Suggestions and recommendations for the interpretation of soil-water characteristic curves

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ABSTRACT: The soil-water characteristic curve has proven to be extremely useful in the application of unsaturated soil mechanics into geotechnical and geo-environmental engineering. Much information regarding the soil-water characteristic curve has been gleaned from other disciplines and consequently, there have been a variety of terminologies and meanings that have come into geotechnical engineering. This paper attempts to advocate a consistent terminology as well as consistent manners for plotting and interpreting the data. A series of suggestions and recommendations are proposed for presenting soil-water characteristic curve data. An attempt is also made to clarify some of the common misconceptions surrounding the soil-water characteristic curve.

1 INTRODUCTION

Soil-water characteristic curves are taking on an increasingly important role in the application of unsaturated soil mechanics to geotechnical and geoenvironmental engineering. Soil-water characteristic curves have long been a part of soil science, soil physics, agronomy and other agriculture-related disciplines. The use of the information contained in soil-water characteristic curves has developed rapidly and it would be beneficial to have some consistency in the terminology and units of measurement, and have recommendations regarding the format for presentation and interpretation of the data.

The primary objective of this paper is to present a series of recommendations and suggestions for geotechnical and geoenvironmental engineering, regarding the presentation and interpretation of soil-water characteristic curve data. It is understood that all recommendations and suggestions will not be acceptable to all engineers for all types of problems but hopefully there can be improved consistency with respect to presentation and use of soil-water characteristic curve data.

2 TERMINOLOGY

There is a lack of consistency in the terminology used to describe the relationship between the amount of water in a soil and soil suction. The lack of a consistent terminology is primarily the result of having numerous disciplines involved with measuring and using the data. The desire, however, is to encourage greater consistency on terminology for the disciplines of geotechnical and geoenvironmental engineering.

Some of the terms used when referring to the relationship between the amount of water in the soil and soil suction, are as follows:

i) soil-water characteristic curve
ii) soil-water characteristics
iii) retention curves
iv) moisture retention curves
v) soil moisture retention curves
vi) water retention curves, and
vii) numerous other terms.

The recommendation is that the term "soil-water characteristic curve" be used in civil engineering related disciplines. The preference is to use "soil-water" because it is the water content of the soil that is measured. The preference is to use the word "characteristic" simply because it appears to have historically been the most common term used in engineering. In addition, the "characteristic" implies that the curve describes the character or the behaviour of the soil. The word "retention" is more closely related to retaining water for plant growth in agriculture.

It is important to view the soil-water characteristic curve as the relationship in one plane of the volume-mass constitutive relationships as shown in Fig. 1. Two independent constitutive volume-mass relationships are required for an unsaturated soil since the overall volume of the soil and the water content of the soil can vary in independent manners. The actual volume and amount of water in the soil must be related to two independent sets of stress state variables (or stress tensors). Soil mechanics in geotechnical engineering has generally focused on applying total stresses to the soil and measuring the volumetric (or void ratio) response. On the other hand, agriculture-related disciplines have applied suctions to a soil and measured the amount of water retained in the soil. Consequently, the two disciplines have focused on different planes of the constitutive surfaces and on two different phenomena. In reality, the soil-water characteristic curve is a function of two independent stress state variables and therefore relating the water content to soil suction is an approximation.

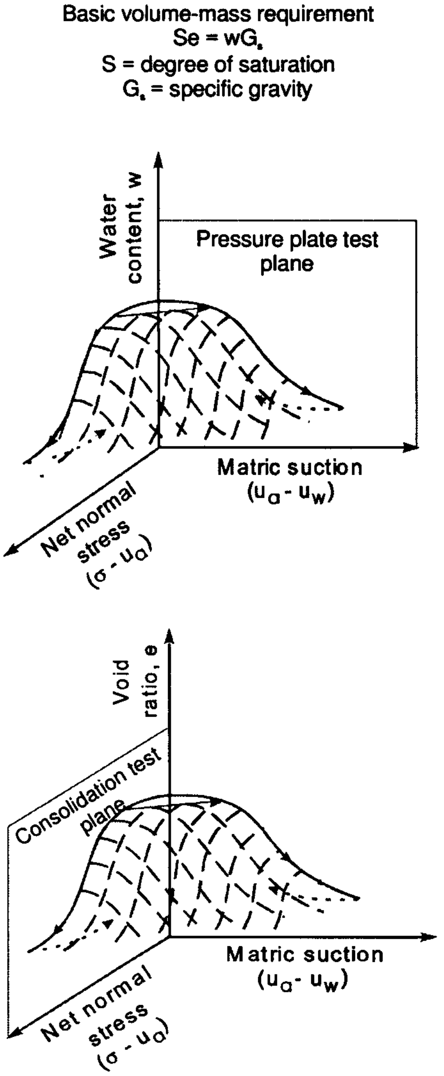

Figure 1. The two independent volume-mass constitutive surfaces showing the two limiting surfaces that have been used to measure soil properties

It is the soil-water characteristic curve information that becomes of primary importance in geotechnical engineering for the estimation of unsaturated soil property functions. These functions are required for seepage, shear strength, volume change, as well as other soil mechanics types of problems. Much information has been transformed from soil science and soil physics, into the field of unsaturated soil mechanics. It is important to give credit to the soil science and soil physics disciplines but it is also important to have the most appropriate terminology, system of units, presentation and interpretation procedures for engineering purposes.

The terminology associated with the suction of a soil has also not been consistent throughout the literature. It is suggested that the term, “soil suction”, be used when referring to either total suction or any component of suction in a general sense, or when more than one component of suction is plotted on the same scale of a graph. When reference is made to a specific component, the name of the component should be used. Also, the spelling of the names of the components should be consistent with the original definitions found in the soil science literature. The component of suction related to the capillary phenomenon should be called “matric suction”, and the component of suction related to the amount of salts in the pore fluid should be called, “osmotic suction”.

3 COMPONENTS OF SOIL SUCTION

There are numerous factors that have been suggested as contributing factors to soil suction (Nakano, 2001). At the same time there appears to be two primary components of soil suction; namely, matric suction and osmotic suction. Krahn and Fredlund (1972) tested two soils and independently measured the matric, osmotic and total suctions of numerous specimens (Figure 2). The test results showed that the matric plus the osmotic components of suction, essentially add up to total suction. While there may be other components of soil suction, it would appear that the matric and osmotic components are the dominant components making up total suction.

From thermodynamic considerations it has been hypothesized that there are two primary mechanisms that can result in a vapor pressure reduction at the air-water interphase (i.e., contractile skin). The mechanisms are a curved meniscus giving rise to matric suction and salts in the pore fluid giving rise to osmotic suction. Geotechnical Engineers are most commonly solving problems related to changes in the negative pore-water pressure of the soil. Consequently, it is the matric suction component that is of most relevance in unsaturated soil mechanics, just as positive pore-water pressures are of greatest importance in saturated soil mechanics.

There are two types of plots found in the literature where soil suction is plotted versus water content. Figure 2 shows the initial components of soil suction on as-compacted soil specimens. This is NOT a soil-water characteristic curve since it is pos sible to take each of the data points and continue on to measure the soil-water characteristic curve for the specimen. In other words, each data point would be considered as a "new soil" since each specimen may have a different soil structure and subsequently yield a different soil-water characteristic curve. It is suggested that the as-compacted water content versus soil suction plot have the axes reversed from those of a soil-water characteristic curve in order to assist in avoiding confusion.

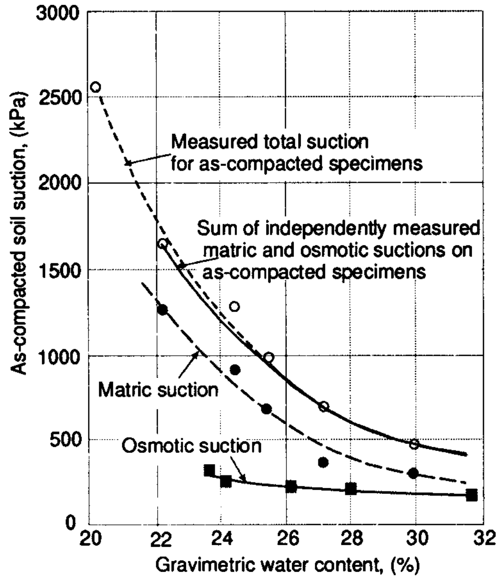

Figure 2. Independent measurements of matric, osmotic and total suction for a clayey soil compacted at various water contents.

4 COMPONENTS OF SOIL SUCTION ON THE SOIL-WATER CHARACTERISTIC CURVE

Considerable confusion has arisen in the application of soil-water characteristic curve information in geotechnical engineering. The confusion arises primarily over the mixed components of suction commonly plotted to make up the soil-water characteristic curve. Pressure plate apparatuses are generally used to apply suctions up to 1500 kPa. The water contents at equilibrium are measured. Vacuum desiccators are generally used to equilibrate small soil specimens for suctions greater than 1500 kPa. The equilibrium water content corresponds to total suctions. The matric and total suction data obtained in the laboratory, are routinely plotted on the same graph. In other words, the lower values of soil suction are matric suction while the higher values of suction are total suction.

The total suction values are generally in the residual suction range for the soil. Figure 3 shows how the two components of soil suction inter-relate to total suction for a silty clay soil. It is not suggested that there be any change in the manner in which soil-water characteristic curve data is routinely plotted. There simply needs to be a recognition that mixed components of suction are being plotted and that the mechanisms related to classic soil mechanics (i.e., seepage, shear strength and volume change), are quite different in the low and high soil suction ranges. For example there can be hydraulic flow of liquid water in a soil up to residual suction conditions but it appears that vapor flow moisture is of most significance in the residual suction range.

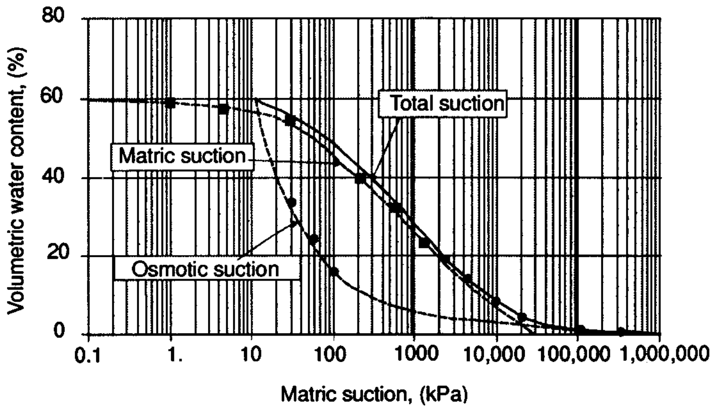

Figure 3. The components and total suction for a typical silty clay soil.

5 UNITS OF SOIL SUCTION

One of the first units used as a measure of soil suction was pF. The pF unit is equal to the logarithm (to the base 10) of the absolute value of a column of water in centimeters that equilibrates with the suction in the soil. The pF scale was widely used in agronomy and soil physics for many years. More recently there appears to be a substantial move towards an acceptable SI system of units.

There are numerous disadvantages to using the pF system of stress measurements for engineering. For example, the pF scale does not translate across the water table from positive to negative pore-water pressures. This gives the perception that there is a division between positive pore-water pressure and negative pore water pressure conditions (i.e., between saturated soil mechanics and unsaturated soil mechanics). Also, the logarithm is being taken of a negative water head. But most importantly, pF is not an acceptable SI unit of measurement.

The most commonly used unit for soil suction appears to be kilopascals, kPa. When referring to high suctions it might be preferable to use Megapascals (i.e., 1000 kPa = 1 MPa). There are many other units of stress used in the literature for soil suction (e.g., psi, psf, kgf/cm^2, tsf, etc). There may be need to use different units for soil suction in some cases but there are definite benefits related to ease and accuracy of interpretation related to using a consistent set of units such as kPa.

6 RANGE OF UNITS OF SOIL SUCTION

There is an upper and lower limit to the range for soil suction. The lower limit is zero. This corresponds to the case of zero pore-water pressure and (theoretically) no salts in the pore fluid when considering total suction. The upper limit of soil suction corresponds to a dry soil (i.e., zero water content). The upper limit of soil suction is generally in the order of 1,000,000 kPa. Soil suction approaches, approximately 1,000,000 kPa when a soil has lost all its water and the relative humidity approaches zero.

Soil-water characteristic curve data are usually plotted with soil suction on a logarithmic scale since the data vary over several orders of magnitude. Therefore, the maximum soil suction has a logarithm of 6 on the SI scale. Unfortunately, there is no lower limit on the logarithm scale as soil suction approaches zero. The logarithm scale is particularly valuable for determining the air-entry value and residual conditions for the soil.

It is recommended that soil-water characteristic curve data always be plotted on a logarithmic scale for interpretation purposes. This applies regardless of the soil suction range over which measurement have been made. It is recommended that the lower limit of soil suction required for most cases is about 0.1 kPa. This is essentially the lowest suction that can be applied to a soil through a high air entry disk. Figure 4 shows an example of a soil-water characteristic curve data set (desorption or drying curve) with soil suction plotted from 0.1 to 1,000,000 kPa. Even if there may not be any data in the high suction range, it is still possible to get a perspective or "feel" for the entire soil-water characteristic curve.

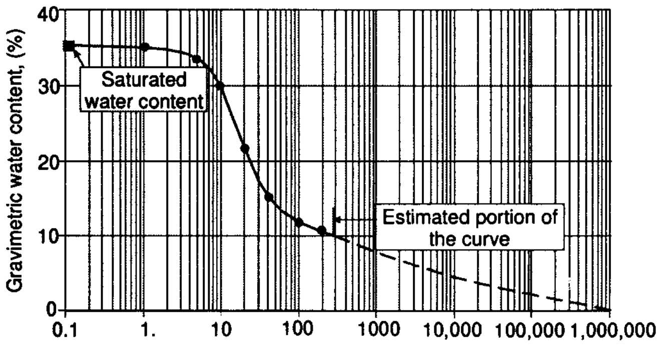

Figure 4. Typical soil-water characteristic curve data set (desorption or drying branches) for a sandy soil.

It is recognized that it may also be of benefit to plot portions of the soil-water characteristic curve at an expanded scale when solving engineering problems.

Klute (1996) suggested that there was a need to separate the drying curves into i.) an initial drying curve, IDC, and ii.) a main drying curve, MDC. Most data assembled in data bases comes under the IDC category. The other portion of the hysteresis loop was called the main wetting curve, MWC.

7 DESCRIPTION OF THE AMOUNT OF WATER IN THE SOIL

There have been numerous designations used as a measure of the amount of water in the soil. The three most basic measures are:

i) volumetric water content, θ_w,
ii) gravimetric water content, *w*, and
iii) degree of saturation, *S*.

All three of the above variables will convey similar information to the engineer provided the structure of the soil is essentially incompressible. Clayey soils may undergo volume change as a result of a soil suction increase. In this case, it is the degree of saturation variable that provides the indication of the air entry value of the soil.

Volumetric water content has most commonly been used in agriculture-related disciplines when plotting soil-water characteristic curve data. Volumetric water content is defined as an instantaneous water content in the sense that the volume of water in the soil is referenced to the present total volume. However, it is generally not the instantaneous volumetric water content that is being plotted since the volume of water is usually referenced back to the original volume of soil. Consequently, both the gravimetric water content representation and the volumetric water content representation portray similar information.

It is recommended that gravimetric water content be used when plotting the soil-water characteristic curve for geotechnical engineering. This is particularly true when continuous volume measurements have not been made. At the same time, it is recognized that volumetric water content appears in the formulation of transient flow processes when using a referential element. Care must be exercised when using volumetric water content to ensure that the correct reference volume is used in both the mathematical formulations and the laboratory measurements. If continuous volume measurements are made during laboratory testing, then volumetric water content, θ_w, or degree of saturation, S, can be used in plotting the soil-water characteristic curve. If the volume of water in the soil is always referenced back to the original total volume, then is is better that this variable simply be referred to as, V_w/V_t where V_w is the present volume of water and V_t is the initial total volume of the soil specimen.

If the soil-water characteristic curve data is to be used to estimate unsaturated soil property functions, it is of benefit to normalize or dimensionalize the water content scale. The dimensionless water content, Θ_d, can be defined as follows:

$$\Theta_d = w / w_s \qquad (1)$$

where: w = any gravimetric water content, and w_s = gravimetric water content at saturation.

The total range of water contents from the saturated state under zero confining pressure to zero water content, are reduced to a scale of 1.0 to 0.0, respectively.

The normalized water content, Θ_n, can be defined as follows:

$$\Theta_n = (w - w_r)/(w_s - w_r) \qquad (2)$$

where: w_r = gravimetric water content at the commencement of residual conditions.

There are roles for each of these definitions in geotechnical and geoenvironmental engineering. For example, the overall soil-water characteristic curve may need to be best-fit to obtain three soil parameters (i.e., *a, n,* and *m* when using the van Genuchten (1980) or the Fredlund and Xing (1994) soil-water characteristic curve equations), corresponding to the dimensionless water content plot. This information allows the air entry value, the inflection point, and the residual point to be at determined

The data can then be plotted to a normalized water content scale with the omission of data points in the residual range. A second best-fit analysis of the revised data set can be performed with one of the soil parameters (i.e., *m* soil parameter), set to 1.0. Research into the coefficient of permeability, the shear strength and the volume change behavior of unsaturated soils, it is suggested that the normalized water content provides a superior presentation for understanding unsaturated soil property functions.

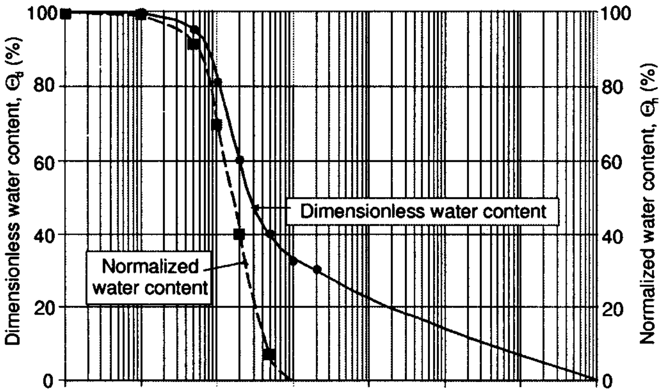

Figure 5. The data for the sandy soil shown in Figure 4 plotted as dimensionless water content and normalized water content.

Figure 5 shows the data presented in Figure 4 plotted both in terms of dimensionless water content and normalized water content.

8 COORDINATE SYSTEM FOR PLOTTING SOIL-WATER CHARACTERISTIC CURVE DATA

A review of the research literature indicates that numerous graphical representations have been used for soil-water characteristic curve data. Soil suction has been plotted on the abscissa or on the ordinate, and it has been plotted on an arithmetic or logarithm scale. The same is true for the water content of the soil. There may be a need, in some cases, to use different types of plots but there is also benefit in using one consistent set of coordinates for plotting the data.

It is recommended that soil suction be plotted on the abscissa and water content be plotted on the ordinate. It is further recommended that soil suction be plotted to a logarithmic scale ranging from (possibly) 0.1 kPa to 1,000,000 kPa. It is not always possible to obtain an even distribution of data points along the semi-log plot of soil suction; however, a typical distribution of data points might be as follows: 1, 2, 5, 7, 10, 20, 50, 70, 100, 200, 500, 700, 1000, 10000, 20000, 50000, and 100,000 kPa.

It is suggested that the basic plot use gravimetric water content on the left side of the graph with dimensionless water content scaled on the right side of the graph (Fig. 5).

By using similar axes and similar scales for all soils, it is possible to more clearly anticipate the phenomenological behavior of the soil. The break points along the soil-water characteristic curve (i.e., air entry value and residual suction) should be as obvious as is possible from the data. A sandy soil will have a soil-water characteristic curve that is definitely different from that of a clayey soil.

Figure 6 shows an example of a poor selection of scales and coordinates used for the plotting of the soil-water characteristic curves for two residual soils. The same data are re-plotted in Fig. 7 using the recommended scales and procedures. It is possible on the latter plot to more readily interpret the significance of the data. For example, the air entry value becomes more definite and residual conditions can be estimated.

Variables that should be defined from the soil-water characteristic curve, if possible, are the:

i) saturated water content, w_s
ii) air entry value, ψ_{aev}
iii) inflection point suction, ψ_{inf}
iv) inflection point water content, w_{inf}
v) slope at the inflection point, n_{inf}
vi) residual suction, ψ_r, and
vii) residual water content, w_r.

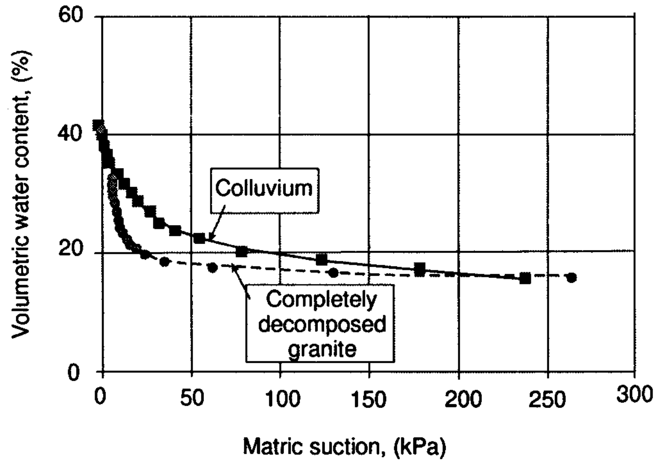

Figure 6. Soil-water characteristic curve data for two residual soils plotted in a manner somewhat difficult to interpret.

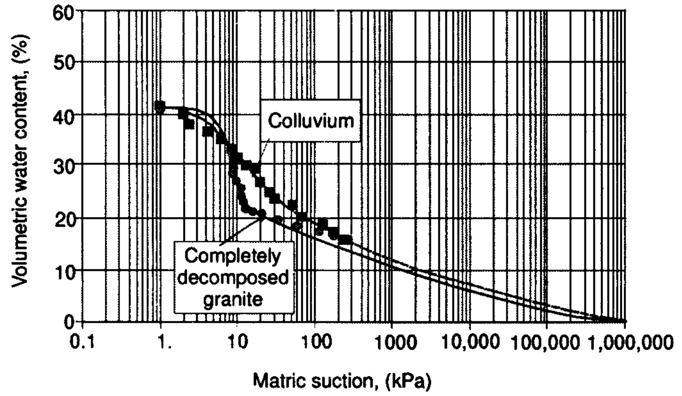

Figure 7. The soil-water characteristic curve data plotted to the recommended scales for the two residual soils shown in Figure 6.

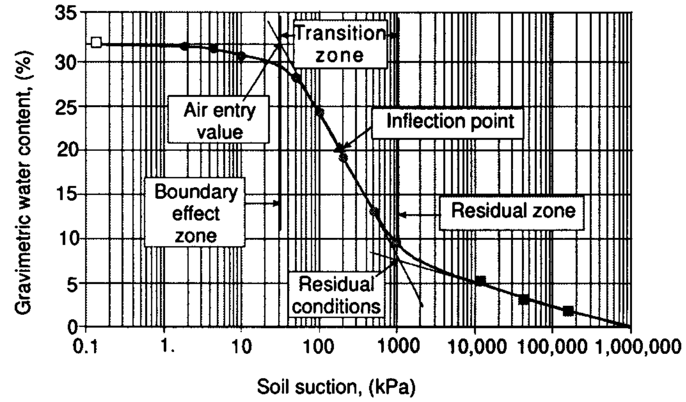

Figure 8. A pressure plate and vacuum desiccator data set showing the construction procedures to obtain the air entry value and the residual water content.

Figure 8 shows an ideal data set along with the definition of each of the above variables. The graphical procedure to determine each of the above variables is also shown in Fig. 8. Straight lines on a semi-log plot are necessary for the constructions. The first line is horizontal through saturation water content. The second line passes tangent to the steepest portion of the soil-water characteristic curve data. The third line passes through 1,000,000 kPa and extends back through data points at high suctions (provided the data are available).

9 CONCLUDING REMARKS

Soil-water characteristic curve is proving to be extremely valuable in the implementation of unsaturated soil mechanics into routine geotechnical engineering practice. There has been a lack of consistency in presenting and interpreting soil-water characteristic curve data. This paper provides suggestions and recommendations for producing greater consistency to the interpretation of the data. With improved consistency in the definitions of all variables involved, there will also be a clearer understanding of the meaning of all variables related to the soil-water characteristic curve.

The soil-water characteristic curve is hysteretic in the sense that there is an independent desorption (drying) curve and an independent adsorption (wetting) curve. While this behavior is recognized, it does not conflict with the suggestions and recommendations proposed in this paper. However, this paper has made use of the desorption curve in describing the interpretation of laboratory data.

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