	1.34	1.61
Specific Gravity, G_s	2.75	2.73
Field Void Ratio, e*	1.05	0.7
Field Degree of Saturation, S (%)†	81	20
Liquid Limit, w_l (%)	83	39
Plastic Limit, w_p (%)	30	31
Plasticity Index, I_p (%)	53	8
Clay Size Fraction, C (%)	66	13
USCS Symbol	CH	SM

* $e = (G_s \gamma_w/\gamma_d) - 1$

† $S = w\, G_s/e$

3 WATER RETENTION BEHAVIOR

The SWCC was determined according to the ASTM Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge (D6836-02(2008)e2) on 10 mm thick samples obtained from undisturbed cores. Predetermined suction values were applied using pressure plate/membrane extractors manufactured by Soil Moisture Equipment Inc. The porous plates and the cellulose membranes were submerged in distilled and de-aired water for 24 hours to expel air bubbles. Thereafter, the specimens along with the retaining ring were placed on their respective porous plate or cellulose membrane and allowed to saturate. Next, the excess water was removed and each plate or membrane was placed in the designated extractor. For each suction value, the expelled water from the samples was monitored in a graduated burette. When two consecutive readings nearly matched over a 24 hour period, the test was terminated and the sample water content was determined.

For Regina clay, test data were compared with estimations using a unimodal equation (Fredlund et al., 2000) that utilized the geotechnical index properties (w, G_s, and γ_d) and the best fit of the measured GSD data (Fredlund et al., 2002). Based on a physico-empirical approach, the computer software of SoilVision Systems Ltd. divided the GSD into uniform particle sizes, each size assigned an individual SWCC calculated from the database of measured SWCC, and all summed to develop the entire curve.

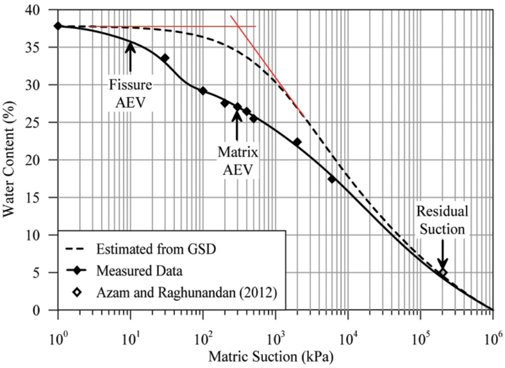

Figure 1. SWCC of Regina clay.

Figure 1 gives the SWCC of Regina clay. The estimated SWCC followed the typical theoretical trend. The full saturation water content equaling 38% remained constant up to the AEV of 300 kPa. Desaturation occurred at an increased rate between the AEV and the residual suction of 2000,000 kPa (at $w = 5\%$) and the curve finally joined the abscissa at 10^6 kPa under completely dry soil conditions.

The measured data fitted well to a bimodal distribution with two air entry values: a lower value (10 kPa) corresponding to drainage through fissures followed by a higher value (300 kPa) associated with seepage through the soil matrix. When the undisturbed samples were gradually desatuarted, air first entered into the fissures at low suction. Although these fissures are sealed due to hydration of expansive soils (Azam & Wilson 2006), numerous swell-shrink cycles over geologic time render these discontinuities to have much lower tensile strengths than the soil aggregates. This led to a quick drainage through these paths of least resistance. Subsequent application of suction affected the soil aggregates and eventually forced air to enter into the pore system of the aggregate. The matrix AEV matched the one obtained from GSD estimation because water movement through an aggregate is governed by the arrangement of individual particles. Furthermore, the downward SWCC shift of the undisturbed soil is attributed to its flocculated morphology in contrast to a dispersed fabric for the GSD sample (dispersion was ensured using sodium hexametaphosphate). The corresponding larger pores in the geologic samples were easy to dewater because of a reduced capillarity. This resulted in a greater water content reduction at the same matric suction. Beyond the residual state, the two curves converged as the water present in both of the samples was electrochemically attached to the clay surfaces. The 5% residual water corresponded to the adsorbed water, as confirmed through thermogravimetric analysis (data not given in this paper).

The SWCC given in the form of water content versus matric suction is the best representation for expansive soils. The measured value of gravimetric water content is independent of volume increase due to sample saturation. The use of the degree of saturation on the ordinate is not appropriate because it depends on void ratio. Furthermore, the definition of the degree of saturation for fissured expansive soils is not straight forward. Since such soils consist of discontinuities and soil aggregates, the calculated degree of saturation pertains to an average value for the entire soil mass. A more accurate approach for this calculation is to consider only the soil aggregates as saturated (up to the matrix AEV) and the fissures as air filled cracks. This is close to an equilibrium field microstructure that allows alternate swelling and shrinkage (Ito & Azam 2010). In this approach, the change of water volume in the soil mass equates to the volume change of the soil aggregates and that of the cracks. Gens & Alonso (1992) explained the two levels of soil structure in their framework as follows: the microstructure is governed by physicochemical interactions between the expansive clay minerals thereby forming aggregates whereas the macrostructure includes both the aggregates and the fissures.

Figure 2 presents the SWCC of Avonlea sandstone. Once again, the measured data fitted well to a bimodal distribution with two air entry values: a lower value (5 kPa) corresponding to drainage through cracks followed by a higher value (100 kPa) associated with flow through the soil matrix. When the field samples were progressively desaturated, air first entered into the discontinuities at low suction. Material erosion and dissolution during water flow enlarged these features thereby resulting in a lower fissure AEV compared to that of Regina clay. The fissures originate from geologic overburden removal and grow over time under the harsh climate prevalent in the area. Seasonal variations in water availability (snow melt in spring and rainfall in summer) and water deficiency (low rainfall and freezing in fall and winter) result in physical and chemical weathering of the deposit at Avonlea (Imumorin & Azam 2011). The associated reduction in grain sizes precludes the use of GSD for SWCC estimation. Furthermore, the finer particles get trapped in the relatively bigger soil pores left behind by the coarser particles and impart dual porosity to sandstone. Water flow through the newly formed smaller pores result in a high matrix AEV, albeit three times lower than that of Regina clay. Finally, the residual suction was found to be only 1200 kPa at $S = 15\%$. The low matrix AEV and residual suction are attributed to the low clay content of the sandstone.

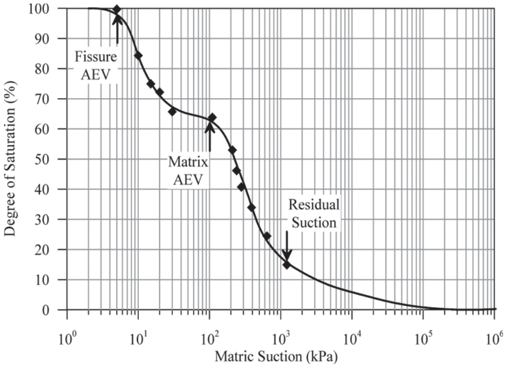

Figure 2. SWCC of Avonlea sandstone.

The SWCC in Figure 2 is given in the form of degree of saturation versus matric suction. This is the most suitable parameter for erodible soils exhibiting dual porosity because of its direct applicability to field conditions. In this representation, the SWCC pertains to the intact soil for which the degree of saturation can be calculated with reasonable accuracy because soil volume change is negligible. The commonly observed mass wasting due to erosion and dissolution in the field is different from changes in void ratio that are calculated using the three phase soil-water-air system.

4 SUMMARY AND CONCLUSIONS

The water retention behavior of natural soils possessing cracks is different from that of compacted soils or well-graded sandy soils. This is particularly true for swelling soils and erodible soils of southern Saskatchewan, Canada. Glacial geology and harsh climate govern the SWCC of the expansive clay in Regina and the cemented sandstone at Avonlea. The removal of glacial overburden has resulted in the development of hair-line discontinuities within the surface layer of these sediments. Seasonal weather variations lead to swelling and shrinkage in the clay and erosion and dissolution in the sandstone. The overall influence of geology and climate on the behavior of these two natural soils was investigated. The main conclusions of this research are summarized as follows:

- The SWCC for cracked soils is characterized by a bimodal distribution with two air entry values: a lower value corresponding to drainage through fissures followed by a higher value associated with seepage through the soil matrix.
- The fissure AEV and the matrix AEV, obtained by using high quality undisturbed field samples, were found to be 10 kPa and 300 kPa for Regina expansive clay and 5 kPa and 100 kPa for Avonlea cemented sandstone.
- The most appropriate way of presenting the SWCC of expansive soils is to use water content versus matric suction because the measured gravimetric water content is independent of volume increase due to sample saturation.
- The best way to understand field behavior of erodible soils with dual porosity is to plot the SWCC in the form of degree of saturation versus matric suction because of negligible volume changes in such soils.

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