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State of Practice for use of the Soil-Water Characteristic Curve in Geotechnical Engineering

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State of Practice for use of the SWCC in Geotechnical Engineering

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Abstract

Routine geotechnical engineering practice has witnessed a significant increase in the usage of unsaturated soil mechanics principles. The laboratory measurement of the soil-water characteristic curve, SWCC, for a soil has been labelled as a primary reason for the improved understanding of unsaturated soil behaviour. Laboratory measurement of the “shrinkage curve”, has yielded further insight into the estimation of unsaturated soil property functions, USPF. The USPFs provide the necessary information for the simultaneous numerical modeling of the saturated and unsaturated portions of the soil profile. This paper presents a state-of-practice summary of the engineering protocols that have emerged amidst the numerous research studies reported over the past couple of decades. It also introduces issues related to hysteresis associated with the soil-water characteristic curve and suggests a pathway forward.

Keywords: Soil-Water Characteristic Curve, Shrinkage Curve, Unsaturated soil properties, Soil suction.

Résumé

La pratique courante de l'ingénierie géotechnique a connu une augmentation significative de l'utilisation des principes de la mécanique des sols non saturés. La mesure en laboratoire de la courbe caractéristique sol-eau, SWCC, pour un sol a été qualifiée de principale raison expliquant la meilleure compréhension du comportement du sol non saturé. La mesure en laboratoire de la «courbe de retrait» a permis de mieux comprendre l'estimation des fonctions des propriétés insaturées du sol, USPF. Les USPF fournissent les informations nécessaires pour la modélisation numérique simultanée des parties saturées et insaturées du profil de sol. Cet article présente un résumé de l'état de la pratique des protocoles d'ingénierie qui ont émergé parmi les nombreuses études de recherche rapportées au cours des deux dernières décennies. Il introduit également des problèmes liés à l'hystérésis associée à la courbe caractéristique sol-eau et suggère une voie vers l'avant.

Introduction

Unsaturated soil mechanics principles and procedures are being increasingly applied to a wide range of geotechnical engineering problems. Commonly encountered problems are those related to the infiltration of water into the soil, its movement within the soil or actual evaporation and removal of water to the atmosphere. There are two soil property functions required in order to numerically model the movement of water through the soil; namely, the hydraulic conductivity and the water storage relationships. There are also a wide range of unsaturated soils problems requiring the quantification of shear strength and volume change properties. In all cases the unsaturated soil properties take the form of nonlinear relationships, particularly when the air-entry of the soil is exceeded (Fredlund 2006). The past few decades have witnessed an ever increasing acceptability for using of the soil-water characteristic curve, SWCC, for the estimation of unsaturated soil property functions. In fact, the SWCC is often referred to as the

key to the implementation of unsaturated soil mechanics in geotechnical engineering practice (Fredlund 2015; Zhang 2016; Zhang and Chen 2005; Zhai et al. 2017).

The term, soil-water characteristic curve (and water retention curve), have been used in diverse ways without providing a clear and precise definition as to its meaning (Fredlund et al. 2018). Some variations in the application of the SWCC are the result of the numerous related disciplines that use similar terminologies. Soil physics and other agronomy-related disciplines predate usage of the terminology in geotechnical engineering. The experience within these disciplines have been particularly helpful in establishing testing protocols and data interpretation principles for describing unsaturated soil behavior. Soil physics made extensive use of the relationship between the amount of water in the soil and soil suction since the early 1900s. Analytical models have been developed for the prediction of the amount of water availability for plant growth (Klute 1965).

Geotechnical engineers have attempted to transfer and directly apply the research findings in soil physics while paying limited attention to the basic assumptions that have been invoked. Of particular importance in geotechnical engineering applications is the assumption that volume changes during suction changes are of secondary interest and can be assumed to be negligible. Geotechnical engineers were involved with a wide range of soil types with both high and low volume changes associated with changes in soil suction. Of particular interest to geotechnical engineers was the ability to estimate unsaturated soil property functions and the realization that the estimations are adequate for analyzing commonly encountered unsaturated soils problems.

A wide range testing procedures and interpretation procedures have been proposed and used for unsaturated soil in the agriculture related disciplines. The primary objective of this paper is to present procedures for the estimation of various unsaturated soil property functions. The procedures are based on information related to the soil-water characteristic curve, SWCC, and the changes in volume as water content is changed upon drying or wetting (i.e., the shrinkage curve, SC). The paper illustrates the synergistic relationship which exists between the main (drying) soil-water characteristic curve and the shrinkage curve. The ease with which these unsaturated soil relationships can be measured in the laboratory has strongly influenced the procedures that have become the state of practice in geotechnical engineering.

The scope of the paper is limited to laboratory test procedures that appear to be most commonly used in geotechnical engineering practice. In other words, not all proposed constitutive equations are taken into consideration. The laboratory test and curve fitting procedures will be applied to one soil type (e.g., Regina clay) where both volume change and desaturation occur as the soil dries. It needs to be emphasized that other fitting equation would also satisfy the proposed general paradigm.

Definition of an Unsaturated Soil

The United States Geological Survey (Robinson and Spieker 1978), defines the vadose zone as “that part of the earth between the land surface and the water table (i.e., atmospheric pressure)”. In geotechnical engineering the vadose zone is more commonly referred to as the “unsaturated soil zone” even though the soil zone immediately above the phreatic surface (i.e., the capillary zone) has voids that are essentially filled with water. The soil in the capillary zone may have

some occluded air bubbles and as such the pore fluid has increased compressibility. Stated another way, the “unsaturated soil zone” is defined on the basis of the stress state of the soil (i.e., negative pore-water pressures) rather than on the amount of air or water existing in the voids. This definition of the “unsaturated soil zone” is important since it is the determination of the soil-water characteristic curve, SWCC, starting at near-zero suctions, that is used for the estimation (or quantification) of the soil properties assigned when pore-water pressures are negative.

The unsaturated soil zone is commonly divided into three sub zones; namely, i.) capillary zone immediately above the phreatic surface, ii.) two-phase zone with continuous water and air fluid phases, and iii.) dry zone where the water phase becomes discontinuous. The demarcation between these sub zones is based on changes in the rate of degree of saturation change in the soil in response to changes in the negative pore-water pressure (Fredlund 2015).

Theoretical Context Considerations

There are two independent stress state variables that can be used for describing unsaturated soil behaviour; namely, i.) net total (along with shear stress) variables with components in three orthogonal directions, $[(\sigma_1 - u_a), (\sigma_2 - u_a), \text{ and } (\sigma_3 - u_a)]$, and ii.) isotropic matric suction (or soil suction), $(u_a - u_w)$. The theoretical justification for using independent stress state variables is based on equilibrium considerations of a multiphase continuum (Fredlund and Morgenstern 1977; Fredlund 2016).

There are two possible volume-mass properties that can change in response to a change in stress state. These are: i.) a change in overall volume (i.e., void ratio change, (de) , and ii.) a change in degree of saturation, (dS) . The basic volume-mass relationship can be written as follows.

$$Se = wG_s \quad [1]$$

where S = degree of saturation; e = void ratio; w = gravimetric water content; and G_s = specific gravity of soil solids. Incremental differentiation of Eq. [1] shows that a change in gravimetric water content can occur as a result of either a change in void ratio or a change in degree of saturation (Fredlund and Rahardjo 1993).

$$\Delta w = \frac{S_f \Delta e + e_f \Delta S}{G_s} \quad [2]$$

where Δw = change in gravimetric water content, Δe = change in void ratio, ΔS = change in degree of saturation, and f = refers to the “final” volume-mass states. It is important to quantify the effects of void ratio change and the effects of degree of saturation change when dealing with unsaturated soil behaviour since associated physical processes can be quite different in each case. For example, changes in void ratio affect the hydraulic conductivity of a soil differently than changes in degree of saturation. This paper uses the “shrinkage curve”, (i.e., void ratio versus gravimetric water content relationship), to assist in the separation of the physical processes (Zhang, 2016).

Transition from the Field to the Laboratory

The relationship between the pore-water stress state in the field and the laboratory measurement of the soil-water characteristic curve can be visualized for the soil under study (Fredlund 2015). Let us consider the case of a medium sand deposit where the water table (or phreatic surface) is located 3 meters below the ground surface (see Figure 1). Let us also assume that the water table was previously at ground surface and then was slowly lowered to the 3 meter depth. The negative pore-water pressures in the sand would correspond to hydrostatic equilibrium conditions. Let us suppose that a borehole was drilled through the sand deposit and water content samples were taken every 30 centimeters.

Figure 2 shows a plot of measured gravimetric water content versus the negative pore-water pressures (or matric suctions) defined under equilibrium conditions. Equilibrium conditions exist when the water table remains fixed and there is no moisture flux at the ground surface. This relationship is constitutive in character and provides information on changes related to the physical properties of the soil. At low suctions (approaching the water table) that water content of the soil is 38%. The water content significantly decreases as suctions exceeding the capillary rise are applied. Also shown in Figure 2 is a second change in slope (on a semi-log plot) as it becomes increasingly difficult to extract water from the soil. As such, the rate of change in the amount of water held in the soil at increasing suctions (on a semi-logarithm plot) provides a general indication of the three main zones under which an unsaturated soil can exist; namely i.) capillary zone, ii.) two-phase zone, and iii.) dry zone).

The above description provides an indication of the relationship between the field soil conditions (including its stress state), and an important laboratory test that has become the key to the implementation of unsaturated soil mechanics; namely, the soil-water characteristic curve, SWCC (Fredlund 2002). Geotechnical engineers have been able to benefit greater from past experience and research undertaken in soil physics, soil science and agronomy-related disciplines. At the same time it has been important for geotechnical engineers give careful scrutiny to the end goals of geotechnical engineering practice.

Consistent with the above description is the approach that has been taken in soiltesting procedures that have been adopted by geotechnical engineers when testing unsaturated soils. Let us suppose that a single undisturbed soil sample was retrieved from the “medium sand” deposit at a depth of 1.5 meters below ground surface. The entire deposit is assumed to be homogeneous, of low compressibility, with physical properties as indicated in Figure 1. The goal of the geotechnical engineer is to perform a relatively inexpensive test on the undisturbed soil sample that could provide him with information related to the physical behaviour of the entire sand deposit. His goal is achieved, to a large extent by measuring the amount of water in the soil as the soil is slowly dried through the application of tension to the water phase. The measured relationship can be referred to as the (main) drying soil-water characteristic curve for the sand deposit (see Figure 2).

General Equation for the SWCC

Let us now consider a more general, but typical soil-water characteristic curve, such as is shown in Figure 3. The SWCC is plotted in terms of gravimetric water content corresponding to various soil suction values. Recommended test procedures are described in ASTM D6836-16 (2016). The drying SWCC (w -SWCC) can extend from a fraction of 1 kPa to one million kPa. It should

be noted that the SWCC is plotted in terms of matric suction values in the low suction range (up to ~1500 kPa), and in terms of total suction in the high suction range. Data for the drying SWCC generally takes on the form of a single sigmoidal mathematical function on a semi-log graph. The dashed lines simply represent distinct changes in slope on a semi-log plot.

Subsequent analyses involving the w -SWCC can be simplified and expedited if the relationship is represented as a continuous mathematical function. The w -SWCC will be used for the estimation of unsaturated soil property functions required for numerical modeling purposes. There are numerous equations that have been proposed to best-fit to experimental w -SWCC data (van Genuchten 1980; Fredlund and Xing 1994; Pham and Fredlund 2011). The selected equation should be able to fit the data in the low suction range while ending at zero water content at a suction of one million kPa. The Fredlund and Xing (1994) equation generally meets these requirement. If a soil specimen undergoes excessive volume change upon drying it might be difficult to fit the entire data range with a single sigmoidal equation. It can also be used in a bimodal form with the generation of a slightly different equation (Zhang and Chen 2005) or using the equation from Satyanaga et al. (2013).

The Fredlund and Xing (1994) equation has 4 fitting parameters including residual suction. Residual suction can be approximated using the empirical construction procedure suggested by Vanapalli et al. (1998). The variables of the SWCC (i.e., air-entry value, inflection point, residual water content and residual suction) can also be obtained using the Zhai and Rahardjo (2012) equation. The initial fitting of the gravimetric water content SWCC (w -SWCC) should not be confused with later fitting of the degree of saturation SWCC (S -SWCC). Also, the fitting parameters for w -SWCC will have a slightly different physical meaning from those assigned to the degree of saturation SWCC, (S -SWCC). The Fredlund and Xing (1994) SWCC equation can be written as follows.

$$w(\psi) = \frac{w_s C(\psi)}{(\ln(\exp(1) + (\psi/a_f)^{n_f}))^{m_f}} \quad [3]$$

where $w(\psi)$ = water content at any soil suction, ψ , a_f = fitting parameter related to the suction near the inflection point on the w -SWCC, n_f = fitting parameter related to the maximum rate of gravimetric water content change, m_f = fitting parameter related to the curvature near residual gravimetric water content conditions, ψ_r = suction near residual conditions of the soil, and $C(\psi)$ = correction factor directing the w -SWCC towards a suction of 10^6 kPa at zero water content is written as;

$$C(\psi) = 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln(1 + 10^6/\psi_r)} \quad [4]$$

Generally a close fit can be achieved with laboratory data when using the Fredlund-Xing (1994) equation; however, this is not always the case. Further details on the calculation of the fitting parameters are presented by Zhai and Rahardjo (2012). The data shown in Figure 3 shows a gradual downward bend around 20 kPa. However, it should be noted that this bend may not indicate the true air-entry value of the soil. It will only indicate the true air-entry value for the soil when there is no volume change as soil suction is increased. The “true” air-entry value needs

to be determined from the degree of saturation SWCC (S -SWCC). It should be noted that Eq. [3] can also be used to best-fit the degree of saturation versus suction data provided the degree of saturation variable is substituted for gravimetric water content.

Changes in gravimetric water content do not allow for the assessment of the independent processes that might occur as the soil dries. In other words, changes in the measured gravimetric water content might be the result of volume changes (i.e., void ratio changes), or degree of saturation change. By combining the w -SWCC with the SC it is possible to give consideration to the two independent processes of volume change and degree of saturation change. Following is an explanation of the important role played by the shrinkage curve when considering a soil with a compressible structure.

Importance of the Shrinkage Curve, SC

The question might rightly be asked as to why the shrinkage curve for the soil becomes of such significance value when it received minimal attention in the past. The answer, in part, is related to understanding the end goal for applying SWCCs. The primary end goal in agriculture-related disciplines was related to the quantification of water storage in the soil (Klute 1986). The estimation of hydraulic conductivity was of secondary interest. The amount of water in a soil was quantified in terms of volumetric water content and the soil was assumed to undergo negligible volume change as soil suction was increased. The assumption of “no volume change” made for easy and meaningful interpretation of SWCC laboratory data (Fredlund and Zhang 2017).

It is also noteworthy that classic soil mechanics had mainly focused on understanding the behaviour of saturated soils and properties that were defined as constant values (e.g., coefficient of permeability, coefficient of volume change, effective cohesion and angle of internal friction). The effect of changes in volume-mass properties on the saturated soil properties was generally assumed to be of secondary interest. The paradigm changed with the realization that changes in degree of saturation significantly changed soil behaviour. Geotechnical engineers were also called upon to analyze the performance of an extremely wide range materials. Consequently, it became necessary to revisit the laboratory testing and analytical protocols used when solving unsaturated soil mechanics' problems.

Shrinkage curves, SCs, can readily be measured in the laboratory by using a small specimen about 12 mm thick and 37 mm in diameter as shown in Figure 4. The smaller size is used to ensure the specimen does not crack. The soil specimens are confined in a metal ring and can be prepared in a slurry state, a compacted state or an undisturbed state. The initial conditioned state should be the same for the SC test and the independently run SWCC test.

The mass and the volume of the soil specimen for the SC can be measured periodically as the soil is allowed to dry while being exposed to room temperature conditions. The challenge has been to find a reliable means of measuring the volume of the soil specimen each time the mass is measured (Wong et al. 2017). ASTM D427-04 (1998) describes a standard procedure for measuring the volume of a shrinkage limit soil specimen through use of the mercury immersion technique; however, the use of mercury in laboratories is now prohibited and the volume of shrinkage curve soil specimens is more commonly measured using micrometer calipers.

Shrinkage curve equation for gravimetric water content versus void ratio

Leong and Wijaya (2015) summarized a number of equations that have been proposed for the fitting of complex multi-modal shrinkage curves; the type sometimes encountered when drying from a variety of initial conditions. The M. Fredlund (2000) proposed mathematical equation has the form of a hyperbole and is used in this paper to illustrate the best-fit of measured shrinkage curve data. The interest in this paper is limited to soils that are initially allowed to become saturated prior to the commencement of the SC test.

$$e(w) = a_{sh} \left(\left(\frac{w}{b_{sh}} \right)^{c_{sh}} + 1 \right)^{1/c_{sh}} \quad [5]$$

where a_{sh} = minimum void ratio upon complete drying, b_{sh} = variable related to the slope of the drying curve calculated as: $b_{sh} = (a_{sh} \times S_o)/G_s$, and c_{sh} = variable related to the sharpness of curvature as the soil desaturates, and S_o = initial conditioned degree of saturation. The initial emphasis is on characterizing the drying SC with the suggestion that the effects of hysteresis can be handled independently once the drying behaviour is established.

The measurement of the SWCC starts near with the specimen being allowed free access to water. The initial degree of saturation will be near 100% (e.g., $S = 98\%$). Figure 5 shows a typical shrinkage curve for which the fitting parameters are; $a_{sh} = 0.40$; $b_{sh} = 0.146$ and the $c_{sh} = 3.0$. The specific gravity of the soil is 2.68.

Parametric study of the Shrinkage Curve

Each of the fitting parameters associated with the M. Fredlund (2000) shrinkage curve equation has physical significance. The effect of changing each of the variables can be observed through use of a parametric study. In addition to measuring the shrinkage curve, it is also possible to estimate the shrinkage curve with sufficient accuracy for many geotechnical engineering problems. The following text describes the effect of each of the shrinkage curve fitting parameters and also suggests a procedure for estimating the parameters (Fredlund and Zhang 2017).

Significance of the a_{sh} variable

The a_{sh} variable is relatively easy to determine since it is the minimum void ratio that a soil can attain upon complete drying. The a_{sh} variable can either be assumed by analyzing the complete shrinkage test dataset or by simply setting the a_{sh} variable equal to the minimum void ratio corresponding to an oven-dried soil specimen. Figure 6 shows a series of shrinkage curves for soils with various void ratios upon complete drying (i.e., a_{sh} ranging from 0.4 to 1.0). The c_{sh} was set to 3.0 and the b_{sh} variable is calculated from the a_{sh} variable, the specific gravity and the initial degree of saturation.

Estimation of the a_{sh} variable

The a_{sh} variable can be estimated from the shrinkage limit, SL, of the soil. The shrinkage limit test was introduced into soil mechanics in the 1920s but gradually became a soil

classification test that was deemed to not be necessary in routine geotechnical engineering. However, the shrinkage limit test has now taken on renewed significance in that it provides information of significance relative to the SC.

Casagrande (1932) showed that the shrinkage limit, SL , of a slurry or remolded soil could be estimated from the liquid limit and plasticity index of a soil. The shrinkage limit of a soil has been shown to lie either above or below the A-Line on the Casagrande plasticity chart. The A-Line on the plasticity chart corresponds to a straight line that is mathematically defined as follows.

$$PI_A = 0.75 LL_s - 15 \quad [6]$$

where PI_A = plasticity index on the A-Line, and LL_s = measured liquid limit of the selected soil. The shrinkage limit, SL_s , of the soil can then be written in terms of the plasticity index of the soil, PI_s .

$$SL_s = 20 + (PI_s - PI_A) \quad [7]$$

Holtz and Kovacs (1981) suggest that the estimation of the shrinkage limit of a slurry or remolded soil appears to be of similar accuracy to those measured in a laboratory. The ability to accurately estimate the shrinkage limit of a soil from the other plasticity classification values means that one of the primary variables associated with the characterization of the volume-mass behavior of a soil can be determined independent of the measurement of the entire shrinkage curve. The shrinkage limit of the soil, SL_s , is equal to the amount of water required to fill the voids when the soil is dried to its minimum void ratio.

$$a_{sh} = SL_s * G_s \quad [8]$$

where the initial degree of saturation of the slurry soil is assumed to be 100%. Consequently, the a_{sh} parameter for the shrinkage curve can be calculated from the soil plasticity values.

Significance and calculation of the b_{sh} variable

The second variable required for the hyperbolic characterization of the shrinkage curve equation is b_{sh} (M. Fredlund et al. 2002). The b_{sh} variable is calculated from the a_{sh} variable, the specific gravity, G_s , and the initial degree of saturation, S_o , as shown in Eq. [9].

$$b_{sh} = a_{sh} S_o / G_s \quad [9]$$

The initial degree of saturation of an initially slurry soil is generally between 90 and 100%. Figure 7 shows a plot of b_{sh} versus a_{sh} for a range of initial degrees of saturation and a specific gravity of 2.70. The graph illustrates that the b_{sh} variable is also known once the a_{sh} variable has been determined. It is estimated that b_{sh} varies between +/- 10%.

Significance of the c_{sh} variable

The remaining fitting parameter for the shrinkage curve is the c_{sh} variable when using the M. Fredlund (2000) equation. The c_{sh} variable defines the rate of curvature of the shrinkage curve when moving between the saturated state and the completely dried state.

Figure 8 shows a family of shrinkage curves where the c_{sh} variable is arbitrarily varied while the a_{sh} variable is set at 0.6 and the specific gravity is 2.70. The initial degree of saturation was assumed to be 98%. The results show that there are practical limits to the c_{sh} variable. For example, a c_{sh} value of 50 (Note: not shown in Fig. 8) will essentially produce a horizontal line from the initial void ratio, a_{sh} to the initial saturation line ($\sim 100\%$), and then follow up the initial saturation line. On the other hand, a c_{sh} value of about 1.5 produces a gradual curve that immediately starts to curve from the completely dry void ratio and gradually tends towards saturation.

The common range of c_{sh} values for soils lies between 3 and 15. Soils with a c_{sh} value of 15 are considered to be low compressibility soils while soils with a c_{sh} value of 1.5 would have much higher compressibility (or undergo considerable volume change) as soil suction is increased. It would appear to be necessary to make several volume-mass measurements on a soil specimen as it dries in order to quantify the most likely value for the c_{sh} variable. A typical value of c_{sh} for a moderately compressible silty soil would be about 5.

The research literature shows that a number of studies have been undertaken on the shrinkage curve behaviour of soils (Ho 1988; Marinho 1994,2017; Tripathy et al. 2002). A further fitting study of shrinkage curve test results was recently undertaken by Wong et al. (2018). The c_{sh} fitting parameter was found to vary with the plasticity of the soil and a close correlation was found with the plasticity ratio, PL/LL as shown in Figure 9. Each dot in Figure 9 represents the best-fit c_{sh} value from 27 soils. The best-fit equation for c_{sh} was found to be as follows.

$$c_{sh} = 1.7 + e^{3.1^{PL/LL}} \quad [10]$$

Combining the SWCC and the SC for a highly compressible soil

The following section illustrates how measured w -SWCC and SC data can be combined when giving analyzing a soil that undergoes considerable volume change as suction is increased. The laboratory results were measured on Regina clay that was initially mixed to a slurry state and then consolidated to 196 kPa (Fredlund 1964). Regina clay has a liquid limit of 75%, a plastic limit of 25% and a shrinkage limit of 15%. The initial gravimetric water content was 53.5%, the degree of saturation was 96.9% and the specific gravity was 2.83.

The shrinkage curve, SC, from several tests on Regina clay are shown in Figure 10. The SC remains at essentially constant degree of saturation as drying occurs and then levels off to a completely dry void ratio of 0.5. The fitting parameters for the M. Fredlund (2000) equation are as follows; $a_{sh} = 0.480$; $b_{sh} = 0.161$; and $c_{sh} = 4.00$.

Figure 11 shows the measured gravimetric water contents plotted versus soil suction, w -SWCC, for Regina clay consolidated to 196 kPa. Its initial water content was 53.5%. There was a gradual downward trending of the w -SWCC plot as matric suction was applied. The water content versus suction tends towards a straight line relationship for suctions in excess of about 40 kPa were applied. The relationship showed a slight further bend in the high suction range as suctions tended towards 1,000,000 kPa. Due to the sigmoidal shape of the relationship, the complete range of the data can be best-fit using the empirical equation proposed by Fredlund-

Xing (1994). It should be noted that the curvatures are quite gradual and do not represent the “true” air-entry value of the soil. The best-fit of the data yields the following parameters; $a_f = 140$ kPa, $n_f = 0.87$, and $m_f = 0.72$. Residual suction can roughly be estimated to be around 200,000 kPa.

Matric suctions were applied to the Regina through use of a pressure plate device for suctions up to 1500 kPa. Data points at higher suctions measured the equilibrium water content in small soil specimens allowed to come to equilibrium in desiccators kept at fixed relative humidities.

The significance of the w -SWCC relationship can be further analyzed by using the shrinkage curve relationship shown in Figure 10 to calculate other volume-mass soil properties versus soil suction. The degree of saturation can be written as a function of gravimetric water content and void ratio.

$$S(w) = \frac{w(\psi)G_s}{e(w)} \quad [11]$$

where: $w(\psi)$ = gravimetric water content is written as a function of soil suction (i.e., the w -SWCC), and $e(w)$ = void ratio written as a function of gravimetric water content (i.e., the shrinkage curve). Figure 12 shows the calculated degree of saturation data points versus soil suction for the drying SWCC. The best-fit line through the data can be designated as S -SWCC. The “true” air-entry value, AEV, of the soil should be determined from the S -SWCC. The results show that there is quite a distinct air-entry value for Regina clay of about 4,000 kPa. Figure 12 also shows an empirical construction procedure (Vanapalli et al. 1998) that can be used to identify a specific air-entry value. The degree of saturation also indicates that residual condition can be more clearly identified as occurring at a suction of about 200,000 kPa and a residual degree of saturation is about 20 percent.

Volumetric water content, θ , data points can be calculated using the following equation.

$$\theta(w) = \frac{w(\psi)G_s}{1 + e_o} \quad [12]$$

where $\theta(w)$ = volumetric water content as a function of gravimetric water content, $w(\psi)$ = gravimetric water content as a function of soil suction and e_o = initial void ratio. It should be noted that volumetric water content has been defined with reference to the initial overall volume and also with reference to the instantaneous overall volume (Zhang et al, 2016). The two definitions give differences that are dependent upon the amount of volume change that occurs and the manner in which volumetric water content is used in theoretical derivations.

Figure 13 presents a plot of instantaneous volumetric water content versus soil suction for the Regina clay preconsolidated at 196 kPa. There is a gradual curvature in the plot which is somewhat similar to that observed when using the gravimetric water content SWCC. While the volumetric water content plot does not yield the “true” AEV, it is the volumetric water content versus soil suction plot that must be differentiated in order to compute the water storage under any designated soil suction.

The void ratio corresponding to each data point can be written as a function of gravimetric water content which is a function of soil suction using Eq. [5]. Figure 14 shows a plot of void ratio versus soil suction. There is a gradual change in curvature of the graph at around 45 kPa. However, it should be noted that the curvature simply represents a change in void ratio with respect to applied suction. The soil did not start to desaturate until the void ratio was reduced to about 0.7 (or the water content of about 25% which is near the plastic limit of the soil). The minimum void ratio achieved upon complete shrinkage was 0.48.

All of the volume-mass relationships have been shown for the drying SWCC for initially slurry Regina clay. These relationships can be generated as a result of data obtained from two laboratory tests that are quite common in most soil physics and soil science testing laboratories as well as an ever increasing number of geotechnical material testing laboratories.

Changes in the volume of the soil specimens, as soil suction is increased, can significantly affect the interpretation of soil-water characteristic curve information. It is important to use analytical protocols that properly account for the independent effects of volume change when interpreting the w -SWCCs.

Hysteresis

The material presented thus far has been directed towards obtaining and analyzing data associated with the drying SWCC. It is obvious that this is not the entire picture since the drying and wetting SWCCs differ due to hysteresis (Haines 1923). The cost of measuring both the drying and the wetting SWCCs is prohibitive for most geotechnical engineering projects. Consequently, reasonable judgement and based on past experience and theoretical considerations are used to chart the course of action.

This research paper is not meant to be a thorough analysis of engineering problems associated with hysteresis in unsaturated soils. Rather, it is meant to: i.) suggest terminology that envelopes the various hysteretic functions that might be encountered, ii.) illustrate the independent roles of the various volume-mass functions, and iii.) suggest a pathway forward that provides an acceptable set of assumptions, approximations and estimation procedures for geotechnical engineering practice. The suggestions are meant to be a starting point for future research related to hysteresis in unsaturated soils.

The SWCC term has often been used in diverse ways without a clear definition as to its meaning. SWCC is really a family of relationships with two bounding curves and an infinite number of scanning curves (Klute 1965; Pham 2005). The term SWCC is also sometimes referred to as a unique relationship and as any variable used to designate the amount of water in a soil and soil suction. This usage of the terminology does not give full respect to the complexities associated with the hysteresis phenomena. It is well beyond the scope of this paper to fully address issues related to hysteresis; however, it is also important to discuss the terminology geotechnical engineers become aware of in order to address issues related to hysteresis.

Klute (1965, 1985) suggested that there are three primary SWCC bounding curves that can be designated as the: i.) initial drying curve, ii.) main drying curve, or iii.) main wetting curve. The result is a family of curves because the drying and wetting processes are hysteretic (Pham et al,

2003, 2005 and Zhai et al. 2017). There are also an infinite number of possible scanning curves that go between the bounding curves. It should also be noted that the amount of water in the soil may be quantified in terms of: i.) gravimetric water content, ii.) degree of saturation or, iii.) volumetric water content. Figure 15 illustrates the family of SWCCs when using the degree of saturation to designate the amount of water in the soil.

A couple of observations can be noted with respect to the family of SWCCs. First, there is approximate parallelism between the drying and wetting SWCCs when the suction data is plotted on a semi-log scale. Second, the estimated shift at the inflection point on the drying and wetting curves can be approximated as a percentage of a log cycle. Both of these assumptions are approximate and are dependent upon the soil type (Pham et al. 2003, 2005).

The soil suction axis is generally plotted using matric suction as the state variable in the (low) suction range up to about 1500 kPa. Beyond 1500 kPa soil suction is plotted in terms of the total suction component. The change in the soil suction component over the possible range of suction values has not appeared to cause serious problems in practice.

While degree of saturation appears to be the most fundamental designation of the amount of water in the soil, it is the gravimetric water content that is the easiest and most commonly measured water content variable measured using pressure plate apparatuses (Fredlund and Houston, 2013). Therefore, the degree of saturation variable becomes a computed value dependent on the overall volume of the soil. When the soil undergoes volume change as soil suction is changed, variations in the designation of the amount of water in the soil can lead to considerably different interpretations of laboratory test data (Fredlund and Rahardjo 1993). The effects of volume change as soil suctions change can readily be taken into account through either the measurement or estimation of the shrinkage curve as earlier described in this paper.

Let us start by sorting out the terminology designation required for representing all of the commonly used volume-mass versus soil suction relations in geotechnical engineering (Fredlund et al. 2018). Table 1 presents a summary of the suggested designation that can be used for soil-water characteristic curves describing the amount of water in the soil. The “pre SWCC” variable (i.e., w , S , or θ), designates the measure of the amount of water in the soil while the “post SWCC” variable (i.e., i for initial, d for drying, or w for wetting), identifies the bounding curve under consideration.

Each of the family of SWCCs have independent roles to play in understanding unsaturated soil property functions. For example, it is the S -SWCCs that can be integrated to compute the permeability function for an unsaturated soil. It is also the S -SWCC drying curve that is used to determine the “true” air entry value of a soil (Fredlund 2017). At the same time, it is the θ -SWCCs that can be differentiated to get the water storage function for an unsaturated soil. The w -SWCC is most easily measured in the laboratory and forms the basis for the calculation of other volume-mass functions when combined with shrinkage curve data. Figure 16 illustrates that labels for the family of gravimetric water content SWCCs.

Table 2 shows the suggested terminology and labels for the volume change characteristics written in terms of void ratio.

Summary Comments

One of a number of possible approaches have been taken towards hysteresis complications in geotechnical engineering practice. These approaches can be summarized as follows:

- 1.) Attempt to measure both the drying and wetting bounding curves in the laboratory. While this is a preferable choice, it is not always acceptable from a budget and cost-effective approach.
- 2.) Measure the drying curve and use only the drying SWCC in subsequent estimations of unsaturated soil property functions. This approach builds a natural bias into further soil property estimations that might be performed. The bias might be towards an upper bound or lower bound soil property function.
- 3.) Measure the drying SWCC and estimate a possible shift to apply to the inflection point for the estimation of the wetting SWCC (Pham et al. 2003; Zhai et al. 2017). It might then be possible to use both the drying and wetting SWCCs, along with scanning curves, in solving problems depending upon the software used.
- 4.) If the wetting SWCC is estimated from the drying SWCC, it is further possible to compute a “median” SWCC which is used in the analysis of a specific unsaturated soils problem. This assumption may be justifiable when taken the natural non-homogeneity of the soil into consideration.

The present state of geotechnical engineering practice allows the unsaturated portion of the soil profile to be characterized in a manner similar to that used in saturated soil mechanics. However, it is necessary to combine a series of estimation procedures along with the basic unsaturated soil property functions to be measured in the laboratory. These are the drying gravimetric water content SWCC (w -SWCC_d) and the shrinkage curve, SC. It is necessary to independently consider each of the volume-mass property functions when the soil undergoes volume change as soil suction is increased.

Estimation procedures have become quite acceptable in determining acceptable unsaturated soil property functions for the analysis of unsaturated soils problems. The author is of the opinion that research studies involving unsaturated soils will prove to be extremely valuable in the future.

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List of Figures

Figure 1 Unsaturated soil zones within the profile of a medium sand deposit.

Figure 2. SWCC corresponding to drying equilibrium conditions for medium sand.

Figure 3. Matric suction and total suction data for the w -SWCC showing changes in slope.

Figure 4. Establishing similar initial volume-mass conditions for the w -SWCC and SC tests.

Figure 5. Typical shrinkage curve for a compressible soil.

Figure 6. Effect of varying the a_{sh} fitting parameter of the shrinkage curve.

Figure 7. Relationship between the a_{sh} and b_{sh} parameters.

Figure 8 Effect of varying c_{sh} on the shrinkage curve.

Figure 9 Relationship of c_{sh} to the plasticity ratio (i.e., PL/LL) (after Wong et al. 2018).

Figure 10. Shrinkage curve for Regina clay.

Figure 11. Gravimetric water content versus soil suction for Regina clay consolidated to 196 kPa.

Figure 12. Degree of saturation versus soil suction for Regina clay consolidated to 196 kPa.

Figure 13. Volumetric water content versus soil suction for Regina clay consolidated to 196 kPa.

Figure 14. Void ratio versus soil suction for Regina clay consolidated to 196 kPa.

Figure 15 Hysteresis with respect to drying and wetting (after Klute 1986).

Figure 16. Suggested labelling for the gravimetric water content versus soil suction characteristic family of curves.

Figure 17. Labelling for the void ratio versus suction characteristic curve.

List of Tables

Table 1: Various Designations for the Soil-Water Characteristic Curves, SWCC.

Table 2: Designations for the Volume Change Characteristic Curve, (e -CC).

Figure 1 Unsaturated soil zones within the profile of a medium sand deposit.

Figure 2. SWCC corresponding to drying equilibrium conditions for medium sand.

Figure 3. Matric suction and total suction data for the w -SWCC showing changes in slope.

Figure 4. Establishing similar initial volume-mass conditions for the w -SWCC and SC tests.

Figure 5. Typical shrinkage curve for a compressible soil

Figure 6. Effect of varying the a_{sh} fitting parameter of the shrinkage curve

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Figure 14. Void ratio versus soil suction for Regina clay consolidated to 196 kPa.

Figure 15 Hysteresis with respect to drying and wetting (after Klute, 1965, 1985).

Figure 16. Suggested labelling for the gravimetric water content versus soil suction characteristic family of curves.

Figure 17. Labelling for the void ratio versus suction characteristic curve.

Table 1: Various Designations for the Soil-Water Characteristic Curves, SWCC

Water content variable	Initial drying curve	Main drying curve	Main wetting curve
Gravimetric water content	$w\text{-SWCC}_i$	$w\text{-SWCC}_d$	$w\text{-SWCC}_w$
Degree of saturation	$S\text{-SWCC}_i$	$S\text{-SWCC}_d$	$S\text{-SWCC}_w$
Volumetric water content	$\theta\text{-SWCC}_i$	$\theta\text{-SWCC}_d$	$\theta\text{-SWCC}_w$

Table 2: Designations for the Volume Change Characteristic Curve, ($e\text{-CC}$)

Volume change variable	Initial drying curve	Main drying curve	Main wetting curve
Void ratio	$e\text{-CC}_i$	$e\text{-CC}_d$	$e\text{-CC}_w$