Identification of key parameters on Soil Water Characteristic Curve

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Abstract: In environmental geotechnics, transport phenomena in unsaturated soils significantly depends on the degree of saturation, because many substances are dissolved in pore water and get distributed in soil by advection with the convective flow of pore water or diffusion in the pore water itself, although there is no convective flow. By reducing the amount of pore water, this transportation path becomes less effective. Therefore, identification of key parameters which affect the soil water characteristic curve (SWCC) is an important issue in unsaturated soil mechanics for analyses of any geo-environmental problems. Although broad studies have been done on unsaturated soil behavior, but there is still no unified model which can be able to simulate soil water characteristic curve, accurately. During past decades, several mathematical functions have been proposed to model the SWCC and because of various key parameters which affect the SWCC, the proposed models are not so comprehensive. Therefore, the curves obtained from conventional tests often cannot be directly applied in practice, and the mathematical expressions from one condition cannot be used to simulate another situation. The effects of initial void ratio, initial water content, stress condition and high suction were studied in this work revealing that water content and stress state are more important than the other factors, but their influences tend to decrease when suction increases.

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Key words: Soil-water characteristic curve (SWCC), unsaturated soil, void ratio, water content, loading history.

1. Introduction

The soil-water characteristic curve (SWCC) is described as the relationship between the degree of saturation, S_r, (or the volumetric water content, θ) and the matric suction, S ($= u_a - u_w$) where u_a and u_w are pore air and pore water pressure, respectively. SWCC usually obtained by drying or wetting a soil sample under constant stress while monitoring the changes of water content in the soil. The curve is also called the soil moisture characteristic curve or the soil water retention curve.

The soil-water characteristic curve can usually give an indication of the hydraulic properties of the soil, and is a fundamental property in soil physics and soil mechanics. The soil-water characteristic curve is widely used to predict hydraulic conductivity, soil water storage, field capacity and soil aggregate stability in agricultural engineering (Brady, 1999). It is also one of the most fundamental geotechnical properties of soils and is used in estimating the shear strength, stress-strain relationships and permeability of unsaturated soils (Mualem, 1976; Fredlund *et al.*, 1994; Assouline, 2001; Fredlund *et al.*, 1996; Wheeler, 1996). In fact, this curve presents the basic characteristics of a partially saturated soil.

Many experimental tests had been done to obtain the SWCC for different types of soil under different conditions. Due to the limitations of time and of accurately measuring suction, a wide range of suction tests have not been performed and the various factors affecting the SWCC have not received great attention. This paper concentrates on key parameters on the SWCC as reported in published data and provides some useful conclusions for practical purposes. Figure.1 presents a typical SWCC curve during drying path, which usually consists of three zones: capillary saturation zone, desaturation and residual saturation zones. When the suction value exceeds the air-entry value (AEV), the degree of saturation decreases rapidly at relatively low suction values and then reduces more gradually when the suction becomes high.

Recently, many hydro mechanical constitutive models have been developed for partially saturated soils. Because of the complicated microstructure of partially saturated soil and its importance on unsaturated soil behavior, the SWCC should preferably be used to model the soil behavior accurately. But there are many influences on the SWCC, and without further studies on whether the soil water characteristic curve from conventional tests can be used or not, the resulting large errors may lead to misunderstanding and wrong engineering solutions.

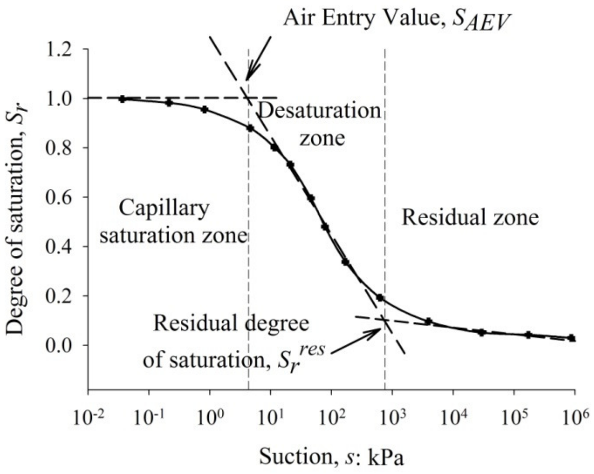

Figure.1. Typical SWCC showing the regions of desaturation (Vanapalli *et al*., 1999)

2. Key parameters influencing the SWCC

The pressure plate test was commonly used to measure suction indirectly using the axis translation technique, which is not able to apply significant stress level. Hence, it cannot be used to study the effect of overload stress (i.e. the loading history of specimens). Therefore, SWCC curve generated by pressure plate apparatus should be considered very carefully. Other factors such as soil structure (and aggregation), initial water content, void ratio, type of soil, mineralogy, and compaction method also have significant effects on SWCC. Among these factors, stress history and initial water content often have the greatest effect on soil structure, which potentially control the nature of the soil-water characteristic curve.

2.1. Effect of initial void ratio

Tarantino (2009) studied the effect of initial void ratio on the SWCC. The material properties are listed in Table 1.

Table.1. Summary of the soil property

G_s	w_p	w_l	I_p
2.67	29.6%	43%	13.4

Each specimen was set in the modified oedometer apparatus for unsaturated soil, and suction was applied by the pressure plate method. Air entry value of the soil is the matric suction value from which air starts to enter into the soil, which is also referred to as bubbling pressure (Brooks and Corey, 1977), from which the maximum pore size in a soil specimen can be measured or estimated. The AEV (denoted as S_{AEV}) shows the magnitude of the capillary saturation zone for a given soil (Figure.1). Figure.2a shows the relation between AVE and void ratio.

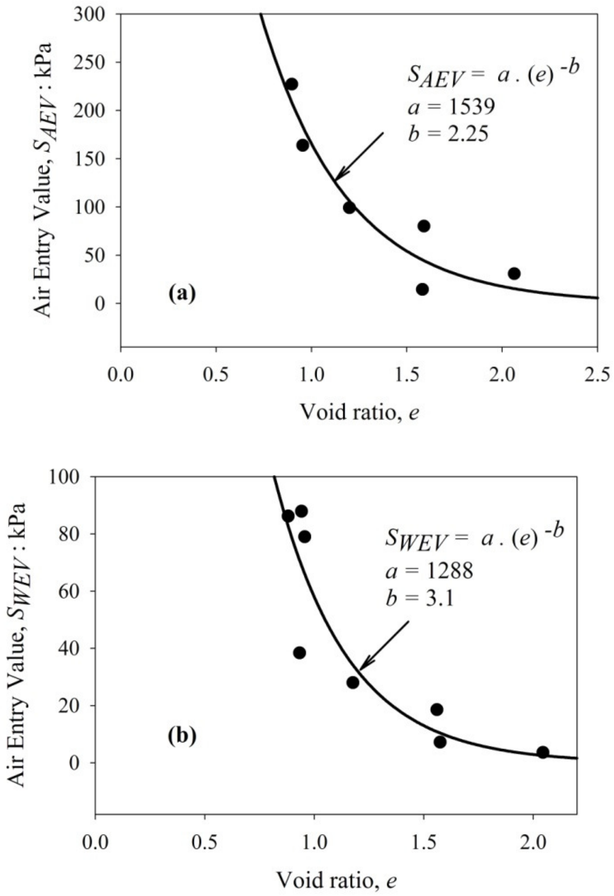

Figure.2. Relationship between void ratio and air-entry value (a); water-entry value (b) (Tarantino, 2009)

As shown in this Figure, The larger amount of AEV should be in inverse proportion to the void ratio of the soil. Similar to the AEV when a soil is wetted up the fully saturation state, matric suction reduces to a certain value called WEV (water-entry value). The relationship between WEV (denoted as S_{WEV}) and degree of saturation is showed in Figure.2b.

Figure.3. presents the variation of the residual degree of saturation (S_r^{res}), which is the degree of saturation at the start of the residual saturation zone followed by AEV. It can be seen from Figures.2 and 3 that the smaller value of initial void ratio (i.e. the denser the soil) leads to the higher the air-entry value, and the higher the residual degree of saturation. The air-entry value and the residual degree of saturation (S_r^{res}) can be expressed together by void ratio (e) using empirical relationships.

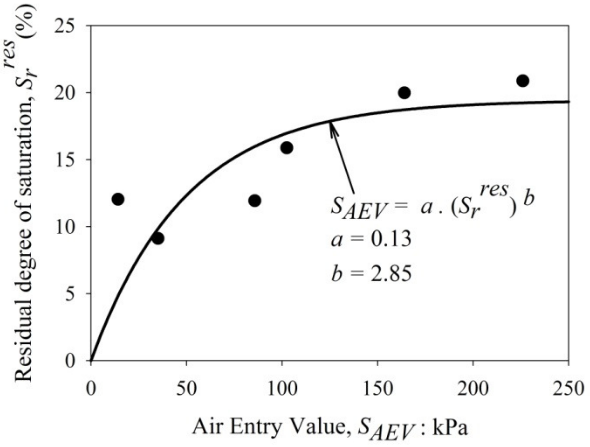

Figure.3. Relationship between AEV and residual degree of saturation (Tarantino, 2009)

The AEV is an important parameter for partially saturated soils since the degree of saturation starts to decrease dramatically when the suction exceeds the AEV. As shown in Figure.2a, according to different values of initial void ratio, there is a wide range of AEVs values, so the denser soil gives, the higher AEV, which implies that for soils with small void ratio, trivial changes in degree of saturation, can be assumed at low suctions, i.e. the soil can be treated as fully saturated. This might be a helpful observation when soils from different depth are being dealt with.

2.2. Effect of initial water content

Figure.4. illustrates the effect of initial water content on the SWCC obtained by Vanapalli *et al.* (1999). The samples were of sandy-clay-till obtained from Indian Head, Canada, which is classified as clay with low liquid limit. The liquid limit, plastic limit and grading properties are listed in Table 2.

Table.2. Summary of the soil property

Soil type	Sand	Silt	Clay	w_l	w_p
Compacted till	28%	42%	30%	35.5%	16.8%

The AASHTO standard compacted maximum density is 1.80 g/cm^3 at optimum water content of 16.3%. The specific density of the soil solids is 2.73. All samples were compacted and prepared with the required initial water content and density, and then placed between filter paper and porous stones in consolidation rings, then were loaded to 3.5 kPa in a conventional oedometer. The initial water content has considerable influence on the shape of SWCC curves. The higher initial water content, gives the steeper SWCC. The air-entry value also increases with initial water content. The resistance to desaturation is relatively low in the dry of optimum specimens in comparison to optimum and wet specimens. Therefore, the effect of desaturation is more obvious in specimens with high initial water content, especially at low suction. SWCCs with different initial water content tend to converge at high suction values.

2.3. Effect of stress state

In the field, due to different loading history, soil normally experiences a certain stress, which is recognized to have some influences on SWCC (Fredlund and Rahardjo, 1993). Vanapalli *et al.* (1996; 1998; 1999) studied the influence of total stress state on the SWCC of a compacted fine-grained soil indirectly. Since the conventional pressure plate apparatus does not allow any external loading, an equivalent pressure is applied to study the effect of loading history on SWCC. Equivalent pressure can be explained by Figure.5. A saturated specimen was placed in an oedometer, under constant volume conditions and loaded to 200 kPa (point A in Figure.5). Then it was allowed to swell under a nominal pressure (3.5 kPa) (point B). When the specimen had experienced maximum pre-stress pressure (200 kPa), it had a void ratio corresponding to 100 kPa on the initial compression branch after swelling under the applied pressure of 3.5 kPa (point C). The equivalent pressure for this specimen is equal to 100 kPa.

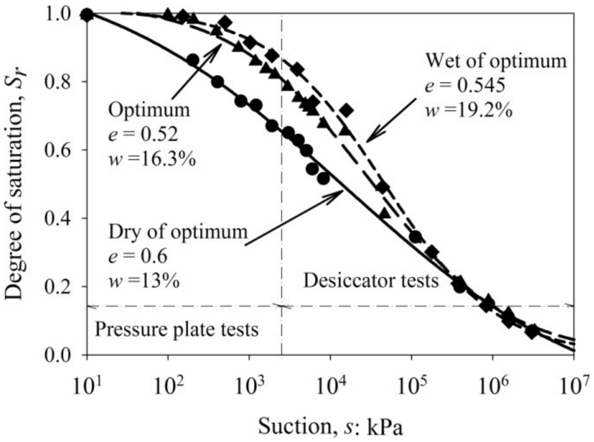

Figure.4. SWCCs for specimens compacted at different initial water contents (Vanapalli *et al.*, 1999)

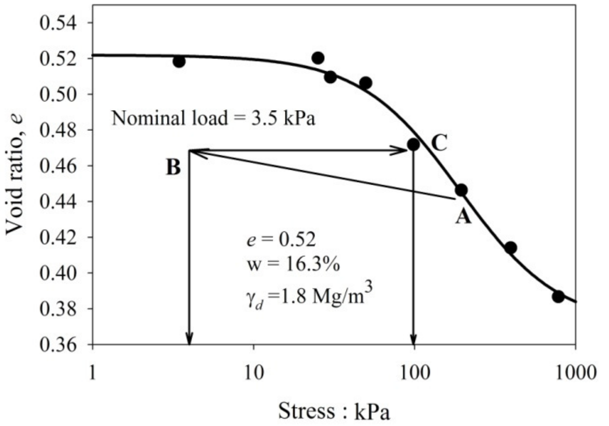

Figure.5. Void ratio *vs* applied stress for an initial void ratio of 0.52 (Vanapalli *et al*., 1999)

The SWCCs developed for the specimens compacted dry of optimum and with equivalent pressures of 25, 35, 80 and 200 kPa are shown in Figure.6. It can be seen, the air-entry value of specimens increases with increasing equivalent pressure. In general, beyond the air-entry value, specimens subjected to higher equivalent pressures have higher degrees of saturation at any given suction.

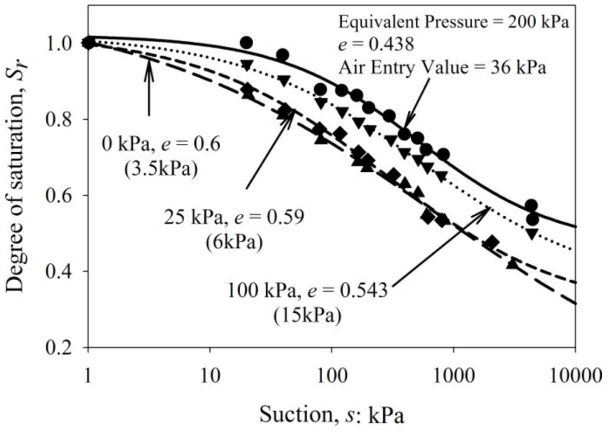

Figure.6. SWCC for specimens compacted dry of optimum water content (Vanapalli *et al*., 1999)

To explain this phenomenon, Vanapalli *et al*. (1999) suggested that when investigating the structure of partially saturated soils, there are two kinds of structure to be considered: macrostructure and microstructure. Soil microstructure is described as the elementary particle associations within soil, whereas the arrangement of soil aggregates is referred to as the macrostructure (Mitchell, 1976).

Macro-structure controls soil-water characteristic behavior of compacted specimens with initial water contents in the dry side of optimum moisture, particularly at low suction values. The air-entry value and the residual state of saturation increase with the equivalent pressure for specimens with dry of optimum initial water content conditions. Microstructure seems to govern the soil-water characteristic behavior of specimens compacted wet of optimum and resists the desaturation (drying). This interpretation has to be confirmed by the inspection of soil structure at different water contents.

Ng and Pang (2000) investigated the influence of stress state on the SWCC of an “undisturbed” or natural, completely decomposed volcanic soil. A conventional volumetric pressure plate extractor and a modified one were used together. Three undisturbed or natural specimens were directly cut from the block into oedometer rings. The net normal stress levels considered in the modified volumetric pressure plate extractor were 40 and 80 kPa, which were appropriate for many relatively shallow slope failures in Hong Kong. Samples were first loaded to 40 and 80 kPa applied net normal stress, respectively, in oedometers with free drainage for 24 h for pre-consolidation purpose. Then they were removed and placed in the modified volumetric pressure plate extractor to subject the SWCCs to a predetermined stress. The required stress applied to each specimen was maintained throughout the tests. The measured SWCCs from their research are shown in Figure.7.

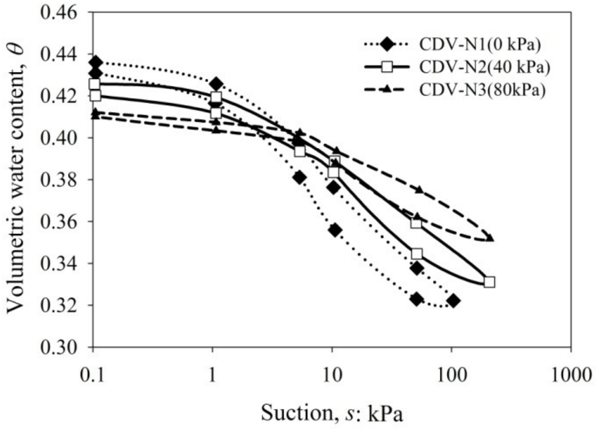

Figure.7. Effects of stress state on SWCC (Ng and Pang, 2000)

The results indicated that as matric suction increases, the volumetric water content of all specimens decreases but at different rates. The higher applied load, leads to the lower rate of reduction in volumetric water content. The point where the volumetric water content starts to decrease significantly indicates the air-entry value.

Figure.7 shows a general tendency that soil specimens subjected to higher stresses possess higher air-entry values, which is related to the presence of a smaller average pore sizes distribution in soil specimens under higher applied load. Stress history or applied stress seems not to affect significantly the shape of SWCC, although the AEV increases and the rate of change of the degree of saturation decreases with the increasing net total stress.

2.4. Effect of high suction values

It has been shown that different initial values of void ratio, water content and stress state will influence the SWCC, especially at low suctions. In this section the effects at high suction values are investigated.

Regardless of the initial conditions of water content (i.e. dry of optimum, optimum and wet of optimum) and stress history, the soil-water characteristic behavior appears to be similar at high suctions (i.e. 20000−300000 kPa), as shown in Figure.8. In other words, as Vanapalli *et al*. (1999) explained, the inner forces between soil aggregates are very strong in resisting desaturation behavior at the high suction values. Apparently, water films at these suctions are so thin that all the water is within the range of influence of osmotic and adsorptive fields. Therefore, soil structure (and aggregation) seems to have negligible influence on the soil-water characteristic behavior in this high suction range. From this, it can be concluded that when suction is very high, the effect of initial water content and stress history can be ignored.

3. Conclusion

The SWCC is an important soil function in unsaturated soil mechanics. When combined with constitutive models, different factors corresponding to field situations should be considered. In this paper some of these key parameters are discussed in the context of how they affect the SWCC. Among these factors stress state and initial water content have the greatest influence. However, at high suction values the effect of these factors tends to diminish. More tests are needed to understand the general features of the SWCC, especially to provide data about soil structure, microstructure and macrostructure. It is not practicable and necessary to test samples under every condition. For this reason a basic series of tests for each type of soil should be performed to establish the main effects and the influence they have on the SWCC of the soil.

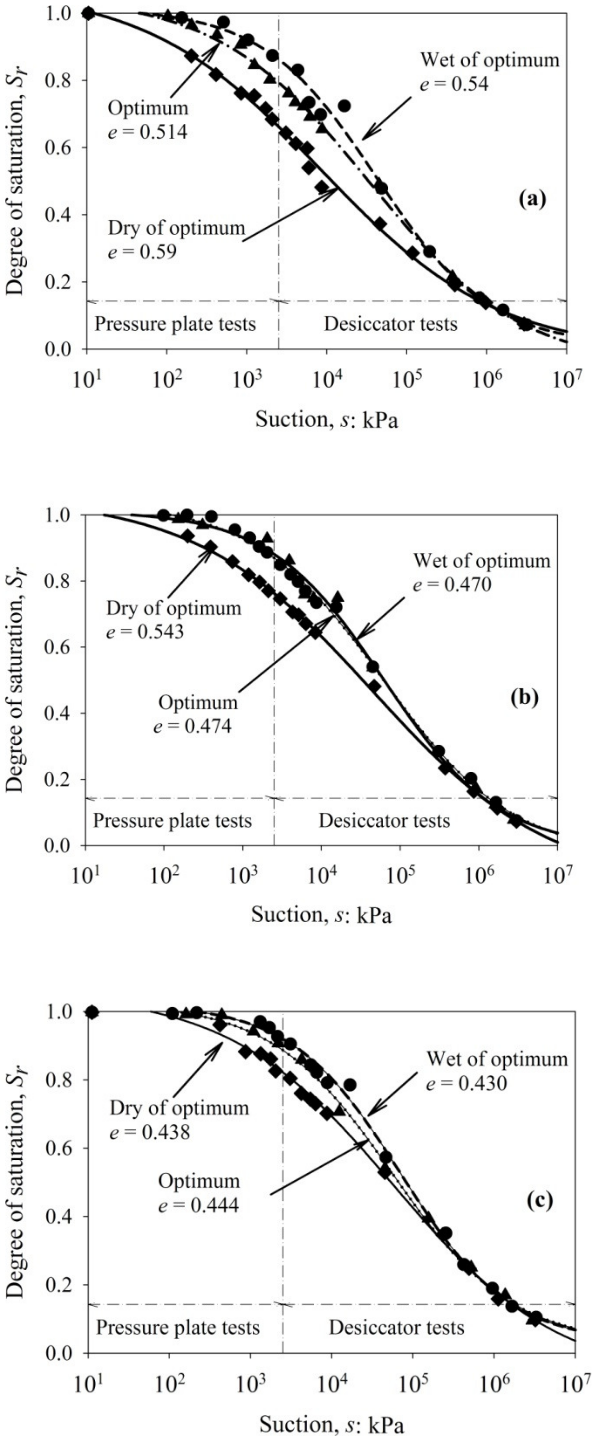

Figure.8. SWCC under different equivalent pressures (a) 25 kPa; (b) 100 kPa; (c) 200 kPa (Vanapalli *et al*., 1999)

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