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Testing steady-state analysis of single-ring and square pressure infiltrometer data

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ABSTRACT

Testing reliability of the saturated soil hydraulic conductivity, K_s, estimated by applying the steady-state single-ring (SR) model to the quasi steady-state infiltration rates obtained with a single-ring pressure infiltrometer (PI) increases confidence in the estimated K_s values. Determining a means to estimate K_s from infiltration data collected with a square infiltrometer allows the use of sources of different shapes. Using numerically simulated infiltration rates for six homogeneous soils ranging in texture from sand to silty clay loam, this investigation suggested an overall good performance of the SR model, with estimated K_s values differing by not more than 25% from the true values for the 90% of the 96 considered runs. Larger errors were generally obtained for the silty clay loam soil. Even in this case, however, a small ring radius (0.038 m), a relatively high initial soil water content (initial effective saturation = 0.4) and a relatively high depth of ponding (0.10 m) allowed the obtainment of accurate predictions of K_s (error = 13%) with a run of practically sustainable duration (4 h). The SR model was also usable to analyze quasi steady-state infiltration data collected with a square infiltrometer when infiltration was assumed to occur through a circular source having the same area of the square infiltrometer. With this assumption, the estimates of K_s differed from the true values by not more than a practically negligible 16%. The results of this investigation should help better interpret K_s values obtained with the PI and also improve the experimental methodology, depending on the soil. Moreover, a wider applicability of the infiltrometer techniques, i.e. not limited to a circular source, can be expected. Soil heterogeneity should be taken into account in the future since heterogeneity is common in the field.

1. Introduction

The saturated soil hydraulic conductivity, K_s, is one of the most important soil properties controlling soil hydrologic and erosion processes such as rainfall partition into infiltration and surface runoff. Especially for structured soils, this property should be measured directly in the field to minimize disturbance of the sampled soil volume and to maintain its functional connection with the surrounding soil (Bouma, 1982). Reliable field data should be collected with a reasonably simple and rapid experiment.

The single-ring pressure infiltrometer (PI) (Reynolds and Elrick, 1990) is a practically simple device that has frequently been applied in the field in the past 20 years (Vauclin et al., 1994; Ciollaro and Lamaddalena, 1998; Bagarello and Iovino, 1999; Angulo-Jaramillo et al., 2000; Bagarello et al., 2000, 2013a, 2014; Reynolds et al., 2000; Bagarello and Sgroi, 2004; Mertens et al., 2002; Gómez et al., 2005; Verbist et al., 2009, 2010, 2013). This technique uses a small radius metal ring that is inserted into the soil to a short depth. A constant hydraulic head, H, is established within the infiltration ring and flow rate into the soil is monitored. Flow goes through an initial decreasing phase and then it approaches steady-state conditions (Elrick and Reynolds, 1992b). Three-dimensional, steady, ponded flow out of the ring is then used to determine K_s with an analysis, developed by Reynolds and Elrick (1990), based on variably saturated flow theory and including the hydrostatic pressure, capillarity and gravity components of flow out of the ring. This analysis employs shape factors that were numerically determined for three soils (sand, loam and clay) and a clay cap/liner. To our knowledge, the steady analysis by Reynolds and Elrick (1990) has not been assessed against simulated PI experiments performed in different soils and involving a transient infiltration phase, as it occurs in real field conditions.

The analysis by Reynolds and Elrick (1990), as well as other PI analyses (Wu et al., 1999), applies to a circular source but using sources of different shapes could be advisable in particular circumstances. For example, a square infiltrometer could allow, at least in theory, to sample completely an area of interest whereas, with a circular source, there are zones of the field that cannot be sampled, thus precluding the possibility to uniformly collect data. This is a possible limitation of this device since intensively sampling soil represents an important step toward an improved interpretation and simulation of hydrological processes at the field scale (Gómez et al., 2005; Bagarello et al., 2013b). Employing a square infiltrometer raises a problem in the calculation of

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K_s since the developed equations include the ring radius that has to be replaced by a suitable alternative quantity if a square source is being used. Gómez et al. (2005) used a square infiltrometer and they determined K_s by assuming that the ring radius coincided with the side length of the infiltrometer. However, these authors did not test their assumption.

Numerical simulation of an infiltration process into an initially unsaturated porous medium is a powerful tool to test hypotheses and to check factors affecting the applicability of a particular analytical procedure to estimate soil characteristics (Bagarello et al., 2013a). For example, numerically simulated data were used by Wu et al. (1993) to explain erratic K_s estimates obtained by the borehole permeameter technique in soils with macropores and abrupt layers. Lai and Ren (2007) and Lai et al. (2010) used numerical simulation to improve determination of K_s by the double-ring infiltrometer. Dušek et al. (2009) analyzed single-ring numerically generated data to test the dependence of the infiltration rate on several factors, including ring diameter and insertion depth and ponding depth of water on the infiltration surface. Bagarello et al. (2013a) used numerical simulation to test the performances of the two-ponding-depth (TPD) procedure of analysis (Reynolds and Elrick, 1990) for PI data collected in heterogeneous soils. Numerically simulated data were used by Reynolds (2013) to assess different borehole infiltration analyses for determining K_s in the vadose zone. Therefore, numerical simulation of a single-ring infiltration process appears suitable to test the steady-state analysis developed for the PI.

In this investigation, numerically simulated infiltration data were used with the following objectives: i) to assess the steady-state analysis developed by Reynolds and Elrick (1990) for a single-ring pressure infiltrometer experiment simulated for different soils, and ii) to determine a means to estimate saturated soil hydraulic conductivity from quasi steady-state infiltration data collected with a square infiltrometer.

2. Theory

The analytical expression for steady, ponded flow out of a ring into rigid, homogeneous, isotropic, uniformly unsaturated soil is (Reynolds and Elrick, 1990):

$$Q_s = \frac{r}{G}(K_s H + \phi_m) + \pi r^2 K_s \tag{1}$$

where Q_s ($L^3 T^{-1}$) is the steady-state flow rate, r (L) is the ring radius, K_s ($L T^{-1}$) is the saturated soil hydraulic conductivity, H (L) is the ponded head of water on the infiltration surface, ϕ_m ($L^2 T^{-1}$) is the matric flux potential and G is a dimensionless shape factor expressing the interactions between ring radius, depth of ring insertion, d (L), depth of ponding in the ring, soil capillarity and gravity. According to Eq. (1), steady-state flow rate out of the ring is the sum of three components, i.e. flow due to the hydrostatic pressure of the established ponding depth of water on the infiltration surface (first term on the right of the equation), flow due to the capillarity of the unsaturated soil under and adjacent to the ring (second term), and flow due to gravity (third term). With a larger source, the relative contribution of both the hydrostatic pressure and the soil capillarity to total flow decreases whereas that of gravity increases (Reynolds et al., 2002). Eq. (1) was developed under the assumption that ponding does not occur around the outside of the ring during a measurement (Reynolds, 2008; Reynolds and Elrick, 2002). Values of G for a circular source, four porous media and different combinations of H, d and r were determined numerically by Reynolds and Elrick (1990). These authors also found that G is nearly independent of soil hydraulic properties and H for $H \geq 0.05$ m. Therefore, for practical application of the PI technique, the following relationship, specifically developed for $0.03 \text{ m} \leq d \leq 0.05$ m, $0.05 \text{ m} \leq r \leq 0.10$ m and $0.05 \text{ m} \leq H \leq 0.25$ m, can be used to obtain an estimate of G (G_e) (Reynolds and Elrick, 1990):

$$G_e = 0.316\frac{d}{r} + 0.184. \tag{2}$$

For a given insertion depth, G_e is a function of the ring radius. According to Reynolds and Elrick (2002), however, Eq. (2) is usable for practical purposes within wider ranges of both d ($0 < d \leq 0.10$ m) and H ($0.05 \leq H \leq 1$ m) without substantially compromising the reliability of the estimates (Youngs et al., 1993).

Eq. (1), with Eq. (2) inserted, can be written as (Reynolds and Elrick, 1990):

$$K_s = \frac{\alpha^* G_e \; Q_s}{r(\alpha^* H + 1) + G_e \alpha^* \pi r^2} \tag{3}$$

where α^* (L^{-1}) is equal to:

$$\alpha^* = \frac{K_s}{\phi_m}. \tag{4}$$

The α^* parameter is expressive of the relative importance of gravity and capillarity flow. A large α^* suggests low capillarity due to coarse soil texture or extensive soil structure and vice versa. In this investigation, Eq. (3) was indicated as the SR (i.e., single-ring) model for K_s calculation.

The ring infiltrometer equation for steady ponded flow can be recast as:

$$i_s = \frac{Q_s}{\pi r^2} = \frac{Q_s}{A} = \left[\frac{r}{A G_e{}^e}\left(H + \alpha^{*-1}\right) + 1\right] K_s \tag{5}$$

where i_s ($L T^{-1}$) is the steady infiltration rate and A (L^2) is the area of the infiltration surface. According to Eq. (5), K_s depends on steady infiltration and, as a consequence, all shapes (e.g. circles, squares, rectangles, triangles) could be expected to yield the same i_s and K_s values if they have the same total infiltration surface. However, a necessary passage to apply Eq. (3) with a non-circular source is to assume that the source is circular, so that an equivalent radius can be defined. This assumption needs testing because Eq. (3) was explicitly developed with reference to a circular source but, for a given equivalent radius, the wetted perimeter per unit surface area changes with the shape of the source. Only to make an example, Eq. (3) with $r = 10$ cm could indifferently be used with a circular source of $r = 10$ cm, a square source with a side length of 17.72 cm, and a rectangular source of 2.5×125.7 cm^2. All these sources have the same infiltration area ($A = 314$ cm^2) but they differ by the wetted perimeter (circular, 63 cm; square, 71 cm; rectangular, 256 cm).

3. Materials and methods

3.1. Soils and numerical simulations

Numerical simulations were carried out for the six homogeneous soils selected by Hinnell et al. (2009). Soil hydraulic properties were modeled according to the van Genuchten–Mualem model (Mualem, 1976; van Genuchten, 1980) with hydraulic parameters taken from Carsel and Parrish (1988) (Table 1):

$$\Theta(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \left(1 + |\alpha_{vG} h|^n\right)^{-m} \quad m = 1 - \frac{1}{n} \tag{6a}$$

$$K(h) = K_s \Theta^{0.5}\left(1 - \left(1 - \Theta^{1/m}\right)^m\right)^2 \tag{6b}$$

where Θ is the effective saturation, h (L) is the soil water pressure head, θ (L^3L^{-3}) is the volumetric soil water content, θ_s (L^3L^{-3}) and θ_r (L^3L^{-3}) are the saturated and residual volumetric water contents, respectively, α_{vG} (L^{-1}), m and n are soil-specific empirical parameters of the van