Methods of Predicting Permeability Coefficient of Unsaturated Soils Using Soil Water Characteristics Curve

Tesfay Agele Gebru

Lecturer, Department of Natural Resource Management, Adigrat University, Adigrat, Tigray, Ethiopia

Abstract: *In the practical applications of unsaturated soil mechanics, the Permeability Coefficient (PC) is a key engineering soil property that influences the design safety of geotechnical structures. However, in the practical world, there is no engineering soil property that can vary more widely than that of the PC especially for unsaturated soils. Determination of the saturated PC either in the field or laboratory is relatively simple and not expensive. However, for unsaturated soils; it is time consuming, difficult and hence costly. So in most cases, predicting the PC by empirical or theoretical equations seems to be a good choice. Consequently, much of research attention has been shifted towards emerging semi-empirical and statistical models to predict the unsaturated PC using the saturated PC and the soil-water characteristic curve (SWCC). Thus this paper presents: 1) the nature and property of unsaturated soils with respect to their permeability behavior; 2) factors influencing the magnitude and direction of the unsaturated PC; 3) the explanatory power of the existing models of predicting PC of unsaturated soils using SWCC. Accordingly, wetting-drying cycles, compaction water content, stress state, and compaction energy are among parameters that influence the SWCC and the PC of unsaturated soils. Fredlund and Xing (1994) equation for SWCC was found effective in predicting the PC of unsaturated soils in the case where experimental soil-water characteristic data are not available. Generally, for a porous medium with an incompressible structure, the permeability function can be expressed in three different forms: empirical functions of soil suction or volumetric water content, macroscopic models based on the "effective" degree of saturation, and statistical models where the relative permeability is calculated from the SWCC. The models are interrelated to each other and one form of model can be transformed to another form.*

Key words: *Unsaturated soils; Permeability Coefficient; Soil water characteristics curve*

1. Introduction

The Permeability Coefficient (PC) is a key engineering property required in the design of geotechnical structures such as the earth dams, pavements, retaining walls and geo-environmental structures used for the management of agricultural, municipal, mine and nuclear wastes through the use of soil covers and liners. These days, engineers have pointed out that the flow behavior in soils both in saturated and unsaturated conditions are to be well understood to design soil structures based on rational procedures (Lobbezoo. and Vanapalli, 2002). Many geotechnical and geoenvironmental problems include consideration of water flow through unsaturated soil (Leong and Rahardjo 1997). This requires an understanding on the PC within the soil, but features of unsaturated soil are subject to constant change (Samad et al., 2018).Therefore, knowledge of the unsaturated permeability function is crucial in the analysis of the flow process in the unsaturated zone (Arezoo et al., 2015).

In reality, there is no engineering soil property that can vary more widely than that of the PC (PC). For saturated soils the coefficient of soil permeability can vary more than 10 orders of magnitude when considering soils that range from a gravel to clay. Soils that become unsaturated are even more difficult to analyze as there is a possibility of variation in the PC ranging above 10 orders of magnitude with in a single soil. This wide range in PC has proven to be a major obstacle in analyzing seepage problems (Fredlund et al., 1994; Samad et al., 2018).

In the case of saturated soil in which the void space is completely filled with water, the PC is correlated to the void ratio and/or the parameters of the particle size distribution curve such as effective size, D10 and uniformity coefficient (Cu) (Hazen, 1930; Chapuis, 2004) of the soil. On the other hand, the void space in unsaturated soil is filled partly with water and the rest with air. Thus, the permeability of water in unsaturated soil is affected not only by the void ratio, pore size distribution, voids distribution and dry density (Gallage and Uchimura, 2010) but also by the degree of saturation (Lloret and Alonso., 1980).

More importantly, the PC of unsaturated soil is a very important parameter in unsaturated soil mechanics, such as seepage, consolidation, strength, slope instability analysis induced by rainfall, and contaminant transport (Zhang and Zhao, 2012). Its magnitude is mainly determined by the mineral composition of soil particles, pore size distribution, and water content. As a result of the existence of capillary effect, when water is flowing in the unsaturated soil, it usually flows along such pores that initially filled with water; therefore, the PC for soil samples varies greatly with different water content. (Zhang and Zhao, 2012).

For many Geotechnical problems evolving unsaturated soil conditions, knowledge of the pore water pressure or hydraulic head is primary interest. This is particularly more valuable when one considers the difficulties of the work involved in measuring the unsaturated PC for soils (Fredlund et al., 1994).

It is a common engineering practice to determine the saturated PC either in the laboratory or in the field. The procedures for determining the saturated PC are relatively simple and are not expensive (Lobbezoo. and Vanapalli, 2002). However, though experimental procedures are also available to directly measure the PC of unsaturated soils; they are time consuming and difficult and hence costly (van Genuchten, 1980; Agus et al., 2003; Chaminda et al., 2013). This is due to the serious dependence of the PC on the saturation degree, which is quite difficult to directly measure in the experiment, especially in the case of low saturation degree, and is relatively time consuming. So in most cases, determining the PC of unsaturated soils directly through experiments are not a wise method, and predicting the coefficient by empirical or theoretical equations seems to be a good choice (Zhang and Zhao, 2012; Arezoo et al., 2015).

Consequently, much of research attention has been shifted towards emerging semi-empirical models to predict the unsaturated PC using the saturated PC and the soil-water characteristic curve (SWCC) (Gardner 1958; Brooks and Corey 1964; van Genuchten 1980; Fredlund et al, 1994; Leong and Rahardjo 1997).

However, each model results in a different estimation curve for the unsaturated permeability function, and no unified model which can be used for all soil types has been put forward to date and the reason for this difference is not well understood. Thus the intention and aim of this study is to provide a general overview on the nature and property of unsaturated soils with respect to their permeability behavior; familiarize with the predicting methods of the PC of unsaturated soils using SWCC and the underlying differences; and create an in-depth understanding of the relationship between permeability of unsaturated soils and SWCC

The SWCC is defined as the relationship between the soil suction and the water content (either gravimetric, w, volumetric, θ, or degree of saturation, S). The permeability function of a soil affects the infiltration characteristics and will determine the strength and volume change behavior of the soil as the water content changes. The PC of a soil is a maximum at saturation. As the soil desaturates, the PC of the soil decreases.

2. The Nature and property of Unsaturated Soils

An unsaturated soil is commonly referred to as a three-phase mixture (i.e., solids, air, and water however, Fredlund (2006) depicts that there is a fourth independent phase called the contractile skin or the air–water interface The contractile skin acts like a thin membrane interwoven throughout the voids of the soil, acting as a partition between the air and water phases. It is the interaction of the contractile skin with the soil structure that causes an unsaturated soil to change in volume and shear strength. The unsaturated soil properties change in response to the position of the contractile skin (i.e., water degree of saturation) (Fredlund, 2006). It is important to view an unsaturated soil as a four-phase mixture for purposes of stress analysis, within the context of multiphase continuum mechanics. Consequently, an unsaturated soil has two phases that flow under the influence of a stress gradient i.e., air and water and two phases that come to equilibrium under the influence of a stress gradienti.e., soil particles forming a structural arrangement and the contractile skin forming a partition between the fluid phases (Fredlund and Rahardjo 1993).

The contractile skin has physical properties differing from the contiguous air and water phases and interacts with the soil structure to influence soil behavior. The contractile skin can be considered as part of the water phase with regard to changes in volume–mass soil properties but must be considered as an independent phase when describing the stress state and phenomenological behavior of an unsaturated soil.

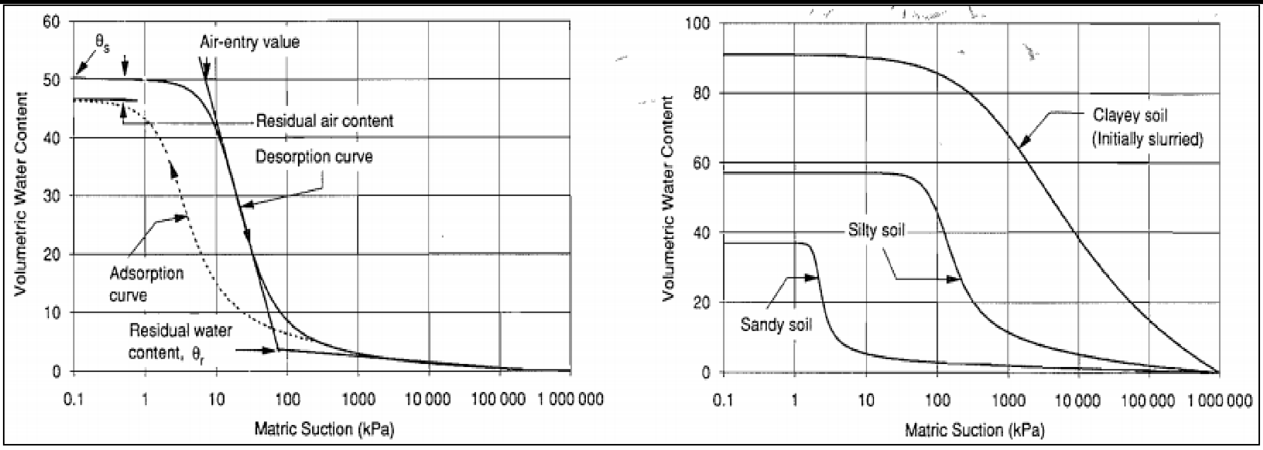
A wide range of problems in Hydrology, Soil Physics, Geoenvironmental Engineering and Geotechnical Engineering are associated with unsaturated soils. Axial and lateral load capacity of foundations, contaminant transport through soil, earth slope failure after extended periods of rainfall, seepage through earthen structures, and shrinking and swelling of problematic fine grained soils are some of the examples. These entire problems share a single commonality; movement (flow) of water through the pore space. The ability of water to move through a given soil is measured by permeability coefficient. Therefore, accurate evaluation of the permeability is important for accurate modeling of flow and deformation problems in unsaturated soils (Ravichandran and Krishnapillai, 2011).

Hydraulic conductivity with respect to water phase K (w) is measuring the available space for water through the soil. Obviously, the mass of water flowing through a soil is proportionally related to the PC. In unsaturated soils, as suction increases and pores desaturate, the PC decreases. In fact, there is limitation in the flow of water as suction increases. Meanwhile, water in large pores is replaced by air as soil desaturates ; therefore water flows through smaller pores and this process can increase the permeability. As a result, there is a relationship between PC and SWCC (Farzad, 2011).

The saturated PC can be described as a factor relating water flow rate to the hydraulic gradient and is a measure of the ease of water movement in soil. The resistance of water movement in a saturated soil is primarily a function of soil particle size and their arrangement and distribution of pores. All the pores are essentially filled with water in a saturated soil. In other words, water flows through all the pore channels under fully saturated conditions (S=100%). As a result, the PC of saturated soils is considered to be a function of void ratio (e), and assumed to be constant value (Lambe and Whitman, 1979). Darcy's law is also valid for unsaturated soils (Freeze, 1971; Fredlund, 2006). The unsaturated PC of a soil is dependent on the pore-size distribution and the amount of pore space available for water. However, in an unsaturated soil, the PC is a function of the combined changes in the void ratio and the degree of saturation (Lloret and Alonso, 1980; Fredlund, 1981).

From a practical perspective, the change in void ratio in an unsaturated soil is relatively small and hence its effect on the PC can be considered secondary. The flow of water in an unsaturated soil can only occur through the continuous channels of soil pores that contain water. The reduction in degree of saturation of soil (S<100%) associated with an in increase in air content results in an increase in the negative pore-water pressure (i.e., soil suction) of the soil.

The PC has been shown to be a relatively unique function of the water content of a soil during desorption process and a subsequent sorption process. The function appears to be unique as long as the volume change of the soil structure is negligible or reversible. There is one permeability function for desorption process and another function for the sorption process in an unsaturated soil. Both functions have a similar characteristic shape and as such can be fitted with a similar form of mathematical equation (Fig 1.). Most engineering problems usually involve either desorption process or sorption process. Even in many cases where both desorption and sorption processes are involved, a single equation is appropriate for engineering purposes.



(a) (b)

Figure 1: Typical desorption and adsorption curve for silty soil (a); Soil-water characteristic curves for sandy, silty and clayey soils (b) (Fredlund et al., 1994)

2.1. Factors Influencing the Unsaturated Permeability Coefficient

Several parameters influence the SWCC behavior. Some of the key parameters include wetting-drying cycles (i.e., hysteresis), compaction water content, stress state, and compaction energy. The parameters that influence the SWCC also influence the PC of unsaturated soils (Lobbezoo. and Vanapalli, 2002). This section examines the influence of these parameters on the relative permeability, *kr* versus degree of saturation, *S*γ relationship.

2.1.1. Wetting and Drying Cycles

The water flow behavior in a soil in the drying (desorption) and wetting (absorption) phases is different. Thus, the SWCC behavior and the variation of the water PC with respect to soil suction exhibit hysterisis. Nielsen et al (1972) in their study depicts that the PC of an unsaturated coarse grained soil is uniquely related to the degree of saturation, S or the volumetric water content, θ, both in the wetting and drying cycles. Besides, Fredlund and Rahardjo (1993) had reflected similar observations in the analysis of Liakopoulous's (1965) experimental results on a sandy soil. This implies that there is no hysterisis in the relationship between the unsaturated PC and the degree of saturation or volumetric water content. This is mainly due to the reason that the volume of water flow is a direct function of the volume of the water in soil.

2.1.2. Compaction Water Content

The compaction water content has a significant influence on the resulting soil structure in a fine-grained soil (Lambe, 1958). Several researchers have shown that flow behavior in fine-grained compacted soils is significantly influenced by the soil structure (Lambe, 1958). Furthermore, Vanapalli et al (1999) has shown that the behavior of the SWCC for fine-grained soils is also significantly influenced by variations in soil structure. The experimental results of Gao et al. (2008) on clay under different compaction conditions indicated that the PC decreases with the increase of compaction water content, and the difference reduces with the increase of suction, and PC can be assumed identical when the suction reach to 1000 kPa.

2.1.3. Compaction Energy

Compaction energy has a significant effect on the flow behavior of soils, particularly fine grained soils (Lambe, 1958). The effect of a variation of compaction energy on the SWCC was studied using published data for Mudstone by Leong and Rahardjo (2002). The data available for this soil included the saturated PC and the SWCC for various compaction energies and initial moisture contents. The unsaturated PC for the various conditions can be predicted using similar procedures as discussed above.

2.1.4. Stress State

According to Elzeftawy and Cartwright (1981), Applied loading has not significant influence on the relationship between the relative Permeability Coefficient, *kr*, and the adjusted degree of saturation S^{γ} for estimating the unsaturated PC of all soils types

3. Permeability of Unsaturated Soils

In saturated soils, permeability is a function of void ratio (e), and remains essentially constant throughout the process of seepage flow. However, in unsaturated soils, both water and air phases affect the flow of water within the soil, and the hydraulic conductivity of the soil is related to the amount of water content and soil void spaces (Fredlund and Rahardjo, 1993). Studies have shown that permeability of unsaturated soil is related to two variables, special vertical stress and matric suction, that control the water content in unsaturated soil (Mirzaii and Yasrobi, 2012). The matric suction has a significant influence on soil water content. The decreasing water content because of increased matric suction causes a considerable decrease in permeability of unsaturated soil. The soil PC of unsaturated soil changes more than 10 times as the matric suction changes. Evaluations show that permeability of unsaturated soil has a close relation with the SWCC (SWCC) in drying and wetting processes (Fredlund, et al., 1994; Mirzaii et al., 2012). In other words, unsaturated soil permeability has hysteresis behavior, as does the soil-water characteristic curve, which as the restructuring of the soil becomes minimal or reversible causes decreased hysteresis (Fredlund and Rahardjo, 1993; Fredlund, 2006; Gallage et al., 2013]. So, it seems necessary to indicate the permeability function in front of the matric suction. So for unsaturated soils, the PC with respects to water content is a function of void ratio (e) and water content (w). Since void ratio, water content and degree of saturation, S, are interrelate and K_w can be expressed as a function of any two of three parameters (Leong and Raharljo, 1997), i.e.

$$K_w = f(e, w), = f(S, e); = f(S, n) \tag{1}$$

If the soil structure is assumed to be incompressible, then it is possible to decouple the two parameters in Eq. (1) where the saturated Permeability Coefficient, (k_s) will quantify the effect of void ratio and another function will account for the effect of water content in soil.

For unsaturated soils the Permeability Coefficient, k_w, can be also expressed as a function of a matric suction (ua-uw,) and the saturated PC, k_s (Kasim et a., 1998) as:

$$K_w = f\{(u_a, -u_w.), k_s \tag{2}$$

When the pore-air, pressure (u_a), remains constant at atmospheric condition (i.e., $u_a = 0$), the Permeability Coefficient, k_w, for unsaturated soil can be defined as a function of negative pore-water pressure and the saturated Permeability Coefficient, i.e.,

$$k_w = f\{-u_w), k_s\} \tag{3}$$

4. Determination of the Soil Water Characteristic Curve

In unsaturated soils it is necessary to know the relationship between matric suction and water content in order to mathematically find the Permeability Coefficient. As a result, SWCC should be considered and predicting the hydraulic conductivity is associated with finding an appropriate equation for SWCC. The majority of statistical equations which have been proposed for predicting the SWCC are derived from equation (1): (Leong et al., 1997). Numerous empirical equations have been proposed to simulate the SWCC. Among the earliest, an equation proposed by Brooks and Corey 1964 is known. It is in the form of a power law relationship given as:

$$\Theta = \left(\frac{\psi b}{\psi}\right)^{\lambda} \quad (4)$$

Where, Θ is dimension less normalized volumetric water content = θ-θr/θs-θr, θr and θs are the residual and saturated volumetric water content of the soil respectively, ψ= soil suction, ψb = air entry value and λ = pore size distribution index.

The following linear relationship between the logarithm of volumetric water content and suction was proposed by (Williams et al. 1983) to describe the SWCC of many soils of Australia.

$$\ln(\psi) = a_1 + b_1 \ln(\theta) \quad (5)$$

Where, a_1 and b_1 are curve fitting parameters.

Another frequently used form for the relationship between suction and normalized VWC was given by Van Genuchten (1980):

$$\theta = \left[\frac{1}{1+(p\psi)^n}\right]^m \quad (6)$$

Where, p, n and m are three different soil parameters. This equation gives more flexibility than the previous ones.

5. Existing Models for predicting permeability of Unsaturated Soils

It is common practice to express the PC of unsaturated soil (k_{us}) as a scalar product of saturated permeability tensor (k_s) and relative permeability (kr) i.e.

$$k_{us} = kr * ks \quad (7)$$

ks can be experimentally measured or estimated by the PC models, and kr can be calculated with the unsaturated PC models.

Childs (1940) was one of the first investigators who demonstrated that the SWCC could be used as a tool to obtain the pore-size distribution of a soil. Since then, several procedures have been presented in the literature that uses the SWCC and the saturated PC to predict the variation of the PC of an unsaturated soil with respect to suction (Gardner 1958; Brooks and Corey 1964, van Genuchten 1980, Fredlund et al 1994, Leong & Rahardjo 1997). The PC of an unsaturated soil with an incompressible structure is a function of the degree of saturation (or the volumetric water content). A number of empirical relationships have been proposed for the PC as a function of S, θ, or ψ.

Three different types of modeling techniques are commonly used to predict the unsaturated PC. These include empirical, macroscopic and statistical models. Each of these types of models for the permeability function is described briefly in the following sections.

5.1. Empirical Equations

Empirical equations arise from the need for an equation to describe the variation of permeability with matric suction or volumetric water content (Leong and Rahardj, 1997). Empirical models or equations are developed using the results of laboratory tests that is purely a data driven method. Several researchers have summarized and normalized the data into a curve or function (Richards, 1952; Gardner 1958).

These equations can be used in engineering practice when measured data are available for the relationship between the PC and suction, range of degree of saturation and exhibit a significant deviation in low degree of saturation range. Here below are some empirical equations listed.

Table1. Some empirical equations developed by different researchers in different times.

Function	References
$k = ks$, for $\psi \le \psi aev$	Brooks and Corey 1964
$kr = (\psi / \psi aev)$, for $\psi \ge \psi aev$	Brooks and Corey 1964
$K = \ddot{\Theta}^n$ where, $\ddot{\Theta} = (\theta-\theta r/\theta s-\theta r)$	Averjanov 1950
$K = Ks\left(\frac{\theta}{\theta s}\right)^n$	Campbell 1973
$K = \exp[-\alpha(\psi - \psi aev)]$, for $\psi aev \le \psi \le \psi aev$	Rijtema 1965
$\theta_w = C(\psi)\frac{\theta_s}{\left\{\ln\left[\exp(1) + (\frac{\psi}{a})^n\right]\right\}^m}$	Fredlund and Xing (1994)

Source (Fredlund et al., 1994)

Most proposed empirical SWCC equations have two common problems (Fredlund 2006). Firstly, most empirical equations become asymptotic to a horizontal line in the low suction range which means the coefficient of water volume change with respect to a change in matric suction, approaches zero. Using such a SWCC equation for numerical modeling in the low suction range will lead to numerical instability and is construed as incorrect. Secondly, most empirical equations become asymptotic to a horizontal water content line going to infinity at high suctions beyond residual condition which is unreasonable (Chin et al., 2010). However, these problems have been overcome by Fredlund and Xing (1994) equation (Table 1). Fredlund and Xing (1994) equation gives a SWCC with a small gradient in the low suction range and with the incorporation of the correction function, C(ψ) , the Fredlund and Xing (1994) equation is always directed to a soil suction of 1 GPa at zero water content.

5.2. Macroscopic/mechanistic Models

Macroscopic models are analytical expressions that take into account many variables that influence the flow of water through the soil (Brooks and Corey 1964). They are based on a mechanistic view that the fluid-filled pores could be represented as bundles of capillary tubes of various sizes. The distribution of the fluid-filled pores is defined by applying the capillary model to the SWCC. A well-known example of this type of models is that of Brooks and Corey (1964), which was built on the work of Burdine et al. (1950) and Burdine (1953). In the Brooks and Corey (1964) development, the Poisseuille equation was used to describe the flow through fluid-filled tubes (or pores).

The hydraulic radius of these pores was obtained by integration across all the pore-water volume represented by the SWCC. A tortuosity factor was included in the derivation to account for the difference between the actual and mean pore velocities and the actual and mean pressure gradients. Based on the experimental data of Burdine et al. (1950) and the analytical value obtained by Wyllie and Gardner (1958) the following relationship for tortuosity was proposed.

$$\frac{TS{=}1}{TS} = \left[\frac{S-Sr}{1-Sr}\right]^2 = Se \tag{8}$$

Where *TS* is the tortuosity as a function of the degree of saturation, and (*TS*=1) is the tortuosity at saturation.

The term $\frac{TS=1}{TS}$ is the effective degree of saturation, *S*e, where *S* is the degree of saturation and *S*r is the residual degree of saturation.

Brooks and Corey (1964) developed the following expression for the relative permeability, k_r:

$$K_r = \frac{k(\psi)}{ks} \tag{9a}$$

$$k_r = \left[\frac{s-sr^2}{1-sr}\right]^2 * \frac{\int_0^s ds/\psi^2}{\int_0^1 ds/\psi^2} \tag{9b}$$

Where, kr is the relative permeability, k ψ is *the* permeability function *and ks* is the PC at saturation, and ψ is soil suction. It was found that the soil–water characteristic curve could be represented as a function of S_e:

$$Se = 1 \text{ for } \psi \leq \psi \text{ aev} \tag{10a}$$

$$Se = \left[\frac{\psi aev}{\psi}\right]^{\lambda} \quad \text{for } \psi > \psi \text{ aev} \tag{10b}$$

Where, λ is the slope [Δlog *S*e/Δlog ψ] of SWCC on a log–log plot. The parameter, λ is called the pore-size distribution index. The effective degree of saturation, rather than the degree of saturation, is commonly used in macroscopic models to account for the "mobile" water phase in the soil (Mualem, 1986). Substituting the effective degree of saturation, *S*e, into the equation for relative permeability gives the following relationship:

$$K_r = Se^2 \frac{\int_0^s dSe/\psi^2}{\int_0^1 dSe/\psi^2} \tag{11}$$

Using the relationship for the effective degree of saturation given in eq. [10b], the relative permeability can be written in a simplified form as:

$$kr = Se^{(2+3\lambda)/\lambda} = Se^{\delta} \tag{12}$$

Where, **λ** is an empirical index.

An equivalent expression for relative permeability in terms of suction can be given as:

$$Kr=1, \text{ for } \psi < \psi aev \tag{13}$$

$$kr = \left[\frac{\psi aev}{\psi}\right]^{\eta} \quad \text{For, } \psi \geq \psi aev \tag{14}$$

Where □□is = (2+3□) and is called the pore-size distribution coefficient.

5.3. Statistical Models

Statistical models are the most widely used models for predicting the unsaturated PC. These models have been developed by considering the probability of liquid phase continuity between pores of various sizes in formulating the probability function. Several functions developed using the statistical approach require knowledge of the residual degree of saturation for the soil (i.e., where an increase in soil suction does not result in significant reduction in water content).

The statistical models are developed based upon the assumption that the soil pores consists of a network of interconnected pores. When a fluid occupies a portion of the pore space, a fluid-filled tube forms and the flow of that particular fluid occurs only through the flow tubes. In addition to the size and the distribution of these tubes, the degree of saturation also affects the flow of a given liquid. The statistical method is used to quantify the size and the distribution of these flow tubes. It should be noted that the distribution of the pores and pore sizes affect the suction at a given degree of saturation. Therefore, the suction-degree of saturation relationship can be indirectly used to develop the permeability function for unsaturated soils (Fredlund, 1994; Mualem and Dagan, G., 1978, Leong and Rahardjo, 2002) i.e., a calibrated SWCC model can be used to predict the permeability of unsaturated soil at various degree of saturation.

Of the many permeability functions, to our knowledge, the model proposed by Fredlund et al (1994) shown in Equation (15) is commonly used in the finite element simulations of coupled deformation flow problems in unsaturated soil. The model uses the SWCC proposed by Fredlund and Xing (1994). Since the residual water content is assumed to be zero in the Fredlund and Xing model, the normalized water content and the degree of saturation are equal. Therefore, this permeability function can be utilized with either volumetric or gravimetric water content or with the degree of saturation (Ravichandran and Krishnapillai, 2011).

$$K_r(\psi) = \frac{\int_{\ln(\psi)}^{b} \frac{\theta(e^y)-\theta s}{e^y} \theta' e^y dy}{\int_{\ln(\psi aev)}^{b} \frac{\theta(e^y)-\theta\psi}{e^y} \theta' e^y dy} \tag{15}$$

The functions $\boldsymbol{\theta}$ and *C* are given by:

$$\theta = C(\psi) \frac{\theta s}{\ln(e(\frac{\psi}{a})^n))^m} \tag{16}$$

$$C(\psi) = 1 - \frac{\ln(1+\psi)/Cr}{\ln(1+10^6)/Cr} \tag{17}$$

Where ψ is the soil suction, *Kr* is the relative permeability at suction, ψ *aev* is the air-entry value of the soil under consideration, y is a dummy variable of integration representing a suction, *b* = ln (l, 000,000), θ is the volumetric water content and θ' is the derivative of θ, *Cr* is a parameter related to residual water content, and ***a**,* *n* and *m* are the fitting parameters for the SWCC. The parameter *a* represents the air-entry suction, the parameter *n* represents the pore size distribution of the soil, and parameter *m* relates to the asymmetry of the soil water characteristic curve.

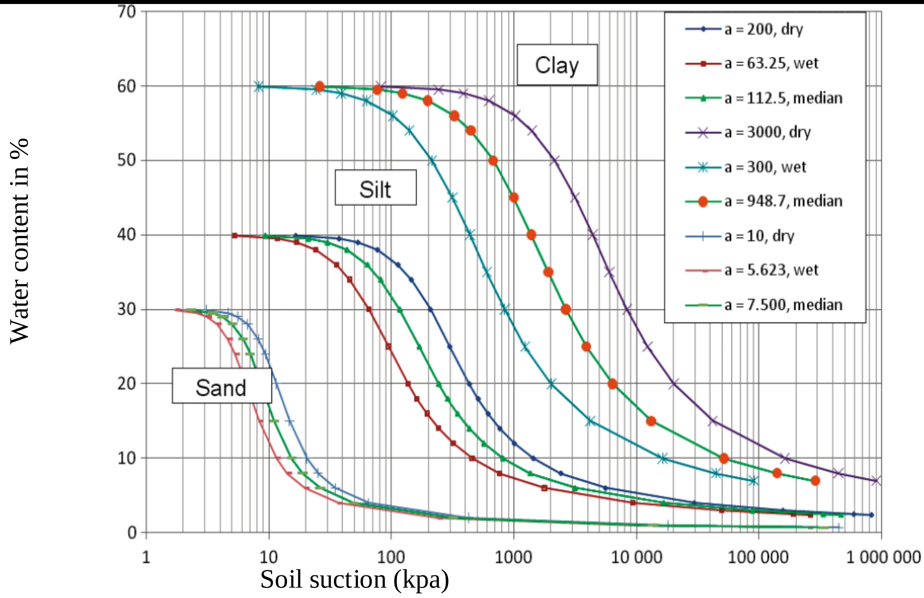


Fig 2. Comparison of three sets of drying, wetting, and median curves for three typical soils

6. Conclusion

- ❖ PC is required for many geotechnical applications. However, such measurements for unsaturated soils are time consuming and tedious especially at low water content it is not easy to perform and demand a highly accurate means of determination of water volume change.
- ❖ Since establishing the SWCC is generally not as difficult as measuring the PC at various suction levels, the task of defining the PC function can be simplified by calculating the PC from the SWCC
- ❖ The permeability function of un saturated soils have a wider engineering applications, on the consolidation of compacted soils, modeling of flow and volume change in collapsing soils, prediction of heave in expansive clays, and modeling of the migration of contaminants within the vadose zone
- ❖ As many researchers pointed out, the equation for the SWCC proposed by Fredlund and Xing (1994) was found to be effective in the prediction of the PC for unsaturated soils. In the case where experimental soil-water characteristic data are not available in the high suction range, this equation can be used to estimate the soil water characteristic behavior in this range.
- ❖ Generally SWCC can be used as a tool to propose simple estimation techniques for interpreting engineering behavior of unsaturated soils.
- ❖ For a porous medium with an incompressible structure, the permeability function can be expressed in three different forms:
  - o As empirical functions of soil suction or volumetric water content.
  - o As macroscopic models based on the "effective" degree of saturation and
  - o As statistical models in which the relative permeability is calculated from the SWCC.
- ❖ And they are interrelated to each other due to the relationship between the volumetric water content, degree of saturation, and soil suction. As a result, one form of model can be transformed to another form with the existing relations

REFERENCE

[1] Aubertin, M., Mbonimpa, M., Bussière, B. and Chapuis, R.P., 2003. A model to predict the water retention curve from basic geotechnical properties. *Canadian Geotechnical Journal*, *40*(6), pp.1104-1122.

[2] Averjanov, S.F., 1950. About permeability of surface soils in case of incomplete saturation. *English Collection*, *7*, pp.19-21.

[3] Brooks, R.H. and Corey, A.T., 1964. Hydraulic properties of porous media. Colorado State University (Fort Collins), Hydrology Paper 3.

[4] Burdine, N., 1953. Relative permeability calculations from pore size distribution data. *Journal of Petroleum Technology*, *5*(03), pp.71-78. by A. Klute. American Society of Agronomy, Inc. and Soil Science Society of America, Inc. Madison, Wis., U.S.A. pp. 799-823.

[5] Campbell, J.D. 1973. Pore pressures and volume changes in unsaturated soils. Ph.D. thesis, University of Illinois at Urbana-Champaign, Urbana-Champaign, Ill.

[6] Chapuis, R.P., 2012. Predicting the saturated hydraulic conductivity of soils: a review. *Bulletin of engineering geology and the environment*, *71*(3), pp.401-434.doi:10.1139/t04-022.

[7] Childs, E.C. 1940. The use of soil moisture characteristics in soil studies. Soil Science, 50: 239 252.

[8] Childs, E.C., and Collis-George, G.N. 1950. The permeability of porous materials. Proceedings of the Royal Society of London, Series A, 201: 392-405.

[9] Chin, K.B., Leong, E.C. and Rahardjo, H., 2010. A simplified method to estimate the soil-water characteristic curve. *Canadian Geotechnical Journal*, *47*(12), pp.1382-1400.

[10] Daliri, F., 2011. A review of theoretical and experimental methods to measure Permeability Coefficient of unsaturated soils. *Electronic Journal of Geotechnical Engineering*, *16*, pp.1665-1677.

[11] Elzeftawy, A. and Cartwright, K., 1981. Evaluating the saturated and unsaturated hydraulic conductivity in soils. In Permeability and Groundwater Contaminant Transport, ASTM STP 746, T.F. Zimmie and C.D. Riggs, Eds. Amer. Soc. Testing and Materials, 1981, 168-181.

[12] Farzad Daliri, .2011. A Review of Theoretical and Experimental Methods to Measure Permeability Coefficient of Unsaturated Soils Ph.D. Candidate Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada.

[13] Fredlund, D. G. and Rahardjo, H., 1993. Soil Mechanics for Unsaturated Soils, John Wiley & Sons, New York, NY, USA.

[14] Fredlund, D. G., 2006. Unsaturated soil mechanics in engineering practice. Journal of Geotechnical and Geoenvironmental Engineering, vol. 132, no. 3, pp. 286–321.

[15] Fredlund, D. G., Xing, A. and Huang, S., 1994. Predicting the Permeability Function for Unsaturated Soils Using the Soil-Water Characteristic Curve. Canadian Geotechnical Journal, Vol. 31, No. 4, pp. 533-546. doi:10.1139/t94-062.

[16] Fredlund, D.G., and Xing, A. 1994. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal, 31: 533-546.

[17] Freeze, R.A., 1971. Influence of the unsaturated flow domain on seepage through earth dams. Water Resources Research, 7:929-940.

[18] Gallage, C., Kodikara, J. and Uchimura, T., 2013. Laboratory measurement of hydraulic conductivity functions of two unsaturated sandy soils during drying and wetting processes. Soils and Foundations, vol. 53, no. 3, pp. 417–430.

[19] Gallage, C.P.K. and Uchimura, T., 2010. Effects of dry density and grain size distribution on soil-water characteristic curves of sandy soils. *Soils and foundations*, *50*(1), pp.161-172. doi:10.3208/sandf.50.161

[20] Gao, L.X., Luan, M.T., and Yang, Q., 2008. Experimental Study on Permeability of Unsaturated Remolded Clay. Electronic Journal of Geotechnical Engineering (EJGE), Vol. 13, Bund. D, pp. 1–15.

[21] Gardner, W.R. 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science, 85: 228-232.

[22] Hazen, A., 1930. Water supply. *American civil engineers handbook*, pp.1444-1518.

[23] Holtz, R. D. and Kovacs, W. D., 1981. An Introduction to Geotechnical Engineering, Prentice-Hall, Upper Saddle River, NJ, USA,

[24] Kasim, F., Fredlund, D. and Kassimt, K.A., 1998. Permeability Functions for Unsaturated Residual Soils. World engineering congress to wards engineering version. University of saskdchewan, Canada.

[25] Lambe, T.W. and Whitman, R.V., 1979. Soil Mechanics, SI Version John Wiley & Sons, New York.

[26] Lambe, T.W., 1958. The engineering behavior of compacted clay, ASCE J. Soil Mech. Found. Div., Paper No. 1655, 84: 1-35.

[27] Leong, E.C. and Rahardjo, H., 1997. Permeability functions for unsaturated soils. Journal of Geotechnical and Geoenvironmental Engineering. 123: 1118-1126.

[28] Leong, E.C. and Rahardjo, H., 2002. Soil-water characteristic curves of compacted residual soils. Unsaturated Soils Proceeding of the 3rd International Conference on Unsaturated Soils, UNSAT 2002, Eds Juca et al: 271-276.

[29] Liakopoulous, A.C., 1965. Theoretical solution of the unsteady unsaturated flow problems in soils. Bulletin of the International Association of Science and Hydrology, 10: 5-35.

[30] Lloret, A. and Alonso, E.E., 1980. Consolidation of unsaturated soils including swelling and collapse behaviour. *Géotechnique*, *30*(4), pp.449-477. doi:10.1680/geot.1980.30.4.449

[31] Lobbezoo, J.P. and Vanapalli S.K., 2002. A simple technique for estimating the Permeability Coefficient of unsaturated soils.

[32] Mirzaii A. and Yasrobi, S. S., 2012. Effect of net stress on hydraulic conductivity of unsaturated soils. Transport in Porous Media, vol. 95, no. 3, pp. 497–505

[33] Mirzaii, A. Yasrobi, S. S. and Khalili, N., 2012. Experimental investigation of hydraulic conductivity in unsaturated compressible soils. In proceedings of the 2nd European Conference on Unsaturated Soils, pp. 205–212, Napoli, Italy.

[34] Mualem, Y. 1976a. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research, 12: 593-622.

[35] Mualem, Y. 1976b. Hysteretical models for prediction of the hydraulic conductivity of unsaturated porous media. Water Resources Research, 12: 1248-1 254.

[36] Mualem, Y. 1986. Hydraulic conductivity of unsaturated soils: prediction and formulas. In Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agronomy, *Edited*

[37] Mualem, Y. and Dagan, G., 1978. Hydraulic conductivity of soils: Unified approach to the statistical models. *Soil Science Society of America Journal*, *42*(3), pp.392-395.

[38] Nielsen, D.R., Jackson, R.D., Cary, J.W., and Evans, D.D., 1972. American Society Agronomy and Soil Science, America, Madison, WI.

[39] Oh, S., Lu, N., Kim, Y.K., Lee, S.J. and Lee, S.R., 2012. Relationship between the soil-water characteristic curve and the suction stress characteristic curve: Experimental evidence from residual soils. *Journal of Geotechnical and Geoenvironmental Engineering*, *138*(1), pp.47-57.
[40] Patil, N.G. and Singh, S.K., 2016. Pedotransfer functions for estimating soil hydraulic properties: A review. *Pedosphere*, *26*(4), pp.417-430.
[41] Rahimi, A., Rahardjo, H. and Leong, E.C., 2015. Effects of soil–water characteristic curve and relative permeability equations on estimation of unsaturated permeability function. *Soils and Foundations*, *55*(6), pp.1400-1411.http://dx.doi.org/10.1016/j.sandf.2015.10.006
[42] Ravichandran, N. and Krishnapillai, S., 2011. A statistical model for the relative hydraulic conductivity of water phase in unsaturated soils. *International Journal of Geosciences*, *2*(04), p.484. doi:10.4236/ijg.2011.24051. Published Online November 2011 (http://www.SciRP.org/journal/ijg)
[43] Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil science society of America journal*, *44*(5), pp.892-898.
[44] Vanapalli, S. K., Fredlund, D. G., and Pufahl, D. E. 1999. The influence of soil structure and stress history on the soil-water characteristics of a compacted till. Geotechnique, 49: 143-159.
[45] Wind, G.P., 1955. A field experiment concerning capillary rise of moisture in a heavy clay soil. *NJAS wageningen journal of life sciences*, *3*(1), pp.60-69.
[46] Zhang, X. and Zhao, C., 2012. Research on the Influence of Soil Density on the Permeability Coefficient of Unsaturated Soils. *Physical and Numerical Simulation of Geotechnical Engineering*, (7), p.20.