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The role of the initial soil water content in the determination of unsaturated soil hydraulic conductivity using a tension infiltrometer

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ABSTRACT

The unsaturated hydraulic conductivity *K(h)* is a key soil parameter governing the water and solute transportation processes. The course of this function depends on the geometry of the pores which is determined by the soil's physical and chemical properties. Many studies focus on the comparison of soil hydraulic conductivity under different conditions. Despite the recent progress in this research field, no reference method for measuring the *K(h) in situ* exists. This study focuses on the effect of the initial water content of the soil as a factor influencing the measured *K(h)*. The study was performed *in situ* over short time period and with several replications close to each other in order to reduce the effect of other factors which could cause variations. Two tension infiltrometers were used and compared: A Hood infiltrometer IL-2700 and a Minidisk infiltrometer. Three different levels of initial water content (dry, medium wet and wet) were applied for each of the two infiltrometers, and three pressure heads (–0.5; –1 and –3 cm) for each measurement. According to the results, the Minidisk infiltrometer showed significant sensitivity to the initial water content, while measurements performed using the Hood infiltrometer were more stable.

Keywords: soil hydraulic properties; unsaturated flow; infiltration; soil moisture; pressure head

Most of the natural processes involving the soil-water-atmosphere-plant interaction occur under unsaturated conditions of the soil. Hydraulic conductivity is a property describing the ease with which water can move through the soil profile. This movement is influenced by many factors; e.g. porosity of the soil and saturation of the soil profile. The rate in which the water moves through the porous system of the soil profile can be characterised by the hydraulic conductivity as a function of volumetric water content $K(\theta)$, or pressure head, *K(h)*.

There are different ways to determine the *K(h)* relationship, preferably it should be measured *in situ*. No reference measurement method concerned with tension infiltrometer exists, however different types have been designed and used (i.e. Perroux and White 1988, Ankeny et al. 1991, Vandervaere et al. 1997, Špongrová et al. 2009). The advantages of using tension infiltrometers, such as a minimal disturbance of the soil surface, simplicity and replicability of the measurements were evaluated i.e. by Ventrella et al. (2005) or Walker et al. (2006). Time and labour consuming work *in situ* with infiltrometers can be simplified by automatic data logging (i.e. Špongrová et al. 2009, Rodný et al. 2013).

The conductivity of unsaturated soils depends generally on the structure and texture of the given soil profile. When the soil profile is unsaturated, some of the pores are filled with air and the hydraulic conductivity decreases. A summary of the issues affecting the hydraulic conductivity were evaluated by Johnson (1963). There are a number

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of chemical-physical conditions of the soil profile which vary over time such as the specific surface of the porous system, distribution of soil water content, chemical and physical nature of the water, biological activity, temperature, percentage of entrapped air in the soil and atmospheric pressure. In addition, the measured value of hydraulic conductivity is affected by the length of application time and the type of equipment or methods used. Temporal changes are caused by crop seasonality or seasonal variability, irrigation practices, erosion processes and the effects of traffic-induced compaction of the soil.

Another factor influencing the value of the measured unsaturated soil hydraulic conductivity is the initial water content of soil. Benson and Trast (1995) observed during their experiments a decreasing hydraulic conductivity with an increasing initial saturation degree. On the other hand, Logsdon (1993) did not discover any relationship between the initial water content and the fluctuation of *K(h)* during a growing season.

As well as other things, the devices used for infiltration tests can possess different sensitivity to the particular factors affecting the soil unsaturated hydraulic conductivity. The aim of this study was to investigate the influence of the initial water content of soil (θ_i) on the measured value of *K(h)* as a factor determining the measured result. Thus all other sources of variation were reduced as much as possible and two different types of tension infiltrometers were used and compared.

MATERIAL AND METHODS

The following devices were used: a Hood infiltrometer IL-2700 (HI; Umwelt Geräte Technik, GmbH., www.ugt-online.de) and a Minidisk infiltrometer (MI; Decagon Devices, Inc., www.decagon.com), described by Ankeny et al. (1991). The unsaturated hydraulic conductivity was measured using both infiltrometers at three different levels of θ_i (dry, medium wet and wet). The infiltration tests were replicated five times and three pressure heads were applied for each infiltrometer.

By setting the pressure head on the MI, the size of soil pores which take part in conducting the water can be limited. The sequential decrease of (negative) pressure heads went ahead to drain smaller and smaller pores. The infiltration rate then decreases when more water-conducting pores were emptied. However the procedure recommended by the producer was to start measurements from the lowest to the highest pressure head, that is –3.0; –1.0 and –0.5 cm in this study.

A good and consistent hydraulic contact between the measuring device membrane and the soil is essential for the MI. Thus, vegetation cover was trimmed down to ground level and a thin layer of fine silica sand (particle size from 0.063–0.40 mm) was used as a contact material.

The HI was introduced by Schwärzel and Punzel (2007). It did not use any membrane and no contact material was needed. There is a direct contact between water held in the hood and the soil surface. This overcomes a problem associated with the influence of the contact material. The only adjustment required to the terrain is to cut the vegetation to about 5 mm. Moreover, Buczko et al. (2006) recommended sealing the hemispherical hood and soil by the application of a thin layer of sand around the hood (Figure 1).

The HI consists of three major components: the hood (16 cm in diameter), Mariotte water supply (water reservoir) and U-Tube manometer. As Buczko et al. (2006) explained, it is a modified version of the closed-top infiltrometer designed by Dixon (1975). Water is applied to the closed-top infiltrometer which applies the negative pressure to the soil surface. It is based on the principle, that natural positive air pressure can be simulated by an equivalent negative air pressure above the ponded surface water (Dixon 1975). With the HI the application of pressure heads has to be carried out from the highest to the lowest, as will become apparent from the design of this infiltrometer. That is –0.5; –1.0 and –3.0 cm in this study. The HI automatically records the infiltration water.

Soil conditions that are as homogeneous as possible were required to minimize the effect of soil heterogeneity and thus enabling the evaluation of other factors. The experimental area was located in the campus of the Czech University of Life Sciences Prague. The soil is Haplic Chernozem (FAO/ISRIC 2006) with a loamy texture and permanent grass cover on the soil surface as described i.e. in Doležal et al. (2012). The infiltration tests were carried out *in situ* under natural conditions, during summer within several weeks in order to minimize seasonal effects. Three levels of θ_i were maintained for the respective plots of the experimental field.

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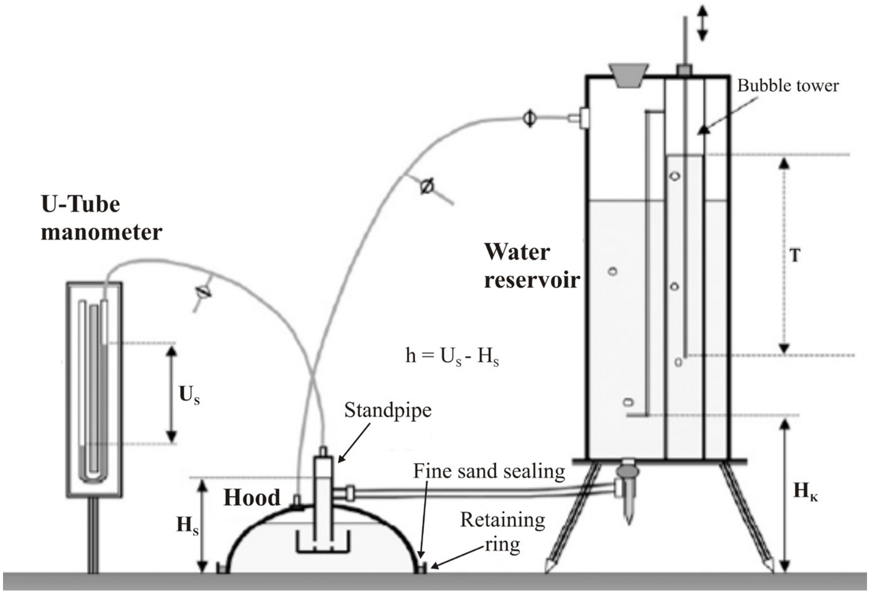

Figure 1. Diagram of the Hood Infiltrometer (adapted with using a picture from UGT GmbH.; http://www.ugt-online.de/). h – effective pressure head (cm), determined as a difference between the height of the water level in the standpipe (H_s) and the negative pressure at the manometer (U_s); required pressure head is adjusted as difference between H_k (distance between soil surface and air outlet) and T (immersion depth of the air intake pipe)

They were called dry, medium wet and wet for simplicity. Before starting the infiltration tests, the θ_i was measured in an area closely surrounding the infiltrometers using both gravimetric and an indirect method. The Theta Probe (Delta-T Devices, Ltd) soil moisture sensor was used during the whole experiment for the quick examination of the soil water content (0–6 cm). Furthermore, five disturbed soil samples in five replications for each θ_i were taken from depths of 10 cm down to 50 cm of the soil profile in order to investigate soil moisture homogeneity. These samples were taken about 1 m from the infiltration spots in order to avoid any influence. The average values of θ_i for dry, medium wet and wet measuring spots were 25.1, 32.5 and 38.3% vol. for HI and 23.9, 31.7 and 35.4% vol. for MI, respectively. These values were obtained by the Theta Probe sensor. All the obtained values are shown in Figure 2 together with their standard deviations (SD).

After the measurements, the undisturbed soil samples were taken so that basic soil physical characteristics such as particle density, dry bulk density and porosity could be determined. Table 1 shows

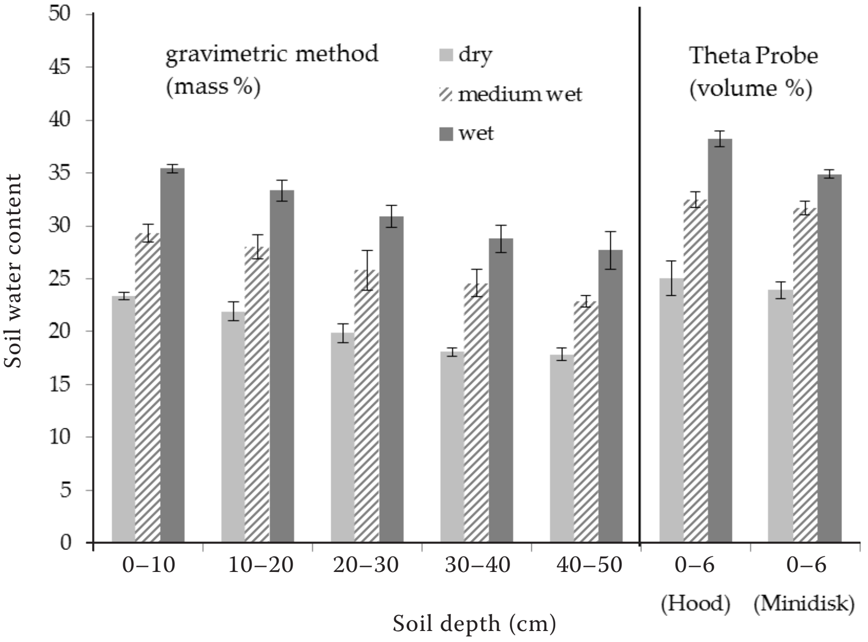

Figure 2. Average θ_i for the three levels: dry, medium wet and wet, and their standard deviations. Soil profile down to 50 cm was investigated by gravimetric method; quick measurements at soil surface were done by the Theta Probe soil moisture sensor

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Table 1. Basic physical characteristics of the study area with respect to the levels of θ_i

	Dry bulk density (g/cm^3)			Total porosity (%)		
	dry	medium wet	wet	dry	medium wet	wet
Average	1.60	1.59	1.59	38.09	38.68	38.29
Standard deviation	0.02	0.02	0.03	0.93	1.10	1.27
Minimum	1.55	1.57	1.53	37.35	37.21	36.96
Maximum	1.62	1.62	1.62	39.92	40.15	40.47

that the study area is rather homogeneous with respect to the basic properties of porous system.

All infiltration data were processed according to the methodology recommended by the producers. Data taken by the MI was evaluated according to Zhang (1997). Data taken by the HI was evaluated using steady-state data analysis according to Wooding (1968) and Reynolds and Elrick (1991). The methodologies are described in more detail in Báťková et al. (2013).

RESULTS AND DISCUSSION

The measurements using both types of infiltrometers were started with as similar θ_i as possible to enable their comparison. However, measurements under natural conditions were confronted with varying weather conditions such as temperature, precipitations, sunshine, wind etc. As a consequence it was difficult to obtain accurate values of θ_i for both infiltrometers.

The infiltration tests carried out by both infiltrometers for all θ_i conditions were evaluated and *K(h)* values were calculated. As the most evident observation, the hydraulic conductivity *K(h)* taken with the MI differed from that measured by the HI at the same pressure head *h* as much as two orders of magnitude (average values in Table 2 and Figure 3). The latter value is significantly higher than the former one. This finding is in agreement with the studies by Schwärzel and Punzel (2007) and by Špongrová (2010).

The difference can partly be explained by the hysteresis of the *K(h)* curve, as the pressure heads were applied in a stepwise, increasing sequence by the MI but in a decreasing sequence by the HI. However, a more relevant explanation is that the characteristics of water movement, namely the size of the soil pores involved, were different.

Table 2. Average unsaturated hydraulic conductivities measured by both infiltrometers at three applied pressure heads and with respect to the three levels of θ_i, and their variation coefficients

h (cm)	Minidisk infiltrometer			Hood infiltrometer		
	–0.5	–1	–3	–0.5	–1	–3
	average *K(h)* (m/s)					
Dry	5.5E-06	3.8E-06	8.7E-07	1.6E-04	1.4E-04	7.7E-05
Medium wet	3.6E-06	1.8E-06	5.0E-07	1.7E-04	1.4E-04	7.4E-05
Wet	6.4E-06	3.3E-06	2.3E-07	1.4E-04	1.0E-04	7.2E-05
	CV (%)					
Dry	38.7	35.6	28.3	9.7	16.1	5.6
Medium wet	66.1	64.8	21.1	4.8	12.1	29.8
Wet	31.5	45.3	35.0	16.0	29.9	21.3

h – pressure head; *K(h)* – unsaturated hydraulic conductivity as a function of the pressure head *h; CV* – coefficient of variation

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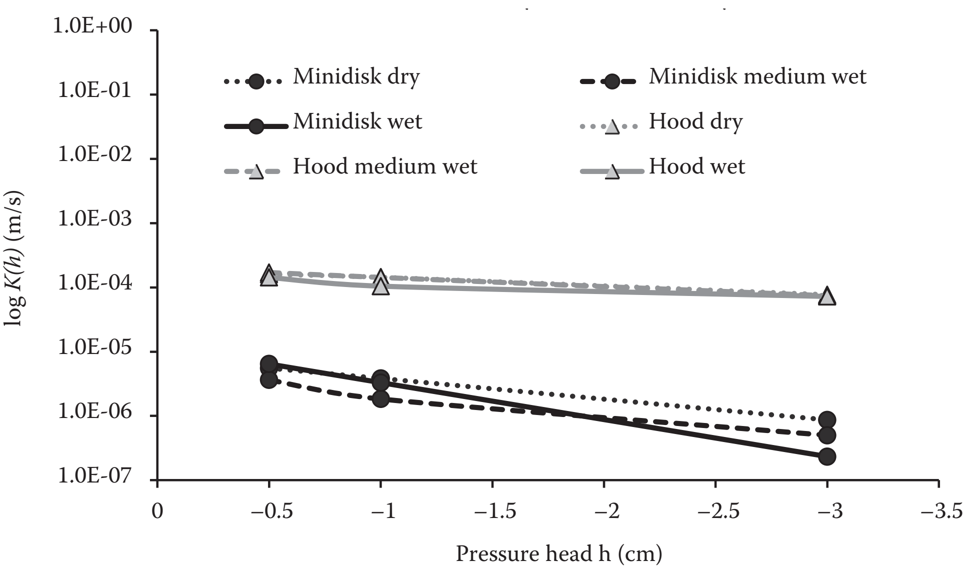

Figure 3. Unsaturated hydraulic conductivity *K(h)* curves measured by both infiltrometers. Arrows indicate direction of the measurements (drying curve for the HI (Hood infiltrometer), wetting curve for the MI (Minidisk infiltrometer))

As a matter of fact, there is a water layer in the HI which was maintained on the soil surface at negative pressure. Virtually all the pores in the near-surface soil layer, especially the large pores, are saturated. Air has no access to the soil surface, unless from below through the wetted soil, which is a long and difficult path. Therefore, many large pores near the soil surface remain saturated because they have no opportunity to drain. The infiltration rate measured by the HI is a product of the saturated (or near-saturated) hydraulic conductivity and the hydraulic gradient in the near-surface layer.

On the contrary, the soil in contact with the porous plate of the MI is not forced to remain saturated because the atmospheric air has more or less free access to it from the side. The large pores in the near surface layer wait for the first occasion to drain, which is easy for them. The infiltration rate measured is a product of the much-less-than-saturated hydraulic conductivity of the soil and the corresponding hydraulic gradient; this product is usually much lower than the analogous product for the HI.

Coefficients of the variation (*CV*; Table 2) were calculated in order to evaluate the variation of particular *K(h)* values measured by both infiltrometers for the three levels of θ_i. The results show that *K(h)* values obtained by the MI were highly variable compared to those obtained by the HI, as is apparent from the curves in Figure 3. This variability can be explained by the natural variability of the soil. The MI is a very small device with a small diameter tension disk. For this reason this device is more susceptible to measure the natural variability of the soil, while the HI with approximately 12.5 times bigger infiltration surface is less susceptible.

When comparing the *CV* for the three levels of θ_i, there is no trend, but the variation of *K(h)* for medium wet spots for the MI is significantly higher than others. When comparing the *CV* for applied pressure heads, the values fluctuated less for pressure head –0.5 cm for the HI and for pressure head –3.0 cm for the MI. Both these pressure heads were the first used by these infiltrometers. This shows that the infiltrometers are inclined to produce repeatable results under the same initial conditions, while the following flow is influenced by the flow under the first tension applied. This is valid more for the HI as confirmed by the values of *CV*.

In order to assess the influence of θ_i on the measured value of *K(h)* as a factor of measurement accuracy, the θ_i was plotted against the *K(h)* measured for the first applied pressure head of each infiltrometer (Figure 4).

The results from both infiltrometers showed a trend of decreasing hydraulic conductivity when θ_i increased. This trend was conclusive for the MI where the coefficient of determination (r^2) reached 0.98, while for the HI there is a weak dependence $r^2 = 0.31$.

In conclusion, this study focused on measuring the unsaturated hydraulic conductivity of soil and the performance of two different tension infil-

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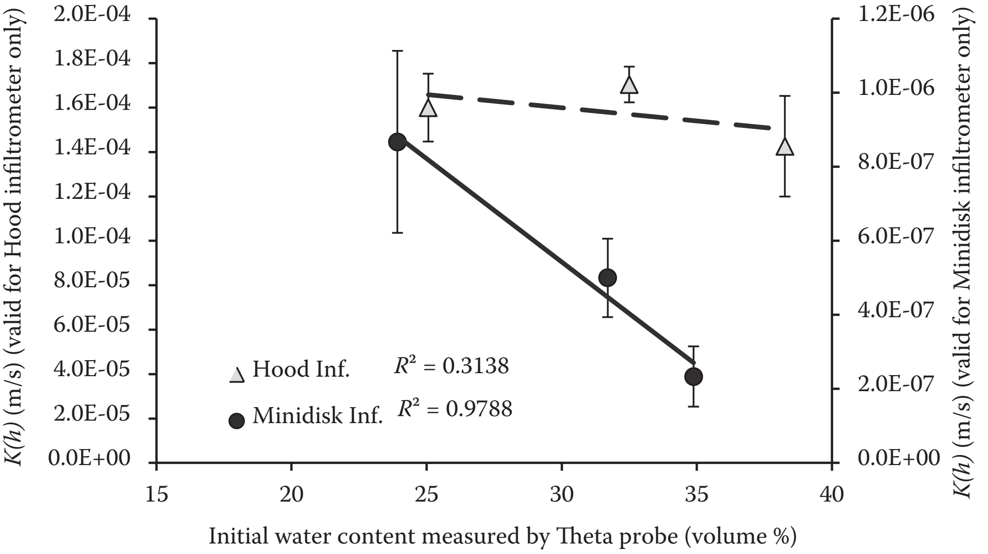

Figure 4. Relationship of the first applied pressure head (−3 cm for the MI (Minidisk infiltrometer) and −0.5 cm for the HI (Hood infiltrometer); average values with their standard deviations) and θ_i taken by the Theta probe sensor. R^2 – coefficient of determination

trometers, HI and MI. Particular attention was given to the influence of different θ_i conditions on the measured data; three different levels of θ_i were used.

Results of the *K(h)* with three applied pressure heads (−0.5, −1.0 and −3.0 cm) were compared. Both infiltrometers were operated according to their user's manual, thus the infiltration tests for both infiltrometers were carried out with the opposite order of applied pressure heads: wetting curve for the MI and drying curve for the HI.

The following observations were made: firstly, the *K(h)* values obtained by the MI were around two orders of magnitude lower than those obtained by the HI (m/s), which can be explained by the different character of water infiltrating; secondly, the values of *K(h)* obtained by the MI were significantly more biased than those obtained by the HI; thirdly, from the relationship of the first applied pressure head (−3 cm for MI and −0.5 cm for HI) and θ_i it can be concluded, that values of *K(h)* based on the infiltration test carried out by the MI show a high susceptibility to θ_i. This is in agreement with the whole design of this infiltrometer as it is a small, handy, portable device with a small water reservoir and small area of infiltration. However, the influence of θ_i should always be taken into consideration. Values of *K(h)* based on the infiltration test carried out by the HI are much less influenced by different θ_i of the soil. The θ_i has no significant influence on the other applied tensions for both infiltrometers.

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