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Review Paper

Estimate of soil hydraulic properties from disc infiltrometer three-dimensional infiltration curve. Numerical analysis and field application

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SUMMARY

Based on the analysis of Haverkamp et al. (1994), this paper presents a new technique to estimate the soil hydraulic properties (sorptivity, *S*, and hydraulic conductivity, *K*) from the full-time cumulative infiltration curves. The proposed method, which will be named as the Numerical Solution of the Haverkamp equation (NSH), was validated on 12 synthetic soils simulated with HYDRUS-3D. The *K* values used to simulate the synthetic curves were compared to those estimated with the NSH method. A procedure to detect and remove the effect of the contact sand layer on the cumulative infiltration curve was also developed. A sensitivity analysis was performed using the water level measurement as uncertainty source and the procedure was evaluated considering different infiltration times and data noise (e.g. air-bubbling in the infiltrometer). The good correlation between the *K* used in HYDRUS-3D to model the infiltration curves and those obtained by the NSH method ($R^2 = 0.98$) indicates this technique is robust enough to estimate the soil hydraulic conductivity from complete infiltration curves. The numerical procedure to detect and remove the influence of the contact sand layer on the *K* and *S* estimates resulted to be robust and efficient. A negative effect of the curve infiltration noise on the *K* estimate was observed. The results showed that infiltration time was an important factor to estimate *K*. Smaller values of *K* or lower uncertainty required longer infiltration times. In a second step, the technique was tested in field conditions on 266 different soils at saturation conditions, using a 10 cm diameter disc infiltrometer. The NSH method was compared to the standard differentiated linearization procedure (DL), which estimates the hydraulic parameters using the simplified Haverkamp et al. (1994) equation, valid only for short to medium times. Compared to DL, NSH was considerably less affected by the infiltration bubbling and the contact sand layer, and allowed more robust estimates of *K* and *S*. Although comparable *S* values were obtained with both methods, the NSH technique, which is not limited to short times, resulted in more accurate and robust estimates for *K*. This paper demonstrates the NSH method is a significant advance to estimate of the soil hydraulic properties from the transient water flow.

Contents

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1. Introduction

In situ determination of soil hydraulic properties (sorptivity, *S*, and hydraulic conductivity, *K*) is a fundamental requirement of physically based models describing field infiltration and runoff processes. Over the last two decades, the tension disc infiltrometers (Perroux and White, 1988) have become popular devices for *in situ* estimates of *K* and *S*. This instrument consists of a disc base covered by a membrane, a graduated water-supply reservoir and a bubbling tower with a moveable air-entry tube that imposes the pressure head at the cloth base. The cumulative infiltration curve is measured from the water level drop in the reservoir. The diameter of the disc base can vary from the 25 cm proposed by Perroux and White (1988) to the 3.2 cm used by Madsen and Chandler (2007) for microtopography studies. Correct measurements of the water infiltration with the tension infiltrometer require the disc base to be completely in contact with the soil surface. To achieve this connection, Perroux and White (1988) recommended trimming any vegetation within the sample to ground level and covering the soil with a material with high hydraulic conductivity (contact sand layer). Although this procedure allows infiltration measurements in most field situations, the water initially stored in the contact layer alters the cumulative infiltration curve and, consequently, the estimation of *K* and *S* (Angulo-Jaramillo et al., 2000). In those cases, the influence of the contact layer should be removed. More recently, Špongrová et al. (2009) showed that the cumulative infiltration noise induced by the bubbling in the infiltrometer reservoir can have a significant effect on the *K* estimation.

The soil hydraulic properties are calculated by analysing the cumulative water-infiltration curve. Several methods to estimate the soil hydraulic properties have been proposed: (i) methods based on the Wooding (1968) equation, which uses steady-state data (Smettem and Clothier, 1989; Ankeny et al., 1991; Reynolds and Elrick, 1991), (ii) methods based on the transient state data (e.g. Vandervaere et al., 2000) and (ii) methods which combine both transient and steady states, like BEST methods (Lassabatere et al., 2006; Yilmaz et al., 2010). Compared to the standard steady-state water flow method, the transient water flow procedure, that requires shorter experiments, involves smaller sampled soil volumes and more homogeneous initial water distribution (Angulo-Jaramillo et al., 2000), which leads to better estimates and better representativeness of the local hydraulic properties.

These are the reasons why we do not address steady state methods in this paper. Several model have been developed to estimate the soil hydraulic parameters from the transient water flow (Warrick and Broadbridge, 1992; Zhang, 1998). Haverkamp et al. (1994) obtained a quasi-exact equation describing the three-dimensional unsaturated cumulative infiltration curve for disc infiltrometers. Lassabatere et al. (2009) evaluated this equation with respect to their ability to reproduce numerically generated cumulative infiltration from 10 cm radius disc sources for four soils (sand, loam, silt and silty clay), and observed that the quasi-exact formulation was suitable for sand, loam and silt soils when their soil-dependent and saturation-independent shape parameters, γ and β, were properly chosen (between 0.75 and 1 and 0.3 and 1.7, respectively). Due to relative the complexity of this equation, Haverkamp et al. (1994) proposed a simplified version, which allows estimating *K* and *S* using linear fitting techniques. Vandervaere et al. (2000) compared the existing methods to analyze the transient state of the simplified Haverkamp et al. (1994) equation (for more details, see Section 2). They concluded that the DL (for Derivative Linearization) method, which consists in a linear fit of a the derivative of the cumulative infiltration data with respect to the square root of time, allowed the best estimations of *K* and *S* when contact sand layer was used. However, these methods, like the DL method, are only applicable for short to medium time and can be questioned when steady state is reached too quickly, e.g. when infiltration is controlled by capillary forces (Angulo-Jaramillo et al., 2000).

This work proposes an inverse analysis of the complete Haverkamp et al. (1994) equation (Numerical Solution of the Haverkamp equation, NSH) to estimate the soil hydraulic properties from the cumulative infiltration curve measured with a disc infiltrometer. Due to the multiple tension methods used in the infiltrometry technique require long infiltration measurements, and the objective of this work is optimizing the field measurements, only infiltration measurements at saturation conditions were considered. This technique accounts for the effect of a sandy layer embedded below the infiltrometer on cumulative infiltration, and removes its impact on estimates. The procedure was validated with regards both analytically generated data and field experiments for the case of water infiltration with zero pressure head at surface. At first, the water infiltration was computed for the case of zero water pressure head at surface and dry initial state for 12 different synthetic soils, using HYDRUS-3D. This numerical data were analyzed with the NSH method and the estimated hydraulic values were compared to the original ones. The effect of noise on data (e.g. due to air bubbling in the Mariotte reservoir of the infiltrometer) and the consequences on the quality of NSH estimates were also numerically assessed. In a second step, the NSH method was evaluated under field conditions and tested on 266 experimental infiltration curves. The results were compared to the DL procedure, which can be considered as a reference method for the analysis of the transient state of infiltration. The influence of the infiltration curves noise and the effect of the contact sand layer on the *K* and *S* estimates was evaluated and discussed for all methods.