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An improved method for determining Brooks–Corey model parameters from horizontal absorption

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ABSTRACT

Low-cost, simple, rapid and accurate approaches for measuring soil hydraulic properties are of great importance in the application of hydrologic models of the vadose zone. A recently proposed method of constant-saturation absorption (MCSA) for determining Brooks–Corey (BC) model parameters is promising. However, this method has not been tested using experimental data. In this paper, measured soil–water diffusivity or soil–water retention curves (SWRCs) of 20 soil samples were used to test the reliability of MCSA. The results indicate that MCSA consistently estimated soil–water diffusivities by the Bruce and Klute method, but it substantially overestimated air-entry suctions (h_d) and thereby soil suction. A new method (MCPA) is proposed herein to overcome the problems associated with MCSA. Using the improved method, estimated SWRCs are consistent with observation. With the estimated soil hydraulic parameters, HYDRUS-1D generated very accurate simulations of the cumulative absorption curves. Compared with direct or other indirect methods, MCPA is a more accurate, low-cost, and simple method, and it is especially useful for rapid determination of SWRC for soil–water movement simulations. However, if unsaturated soil–water diffusivity is of greater concern, our results also indicate that MCSA more accurately predicts this quantity and thus should be preferred.

1. Introduction

The vadose zone is critical to controlling the hydrologic cycle and solute transport. Quantitative prediction and assessment of the behaviors of water flow and solute transport in the vadose zone are very important for making appropriate measurements for improving the usage efficiency of water resources and fertilizers and to protect groundwater from contamination. Numerical solutions are successfully and commonly used to simulate water flow and solute transport in unsaturated soils. Soil hydraulic properties (soil–water retention curves or SWRCs, hydraulic conductivity, or water diffusivity) are required inputs for hydrologic simulations. Normally, one of the main difficulties in the application of hydrologic models is the rapid acquisition of accurate soil hydraulic properties at low cost. In the last several decades, direct and indirect methods have been developed to determine those properties (Dane and Puckett, 1992; Durner and Lipsius, 2005; van Genuchten, 1992). Direct methods measure soil hydraulic properties according to their basic definitions, whereas indirect methods estimate them from other soil properties (e.g., soil particle size distribution, soil organic content, or soil–water movement processes) that are readily measured. More details and reviews of these methods are in Shao and Horton (1998) and van Dam et al. (1992). Direct methods are time consuming and expensive, and measurable data ranges are typically limited. Among the indirect methods, pedotransfer functions are localized and appropriate for simulations at large scales rather than at specific sites. Numerical inversion has difficulties such as failure of solution convergence and the uniqueness of estimated parameters (Shao and Horton, 1998). These problems have restricted the practical use of the methods. Thus, simple, rapid, accurate and low-cost methods for determining soil hydraulic model parameters remain scarce and continue to be one of the main topics of soil physical research (Londra and Valiantzas, 2011; Ma et al., 2009; Shao and Horton, 1996, 1998; Valiantzas and Londra, 2008, 2012; Wang et al., 2002, 2004).

Recently, a promising indirect method (Londra and Valiantzas, 2011; Ma et al., 2009; Shao and Horton, 1998; Wang et al., 2002) was proposed based on approximate solutions to the Richards equation (Richards, 1931) with specific soil hydraulic property functions, such as the Brooks–Corey (BC) model (Brooks and Corey, 1964) and the van Genuchten (VG) model (van Genuchten, 1980). The concept of an integral or analytical method was first proposed by Shao and Horton (1998) for estimating VG model parameters, and it was further

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developed by Wang et al. (2002) and Ma et al. (2009, 2010) to determine BC model parameters from horizontal absorption. Using the means, VG or BC model parameters can be estimated by simple relation equations of saturated hydraulic conductivity, sorptivity, characteristic length of the wetted zone, and initial, residual and saturated soil moisture contents. These variables are easy to determine by conventional approaches and horizontal absorption experiments. Compared with direct methods and other indirect methods, the analytical method is simple, rapid, and low-cost.

However, some problems remain to be solved for the analytical or horizontal absorption methods. For example, the first-order approximation of the VG model used by Shao and Horton (1998) only applies to the near-saturation range of SWRCs. The assumption of soil matric suction distribution made by Wang et al. (2002) may be valid for moderate-texture soils but not for heavy-texture or light-texture soils. The method proposed by Ma et al. (2009, 2010) extended the applicable texture range of the horizontal absorption approach, but the theory has not been validated by measured SWRCs. Moreover, Wang et al. (2002) and Ma et al. (2009, 2010) tested their methods using only the given soil hydraulic parameters and constant-saturation absorption processes simulated by the HYDRUS-1D software (Šimůnek et al., 2005). Because effective water saturation does not vary with soil suction when the latter is smaller than air-entry suction in the BC model, the constant-saturation inlet boundary used in the approximate solutions of Wang et al. (2002) and Ma et al. (2009) was different from the one in actual horizontal absorption experiments. Although effective water saturations at both inlet boundaries were equal to one, the water pressure head at the inlet (h_p) was equal to the air-entry pressure head ($-h_d$) in the solutions of Wang et al. (2002) and Ma et al. (2009), whereas $h_{p.}$ values were typically near zero in the aforementioned experiments. As a result, the air-entry suction of the BC model may be overestimated in Ma et al. (2009), in which observed horizontal absorption data were used without considering this difference of water pressure heads at the inlet boundaries.

Therefore, the objective of the research was to derive an improved expression for more accurate estimation of air-entry suction. The expression was verified with horizontal absorption experiments for twenty soils, and the estimated soil–water retention curves and soil–water diffusivity curves were compared with the measured values.

2. Theory

The Brooks–Corey model (Brooks and Corey, 1964) describing soil hydraulic properties is the soil–water retention curve

$$S(h) = \begin{cases} \dfrac{\theta-\theta_r}{\theta_s-\theta_r} = \left(\dfrac{h_d}{h}\right)^n & h > h_d \\ 1 & h \le h_d \end{cases} \tag{1}$$

and the soil hydraulic conductivity curve

$$K(h) = \begin{cases} K_s\left(\dfrac{h_d}{h}\right)^m = K_s S^{l+1+2/n} & h > h_d \\ K_s & h \le h_d \end{cases} \tag{2}$$

where θ is volumetric soil–water content (cm^3 cm^{-3}), θ_r and θ_s are residual and saturated water contents (cm^3 cm^{-3}), respectively, S is effective water saturation, h is soil matric suction (cm), K is hydraulic conductivity (cm min^{-1}), K_s is saturated hydraulic conductivity (cm min^{-1}), n is a constant related to the shape of SWRC, and $m = (l+1)\,n+2$, where l is the soil pore tortuosity factor, for which $l = 2$ is typically used.

Soil–water diffusivity can be obtained from $S(h)$ and $K(h)$ by the following relationship.

$$D(S) = -K\frac{dh}{d\theta} = D_s S^L, \tag{3}$$

where D is soil–water diffusivity (cm^2 min^{-1}), D_s is soil–water diffusivity at saturation (cm^2 min^{-1}), and L is a shape coefficient of the power-function soil–water diffusivity curve.

2.1. Method based on constant-saturation absorption (MCSA)

The method of Ma et al. (2009, 2010) was derived based on an approximate analytical solution to the Richards equation (Richards, 1931) for one-dimensional horizontal absorption into homogeneous soils, with initially uniform moisture contents under constant-saturation boundary conditions. For differentiating from the method below, we call this the method of constant-saturation absorption (MCSA). The complete expressions in MCSA (Ma et al., 2009) for estimating soil hydraulic parameters are.

$$n = \frac{a}{1-2a}, \tag{4}$$

$$h_d = \frac{1+a}{(1-2a)\left(1-S_i^{1+1/a}\right)}\cdot\frac{s^2}{2K_s(\theta_s-\theta_i)}, \tag{5}$$

$$L = \frac{1}{a}, \tag{6}$$

$$D_s = \frac{1+a}{a\left(1-S_i^{1+1/a}\right)}\cdot\frac{s^2}{2(\theta_s-\theta_i)(\theta_s-\theta_r)}, \tag{7}$$

where θ_i is the initial soil–water content (cm^3 cm^{-3}), S_i is the initial effective water saturation, A is the average increase in soil–water content in the wet zone (cm^3 cm^{-3}) and s is the sorptivity (cm min$^{-0.5}$), and a and b are constants for a specific soil with a specific initial moisture content which can be determined from the formulas below for initially dry soils.

$$a \approx \frac{\theta_s-\theta_i-A}{\theta_i-\theta_r+A}, \quad b = 1-S_i^{\frac{1}{a}}, \tag{8}$$

For determining BC model parameters, apart from the values of θ_i, θ_r and θ_s, only a conventional constant water head experiment (for measuring K_s) and simple horizontal absorption experiment with initially dry soils were required. The parameter d is defined as the characteristic length of the wetting zone (cm min$^{-0.5}$). A, d and s can be obtained by fitting Eqs. (9) and (10) to the observed wetting front advance and cumulative infiltration volume versus time during the horizontal absorption experiments.

$$x_f = d\cdot t^{0.5}, \tag{9}$$

$$I = s\cdot t^{0.5} = A\cdot x_f, \tag{10}$$

where I is cumulative absorption at the water inlet (cm), x_f is the wetting front advance (cm), t is infiltration time (min) and $A = s/d$. Then, a can be calculated by Eq. (8), and the BC model parameters (n, h_d, L and D_s) are subsequently estimated by Eqs. (4) through (7).

2.2. Method based on constant pressure head absorption (MCPA)

As discussed above, for actual horizontal absorption experiments, the saturated inlet boundary typically corresponds to $h_{p.} \approx 0$, whereas $h_{p.} = -h_d$ is used in the derivation of MCSA. Thus, to derive a more accurate expression, it is necessary to estimate h_d based on the inlet boundary of the aforesaid experiments. In contrast with MCSA, the new expression, called MCPA, was derived based on constant pressure head absorption.