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**A new approach to improve soil-water characteristic curve
to reduce variation in estimation of unsaturated
permeability function**

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Title: A new approach to improve soil-water characteristic curve to reduce variation in estimation of unsaturated permeability function

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Abstract:

Unsaturated permeability function is often estimated from soil-water characteristic curve (SWCC) of a soil. A complete SWCC measurement can improve the estimation of unsaturated permeability function. In most laboratories, SWCC can be measured up to 100 kPa suction using a Tempe cell. However, the complete measurement of SWCC is an expensive and time-consuming task. Therefore, this paper presents a new approach to estimate SWCC data points beyond 100 kPa suction in order to complement the measured SWCC up to 100 kPa suction. The new SWCC is then used to estimate the unsaturated permeability function. The proposed approach uses knowledge of grain-size distribution curve and the measured SWCC data at 100 kPa suction to estimate the SWCC data points beyond 100 kPa suction. In order to verify the proposed procedure, SWCC tests were conducted over a wide range of suctions for coarse kaolin and a triaxial permeameter system was used to directly measure the unsaturated permeability of the coarse kaolin. The proposed procedure is found to reduce the variation between unsaturated permeability functions estimated by various estimation models.

Key words:

Grain-size distribution, soil-water characteristic curve, unsaturated permeability function, estimation, direct measurement

Introduction:

Unsaturated permeability function is often estimated from soil-water characteristic curve (SWCC) of a soil by various estimation models proposed up to date. The estimation procedure consists of best-fitting the measured SWCC data by a best-fit SWCC equation and integration of the best-fitted SWCC by means of an integration method (i.e., relative permeability equation). The variation between the estimated unsaturated permeability functions using different estimation models was investigated by Rahimi et al. (2015, 2014). It was shown that the measured SWCC data ranges were the most important parameter which caused the variation between all the estimated unsaturated permeability functions obtained from the various models. It was also shown that the complete measured SWCC could eliminate the variation between all the estimated unsaturated permeability functions. Kunze et al. (1968) has reported that a complete SWCC measurement may improve the estimation of unsaturated permeability function. The complete measurement of SWCC may not be practical due to the time and equipments required. However, in most laboratories, SWCC can be measured up to 100 kPa using a Tempe cell. Therefore, the objective of this study is to propose a new approach for estimating SWCC data points beyond 100 kPa to complement the measured SWCC up to the 100 kPa suction. The new SWCC is then used to estimate the unsaturated permeability function. The proposed approach uses the knowledge of grain-size distribution curve and the measured SWCC data at 100 kPa suction to estimate the SWCC data points beyond 100 kPa suction value.

A term Pedo-Transfer Function (PTF) has been used to describe SWCC estimation functions that relate basic soil properties to yield a soil property function (Bouma 1989; Wösten et al. 2001). The estimation algorithms for SWCC have been classified into four major approaches by Johari et al. (2006): 1) in the first approach, the water contents at different matric suction

values are estimated statistically (Gupta and Larson 1979; Saxton et al. 1986). The water contents and soil properties are then correlated at a selected suction value using regression analysis followed by a curve-fitting procedure, 2) in the second approach, regression analysis is used to correlate soil properties with the fitting parameters of an analytical equation representing the SWCC (Ahuja et al. 1985; Zapata 1999; Chin et al. 2010), 3) in the third approach, the SWCC is estimated using a physics-based conceptual model (Arya and Paris 1981; Kovács 1981; Smettem and Gregory 1996; Fredlund 2002) that involves the conversion of a grain size distribution into a pore-size distribution, 4) in the fourth approach, artificial intelligence methods, such as neural networks, genetic programming and other machine learning methods (Pachepsky et al. 1996; Johari et al. 2006; Garg et al. 2014) that involve training the model with an existing database and using the model to estimate the SWCC of other soils, are used.

It should be noted that, although PTF can be used to estimate the SWCC of a soil, it still has limitations due to the underlying assumptions used in the method. Therefore, the estimated SWCC may not be the same as the measured one. The proposed procedure is similar to the third approach (a physics-based conceptual model) which involves the conversion of the grain size distribution into a pore-size distribution. However, the proposed procedure is independent of the soil database and is applicable for suctions beyond 100 kPa.

Methodology

A grain-size distribution curve (GSD) of a typical soil is shown in Figure 1.

A random assembly of soil grains creates a specific pore-structure for any soil and the SWCC of a soil is greatly dependent on its pore-structure (Rahardjo et al. 2012; Sillers et al. 2001; Fredlund and Xing 1994). One of the possible assemblies of a soil with an idealized dense

packing condition (Jaafar and Likos 2011) is shown in Figure 1 and the pore space created by the soil grains can be seen in the figure. The radius of the pore can be computed using knowledge of the grain sizes creating that pore. The pore-structure of a soil is usually considered as a series of capillary tubes with various sizes (Fredlund and Rahardjo 1993). The pore size is related to the height of each capillary tube using the Young-Laplace equation which is equivalent to a suction value (Fredlund and Rahardjo 1993). It is assumed that the pore will be emptied once the suction applied to the soil increases beyond its equivalent suction. Once the suction applied to the soil has increased beyond the suction equivalent to the largest pore size, the soil starts to desaturate.

In a soil with an idealized dense packing condition, for any grain size available in the grain size distribution curve, the assembly of three soil grains of the same size (see Figure 2) would create the largest possible pore size for this grain size and the smaller grain sizes. It should be noted that the assembly of a particular grain size with its smaller grains would result in smaller pore sizes. Therefore, the largest pore that is created by the assembly of three grains of the same size would be emptied at its equivalent suction as computed by the Young-Laplace equation. The smaller pores created by the assembly of that grain size with its smaller grain sizes would remain saturated at that suction. This means that, for any grain size, the percent finer, PF (%), could be related to the water content at the equivalent suction of that grain size. In other words, the water content for that grain size reflects that the smaller pores remain fully saturated at the equivalent suction. If the soil grains are assumed to have a spherical shape with an idealized dense packing condition similar to that shown in Figure 2, the radius of the pore can be computed according to Equation 1, which is known as Descartes' theorem.

$$\frac{1}{R_p} = \frac{6 + 4\sqrt{3}}{D_g} \quad (1)$$

where D_g is diameter of the grain and R_p is radius of the pore created by three grains of the same size

The capillary height of the corresponding pore can be expressed in terms of the radius of that pore according to Equation 2 known as the Young-Laplace equation as follows:

$$h_c = \frac{2T_s}{\rho_w g R_p} \quad (2)$$

where h_c the capillary height (m), T_s is the surface tension (N/m), ρ_w is the water density (kg/m^3), g is the gravitational acceleration (m/s^2) and R_p is the radius of the pore (m). The equivalent suction (ψ), corresponding to each available grain diameter in the grain-size distribution curve of the soil can be computed according to Equation 3, which is obtained by substituting Equation 1 into Equation 2.

$$\psi = (12 + 8\sqrt{3}) \frac{T_s}{\rho_w g D_g} \quad (3)$$

where ψ is the soil suction, (m). By using Equation 3, the x-axis of the grain size distribution curve (i.e., diameter) can be converted to equivalent suction (ψ).

The percent finer, PF (%), of that grain size could represent the percentage of smaller pores corresponding to that grain size. Therefore, the water content at any grain size can be computed according to Equation 4.

$$wc = \frac{PF(\%) \times wc_{Sat}}{100} \quad (4)$$

where w_c is the water content of the soil for any computed suction from Equation 3 and $w_{c_{sat}}$ is the saturated water content of the soil. Therefore, the SWCC data point beyond suction of 100 kPa can be estimated using the actual measurement of SWCC at 100 kPa and the GSD by the following step by step procedure:

- 1- The diameter corresponding to a suction of 100 kPa is computed according to Equation 3 and is called $D_{(100)}$
- 2- The percent finer (PF), corresponding to $D_{(100)}$ is determined from the GSD curve and multiplied by the saturated water content of the soil as a first estimation of water content, $w_{c(100)}$, at 100 kPa
- 3- The first estimate of water content at 100 kPa, $w_{c(100)}$, is scaled to the measured water content of the soil at 100 kPa, $w_{c(m)}$, and the scaled factor is equal to $S_f = \frac{w_{c(100)}}{w_{c(m)}}$
- 4- The equivalent suction, $\psi_{(X_n)}$, of the available grain diameters, $D_{(X_n)}$, smaller than $D_{(100)}$ is computed according to Equation 3
- 5- The percent finer, PF, corresponding to $D_{(X_n)}$ smaller than $D_{(100)}$ is multiplied by the saturated water content of the soil as a first estimation of water content, $w_{c(X_n)}$, at the computed suctions, $\psi_{(X_n)}$
- 6- The first estimation of water content, $w_{c(X_n)}$, at the computed suctions, $\psi_{(X_n)}$, is scaled by dividing it by the scaled factor, S_f

Figure 3 shows a schematic diagram of the proposed procedure.

Evaluation of the proposed method

The proposed method for estimating the SWCC data points in a higher suction range was evaluated using the soil database from the SoilVision (2006) database. SoilVision (2006) is a

large soil database consisting of over 6000 soils that includes details of the grain size distribution, texture, bulk density, porosity, specific gravity, saturated volumetric water content, SWCC and saturated and unsaturated coefficients of permeability. As described earlier, knowledge of the grain size distribution (GSD) and soil-water characteristic curve (SWCC) are required for the estimation procedure. There are 879 soils in the SoilVision database that contain both SWCC and grain size distribution data. However, only 145 of these soils fulfil the following criteria for selection to be used in this study.

- 1- The SWCC measurements must be available from saturations to at least one suction point beyond 100 kPa.
- 2- The SWCC measurements must be available for suctions around 100 kPa (i.e., 90-110 kPa).
- 3- The GSD must be available for grain diameters ($D_{(Xn)}$) equivalent to $\psi(Xn)$ beyond 100 kPa.

From the 145 soils in the SoilVision database which met the above criteria, forty (40) soils as shown in Table 1 were then randomly selected for use in the evaluation of the proposed method. The proposed method was applied to the selected soil database.

The measured SWCC data points versus the estimated SWCC data points are shown in Figure 4. The variability of the estimated SWCC data points versus the measured SWCC data points was computed by calculating the coefficient of determination, R^2 , according to Equation 5.

$$R^2 = 1 - \frac{SSE}{SST} \quad (5)$$

where $SST = SSR + SSE$, $SSR = \sum_{i=1}^X (\hat{\theta}_{wi} - \bar{\theta}_{wi}) = 0$, $SSE = \sum_{i=1}^X (\theta_{wi} - \hat{\theta}_{wi}) = 0$, $\bar{\theta}_w$ is the average measured volumetric water content, $\hat{\theta}_w$ is the estimated volumetric water content, X is the number of data points and i is a counter.

As shown in Figure 4, the coefficient of determination, R^2 , was computed to be 0.906 showing a good agreement between the measured and estimated SWCC data points. The reliability of the estimation procedure was investigated by computing the confidence interval of the observed error, $(\theta_{wi} - \hat{\theta}_{wi})$, using a normal distribution in accordance with Equation 6.

$$\mu(\theta_{wi} - \hat{\theta}_{wi}) \pm Z_{\alpha/2} \sigma(\theta_{wi} - \hat{\theta}_{wi}) \quad (6)$$

where $\mu = \frac{1}{X} \sum_1^X \theta_{wi}$, $\sigma = \sqrt{\frac{1}{X} \sum_1^X (\theta_{wi} - \mu)^2}$, α is the significance level.

The 95% confidence interval of the observed errors, $(\theta_{wi} - \hat{\theta}_{wi})$, is shown in Figure 4 by dashed lines and it was found to be (-0.046, 0.083).

Figure 5 shows the GSD and the measured and estimated SWCC data point for two soils, 10839 and 11537, from the selected database presented in Table 1.

The soil numbers 10838 and 11537 are classified as clay and sandy loam according to USDA soil classification as indicated in SoilVision database. As shown in Figure 5b, the estimated SWCC data points had a good agreement with the measured SWCC data points for soil number 11537, while for soil 10839 the estimated SWCC data points underestimated the measured values (i.e., the estimated data points fell in the lower 95% confidence interval). The underestimated SWCC data points of the soil number 10839 could be due to the high clay content (i.e., clay = 47.83 %) as shown in Table 1. It has been stated by Fredlund et al. (2002) that the main limitation associated with using the PTF methods is related to the increase of fines content of the soil. It should be noted that the effect of soil fabric is not considered in this study and further research is required on how to take into account its effect.

The estimated SWCC data points in the high suction range can be used to complement the measured SWCC data up to the 100 kPa suction value. The best-fit SWCC equation can be used to best-fit the completed SWCC data points including the measured and estimated ones by minimizing the residual sum of squares (SSE). The best-fitted SWCC can then be integrated to estimate the unsaturated permeability function. It should be noted that the estimated SWCC data points might contain error from the actual SWCC measurements. Therefore, only two data points beyond the suction value of 100 kPa should be selected to complement the actual measured SWCC data points of soil up to a suction of 100 kPa. If more than two estimated SWCC data points in the high suction range are selected, these estimated points tend to influence the best-fitting procedure; as they could reduce the accuracy of the best-fit SWCC to the actual SWCC data below 100 kPa.

Example soils from selected database to illustrate the application of the proposed procedure

Four different best-fit SWCC equations of Fredlund and Xing (1994), Fredlund and Xing (1994) with $C(\psi)=1$ as recommended by Leong and Rahardjo (1997a), van Genuchten (1980) and van Genuchten (1980) with $m=1-1/n$ as described in details in Rahimi et al. (2015) were used to best-fit the: (a) the measured SWCC data up to a suction value of 100 kPa, (b) all the measured SWCC data points (i.e., available from the literature) and (c) combination of the measured SWCC data up to a suction value of 100 kPa and estimated SWCC data points by the proposed procedure. Selected estimation models (i.e., FMM, VMM, FCM $C(\psi)=1$ and VCM $m=1-1/n$) from the matrix of unsaturated permeability estimation models by Rahimi et al. (2015) were then used to estimate the unsaturated permeability functions of 11537 and 10838 soils and the results are shown in Figure 6 and Figure 7, respectively.

As shown in Figure 6a, using only the measured SWCC data up to a suction value of 100 kPa resulted in best-fit SWCCs varying from each other resulting in a large variation in unsaturated permeability functions as shown in Figure 6b. When all the measured SWCC data points were used in best-fitting exercise, the best-fitted SWCCs were close to each other (see Figure 6c) and consequently resulted in a smaller variation in unsaturated permeability functions (see Figure 6d). In addition, using the combination of measured SWCC data up to a suction value of 100 kPa and estimated SWCC data points by the proposed procedure resulted in best-fit SWCCs that were close to each other (see Figure 6e) and consequently resulted in a smaller variation unsaturated permeability functions (see Figure 6f). Therefore, the estimated unsaturated permeability functions using the combination of measured SWCC data up to a suction value of 100 kPa and estimated SWCC data points by the proposed procedure were more or less the same as the estimated unsaturated permeability functions using all the measured SWCC data points. This characteristic shows that the proposed procedure could reasonably reduce the variation between unsaturated permeability functions estimated by the different models. The same characteristic was observed for soil number 10838 as shown in Figure 7.

Verification against direct measurement of unsaturated permeability

SWCC and direct measurement of unsaturated permeability tests were performed on coarse kaolin, which was produced by Kaolin Malaysia SDN BHD (Malaysia). Soil specimens were prepared from reconstituted coarse kaolin to have homogeneous and uniform composition. The grain-size distribution of the coarse kaolin is shown in Figure 8.

The liquid and plastic limits of the coarse kaolin are 50.2% and 30.3%, respectively. The soil specimens for SWCC and permeability tests were prepared by static compaction (Ong 1999)

at the maximum dry density (ρ_{dmax}) of 1.4 Mg/m³ and optimum water content (w_{opt}) of 23.9%. The maximum dry density and optimum water content of the coarse kaolin were obtained from the standard Proctor compaction test (ASTM D698 1997). The coarse kaolin is classified as silt with high plasticity (MH) according to the unified soil classification system. The specimens were prepared at a diameter of 50 mm and height of 30 mm. SWCC tests were performed using a Tempe pressure cell, 5-bar pressure plate, 15-bar pressure plate and saturated salt solutions in order to cover a wide suction range. A detailed explanation of all the test methods and procedures can be found in Rahimi (2015). A triaxial apparatus similar to the triaxial apparatus for unsaturated soil testing described by Fredlund and Rahardjo (1993) was used to conduct the unsaturated permeability tests. The design of the triaxial apparatus used in this study was based on the modifications done by Goh et al. (2014) and a detailed tests procedure can be found in Samangan et al. (2003).

Figure 9a shows the measured SWCC data up to a suction value of 100 kPa and Figure 9c shows the full measured SWCC data. As shown in Figure 9a and 9b, the measured SWCC data were best-fit using the four SWCC equations described in Rahimi et al (2015). By comparing Figure 9a and Figure 9c, it can be seen that the best-fit SWCCs obtained using the full measurement of SWCC data were similar over the entire suction range while the best-fit SWCCs obtained using only the measured data up to the suction value of 100 kPa had the same shape until a suction value of 100 kPa, beyond which they started to vary significantly. This is similar to the conclusion obtained for the soils from the database.

The estimated unsaturated permeability curves by FMM, VMM, FCM $C(\psi)=1$ and VCM $m=1-1/n$ estimation models (Rahimi et al. 2015) using the best-fit SWCCs for SWCC data up to 100 kPa along with the directly measured unsaturated permeability data of coarse kaolin are shown in Figure 9b. The estimated unsaturated permeability curves by FMM, VMM,

FCM $C(\psi)=1$ and VCM $m=1-1/n$ estimation models (Rahimi et al. 2015) using the best-fit SWCCs for the full measurement of SWCC data along with the directly measured unsaturated permeability data of coarse kaolin are shown in Figure 9d. By comparing Figure 9b and, Figure 9d, it can be seen that the variation between the estimated unsaturated permeability curves was quite small when the best-fit SWCCs using the full measurement of SWCC data were used as compared to that when only the best-fit SWCCs using measured SWCC data up to 100 kPa were used.

Figure 9e shows the results of the best-fit SWCCs for the coarse kaolin using the measured SWCC data up to 100 kPa in combination with the estimated SWCC data points using the proposed procedure. The four best-fit SWCCs were quite close to each other as shown in Figure 9e as compared to that shown in Figure 9a, which only used the measured SWCC data up to 100 kPa. The estimated unsaturated permeability curves for the coarse kaolin using the best-fit SWCCs by the measured SWCC data up to 100 kPa in combination with the estimated SWCC data points are shown in Figure 9f. It can be seen from the figure that the variation between the estimated unsaturated permeability curves was significantly lower than that shown in Figure 9b, where only the measured SWCC data up to 100 kPa was used.

Conclusions

The estimated SWCC at a higher suction by the proposed procedure (using the grain size distribution and SWCC measured data of up to 100 kPa) successfully eliminated the variation in best-fit SWCCs and estimated unsaturated permeabilities due to the limited measured SWCC data. The proposed method also provided a good fit to the directly measured unsaturated permeability data. Therefore, this method can be used to eliminate the need for SWCC measurement over a wide suction range. This approach can provide a reliable

estimation of unsaturated permeability in a reasonable amount of time with inexpensive equipment.

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Tables

Table 1-Selected soil database for evaluation of the proposed estimation procedure of SWCC data points in a high suction range

	Soil counter	Minimum diameter (mm)	PF of minimum diameter (%)	Maximum measured suction (kPa)	Maximum estimated suction (kPa)	Clay (%)	Silt (%)	Sand (%)
1	262	0.0028	0.120	513291.9	619.1	16.71	78.75	4.74
2	1446	0.002	0.520	1500.93	400.248	57.47	35.72	6.81
3	10760	0.002	0.318	981	981	42.23	25.4	32.243
4	10762	0.002	0.075	1500.93	500.31	12.55	21.05	66.18
5	10763	0.002	0.215	1500.93	500	25.75	18.79	55.37
6	10765	0.002	0.405	1500.93	500.31	41.55	13.79	44.65
7	10774	0.002	0.080	1471.5	392.4	11.61	11.19	77.05
8	10776	0.002	0.490	1471.5	392.4	53.94	9.32	36.29
9	10777	0.002	0.470	1471.5	392.4	50.1	10.36	39.36
10	10831	0.002	0.470	1471.5	294.3	66.54	29.53	3.89
11	10836	0.002	0.170	1554.885	619.011	20.35	66.33	13.32
12	10838	0.002	0.435	1554.885	619.011	66.54	29.53	3.89
13	10839	0.002	0.403	1554.885	619.011	47.83	42.5	9.66
14	10843	0.002	0.351	1554.885	619.011	41.37	52.32	6.3
15	10847	0.002	0.407	1554.885	619.011	57.46	38.21	4.3
16	10851	0.002	0.581	1554.885	619.011	70.97	28.32	0.71
17	10862	0.002	0.219	1554.885	619.011	25.37	64.93	9.7
18	10980	0.002	0.450	1471.5	784.8	52.6	32.29	14.84
19	10981	0.002	0.570	1471.5	784.8	69.35	27.92	2.72
20	10982	0.002	0.630	1471.5	784.8	76.74	20.52	2.68
21	11037	0.002	0.380	1471.5	294.3	47.62	51.28	1.1
22	11159	0.002	0.435	1500.93	500.31	62.37	34.89	2.73
23	11219	0.002	0.200	1013.373	567.509	30.04	69.78	0.17
24	11222	0.002	0.290	961.7724	961.772	34.62	65.35	0.03
25	11224	0.002	0.205	961.7724	961.772	43.79	56.21	0
26	11261	0.002	0.151	1471.5	618.03	19.03	80.3	0.67
27	11267	0.0014	0.137	163.827	163.827	18.59	79.51	1.9
28	11271	0.002	0.181	931.95	931.95	23.67	75.16	1.17
29	11405	0.002	0.070	1471.5	981	11.27	87.56	1.17
30	11409	0.002	0.473	1471.5	981	54.93	37	8.05
31	11410	0.002	0.544	1471.5	981	62.51	29.62	7.77
32	11474	0.0014	0.137	1471.5	1471.5	14.83	6.93	78.18
33	11477	0.002	0.011	1471.5	490.5	1.16	3.16	95.68
34	11496	0.0014	0.111	500	500	16.49	16.94	65.76
35	11497	0.0014	0.137	300	300	14.83	6.93	78.18
36	11525	0.0014	0.142	300	300	19	10.97	69.68
37	11537	0.0014	0.115	500	500	15.62	19.58	64.51
38	11540	0.0014	0.225	400	400	34.69	37.68	26.88
39	12217	0.001	0.397	324.319	324.319	52.58	46.6	0.82
40	18748	0.002	0.250	1000000	870.9634	32.76	22.46	43.45

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Figure 1-Grain-size distribution of a typical soil
70x57mm (300 x 300 DPI)

Figure 2-Idealized dense packing condition of soil grains

242x261mm (96 x 96 DPI)

Figure 3-A schematic diagram for the proposed estimation method

87x144mm (96 x 96 DPI)

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Figure 6-SWCC and estimated unsaturated permeability function of soil number 11537
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259x371mm (300 x 300 DPI)

Figure 8-Grain-size distribution curve of coarse kaolin

65x50mm (300 x 300 DPI)

Figure 9-SWCC and estimated unsaturated permeability function of coarse kaolin 259x369mm (300 x 300 DPI)