

# Effects of residual suction and residual water content on the estimation of permeability function



Qian Zhai<sup>a</sup>, Harianto Rahardjo<sup>b,\*</sup>, Alfrendo Satyanaga<sup>a</sup>

<sup>a</sup> School of Civil and Environmental Engineering, Nanyang Technological University, Block N1, B1a-01a, Nanyang Avenue, 639798, Singapore

<sup>b</sup> School of Civil and Environmental Engineering, Nanyang Technological University, Block N1, #1B-36, 50 Nanyang Avenue, Singapore 639798, Singapore

## ARTICLE INFO

### Keywords:

Unsaturated soil  
Soil-water characteristic curve  
Best fit equation  
Fitting parameters  
SWCC variables  
Permeability function

## ABSTRACT

Soil-water characteristic curve (SWCC), which defines the relationship between water amount in the soil and matric suction, contains key information for the application of unsaturated soil mechanics principles to engineering practice. Best fit equations are commonly used for representation of the SWCC for unsaturated soils. Normally, these best fit equations are mathematically continuous and governed by a few fitting parameters. Either volumetric water content,  $\theta_w$  or normalized volumetric water content,  $\Theta$ , is adopted in the different best fit equations. If  $\theta_w$  is used to establish SWCC, the parameter related to residual suction,  $C_r$  needs to be defined prior to fitting process of SWCC data. On the other hand, if  $\Theta$  is used to develop SWCC, the residual volumetric water content,  $\theta_r$ , needs to be defined prior to fitting process of SWCC data. Results of analyses in this study indicate that the performance of the best fit equation is not affected by the value of  $C_r$ , but it is significantly affected by the value of  $\theta_r$ . As a result, the performance on the estimation of the permeability function is also affected by the value of  $\theta_r$ . Different types of soils are used to investigate the effect of  $C_r$  and  $\theta_r$  on the performance of the best fit equation and the estimation of the permeability function.

## 1. Introduction

Soil-water characteristic curve (SWCC) defines the relationship between the amount of water in soil and soil suction. The SWCC is normally determined from experimental data and the best fit equation is adopted to provide a continuous model. The best fit equations are normally governed by a few fitting parameters, and these fitting parameters are typically determined using a curve fitting technique. As the fitting parameters are determined from a regression procedure, these fitting parameters are mathematical solutions rather than physical soil properties.

Two forms of water content, either volumetric water content,  $\theta_w$ , (e.g., Fredlund and Xing, 1994) or normalized volumetric water content,  $\Theta$ , (e.g., van Genuchten, 1980), are adopted in different best fit equations, where,  $\Theta = (\theta_w - \theta_r) / (\theta_s - \theta_r)$ ,  $\theta_w$  = volumetric water content,  $\theta_s$  = saturated volumetric water content, and  $\theta_r$  = residual volumetric water content. Parameter  $C_r$  in Fredlund and Xing's (1994) equation which is related to the residual suction and parameter  $\theta_r$  in van Genuchten's (1980) which is related to the residual volumetric water content need to be defined before regression analysis is carried out. The effect of the value of  $C_r$  and  $\theta_r$  on the performance of Fredlund and Xing's (1994) equation and van Genuchten's (1980) equations is

investigated and discussed in this paper. Four sets of soil, including two sets of coarse-grained soils and two sets of fine-grained soils, are used to investigate the effect of the values of  $C_r$  and  $\theta_r$  on the performance of best fit SWCC equations and the estimation of the permeability function.

## 2. Literature review

There are various best fit equations that have been proposed by different researchers (Brooks and Corey, 1964; Gardner, 1958; Farrel and Larson, 1972; van Genuchten, 1980; William et al., 1983; Fredlund and Xing, 1994; Kosugi, 1994 and Satyanaga et al., 2013). Studies by Leong and Rahardjo (1997) and Zapata (1999) concluded that Fredlund and Xing's (1994) equation, as illustrated in Eq. (1), performed best among the available equations for best fitting the SWCC data. Zapata (1999) also suggested that van Genuchten's (1980) equation, as illustrated in Eq. (2), performed well in best fitting fine-grained soils.

$$\theta = C(\psi) \frac{\theta_s}{\left\{ \ln \left[ e + \left( \frac{\psi}{a} \right)^n \right] \right\}^m} \quad (1)$$

where:  $C(\psi)$  = correction factor  $C(\psi) = 1 - \frac{\ln \left( 1 + \frac{\psi}{C_r} \right)}{\ln \left( 1 + \frac{10^6}{C_r} \right)}$ ,  $C_r$  = input value,

\* Corresponding author.

E-mail addresses: [zhaiqian@ntu.edu.sg](mailto:zhaiqian@ntu.edu.sg) (Q. Zhai), [chrahardjo@ntu.edu.sg](mailto:chrahardjo@ntu.edu.sg) (H. Rahardjo), [Alfrendo@ntu.edu.sg](mailto:Alfrendo@ntu.edu.sg) (A. Satyanaga).

can be a roughly estimated value for residual suction,  $C_r = 1500$  kPa for most cases as suggested by Fredlund and Xing (1994) and Zhai and Rahardjo (2012a, 2012b)

$\theta$  = volumetric water content,

$\psi$  = matric suction,

$e$  = Euler's number and

$a$ ,  $n$  and  $m$  = fitting parameters.

$$\Theta = \left[ \frac{1}{1 + (ah)^b} \right]^c \quad (2)$$

where:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r},$$

$\theta$  = volumetric water content,

$\theta_s$  = saturated volumetric water content,

$\theta_r$  = residual volumetric water content,

$h$  = pressure head and

$a$ ,  $b$  and  $c$  = fitting parameters.

Vanapalli et al. (1996) presented that water phase might not be continuous in the residual zone as illustrated in Fig. 1. It is observed from the shrinkage curve, that insignificant soil volume changes occur after air-entry value. The statistical method for estimation of the permeability function is based on two major assumptions such as Poiseuille's law for liquid flow and constant pore-size distribution function. From the shrinkage curve, a significant soil volume change is observed at suctions before the air-entry value and it becomes insignificant beyond the air-entry value. On the other hand, the water flow at suctions beyond the residual suction was more in a vapor form than in a liquid form. Therefore, SWCC variables are important parameters for the estimation of the permeability function. Zhai and Rahardjo (2012a) derived equations for determination of SWCC variables (i.e. air-entry value, residual suction and residual water content) from the SWCC fitting parameters. Inflection point is required for determining the air-entry value, residual suction and residual water content. Zhang and Fredlund (2015) and Zhai and Rahardjo (2012a, 2013) derived equations for determination of the inflection point on arithmetic scale. In this paper, a new mathematical equation was developed for the determination of the inflection point on log-scale.

Based on theory from Childs and Collis-George (1950) and simplification method from Kunze et al. (1968), Fredlund et al. (1994) proposed a simple equation with the integration form for the estimation

of the permeability function from SWCC. To simplify the problem (i.e., make all the individual group of pores to have the same pore-size density), Kunze et al. (1968) proposed to evenly divide the volumetric water content into finite numbers of interval. Kunze et al. (1968) divided the entire SWCC into finite numbers of segment and each segment has the same range of volumetric water content but different ranges of matric suction. As explained by Rahimi et al. (2015), inverse function  $\psi = f^{-1}(\theta_w)$  needs to be adopted to calculate suction,  $\psi$ , from the volumetric water content,  $\theta_w$  using Kunze et al.'s (1968) method. Sometimes, it is not easy to calculate the suction from the volumetric water content due to the complex form of the best fit equation. In addition, iteration may be needed to solve the inverse function. To avoid the calculation of suction from the volumetric water content, Zhai and Rahardjo (2015) proposed to evenly divide the suction instead of volumetric water content into finite numbers of interval. Zhai and Rahardjo's (2015) method divided the SWCC into finite numbers of segment and each segment has the same range of matric suction and different ranges of degree of saturation. The degree of saturation of each segment represents the pore-size density in the pore-size distribution function. Bharat and Sharma (2012) presented that Fredlund-Xing-Kunze model required the first derivative of volumetric water content and commented the small value of  $C_r$  would affect the SWCC and the prediction result on the permeability function. On the other hand, Zhai and Rahardjo's (2015) method does not require the first derivative of volumetric water content and gives good prediction on the permeability function.

By varying the value of  $C_r$  and fixing values of  $a$ ,  $n$  and  $m$  in Fredlund and Xing's (1994) equation, Bharat and Sharma (2012) found that small values of  $C_r$  influenced the SWCC near saturation. Consequently, Bharat and Sharma (2012) and Bharat (2014) concluded that Fredlund-Xing-Kunze model had limitation in prediction of the permeability function. Bharat and Sharma (2012) also indicated the value of  $C_r$  could affect the shape of SWCC near saturation but they did not comment on the effect of  $C_r$  on the performance of Fredlund and Xing's (1994) equation in best fitting SWCC data. Bharat and Sharma (2012) only carried out parametric study (i.e., varying value of  $C_r$  and fixing value of  $a$ ,  $n$  and  $m$ ), but they did not perform best fitting study (i.e., varying  $a$ ,  $n$  and  $m$  to fit experimental data). In this study, regression procedure was carried out to investigate the effect of  $C_r$  on the performance of Fredlund and Xing's (1994) equation in best fitting SWCC data. The recent work from Rahimi et al. (2015) suggested that Fredlund-Xing-Kunze model could give reasonable prediction on the permeability function. Zhai and Rahardjo (2013) pointed out that fitting parameters in Fredlund and Xing's (1994) equation for the SWCC in the form of degree of saturation could be different from that

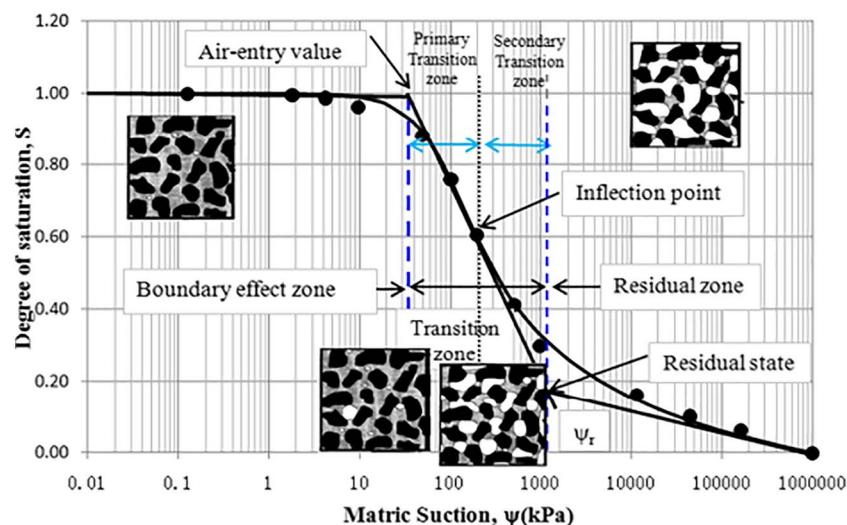


Fig. 1. Illustration of the condition of water phase at different zones (Vanapalli et al., 1996).

Download English Version:

<https://daneshyari.com/en/article/5770613>

Download Persian Version:

<https://daneshyari.com/article/5770613>

[Daneshyari.com](https://daneshyari.com)