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

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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.

### 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:

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

where
\begin{equation}
C(s) = 1 - \frac{\ln \left( 1 + \frac{s}{s_{re}} \right)}{\ln \left( 1 + 10^6 \right) s_{re}}
\end{equation}

\( s_{re} \) 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.

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 form the four grading parameters \( d_{10}, d_{30}, d_{50}, d_{60} \).

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

Table 3 Fitting analysis of between SWCC parameters \( a \) and grading parameters

| Regression statistics | Analysis of variance |
|-----------------------|----------------------|
| Multiple R            | 1                    |
| df                    | df                   |
| SS                    | SS                   |
| MS                    | MS                   |
| R Square              | 1                    |
| Analysis of variance  | 4                    |
| 2740.50               | 685.12               |
| Adjusted R Square     | 65535                |
| Residual 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                |
| \( X_1(d_{10}) \)     | -122.31              |
| 0                     | 65535                |
| -122.3                | -122.31              |
| \( X_2(d_{30}) \)     | -965.99              |
| 0                     | 65535                |
| -965.9                | -965.99              |
| \( X_3(d_{50}) \)     | 4110.57              |
| 0                     | 65535                |
| 4110.5                | 4110.57              |
| \( X_4(d_{60}) \)     | -2920.1              |
| 0                     | 65535                |
| -2920                 | -2920.01             |

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

\begin{equation}
a = 24.66 + 597.82d_{10} + 2250.24d_{30} -11871.56d_{50} + 8526.75d_{60}
\end{equation}

Table 4 Fitting analysis of between SWCC parameters \( n \) and grading parameters

| Regression statistics | Analysis of variance |
|-----------------------|----------------------|
| Multiple R            | 1                    |
| df                    | df                   |
| SS                    | SS                   |
| MS                    | MS                   |
| R Square              | 1                    |
| Analysis of variance  | 4                    |
| 2740.50               | 685.12               |
| Adjusted R Square     | 65535                |
| Residual error        | 0                    |
| Total                 | 4                    |
| 2740.5043             | /                    |
| 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 \( n, m \) can be obtained through regression analysis which deduced form the four grading parameters \( d_{10}, d_{30}, d_{50}, d_{60} \) as follow,

\begin{equation}
a = 24.66 + 597.82d_{10} + 2250.24d_{30} -11871.56d_{50} + 8526.75d_{60}
\end{equation}
The functional expression of the SWCC parameters $n$ through regression analysis which deduced form the four grading parameters $d_{10}, d_{30}, d_{50}, d_{60}$ as follow,

$$n = 14.12 - 122.31d_{10} - 965.99d_{30} + 4110.576d_{50} - 2920.01d_{60}$$

(4)

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

$$m = 0.15 - 1.231d_{10} + 47.48d_{30} - 201.87d_{50} + 150.35d_{60}$$

(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.

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