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Influence of the Infiltration Disk Radius on Determination of Unsaturated Hydraulic Conductivity of Non-structural Sandy Soil

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Abstract. Unsaturated hydraulic conductivity ($K(h)$) is important soil-physical characteristic, especially by determination of infiltration intensity, irrigation regime, drainage proposals, simulation of pollutants and other agricultural and hydrological processes. $K(h)$ is determined by soil structure and texture. Measurements are therefore considerably influenced by the heterogeneity of the soil composition. The disc infiltrometer has become a popular apparatus for measuring in situ $K(h)$ of the soil at some prescribed potential. A number of different methods have been proposed for calculating $K(h)$ using the flow rate ($Q(t)$), from the infiltration disc with different radius. Measurements of $Q(t)$ on a Sekule sandy soil were made using minidisc infiltrometer (METER Group Inc., Pullman W.A.) with radius of 22,5 mm and disc tension infiltrometer (Eijkelkamp Soil and Water B.V.) with radius of 100 mm. Measurements were made at potentials of -20 mm with both devices. $K(h)$ values were calculated using 2 different methods. The aim of our work was to test two $K(h)$ measuring devices with different size of infiltration ring in order to check how the differences affects $K(h)$ determination. This would give an idea which method would be more appropriate to use regarding the time-consume, effort and better characterization of the soil heterogeneity. Statistically significant difference ($p < 0.05$) was found when applying both methodologies. However, there is still a need to understand how both methodologies influence the variation of the parameters.

1. Introduction

Surface conditions of a field influence the infiltration of water into the soil profile. At the beginning and receding periods of a storm event, when the soil is not saturated, unsaturated hydraulic conductivity ($K(h)$) of the thin surface soil affects the vertical infiltration process [1]. Moreover, saturated hydraulic conductivity (K_s) of the surface layer will influence overland runoff produced relative to the downward infiltration in the subsoil during a storm event [1].

The tension disc infiltrometer allows measurements of infiltration with a constant and small negative pressure head, h_0 , at the soil surface, and has been extensively used in recent decades to measure the near-saturated hydraulic conductivity [2], [3], [4], [5], [6]. Various methodologies have been proposed to determine $K(h)$ from three-dimensional infiltration experimental data from circular source at soil surface using the tension disc infiltrometer. Among these, some are based on steady-state flow data and others on transient flow data [7], [8], [9], [10], [11], [12].

Most studies on the scale effects of hydraulic properties focused on the support (sample size) effects. [13] found that the K_s rates decreased rapidly with increasing ring diameter. [14] confirmed that a larger



sample size had a greater probability for the presence of large macropores, resulting in larger K_s values. [15] recognized variation of estimated values of K_s between different disk sizes. [16] investigated the influence of sample volume and shape on estimates of saturated flow in a cylinder infiltrometer and showed that the mean infiltration rate increased as the diameter increased, whereas the standard deviation and range also increased with increasing diameter. [17] observed that the variability of the measured hydraulic conductivity was greater for smaller inner rings and gradually decreased as the inner ring size increased. [18] investigated the combined effects of the inner and outer ring sizes of a double-ring infiltrometer on the measurements of field K_s , and they found that the inner ring size was a more important factor to be considered than the buffer index itself (or the outer ring size) in practice. [19] quantified three important variability components, i.e., measurement technique, spatial arrangement in sampling and differing landscape features, to map K_s distribution. Different measurement methods can yield different mean K_s values, and spatial patterns. K_s values measured with a tension infiltrometer were significantly greater than those measured with the soil core and Guelph permeameter methods. The total variability of K_s obviously decreased with decreasing sampling extent.

The objective of this study was to quantify the effect (i) of different infiltration ring size and (ii) different calculation methods on K determination.

2. Materials and methods

2.1. Study area

Study area (Site S) is located near Sekule (48°37'10'' N, 16°59'50'' E) in the Borská nížina lowland (southwest Slovakia). The region is in transition zone between temperate oceanic and continental climates. Mean annual temperature is 9°C. Mean annual precipitation is 550 mm, and it is mainly summer-dominant. Aeolian sandy soil from these sites is classified as an Arenosol [20] and sandy texture was measured for whole soil profile [21]. Physical parameters of sand dunes at site S, especially the grain size distribution were almost similar through the whole soil profile; since Arenosols are unconsolidated sand deposits, the soil profile is without any different soil horizons to the depth of 2 m, we assumed that the only effect on measured K values had different size of infiltration disc.

Physical and chemical properties of soil at site S are stated in table 1. C_{org} was determined by oxidation with $K_2Cr_2O_7-H_2SO_4$ and titration of non-reduced dichromate at the mean sample collected sites. Soil texture was determined by the pipette method [22], [23]. Soil pH was determined potentiometrically (1:2.5 – soil: distilled water). Percent calcium carbonate (% $CaCO_3$) was estimated by Calcimeter [24].

Table 1. Physical and chemical properties of soil at site S (top 10 cm of soil profile).

Site	Sand (%)	Silt (%)	Clay (%)	Depth of organic layer (cm)	$CaCO_3$ (%)	C_{org} (%)	pH (H_2O)	pH (KCl)
S	91.30	2.80	5.90	10	<0.05	9.90	5.14	3.91

2.2. Field measurement methods and theory of water flow from tension discs

All field experiments described in this part were conducted on 7th September 2017.

Volumetric soil water content θ ($m^3 m^{-3}$) of the superficial (0–5 cm) soil layer was measured with the moisture meter HH2 and soil moisture sensor SM200 (Delta-T Devices Ltd., Cambridge, UK). Harmonization of different methods for soil moisture measurements was presented by [25].

Field measurements of infiltration were performed using a minidisk infiltrometer and disc tension infiltrometer. $K(h)$ was measured by the minidisk infiltrometer (METER Group Inc., Pullman W.A.) with infiltration disc radius of 22,5 mm and disc tension infiltrometer (Eijkelkamp Soil and Water B.V.) with radius of 100 mm under a negative tension $h = -20$ mm (figure 1). Infiltration experiments were accomplished at 200 cm × 200 cm cell. Prior to the measurements, the litter layer was removed gently to prevent disturbance of the mineral soil.

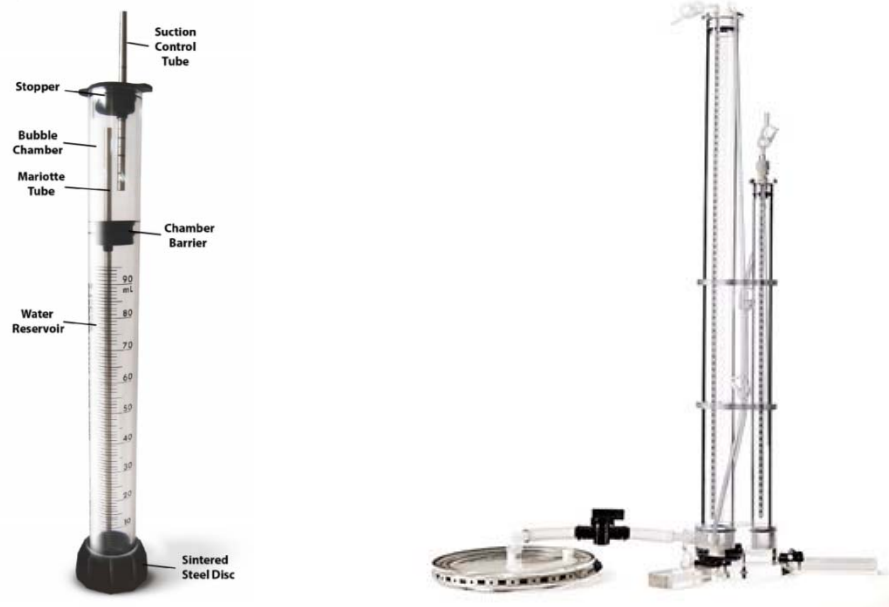


Figure 1. Minidisk infiltrometer (left) and disc tension infiltrometer (right).

(source <http://www.soilmeasurement.com>; <http://manuals.decagon.com>)

[26] equation which is at the basis of the steady-state flow theory approximates the steady infiltration rate, $q_{h\infty}$, from a disc as

$$q_{h\infty} = K_{(h)} + \frac{4\phi_h}{\pi} \frac{1}{r_d} \quad (1)$$

where $K(h)$ is the hydraulic conductivity at the imposed pressure head h [LT^{-1}], r_d is radius of disc [L], ϕ_h is the matrix flux potential [L^2T^{-1}] defined by

$$\phi_h = \int_{h_n}^{h_0} K(h)dh \quad (2)$$

Equation 1 was obtained under the assumption of a quasilinear soil [27], i.e., following [28] $K(h)$ relation:

$$K_{(h)} = K_s \exp(\alpha h) \quad (3)$$

where K_s is the hydraulic conductivity at natural saturation and α is a fitting parameter [L^{-1}]. From Equation 3 Equation 2 reduces to

$$\phi_h = \frac{K_{(h)}}{\alpha} \quad (4)$$

and Equation 1 can be transformed to

$$q_{h\infty} = K_{(h)} \left[1 + \frac{4}{\pi R \alpha} \right] \quad (5)$$

From measurement of steady-state infiltration fluxes, q_{∞} , generating from two discs of different radius, r_1 and r_2 , namely q_1 and q_2 , the solution of Equation 1 gives [2]:

$$K_{(h)} = \frac{q_1 r_1 - q_2 r_2}{r_1 - r_2} \quad (6)$$

and

$$\phi_h = \frac{\pi}{4} \frac{q_1 - q_2}{\frac{1}{r_1} - \frac{1}{r_2}} \quad (7)$$

Several researchers [3], [4], [10] oriented their work on finding analytical solutions for transient flow from disc infiltrometers. Expressions for transient infiltration have in common the two-term cumulative infiltration equation analogous to [29] equation:

$$I = C_1 \sqrt{t} + C_2 t \quad (8)$$

where the C_1 [$LT^{-0.5}$] and C_2 [LT^{-1}] are coefficients and t is time.

Coefficients C_1 and C_2 of [10] method, at any infiltration time, are obtained by fitting infiltration data vs. time in Equation 1 using least squares optimization technique. [10] proposed linear relationships between the coefficients of Equation 8 and the sorptivity S and the near-saturated hydraulic conductivity $K(h)$:

$$C_1 = S A_1 \quad (9)$$

$$C_2 = K_{(h)} A_2 \quad (10)$$

where A_1 and A_2 are dimensionless parameters.

Empirical expressions have been proposed to calculate A_1 and A_2 parameters [10]. Because the main purpose of this study is the estimation of $K(h)$, the necessary parameter A_2 can be calculated using the following equations:

$$A_2 = \frac{11.65(n^{0.1} - 1) \exp[2.92(n - 1.9)ah]}{(\alpha r)^{0.91}}, n > 1.9 \quad (11)$$

$$A_2 = \frac{11.65(n^{0.1} - 1) \exp[7.5(n - 1.9)ah]}{(\alpha r)^{0.91}}, n < 1.9 \quad (12)$$

where α and n are the [30] equation parameters, h is the infiltrometer negative pressure head, and r is the disc infiltrometer radius.

2.3 Statistical analysis

Differences between the parameters estimated in different sites were evaluated using single factor ANOVA with Tukey's Honestly Significant Difference (HSD) post-hoc test. The statistical significance in the analysis was defined at $p < 0.05$.

3. Results and discussions

Infiltration experiments were conducted through the use of a minidisk infiltrometer (MD) and disc tension infiltrometer (TD) on designated area with dimensions 200 cm x 200 cm. Before the infiltration measurements actual values of θ were measured. Data was processed and values of hydraulic parameters (stated in table 2) were computed according the following Equations.

Example of parameter C_2 (from Equation 10) computation for minidisc infiltrometer according experimental cumulative infiltration data versus the square root of time and fitted infiltration equation for pressure heads -2 cm for a Sandy soil.

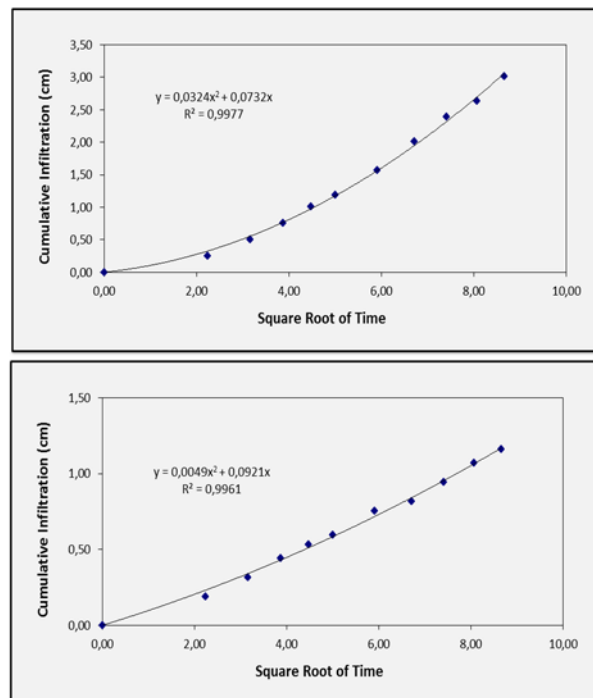


Figure 2. Presentation of experimental cumulative infiltration data versus the square root of time and fitted infiltration equation for pressure heads -2 cm for a Sandy soil – computation of C_2 parameter for minidisc infiltrometer.

Table 2. Hydraulic parameters of site S. Soil water content, θ ($\text{m}^3 \text{m}^{-3}$), in the upper 5 cm of soil profile, hydraulic conductivity, $K_{hg}(-2 \text{ cm})$ and $K_{hsc}(-2 \text{ cm})$ computed according to steady-state flow theory, and K_{hz} computed according to analytical solutions for transient flow from minidisc (MD) and tension disc (TD) infiltrometer. Arithmetic means and standard deviation with the same letter are not significantly different from each other (Tukey's HSD test, $P > 0.05$).

Measurement method	Attribute	Arithmetic mean	Minimum value	Maximum value	Standard deviation	N
	θ ($\text{m}^3 \text{m}^{-3}$)	0,0590000	0,05100	0,073000	0,008099383	10
MD	$K_{hg}(-2 \text{ cm})$ (cm s^{-1})	0,01288290 ^a	0,00744	0,035959	0,008497933 ^a	10
	$K_{hz}(-2 \text{ cm})$ (cm s^{-1})	0,00568570 ^a	0,00285	0,018737	0,004821855 ^a	10
TD	$K_{hg}(-2 \text{ cm})$ (cm s^{-1})	0,03330469 ^b	0,00315	0,135498	0,04535525 ^b	10
	$K_{hz}(-2 \text{ cm})$ (cm s^{-1})	0,02105081 ^b	0,00200	0,085644	0,02866758 ^b	10
MD+TD	$K_{hsc1}(-2 \text{ cm})$ (cm s^{-1})	0,04050990 ^b	0,00160	0,172676	0,05861612 ^b	10
	$K_{hsc2}(-2 \text{ cm})$ (cm s^{-1})	0,02608650 ^b	0,00171	0,109545	0,03705212 ^b	10
	ϕh (-2 cm) ($\text{cm}^2 \text{s}^{-1}$)	0,04639160	-0,292741	0,075959	0,11320250	10

Values of near-saturated hydraulic conductivity were computed according to Equation 5 (K_{hg}), Equation 8 and 10 (K_{hz}) and Equation 6 (K_{hsc}). Values of matrix flux potential (ϕh) were computed according to Equation 7. Parameter A_2 was estimated for sandy soil, $h=-2 \text{ cm}$ and $r = 2.25 \text{ cm}$ and 10 cm using Equation 11. Parameter α from Equation 5 was determined from [31], for unstructured fine textured soil as $\alpha = 4 \text{ m}^{-1}$.

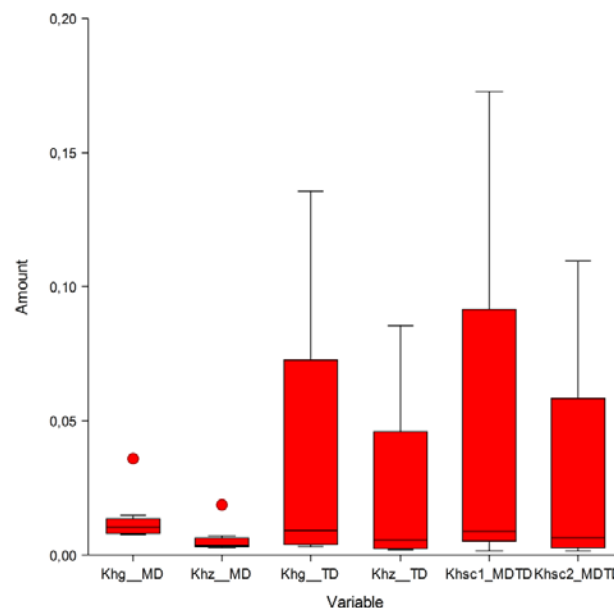


Figure 3. Box plot [32] describing statistical parameters of estimated $K(h)$ from minidisc (MD) and tension disc (TD) data and from combination of steady-state flow data from both discs (MDTD). (source:ncss.com/software/ncss)

Analysis of the obtained dataset revealed that absolute minimal and maximal values of $K(h)$ were computed for multiple disc method (K_{hsc1} , K_{hsc2}), which combine the steady-state flow data from both discs. The same fact is obviously valid also for arithmetic mean values.

According to table 2 and figure 3 estimated values of near-saturated hydraulic conductivity can be divided into two groups. Significant differences are according to Tukey's HSD test, between both datasets (K_{hg} and also K_{hz}) obtained from minidisc and from tension disc infiltrometer. Our findings are in agreement with [16], since arithmetic mean values of $K(h)$ increased with radius of infiltrometer disc.

At the same time also the values of standard deviation increased with disc radius for both computational methods (steady-state flow and transient flow theory). TD datasets and combined MDTD datasets are not significantly different from each other, since MDTD dataset included great standard deviation from TD data.

4. Conclusions

The infiltration experiments were conducted on homogenous sandy soil using tension infiltrometers with different disc radius. The values of near-saturated hydraulic conductivity were computed according to steady-state flow theory and according to analytical solutions for transient flow. According to analysis of obtained results we can state, that in the conditions of our experiment:

- (i) absolute minimal and maximal values of $K(h)$ were obtained through multiple disc method, which combine the steady-state flow data from different discs; same is valid also for corresponding arithmetic mean values;
- (ii) significant differences are between minidisc (MD) and tension disc (TD) infiltrometer $K(h)$ datasets; arithmetic mean values of $K(h)$ increased with radius of infiltrometer disc and at the same time also the values of standard deviation increased with disc radius for both computational methods (steady-state flow and transient flow theory);
- (iii) TD datasets and combined MDTD datasets are not significantly different from each other.

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