A simple and practical method for predicting soil water characteristic curve based on grading parameters

Junran ZHANGⁱ⁾, Xingcui WANGⁱⁱ⁾, Yehui LINⁱⁱⁱ⁾ and Tong JIANG^{iv)}

i) Lecturer, Henan Province Key Laboratory of Rock and Soil Mechanics and Structural Engineering, North China University of Water Resources and Electric Power, No.136, Jinshuidong Road, Zhengzhou, Henan 450045, China

ii) Graduate Student, School of Resources and Environment, North China University of Water Resources and Electric Power, No.136, Jinshuidong Road, Zhengzhou, Henan 450045, China

iii) Undergraduate Student, School of Resources and Environment, North China University of Water Resources and Electric Power, No.136, Jinshuidong Road, Zhengzhou, Henan 450045, China

iv) Professor, Henan Province Key Laboratory of Rock and Soil Mechanics and Structural Engineering, North China University of Water Resources and Electric Power, Zhengzhou, Henan 450045, China

ABSTRACT

For unsaturated soils, the soil water characteristic curve (SWCC), which represents the relationship between degree of saturation and suction, is a crucial function for determining both the soil hydraulic property and its coupled mechanical properties. However, because the tests for measuring the SWCC take a long time and the process is complicated. It is very necessary to propose a simple and practical method for predicting the SWCC of unsaturated soil. The grading curves and grading parameters of the five soils in the literature were obtained. And the fitting parameters a , n , m of the Fredlund and Xing model for five soils were obtained also. By means of the regression analysis between the grading parameters and fitting parameters of SWCC, a simple and practical method was proposed for predicting the SWCC curve based on the grading parameters. This may be helpful for engineering practice at an early stage when not much experimental data are available.

Keywords: unsaturated soil, grading curve, soil water characteristic curve, regression analysis

1 INTRODUCTION

For unsaturated soils, the soil water characteristic curve (SWCC), which represents the relationship between degree of saturation and suction, is a crucial function for determining both the soil hydraulic property and its coupled mechanical properties. Many scholars have studied the effects on the SWCCs due to void ratio and confining stress. Thu et al. (2007) [10] studied the effects of confining stress on the SWCCs. Sun et al. (2007a, b, c, d)[5-8] studied the affecting factors of the SWCC by results of the pressure plate tests, and concluded that the direct affecting factor is void ratio rather than the stress or stress history. Gallage and Uchimura (2010)[2] studied the effects of dry density and grain size distribution on SWCCs of sandy soils. Gao et al. (2016, 2017) [3-4] studied the

soil-water retention behavior of compacted soil with different soil structure and dry densities over a wide suction range.

The SWCC plays a key role in unsaturated soil mechanics. It is expensive and time consuming, however, and it may require special techniques or equipment to measure the SWCC in laboratories (Gallage and Uchimura, 2010)[2]. It has long been aware that the SWCC is correlated to soil properties like the soil particle size distribution (PSD) and void ratio. For a soil with large clay or organic contents, its microstructure or fabric may be more complicated due to its physicochemical interactions. And for a sandy soil, regarding its relatively small void ratio variation, its SWCC may be directly predicted from its PSD, which may provide a fast and inexpensive way of the SWCC estimation. Thus, the SWCC can be estimated from the

soil gradation. This may be helpful for engineering practice at an early stage when not much experimental data are available. In this paper, a simple and practical method was proposed for predicting the soil water characteristic curve based on the soil grain grading parameters.

2 BASIC PROPERTIES OF THE FIVE SOILS

Five soils including expansive soil (Zhang et al. 2016)[12], silty soil (Zhang et al. 2018)[13] and sandy soils(Wang et al. 2017)[11] were chosen for the study considering the breadth of soil types. The particle size distribution curves of five soils are shown in Fig. 1.

In geotechnical engineering, d_{10} , d_{30} , d_{50} , and d_{60} (particle sizes at 10%, 30%, 50%, and 60% passing by weight, see Figure 1) are four important particle sizes in describing soil gradation [Terzaghi et al. 1996][9]. The grading parameters d_{10} , d_{30} , d_{50} , and d_{60} of the five soils are shown in Table 1.

Fig.1 Grading curves of five soils

Table 1 Grading parameters

Soil types	d_{10}	d_{30}	d_{50}	d_{60}
Silt	0.0019	0.0105	0.0282	0.0355
Expansive soil	0.0005	0.0033	0.0109	0.0189
Fine sand #350	0.0181	0.1389	0.2326	0.2834
Fine sand(Yang)	0.1789	0.2390	0.3192	0.3662
Edosaki Sand	0.2278	0.2501	0.2704	0.2921

3 SOIL WATER CHARACTERISTIC CURVE THE FIVE SOILS

The renowned mathematical equation developed by Fredlund and Xing (1994)[1] was adopted to fit the SWCC of five soils, as shown in Fig. 2 ~ Fig. 6. The SWCC equation proposed by Fredlund and Xing (1994)[1] can be expressed as:

Fig.2 Soil water characteristic curve and fitting curve of the silty soil

Fig.3 Soil water characteristic curve and fitting curve of the expansive soil

Fig.4 Soil water characteristic curve and fitting curve of the Fine sand #350

$$S_r = \frac{C(s)}{\left\{ \ln \left[2.71828 + \left(\frac{s}{a} \right)^n \right] \right\}^m} \quad (1)$$

where

$$C(s) = 1 - \frac{\ln\left(1 + \frac{s}{s_{re}}\right)}{\ln\left(1 + \frac{10^6}{s_{re}}\right)} \quad (2)$$

s_{re} is the residual suction, and a , n and m are three fitting parameters. The fitting parameters of the SWCC in Fig. 2 ~ Fig. 6 are shown in Table 2.

Fig.5 Soil water characteristic curve and fitting curve of the Fine sand (Yang)

Fig.6 Soil water characteristic curve and fitting curve of the Edosaki sand

Table 2 Fitting parameters of the SWCC

Soil types	<i>a</i>	<i>n</i>	<i>m</i>
Silt	17.96504	15.79136	0.30609
Expansive soil	63.74111	0.62328	0.94528
Fine sand #350	3.19608	6.31708	2.38154
Fine sand(Yang)	2.51255	4.15377	1.90309
Edosaki Sand	4.22415	3.22708	1.08014

4 REGRESSION ANALYSIS BETWEEN GRADING PARAMETERS AND FITTING PARAMETERS

Through the function of regression analysis in the Office Excel software, the functional expressions of the SWCC parameters a , n , m can be obtained through regression analysis which deduced from the four grading parameters d_{10} , d_{30} , d_{50} , d_{60} .

The specific process and parameter of its regression analysis are show in Table 3, Table 4 and Table 5.

Table 3 Regression analysis of between SWCC parameters a and grading parameters

SUMMARY OUTPUT					
Regression statistics		Analysis of variance			
Multiple R	1		df	SS	MS
R Square	1	Analysis of variance	4	2740.50	685.12
Adjusted R Square	65535	Residual error	0	0	65535
Standard error	0	Total	4	2740.5043	/
observations	5				
	Coefficients	Error	t Stat	Lower 95%	Upper 95%
Intercept	24.6624	0	65535	24.66	24.66
$X_1(d_{10})$	597.823	0	65535	597.82	597.82
$X_2(d_{30})$	2250.24	0	65535	2250.2	2250.24
$X_3(d_{50})$	-11871.	0	65535	-11871	-11871.57
$X_4(d_{60})$	8526.75	0	65535	8526.7	8526.75

The functional expression of the SWCC parameters a through regression analysis which deduced from the four grading parameters d_{10} , d_{30} , d_{50} , d_{60} as follow,

$$a = 24.66 + 597.82d_{10} + 2250.24d_{30} - 11871.56d_{50} + 8526.75d_{60} \quad (3)$$

Table 4 Regression analysis of between SWCC parameters n and grading parameters

SUMMARY OUTPUT					
Regression statistics		Analysis of variance			
Multiple R	1		df	SS	MS
R Square	1	Analysis of variance	4	135.97	33.99
Adjusted R Square	65535	Residual error	0	0	65535
Standard error	0	Total	4	135.9755	/
observations	5				
	Coefficients	Error	t Stat	Lower 95%	Upper 95%
Intercept	14.12	0	65535.00	14.12	14.12
$X_1(d_{10})$	-122.31	0	65535.00	-122.3	-122.31
$X_2(d_{30})$	-965.99	0	65535.00	-965.9	-965.99
$X_3(d_{50})$	4110.57	0	65535.00	4110.5	4110.57
$X_4(d_{60})$	-2920.1	0	65535.00	-2920	-2920.01

The functional expression of the SWCC parameters n through regression analysis which deduced from the four grading parameters d_{10} , d_{30} , d_{50} , d_{60} as follow,

$$n = 14.12 - 122.31d_{10} - 965.99d_{30} + 4110.576d_{50} - 2920.01d_{60} \quad (4)$$

Table 5 Regression analysis of between SWCC parameters m and grading parameters

SUMMARY OUTPUT					
Regression statistics		Analysis of variance			
Multiple R	1		df	SS	MS
R Square	1	Analysis of variance	4	2.69	0.67
Adjusted R Square	65535	Residual error	0	0	65535
Standard error	0	Total	4	2.69	/
observations	5				
	Coefficients	Error	t Stat	Lower 95%	Upper 95%
Intercept	0.15	0	65535	0.15	0.15
$X_1(d_{10})$	-1.23	0	65535	-1.23	-1.23
$X_2(d_{30})$	47.48	0	65535	47.48	47.48
$X_3(d_{50})$	-201.87	0	65535	-201.8	-201.87
$X_4(d_{60})$	150.35	0	65535	150.35	150.35

The functional expression of the SWCC parameters m through regression analysis which deduced from the four grading parameters d_{10} , d_{30} , d_{50} , d_{60} as follow,

$$m = 0.15 - 1.231d_{10} + 47.48d_{30} - 201.87d_{50} + 150.35d_{60} \quad (5)$$

With Eq. (3 ~ 5) the SWCC parameters a , n , m can be predicted from the four grading parameters d_{10} , d_{30} , d_{50} , d_{60} . So the SWCC curves can be obtained by Eq. (1 ~ 2). It should be mentioned that the quantification of the SWCC here was based on a simple assumption. Effects the void ratio on the SWCC and the hysteresis of the water retention ability were not considered.

5 CONCLUSIONS

1) The soil grain grading parameters d_{10} , d_{30} , d_{50} , d_{60} and fitting parameters a , n , m of the SWCCs were analyzed by the regression analysis in the Office Excel software.

2) A simple and practical method was proposed for predicting the soil water characteristic curve based on the soil grain grading parameters. Effects the void ratio on the SWCC and the hysteresis of the SWCC were not considered.

3) This study results may be helpful for engineering practice at an early stage when not much experimental data are available.

ACKNOWLEDGEMENTS

The authors express their gratitude for the grant

provided by the National Natural Science Foundation of China (Nos. 41602295 and U1704243). The work was partially supported by the High-level Talents Foundation of the North China University of Water Resources and Electric Power (201501001).

REFERENCES

- 1) Fredlund D. G., Xing A. (1994): Equations for soil-water characteristic curve, *Canadian Geotechnical Journal*, 31(4), 521-532.
- 2) Gallage CPK, Uchimura T. (2010): Effects on dry density and grain size distribution on the soil-water characteristic curves of sandy soils, *Soil and Foundations*, 50(1): 161-172.
- 3) Gao Y., Sun D.A., Zhou A.N. (2016): Hydro-mechanical behaviour of unsaturated soil with different specimen preparations, *Canadian Geotechnical Journal*, 53(6): 909-917.
- 4) Gao Y., Sun D.A. (2017): Soil-water retention behavior of compacted soil with different densities over a wide suction range and its prediction, *Computers and Geotechnics*, 91: 17-26.
- 5) Sun D.A., Cui H.B., Matsuoka H., Sheng D.C. (2007a): A three-dimensional elastoplastic model for unsaturated compacted soils with hydraulic hysteresis, *Soils and Foundations*, 47(2), 253-264.
- 6) Sun D.A., Sheng D.C., Cui H.B., Sloan S.W. (2007b): A density-dependent elastoplastic hydro-mechanical model for unsaturated compacted soils, *International Journal for Numerical and Analytical Methods in Geomechanics*, 31(11), 1257-1279.
- 7) Sun D.A., Sheng D.C., Sloan S.W. (2007c): Elastoplastic modelling of hydraulic and stress-strain behavior of unsaturated soils, *Mechanics of Materials*, 39(3), 212-221.
- 8) Sun D.A., Sheng D.C., Xu Y.F. (2007d): Collapse behavior of unsaturated compacted soil with different initial densities, *Canadian Geotechnical Journal*, 44(6), 673-686.
- 9) Terzaghi K., Peck R., Mesri G. (1996): Soil mechanics in engineering practice, *John Wiley & Sons*.
- 10) Thu T.M., Rahardjo H., and Leong E.C. (2007): Soil-water characteristic curve and consolidation behavior for a compacted silt, *Canadian Geotechnical Journal*, 44(3): 266-275.
- 11) Wang J.P., Hu N., Francois B., Lambert P. (2017): Estimating water retention curves and strength properties of unsaturated sandy soils from basic soil gradation parameters, *Water Resour. Res.*, 53, 6069-6088.
- 12) Zhang J.R., Sun D.A., Zhou A.N., Jiang T. (2016): Hydro-mechanical behaviour of expansive soils with different suctions and suction histories, *Canadian Geotechnical Journal*, 53(1): 1-13.
- 13) Zhang J.R., Jiang T., Wang X.C., Liu C., Huang Z.Q. (2018): Influences of drying and wetting cycle and compaction degree on strength of Yudong silt for subgrade and its prediction, *Advances in Civil Engineering*, Article ID 1364186, 10 pages.