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ABSTRACT

The soil-water characteristic curve has traditionally been defined over a limited suction range; usually from 0 to 1500 kPa. Soils, however, change from saturation to a dry condition over a range of suctions from zero to approximately 1,000,000 kPa. This paper provides a description of the soil-water characteristic curve as well as a rationale for extending this function over a range of suctions up to 1,000,000 kPa. Key factors controlling the soil-water characteristic curve over this range in suctions are also described. A method for estimating the state of residual saturation from the extended curve is presented. An estimate of the residual condition is required by a number of techniques which use the soil-water characteristic curve as a basis for estimating unsaturated soil property functions.

RÉSUMÉ

Traditionnellement, la courbe caractéristique sol-eau a été définie pour une limite de pression se situant habituellement entre 0 et 1500 kPa. Cependant, les sols changent d'une condition de saturation à une condition sèche dont la pression varient de zéro à approximativement 1,000,000 kPa. Cette publication fournit une description de la courbe caractéristique sol-eau et fournit une solution rationelle pour l'expansion de cette fonction pour des pressions atteignant jusqu'à 1,000,000 kPa. Les facteurs-clé contrôlant la courbe caractéristique sol-eau dépassant ces valeurs de pression sont aussi décrits. Une méthode pour estimer l'etat de saturation résiduelle à partir de la courbe étendue est présentée. Une estimation de la condition résiduelle est requise par un certain nombre de techniques qui utilisent la courbe caractéristique sol-eau comme base pour l'estimation des propriétés du sol non saturé.

INTRODUCTION

Much of the land surface of the earth is comprised of unsaturated soils. One third of the earth's land surface is situated in arid or semi-arid regions where the potential evaporation exceeds precipitation (Dregne 1976). Geotechnical engineering involving unsaturated soils requires an appropriate theoretical base and appropriate methods for the characterization of their physical properties. The concept of stress state variables to describe the behavior of unsaturated soils was introduced by Fredlund and Morgenstern (1977). A rational engineering approach to describe the behavior of unsaturated soils in terms of the stress state variables; net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$, has been presented in Fredlund and Rahardjo (1993).

The current technology to develop numerical models far exceeds our ability to measure the properties of an unsaturated soil. The measurement of the properties of unsaturated soils is costly and time consuming. Estimates of these properties using empirical procedures may be sufficient for most applications. The soil-water characteristic curve is a fundamental relationship of unsaturated soils which provides a conceptual and interpretative tool by which the behavior of unsaturated soils can be understood. As the soil moves from a saturated state to dry conditions, the distribution of the soil-water-air phases changes as the stress state changes. It is the interactions between these phases and the distribution of these phases (i.e., volume, geometry, and continuity) that control unsaturated soil properties. For example, in some cases the behavior may be primarily related to the volume of the separate phases (e.g., water content), or the continuity and tortousity of the liquid phase (e.g., coefficient of permeability, molecular diffusion) or the air phase (e.g., coefficient of vapour or oxygen diffusion). In other cases it is the inter-phase contact area that controls stress transfers (e.g., shear strength, volume change) or inter-phase mass transfers (e.g., chemical adsorption, volatilization) (Barbour 1995). These inter-phase relationships can be derived from the soil-water characteristic curve data and consequently can be used to estimate unsaturated soil properties. This paper is an attempt to describe the phase relationships from a saturated condition to a dry condition. A graphical procedure to define the residual state using the entire soil-water characteristic curve data is also presented.

SOIL-WATER CHARACTERISTIC CURVE - TRADITIONAL MODEL

The soil-water characteristic curve defines the relationship between water content and soil suction. The water content can be represented by gravimetric water content, volumetric water content, or the degree of saturation. The key features of the soil-water characteristic curve are illustrated in Figure 1 and include the air-entry value, $(u_a - u_w)_{aev}$, and the residual degree of saturation (S_r) with the corresponding suction $(u_a - u_w)_r$. Conceptually, the air-entry value represents the differential air pressure minus water pressure that is required to cause desaturation of the largest pores (i.e., "air entry"). Residual saturation is can be understood to be the degree of saturation at which the liquid phase begins to be discontinuous. Consequently, it is considered to be the suction value beyond which it becomes increasingly difficult to remove water from sample by drainage. Traditionally the soil-water characteristic curve has been defined over a limited range of suctions from zero to 1500 kPa. A suction value of approximately 1500 kPa corresponds to the wilting point for many plants and is often used to define the residual suction; however, this may not actually correspond with a "residual" condition.

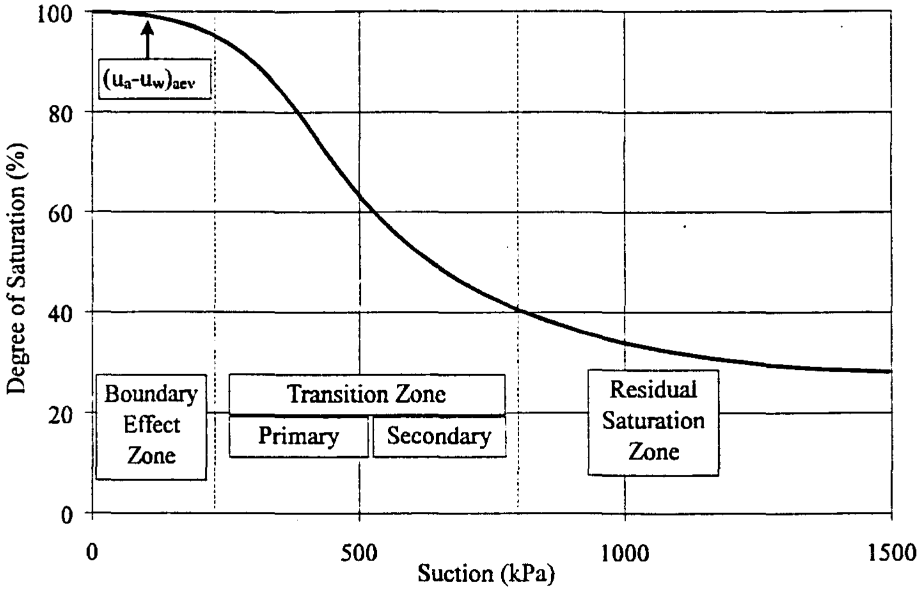
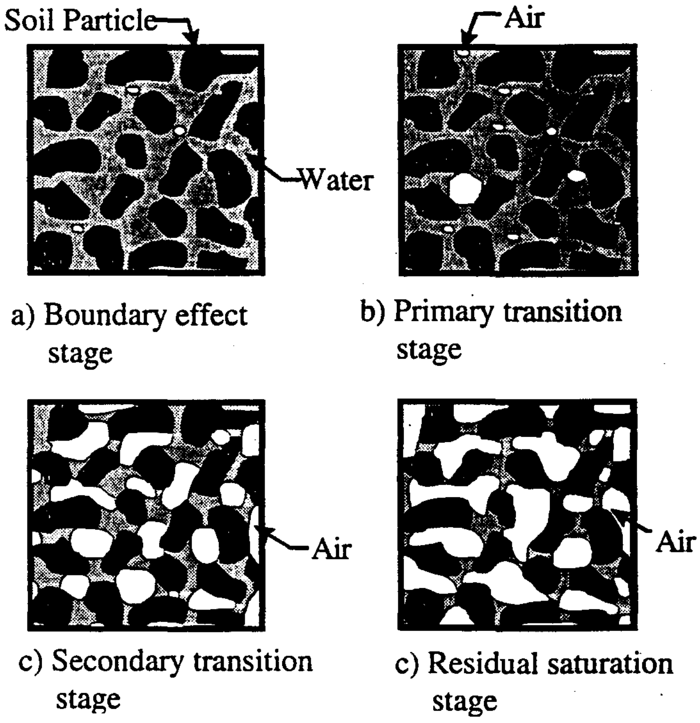


FIGURE 1 Typical soil-water characteristic curve illustrating key features and stages of drainage.

Some authors show suction along the soil-water characteristic curve to increase asymptotically to infinity as the degree of saturation approaches the residual state (Nitao and Bear 1996). This residual state for gravel, sand, and silt is well-defined and occurs at relatively low values of suction (i.e., 0 to 300 kPa). However, for fine-grained soils the residual state may be difficult to define. For clays of low plasticity, the residual state may be expected to be in the range of 500 to 1,500 kPa; however, for intermediate to highly plastic soils, the residual state can be greater than 1,500 kPa. In several cases (e.g., highly plastic clays), it is difficult to define a residual state.

There are three identifiable stages of desaturation (Figure 1); namely, the boundary effect stage, the transition stage (i.e., primary and secondary) and the residual stage of saturation. Figure 2 illustrates the variation in the wetted area of contact for the different stages of the Soil-Water Characteristic Curve. In the boundary effect stage almost all of the soil pores are filled with water. The soil starts to de-saturate at the air-entry value in the transition stage. The flow of water is in the liquid phase as the applied suction increases. The soil de-saturates rapidly with increasing suction. The connectivity of the voids or pores continues to reduce with increased values of suction and eventually large increases in suction lead to relatively small changes in the degree of saturation. This stage is referred to as the residual stage of saturation.

The various phases for a soil-water characteristic curve for a typical uniform sand can also be seen in the confocal microscope photographs taken using a Bio-Rad MRC-600 scanning confocal laser, mounted on a Nikon Microphot-FXA microscope (Figure 3). In this photograph the white color is water, the dark color is soil particles and the grey is the air phase. It can be seen that even as the air begins to penetrate the soil pores, the geometry of the air phase is influenced by the pore-geometry. The curvature of the meniscus continues to increase as drainage proceeds. It is also evident that even when the pore appears to be completely drained a liquid phase continues to exist within the pore-throats and as an adsorbed film along the particle surface.



a) Boundary effect stage

b) Primary transition stage

c) Secondary transition stage

c) Residual saturation stage

FIGURE 2. Illustration of various stages of a soil-water characteristic curve (Vanapalli 1994)

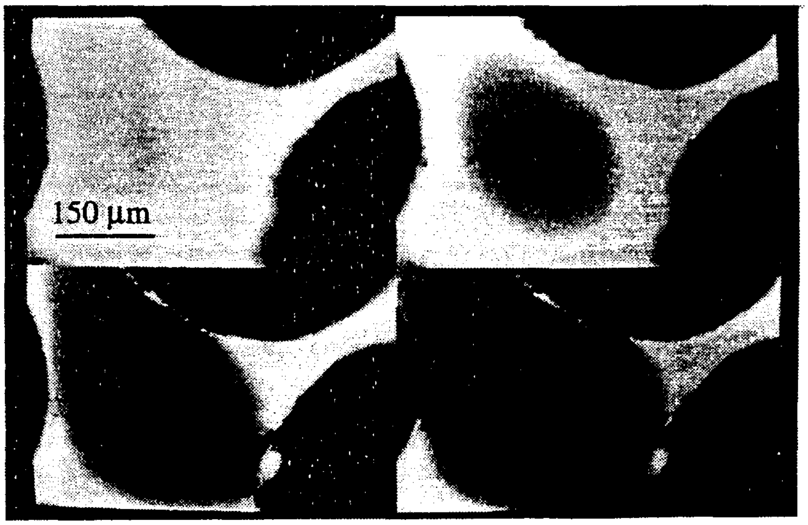


FIGURE 3. Bio-Rad MRC-600 photograph showing various stages of saturation for a sand

EXTENSION OF SOIL-WATER CHARACTERISTIC CURVE TO 1,000,000 kPa

Models based on soil-water characteristic curve data developed for a limited range of suction (i.e. 0 to 1500 kPa) may not be suitable for the prediction of unsaturated flow properties at low water contents and high suctions. For example, in the prediction of cover performance, estimates of actual evaporation are required. These predictions require that the soil-water characteristic curve be defined at suctions exceeding 3000 kPa (Wilson et al. 1994).

There appears to be a common value of total suction (i.e., the sum of matric suction and osmotic suction) at which all soils approach zero water content. The suction value corresponding to zero water content is approximately 1,000,000 kPa. Experimental results of Fredlund (1964), Vanapalli (1994) and Russam (1958) on various soils using pressure plate and desiccator tests for determining soil-water characteristic curves support this phenomenon. This experimentally observed behavior is also supported using thermodynamic principles (Richards 1965). Luckner et al. (1991), however, expressed some concerns about using a soil-water characteristic curve defined over the entire range of suctions based on pressure plate and dessicator tests since these techniques are based on different modes of water movement (i.e., liquid flow versus vapour migration). If the soil-water characteristic curve is viewed from a phenomological point of view, however, the total suction represents the total energy deficiency in the water phase. Whether equilibrium with that energy state is obtained by liquid flow or by equilibration with the vapour phase is not of concern for the definition of the soil-water characteristic curve, although it should be taken into consideration when the soil-water characteristic curve is used to predict the behavior of unsaturated soils.

Typical soil-water characteristic curves for various soils for the entire range of suction are shown in Fig. 4. These curves illustrate that the key features of the air-entry value and residual degree of saturation are still well defined for most soils. A coarse-grained soil such as a gravel or sand has large interconnected pores and shows a tendency to desaturate at a fast rate with increasing values of suction. The rate of desaturation decreases with an increase of fines. The water holding capacity or storage capacity of a soil which corresponds to a particular value of suction, is higher for a soil with a higher percentage of fines. The air-entry value is also higher for soils which have more fines.

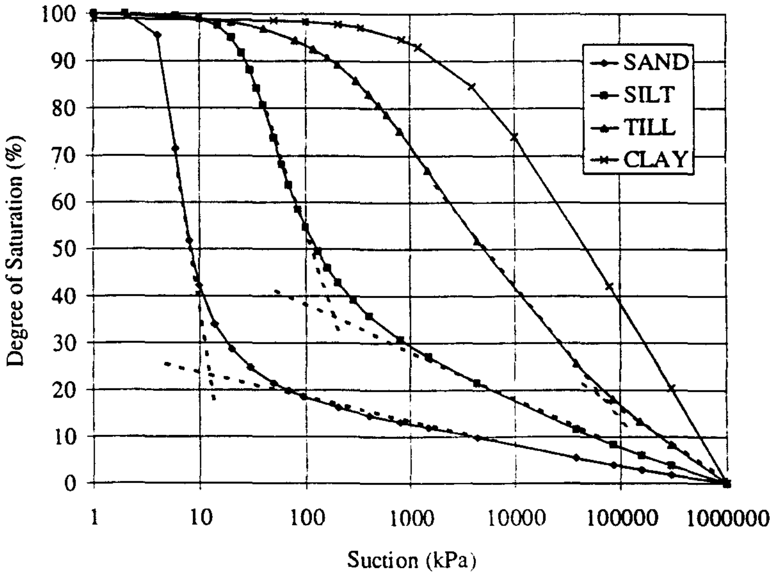


FIGURE 4. Typical soil-water characteristic curve for four soils from Saskatchewan, Canada.

Distinguishing features of the soil-water characteristic curve, such as the air-entry value and the residual state, for fine-grained soils depend on several factors such as soil structure (and aggregation), initial water content, void ratio, type of soil, texture, mineralogy, stress history, method of compaction (Vanapalli 1994). Compacted fine-grained soils typically have two levels of structure, a macro level and a micro level. The soil microstructure, is described as elementary particle associations within the soil aggregates, whereas the arrangement of these soil aggregates is referred to as the macrostructure (Mitchell 1993). The resulting structure of compacted specimens of fine-grained soils will be different if they are prepared at different initial water contents. Consequently, the soil-water characteristic curve of such specimens will also be different. A fine-grained soil, compacted at dry of optimum conditions has an open structure with relatively large interconnected pores and desaturation behavior is similar to that of a sandy soil. The pore spaces for the same soil compacted at a water content wet of optimum are not generally interconnected or are in an occluded state. These soils have a higher storage capacity due to their different structure. There are no visible inter-clod pores in these soils, therefore there is more resistance to desaturation under an applied suction than for specimens compacted dry of optimum. The boundary between the occluded pore space and the open pore conditions occurs approximately around the optimum water content (Marsall 1979). Typical soil-water characteristic curves of a glacial till compacted at different initial water contents are shown in Figure 5.

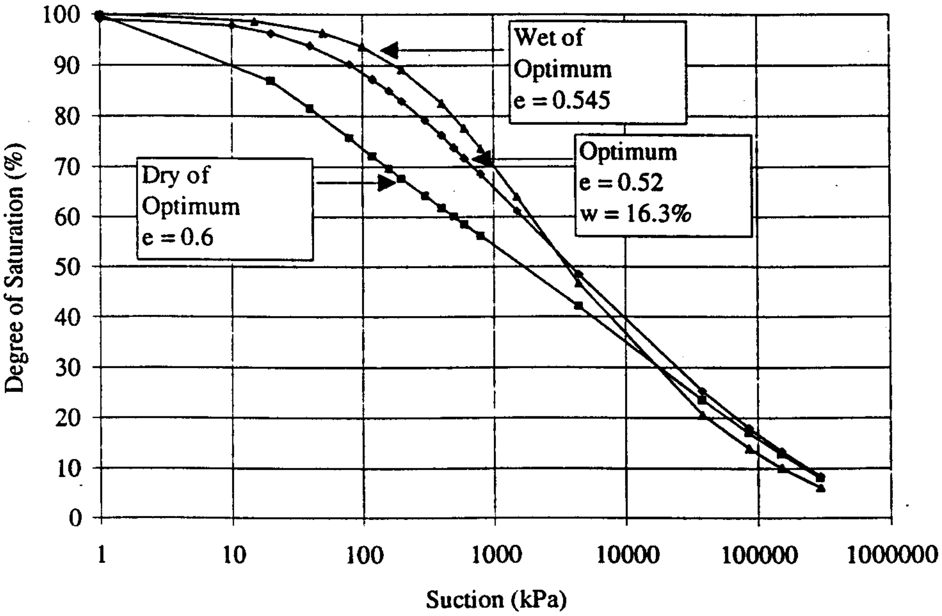


Figure 5. Soil-water characteristic curves for a glacial till compacted at different water contents

There is no general consensus in the literature with respect to the definition of residual suction or the residual state in soils. It is often necessary to define residual conditions in order to obtain the fitting parameters in numerical models such as those proposed for predicting permeability (van Genuchten 1980; Fredlund et al. 1994) or shear strength (Vanapalli et al. 1996; Fredlund et al. 1995). Such equations offer computational advantages and are useful in developing closed form solutions. However, when the entire suction range is used to define the soil-water characteristic curve, a graphical procedure can be used to define the residual condition (Figure 4). This procedure is similar to the Casagrande construction for finding the point of 100% consolidation on a deflection versus log time relationship. The Casagrande procedure involves first drawing a tangent line through the inflection point on the straight line portion of the soil-water characteristic curve. The residual state can be defined as the point where the line extending from 1,000,000 kPa intersects the previous tangent line. This procedure appears to be suitable for most soils except for very fine soils, such as expansive soils and slurried soils, which desaturate continuously without exhibiting a distinct break.

SUMMARY

There appears to be increasing use of the soil-water characteristic curve in the prediction of unsaturated soil properties. Numerous investigators are using the soil-water characteristic curve defined over the suction range of zero to 1,000,000 kPa for predicting properties such as the coefficient of permeability and shear strength. These models have a definite advantage for predicting unsaturated soil properties over the entire range of suction and water contents. The graphical procedure presented in this paper is proposed for those cases in which a residual state must be defined. More fundamental research however is recommended to fully understand the soil-water characteristic curve, particularly as it relates to the development of methods for estimating the properties of unsaturated soils.

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