Soil-Water Characteristic Curve Model-Silty Sand Soil

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ABSTRACT

The implementation of unsaturated soil mechanics into engineering practice is dependent, to a large extent, upon the ability to estimate unsaturated soil property functions. The soil-water characteristic curve is the basis for estimating the permeability function for an unsaturated soil. The negative pore pressure measurement is costly, time consuming, insufficiently reliable and needs highly accurate techniques to be measured. However, a theoretical model can introduce a perfect solution to understand the behavior of unsaturated soil when testing is difficult.

A theoretical model based on the microscopic forces is presented in this paper. The model describes the soil-water characteristic curve (SWCC) and how the water is held within a porous material with a relatively low degree of saturation. Experimental measurements of capillarity and negative pore water pressure were obtained for the columns of glass beads and soil within a narrow grading range. An estimated curve for the degree of saturation *versus* matrix suction is obtained and compared to a predicted theoretical curve using the model proposed in this study. The proposed method seems to provide a reasonable predictive tool.

KEYWORDS: Soil-water characteristic curve, Degree of saturation, Theoretical model, Matrix suction.

INTRODUCTION

Soil in Jordan is always in an unsaturated state. This is because the climate in Jordan is considered arid to semi-arid. In recent times, designers of effective cover and liner systems for landfills have taken advantage of the capillary barrier phenomena to reduce infiltration (Nicholson et al., 1989). Capillary barriers in an unsaturated soil profile are formed using coarse-grained materials that drain to low degrees of saturation, and hence low unsaturated permeability, under small matrix suction. The layer of coarse-grained material has a lower unsaturated permeability than the overlying finer grained material and acts to limit infiltration.

The soil-water characteristic curve or water retention curve relates the water content or degree of saturation to matrix suction of a soil. Soil-water characteristic curve (SWCC) is one of the fundamental properties of unsaturated soils. It has been found to change with matrix suction. Various (SWCC) equations have been proposed for predicting the relationship (SWCC) *versus* suction for unsaturated soils. Some of these equations are based on regression analysis of experimental data, while others are embodied in more complex theoretical models.

Many researchers have tried to produce a relationship between the water content or volumetric water content and matrix suction. Several empirical equations have been proposed to simulate the (SWCC). Each equation appears to apply for a particular group of

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soils. Numerical models hold significant potential in the area of unsaturated soil mechanics for both the prediction of future behavior and the understanding of processes (Rosenblueth, 1975; Li, 1992; Anderson and Woessner, 2002; Fredlund et al., 2008; Fredlund and Gitirana, 2011). The application of unsaturated numerical models for water flow has found practical application in the design of different geotechnical aspects. In all of these applications, unsaturated behavior is essential, both in terms of flow and slope stability analysis. Design of effective capillary barrier systems requires a thorough understanding of the soil-water interactions that take place in both coarse- and fine-grained unsaturated soils (Reinson, 2001; Reinson et al., 2005). Running numerical models which do not fully capture the unsaturated processes for these types of models can result in non-applicable models which do not truly represent the phenomena of interest. Unfortunately, the highly non-linear nature of the unsaturated flow through gravel-type materials results in significant numerical challenges. Non-convergence issues as well as greatly increased solution times are common and result in a general trend of reducing model runs in geotechnical engineering practice. Reducing the number of model runs in a sensitivity analysis further reduces the ability of the user to fully interpret what the model is indicating.

Vanapalli et al. (1999) have reported that the soil-water characteristic curve depends on several factors, such as soil structure, initial water content, void ratio, type of soil, texture, mineralogy, stress history and method of compaction. According to them, the initial moulding water content and the stress history have most influence on the soil structure, which in turn dominates the nature of the soil-water characteristics for fine-grained soils. Vanapalli et al. (1999) stated that "specimens of a particular soil, in spite of having the same texture and mineralogy, can exhibit different soil-water characteristics if they are prepared at different initial moulding water contents and possess different stress histories".

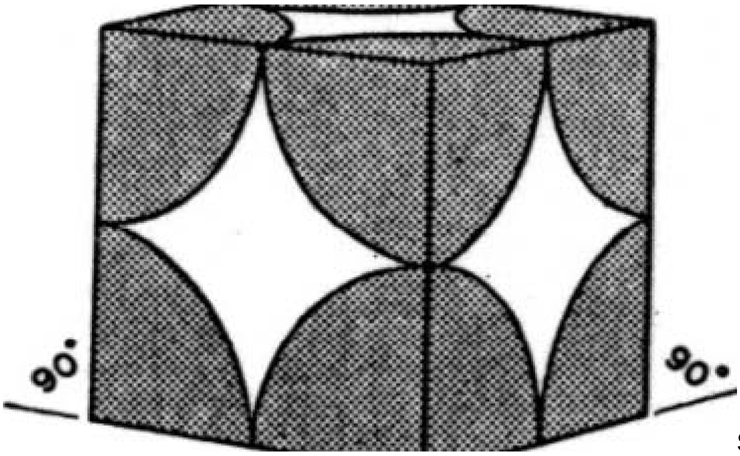
In this paper, a theoretical model has been proposed to predict (SWCC) based on microscopic parameters (i.e., surface tension, particle size, degree of saturation and pore geometry). Maaitah et al. (2010) showed that the best shape of the water meniscus between the soil particles is circular. Consideration of the different roles of pore air pressure, pore water pressure within bulk water and pore water pressure within meniscus water suggests that the degree of saturation will have a significant effect more than water content. This means that the degree of saturation gives a clear view about the sample's mechanical behavior (Wheeler and Karube, 1996; Wheeler et al., 2003; Honda et al., 2011). The advantages and limitations associated with various proposed (SWCC) equations are discussed in this paper.

In this study, a coarse-grained porous medium composed of spheres is considered as a step towards a better general understanding of coarse-grained materials. The laboratory study used a porous medium (i.e., glass beads, silt and fine sand) that was nearly uniform in size and shape and considered to be "ideal" for this study which is not the case in the field. Theoretically derived values from the proposed model in this study are compared with experimental measurements of soil-water interactions in coarse-grained unsaturated porous media obtained using direct visual observations from a series of controlled experiments.

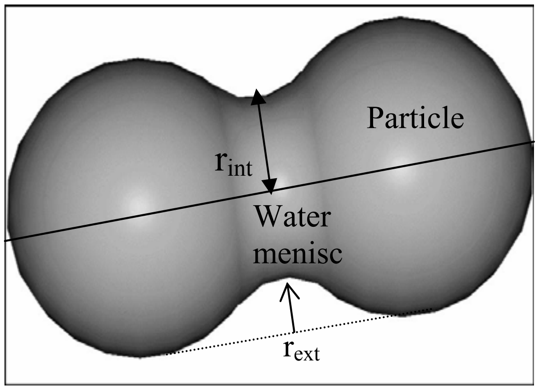
The research program presented here involved: (i) investigation of capillary concept to estimate the SWCC for uniform glass beads, (ii) experimental observations of water retention in the glass bead medium, (iii) development of an SWCC based on mathematical derivation. This paper shows that the capillary potential of the small spheres was greater than that of the larger spheres. The smallest spheres supported water by surface tension throughout the length of the column after the column was saturated and drained. The water was found to be supported at progressively lower levels in the medium as the sphere size increased.

Mathematical Derivation

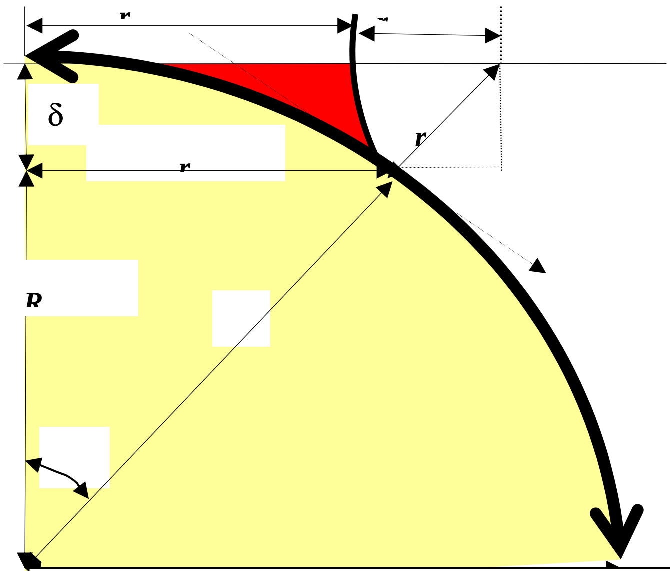
At a low degree of saturation, the water is held at the contact point between the soil particles. The smaller the particles are, the higher is the capillarity force which can hold capillary water. In addition, at a lower degree of saturation where the water phase is discontinuous, the air phase is continuous and the air pressure is greater than the water pressure. Therefore, the suction (i.e., negative pore water pressure) becomes difficult to measure. Particle size, effect of surface tension, hydraulic hysteresis and pore geometry play an important role in unsaturated soil behavior rather than in the saturated case. In contrast, the degree of saturation is simple to measure.



Scheme 1



Scheme 2



Scheme 3: Geometry of meniscus at point of contact

It is accepted that meniscus shape is the most important variable in the interpretation of calculating the (SWCC). Different theoretical models have been developed to understand the behavior of unsaturated soil by assuming that the meniscus shape might be circular, elliptical or parabolic (Maaitah, 2007; Maaitah et al., 2010). These models discussed the shear strength and the effect of gas bubbles on the unsaturated soil. It was found that there is not much difference between these assumptions to meniscus shapes. The best shape is the circular one. This result has been utilized to predict the soil-water characteristic curve (SWCC) in this study. The latter can be defined as the relation between the matrix suction (U_a-U_w) and the degree of saturation. The (SWCC) will have a great significance in understanding the capillary water flow through unsaturated soil.

To conclude, Maaitah (2007) and Maaitah et al. (2010) discussed the shear strength and gas bubbles in unsaturated media by assuming that the meniscus shape might be circular, elliptical or parabolic. They found that the best shape is the circular one. In this study, the model uses this result to predict the relationship between matrix suction and surface tension, particle size, degree of saturation and pore geometry.

There may also be a small outward attraction caused by air molecules, but as air is much less dense than the liquid, this force is negligible. All of the molecules at the surface are therefore subject to an inward force of molecular attraction which can be balanced only by the resistance of the liquid to compression. Thus, the water squeezes itself together until it has the lowest surface area possible. Considering a cylinder bounded of total volume V_t, the volume of water can be expressed by subtracting the volume of air outside the meniscus V_a and the volume of solid V_s (see scheme 1 and scheme 3). The depth of water at the point of contact between the soil particles can be written from scheme 1 and scheme 3 as follows:

$$\delta = R(1-\cos\theta). \tag{1}$$

The meniscus radius depends on the assumption of the shape of the meniscus; this means whether the meniscus is assumed as a part of a circle (see schemes 1, 2 and 3). The volume of water is calculated for the half-volume of water at the contact point (i.e., the volume of water revolved around the contact point of two spheres). Initially, the meniscus radius can be found as follows:

$$r_{ext} = \frac{\delta}{\cos\theta}. \tag{2}$$

From the geometry shown in scheme 3, the internal distance of the meniscus is:

$$r_{int} = 2r_{ext}. \tag{3}$$

The total volume can be written as follows:

$$V_t = 9\pi\, r_{ext}{}^2\delta = \frac{9\pi\ \delta^3}{\cos^2\theta}. \tag{4}$$

As illustrated in scheme 3, the half-volume of water at the point of contact can be determined by integration:

$$V_w = \pi\left[10\delta\left(r_{ext}^2\right) - R\delta^2 - (3r_{ext})\left(r_{ext}^2\sin\theta + \delta\, r_{ext}\sqrt{1+\cos^2\theta}\right)\right]$$

$$V_w = \pi\left[10\cos\theta\left(r_{ext}^3\right) - R\cos^2\theta\, r_{ext}^2 - (3r_{ext}^3\sin\theta) - \left(r_{ext}^3\sqrt{1+\cos^2\theta}\right)\cos\theta\right]$$

$$V_w = \pi\left[10\cos\theta - \frac{\cos^3\theta}{(1-\cos\theta)} - 3\left(\sin\theta + \cos\theta\sqrt{1+\cos^2\theta}\right)\right]r_{ext}^3 \tag{5}$$

$$\lambda = \pi\left[10\cos\theta - \frac{\cos^3\theta}{(1-\cos\theta)} - 3\left(\sin\theta + \cos\theta\sqrt{1+\cos^2\theta}\right)\right] \quad (6)$$

$$V_w = \lambda r_{ext} = \lambda\left(\frac{\delta}{\cos\theta}\right)^3 \quad \Rightarrow V_w = \lambda\left(\frac{R(1-\cos\theta)}{\cos\theta}\right)^3 . \quad (7)$$

The void ratio is expressed using the well-known formula:

$$e = \frac{V_v}{V_s} \Rightarrow V_v = e\ V_s .$$

The degree of saturation can be written as follows:

$$S_r = \frac{V_w}{V_V} = \frac{\lambda\left(\frac{R(1-\cos\theta)}{\cos\theta}\right)^3}{V_V} N = \frac{\lambda\left(\frac{R(1-\cos\theta)}{\cos\theta}\right)^3}{e\ V_s} N . \quad (8)$$

This expression is only valid for filling angles up to 45 degrees for open packing arrangement. The contact number (N) per unit volume is a function of the void ratio. By considering a single sphere, the contact number (N) per unit volume can be written as a function of the void ratio. By using simple regression, the contact number is expressed as follows:

$$N=14.8-9.95e. \quad (9)$$

However, the volume of water associated with the sphere being considered is V_w as given in equation 5, so the volume of water associated with each sphere is $N.V_w$. The volume of voids associated with each sphere is simply the void ratio multiplied by the volume of the sphere, so the degree of saturation can be written as follows:

$$S_r = \frac{NV_w}{V_v} = \frac{NV_w}{eV_s} \quad \Rightarrow V_w = \frac{e\ V_s}{N} S_r . \quad (10)$$

By Equating equation 5 and equation 7 and rearranging, the radius of meniscus can be written as follows:

$$r_{ext} = \sqrt[\frac{1}{3}]{\frac{eV_sS_r}{N\lambda}} = \sqrt[\frac{1}{3}]{\frac{eV_sS_r}{\lambda(14.8-9.95e)}} = \left[\sqrt[\frac{1}{3}]{\frac{e\ S_r}{\lambda(3.53-2.37e)}}\right] R . \quad (11)$$

Equations 6, 8, 9 and 10 can then be used to determine a relationship between (u_a-u_w) and the degree of saturation by using a simple excel sheet. The above equations show that the soil-water characteristic curve (SWCC) is a function of pore geometry (particle size distribution), surface tension (temperature and kind of fluid) and degree of saturation.

If viscous forces are absent, the pressure jump across a curved surface is given by the Young-Laplace equation, which relates pressure inside a liquid to the pressure outside it, the surface tension and the geometry of the surface.

$$\Delta U = T\frac{dA}{AV} .$$

This equation can be applied to any surface:

- For a flat surface: so that the pressure inside is the same as the pressure outside (dA/dV = 0.0).
- For a spherical surface: $U_1 = U_o + \frac{2T}{r}$;

where A is the area, V is the volume of water, U is the pore pressure, T is the surface tension and r is the meniscus radius.

- For a toroidal surface, which is the case in this work:

$$(U_a - U_w) = T\left[\frac{1}{r_{ext}} + \frac{1}{r_{int}}\right]\cos 2\theta = T\left[\frac{1}{r_{ext}} + \frac{1}{2r_{ext}}\right]\cos 2\theta = T\left(\frac{3\cos 2\theta}{r_{ext}}\right); \quad (12)$$

where r_{ext} and r_{int} are the radii of the toroid as defined in equations 2, 3 and 11.

The geometry of the meniscus can then be used to determine the difference in pressure between the water and the surrounding air, for a given value of surface tension T. The soil-water characteristic curve can be expressed as in equation 12 and discussed from a theoretical point of view in Figures 1, 2, 3, 4, 5 and 6 for different particle sizes, degrees of saturation and void ratios. The suction calculated above is applied to the soil particles over the water at the point of contact and acts to increase the contact force.

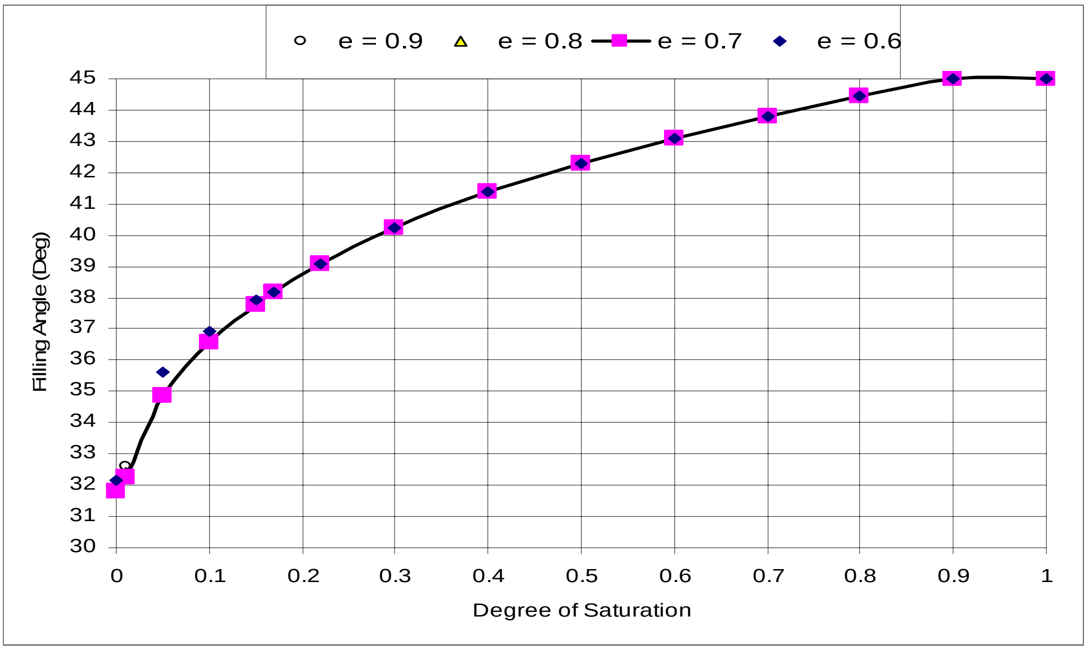


Figure 1: Relationship between the degree of saturation and the filling angle

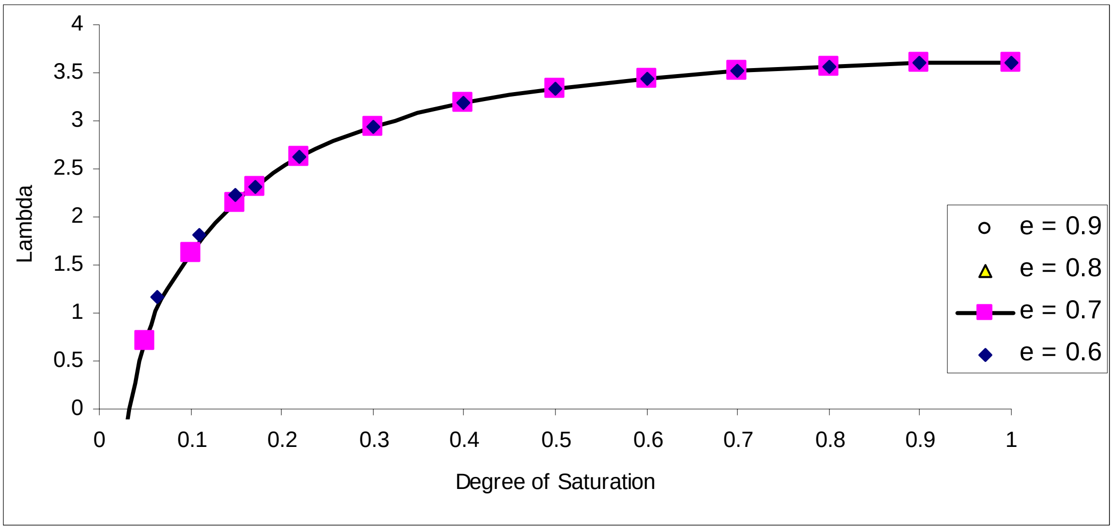


Figure 2: Relationship between the factor lambda (λ) and the degree of saturation

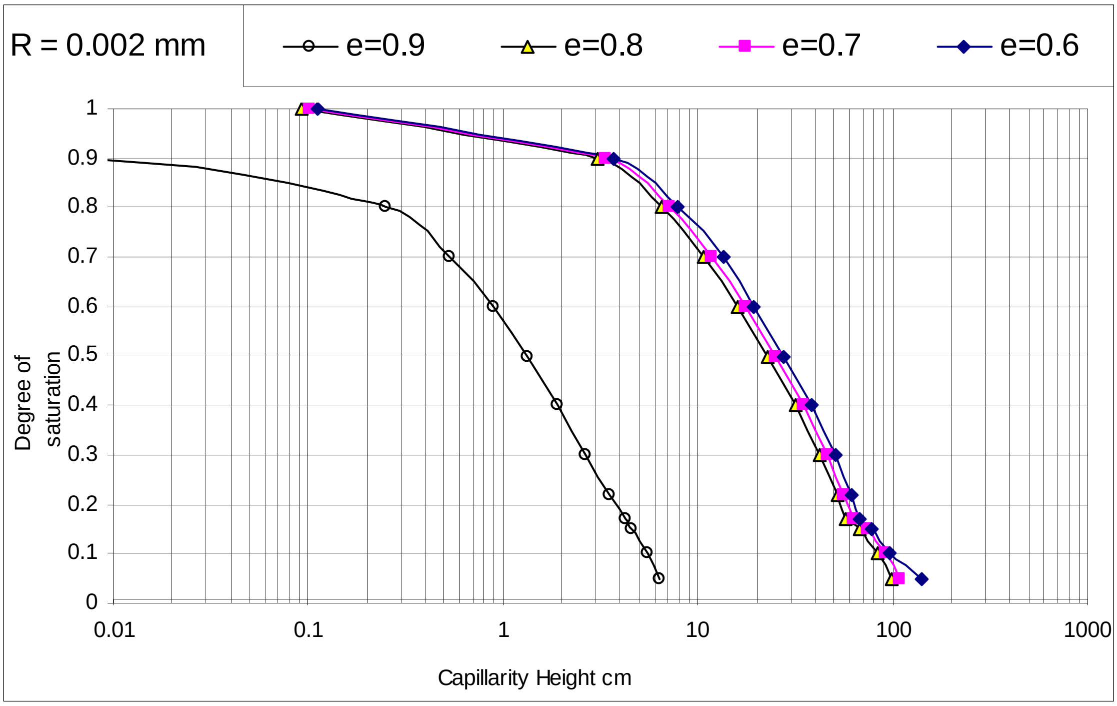


Figure 3: Relationship between the capillary rise height and the degree of saturation-effect of void ratio

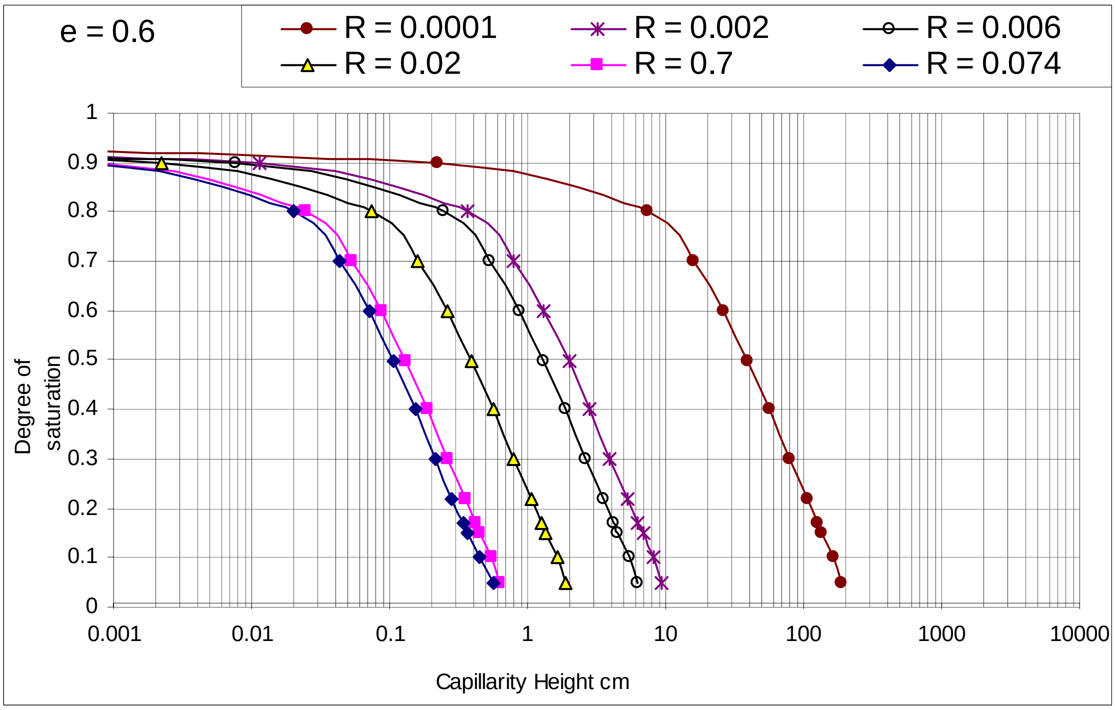


Figure 4: Relationship between the capillary rise height and the degree of saturation-effect of particle size

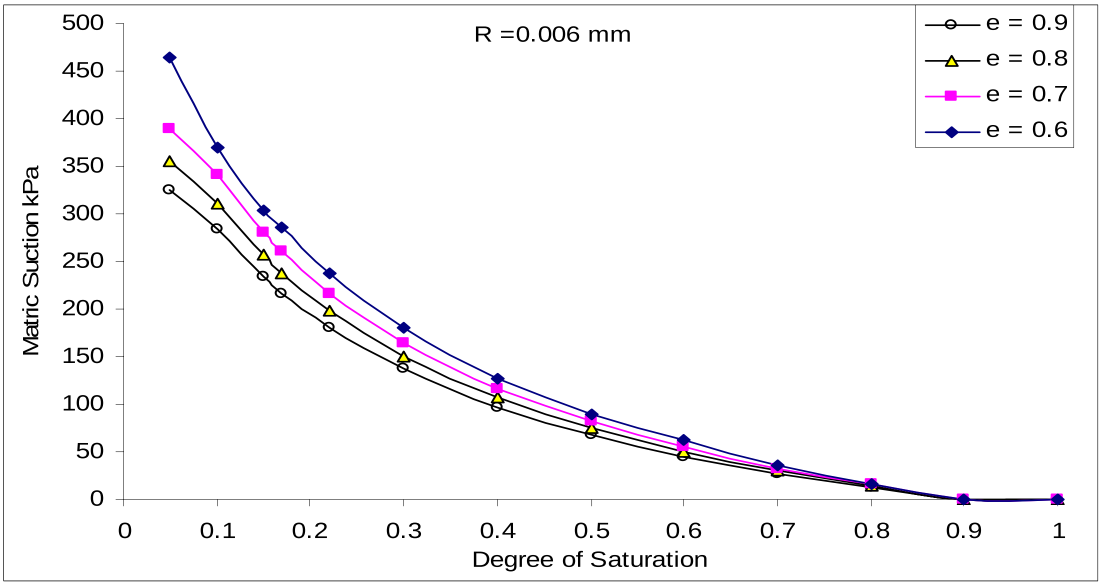


Figure 5: Relationship between suction and the degree of saturation-effect of void ratio

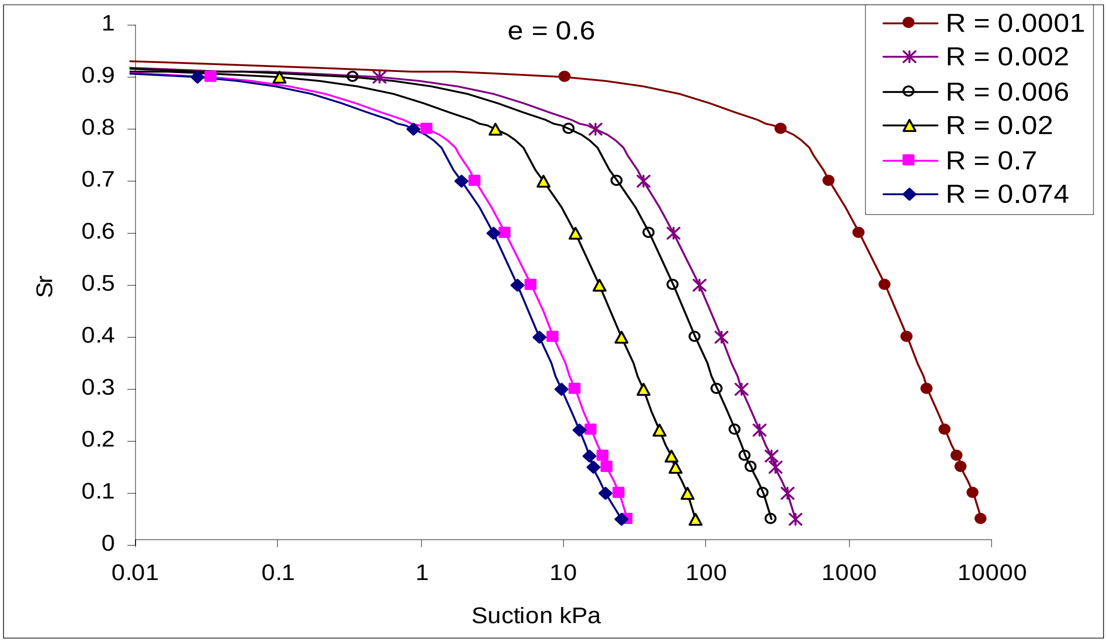


Figure 6: Relationship between suction and the degree of saturation-effect of particle size

The SWCC represents the storage capability of the soil and defines the amount of water retained in the pores under various matrix suction values. Stated in another way, the SWCC represents the relationship between the amount of water within a soil volume and the energy in the water phase (matrix suction). Then, the application of the SWCC as a conceptual, interpretive and predictive model is a suitable tool for understanding unsaturated soil behavior (Barbour, 1998).

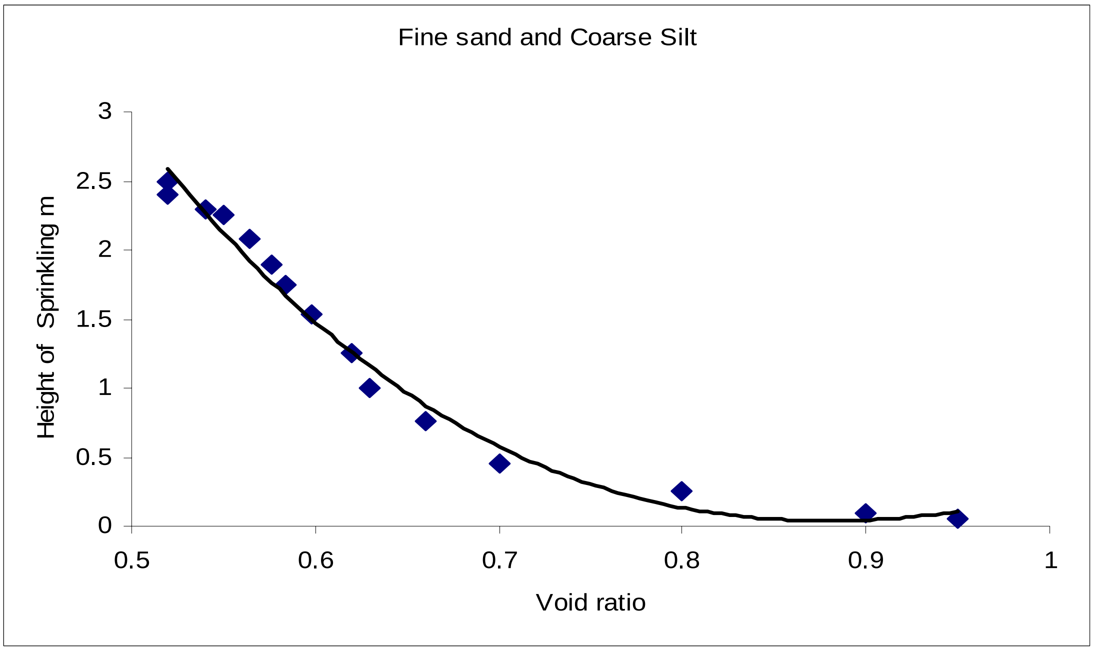


Figure 7: Sprinkling test results

Table 1. Results of capillary test and theoretical prediction for void ratio =0.9

Material type	Range of particle size	Measured capillary height (h_m) mm	Predicted capillary height hp (1)	Predicted capillary height hs (2)
First Group	0.075-0.063	76	79	80
Second Group	0.09-0.038	112	53	126
Third Group	0.063-0.038	119	80	126
Fourth Group	0.15-0.075	58	32	79

Experimental Part and Material Properties

Simple and accurate tests have been conducted in this paper, such as the capillary rise test to verify the above suggested theoretical model. The surface tension was measured for each individual test by using a capillary tube with a diameter equal to 0.7 mm. The values of measured surface tension by the capillary tube varied between 0.073 and 0.075 N/m. The standard value for surface tension, however, according to (Kaye and Laby, 1973) when the temperature is 20^o C is equal to 0.07275 N/m. The difference between the measured surface tension and the standard value is between 1 and 3 percent. This difference is due to the variation of the temperature.

$$T = h_w\, r\, \gamma_w = 0.35(mm) * 21(mm) * 9.81(kN/m^3) = 0.0721\, N/m. \qquad (13)$$

Dry and powdered soil samples are thoroughly mixed and packed into 5 cm glass tubes with a height equal to 2m. The soil is placed in these tubes by sprinkling to achieve the desired void ratio because it is difficult to compact soil in a glass tube. Therefore, a simple sprinkling test has been carried out and the results are shown in Figure 7. A screen at one end and a vented stopper at the other end were fixed. Then, the tube is immersed in water of a shallow depth. This will allow water to be sucked from the soil by capillary action. The distance to which the sample gets saturated may be expressed as a function of time. In this situation, the menisci are developed to the maximum curvature possible for the void sizes in the sample; the corresponding capillary head constant for the soil at a given void ratio. The pressure difference between either end of the line of saturation or the menisci in the pore water is the capillary tension at all times.

The height of water columns in the ideal sample with completely spherical particles can be expressed as follows:

$$h_p = \frac{2T \cos 2\theta}{\gamma_w r_{ext}}; \qquad (14)$$

where:

h_p is the predicted capillary rise height of water column in the soil sample.

r_{ext} is the meniscus radius in the soil (see equation 11).

However, five groups have been selected with a special particle arrangement in each group to verify the above suggested theoretical model.

Table 2. Results of capillary test and theoretical prediction for void ratio =0.65

Material type	Range of particle size	Measured capillary height (h_m) mm	Predicted capillary height hp (1)	Predicted capillary height hs (2)
First Group	0.075-0.063	91	80	100
Second Group	0.09-0.038	154	67	158
Third Group	0.063-0.038	162	100	158
Fourth Group	0.15-0.075	57	40	80

(1): Predicted capillary height (mm) based on maximum size.
(2): Predicted capillary height (mm) based on minimum size.
h_m: Measured capillary height in mm.

First Group: Testing Single Size Glass Beads

The first group has been selected for theoretical purpose only, because such material does not naturally occur. In this kind of particles (i.e., glass beads) which has an ideal shape, it is easy for packing, wetting and confining effects to be highlighted. Moreover, when the findings on this material and the other natural material are compared, the effect of the particle size distribution will be easily outlined. The sizes of this group are located in a very narrow range as shown in Table 1. This group was separated by passing the sieve no. 230 (i.e., 0.063 mm) and retaining on sieve no. 400 (i.e., 0.038 mm). It was washed and sieved several times to remove any colloidal materials and any defects in these particles which may come from manufacture to be perfect to achieve the target. The average of the specific gravity after three trials for the glass beads is equal to 2.59. The void ratios were selected to take into account both cases; loose case or open packing (e= 0.91) and dense case or close packing (e= 0.65), by using the sprinkling test (see Figure 7).

The predicted capillary rise based on minimum particle size gives close agreement to the measured capillary rise as shown in Tables 1 and 2.

Second Group: Different Size Glass Beads

The second group, also, has been selected for theoretical purpose in order to present the effect of different sizes on the behavior of unsaturated soil when the shape of the particles is constant. The comparison between the first group and the second one will demonstrate the effect of the particle shape and size which is higher in the second group. The comparison between the first group and the second group will illustrate the effect of particle size on SWCC (see Figures 3, 4 and 5). The contact number per unit area and the water ring area are higher in the second group. All fine particles that have a diameter less than 0.038 mm were removed by decantation. The predicted capillary rise based on minimum particle size gives close agreement to the measured capillary rise as shown in Tables 1 and 2. This means that the smaller the particles are, the higher is the influence in the capillary rise which means that the prediction should be based on minimum sizes.

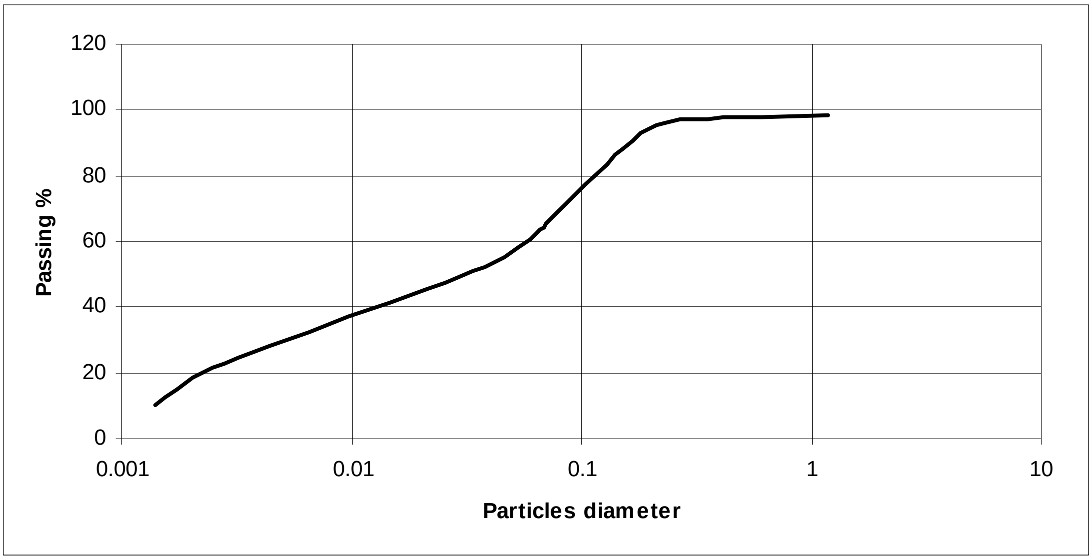


Figure 8: Sieve analysis for fine sand and coarse silt

Third Group: Coarse Silt

The third group is a natural material, where the desired particle sizes have been selected. Virtually, all the particles have rounded, sub-rounded and angular shapes, but with rounded corners from optical microscopic observation. In this group, the sample is coarse silt and separated by passing sieve no. 230 (i.e., 0.063 mm) and retaining on sieve no. 400 (i.e., 0.038 mm). All fine particles that have a diameter less than 0.038 mm were removed by decantation (see Tables 1 and 2). The predicted capillary rise based on minimum particle size gives close agreement to measured capillary rise as shown in Tables 1 and 2. Nearly, there is not much difference between group two and group three.

Fourth Group: Fine Sand

The fourth group is a natural material, where unwanted sizes were removed (i.e., less than 0.074 mm). It has different particle shapes (i.e., sub-rounded and angular) and has different particle sizes from optical microscopic observation. The dominating particle shape is angular with rounded corners. This group is fine sand that was separated by passing sieve no. 100 (i.e., diameter of 0.15 mm) and retaining on sieve no. 200 (i.e., diameter of 0.074 mm). It was washed several times on sieve no. 200 (i.e., diameter of 0.074 mm) to make sure that all the fine materials have been removed (see Tables 1 and 2). The average of the specific gravity after three trials is equal to 2.63 for this group. The predicted capillary rise based on minimum particle size gives close agreement to measured capillary rise as shown in Tables 1 and 2.

Fifth Group: Natural Soil

This group consists of natural soil particles with different particle sizes and shapes. It consists of fine sand, fine silt, medium and coarse silt and clay particles. The particle size distribution is presented in Figure 8. The particle size is a minimum size which is equal to 0.002 mm. The sample was selected to have a low plasticity (i.e., PI = 9) in order to avoid the physico-chemical effect, because this subject is out of the scope of this work. The main objective for using this material is to study the SWCC. The predicted capillary rise in such material is around 1.5m. However, the soil in the glass tube becomes saturated after 2 hours.

DISCUSSION

The relationship between the filling angle (θ) and the degree of saturation is illustrated in Figure 1. The relation between lambda (λ) and the degree of saturation is represented in Figure 2. It is clear that both factors are independent of the void ratio and totally depend on the amount of water between the soil particles. The particle radius (minimum size) and void ratio have a great influence on capillary rise and suction as discussed in Figures 3, 4, 5 and 6.

The term (cos 2θ) in equation 12 represents the effect of contact angle. The latter is equal to zero when the liquid is wetting all the solid and is variable between 0° and 90° when the liquid is partially wetting the solid. It is clear that the contact angle is a function of the pore filling angle, θ, which is a function of the degree of saturation. On extremely hydrophilic surfaces, a water droplet will completely spread (an effective contact angle of 0°). This occurs for surfaces that have a large affinity for water (including materials that absorb water). On many hydrophilic surfaces, water droplets will exhibit contact angles of 10° to 30°. This may be the case in soil-water systems. On highly hydrophobic surfaces, which are incompatible with water, one observes a large contact angle (70° to 90°). Some surfaces have water contact angles as high as 150° or even 180°. On these surfaces, water droplets simply rest on the surface, without actually wetting to any significant extent.

The key elements of an SWCC are illustrated in Figures 1, 2, 3, 4, 5 and 6. The degree of saturation decreases slowly from saturation at zero suction to lower values of water content with increasing matrix suction. The water content change is due to consolidation of the soil matrix for a compressible soil matrix. Pore spaces remain saturated until the air-entry value is reached, defined as occurring at “the matrix suction that must be exceeded before air recedes into the soil pores” (Fredlund and Rahardjo, 1993). The air-entry value is therefore the matrix suction value at which the largest pores begin to drain. The air entry value is around a degree of saturation of 0.85 from Figures 3, 4 and 6. The water content now decreases more rapidly due to the emptying of soil pores. The residual water content occurs when an increase in matrix suction does not produce a significant change in the volumetric water content. At this point, air has entered all the pore spaces within the material and the remaining water is held primarily at grain to grain contacts. The residual water content is around a degree of saturation equal to 5% (Figures 3, 4 and 6). This research begins with an examination of the classic capillary theory for the estimation of air entry of an arrangement of spheres and the work of (Gvirtzman and Roberts, 1991) to estimate the point of residual saturation. The theory is developed here, addressing the physics of matrix suction, air-entry value and residual saturation in turn.

Matrix suction represents the balance of the forces acting across the air–water interface in a porous medium. It is defined as the difference between the air (u_a) and water (u_w) pressures, or (u_a–u_w), see Figure 5. A concave curvature of the air–water interface towards the higher pressure forms, because the cohesive forces between the water molecules at the air–water interface are not equal in all directions (Schemes 1, 2 and 3). This is similar to a bubble, where the pressure inside is greater than the pressure outside. The radius of this curvature can be used to relate the pressure difference (Δu) across the curved surface to the surface tension (see equations 11 and 12). The non-uniform pore size distribution due to changes in suction and capillary pressure components in soil causes hysteresis in the soil water characteristic curve in a wetting-drying path. At constant water content and when drainage is prevented, suction is a function only of temperature and pore structure.

In unsaturated soil, air-water interface and water-solid adsorption happens in the soil pores at a microstructure level. Also, the behavior of water under high negative pressure and the effect of meniscus both occur at a microstructure level, thus giving the microstructure a predominant role. This role has been confirmed by many researchers in recent years in the discipline of unsaturated soil (Delage and Graham, 1995). The distribution of water within unsaturated samples gives different mechanical behaviors due to the different degrees of saturation in the soil profile.

The effect of capillary action in unsaturated soil is much more important than gravity in drawing water into small pores (i.e., small particle radius) rather than large pores. The smallest pores, therefore, will be fully saturated due to capillarity, the intermediate pore size will have an intermediate value for the degree of saturation and the large pores will have a low saturation level. This means that there are different saturation levels within the soil samples or in the whole soil profile, and consequently there will be different values of negative pore water pressure within the soil samples.

The direction of surface tension components is a function of the magnitude of negative pore water pressure and particle arrangement (Fredlund and Rahardjo, 1993). The equilibrium of soil particles in unsaturated soil is affected by surface tension. The interdependency of the relationship between the surface tension or capillary pressure on the one hand and particle arrangements on the other is complicated. It is difficult to describe this relationship mathematically without approximations. The best way of describing this relationship is to base it on microscopic analysis as discussed in the above mathematical model which is suggested in this papar.

CONCLUSIONS

The model quantitatively analyzed the interfacial area between wetting and non-wetting fluids and the solid spheres as a function of the degree of saturation. A potential application of the model is to quantify the air–water interface in the unsaturated zone. General equations were developed for the volume of water stored at grain to grain contacts and for the surface area of various packing arrangements. The following important conclusions can be drawn:

1. There is a good agreement between the predicted and measured capillary rise based on minimum particle size.
2. The smaller the size of the soil particles is, the higher is the capillary rise. This means that the capillary force is much more important than gravity in drawing water into small pores rather than large pores.
3. The measured values to matrix suction have been obtained from simple but accurate techniques based on capillary rise tests.
4. The matrix suction is highly influenced by: degree of saturation, particle size, particle shape and grading.
5. As the particle size and the degree of saturation decrease, the suction increases.
6. The air entry value is found at a degree of saturation of 0.85.
7. The residual water content is around a degree of saturation equal to 5%.
8. The big particle sizes of coarse sand can be utilized as capillary barriers. This is a good technique to prevent the water to reach the base and sub-base in the pavement.
9. The theoretical model which is proposed in this paper is valid for fine sand and silt to be used in the prediction of the soil-water characteristic curve (SWCC). This model relates the matrix suction to pore geometry, surface tension, particle radius and degree of saturation. Other models use the same variables to predict the shear strength.
10. This model can be used in the prediction of unsaturated flow through the soil.

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