A modified hood infiltrometer to estimate the soil hydraulic properties from the transient water flow measurements

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Abstract

In-situ measurements of soil hydraulic properties on covered soil surfaces are of paramount importance in many agronomic or hydrological researches. The hydraulic properties can be estimated from the cumulative infiltration curve measured with tension infiltrometers. The transient water flow analysis, which means shorter experiments, facilitates its use for in situ field application. This paper presents a portable and modified design of the hood infiltrometer, the hat infiltrometer (HI), which applied on covered soil surfaces, allows estimating the soil hydraulic properties from the measured transient cumulative infiltration curve. The HI consists of a water-supply reservoir attaches to a hat base placed on the soil surface. The base of the hat is closed by a system of sticks and a plasticine ring. The HI was tested on two different soils at saturated conditions, and the estimated soprtivity (S) and hydraulic conductivity (K) were compared to the corresponding values obtained with a disc infiltrometer (DI). An additional field experiment was performed to compare the hydraulic properties measured with HI on a bare soil and a soil covered with plants. Results demonstrated that this design allows hermetically closing the base of the hat without disturbing the soil surface. No significant differences between the *K* and *S* values estimated with DI and HI were observed. The values of *S* measured with HI on the covered soil were significantly higher than that measured on the adjacent bare soil. These results indicate that HI can be a viable alternative to estimate the hydraulic properties of covered soils from the measured transient infiltration curve.

Keywords: Disc infiltrometer; Hydraulic conductivity; Sorptivity.

1. Introduction

Measurements of the sorptivity (S) and hydraulic conductivity (K) on undisturbed soil surface is crucial to solve many hydrological engineering, and environmental issues linked to soil water storage and transport in the vadose zone. The tension disc infiltrometer (Perroux and White, 1988) has become a popular infiltration method because of the relatively rapid and portable nature of this technique, its easy *in-situ* applicability, and its ability to measure at unsaturated soil conditions (Angulo-Jaramillo et al., 2000).

The tension disc infiltrometer (Perroux and White, 1988) has become a popular infiltration method because of the relatively rapid and portable nature of this technique, its easy in-situ applicability, and its ability to measure at unsaturated soil conditions (Angulo-Jaramillo et al., 2000). The disc infiltrometer consists of a disc base attached to a graduated water-supply reservoir and a bubbling tower to impose a negative pressure head (h) at the disc base (Perroux and White, 1988). The soil hydraulic properties are commonly calculated from the cumulative water-infiltration curves, which are measured from the drop in the water level of the reservoir tower. Two cumulative infiltration curve analyses are available: the steady-state and the transient water flow methods. Steady-state flow theory has been widely used during the last few decades. However, the assumption of homogeneous isotropic soil with uniform initial water content required by this method (Vandervaere et al., 2000) together with the long time needed to achieve the steady-state water flow, prevents its use to field applications. Determination of soil hydraulic properties from transient water flow analysis, which means shorter experiments and smaller sampled volumes of soil, is obviously in better agreement with assumptions of homogeneity and initial water uniformity (Angulo-Jaramillo et al., 2000). Vandervaere et al. (2000) compared several methods to analyse the transient water flow using the simplified Haverkamp et al. (1994) equation for disc infiltrometer and concluded that the linear fitting technique consisting in differentiating the cumulative infiltration data with respect to the square root of time allowed better estimations of the soil hydraulic properties. More recently, Latorre et al. (2013) demonstrated that estimates of K and S can be significantly improved if the quasi-exact analytical equation of three-dimensional water infiltration from a surface disc source (Haverkamp et al., 1994) is directly employed. The procedure developed by Latorre et al. (2013) also allowed detecting and removing the effect of the contact sand layer, if used, on the K and S estimations.

The disc base of the infiltrometer, which diameter ranges from the 25 cm (Perroux and White, 1988) to the 3.2 cm (Madsen and Chandler, 2007), is usually covered with a tightened nylon cloth of very small mesh. The base should be completely in contact with the soil surface to accomplish correct infiltration measurements. To achieve this contact, Perroux and White (1988) recommended trimming any vegetation within the sample to ground level and cover the soil with a material (i.e. sand layer) of high hydraulic conductivity. However, according to Reynolds (2006), the contact sand layer introduces an offset between the pressure head set on the bubbling tower and the pressure head applied to the soil surface. This offset should be corrected to prevent the introduction of systematic biases in infiltration results (Reynolds, 2006). These limitations were partially solved by Moret-Fernández et al. (2013), who developed an alternative disc base with a malleable membrane (MDB) that allowed excellent soil surface contact without using a contact sand layer. However, this membrane base prevents infiltration measurements on abrupt surfaces or soils covered with plants or crop residues. This problem was solved by UGT (Müncheberg, Germany), who developed a tension infiltrometer where the disc base was replaced by an acrylic (12.4 cm in diameter) hood. The hood is placed open side down onto the soil, within a retaining ring inserted into the soil, and the water-filled hood is directly in contact to the soil surface. Schwärzel and Punzel (2007) compared this new design with the conventional disc infiltrometer that uses a contact sand layer and observed that the hydraulic conductivities measured with this alternative design were 10 times higher than that measured with the disc infiltrometer. Although this system allows infiltration measurements on covered soils, the slow filling of the hood during the firsts infiltration times prevents employing the transient water flow method to estimate the soil hydraulic properties. In this case, the more time consuming multiple head approach should be used . On the other hand, the retaining ring used to close the hood, which is slightly inserted into the soil, may create preferential infiltration channels that distort the infiltration measurements.

The objective of this paper is to present a modified hood infiltrometer, named hat infiltrometer (HI), which can be applied on cover soil surfaces. Unlike to the hood infiltrometer, which employs the multiple head approach, this new prototype allows recording and using the transient infiltration curve to estimate the soil hydraulic properties. Due to the multiple head approach has been satisfactorily applied to the hood infiltrometer, this work will only analyse the transient infiltration flow method. This new prototype was compared with a conventional disc infiltrometer on two different soil conditions, and tested on covered and uncovered soil surfaces.

2. Material and methods

2.1. Infiltrometer design

Similarly to the compact disc infiltrometer (DI), the hat infiltrometer (HI) consists of a hat-shaped base attached at the top to a water-supply reservoir and a bubbling tower that imposes a negative pressure head (*h*) at the hat base (Fig. 1). The hat base is a cylindrical acrylic tube (10 cm internal diameter –i.d-; 10 cm height) attached at the base to a metallic flat ring (3 mm thickness and 10 and 15 cm internal and external diameter, respectively) closed at top by an acrylic lid. Three 1.5-mm deep holes are equidistantly made on the metallic ring, at 2.5 cm from the external diameter. The water reservoir consists of a 5 cm i.d. and 55 cm high acrylic tube. A vertical acrylic tube, that vertically traverses the hat, is connected to the water reservoir through a water flow ball valve (Fig. 1). This vertical tube, which is placed at 1.5 cm from the soil surface, includes a 3 mm i.d. plastic pipe (*air inlet tube*) that is connected to a bubbling tower. A 8 mm i.d. silicone pipe (*air flow tube*) connects the top of the water reservoir tube to the top of the hat (Fig. 1). This tube is closed by an air flow plastic stopcock. To check the pressure head on the soil surface a water manometer is inserted at the top of the hat. Finally, a ±0.5 psi differential pressure transducer (PT) (Microswitch, Honeywell), connected to a datalogger (CR1000, Campbell Scientist Inc.), is installed at the bottom of the water-supply reservoir (Casey and Derby, 2002). The base of the hat is closed by compressing the HI base against the soil surface. To this end, a three detachable sticks system is used (Fig. 1).

2.2. Infiltrometer setup

Installation hat infiltrometer needed the following steps. Firstly, a 10 cm diameter cloth is placed on the soil surface to be measured. This allows reducing the soil surface disturbance during the hat water-filling. A plasticine ring (11-cm i.d and 1.5 cm thickness) is pasted under the hat, and the hat plus the plasticine ring are placed on the soil surface, making sure the 10-cm diameter cloth rested within the hat. Three arm-sticks (30-cm length and 2-cm thickness) (Fig.1), which is welded to a perforated iron metallic head, are equidistantly and perpendicularly placed against the metallic ring perimeter. A 25 cm long vertical screw is screwed at the end of the arm, resting the ends of the screws on the corresponding metallic ring holes. Three sticks (40-cm length and 2-cm thick) are introduced in the corresponding perforated iron heads (Fig. 1) and subsequently are driven into the soil down to 30-cm depth. The iron heads are blocked and the hat base plus the plasticine is compressed against the soil surface by screwing the arm-stick screws against the hat base (Fig. 1). The strong pressure on the metallic ring, which squashes the plasticine against the soil surface, hermetically closes the base of the hat infiltrometer. In order to obtain sealing of the hat, the screws of the arm-sticks should be progressively and alternatively screwed.

Once the HI base is installed, the bubbling tower is connected to the HI *air inlet tube* (Fig. 1) and the water-supply reservoir is assembled on the hat. Next, the *air flow tube* between the hat and the water reservoir is connected and the corresponding stopcock opened. The ball valve for water flow is turned off and the water reservoir is filled with water. Finally, the pressure transducer is connected to the data logger. Saturated infiltration measurements require that the pressure head inside the bubbling tower is equal to the distance between the soil surface and the end of the *air outlet tube* (Fig. 1). To start the infiltration measurements, the ball valve for water flow is turned on and the plastic stopcock for air flow is kept opened until the water level inside the hat reaches 2 to 4 cm height. This mechanism allows the air flows from the hat to the water reservoir, as the hat is filled with water. Once the plastic stopcock is closed, the air for water infiltration is immediately supplied from the bubble tower. Pressure head measured with the water manometer (h_M) corresponds to the pressure head supplied by bubble tower (h_{BT}) plus the water level inside the hat (h_{WL}) (Fig. 1).

2.3. Field testing

A first field experiment to measure the vacuum capacity inside the hat infiltrometer was performed. To this end, two infiltration experiments at saturation conditions were performed in a compacted soil located in an olive tree field in the Estación Experimental de Aula Dei. To monitor the pressure head changes in the hat, the water manometer was replaced by a ±0.5 psi PT connected to the data logger. Ten minutes after the start of the infiltration, the bubbling tower was blocked out and the infiltration continued until the pressure head in the hat was stabilized. This indicates that the vacuum into the hat was broken. The maximum pressure head inside the hat ($h_{BT_{Final}}$) measured during the hat vacuum experiment was calculated according to

$$h_{BT_{Final}} = h_{M_{Final}} - \left(h_{M_{Sat}} - h_{BT_{Sat}}\right)$$

where $h_{M_{Final}}$ is the final hat pressure head once the bubble tower was blocked, $h_{M_{Sat}}$ is the pressure head measured by the PT during the infiltration measurement at saturation, and $h_{BT_{Sat}}$ is the corresponding pressure head supplied by bubbling tower, fixed at 1.5 cm (Fig. 2).

The soil hydraulic properties estimated with this new prototype were subsequently compared with those estimated with a disc infiltrometer (DI) in two experimental fields with different soil conditions (Table 1).

The first field (EEAD) was located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (41°44′N, 0°46′W, altitude 270 m). Soil at the research site is a loam (fine-loamy, mixed, thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Selected physical and chemical properties of the soil were given in López et al. (1996). The infiltration measurements were conducted on a rectangular plot (30 x 10 m^2) under no tillage treatment (NT), set up on a nearly level area (slope 0–2%). The experimental field corresponds to a long-term conservation tillage experiment started in 1991. The field was in the fallow period of 18 months-long winter barley (Hordeum vulgare L.)–fallow rotation. The second field (CODO) was located in the Codo municipality (NE Spain; 41º30’N, 0º15’W). The land use in the area is based on a traditional agro-pastoral system involving dry cereal croplands and extensive sheep production. Soil at the research site is loam (Calcic Petrogypsids) according to the USDA classification (Soil Survey Staff, 2010). More details of chemical analysis of the soil were given Moret-Fernández et al. (2011).

The DI employed in the experiment was a typical Perroux and White (1988) infiltrometer with a base radius of 50 mm. The DI employed in the experiment was a typical Perroux and White (1988) infiltrometer with a base radius of 50 mm. To install the DI a circular thin layer of commercial sand (80–160 μm grain size), with the same diameter as the disc base, was layered on the soil surface. This allowed a good hydraulic contact between the base of the disc (covered with a 20 μm mesh nylon cloth) and the soil surface. Similarly to the HI, the water level in the water reservoir was recorded with a ±0.5 psi PT, which connected to a datalogger (CR1000, Campbell Sci.) was installed at the bottom of the water supply reservoir.

All infiltration measurements were taken on a nearly levelled and bare soil surfaces. The infiltration sites with DI were separated about 30-50 cm from HI measurements. In all cases, only infiltration measurements at soil saturation conditions were conducted. Flow readings, which last up to 10 min, were automatically recorded every 5 s from the drop in water level of the water supply reservoir. The final soil water content, needed to calculate the hydraulic conductivity, was sampled from the upper centimetres of the soil just after removing the disc infiltrometer from the soil surface. The soil dry bulk density (ρ_b), also used to determine the inital volumetric water content of the soil, was determined by the core method with core dimensions of 50 mm diameter and 50 mm height. The core samples were taken near the measurement locations, the same day as infiltration measurements. Ten and four ρ_b samplings were taken in CODO and EEAD, respectively. A total of 30 soil infiltration measurements, 20 in CODO and 10 in EEAD, were completed. The K and S values were calculated from the cumulative infiltration curve using the Latorre et al. (2013) procedure, which analyses the transient cumulative infiltration curve using the cuasi-analytical solution of the Richards equation for a disc water source. The K and S values estimated with DI were compared to the corresponding values measured with HI. To this end an ANOVA test was used.

In order to check the viability of HI on covered soils, an additional field experiment was done in the CODO field (Table 1). The hydraulic properties measured with HI on soil covered with a plant of *Salsola Kali* were compared with the corresponding measurements obtained on the bare soil. Nine replications were performed in both covered and bare soils, and the distance between the pair of infiltration points was around 30-40 cm.

3. Results and discussion

Field experiments demonstrated that the system used to fix the hat infiltrometer on the soil surface is portable and easy to install. This also was an efficient system to hermetically close the base of the hat without disturbing the soil surface. The time needed to install the hat infiltrometer was less than 6 minutes. The hat vacuum experiment showed that the average maximum pressure head allowed inside the hat was 12.1 cm (Fig. 2). Although it was not the objective this paper, these results indicate the hat infiltrometer may be also used in unsaturated infiltration experiments. On average, the time needed to fill the hat up to 2-4 cm height water sheet and the time to start the bubbling in the bubbling tower was about 2-3 seconds and 6 seconds, respectively.

The cumulative infiltration curve obtained with HI showed a large jump in the first seconds of the infiltration measurements (Fig. 3). This corresponds with water filling hat once the ball valve is opened. Despite this irregular shape, the K and S were successfully estimated with the Latorre et al. (2013) procedure which, similarly to DI with contact sand layer, allowed correcting the infiltration jump. This method also allowed estimating the time needed to start the bubbling (Fig. 3). Overall, the deep well observed in the K and S error distribution (Fig. 3)

(Latorre et al., 2013) indicate the infiltration curves recorded with HI allows accurate estimates of the soil hydraulic properties.

No significant differences were observed between the K and S calculated in both fields with the DI and the corresponding values estimated with the HI (Table 2). The standard deviation calculated in the soil hydraulic parameters was similar for the two infiltrometers. These results indicate that the HI can be an alternative instrument to estimate the soil hydraulic parameters from the transient infiltration curve.

Comparison between the hydraulic properties measured in the CODO field on bare and covered soil showed that S under *Salsola* (0.303 mm $s^{-0.5}$) was significantly higher ($p = 0.015$) than that measured in bare soil (0.184 mm $s^{-0.5}$). These differences can be attributed to the higher organic matter content accumulated on the soil surface, under the *Salsola* plant, which may increase the water absorption capabilities during the first infiltration stages. No significant differences in K were observed between the different soil surfaces, which values were 0.064 and 0.068 mm s^{-1} for the bare and covered soil, respectively.

4. Conclusions

This paper presents a modified design of the tension hood infiltrometer, the hat infiltrometer (HI), that allow estimating the sorptivity (S) and hydraulic conductivity (K) on soils covered with plants or residues using the transient cumulative infiltration curve. This new design was tested under saturated conditions on two different soils. No statistical differences were found between the K and S values measured with HI and DI. Compared to the hood infiltrometer (Schwärzel and Punzel, 2007), the HI allows using the transient cumulative infiltration curve to estimate the soil hydraulic properties, which substantially reduces the length of the experiment. Although no infiltration measurements are available under unsaturated soil conditions, field tests demonstrated that HI can also run at negative pressure heads. These results show that the HI can be an alternative to the DI when infiltration measurements are required on covered soils.

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Figures captions

Figure 1. Diagram of the hat infiltrometer.

Figure 2. Cumulative infiltration (circles) and hat pressure head (triangles) curves measured with the hat infiltrometer during the hat vacuum capability experiment. White and grey colours indicate the first and second replication of infiltration measurements

Figure 3. Measured (circles) and modelled (line) cumulative infiltration curves measured with the hat infiltrometer in the bare soil surface of the CODO field (a), and error distribution functions estimated for the sorptivity ,S, (b) and hydraulic conductivity ,K (c) according to the Latorre et al. (2013) procedure.

Table 1. Altitude, average annual, precipitation (P), temperature (T), and average soil dry bulk density (ρ_b) of the experimental plots located in the research farm of the Estación Experimental de Aula Dei (EEAD) and in the Codo municipality (CODO)

Soil	Altitude (m)	P (mm)	T (ºC)	ρ_b (Mg m^{-3})
EEAD	270	390	14.5	1.52
CODO	400	313.7	14.5	1.34

Table 2. Average and standard deviation (parenthesis) values for the K and S parameters estimated with the disc and hat infiltrometer in the CODO and EEAD experimental fields.

	CODO	EEAD	CODO	EEAD
	S (mm $s^{-0.5}$)		K (mm s^{-1})	
Disc	0.185 (0.131)	0.209 (0.07)	0.0062 (0.005)	0.0087 (0.006)
Hat	0.219 (0.098)	0.213 (0.11)	0.0053 (0.007)	0.0067 (0.006)
Sig [1]	0.37	0.93	0.34	0.76

[1] denotes the significance value for the ANOVA analysis

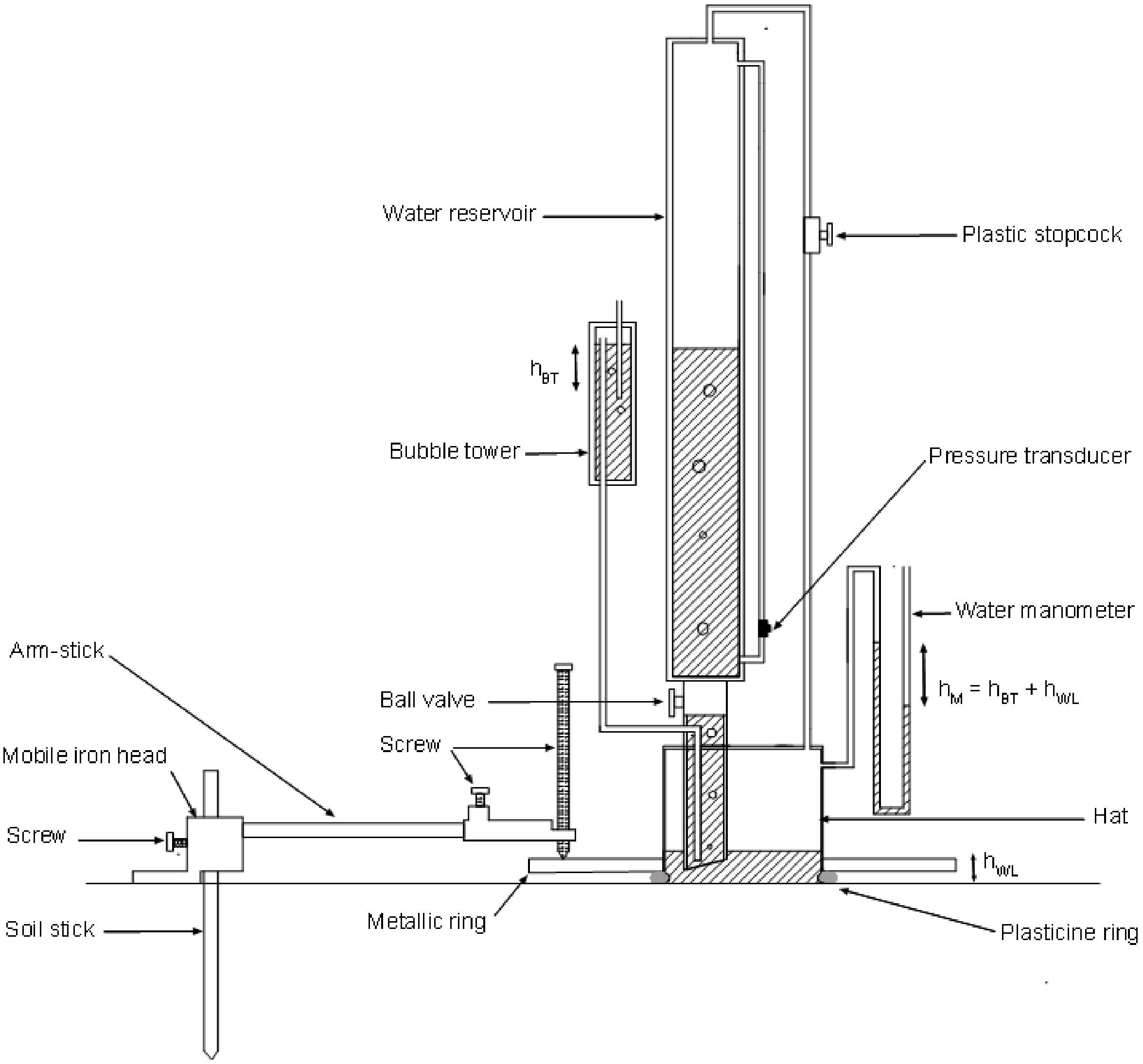
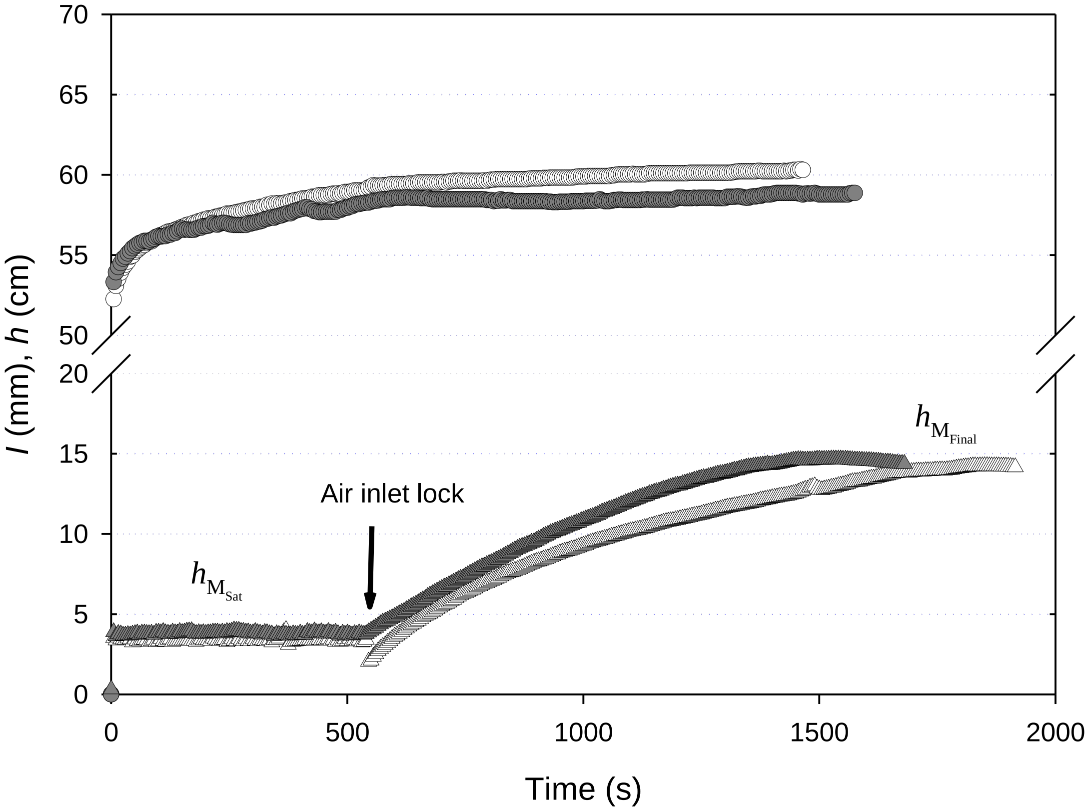

Water reservoir
Plastic stopcock
h_BT
Bubble tower
Pressure transducer
Water manometer
Arm-stick
h_M = h_BT + h_WL
Ball valve
Screw
Mobile iron head
Hat
Screw
h_WL
Soil stick
Metallic ring
Plasticine ring

Fig. 1.


70
65
60
55
50
20
15
10
5
0
I (mm), h (cm)
hMSat
Air inlet lock
hMFinal
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1500
2000
Time (s)

Fig. 2.

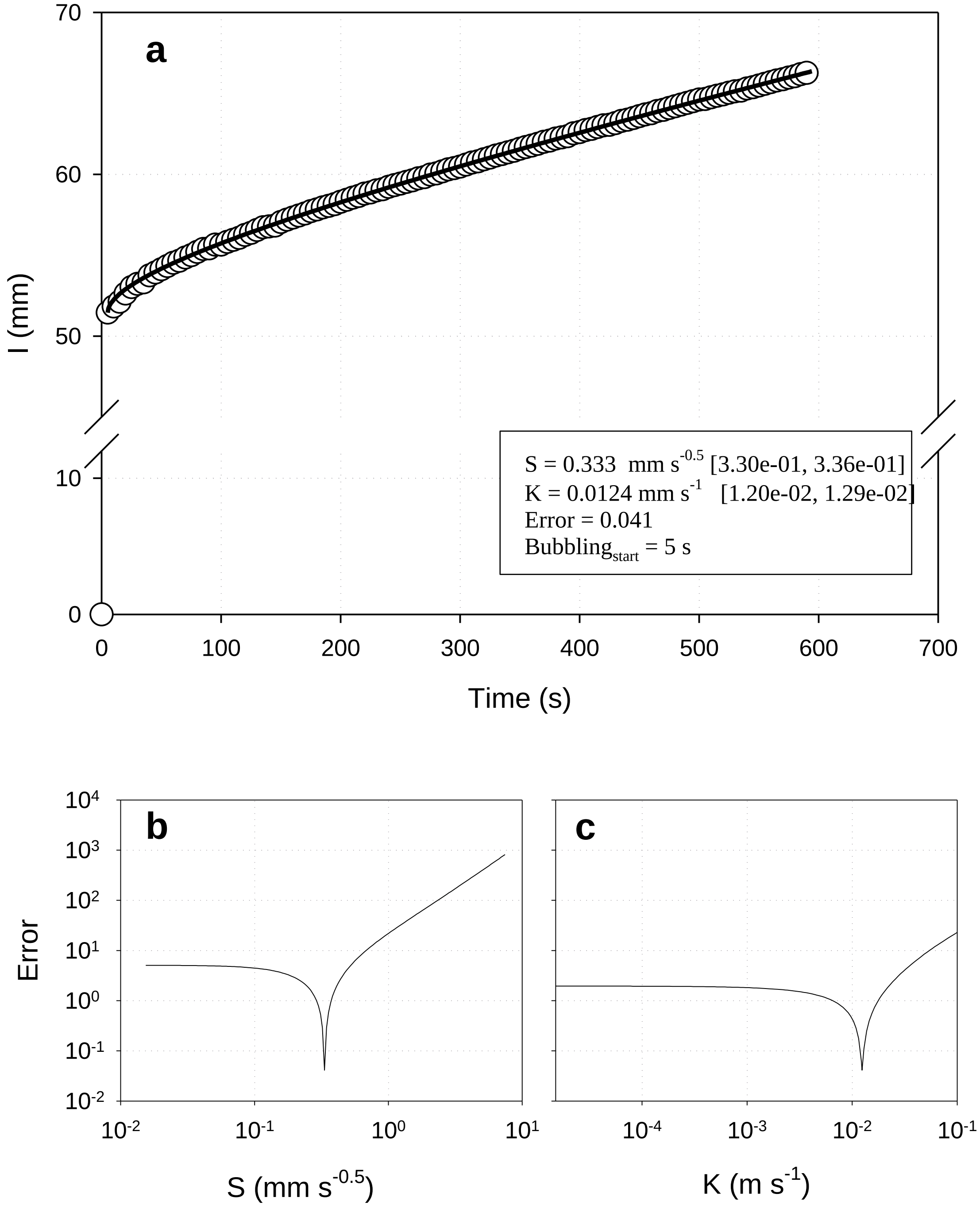
a
S = 0.333 mm s-0.5 [3.30e-01, 3.36e-01]
K = 0.0124 mm s-1 [1.20e-02, 1.29e-02]
Error = 0.041
Bubblingstart = 5 s
I (mm)
Time (s)
b
c
Error
S (mm s-0.5)
K (m s-1)

Fig. 3.