



On the Determination of Unsaturated Soil Property Functions

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ABSTRACT

Unsaturated soil property functions can be estimated based on two relatively simple laboratory tests. These are: i.) the gravimetric water content versus soil suction test, and ii.) the shrinkage curve test. Data reduction and further calculations can be performed using a spreadsheet to compute unsaturated soil property functions, USPFs, such as permeability functions, water storage functions, and shear strength functions. Spreadsheets can also be used to expedite the calculation of other volume-mass versus soil suction relations. The calculations involve: i.) integration, ii.) differentiation and iii.) regression analyses to best-fit published equations for typical unsaturated soils behavior. The calculated USPFs can then be imported to numerical modeling software and used for numerical modeling.

RESUME

Les fonctions des propriétés des sols non saturés peuvent être estimées sur la base de deux tests de laboratoire relativement simples. Ce sont: i.) La teneur en eau gravimétrique par rapport à l'essai d'aspiration du sol, et ii.) L'essai de courbe de retrait. La réduction des données et d'autres calculs peuvent être effectués à l'aide d'un tableur pour calculer les fonctions de propriété du sol non saturé, les USPF, telles que les fonctions de perméabilité, les fonctions de stockage de l'eau et les fonctions de résistance au cisaillement. Des feuilles de calcul peuvent être utilisées pour accélérer le calcul d'autres relations volume-masse par rapport à la succion du sol. Les calculs impliquent: i.) L'intégration, ii.) La différenciation et iii.) Les analyses de régression pour ajuster au mieux les équations publiées pour le comportement des sols non saturés. Les USPF calculés peuvent ensuite être importés dans un logiciel de modélisation numérique et utilisés pour la modélisation numérique.

1 INTRODUCTION

There are two relatively easy-to-measure unsaturated soil relationships that can be measured in geotechnical engineering laboratories; namely, i.) the gravimetric water content versus soil suction test (w -SWCC), and the ii.) shrinkage curve (SC), test (Fredlund et al., 2012). This paper proposes the measurement of the desorption (or drying) curve and the shrinkage curve to obtain the necessary unsaturated soil property functions for geotechnical engineering purposes. The two independent laboratory soil tests can be performed on: i.) slurry, ii.) undisturbed, or iii.) compacted soils. The volume-mass properties of the w -SWCC and SC test specimens should be independently measured at the start of each of the tests (Fredlund and Zhang, 2017). The results are then "blended together" for the calculation of other volume-mass soil-water

characteristic curves such as: i.) volumetric water content soil-water characteristic curve, θ -SWCC, ii.) void ratio characteristic curve, e -CC, iii.) the dry density (and total density) soil-water characteristic curves; ρ_d -SWCC and ρ -SWCC), and the iv.) degree of saturation soil-water characteristic curve, S -SWCC. Each of the volume-mass SWCC relationships have a role to play in the determination of unsaturated soil property functions, USPFs.

Numerous assumptions and estimations are associated with the analysis of unsaturated soil test results. It is important that the best design and analysis procedures become the accepted protocols for engineering practice (Fredlund, 2006). The primary new state variable in unsaturated soil mechanics is soil suction which can vary from values less than 1 kPa (i.e., essentially zero) to one million kPa. It is assumed that soil suction can be used as the single dominant

state variable controlling changes in the behavior of an unsaturated soils (Fredlund, 2016). In other words, soil suction, with emphasis on the drying SWCC, can be used for defining unsaturated soil property functions in the development of a practical applied science for unsaturated soil mechanics.

1.1 Objectives and Scope

The primary objective of this paper is to present a consistent and effective methodology for the determination (via laboratory measurement and estimation procedures), of unsaturated soil property functions, USPFs. The proposed protocols utilize data from two basic laboratory test data sets (i.e., w -SWCC and SC). These two tests provide the minimum data required for estimating the USPFs associated with physical processes involving unsaturated soils. The paper illustrates data reduction from the two mentioned unsaturated soil laboratory tests into continuous mathematical functions that are identified by two or more fitting parameters. The mathematical relationships cover the entire range of possible soil suctions that might be encountered in field conditions. The suggested soil suction range extends from values as low as 0.1 kPa to as high as one million kPa for a completely dry soil.

This paper emphasizes the use of spreadsheets (e.g., EXCEL) for the calculation of the best-fit parameters associated with nonlinear equations. The theories and methodologies presented are also implemented in the SVSOILS software. Attempts to implement unsaturated soil mechanics into engineering practice has shown that estimations of USPFs corresponding to desorption of the soil are adequate for most geotechnical engineering applications (Fredlund, 2017). Use of the desorption boundary behavior (i.e., w -SWCC and SC), appears to provide the minimum information required when modeling the stress state versus volume-mass soil properties for USPFs. The scope of this paper is limited to the application of the Fredlund and Xing (1994) equation for all SWCCs and the M. Fredlund (2000) equation for the shrinkage curve. Similar procedures could be developed using similar mathematical equations representations for the unsaturated soil properties (van Genuchten, 1980; Leong and Wijaya, 2015).

1.2 Steps Involved in the Analysis of Laboratory Data

The calculation of unsaturated soil property functions commences with the laboratory measurement of two basic unsaturated soil relations; namely, i.) the desorption (or drying) gravimetric water content versus soil suction data, (w -SWCC), and ii.) the shrinkage curve data, (SC). There is hysteresis between the

drying and wetting processes; however, it is suggested that consideration be first given to simply analyzing the drying soil behavior with later consideration given to hysteresis associated with the wetting curve. Figure 1 shows the steps involved in “blending” the w -SWCC and SC laboratory data. The “blending” steps ensures that the analysis of the data starts from a common set of volume-mass soil properties. The w -SWCC and the SC laboratory can then be used to calculate other volume-mass soil property relations such as; i.) void ratio versus soil suction, ii.) degree of saturation versus soil suction, iii.) volumetric water content versus soil suction and iv.) density versus soil suction.

Once the basic volume-mass properties versus soil suction are calculated, it is possible to proceed with the determination of physical process functions such as: i.) permeability function, ii.) water storage function, iii.) volume change and density functions, and iv.) shear strength function. EXCEL spreadsheets and SVSOILS are used to illustrate the calculation of some of the unsaturated soil property functions, (USPFs).

1.3 Calculation of Volume-Mass Variables

It is assumed that the specific gravity, G_s has been either independently measured or accurately estimated based on previous experience.

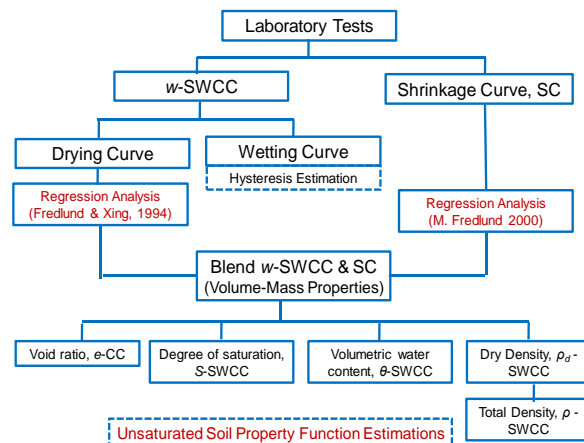


Figure 1. Steps leading to determination of volume-mass soil properties versus soil suction.

When a soil sample is brought into the laboratory, there is a general hierarchy with respect to the measurement of other volume-mass properties. For example, the gravimetric water content, w , and the total density of the soil, ρ , are the first basic measurements to be made. Once these three variables are measured all other volume-mass variables that can be calculated.

1.4 Shrinkage Curve

The shrinkage curve test provides the relationship between volume change (in terms of changes in void ratio) and gravimetric water content as soil suction is increased from a near-zero value to completely dry

conditions (Marinho, 1994). Test specimens for the SC test and the w -SWCC test should be prepared from the “same” soil sample. The SC specimen is commonly about 30 mm in diameter and 10 mm thick while the w -SWCC specimen is commonly about 70 mm in diameter and 30 mm thick (Fredlund and Zhang, 2017; ASTM D427-04, 1998).

Figure 2 shows the measurement of the shrinkage of a soil specimen as drying occurs from a wet soil specimen. The initially wet condition corresponds to a soil specimen that has been allowed to imbibe all the water it can absorb. The initial volume-mass properties should be measured on both the SC specimen and the w -SWCC specimen; however, it is later necessary to “blend” the two sets of laboratory results for calculation of other volume-mass SWCCs.

M. Fredlund (2000) proposed a hyperbolic mathematical equation for the best-fitting of measured shrinkage curve data. The shrinkage curve can thus be reduced to two fitting soil parameters as shown in Eq. [1].

$$e(w) = a_{sh} \left(\left(\frac{w}{b_{sh}} \right)^{c_{sh}} + 1 \right)^{1/c_{sh}} \quad [1]$$

where a_{sh} = minimum void ratio upon complete drying, c_{sh} = variable related to the sharpness of curvature as the soil desaturates, b_{sh} = variable related to the slope of the drying curve calculated as: $b_{sh} = (a_{sh} S_o)/G_s$, and S_o = initial conditioned degree of saturation.



Specimen size:
12 mm thick
37 mm diameter

Figure 2 Use of a micrometer to measure volume at various degrees of drying.

Figure 3 shows the main components of a spreadsheet used to record and reduce the shrinkage curve results. The upper left portion of the spreadsheet lists the measured and calculated volume-mass soil properties.

Use of EXCEL for Regression Analysis on Shrinkage Curve			
Use of the M. Fredlund (2000) Shrinkage Curve equation			
Initial Soil Properties			
Specific Gravity, G_s =	2.700		
Initial w (%) =	40.00		
Total density, ρ =	1800.0		
Dry density, ρ_d =	1285.7		
Initial void ratio, $e =$	1.0000		
Vol. water content, W (%) =	51.429		
Deg. of saturation, S (%) =	98.182		
Fitting Parameters		Values:	
a_{sh} =	0.49984		
c_{sh} =	5.3185		
b_{sh} =	0.18176		$b_{sh} = a_{sh} * S_o / G_s$
Measured input data			
Gravimetric water content (%)		Void ratio, e	Degree of saturation, (%)
40.00	1.0000	98.182	
30.00	0.8500	95.294	
25.00	0.7100	95.000	
20.00	0.6000	0.60091	0.00000
15.00	0.5200	0.52959	
10.00	0.5100	0.50369	
5.00	0.5000	0.49984	
0.00	0.5000	0.49984	
Predicted data			
		M. Fredlund (2000) Eq.	
		Predicted Void ratios	Sum Squared Error
		Shrinkage Curve Eq.	on void ratio data
		1.10310	0.00001
		0.83500	0.00021
		0.70963	0.00000
		0.60091	0.00000
		0.52959	
		0.50369	
		0.49984	
		0.49984	
0.00	0.500	0.0000	
40.00	1.100	98.182	Min
			Max
			Sum of errors
			0.00035

Figure 3 EXCEL Spreadsheet used for regression analysis of SC laboratory data

All initial volume-mass variables are calculated based on: specific gravity, G_s , gravimetric water content and total density, ρ . A series of gravimetric water content, w , and void ratio, e , measurements are made as the soil slowly dries during the SC test (Wong et al., 2017). These w and e measurements can be entered in the middle left portion of the spreadsheet. Usually 5 to 8 sets of measurements are required as the soil dries. Once the SC data has been entered into the spreadsheet, the series of “steps” listed in the upper right portion of the spreadsheet can be followed to obtain the fitting parameters using the EXCEL Solver function (Fig. 4). The best-fit parameters are: $a_{sh} = 0.5008$ and $c_{sh} = 5.745$ for the shrinkage curve. The b_{sh} was calculated to be 0.1801. The drying shrinkage curve behavior can hereafter be referred to in terms of the fitting parameters.

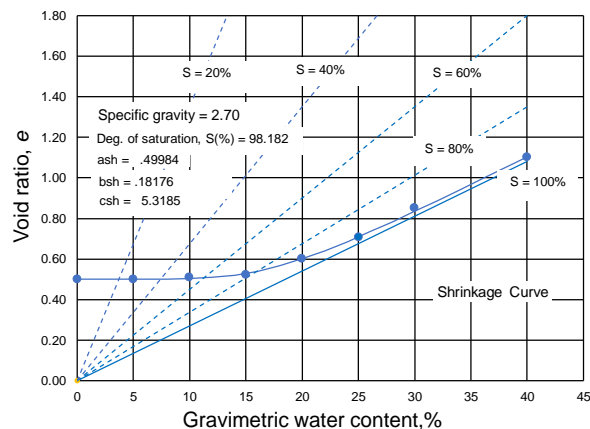


Figure 4 Graphical presentation of shrinkage curve data and regression analysis results

1.5 Gravimetric water content versus soil suction for desorption; the w-SWCC

The gravimetric water content soil-water characteristic curve, (w-SWCC), forms the primary stress state versus soil suction relationship that must be known when undertaking the analysis of unsaturated soil behavior. The w-SWCC function should be established over the entire soil suction range (ASTM D6836-16, 2016). Figure 5 shows a series of pressure plate apparatuses with applied matric suctions up to 500 kPa.



Figure 5 Series of Pressure Plate Cells measuring water content versus matric suction.

Measurement of suction in the high suction range requires the measurement of water content under various total suction conditions. Total suctions can readily be measured using a chilled-mirror *PotentialMeter* (Decagon Devices) (Figure 6).



Figure 6 Chilled-mirror PotentialMeter (Courtesy of Decagon Devices; now Meter Inc.)

There are numerous equations that have been proposed to best-fit the w-SWCC. This paper is limited to the usage of the Fredlund and Xing (1994) SWCC equation, (Eq. [2]).

$$w(\psi) = \frac{w_s C(\psi)}{(\ln(\exp(1) + (\psi/a_f)^{n_f}))^{m_f}} \quad [2]$$

where $w(\psi)$ = water content at any soil suction, ψ , a_f = fitting parameter related to the suction near the inflection point on the w-SWCC, n_f = fitting parameter related to the maximum rate of gravimetric water content change, m_f = fitting parameter related to the curvature near residual gravimetric water content conditions, ψ_r = suction near residual conditions of the soil, and $C(\psi)$ = correction factor equation directing the w-SWCC towards a suction of 10^6 kPa at zero water content (Eq. [3]).

$$C(\psi) = 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln(1 + 10^6/\psi_r)} \quad [3]$$

The compiled data from the Pressure Plate test and the total suction measurements is shown in Fig. 7.

Use of EXCEL for Regression Analysis for Gravimetric Water Content SWCC		(w-SWCC)	
Fitting the Fredlund-Xing (1994) Equation to SWCC data			
Initial Soil Properties			
Specific Gravity, G _s =	2.700		
Initial w(%) =	31.500		
Total density, ρ =	1863.600		
Dry density, ρ _d =	1417.19		
Initial void ratio, e =	0.9052		
Vol. water content, θ =	44.641		
Deg of saturation, S(%) =	93.959		
Fitting Parameters			
a sub fx (grav. w/c) =	74.243		
n sub fx (grav. w/c) =	1.573		
m sub fx (grav. w/c) =	0.7350		
Residual suction, kPa =	1000.0		
Assumptions : Density (water) ρ _w = 1000 kg/m ³ at 4 oC Unit weight, γ = ρg where g = 9.807 m/s ²			
Measured input data		Predicted value	
Soil suction, kPa	Water content (%)	Water content (%)	Sum squared error
0.1	31.5	31.50	0.000
1.0	31.5	31.49	0.000
2.0	31.0	31.46	0.214
4.5	30.8	31.38	0.333
10.0	30.6	31.10	0.249
50.0	27.6	27.69	0.008
100.0	23.7	23.50	0.042
200.0	18.5	18.35	0.022
500.0	12.5	12.83	0.106
1000.0	9.8	9.98	0.033
10000.0	4.7	4.58	0.014
40000.0	3.0	2.70	0.088
150000.0	1.8	1.39	0.168
1000000.0	0.0	0.00	0.000
Sum of square error			1.278

Figure 7 Regression analysis on w-SWCC laboratory data (input data and best-fit parameters)

Figure 7 presents gravimetric water content data based on tests presented by Fredlund (1964) on initially slurry Regina clay. The general layout of the solution spreadsheet is similar to that previously proposed for the analysis of the shrinkage curve data. It should be noted that initial volume-mass variables differ somewhat from those calculated for the shrinkage curve. This difference is intentional in order to later illustrate the “blending” of the result from the SC and the w-SWCC.

It is suggested that an approximation of the residual suction be input prior to solving for the three fitting parameters associated with the Fredlund and Xing (1994) equation (i.e., a_f , n_f , and m_f). It is noted that the

other fitting parameters are only slightly dependent upon the estimation of residual suction. It is adequate to estimate residual suction within one order of magnitude (Vanapalli et al., 1998).

Figure 8 presents the *w*-SWCC data along with regression analysis results. The entire *w*-SWCC function can be calculated from the fitting parameters. The inflection point for the *w*-SWCC function (i.e., *a*) is 74.243 kPa, rate of water extraction (i.e., *n*) is 1.573 and the *m_f* variable is 0.7350. These fitting parameters can be used to represent the entire drying *w*-SWCC function.

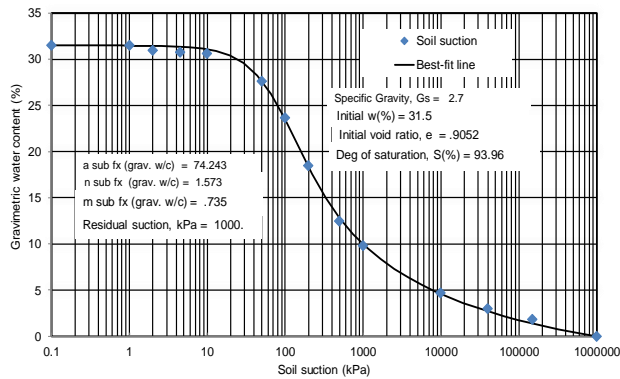


Figure 8 Graphical presentation of *w*-SWCC data and regression analysis results.

Further analyses of the SC and the *w*-SWCC data should be undertaken because an unsaturated soil is known to perform differently with respect to each of the volume-mass variables that are changed. For example, the coefficient of permeability of an unsaturated soil may undergo a modest change due to void ratio changes while undergoing a substantial change when degree of saturation is changed. Therefore, it is important to view the volume-mass soil properties versus soil suction as independent physical relations. Other volume-mass soil properties versus soil suction can now be calculated based on the limited data that has been collected from the SC and the *w*-SWCC. The remainder of this paper explains the calculation of other volume-mass versus soil suction relations.

1.6 Blending the results of the SC and *w*-SWCC laboratory tests

The measured initial volume-mass soil properties may be slightly different for the SC test and the *w*-SWCC test. For example, the initial gravimetric water content for the SC test was 40.0% while the same variable was 31.5% for the *w*-SWCC test. It is recommended that the *w*-SWCC be used as the reference conditions. In other words, the initial gravimetric water content is assumed to be 31.5%, the total density is 1863.6 kg/m³, the void ratio is 0.9052, and the degree of saturation is 93.959%. The fitting parameters for the *w*-SWCC

remain as previously shown. The initial soil properties for the SC test will be made to conform to the *w*-SWCC test values. Of the three fitting parameters for the SC test, only the *b_{sh}* parameter need to be re-calculated using Eq. [4].

$$b_{sh} = (a_{sh} S_o) / G_s \tag{4}$$

The *a_{sh}* and *c_{sh}* variables remain the same; however, the *b_{sh}* variable needs to be changed from 0.1801 to 0.17359 due to the change in the starting degree of saturation. The adjustment of the *b_{sh}* variable means that other volume-mass variables can be calculated corresponding to suction measurements for the *w*-SWCC test. Sample calculations for the remaining volume-mass variables are shown in Figure 9.

Re-Calculation of blended Volume-Mass variables			
Based on Shrinkage Curve fitting parameters and <i>w</i> -SWCC Deg. of Saturation			
Initial Soil Properties		Revised Soil Properties	
<i>w</i> -SWCC		<i>w</i> -SWCC	
Shrinkage Curve		Shrinkage Curve	
G _s (Measured) = 2.700		G _s (Measured) = 2.700	
Initial w(%) = 40.000		Initial w(%) = 31.50	
Total density, ρ = 1800.00		Total density, ρ = 1863.60	
Dry density, ρ _d = 1385.71		Dry density, ρ _d = 1411.71	
Initial void ratio, e = 1.0000		Initial void ratio, e = 0.905797	
Vol. water content, θ(%) = 51.429		Vol. water content, θ(%) = 44.6270	
Deg of saturation, S(%) = 93.8992		Deg of saturation, S(%) = 93.9592	
Fitting Parameters (Shrinkage Curve)		Revised Fitting Parameters (Shrinkage Curve)	
a _{sh} = 0.49881		a _{sh} = 0.49881	
c _{sh} = 5.3185		c _{sh} = 5.3185	
b _{sh} = a _{sh} ⁿ /G _s = 0.18176		b _{sh} = a _{sh} ⁿ /G _s = 0.173824	
Measured <i>w</i> -SWCC Data		Calculated Data	
Soil suction (kPa)	Gravimetric <i>w</i> (%)	Void ratio	Deg. of Saturation (%)
0.1	31.50	0.9129	93.17
1.0	31.50	0.9129	93.17
2.0	31.50	0.8990	93.10
4.5	30.60	0.8916	93.08
10.60	27.60	0.8879	93.05
27.60	27.60	0.8060	92.46
127.70	18.50	0.7044	90.84
500.0	12.50	0.5889	84.81
2000.0	8.00	0.5151	77.77
3000.0	6.75	0.5043	77.77
4000.0	6.00	0.4999	77.77
10000.0	4.50	0.4998	77.77
100000.0	0.00	0.4998	0.00

Other calculated volume-mass properties

Figure 9 Selection of the volume-mass variables for calculation of other SWCCs.

1.7 Void ratio versus soil suction over the desorption range, e-CC

The first separation in volume-mass properties associated with suction changes involves separating volume change (i.e., void ratio changes) from desaturation changes. Volume change effects can be calculated as void ratio changes and desaturation as changes in degree of saturation. Suction changes can increase starting near saturated conditions or else decrease starting from relatively dry conditions. These suction changes are known to produce significant hysteretic effects in terms of volume-mass behavior.

While it is recognized that suction versus volume-mass changes are hysteretic; however, it is suggested that until further research is undertaken, the definition of the shrinkage curve be limited to drying from a near saturated condition for geotechnical engineering applications.

Figure 10 shows the calculation of void ratio characteristic curve, (e-CC), determined from the

presented SC and w -SWCC data. It can be seen that a different estimation of the residual suction can be used for the best-fit analysis. Once again there are three fitting parameters that correspond to the e -CC function. The fitting parameters presented correspond to the e -CC and are consistent with, but independent from the previous fitting parameters for the SC and w -SWCC.

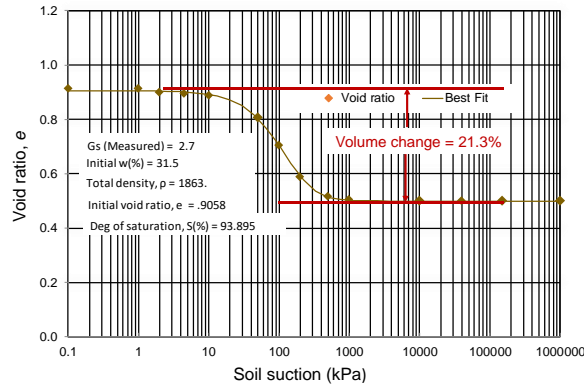


Figure 10 Graphical presentation of e -CC data and the calculated curve from the regression analysis parameters

The Fredlund and Xing (1994) general equation for the SWCC should have the correction factor ($C(\psi)$) omitted since the void ratio becomes asymptotic to a zero slope at suctions beyond residual suction. The plot shows that volume change commences at a suction of about 10 kPa and that no further volume change occurs once the suction exceeds about 400 kPa. The maximum overall volume change was about 21%.

1.8 Degree of saturation versus soil suction over the desorption range; the S-SWCC

The second physical process that can be computed involves desaturation as soil suction increases. Three fitting parameters are obtained from the regression analysis when applying the Fredlund and Xing (1994) equation (i.e., Eq. 2). The graphical plot of the S-SWCC function is shown in Fig. 11. The inflection on the S-SWCC function, a_{fx} is 265.8 kPa which is considerably higher than observed when analyzing the w -SWCC (i.e., 74.24). The “so-called” air-entry values obtained when analyzing the S-SWCC and the w -SWCC functions are correspondently very different. The S-SWCC function indicates that the soil remains essentially saturated to considerably higher suction values than would be indicated based on the w -SWCC function. The n_f obtained from the S-SWCC function is considerably steeper at 2.27 as compared to 1.57 from the w -SWCC function. The m_f fitting parameter is 0.45 from the S-SWCC as compared to 0.735 from the w -SWCC. The comparison of the analysis of the S-SWCC

to the w -SWCC function illustrates the independent functionality of each of the SWCC volume-mass functions.

The logarithm of the soil suction scale can also be converted to an equivalent arithmetic scale for purposes of calculating the “true” air-entry value for the soil. The logarithmic suction scale is converted to an arithmetic scale, ξ , by using the following suction scale transformation.

$$\xi = \log_{10}(\psi) \quad [5]$$

The degree of saturation SWCC with the transformed suction scale retains the same Fredlund and Xing (1994) mathematical form shown in Eq. [2]. The degree of saturation as a function on the transformed suction scale is graphically shown in Fig. 11. The remaining fitting parameters for the transformed degree of saturation equation, (i.e., a_f , n_f , and m_f) remain the same as calculated for S-SWCC.

The “true” air-entry value, AEV, corresponds to the intersection point between a horizontal line through the initial degree of saturation and the line of tangency through the inflection point (Zhang and Fredlund, 2015). The inflection point corresponds to the point where the slope of the function is the largest. A line of tangency is drawn through the inflection point in order to calculate the “true” air-entry value. The above numerical solution provides an empirical procedure for the calculation of a unique value for the “true” air-entry value of a soil. Figure 12 shows the determination of a “true” air-entry value, AEV, of 163.81 kPa for the soil. The analysis of the S-SWCC sets the stage for the next steps which are the estimation of USPFs (e.g., the coefficient of permeability function) (Zhang and Fredlund, 2015).

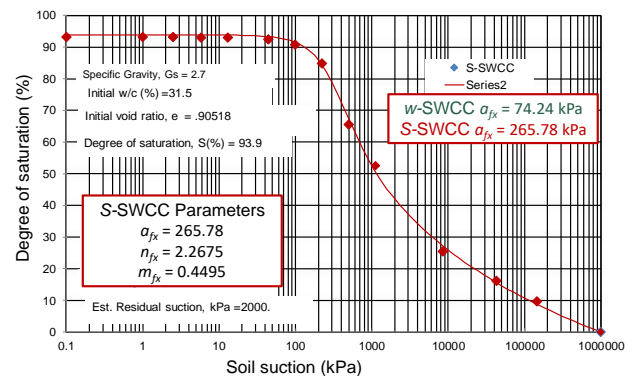


Figure 11 Graphical presentation of S-SWCC regression analysis results

It should also be noted that a number of assumptions have been made throughout the above-proposed analysis. For example, information on the effect of hysteresis associated with drying and wetting,

and the effect of total stress confinement during the drying process have not been taken into consideration.

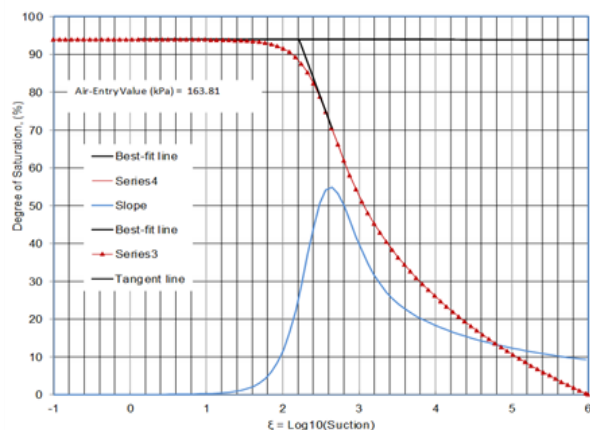


Figure 12 Calculation of the air-entry value, AEV, for the soil

The assumption has been made that these effects remain the topics of future research studies. It is anticipated that while hysteresis and the effect of total confinement are important, they do not represent the dominant effects for many soils and many analyses.

1.9 Calculation of the unsaturated permeability function

The coefficient of water permeability function can also be performed by integration along the degree of saturation USPF. The integration process is more cumbersome than the calculation of the volume-mass

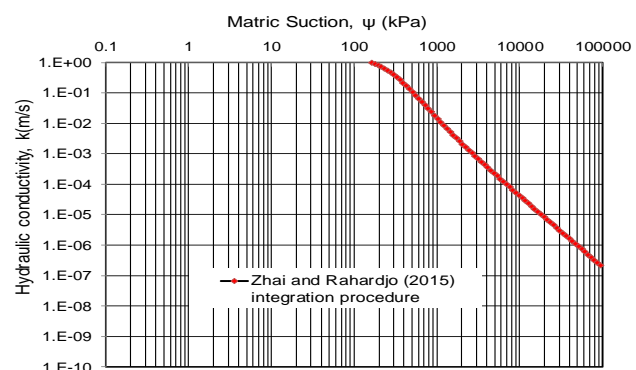


Figure 13 Calculated data points along the permeability function for the Fredlund et al (1994) permeability function calculated using a Spreadsheet (Zhai and Rahardjo, 2015)

presents calculated permeability function as a series of discrete data points. functions. The integration process was published by Zhai and Rahardjo (2015) illustrates the use of the proposed Fredlund and Xing (1994)

integration equation on a spreadsheet. Figure 13 graphically

When the calculations are performed along the S-SWCC function of a unimodal soil, the permeability function remains essentially at the saturated coefficient of permeability until the “true” air-entry value, AEV is reached. Then the coefficient of permeability rapidly decreases as the soil desaturates. This is essentially the form that Brooks and Corey proposed for the permeability function in 1964, and similar to the Gardner (1958) function.

1.10 Volumetric water content versus soil suction over the desorption range; the θ -SWCC

The volumetric water content versus soil suction relationship also serves an independent and important relationship with regard to water storage in the soil. However, it is beyond the scope of this paper to include the spreadsheet calculation of other unsaturated soil property functions.

1.11 Concluding Remarks

An independent stress state variable approach based on soil-water characteristic curve analysis has been proposed for the estimation of volume-mass versus suction relations and other USPFs.

The essential assumptions and elements of the protocol are as follows:

- 1.) Attempts to measure both the drying and wetting bounding curves in the laboratory is not always acceptable from a budget and cost-effective approach even though it would be preferable.
- 2.) It is proposed that in routine geotechnical engineering practice that only the drying SWCC be used for subsequent estimations of unsaturated soil property functions. This approach builds in a natural bias towards the solution of either an upper bound or lower bound soil property function.

The present state of geotechnical engineering practice allows the unsaturated portion of the soil profile to be characterized in a manner similar to that used in saturated soil mechanics. The proposed methodology has been incorporated into the SVSOILS software (M. Fredlund, 2003) and can be implemented in seepage and volume change finite element numerical modeling software packages.

1.12 Acknowledgments

The author is grateful to Golder Associates Ltd for having provided state-of-the-art laboratory equipment for testing unsaturated soil behavior.

1.13 References

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