GeoEdmonton
MOVING FORWARD 2018

Understanding the Family of Soil-Water Characteristic Curves

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ABSTRACT
Soil-Water Characteristic Curves, SWCCs, are a family of volume-mass variables versus soil suction. The SWCC relations are hysteretic in nature and consideration can be given to a number of volume-mass variables. Consequently, there can be many families of curves which are all referred to as soil-water characteristic curves (or water retention curves). It is the intent of this paper to define and describe the multitude of variables associated with the term SWCC.

RÉSUMÉ
Les courbes de retention d'eau, CRE, sont une famille de variables volume-masse par rapport à la succion matricielle du sol. Les relations CRE sont de nature hystérétique et on peut considérer un certain nombre de variables volume-masse. Par conséquent, il peut y avoir de nombreuses familles de courbes qui sont toutes appelées courbes caractéristiques sol-eau (ou courbes de rétention d'eau). L'objectif de cet article est de définir et de décrire la multitude de variables associées au terme CRE.

Introduction

Research in unsaturated soil mechanics over the past few decades has witnessed an ever-increasing reference to the role of the soil-water characteristic curve, SWCC (Fredlund, 2006). The SWCC has been referred to as the key to the implementation of unsaturated soil mechanics in geotechnical engineering practice (Fredlund, 2015). Along with the many references to the SWCC, there has also been considerable confusion about exactly what is meant by the term, SWCC.

The SWCC term has 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 relationships involve various volume-mass soil property values versus soil suction. Soil suction ranges from low values in the order of 0.01 kPa to a maximum value of 1,000,000 kPa (i.e., 7 orders of magnitude). As reported by Klute (1965, 1986), the bounding curves may represent 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). The term SWCC is also sometimes referred to as a unique relationship and as any relationship between the amount of water in a soil and soil suction.

Klute (1965, 1986) also 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. Soil suction may also mean matric suction, total suction or osmotic suction along with arbitrary boundaries between the components of soil suction. Variations in the water content and soil suction designations can lead to considerably different interpretations of laboratory test data (Fredlund and Rahardjo, 1993).

Some of the confusion related to the SWCC terminology is the result of attempting to import past experience and technology from soil physics (and other agriculture-related disciplines) into geotechnical engineering. There is much valuable information to be gleaned from past research in agriculture; however, care and caution needs to be exercised when moving between the two disciplines.

The objectives of this paper are as follows: i.) to define and thereby attempt to standardize appropriate terminologies most suitable for usage in geotechnical engineering practice when referring to the SWCC family of curves, and, ii.) to illustrate the application of use of laboratory measured gravimetric water content soil-water characteristic curve, SWCC, and a shrinkage curve for the estimation of a variety of SWCC relationships (Fredlund and Zhang, 2013). Hydraulic property functions for an unsaturated soil are used to illustrate the application of the family of SWCCs in this paper (Fredlund, 2002).

The authors are the first to realize that it is difficult to obtain a complete consensus on such a broad range of soil property relationships where past terminologies have been generated in different countries and for considerably different application areas. At the same time, the authors want to respect to the assumptions made in developing theories for the past usage of terms. The proposed terms and definitions are meant to form a starting point for discussion purposes and the authors trust that it may initiate further discussion related to the family of SWCCs and their application in geotechnical engineering practice.

The scope of this paper is limited to consideration of the SWCCs when estimating hydraulic property functions for unsaturated soils. It is suggested that similar reviews need to be undertaken for shear strength and volume change type problems.

Historical Assumptions and Definitions Used in Soil Physics

Researchers in soil physics and other agriculture-related disciplines became aware in the early 1900s that there was merit in assessing the relationship between the amount of water in the soil and the affinity with which water was held to the soil. The energy of attraction with which water was held in the soil was termed soil suction (Edlefsen, 1943). Soil suction was given units of stress (tension in the water phase) and referred to as matric suction for values up to approximately 1500 kPa and total suction in the higher suction range up to 1,000,000 kPa.

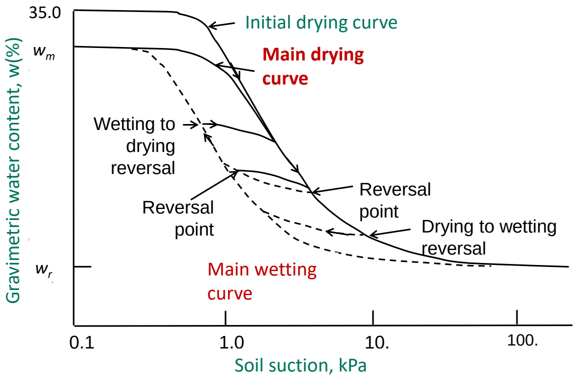

Figure 1. Typical family of SWCCs in terms of gravimetric water content (modified from Klute, 1965, 1985)

Water content versus soil suction was recognized as a family of curves as shown in Figure 1. It was also recognized that the "Main Drying" curve served well as an approximate indicator and the main reference curve for describing various aspects of unsaturated soil behavior.

Within the soil physics discipline the amount of water in the soil was usually quantified in terms of volumetric water content, θ_w, (i.e., volume of water divided by the total volume of the soil specimen). The assumption was usually made that the soil specimen never changed in overall volume as soil suction was increased. The assumptions related to the designation of water content and zero overall volume change need to be revisited when attempting to apply methodologies in soil physics in geotechnical engineering (Fredlund et al, 2012).

Soil-Water Characteristic Curves Required in Geotechnical Engineering

In geotechnical engineering, the amount of water in a soil has historically been measured in terms of gravimetric water content, *w*, (i.e., mass of water divided by mass of dry soil) (Terzaghi, 1943). The equivalent of Figure 1 plotted in terms of gravimetric water content is shown in Figure 2. Also shown in Figure 2 are suggested abbreviations that can be used to represent the "initial drying curve, the "main drying curve", the "main wetting curve" and the "scanning curves". While there is an entire family of SWCCs, it is the "main drying curve" which becomes most important for the application of unsaturated soil mechanics in engineering practice.

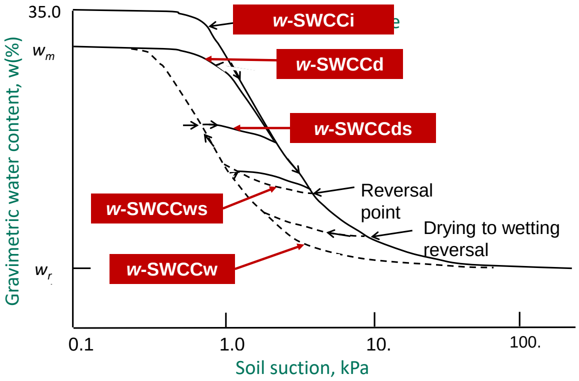

Figure 2. Suggested variables used to represent the family of curves associated with the gravimetric water content versus suction relations.

The experimental effort required to measure all the relationships associated with gravimetric water content versus suction is costly and in general, prohibitive. It is important to understand the physics associated with each of the constitutive relations (Fredlund and Morgenstern, 1976). However, more efficient means must be devised for their determination; namely, estimation procedures such as proposed in other agriculture-related disciplines (Klute, 1986). Only then can unsaturated soil mechanics' procedures be adopted in routine geotechnical engineering practice. As a minimum requirement it is suggested that the "main drying curve, *w*-SWCC$_d$" be measured in the laboratory. It is also suggested that the measurement of the shrinkage curve, SC, should also be considered as "routine" in order that estimation procedures can be used to obtain an understanding of the other SWCC family members.

Basic Measured Volume-Mass-Suction Relations

Figure 3 shows the two easiest unsaturated soil property relations that can be measured in soil mechanics laboratories; namely, i.) the gravimetric water content SWCC, and the ii.) shrinkage curve, (void ratio versus gravimetric water content). Once these two relations are know, other volume-mass relations can be calculated.

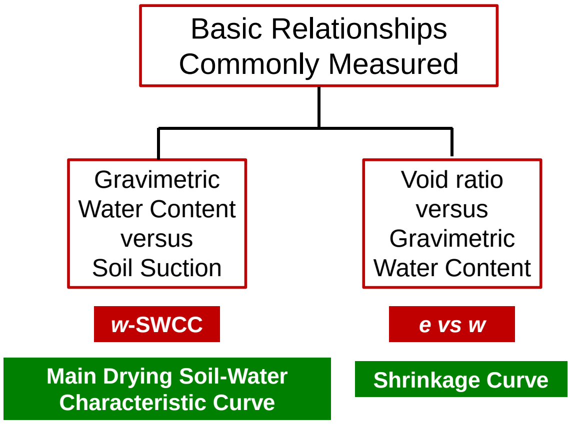

Figure 3. Basic volume-mass-suction relationships that need to be measured in the laboratory.

The authors would like to illustrate how a minimum amount of laboratory data can be used to gain an understanding of the volume-mass constitutive relations for an unsaturated soil. Figure 4. shows a typical set of laboratory test results on a silty clay soil. Gravimetric water contents for matric suctions up to 1500 kPa were obtained using a pressure plate device (Soilmoisture Equipment Corp, 1984; GCTS, 2011) and total suctions versus water content in the high suctions up to 1,000,000 kPa were obtained using a Chilled Mirror humidity device (Decagon, 2009).

The results in Figure 4 define the w-SWCC for the "main drying curve". The measurement of the "initial drying curve" would be preferable; however, it is often difficult to obtain 100% saturation in the soil specimen and it is argued that essentially the same information can be obtained from the "main drying "curve.

It is desirable to have a continuous functional equation that can span seven orders of magnitude commonly encountered in geotechnical engineering practice (i.e., from 0.1 kPa to 1,000,000 kPa). Several equations have been proposed for best-fitting laboratory data for the SWCC such as Mualem, (1976) and van Genuchten, (1980); however, the Fredlund and Xing (1994) equation appears to have an advantage over other proposed equations (Leong and Rahardjo, 1997; Yang et al, 2004). Only the Fredlund and Xing (1994) SWCC equation will be used for illustration purposes in this paper since it ends at 1,000,000 kPa at zero water content for all soils. Three main fitting variables are used to define the w-SWCC$_d$ curve along with the initial gravimetric water content of the soil.

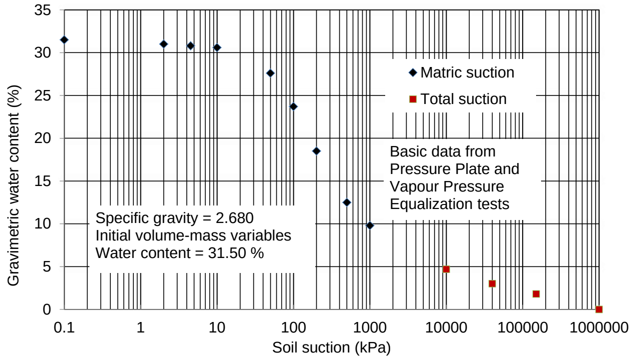

Figure 4. Typical drying gravimetric water content versus matric and total suction for a silty clay.

Figure 5 shows a typical Shrinkage Curve, SC, test data set for a silty clay soil (Haines, 1927; Fredlund et al, 2002). The soil specimen can be prepared in a similar manner for both the SWCC and the SC tests. The SC test specimen gradually dries by evaporation of water to the surrounding environment. Once the soil is air-dried, it can be over-dried. Then other water contents and volumes can be back-calculated. It is possible to best-fit the shrinkage curve data using the equation proposed by Fredlund, 2002; Fredlund et al, 2002). Three fitting variables are required for the shrinkage curve; however, two of the variables are related because the shrinkage curve test is always commenced from a near saturated condition.

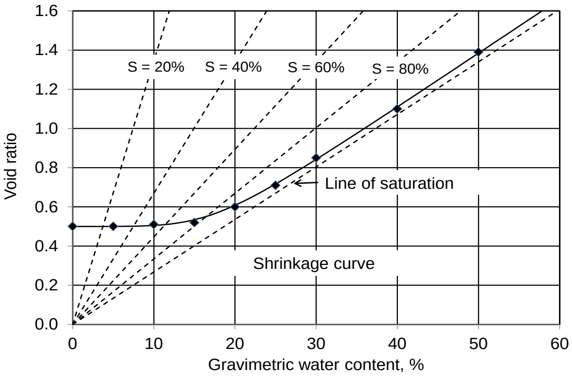

Figure 5. Typical data for the drying shrinkage curve for a silty clay soil.

Calculated Families of SWCCs Defined in Terms of Other Volume-Mass Properties

The complete constitutive behavior for an unsaturated soil should be defined in terms of two stress tensors (Fredlund and Morgenstern, 1977); namely, one tensor for net normal stress changes and the other for soil suction changes (Fredlund and Morgenstern, 1976; Pham and Fredlund, 2008)). However, only the effects of soil suction changes (i.e., drying and wetting) are considered in this paper.

Figure 6 shows the types of volume-mass versus soil suction relations that can be calculated once the basic measurements of the w-SWCC$_d$ and the Shrinkage Curve, SC, have been made. Only the Basic Volume-Mass relationship (i.e., $Se = w\, G_s$; Fredlund and Rahardjo, 1993), is required to complete the calculations for other members of the family of SWCCs. It is also necessary to make various assumptions regarding hysteresis in order to include the "wetting curves".

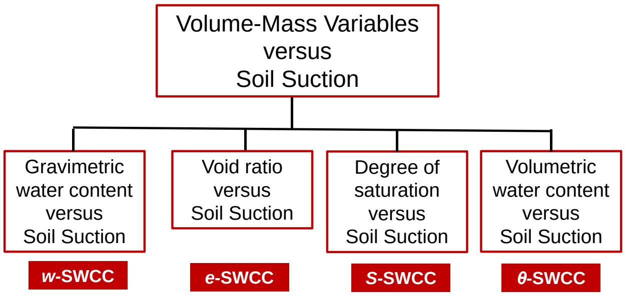

Figure 6. Types of volume-mass versus suction families of curves that can be computed.

The following figures illustrate the general form of the family of SWCCs for: i.) void ratio versus suction, *e*-SWCC, ii.) degree of saturation versus suction, *S*-SWCC, and iii.) volumetric water content versus suction, *θ*-SWCC.

Figure 7 shows the form of the i.) initial drying curve, *e*-SWCC*i*, ii.) main drying curve, e-SWCC$_m$, and the iii.) main wetting curve, e-SWCC$_w$. Possible scanning curves have not been shown in the figure. The "main drying" SWCC is computed based on substituting various suction values into the best-fit equations for e-SWCC$_d$ and the shrinkage curve equation. All of the void ratio relations reduce to a horizontal line when no volume changes occur as soil suction is increased.

Figure 8 shows the form of the i.) initial drying curve, *S*-SWCC*i*, ii.) main drying curve, S-SWCC$_m$, and the iii.) main wetting curve, S-SWCC$_w$. Possible scanning curves have not been shown in the figure. The "main drying" SWCC is computed by substituting various suction values into the best-fit equations for w-SWCC$_d$ and the shrinkage curve equation and calculating the degrees of saturation in accordance with the Basic Volume-Mass equation.

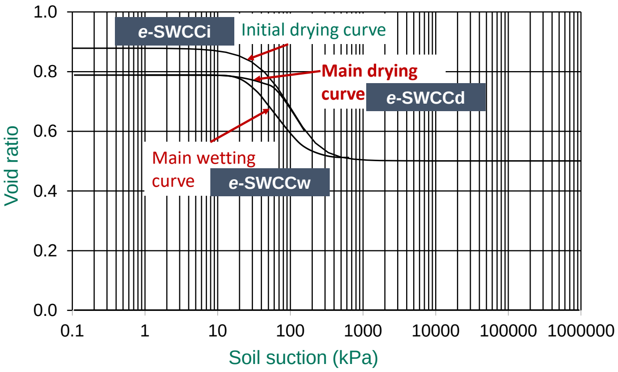

Figure 7. Void ratio versus suction SWCC associated with drying and wetting curves.

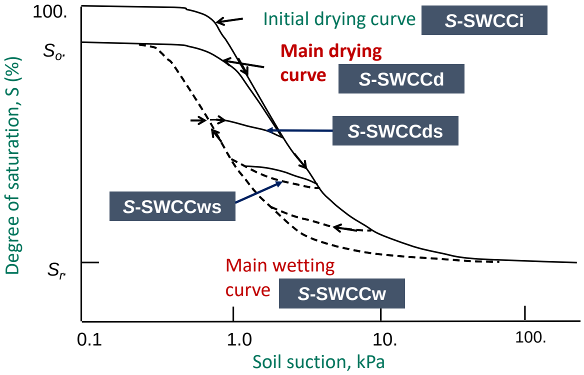

Figure 8. Variables to represent the family of curves associated with the degree of saturation versus suction relations.

The degree of saturation family of SWCCs provide the geotechnical engineer with similar information as obtained from the gravimetric water content SWCC as long as the soil does not undergo volume change as soil suction is increased. Many soils encountered in engineering practice do undergo volume change as soil suction is changed and as such it becomes important to compute all of the volume-mass properties versus soil suction. For example, the air-entry value, AEV, of a soil must be assessed on the basis of the main S-SWCC$_d$. If the soil has undergone volume change during drying, then the AEV measured on the degree of saturation SWCC can be considerably higher than that measured on the gravimetric water content SWCC.

There are several key variables that can be defined on the *S*-SWCC family of curves; namely, the Air-Entry value, AEV, and the Water-Entry value, WEV, of the soil. The AEV is defined based on an empirical construction procedure applied to the main drying curve. The commencement of desaturation is somewhat gradual; however, it is suggested that the intersection of the two lines shown in Figure 9 be referred to as the AEV of the soil.

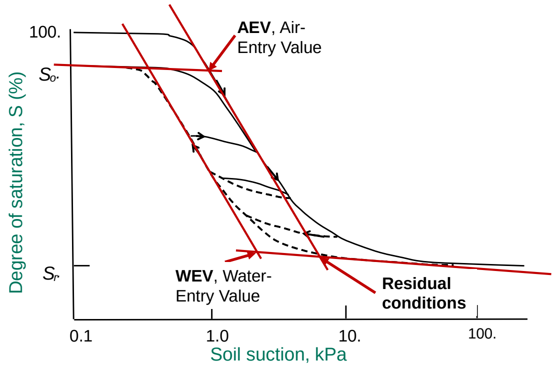

Figure 9. Degree of saturation versus suction family of curves showing the definitions for air-entry value, AEV, water-entry value, WEV, and Residual conditions, (θ_{wr}, ψ_r).

The Residual Condition for the soil can be defined as the point where the main drying curve intersects with a best-fit line in the high suction range (i.e., up to 1,000,000 kPa) (See Figure 9). The residual condition is best defined on the S-SWCC$_d$ curve and the intersection of the two construction lines should be defined using a residual degree of saturation and a residual suction.

The WEV of the soil is defined using a similar construction procedure applied to the main wetting degree of saturation curve, (i.e., S-SWCCw). WEV is the suction under which the water phase become "continuous" upon wetting the soil from an initially dry condition. Once again, the WEV can be empirically defined in accordance with the construction procedure illustrated in Figure 9.

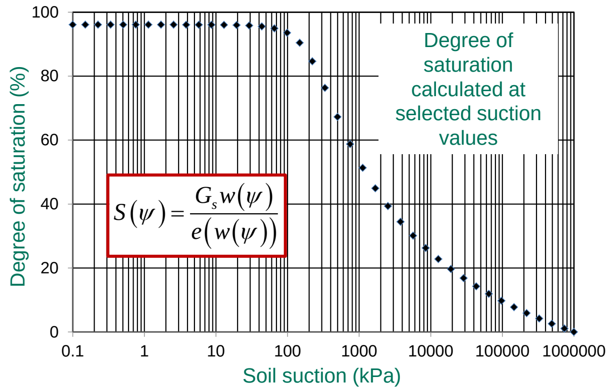

Figure 10. Calculated degree of saturation versus suction for the main drying curve.

Figure 10 shows the form of the main drying curve, S-SWCC$_d$, calculated based on the best-fit equations for the w-SWCC$_d$ and the SC. The "main drying" S-SWCC$_d$ is computed by substituting various suction values into the best-fit equations for w-SWCC$_d$ and the shrinkage curve equation and calculating the degrees of saturation in accordance with the Basic Volume-Mass equation as shown in Figure 10. The degree of saturation family of SWCCs provide the geotechnical engineer with similar information to that obtained from the gravimetric water content SWCC as long as the soil does not undergo volume change as soil suction is increased.

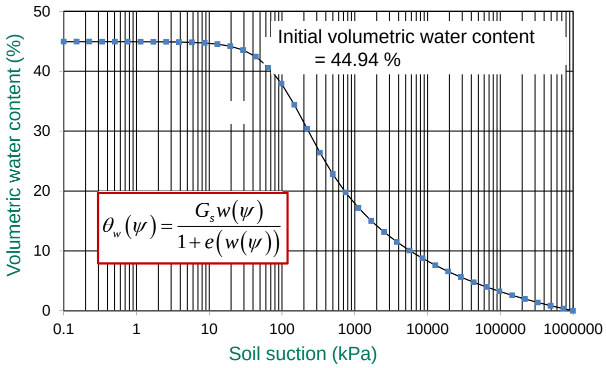

Figure 11. Volumetric water content, θ_w, SWCC for the main drying curve.

The volumetric water content SWCC is commonly used when determining the water storage function associated with transient seepage analyses. Figure 11 shows the form of the main drying curve in terms of volumetric water content, θ-SWCC$_d$, calculated based on the best-fit equations for the w-SWCC$_d$ and the SC. The "main drying" θ-SWCC$_d$ is computed by substituting various suction values into the best-fit equations for w-SWCC$_d$ and the shrinkage curve equation and calculating the degrees of saturation in accordance with the Basic Volume-Mass equation as shown in Figure 11.

Dealing with Hysteresis in Geotechnical Engineering

In general terms, all volume-mass relations for an unsaturated soil display hysteretic behavior. A couple of observed relations should be noted with respect to applications in geotechnical engineering practice. First, there is approximate parallelism between the drying and wetting SWCCs when plotted on a semi-log scale for suction. Second, the estimated shift at the inflection point on the curve can be approximated as a percentage of a log cycle. For example, the wetting curve inflection point might be assumed to be 50% of a log cycle below the inflection point value for the drying curve. Both of the above assumptions approximations and are dependent upon the soil type involved in addition to other factors (Pham et al, 2003, 2005).

Unsaturated Soil Property Functions

The estimation of the hydraulic property function associated with drying are used to illustrate the calculation of unsaturated soil property functions. Figure 12 shows a typical water storage function, m_2^w, for a silty clay soil. The water storage function is calculated by differentiating the θ-SWCC$_d$.

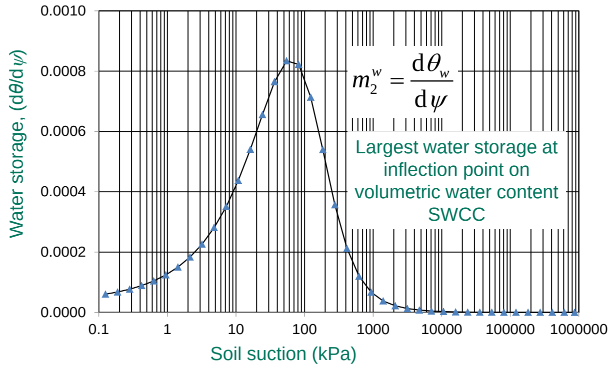

Figure 12. Typical water storage function for the main drying curve.

The permeability function for a soil is obtained by integrating along the SWCC. The integration should take place along the *S*-SWCC curve when determining the effect of changes in degree of saturation. The result of such an integration process for the typical silty clay soil is shown in Figure 13. The void ratio SWCC can be used in an independent manner to determine the effect of changes in void ratio (Zhang and Fredlund, 2015).

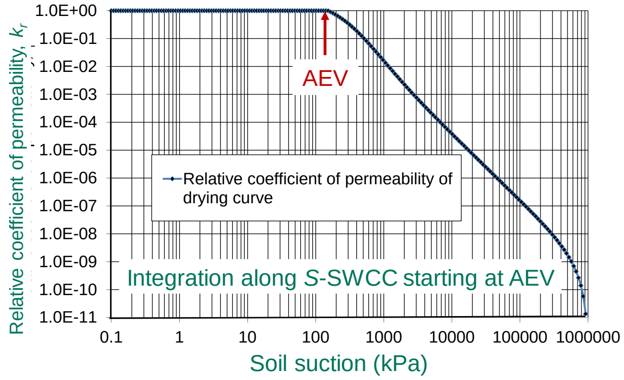

Figure 13. Typical permeability function for the main drying curve (assuming no volume change).

Conclusions

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 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. This paper provides definitions for all volume-mass versus suction relationships required for the estimation of unsaturated soil property functions.

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