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Analysis of single-ring infiltrometer data for soil hydraulic properties estimation: Comparison of BEST and Wu methods

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ABSTRACT

Knowledge of soil hydraulic properties is important for modeling hydrological processes and related contaminant transport. This study compared four methods in analyzing single-ring infiltrometer data to estimate the saturated hydraulic conductivity (K_s) and the water retention parameter (α). These were: (1) original BEST (Beerkan Estimates of Soil Transfer Parameters through Infiltration Experiments, Lassabatere et al., 2006) method, defined as BEST_slope; (2) a modified BEST method, defined as BEST_intercept (Yilmaz et al., 2010); (3) Wu1 (Wu et al., 1999) which attempts the best fit of a generalized solution to the infiltration curve using the whole infiltration curve; and (4) Wu2 (Wu et al., 1999) which is suitable for the steady state flow case. The first three methods are suitable for the transient flow state. The infiltration data of 54 different cases within four soil texture classes (sand, sandy loam, medium loam, and clay loam) were used. The results suggest that the modified version (BEST_intercept) has a better performance (more reasonable estimates) than the original (BEST_slope). Both the BEST_slope and BEST_intercept methods perform poorly for the sandy soils. The Wu1 method performs better in fitting the experimental infiltration curve, and produces more cases with reasonable values (normally positive values) of K_s and α than both the BEST_slope and BEST_intercept. In order to apply these existing methods to wider conditions (e.g., sandy soils, wet soils, basic oxygen furnace slag), the inversion estimation algorithms and the experimental operations in the field require further improvement.

1. Introduction

Knowledge of soil hydraulic properties (e.g., saturated hydraulic conductivity, K_s and water retention parameter, α) is important for modeling hydrological processes and related contaminant transport. These properties vary very much with soils, time and space (Mubarak et al., 2009, 2010; Schaap et al., 2001). High accuracy of measurements and estimation of these properties still remain challenges. Measurements of soil hydraulic properties can be conducted either in the laboratory or in the field using different methods. The methods with minimum soil disturbance, low time consumption and lowest cost are preferred. The Beerkan method (Haverkamp et al., 1996) includes a single-ring infiltration field measurement using a metal or PVC ring inserted into initially unsaturated soils to a given small depth, and appears promising due to its ease of operation and low cost. Furthermore, several studies have promoted its robustness by introducing new algorithms (Braud et al., 2005; Lassabatere et al., 2006, 2009; Yilmaz et al., 2010). Among them is the BEST (Beerkan Estimates of Soil Transfer Parameters through Infiltration Experiments) method. The original method is known as the BEST_slope and the modified version is called the BEST_intercept following Yilmaz et al. (2010). The BEST method is based on the van Genuchten relationship (van Genuchten, 1980) for the water retention curve:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=[1+(\alpha h)^n]^{-m} \tag{1a}$$

with the Burdine condition (Burdine, 1953),

$$m=1-\frac{2}{n} \tag{1b}$$

and the Brooks and Corey relationship (Brooks and Corey, 1964) for hydraulic conductivity:

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\eta} \tag{2a}$$

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with

$$\eta = \frac{2}{\lambda} + 2 + p \quad \text{and} \quad \lambda = mn \tag{2b}$$

where n, m and η are shape parameters; α (water retention parameter), θ_r (residual volumetric soil water content), θ_s (saturated volumetric soil water content), and K_s (saturated hydraulic conductivity) are scale parameters; θ and $K(\theta)$ are soil water content and hydraulic conductivity at unsaturated state, respectively; h is the water pressure head. Usually, θ_r is very low and thus considered to be zero. p is a tortuosity parameter that depends on the chosen capillary model, and a value of 1 is used here following Burdine's condition (Braud et al., 2005; Burdine, 1953).

The BEST (BEST_slope) method performed better than other analysis methods (cumulative linearization, derivative linearization, cumulative infiltration, and infiltration flux) using the same experimental infiltration data (Lassabatere et al., 2006; Xu et al., 2009) in that it (BEST_slope) produced more reasonable results. But there still remain some problems (the occurrence of null or even negative estimates of K_s) with the BEST_slope method as noted by Lassabatere et al. (2010), Xu et al. (2009) and Yilmaz et al. (2010). Recently, Yilmaz et al. (2010) proposed a modified version (BEST_intercept). The modified version solved the problems that the original version does not work or produce some unreasonable estimates (negative K_s) under certain conditions. More experiments are therefore required to further test the performance and application of BEST and its modified version, and to search for answers to the remaining problems. Previous studies (Lassabatere et al., 2006; Xu et al., 2009) have shown a better performance of the BEST method relative to other methods (stated above). Hence, this study compares the BEST with another method, namely the Wu method (Wu et al., 1999). The latter was developed to calculate K_s by best fit of a generalized solution to the infiltration curve of single-ring infiltrometer data. The first method in Wu, hereafter named Wu1, uses the whole infiltration curve and the second, hereafter named Wu2, is based on the assumption that over the last part of the infiltration curve, the event has reached steady state. Bagarello et al. (2009) have shown that the Wu method was reliable in estimating both K_s and α with single-ring infiltrometer data from an Italian study. The Wu analysis method seems also applicable to the infiltration data from Beerkan infiltration experiments.

This study therefore aims to: (1) provide more tests on the performance and application of the BEST method, and to explain any remaining problems; and (2) compare the performance of the BEST and Wu methods in analyzing the same single-ring infiltration data to estimate the soil hydraulic properties, K_s and α.

2. Theory

2.1. BEST (Lassabatere et al., 2006)

Considering an infiltration experiment with zero pressure on an internal-radius r of a circular cylindrical surface above a uniform soil with a uniform initial soil water content, the three-dimensional cumulative infiltration and steady infiltration rate can be approached by the explicit transient two-term equation:

$$I(t) = S\sqrt{t} + (ES^2 + FK_s)t \tag{3a}$$

and steady-state expansion:

$$I_{+\infty}(t) = (ES^2 + K_s)t + G\frac{S^2}{K_s} \tag{3b}$$

$$q_s = ES^2 + K_s \tag{3c}$$

where t is time, $I(t)$ is cumulative infiltration at transient state, $I_{+\infty}$ is cumulative infiltration at steady state, q_s is steady infiltration rate, and S is sorptivity, respectively; constants E, F, and G are defined by Haverkamp et al. (1994) as:

$$E = \frac{\gamma}{r(\theta_s - \theta_0)} \tag{4a}$$

$$F = \frac{2-\beta}{3}\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] + \left(\frac{\theta_0}{\theta_s}\right)^{\eta} \tag{4b}$$

$$G = \frac{1}{2[1-(\theta_0/\theta_s)^{\eta}](1-\beta)} \ln\left(\frac{1}{\beta}\right) \tag{4c}$$

where r, θ_0 and θ_s are the internal radius of cylindrical ring used, initial and saturated volumetric soil water content, respectively; $\beta = 0.6$ and $\gamma = 0.75$, which apply for most soils when $\theta_0 < 0.25\ \theta_s$ (Haverkamp et al., 1994; Smettem et al., 1994); η is a shape parameter that can be estimated (Eq. (2b)) from particle size distribution and soil porosity (for details see Lassabatere et al., 2006).

BEST first estimates the apparent steady-state infiltration rate (q_s) through fitting the last part of the infiltration curve (cumulative infiltration vs. time). Then BEST estimates the sorptivity (S) by fitting the transient cumulative infiltration to the two-term equation, Eq. (3a). The fit is based on the replacement of hydraulic conductivity K_s by its sorptivity function S and the experimental apparent steady-state infiltration rate (q_s) through Eq. (3c) and the following conditions: an accurate reproduction of experimental data; a fit for S between zero and a maximum value that corresponds to a null hydraulic conductivity (capillary driven flow). Once sorptivity is estimated, the saturated hydraulic conductivity is obtained through Eq. (3c), assuming that the apparent steady state has been reached. In order to ensure the validity of Eq. (3a), the data subsets used should be restricted within the maximum time (t_{max}), defined in Lassabatere et al. (2006) as:

$$t_{max} = \frac{1}{4(1-F)^2} t_{grav} \tag{5a}$$

$$t_{grav} = \left(\frac{S}{K_s}\right)^2 \tag{5b}$$

The parameter α is then estimated from the other hydraulic parameters (Haverkamp et al., 2006; Lassabatere et al., 2006):

$$\alpha = \frac{c_p \theta_s (1 - (\theta_0/\theta_s)) K_s [1 - (\theta_0/\theta_s)^{\eta}]}{S^2} = \frac{c_p(\theta_s - \theta_0)(K_s - K_0)}{S^2} \tag{6a}$$

$$c_p = \Gamma(1 + (1/n)) \left\{ \frac{\Gamma(m\eta - (1/n))}{\Gamma(m\eta)} + \frac{\Gamma(m\eta + m - (1/n))}{\Gamma(m\eta + m)} \right\} \tag{6b}$$

where Γ is the usual Gamma function, and K_0 is the initial hydraulic conductivity calculated by Eq. (2); n, m and η can be estimated from particle size distribution and soil porosity (see the details in Lassabatere et al., 2006).

Yilmaz et al. (2010) found that there are some problems in BEST estimates (the occurrence of null or even negative estimates of K_s) under the condition of $q_s \sim ES^2$. They therefore modified the original BEST method by using the intercept ($b_{+\infty}$) of the asymptotic expansion $I_{+\infty}(t)$, as defined in Eq. (3b), to estimate K_s:

$$K_s = G\frac{S^2}{b_{+\infty}} \tag{7}$$

Other than this, the calculation procedure is the same as the original version (details see Yilmaz et al., 2010). In this study, the original version is called BEST_slope, and the modified version is called BEST_intercept.