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Estimate of the soil water retention curve from the sorptivity and β parameter calculated from an upward infiltration experiment

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ABSTRACT

The water retention curve ($\theta(h)$), which defines the relationship between the volumetric water content (θ) and the matric potential (h), is of paramount importance to characterize the hydraulic behaviour of soils. Because current methods to estimate $\theta(h)$ are, in general, tedious and time consuming, alternative procedures to determine $\theta(h)$ are needed. Using an upward infiltration curve, the main objective of this work is to present a method to determine the parameters of the van Genuchten (1980) water retention curve (α and n) from the sorptivity (S) and the β parameter defined in the 1D infiltration equation proposed by Haverkamp et al. (1994). The first specific objective is to present an equation, based on the Haverkamp et al. (1994) analysis, which allows describing an upward infiltration process. Secondary, assuming a known saturated hydraulic conductivity, K_s, calculated on a finite soil column by the Darcy's law, a numerical procedure to calculate S and β by the inverse analysis of an exfiltration curve is presented. Finally, the α and n values are numerically calculated from K_s, S and β. To accomplish the first specific objective, cumulative upward infiltration curves simulated with HYDRUS-1D for sand, loam, silt and clay soils were compared to those calculated with the proposed equation, after applying the corresponding β and S calculated from the theoretical K_s, α and n. The same curves were used to: (i) study the influence of the exfiltration time on S and β estimations, (ii) evaluate the limits of the inverse analysis, and (iii) validate the feasibility of the method to estimate α and n. Next, the $\theta(h)$ parameters estimated with the numerical method on experimental soils were compared to those obtained with pressure cells. The results showed that the upward infiltration curve could be correctly described by the modified Haverkamp et al. (1994) equation. While S was only affected by early-time exfiltration data, the β parameter had a significant influence on the long-time exfiltration curve, which accuracy increased with time. The 1D infiltration model was only suitable for $\beta < 1.7$ (sand, loam and silt). After omitting the clay soil, an excellent relationship ($R^2 = 0.99$, $p < 0.005$) was observed between the theoretical α and n values of the synthetic soils and those estimated from the inverse analysis. Consistent results, with a significant relationship ($p < 0.001$) between the n values estimated with the pressure cell and the upward infiltration analysis, were also obtained on the experimental soils.

1. Introduction

Philip (1957) called sorptivity, S, the first term of his power series expression of the cumulative infiltration of water into a soil. Sorptivity was therefore an index of the capacity of a porous medium to absorb or desorb water, dependent of its water content and diffusivity. The Philip (1957) two-term infiltration equation reduces in the case of horizontal infiltration, or absorption using his own term, to a linear relationship between cumulative infiltration, I, and the square root of time, t, such as $I = S\ t^{1/2}$. This parameter can be analytically calculated as a function of soil water content and diffusivity, which approximation has been found to give good results (Parlange, 1975). The sorptivity can be estimated at the early stages of infiltration, where suction or capillarity forces prevail over gravity. However, as the process progresses, gravity relevance gradually increases. In the latter case, sorptivity can be evaluated with the full infiltration equation using methods such as the disc infiltrometry. During the last three decades, the disc infiltrometer technique has been widely accepted for its versatility and simplicity. Up to date, several procedures to estimate S using a single disc and tension infiltration data have been developed: (i) methods based on the short-time transient state data (e.g. White et al., 1992; Vandervaere et al., 2000); (ii) methods combining both

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early-time transient and steady data, like the BEST method (Lassabatere et al., 2006, 2009; Yilmaz et al., 2010); and (iii) methods based on the whole cumulative infiltration curve (Latorre et al., 2015).

The β parameter, which was initially defined by Haverkamp et al. (1994), is an integral shape constant that depends on soil diffusivity, hydraulic conductivity and initial and final volumetric water content. This is calculated through cumulative infiltration identification analysis (Haverkamp et al., 1994). Its value, only suitable for sand, loam and silt, ranges between 0.3 and 1.7 (Lassabatere et al. (2009). Although β can be analytically calculated from known hydraulic properties (Haverkamp et al., 1994), up to date there is not any experimental method that allows estimating its value.

The soil water retention curve, $\theta(h)$, is defined as the relationship between the soil volumetric water content (θ) and the matric potential (h). This soil function is, together with the hydraulic conductivity function, $K(h)$, one of the main properties that determine the water flow in the vadose zone. One of the most common functions used to describe the soil water retention curve is the unimodal van Genuchten (1980) equation, in which the θ is related to h through two empirical variables: the n and α, which represents a pore-size distribution parameter and a scale factor, respectively. The reference laboratory method to determine $\theta(h)$ is the pressure extractor (Klute, 1986), which estimates $\theta(h)$ from measured h and θ pairs. Although this technique has been improved by incorporating alternative methods to determine θ (Jones et al., 2005; Moret-Fernández et al., 2012), the long time needed to conclude a measurement may limit its use. On the other hand, errors of the pressure plate apparatus may also limit its use in fine-textured soils (Solone et al., 2012). Other laboratory methods to estimate $\theta(h)$ are, for instance, the evaporation method that yields bot $\theta(h)$ and $K(h)$ curves (Gardner and Miklich, 1962; Wind, 1968; Wendroth et al., 1993; Tamari et al., 1993), or methods based on the inverse numerical analysis of the transient water flow (Simunek and Van Genuchten, 1997; Simunek et al., 1998). These last techniques, that involve the inverse solution of the Richard's equation, are increasingly employed because of the short-time of the experiments and the ability to simultaneous estimate of $K(h)$ and $\theta(h)$. These methods can be based on the analysis of downward infiltration (Simunek and van Genuchten, 1997) or upward infiltration processes. Among the different methods included in this last group, Hudson et al. (1996) suggested estimating the soil hydraulic properties from the inverse analysis of an upward flow experiment under laboratory conditions using a constant flux of water at the bottom of the soil sample. This laboratory technique was next improved by Young et al. (2002) who employed a Mariotte system and tensiometers installed along a 15-cm-long soil column. Using pressure head and cumulative flux data as auxiliary variables of the objective function, the soil hydraulic parameters were calculated with HYDRUS-1D by an optimization procedure. More recently, Moret-Fernández et al. (2016) developed a tension sorptivimeter that allowed estimating the soil hydraulic parameters from the inverse analysis of a multiple tension water absorption curve, without using tensiometers. The results demonstrated that the soil hydraulic parameters could be satisfactorily estimated if negative enough tensions were applied. Alternatively, medium negative soil tensions could be used (e.g., $h = -30$ cm) if K_s was previously estimated. At this aim, K_s was calculated according to the Darcy's law. In a similar way, Peña-Sancho et al. (submitted for publication) developed an alternative laboratory method in which, taking into account the hysteresis phenomena, the hydraulic properties were simultaneously estimated from a capillary wetting process at saturation followed by an evaporation process.

Although important efforts have been done to develop new methods to estimate $\theta(h)$ from the inverse analysis of an upward infiltration experiment, the information available in a soil water absorption process has not yet been completely deciphered. Thus, the main objective of this paper is to present a method to determine the van Genuchten (1980) parameters for water retention curve (α and n) from the S and β parameters defined in the 1D infiltration model developed by Haverkamp et al. (1994). To this end, firstly we present a modification of the Haverkamp et al. (1994) model to describe an upward infiltration, or exfiltration in the words of Eagleson (1978). To validate this model, upward infiltration curves simulated by HYDRUS-1D for four soils with different texture (sandy, loamy, silty and clayey) were compared to the corresponding curves calculated with the proposed equation. Assuming a known K_s, which can be obtained by the Darcy's law, the S and β estimated analytically were then compared to the corresponding values calculated by the inverse analysis of theoretical upward infiltration curves generated by HYDRUS-1D. Next, a procedure to calculate α and n from the previously calculated K_s, S and β was presented. Finally, the method was tested on sieved experimental soils of known hydraulic properties.

2. Material and methods

2.1. Theory

The governing equation for one-dimensional Darcian upward flow in a variably saturated rigid porous medium is given by the following form of the Richard's equation (Philip, 1957)

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z} + K(\theta)\right] \tag{1}$$

where θ($\mathrm{L^3\,L^{-3}}$) is the volumetric water content, t (T) is time, K the hydraulic conductivity ($\mathrm{L\,T^{-1}}$), z is a vertical coordinate (L) positive upward, and $D(\theta)$ ($\mathrm{L^2\,T^{-1}}$) the diffusivity defined by Klute (1952) as

$$D(\theta) = K(\theta)\frac{dh}{d\theta} \tag{2}$$

where h (L) is the matric component of soil water potential. The respective initial and boundary conditions for upward infiltration are

$$\begin{aligned} &z = 0, t > 0, \theta = \theta_s \\ &z \geqslant 0, t = 0, \theta = \theta_i \\ &z \to \infty, t > 0, \theta = \theta_i \end{aligned} \tag{3}$$

where θ_s ($\mathrm{L^3\,L^{-3}}$) and θ_i ($\mathrm{L^3\,L^{-3}}$) are the saturated and initial volumetric water content, respectively.

For saturated and steady state condition, Eq. (1) is reduced to the Darcy's law (Lichtner et al., 1996)

$$q = -K_s\frac{dH}{dz} \tag{4}$$

where q is the water flux density ($\mathrm{L\,T^{-1}}$), K_s is the saturated hydraulic conductivity, and $H = h + z$ (L) is the hydraulic head. Note that for saturated soils $h \geqslant 0$.

Taking into account the Parlange et al. (1982) and Haverkamp et al. (1994) analysis, who using the Richards equation (Eq. (1)) derived an analytical law predicting water infiltration into a soil, the 1-D upward cumulative infiltration curve, $I(t)$, measured on an infinite-length soil column with homogeneous initial water content can be described by the quasi-exact equation

$$\frac{2(1-\beta)\Delta K^2}{S_0^2}t = \frac{2\Delta K(I + K_i t)}{S_0^2} - \ln\left\{\frac{1}{\beta}\exp\left[\frac{2\beta\Delta K(I + K_i t)}{S_0^2}\right] + 1 - \frac{1}{\beta}\right\} \tag{5}$$