Combination of Shrinkage Curve and Soil-Water Characteristic Curves for Soils that Undergo Volume Change as Soil Suction is Increased

Combinaison des courbes de retrait et des courbes des propriétés hydriques des sols pour les sols subissant un changement de volume avec une augmentation de la succion

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ABSTRACT: The soil-water characteristic curve, SWCC, is commonly used for the estimation of unsaturated soil property functions, USPF, in geotechnical engineering practice. The indiscriminate usage of the estimation techniques for unsaturated soil property functions can lead to erroneous analytical results and poor engineering judgment. Essentially all estimation procedures for unsaturated soil property functions, USPFs, make the assumption that the soil will not undergo volume change as soil suction is increased. The evaluation of the correct air-entry value has a significant effect on the estimation of subsequent USPFs. This paper describes how the SWCC laboratory results can be properly interpreted with the assistance of a shrinkage curve. Laboratory data sets are then used to illustrate how the test data should be interpreted for high volume change soils.

RÉSUMÉ : La courbe des propriétés hydriques des sols, SWCC, est communément utilisée afin d'estimer les fonctions des propriétés des sols non saturés, USPF, en géotechnique. L'usage abusif des techniques d'estimation des fonctions des propriétés des sols non saturés peut mener à des résultats analytiques erronés et à un mauvais jugement au point de vue ingénierie. Toutes les procédures d'estimation pour les fonctions des propriétés des sols non saturés, USPF, font l'hypothèse que le sol ne subira aucun changement de volume avec une augmentation de la succion. L'évaluation d'une valeur d'entrée d'air correcte a un effet significatif sur l'estimation de subséquents USPF. Cet article décrit comment les résultats de laboratoire des SWCC peuvent être correctement interprétés avec l'utilisation d'une courbe de retrait. Des résultats d'essais enlaboratoire sont alors utilisés pour illustrer comment les données d'un essai doivent être interprétées pour des sols subissant d'importants changements de volumes.

KEYWORDS: soil-water characteristic curves, shrinkage curve, volume change, soil suction, unsaturated soil property functions.

1 INTRODUCTION

The soil-water characteristic curve, SWCC, provides vital information for applying unsaturated soil mechanics in engineering practice. Much of the information regarding the use of SWCC originated in soil physics and agriculture-related disciplines. With time, information regarding the use of the SWCC has been embraced for geotechnical engineering applications (Fredlund, 2002; Fredlund and Rahardjo, 1993).

A common difficulty arises when large volume changes occur in the soil as soil suction is increased. Sludge material and slurry material may be deposited at water contents above the liquid limit of the material. The material is deposited in ponds and allowed to dry in order to increase its shear strength. The geotechnical engineer may be called upon to undertake numerical modeling simulations of the drying process.

2 SIGMOIDAL EQUATIONS FOR SWCCS

There are several sigmoidal type equations that have been proposed to mathematically describe the water content versus soil suction relationship (e.g., van Genuchten, 1980; Fredlund and Xing, 1994). The S-shaped sigmoidal equations have the appearance of being able to fit SWCC data regardless of the measure that is used to represent the amount of water in the soil (e.g., gravimetric water content, volumetric water content, or degree of saturation). The Fredlund and Xing, (FX), (1994) SWCC equation can be used to illustrate the usage of a sigmoidal equation for various designations of water content. The FX (1994) equation uses a correction factor that allows all SWCCs to go to zero water content as soil suction goes to 1,000,000 kPa. The FX (1994) equation is first written in terms of gravimetric water content and can then be used to best-fit the SWCC.

$$w(\psi) = w_s\left[1 - \frac{\ln\left(1+\psi/\psi_r\right)}{\ln\left(1+10^6/\psi_r\right)}\right]\left[\frac{1}{\left[\ln\left[\exp(1)+\left(\psi/a_f\right)^{n_f}\right]\right]^{m_f}}\right] \quad (1)$$

where: $w(\psi)$ = gravimetric water content at any specified suction, ψ; w_s = saturated gravimetric water content; ; ψ_r = residual soil suction; a_f, n_f, and m_f = the fitting parameters for the SWCC equation. Equation 1 is written for the gravimetric water content designation; however, the equation could also be best-fit volumetric water content or degree of saturation versus soil suction. The gravimetric water content SWCC can be used in conjunction with a shrinkage curve to more accurately interpret the parameters required for the estimation of unsaturated soil property functions.

The degree of saturation versus soil suction can be computed by combining Eq. 1 with the shrinkage curve data. The volumetric water content versus soil suction SWCC is also required to obtain the water storage coefficient for the soil. The volumetric water content must be related to the instantaneous overall volume of the soil mass in order to obtain the correct value for numerical modeling purposes. Volume change of the overall soil specimen can be taken into consideration if a "shrinkage curve" is measured. The shrinkage curve is generally measured under conditions of zero net normal stress.

3 USE OF A SHRINKAGE CURVE

The entire shrinkage curve, (i.e., the plot of total volume (or void ratio) versus gravimetric water content), from an initially saturated soil condition to completely oven-dry conditions is of value for the interpretation of SWCC data. As saturated clay soil dries, a point is reached where the soil starts to desaturate. Upon further drying, another point is reached where the soil dries without significant further change in overall volume. The corresponding gravimetric water content appears to be close to residual soil suction.

The shrinkage curve can be experimentally measured from initial high water content conditions to completely dry conditions. A digital micrometer can be used for the measurement of the volume at various stages of drying as shown in Figure 1. Brass rings can be used to contain the soil specimens (i.e., the rings have no bottom). The rings with the soil are placed onto wax paper and dried through evaporation. The dimensions of the soil specimens are appropriately selected such that cracking of the soil is unlikely to occur during the drying process. The initial dimensions selected for the shrinkage curve specimens used in this study were a diameter of 3.7 cm and a thickness of 1.2 cm.

The mass and volume of each soil specimen can be measured once or twice per day. Four to six measurements of the diameter and thickness of the specimen were made at differing locations on the specimens. It has been observed that as the specimen diameter begins to decrease, with the specimen pulling away from the brass ring and the rate of evaporation increases.

The "shrinkage curve" can be best-fit using the hyperbolic curve proposed by Fredlund et al., (1996, 2002). The equation has parameters with physical meaning and is of the following form:

$$e(w) = a_{sh}\left[\left(w/b_{sh}\right)^{c_{sh}}+1\right]^{1/c_{sh}} \tag{2}$$

where: a_{sh} = the minimum void ratio (e_{min}), b_{sh} = slope of the line of tangency, (e.g., = e / w when drying from saturated conditions), c_{sh} = curvature of the shrink-age curve, w = gravimetric water content, G_s = specific gravity and S = degree of saturation.

Once the minimum void ratio of the soil is known, it is possible to estimate the remaining parameters required for the designation of the shrinkage curve. The minimum void ratio the soil can attain is defined by the variable, a_{sh}. The b_{sh} parameter provides the remaining shape of the shrinkage curve. The curvature of the shrinkage curve commences around the point of desaturation is controlled by the c_{sh} parameter.

4 DEGREE OF SATURATION

The degree of saturation of the soil can be written as a function of gravimetric water content (as a function of suction) and void ratio (as a function of gravimetric water content).

$$S(w) = \frac{w(\psi)G_s}{e(w)} \tag{3}$$

The degree of saturation can be further written as a function of gravimetric water content and the equation for the shrinkage curve, both which are functions of soil suction.

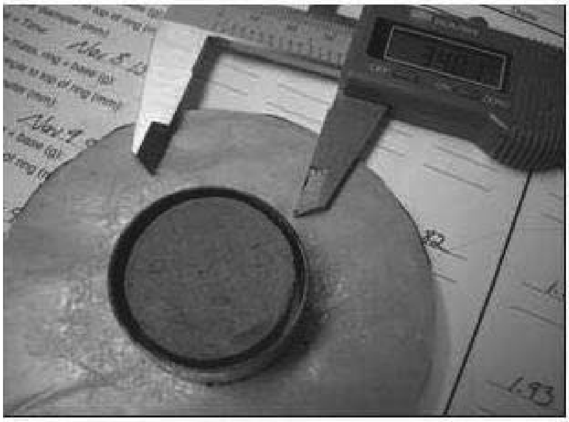

Figure 1. Digital micrometer used for the measurement of the diameter and thickness of shrinkage specimens.

$$S(w) = \frac{w\,G_s}{a_{sh}\left[\left(w/b_{sh}\right)^{c_{sh}}+1\right]^{1/c_{sh}}} \tag{4}$$

The degree of saturation SWCC can also be written as a function of soil suction and the fitting parameters for the gravimetric water content SWCC and the shrinkage curve.

$$S(\psi) = \frac{w_s C(\psi) G_s}{a_{sh}\ D\left[\ln\left[\exp(1)+\left(\psi/a_f\right)^{n_f}\right]\right]^{m_f}} \tag{5}$$

where:

$$D = \left[\left(\frac{w_s C(\psi)}{b_{sh}\left[\ln\left[\exp(1)+\left(\psi/a_f\right)^{n_f}\right]\right]^{m_f}}\right)^{c_{sh}}+1\right]^{\frac{1}{c_{sh}}}$$

5 RESULTS ON REGINA CLAY

The effect of volume change on the interpretation of SWCCs was studied for Regina clay. The laboratory test results are presented and show significance of overall volume change on the interpretation of the SWCC.

The air-entry value, AEV, for Regina clay was determined from the degree of saturation SWCC. The AEV remained constant around 2500 kPa. An empirical construction procedure involving the intersection of two straight lines on a semi-log plot was used to determine a single number associated with the break in curvature.

Regina clay had a liquid limit of 75%, a plastic limit of 25% and contained 50% clay size particles. The material was prepared as slurry and then subjected to various consolidation pressures under one-dimensional loading. After the applied load was removed, the soil specimens were subjected to various applied matric suction values. High suction values were applied through equalization in a constant relative humidity environment. The study then assumed that the air-entry value determined from the degree of saturation SWCC remained a constant value. (This was confirmed by the experimental results). The "*w Break*" on the gravimetric water content SWCCs were then compared to the air-entry value for the soil. The ratio of AEV to *w Break* was used as a measure of the effect of volume change on the interpretation of the correct air-entry value for the soil.

Shrinkage curves and soil-water characteristic curves were measured on Regina clay. Slurry Regina clay was prepared at a gravimetric water content slightly above its liquid limit. The shrinkage curve results are presented in Figure 2. The void ratio of Regina clay decreases as water evaporates from the soil surface. The clay begins to desaturate near its plastic limit. The best-fit parameters for the shrinkage curve are a_{sh} = 0.48, b_{sh} = 0.17, and c_{sh} = 3.30. The specific gravity of the soil was 2.73. Figure 3 shows the gravimetric water content, *w*, plotted versus soil suction for Regina clay was preloaded at 196 kPa. Its initial water content was 53.5%. The high water content specimen showed that a gradual break or change in curvature around 50 kPa. The curvature is not distinct and does not represent the true air-entry value of the material. The gravimetric water content SWCC was best-fit with the FX (1994) equation and yielded the following parameters; that is, a_f = 140 kPa, n_f = 0.87, and m_f = 0.72. Residual suction was estimated to be around 200,000 kPa. It is necessary to use the shrinkage curve to calculate other volume-mass soil properties and properly interpret the SWCC results for the true AEV.

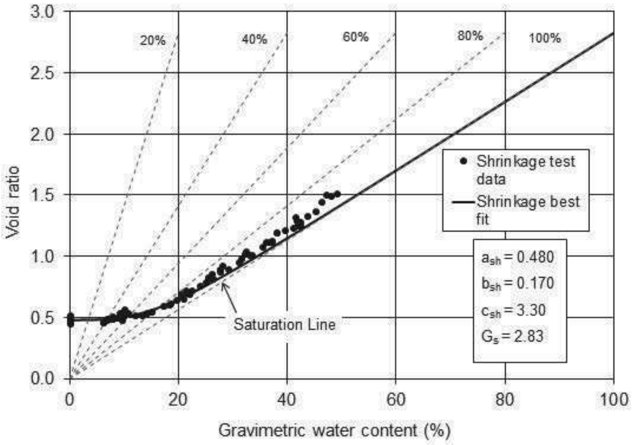

Figure 2. Shrinkage curve for several samples of Regina clay.

The best-fit shrinkage curve equation can be combined with the equation for the FX (1994) equation for the SWCC. The resulting plot of degree of saturation, *S*, versus soil suction is shown in Figure 4. The results show that there is a distinct air-entry value for Regina clay is about 2,500 kPa. The true air-entry value was also found to be similar for all preconsolidated Regina clay samples. The degree of saturation SWCCs must be used to estimate the AEV of the soil and subsequently the calculation of the unsaturated hydraulic conductivity function. The degree of saturation also indicates that residual condition can be more clearly identified as being at a suction of about 200,000 kPa (i.e., residual degree of saturation of 20 percent).

Several other SWCC tests were performed on the Regina clay; each test starting with soil that had been preconsolidated from slurry to differing applied pressures. Figure 5 shows the gravimetric water content versus soil suction plot for a soil preconsolidated to 6.125 kPa. The FX (1994) fitting parameters are a_f = 18.0 kPa, n_f = 0.88, m_f = 0.76 and h_r = 800 kPa.

Figure 6 shows the gravimetric water content versus soil suction plot for a soil preconsolidated to 49.0 kPa. The FX (1994) fitting parameters are a_f = 90.0 kPa, n_f = 1.10, m_f = 0.70 and h_r = 2000 kPa. Figure 7 shows the gravimetric water content versus soil suction plot for Regina clay preconsolidated to the highest pressure of 392 kPa. The FX (1994) fitting parameters are a_f = 120.0 kPa, n_f = 0.84, m_f = 0.70 and h_r = 2000 kPa.

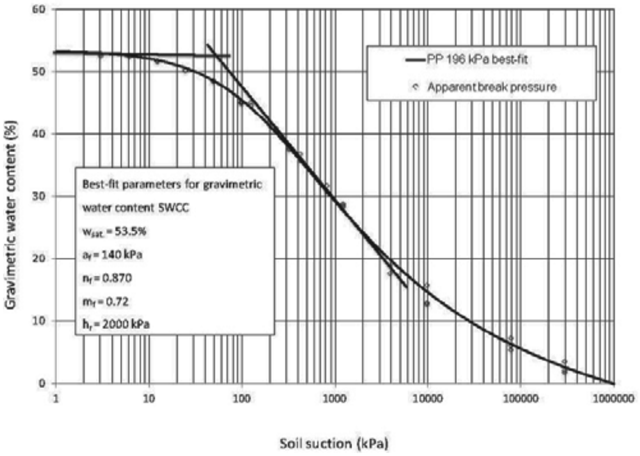

Figure 3. Gravimetric water content versus soil suction for Regina clay preconsolidated to 196 kPa.

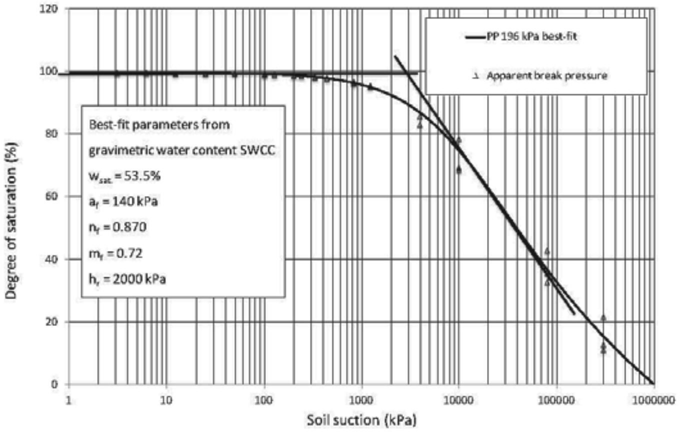

Figure 4. Degree of saturation versus soil suction for Regina clay preconsolidated to 196 kPa.

The measured SWCCs for Regina clay show that the measurement of the gravimetric water content SWCC and the shrinkage curve for a soil are all that is required to obtain an approximation of the volume-mass versus soil suction relationships when the applied net normal stress is zero.

6 INTERPRETATION OF THE REGINA CLAY RESULTS

The difference between the break in the gravimetric water content SWCC and the true AEV for Regina clay is expressed as [AEV/(Break in curvature on *w* SWCC)]. The volume change of the soil is once again expressed as the change in void ratio, Δe, divided by $(1 + e)$ and all void ratio values are determined from the shrinkage curve.

The horizontal axis of Figure 8 shows that the Regina clay soil specimens changed in volume by 65% to 150% as soil suction was increased to residual suction conditions. At 70% volume change, the true AEV is 60 times larger than the break in curvature indicated by the gravimetric water content SWCC. Also at 120% volume change, the true AEV is 129 times larger than the break in curvature indicated by the gravimetric water content SWCC. The laboratory test results clearly indicate the significant influence that volume change as soil suction increases has on the interpretation of the data.

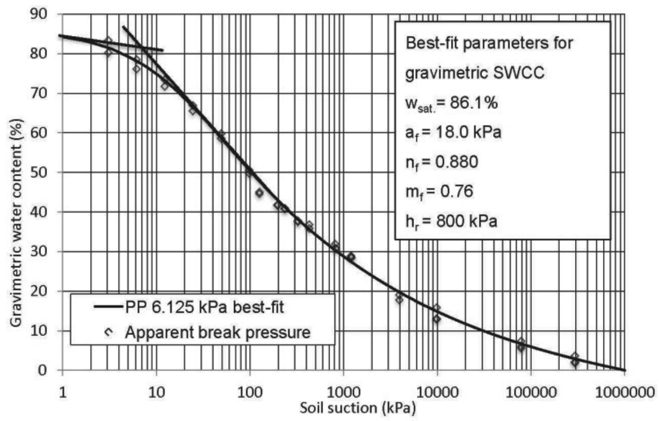

Figure 5. Gravimetric water content versus soil suction for Regina clay preconsolidated to 6.125 kPa.

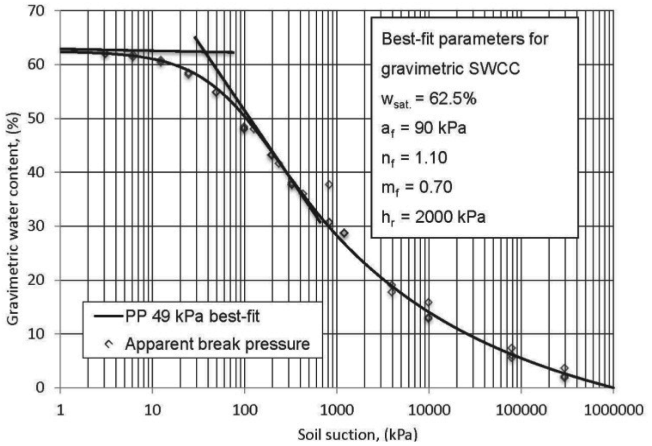

Figure 6. Gravimetric water content versus soil suction for Regina clay preconsolidated to 49 kPa.

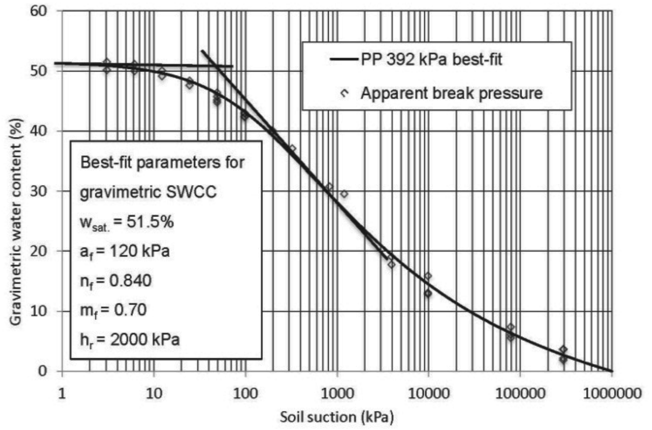

Figure 7. Gravimetric water content versus soil suction for Regina clay preconsolidated to 392 kPa.

The laboratory SWCC test results on Regina clay illustrate the need to separate gravimetric water content SWCC into two components. Part of the change in water content is due to a change in volume while the soil remains saturated. The other part of the change in water content is associated with a change in degree of saturation.

The proposed estimation procedure based on the SWCC and the saturated hydraulic conductivity makes the assumption that the reduction in hydraulic conductivity with suction is due to desaturation of the soil. In other words, it is primarily the increase in tortuosity upon desaturation of the soil that causes the reduction in permeability. Prior to reaching the AEV of the soil, volume change due to an increase in suction needs to be accommodated in an independent manner.

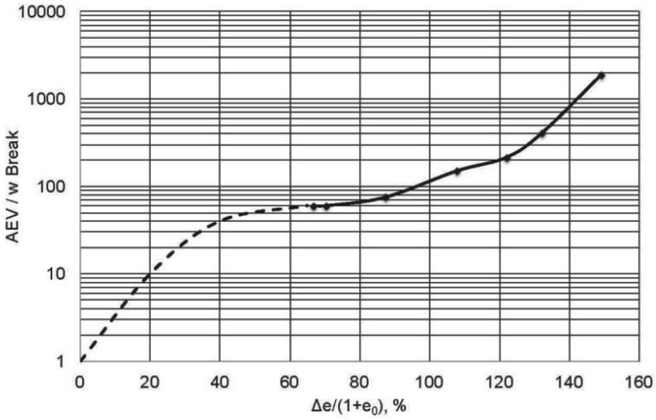

Figure 8. Difference between the break in the gravimetric water content SWCC and the Air-Entry Value for Regina clay.

The estimation of the permeability function with respect to a change in suction can now be considered as having two components; one component due to a change in void ratio and the other components due to a change in the degree of saturation. Further research should be undertaken to verify that the unsaturated soil property functions can indeed be estimated for all types of material by using the interpretation procedure suggested in this paper.

7 CONCLUSIONS AND RECOMMENDATIONS

Changes in the volume of the soil specimens as soil suction is increased can significantly affect the interpretation of the SWCC. This paper presents a procedure that can be used to independently consider the effects of volume change (where the soil remains saturated) from the desaturation of the soil specimen. The effects of volume change are shown to be significant, resulting in erroneous calculations of the permeability function for a soil.

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