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Questions concerning the usefulness and validity of the Soil Water Characteristic Curve in Unsaturated Soil Mechanics

Questions concernant l'utilité et la validité de la courbe caractéristique de l'eau du sol en mécanique des sols non saturés.

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ABSTRACT: It is widely accepted that the SWCC is one of the most fundamental tools in unsaturated soil mechanics. It has long been taken that almost all unsaturated soil property functions can be derived from their saturated equivalents by combination with the SWCC, and this presents a theoretical continuum from saturated to unsaturated soil mechanics. There appear to be several questionable aspects concerning the accepted wisdom of the SWCC. These range from sample preparation and acceptable procedures for constructing the curves to cyclic variation and intrinsic variability of the soil itself. Considerable work is being done towards mathematically modelling the behaviour of unsaturated soils. Lack of a consistent approach to generating curves for use in these mathematical models may make their applicability doubtful.

RÉSUMÉ : Il est largement admis que le SWCC est l'un des outils les plus fondamentaux de la mécanique des sols non saturés. Il a longtemps fallu que presque toutes les fonctions des propriétés des sols non saturés puissent être dérivées de leurs équivalents saturés par combinaison avec le SWCC, ce qui présente un continuum théorique allant de la mécanique des sols saturés à non saturés. Il semble y avoir plusieurs aspects discutables concernant la sagesse acceptée du SWCC. Celles-ci vont de la préparation des échantillons et des procédures acceptables pour la construction des courbes à la variation cyclique et à la variabilité intrinsèque du sol lui-même. Un travail considérable est en cours pour modéliser mathématiquement le comportement des sols non saturés. L'absence d'une approche cohérente pour générer des courbes à utiliser dans ces modèles mathématiques peut rendre leur applicabilité douteuse.

KEYWORDS: SWCC, SWRC, Soil Water Characteristic Curve, Soil Water Retention Curve

1 INTRODUCTION.

Soil scientists realized the value of the relationship between suction and water content of soils in agriculture (in planning of irrigation scheduling for example), long before engineers appreciated its value. The axis translation procedure of applying air pressure to drive water out of samples into ceramic porous plates was standard procedure among soil scientists. Their procedures were adopted by engineers. The relationship resulting from these tests is widely called the soil water characteristic curve, or the soil water retention curve, usually abbreviated to SWCC or SWRC. The low suction, high water content part of the SWCC's drying phase may still be measured by this procedure, though other suction measuring devices are now common. In the traditional test, soil is mixed to a paste close to Liquid Limit consistency, cylindrical forms are filled with slurry and then placed on high air-entry-value ceramic plates. The samples on their plates are housed in pressure vessels and air pressure is applied to force water from the soil into the porous plate and from there to a drain. Since the soil and porous medium are filled with water containing the same concentration of solutes, the equilibrium water content held by the soil against the applied pressure is a measure of matric suction, not total soil suction, which comprises both matric and osmotic suctions. From the upper limit of feasibility for the axis transformation procedure (about 1500 kPa), the remainder of the suction to water content drying relationship is typically found by methods which measure total suction. For natural soils, in natural conditions, moisture content is usually controlled by removal of water through evapotranspiration (suction) and addition of water by rainfall. The usual form of the retention curve implies that suction controls moisture content for both wetting and drying.

2 QUESTIONS CONCERNING PROCEDURES.

For engineering purposes there may be doubts about the value of the drying curve revealed by the procedure outlined above. It traditionally starts from a slurried sample at about the Liquid Limit. In many situations the values of soil properties most useful for design are those which refer to the natural undisturbed soil. The liquid limit is an arbitrary value which may have little to do with the maximum water content that a soil in its natural state would absorb. The properties of a slurried sample may have considerable differences from undisturbed soil. There is a move away from slurrying, but there appears to be no universally accepted, well-defined procedure as was the case with the axis translation method.

Blight (2013) raised objections to the commonly accepted wetting curve. He pointed out that when G.N. Smith introduced the SWCC in his textbook "Soil mechanics for Civil and Mining Engineers" (Smith 1968), his representation was erroneous, showing hysteresis between drying and wetting curves, but none between starting and ending water-content. He also noted that this error is widespread and gives an example from Gonzales and Adams (1980), (Blight's figure 1.8, reproduced here as Figure 1) in which he inserted plausible corrections. He also noted that Fredlund and Rehardjo's (1993) textbook also shows Smith style diagrams which he considered faulty. Blight also gave reasons why the so-called scanning curves, running between wetting and drying curves, are, in his view, fictitious. He also pointed out that the popular log-linear plot of the SWCC is deceptive, and a better appreciation of what is actually happening in soil is given by a simple linear plot.

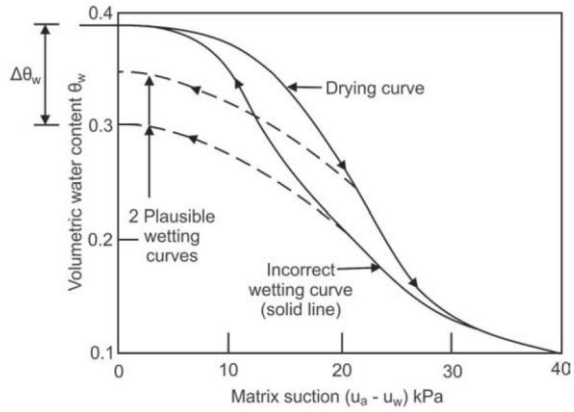

Figure 1. Blight's critique of the G.N Smith representation of the retention curve given by Gonzales and Adams. (Blight 2013 Fig.1.8).

Lourenco et.al. (2007) used linear-linear plots for their retention curves in which continuous monitoring allows retention curve determination in much less time than the traditional procedures. Their figure 5 is shown as Figure 2. They noted the point raised by Toker et. al. (2004) that volumetric measurements cannot be easily integrated into such an experimental set up, which prevents the determination of degree of saturation during the test. They therefore used gravimetric water content, which, as Blight pointed out, is preferable since it is the quantity actually measured. Determination of volumetric water content and degree of saturation involve soil properties which cannot be determined with anything like the same accuracy. One of the reasons for transforming to the other options may be due to various interpretations of the log-linear plots commonly used for the retention curve. The different moisture options lead to changes in the details of the sigmoid form of these plots. Blight pointed out that the sigmoid form of the curve is an artefact of the log scale. All speculation based on the sigmoid form is therefore invalid.

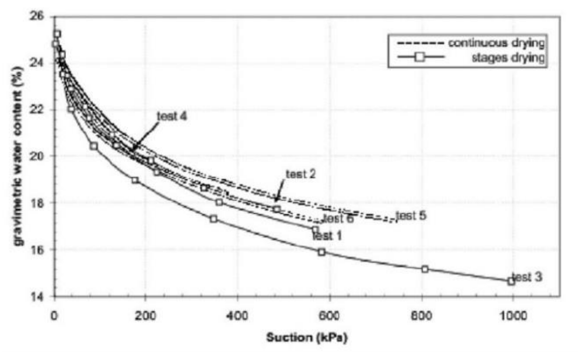

Figure 2. Retention curves from Lourenco et.al.2007 Fig.5

Osinski et.al. (2016) also used linear scales for their retention curves in comparing the SWRC given by pressure plates and by tensiometers. Their results raise two further problems (see their figure 9 reproduced here as Figure 3) . They found significant differences between SWRCs derived by these two methods and their cycling through drying and wetting cycles showed a marked difference between the drying curve for the first cycle and all the other cycles. Tests at the Central University of Technology (CUT) agree reasonably well with these curves when the test starts from a water content comparable to the liquid limit and uses suction only to control water content for the remainder of the test. It is widely held that the first drying curve is the most applicable curve for unsaturated analysis. A problem with both Lourenco and Osinski is that there appears to be no rationale behind their starting and ending water contents. Lourenco's soil was stated to have LL=43.4%. The starting moisture contents for their drying curves were all just above 24%. The graphs suggest this may be appropriate for the moisture content close to zero suction. Osinski's soil is stated to have LL=41.5%, but wetting is only taken to water content about 18%. Since rainfall may lead to water content close to or above the liquid limit, and since this may have a significant effect on hysteresis, as suggested by the first and subsequent drying curves, questions can be raised about the applicability of such curves to field conditions.

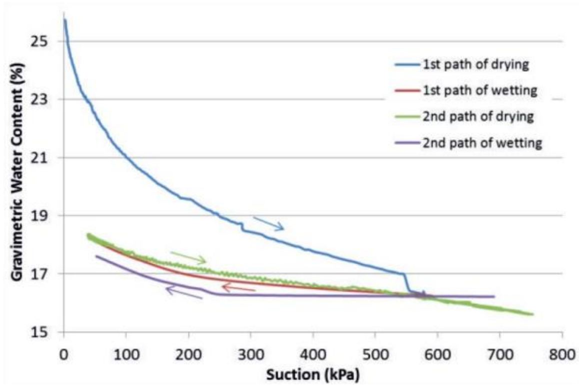

Figure 3. Retention curves from Osinski et. al. 2016 Fig. 9

3 THE LOG : LINEAR REPRESENTATION.

Speculation based on the sigmoid form of the log/linear re presentation of the retention curve can be seen in Fredlund (2018) whose figure 10 is reproduced here as Figure 4.

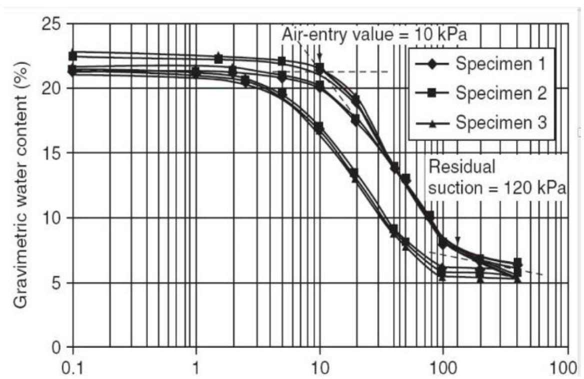

Figure 4. Retention curves from Fredlund (2018) Fig. 10

The sigmoid curve is used to deduce a value of "residual suction" at 120 kPa and an air entry value at 10kPa. A data extraction program (Web Plot) was used to extract the data for one of the curves shown (specimen 2). This data is shown on a linear-linear plot in Figure 5a. The sections between 0kPa to 40kPa and 70kPa to 180kPa are enlarged in Figures 5b and 5c

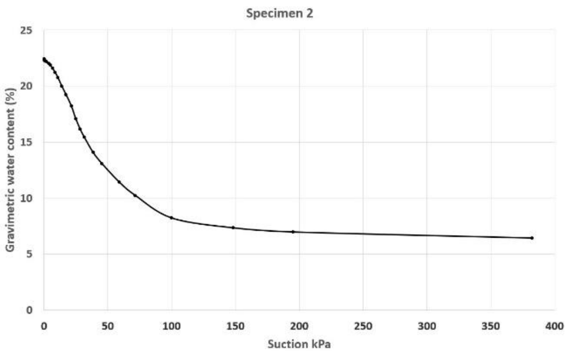

Figure 5a. Linear scales plot of specimen 2 from Figure 4.

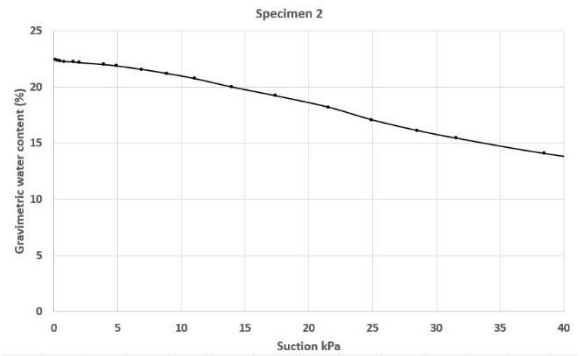

Figure 5b. Linear plot of specimen 2 from 0 kPa to 40 kPa.

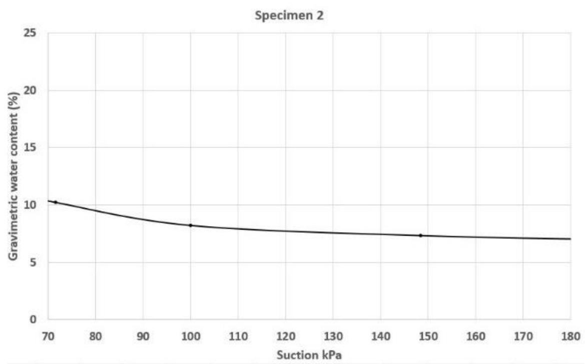

Figure 5c. Linear plot of specimen 2 from 70 kPa to 180 kPa.

There is no indication of anything noteworthy in the region of 10 kPa (Figure 5b) or 120 kPa (Figure 5c). The curve appears to be devoid of any significant inflection or deviation which might indicate an air entry value or a residual suction value. The sigmoid form of the logarithmic plot appears to be as Blight stated – an artefact of the logarithmic scale. A second point is that the curve becomes slightly flatter as it approaches zero suction. But both Lourenco's and Osinski's curves show no such flattening, they continue to steepen. Retention curves produced at CUT are usually plotted in both systems. Linear-linear plots invariably show rapid steepening of the curve as satiation is approached, never flattening. Plotting a log-linear curve in the region of 1 kPa and below is somewhat dubious for such small suctions and may be unreliable. This least reliable part of the curve occupies a disproportionately large part of the graph.

4 WETTING AND DRYING PROCEDURES

Tests performed at CUT deal, wherever practicable with samples disturbed as little as possible. Drying curves have been produced which start with such "undisturbed" samples initially in contact with free water. This should represent satiation water content - the highest water content which can be absorbed without mechanically forcing water into the soil and therefore the maximum likely to be encountered in the field. From this point samples were held over solutions of known relative humidity (RH), from initially very high RH (low suction) progressively to low RH (high suction) and finally to oven dry. Retained water contents were plotted against suction, with a conventionally assumed zero water content (oven dried at 105^{0}C), suction being taken as 1 000 000 kPa. This conventional value is almost certainly a significant over-estimate. A normal laboratory oven circulating ambient air will have a suction at 105^{0}C of about half that value, and even at 150^{0}C the suction will probably be closer to 800 000 kPa unless ambient RH is very low. Wetting curves were produced by following the same procedure, with the same samples being brought to equilibrium with the same solutions in reverse order, and finally being held over pure water, at RH 100, and assumed suction 0. This procedure gave curves very similar to those presented by Blight (Figure 1 dashed lines) and very different to the traditional Smith representation.

There is an objection, however, to this procedure. In the field soil usually gains moisture from rainfall, or possible change in level of the phreatic surface, not from changes in suction. To examine this possibility samples were fed drops of water from a syringe until the surface of the peds remained moist and shiny after allowing several seconds for the water to soak into the soil. In some cases the water content which resulted was higher than the initial water content of the untreated sample left in contact with free water, which in turn, was higher than the liquid limit. This suggests that either the oven drying which the soil had been subjected to had changed the structure of the soil so that its satiation potential was changed, or that the small kinetic energy involved in letting drops of water fall approximately 5mm onto the soil was sufficient to force more water into the soil than it could draw into itself by its own suction. Whatever the reason, the water contents did not always return to the starting values, which were, in turn not the same as the liquid limit, which is the traditional starting point of the SWCC. Continued tests with the same samples showed that after a few cycles of drying to suctions feasible for a normal dry season in central South Africa (100 000 kPa) followed by re-wetting in the above manner, satiation water content returned to a value closer to the starting value. This suggests that oven drying changes soil structure which may return to a structure closer to the original with repeated return to very high water content. Aziz et al. (2018) noted a somewhat similar situation in compacted, non-expansive silt/clay soils used in hydraulic protection structures of the river Po in Italy. Cyclical wetting and drying, modelling seasonal variation expected at the site, led to significant changes in the structure of the soil fabric, with consequent changes in properties, including dilatancy, shear strength, saturated hydraulic conductivity, porosity and air entry value. They did not mention any attempt to determine ultimate satiation water content, but the observed changes would almost certainly lead to changes in this value also. These considerations suggest that the drying and wetting curves in the field may not have the same water content value at the end of the wetting curve as at the beginning of the drying curve, and this value may be higher or lower. This can lead to a drying curve close to, or even above the first drying curve even if the first curve was plotted from satiation rather than the Liquid Limit. The wetting curves were also found to depend on the moisture content to which the sample is dried. This is similar in principle to Blight's modifications of Gonzales and Adams' curves (Figure 1). These observations suggest that to produce a wetting curve meaningful for practical application, the drying curve should go no further than the highest suction likely to be met in the field and the start and end points should approximate the highest water content likely to be achieved after protracted rainfall. Such a curve will not resemble either Smith's or Blight's curves. This also tends to confirm doubts about the value of the traditional log scale for the retention curve. The full retention curve, representing the full range of water content states in natural conditions, moves into the region of positive pore pressure, or negative suction. This cannot be represented as a log-linear curve. Blight is certainly correct that the log linear scale is deceptive. It is also deceptive to consider the suction axis as the independent variable axis for both wetting and drying, since as demonstrated in Blight's curve (Figure 1) one cannot get a sample to take in anywhere close to the amount of water that it takes in either during slurrying or protracted rainfall by simply keeping it in air at RH100, which is taken to be 0 kPa.

These considerations could present a problem for theoreticians struggling with the question of producing a viable mathematical model for unsaturated soils. Zdravkovic et al. (2018) base their modelling on SWCC curves (and SWCC surfaces) which have drying and wetting branches with upper degree of saturation, S_r=1, lower S_r=0, and "scanning" curves running between them, much like the traditional Smith representation. The starting and ending water contents may possibly be very different to field conditions since S_r = 1 for a wide range of water contents, and S_r=0 is unlikely in field conditions.

These observations may throw doubt on whether it is helpful to portray the traditional SWCC as a unique, intrinsic, or characteristic, representation of soil behaviour and suggest two considerations which would need to be taken into account to make the SWCC a theoretically meaningful concept rather than an empirical convenience. The first consideration is whether procedures for producing SWCCs from slurried, compacted and undisturbed samples are adequately differentiated and specified. An understanding needs to be clarified of the relationships, if any, existing between these three cases. It seems possible that a slurry might give meaningful values for highly expansive soils, which typically re-mould themselves. Shrinkage and cracking to considerable depth when subjected to dry conditions is followed by swelling after absorbing water when rain arrives and fills the cracks from the bottom up. But this is not the case with most soils. The second consideration is the question of wetting the sample in a way which bears some relation to the conditions occurring in nature. Neither Blight's procedure of relying on suction alone, nor the traditional apparent reliance on slurrying appear to be a good approximation to nature. The Osinski et al. procedure of adding water by syringe may be a better approximation to nature, but a criterion needs to be agreed upon for the limits at which addition of water starts and ends.

5 SOIL VARIABILITY

There is an additional question-mark hanging over the universal usefulness of the SWCC, and that is the variability of soils over spatial ranges. Soil scientists have for a long time recognized that the agricultural properties of apparently uniform soils exhibit variability on multiple scales. Pachepsky et al. (2000) noted that variability in soil properties tends to be of a fractal nature which varies in scales ranging "from micrometers to the landscape". Variability, particularly variability on fractal scales, has generally been given little regard by engineers. Blight was almost alone among soil mechanics text-book authors in emphasizing the importance of variability. Reliability based design advocates like Phoon (2008) have for a long time pointed out that variability is a vital consideration for engineering design, but relatively few engineers appear to consider it of high importance. Stott and Theron (2017) noted cases where failure of engineering structures could be attributed largely to spatial variability in properties of soils which appeared to be uniform. Miller et al. (1995) found a very strange heave pattern under the ground cover they were studying at an active clay site in Colorado. The cover was intended to simulate a foundation. Their figure 3 (reproduced here as Figure. 6) shows the heave pattern observed. Miller et al. suggested that this strange pattern might be due to the strata underlying the site not being level and this could have allowed moisture to penetrate under the simulated foundation in such a way as to allow a very uneven moisture-content pattern to develop in the underlying clay. Considering the incidence of large variability of suction potential over small spatial ranges found by Stott and Theron (2017), and the large difference in resulting retention curves (Figure 7), it seems that a more likely explanation could be significant variability of swelling potential in the clay beneath the cover. It is quite possible that Fredlund's apparent admission of defeat in attempting to solve the problem of foundations on heaving clay in the question-and-answer session of the 8th Lovel Lecture (Fredlund 2009) could be due to this problem. The current standard practices of soil sampling and analysis do not attempt to assess variability, and as can be seen in Figure 6, the probability of siting a test pit where normal sampling and testing may not indicate the worst conditions which will be faced by construction is large, even though the site measures only10m by 12m. The time and expense of producing a SWCC for such samples would probably not produce meaningful predictions, no matter how well the analysis procedure handled the non-linear differential equations modelling the heave under the foundations.

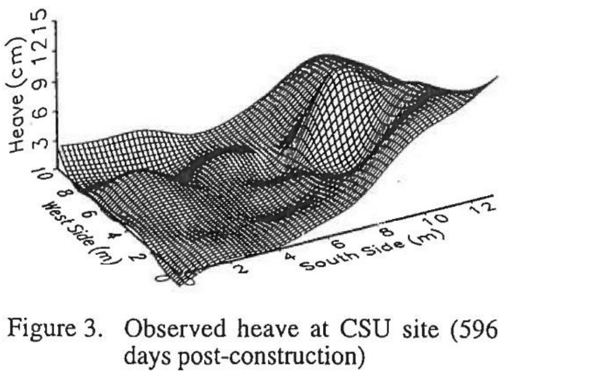

Figure 6 Miller et all's observed heave pattern of a lightly loaded ground cover simulated foundation

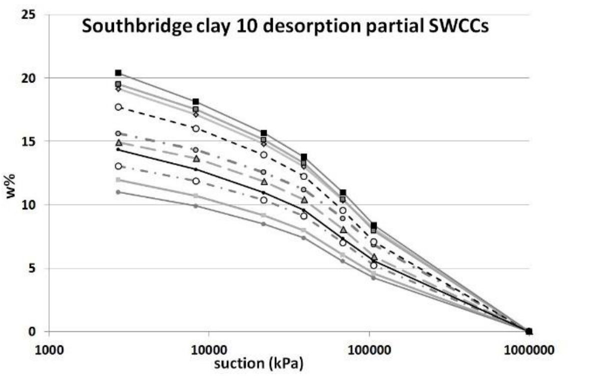

Figure 7. Partial desorption curves for 10 specimens from the clay layer under the foundation of a small shopping centre rendered unsafe by heave damage (Figure 8 from Stott and Theron (2018))

6 CONCLUSIONS

Current practices with the Retention curve appear to follow no standard which would enable results to be compared in a meaningful way. The first drying curve is said to be the most suitable for design purposes. But the drying curve depends on the moisture condition at the start of the test. It might be logical to take the moisture content corresponding the wettest conditions likely to be met in the field. The reason for the common practice of taking the starting value close to the liquid limit is probably because this allows a good contact between sample and porous plate in the axis translation procedure. This may not be a good indication of field conditions. The wetting curve and, all subsequent curves, depend on the suction to which the sample is dried. While it may be convenient to oven dry samples as part of the drying curve, a more meaningful wetting curve would be obtained by subjecting the sample only to the highest value likely to be met in the field at the level of the soil concerned, and oven drying only at the end of all other test procedures.

If the retention curve is to model field conditions it cannot be restricted to unsaturated conditions in all levels of the profile. Such a restriction gives Blight–style curves, which might be of value in desert conditions, but probably not in general geotechnical situations. The form of the retention curve is influenced by the highest water content reached in the field, which may be in the range where pore pressure is positive and suction is negative. For this reason a linear-linear plot would be suitable but a log-linear plot would not. The log-linear representation is deceptive and deductions from the sigmoid curve appear to be artifacts of the log scale. Some of the reasons for using volumetric water content or degree of saturation may therefore be unjustified. The simplest and most accurate values are the gravimetric water contents actually measured.

Taking one or two samples for determination of a Retention curve for a soil may give a poor indication of behaviour for a soil with large intrinsic variability.

7 ACKNOWLEDGEMENTS

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