Catena 155 (2017) 86–92

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Comparison of different methods to estimate the soil sorptivity from an upward infiltration curve

D. Moret-Fernández *, B. Latorre, M. Angulo-Martínez

Departamento de Suelo y Agua, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), PO Box 13034, 50080 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form 28 February 2017
Accepted 9 March 2017
Available online 14 March 2017

Keywords:
Soil hydraulic properties
Hydraulic conductivity
Water retention curve

ABSTRACT

The soil sorptivity, *S*, which is defined as a measure of the capacity of a porous medium to absorb or desorb liquid by capillarity, is commonly estimated under laboratory conditions from upward infiltration measurements. The objective of this work is to compare different methods to estimate *S* from a single upward infiltration curve obtained from both theoretical and experimental soils. An additional analysis of the influence of synthetic infiltration noise on the estimation of *S* was also performed on the theoretical soils. Five different methods were compared: Short Time model for horizontal infiltration (ST), the Cumulative Linearization method (CL) and the Differentiated Linearization (DL) linear regressions models, Short-time (SIM) methods that use the simplified Haverkamp et al. (1994) model, and Complete-time (CIM) upward infiltration method that uses the quasi-analytical Haverkamp et al. (1994) function. Since finite soil columns were considered, the saturated hydraulic conductivity needed to estimate *S* with the Haverkamp et al. (1994) model was calculated from an overpressure step at the end of the water absorption process, using the Darcy's law. The methods were contrasted on four theoretical and six sieved experimental soils, ranging from sand to clay textures. Although all methods showed acceptable estimates of *S* on clean theoretical upward infiltration curves, the ST, SIM and CIM were the methods that gave significant ($p < 0.001$) regression analysis on noisied infiltration curves, and only SIM and CIM presented a relative error < 1%. From these results we can conclude that although acceptable approaches of *S* were obtained with the simplest ST method, the CIM procedure was the most accurate method to estimate *S* in both clean and noised theoretical and experimental upward infiltration curves.

1. Introduction

Estimation of the soil hydraulic properties is of paramount importance within the soil hydrological research field. Among the different soil hydraulic properties, we have the sorptivity, *S*, which is defined as a measure of the capacity of a medium to absorb or desorb liquid by capillarity (Philip, 1957). This parameter can be analytically calculated as a function of the initial and final soil water content and the diffusivity (Parlange, 1975). For horizontal infiltration, Philip (1957) reduced this absorption term to a linear relationship between cumulative infiltration, *I*, and the square root of time, *t*, such as $I = S\,t^{1/2}$

On non-horizontal water flow, the soil sorptivity is commonly estimated at the very early stages of infiltration, where suction or capillarity forces prevail over gravity. Thus, for instance, in cement and concrete researches, where water flow is mainly controlled by the capillarity, *S* is commonly estimated from an upward infiltration process using the Philip (1957) model (Pitroda and Umrigar, 2013; Zhou, 2014). However, the $I = S\,t^{1/2}$ equation must be carefully considered in soils with important gravity flow effects (i.e. sands), where the water flow can rapidly be dominated by soil hydraulic conductivity, *K*. In this case, the chosen time interval is likely to strongly influence the calculated *S* (Bonnell and Williams, 1986). To avoid these problems, Moret-Fernández and Latorre (2016) used the quasi-analytical solution of the Haverkamp et al. (1994) model to accurately estimate *S* from an upward infiltration curve. These authors demonstrated that during the early-medium time stages of the infiltration the *S* was quasi-independent of the β parameter of the Haverkamp et al. (1994) model that is defined as an integral shape constant depending on the soil diffusivity, the hydraulic conductivity function and the initial and final volumetric water content.

Alternatively, *S* can be estimated from downward infiltration measurements using a disc infiltrometer with single disc and infiltration tension (Minasny and McBratney, 2000; Bagarello and Iovino, 2003). In this case, the simplified or the complete quasi-analytical solution of the Haverkamp et al. (1994) model can be used. When the simplified Haverkamp et al. (1994) model is employed, methods based on linear regressions of the infiltration curve with respect to $t^{1/2}$ can be applied

---

* Corresponding author.
E-mail address: david@eead.csic.es (D. Moret-Fernández).

http://dx.doi.org/10.1016/j.catena.2017.03.009
0341-8162/© 2017 Elsevier B.V. All rights reserved.

(Vandervaere et al., 2000; Minasny and McBratney, 2000). In contrast, if the quasi-analytical Haverkamp et al. (1994) model is employed, more complex numerical analyses are required (Latorre et al., 2015).

Comparison between upward and downward infiltration procedures to estimate soil S under laboratory conditions highlights four reasons for which upward infiltration measurements are preferable over downward process: (i) difficulties to hold the disc infiltrometer on the soil cylinder; (ii) collapsing of the soil macropores due to infiltrometer weight (Moret and Arrúe, 2005), which can disturb the estimations of the soil hydraulic properties; (iii) loss of hydraulic contact between infiltrometer disc and soil surface as the soil becomes saturated due to partial soil collapse; and (iv) provide some information not available in downward processes. It is to say, while upward infiltration, due to the capillary rise processes, can detect the influence of smaller porous, the advance of the wetting front in the downward infiltration may mask the influence of these pores, probably because the wetting front advance is faster than the capillary movement.

The soil sorptivity is also an interesting soil hydraulic parameter, since it allows estimating related hydraulic properties. For instance, Moret-Fernández and Latorre (2016) demonstrated that the parameters of the van Genuchten (1980) water retention curve could be estimated from the saturated hydraulic conductivity measured by Darcy's law and the S and β parameters estimated from the inverse analysis of an upward infiltration curve. Thus, given the importance of S to estimate the soil hydraulic properties from upward infiltration measurements, the objective of this work is to compare different models to estimate S from a single upward infiltration measurement. To this end, five different models running from the simplest Philip (1957) equation to the quasi-exact Haverkamp et al. (1994) formulation adapted to an upward infiltration process were compared on theoretical and experimental soils.

2. Material and methods

2.1. Theory

The 1-D upward cumulative infiltration, I (L), for a homogeneous, infinite length soil column with uniform initial water content can be described by the following equation derived from the quasi-exact Haverkamp et al. (1994) model (Moret-Fernández and Latorre, 2016)

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

where t is time (T), $S=S_0(\theta_{0,}\theta_i)$ ($\mathrm{L\,T^{-0.5}}$) is the sorptivity, θ_0 ($\mathrm{L^3\,L^{-3}}$) is the volumetric water content at the infiltration boundary, θ_i ($\mathrm{L^3\,L^{-3}}$) is the initial volumetric water content, $\Delta K=K_i-K_0$, with K_0 ($\mathrm{L\,T^{-1}}$) and K_i ($\mathrm{L\,T^{-1}}$) hydraulic conductivity corresponding to θ_0 and θ_i, respectively, and β is an integral shape parameter. The respective initial and boundary conditions for upward infiltration are

$$\begin{array}{l} z=0, t>0, \theta=\theta_s \\ z\geq 0, t=0, \theta=\theta_i \\ z\rightarrow\infty, t>0, \theta=\theta_i \end{array} \tag{2}$$

where z is a vertical coordinate (L) positive upward, and θ_s ($\mathrm{L^3\,L^{-3}}$) is the saturated volumetric water content. In our case, θ_0 and K_0 correspond to the saturated volumetric water content, θ_s ($\mathrm{L^3\,L^{-3}}$), and the saturated hydraulic conductivity, K_s ($\mathrm{L\,T^{-1}}$), respectively. Although Eq. (1) is suitable for those soils (sand to silt) where the β parameter ranges between 0.3 and 1.7 (Lassabatere et al., 2009), Moret-Fernández and Latorre (2016) reported that during the medium time stages of an upward infiltration S was not affected by β, and consequently Eq. (1) could be applied to all type of soils, including clays.

For early to intermediate infiltration time and assuming $K_n\rightarrow 0$, Eq. (1) results (Haverkamp et al., 1994)

$$I=S\sqrt{t}-\frac{2-\beta}{3}K_s t \tag{3}$$

which can be expressed as

$$I=C_1\sqrt{t}-C_2 t \tag{4}$$

where

$$C_1=S \tag{5}$$

and

$$C_2=\frac{2-\beta}{3}K_s \tag{6}$$

Using algebraic combinations or the derivation with respect to the square root of time, Eq. (4) can be respectively expressed as:

$$\frac{I}{\sqrt{t}}=C_1-C_2\sqrt{t} \tag{7}$$

$$\frac{dI}{d\sqrt{t}}=C_1-2C_2\sqrt{t} \tag{8}$$

The value of the constants C_1 and C_2 are estimated to calculate sorptivity and hydraulic conductivity. For this purpose, different fitting procedures which use Eq. (4) or its time-derived version can be adopted. These methods were referred as CL for Cumulative Linearization (Eq. 7) and DL for Differentiated Linearization (Eq. 8) (Vandervaere et al., 2000).

For horizontal infiltration or absorption processes, Eq. (1) is reduced to the Philip (1957) one-term model

$$I=S\sqrt{t} \tag{9}$$

This simple equation is commonly applicable during the very early time of upward or downward infiltrations, where suction or capillarity forces prevail over gravity.

Parlange (1975) demonstrated that, for homogeneous, uniform initial water content and infinite length soil column, the soil sorptivity could be expressed as

$$S^2(\theta_s,\theta_i)=\textstyle\int_{\theta_i}^{\theta_s}D(\theta)[\theta_s+\theta-2\theta_i]\mathrm{d}\theta \tag{11}$$

where $D(\theta)$ ($\mathrm{L^2\,T^{-1}}$) is the diffusivity defined by Klute (1952) as

$$D(\theta)=K(\theta)\frac{dh}{d\theta} \tag{12}$$

Table 1
Values of initial (θ_i), saturated (θ_s) and residual (θ_r) water content, α and n parameters of the van Genuchten (1980) water retention curve, saturated hydraulic conductivity (K_s) and the sorptivity (S) (Eq. 15) calculated from the soil hydraulic properties from the different theoretical soils.

	θ_i cm^3 cm^{-3}	θ_s	θ_r	α cm^{-1}	n	K_s mm s^{-1}	S mm s$^{-0.5}$
Sand	0.045	0.43	0.045	0.145	2.68	$8.25\cdot 10^{-2}$	1.521
Loam	0.078	0.43	0.078	0.036	1.56	$2.88\cdot 10^{-3}$	0.367
Silt	0.034	0.46	0.034	0.016	1.37	$6.93\cdot 10^{-4}$	0.238
Clay	0.068	0.38	0.068	0.008	1.09	$5.55\cdot 10^{-4}$	0.076