Czech University of Life Sciences Prague
Faculty of Agrobiology, Food and Natural Resources
Department of Water Resources

Factors affecting determination of unsaturated soil hydraulic conductivity in situ using tension infiltrometer

Diploma Thesis

Supervisor: prof. Ing. Svatopluk Matula, CSc.
Author: Jana Lufinková

2012

Statement

I declare that I wrote my diploma thesis “Factors affecting determination of unsaturated soil hydraulic conductivity in situ using tension infiltrometer” by myself and I have used only the sources mentioned at the end of the thesis.

In Prague on 23rd April 2012

Jana Lufinková

Acknowledgment

Many thanks to my supervisors prof. Svatopluk Matula from Czech University of Life Sciences and prof. Willibald Loiskandl from University of Natural Resources and Life Sciences for their help and support.

Thanks to Markéta Miháliková, for her all round help and supervision, and for enabling me to measure in her laboratory.

Many thanks also to my home school Czech University of Life Sciences for lending me the measuring devices.

I wish to express a special thank you to my family – namely my mother, father, sister and all grandparents for their financial and moral support during my studies.

Summary

This Diploma Thesis focuses on the unsaturated hydraulic conductivity of soil and the performance of two different tension infiltrometer devices used in its measurement. Particular attention is given to different initial water content conditions of the soil profile and the influence of this condition to the measured data.

The two devices used in the measurement of hydraulic conductivity were Hood Infiltrometer IL-2700 (Umwelt Geräte Technik, GmbH.) and Mini Disk Tension Infiltrometer (Decagon Devices, Inc.). Results of the unsaturated hydraulic conductivity of these two devices were compared.

The Hood Infiltrometer was used because it is a relatively new device and not many articles have been published regarding the use of this infiltrometer. For comparison to the Hood Infiltrometer, the Mini Disk Tension Infiltrometer was used as it is a very simple and easy-to-use device. The comparison of these two devices is made with respect to the initial water content of the soil profile. The measurements were done under three different tensions (-0.5; -1 and -3 cm).

Three levels of initial water content – dry, medium wet and wet - and their influence on measured unsaturated hydraulic conductivity were investigated. The initial water content was measured at an area closely surrounding the infiltrometers using both gravimetric and an indirect method. The average values of initial water content by volume for dry, medium wet and wet measuring spot were 25.1, 32.5 and 38.3 % for Hood Infilrometer and 23.9, 31.7 and 35.4 % for Mini Disk Tension Infiltrometer.

The values for the hydraulic conductivity from Mini Disk Tension Infiltrometer and Hood Infiltrometer vary. The values of unsaturated hydraulic conductivity obtained by Hood Infiltrometer are significantly higher than values measured by Mini Disk Tension Infiltrometer.

The results from both devices show that there is an indirect dependence of the unsaturated hydraulic conductivity on the initial water content. It means that with increasing water content the unsaturated hydraulic conductivity measured with Hood Infiltrometer and Mini Disk Tension Infiltrometer decreases. This trend was conclusive especially for Mini Disk Tension Infiltrometer. For the Hood Infiltrometer a weaker dependence of unsaturated hydraulic conductivity on the initial water content is visible.

The tendency of decreasing hydraulic conductivity with increasing pressure head was observed for both devices. The results from both infiltrometers show that the values of unsaturated hydraulic conductivity fluctuate less for tension -0.5 applied for Hood Infiltrometer and for tension -3 performed for Mini Disk Tension Infiltrometer. Both tension -0.5 for Hood Infiltrometer and -3 for Mini Disk Tension Infiltrometer are the first performed tensions for these devices. The reason probably is that the following flow is influenced by the flow under the first tension applied.

Keywords

Unsaturated hydraulic conductivity, Infiltration, Mini Disk Tension Infiltrometer, Hood Infiltrometer

Content and list of figures

List of appendices

1 Introduction

Unsaturated hydraulic conductivity is a very important hydrophysical characteristic of a given soil profile. The unsaturated hydraulic conductivity can be described as the velocity with which the water flows through a porous media such as a soil profile. This characteristic should be measured preferably in situ as it gives more representative values than measuring in the laboratory. It is used for example to prevent or minimize the potential contamination of groundwater by soluble pollutants.

There are a variety of ways to measure the unsaturated hydraulic conductivity and this thesis deals with two devices – Hood Infiltrometer and Mini Disk Tension Infiltrometer. Both are tension infiltrometers. Despite the fact that it is a time consuming method, tension infiltrometry became very popular due to its accuracy and provision of more representative values of hydraulic conductivities.

Still there does not exist any reference method for measuring the unsaturated hydraulic conductivity. Thus two devices for estimation the hydraulic conductivity were used and compared. The conditions which in general affect the measurements of hydraulic conductivity are: tillage and crop effect, time variability, particle size distribution, contact material, pressure head and initial water content. This thesis focuses on different initial water contents of the soil profile. Three different levels of water content are used and measurements from two devices with three tension settings are then compared. The difference in time is neglected because all the measurements were made in a very small interval. The other conditions such as tillage and crop effect, contact material and particle size distribution are described only theoretically.

2 Objectives of the Thesis

There are two main objectives of the Thesis:

i) to summarize the most important factors affecting the determination of unsaturated hydraulic conductivity and final values of unsaturated hydraulic conductivity and to identify factor(s) which require more detailed investigation

ii) to evaluate the effects of the identified factor(s) based on this study.

Hypothesis

The objectives of the thesis were formulated on the basis of following hypotheses:

i) The measurement of unsaturated hydraulic conductivity is affected by different conditions during the measurement including common changes in soil, weather, season and vegetation. These factors can be identified and evaluated.

ii) The initial water content of soil has significant influence on the measured values of unsaturated hydraulic conductivity.

3 Literature review

3.1 Hydraulic conductivity and Infiltrometers

Hydraulic conductivity is a property describing the ease with which the water can move through the soil profile. The movement is influenced by many factors; e.g. porosity of the soil and saturation of the soil profile. The soil profile can be saturated or unsaturated.

Most of the natural processes involving the soil-water interaction occur under unsaturated conditions of the soil. Unsaturated flow has become a very important topic and much research has been made in recent times.

The difference between the saturated and unsaturated flow is that if the soil is saturated, all pores are filled with water and the hydraulic conductivity reaches its maximum value. When the soil profile is unsaturated, some of the pores are filled with air and the hydraulic conductivity usually decreases. The conductivity of unsaturated soils depends generally on the structure and texture of the soil profile, as Hillel (1998) and Kutílek (1994) reported.

The dependence of the unsaturated hydraulic conductivity of sandy and clayey soil versus suction is visible on Figure (1).

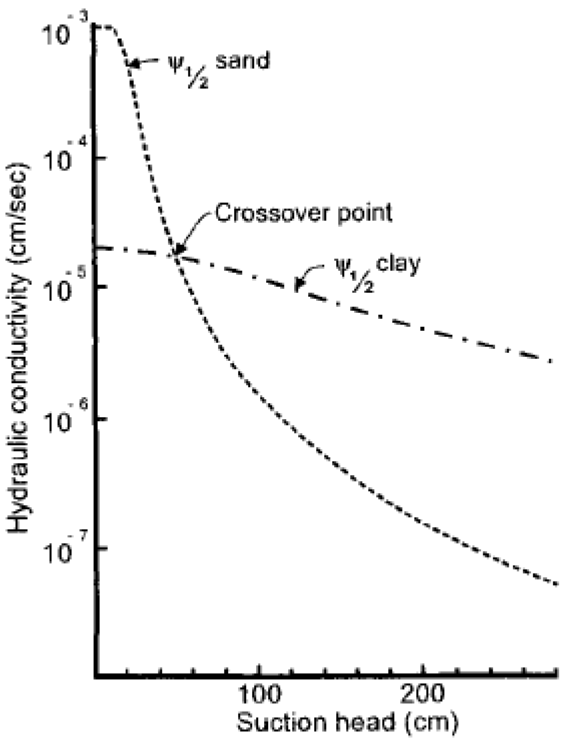


Figure 1 - Dependence of unsaturated hydraulic conductivity on suction in different soils, on log-log scale, Hillel (1998)

Both saturated and unsaturated hydraulic conductivities are important hydrophysical characteristics of the soil. The hydraulic conductivity is not constant for the given soil but it varies with time and this characteristic is unique for each soil type. Špongrová et al. (2009) mentioned that the rate in which the water moves through the soil profile and its pores can be characterized by hydraulic conductivity function *K* in relation to volumetric water content of the pressure head of soil water. These two properties (the water content and pressure head) have to be measured preferably in situ. Ankeny et al. (1991) showed that the values of water infiltration and water movement are very important to prevent or minimize potential contamination of groundwater by chemicals. Angulo-Jaramillo et al. (2000) also stress the importance of knowing hydrodynamic functions of soils for the management and prognosis of hydrodynamical flows in both natural and anthropogenic soils. Ankeny et al. (1991) continues, by stating that a simple (and if possible) fast measurement and determination of hydraulic conductivity is necessary.

Some possibilities on how to measure and determine hydraulic conductivity of the unsaturated zone exists. This thesis is focused on tension infiltrometers. Tension infiltrometry uses the near-saturated hydraulic conductivity, which is without the influence of preferential flow. The preferential flow affects the saturated flow. According to Špongrová et al. (2009) working in situ and especially with infiltrometers to determine the unsaturated hydraulic conductivity functions *K (h)* is time consuming and thus also costly. According to Kechavarzi et al. (2009) this was partially solved by automation of the measurement which was developed by many authors.

The time consumption and costs are also confirmed by Reynolds et al. (2000), who described hydraulic conductivity as being “difficult to measure”. Walker et al. (2006) wrote in their article that tension infiltrometers have started to become used for determination of saturated or unsaturated hydraulic conductivity, macropore flow and also sorptivity. They mentioned that the big advantage of this device is its nondestructive use and also its simplicity. Other advantages such as relatively low price of the device, minimal disturbance of the soil surface and also the replicability of the measurements are mentioned by Ventrella et al. (2005).

Elrick and Reynolds (1992) published an article which shows that infiltration in soil is three-dimensional and can be both transient and steady state. First there is the phase of transient flow which then gives way to steady state flow. According to Hillel (1998), steady-state flow is defined as a system where flux, gradient and water content are constant in time, whereas for transient flow these parameters vary. Elrick and Reynolds (1992) described that after the steady state phase is reached, the wetting zone increases in size. The determination of hydraulic conductivity can be done by positive or negative pressure heads. The tension infiltrometer which uses negative pressure head, can determine the early-time transient and steady-state flow rates just by the corresponding scale of the unsaturated hydraulic conductivity. As an example, the tension flux potential is given. According to these authors, the transient and steady infiltration of water into the vadose zone is dependent on pores and their position and network and also on soil particles. Lin and Mc Innes (1995) wrote that hydraulic conductivity can be determined from infiltration data from theoretical analyses of uniform water flow under the tension infiltrometer. Ankeny et al. (1991) observed that for measuring the unsaturated hydraulic conductivity, only steady-state infiltration measurements are needed and no initial water content knowledge is required. It is very important to be careful during installation of the infiltrometer because the soil structure should not be destroyed by placing or driving the contact ring to the soil surface. And – of course – the repetition of measurements should be done on identical surfaces.

Selecting the proper method to estimate the hydraulic properties of the soil is necessary to obtain representative values of hydraulic conductivity as presented by Bagarello et al. (2000) in their article.

Tension infiltrometry has become a popular tool for determination of unsaturated hydraulic conductivity and other near saturated hydraulic properties and also for examining the effects of macropores on infiltration. Traditionally, hydraulic conductivity is calculated from steady-state data using quasi-analytical solution of Wooding, which calculate K with steady infiltration from a circular source (Ventrella et al. 2005).

According to Lal and Shukla (2004) flow in the unsaturated zone is tortuous and for the flow descriptions usually the Darcy-Buckingham and Richards equations are used. But Darcy-Buckingham equation alone is usable only for a situation where the water content remains constant. This is seldom observed in natural conditions. There then has to be the continuity equation in combination with Darcy-Buckingham.

There are some equations which were mentioned by Elrick and Reynolds (1992). For the tension infiltrometers they wrote: “Water is applied to the infiltration surface under a steady water potential, ψ_t *[L]*, where $\psi_t \leq 0$. Consequently, only an unsaturated wetting zone develops, within which the water potential varies from $\psi = \psi_t \leq 0$ at the infiltration surface to $\psi = \psi_i$ at the wetting front", where ψ is water potential, ψ_i is initial or background pore water potential in surrounding unsaturated soil and ψ_t is characterized as steady water potential.

A simple schema of tension infiltrometer is shown in Figure (2). Wetting zone is drawn like a three-dimensional flow of water. The Mariotte bottle is designed so that a range of negative pressure heads which will then be applied via the disk or membrane can be set For the tension infiltrometer, water infiltrates under a steady state negative potential ψ_t, where $\psi_t \leq 0$. Only unsaturated wetting zone occurs were water potential varies from values $\psi \leq \psi_t \leq 0$ (at the infiltration surface) and $\psi = \psi_i$ (at the wetting front), where ψ_i is background water potential of the soil.

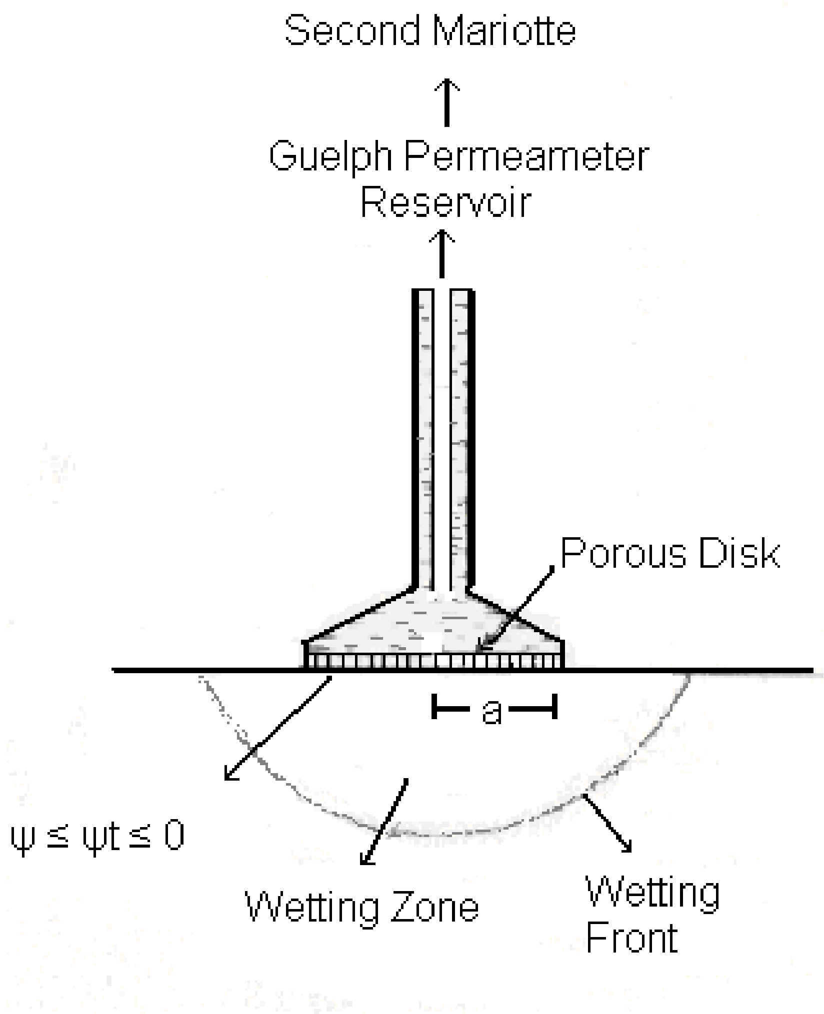


Figure 2 - Tension infiltrometer attachment, illustration based on Elrick and Reynolds (1992)

The schema of tension infiltrometer was drawn also by Gardner and Gardner (1939) and is shown on Figure (3).

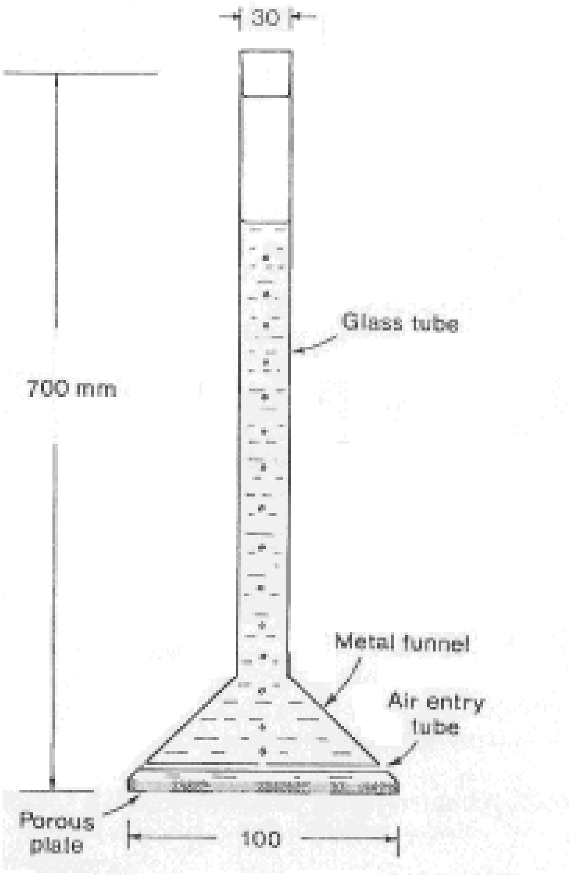


Figure 3 - The tension infiltrometer of Gardner published in 1939 with dimensions in milimetres (White et al. 1992)

According to Reynolds and Elrick (1991) the tension infiltrometer is basically built from a double Mariotte bottle which can be connected to a porous membrane or disk which has direct contact with soil surface. The first Mariotte bottle works like a water supply for the flow of water to the soil, the second is used to change the tensions caused on the membrane or disk. Many tension infiltrometers have been developed but they are all based on this principle. However, there is one special exception and it is the Hood Infiltrometer. This device does not consist of a membrane or disk. It has direct contact with soil surface what will be explained in the Chapter 3.3.2 dedicated to Hood Infiltrometers.

The cumulative infiltration from the tension infiltrometer can be expressed in length units (this can be also calculated as volume of water read from the Mariotte bottle and then divided by the cross section area *A* of the column) as reported by Lal and Shukla (2007).

Ankeny et al (1988) presented evidence that all tension infiltrometers are based on Clothier and White`s (1981) device which uses a sintered glass plate of 8.6 cm diameter as a contact disk and the tension is controlled simply by a hypodermic needle. The schema of this apparatus is illustrated in Figure (4).

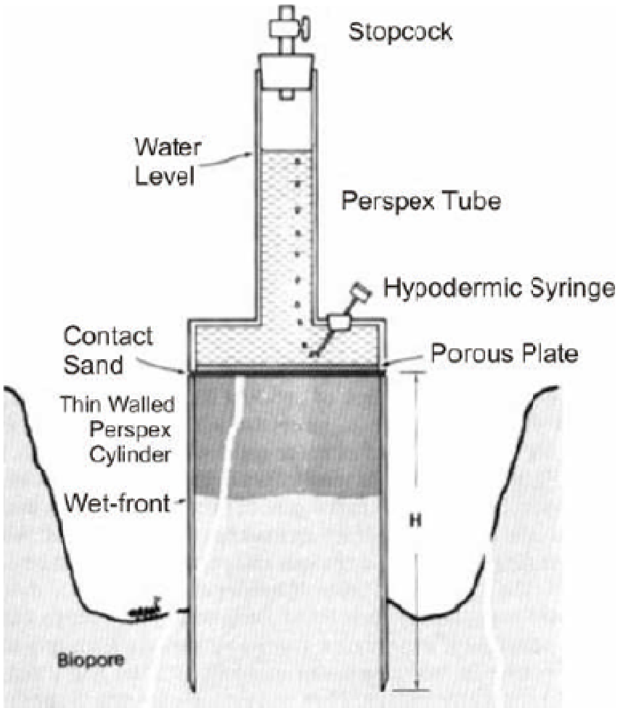


Figure 4 - The sorptivity tube tension infiltrometer of Clothier and White (White et al. 1992)

3.2 Forces and flow under tension disk infiltrometers

Infiltration or hydraulic conductivity can be described as the downward entry of water into the soil profile (Johnson 1963).

Hydraulic conductivity is usually described in unit length per unit time, usually in these units (by Lohman, 1972) as shown in equation (1):

$$K = -\frac{ft^3}{ft^2 day(-ft \cdot ft^{-1})} = ft \cdot day^{-1} \left[LT^{-1}\right] \tag{1}$$

where K is the hydraulic conductivity.

Equation (1) can be also rewritten as interpretation for SI units:

$$K = -\frac{m^3}{m^2 day(-m \cdot m^{-1})} = m \cdot day^{-1} \left[LT^{-1} \right] \quad (2)$$

where 1 ft is 0.305 m.

Kim and Kim (2009) stated that unsaturated soil has a force which enables the soil to absorb water by capillary forces. This force can also be named as total suction. This force makes the behavior of unsaturated soil different from saturated soil.

The relationship between suction and saturation degree is visible on the Soil Water Retention Curve (SWRC) in Figure (5). Drying curve is the upper one, wetting curve is situated below as it is described also in the graph.

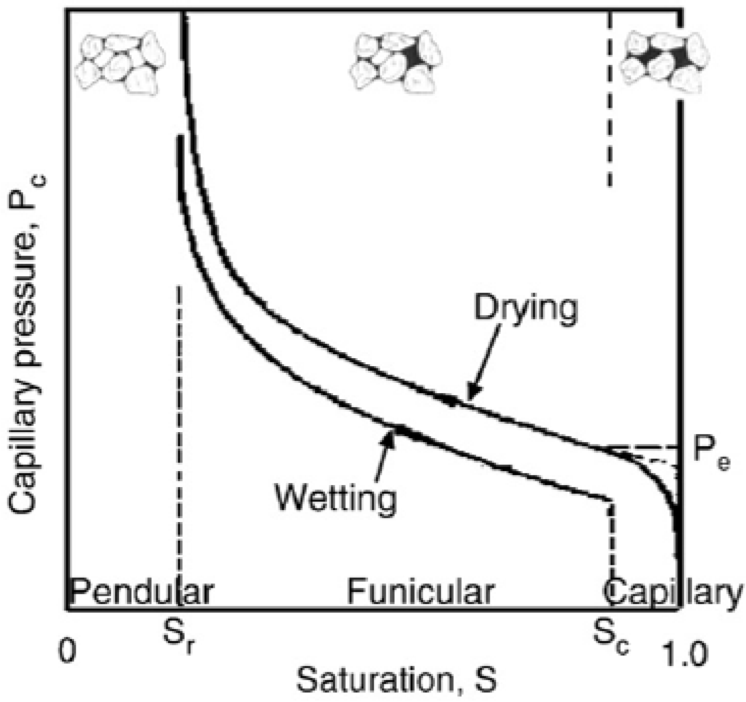


Figure 5 - SWRC curves according to states of saturation (pendular, funicular and capillary, Kim and Kim (2009)

The flow under tension infiltrometers is three-dimensional. This is presented in Figure (6).

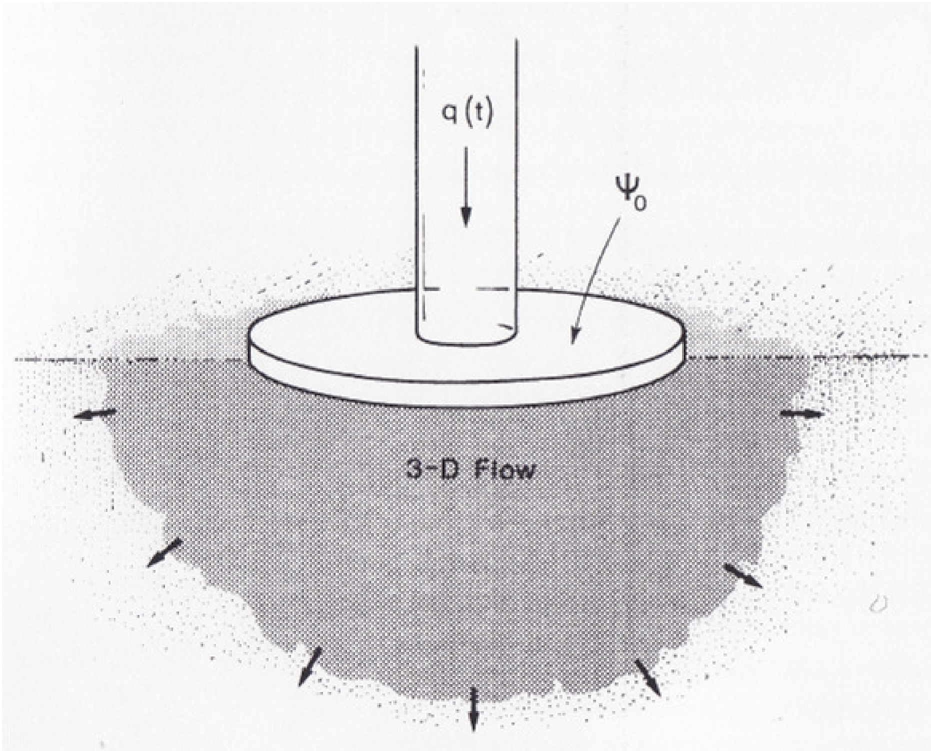


Figure 6 - Schema of unconfined three-dimensional flow from water source placed on the soil surface, White et al. (1992)

Angulo-Jaramillo et al. (2000) and Šimůnek and van Genuchten (1997) wrote that the methods to determine hydraulic properties of soil are based on steady state flow, transient flow or on numerical model and inverse parameter estimation techniques. Their description is as follows:

3.2.1 Steady-State flow equations

The steady state flow means that there is no change in pressure head with respect of time. This statement is mathematically symbolized by a simple equation $dh/dt=0$. It means that the change in head (*dh*) with respect to the change in time (*dt*), equals zero.

Steady state flow practically does not occur in nature, but it is used due to the fact that the flow in nature is closely approached in nature and in aquifer tests. This condition is usually symbolized by $dh/dt \rightarrow 0$. The steady-state flow equations are based on Darcy`s law, which says that the rate of laminar flow of water through porous media is proportional to the hydraulic gradient.

The Darcy Law is written in this form (equations 3 and 4):

$$q = \frac{Q}{A} = -\frac{Kdh}{dl}\left[LT^{-1}\right] \tag{3}$$

which is the same as the hydraulic conductivity equation in this form:

$$K = -\frac{q}{dh/dl}\left[LT^{-1}\right] \tag{4}$$

as presented by Lohman (1972).

As it was written by Ankeny et al. (1991), there is only a need to measure steady-state infiltration for determining the water flow in agricultural soils. Description of the steady-state infiltration equations are as follows:

Under the tension infiltrometer there is a three-dimensional steady-state infiltration of water. This was described by Wooding (1968) in a quasi-analytical equation (5) which counts with steady infiltration from a circular source (Ventrella et al. 2005):

$$Q = \pi r^2 K + 4r\phi \tag{5}$$

where Q is steady infiltration flux, K saturated hydraulic conductivity, ϕ matric flux potential and r radius of the disc permeameter. Using Kirchhoff integral transformation from Richard's equation, the soil water potential as matric flux potential can be calculated (Hillel, 1998) as shown in equation (6):

$$\Phi(\psi) = \int_{\psi_i}^{\psi} K(\psi)d\psi \tag{6}$$

where ψ is soil water pressure head.

Or for h as pressure head it stands in this form (Shouse and Mohanty, 1998), in equation (7):

$$\Phi(h_o) = \int_{h_i}^{h_0} K(h)dh \tag{7}$$

where $h_i \leq h_0 \leq 0$. Where h_i is initial pressure head of dry soil, h_0 is the arbitrary supply pressure head.

The hydraulic conductivity function can then be calculated from equation (8) according to Ankeny et al., (1991):

$$K(\psi) = K_s \exp(\alpha\psi) \tag{8}$$

where α is constant.

Based on equation (7) which can be rewritten also in this form (Lin and Mc Innes, 1995):

$$K(\psi) = K(\psi_0)\exp[\alpha(\psi - \psi_0)] \tag{9}$$

as we can assume that the steady-state infiltration rate Q calculated from circular tension infiltrometer is according to equation (10) approximately:

$$Q(\psi_0) = [\pi a r^2 + 4r] \cdot \int_{\psi_i}^{\psi_0} K(\psi)d\psi \tag{10}$$

where r is radius of infiltration surface depending on disk radius, ψ_i is initial pressure head, ψ_0 is surface pressure head, K is known hydraulic conductivity, where $K(\psi_0) >> K(\psi_i)$ is valid.

The previous equation (10) can then be rewritten in the form for hydraulic conductivity:

$$K(\psi_0) = Q(\psi_0)/[\pi r^2 + 4r/\alpha] \tag{11}$$

which is based on the equation described by Ankeny et al. (1991). In this equation the measurements of $Q(\psi_0)$ value at two supply water potentials (ψ_1 and ψ_2) both $K(\psi_0)$ and α as the constant may be determined.

For the multiple head devices, as published by Elrick and Reynolds (1992) two or more pressure heads are used sequentially to the soil surface to infiltrate and from this the unsaturated hydraulic conductivity are solved

1. using simultaneous equations (for two pressure heads applied sequentially);

2. least squares regression (also for more pressure heads);

3. piece wise fitting of exponential curves (also for more pressure heads).

3.2.2 Transient flow

Transient flow is described by many authors. Use of the transient flow equation (12) is based on the theory of transient axisymmetric infiltration from a circular source of water applied at the soil surface. Some authors showed, that additional term accounting for side effects, which occurs due to the axisymetric flow geometry, is linear in time (Vandervaere et al., 2000):

$$I_{3D} - I_{1D} = \frac{\gamma S^2}{R(\theta_0 - \theta_n)} t \tag{12}$$

where the indexes 3D and 1D stand for axisymmetric three dimensional and one-dimensional process and γ is a constant, which can be said to be equal to √3 when the gravity forces are neglected at the periphery of the disc, R is disc radius and S is sorptivity. Smetten et al. 1994, Vandervaere et al., 2000 set the value for γ as 0.75.

For short to medium times, the previous equation (12) can be rewritten into an infiltration equation in this form (13):

$$I_{3D} = S\sqrt{t} + \left[\frac{2-\beta}{3}K + \frac{\gamma S^2}{R(\theta_0 - \theta_n)}\right] \tag{13}$$

where β is a constant (0< β<1). This equation can be simply rewritten in form (14):

$$I = C_1\sqrt{t} + C_2 t \tag{14}$$

where the subscript for 3D flow is omitted and with:

$$C_1 = S;\ C_2 = \frac{2-\beta}{3}K + \frac{\gamma S^2}{R(\theta_0 - \theta_n)}. \tag{15}$$

3.2.3 Numerical model and Inverse Parameter Estimation

The numerical model and inverse parameter estimation procedure is well described by Schwärzel and Punzel (2007). They presented the Richard`s equation for symmetric isothermal Darcian flow in this form (equation 16):

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right) + \frac{\partial K}{\partial z} \tag{16}$$

where θ is the volumetric water content, t is time, r is radial coordinate, h represents pressure head and K is unsaturated hydraulic conductivity. This equation was also used by Šimůnek et al. (1998), who suggested numerical modelling to estimate hydraulic conductivity from the disk infiltrometer, from cumulative infiltration data at several heads. Kodešová et al. (2006) wrote that the single Richard’s equation for HYDRUS-1D is used for the single-porosity model, which describes one-dimensional isothermal Darcian flow in variably saturated soil.

“HYDRUS is a public domain Windows-based modeling environment for analysis of water flow and solute transport in variably saturated porous media. The software package (for HYDRUS 1D) includes the one-dimensional finite element model HYDRUS for simulating the movement of water, heat, and multiple solutes in variably saturated media. The model is supported by an interactive graphics-based interface for data-preprocessing, discretization of the soil profile, and graphic presentation of the results. HYDRUS 2D is a software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media“ as written in manual of HYDRUS.

Using the HYDRUS-2D model, the previous Equation (16) was numerically solved for the following initial and boundary conditions $\theta_i(z)$. Equation (17) describes the initial water content condition:

$$\theta(r, z, t) = \theta_i(z);\ \ t = 0 \tag{17}$$

equation (18) describes the time-variable pressure head below the tension infiltrometer:

$$h(r, z, t) = h_0(t);\ \ 0 < r < r_0;\ z = 0 \tag{18}$$

This equation (19) prescribes the zero-flux condition at the surface of the soil:

$$\frac{\partial h(r, z, t)}{\partial z} = 1;\ \ r > r_0;\ \ z = 0 \tag{19}$$

The last equation (20) says that other boundaries are sufficiently distant from the infiltration source and that they have no influence on the flow process of tension infiltrometer.

$$h(r, z, t) = h_i; \; r^2 + z^2 \to \infty \tag{20}$$

In equations (17) to (20) θ_i represents initial volumetric water content, h_0 is time-variable supply pressure head done by disk infiltrometer and h_i is initial pressure head, r_o is the disk radius, z is the vertical coordinate (in centimeters) and t is time.

3.3 Tension infiltrometers

3.3.1 Mini Disk Tension Infiltrometer

The Mini Disk Tension Infiltrometer is an infiltrometer with a single disk and multiple tensions (also called pressure heads) manufactured by Decagon Devices, Inc. This was described by Ankeny et al. (1991). This device has a great advantage due to being very small and portable. The total height of this infiltrometer is just over 32 cm and the volume of water required to operate with it is about 135 ml.

Table 1 below shows the decisive parameters of the Mini Disk Tension Infiltrometer.

Table 1 - Mini Disk Tension Infiltrometer parameters, Decagon Devices, Inc. [online]

Mini Disk Tension Infiltrometer parameters	
Total Length	32.7 cm
Diameter of Tube	3.1 cm
Volume of Water Required to Operate	135 ml
Sintered Stainless Steel Disc	4.5 cm diameter, 3 mm thick
Length of Water Reservoir	21.2 cm
Length of Suction Regulation Tube	10.2 cm
Length of Mariotte Tube	28 cm
Suction Range	0.5 to 7 cm of suction

The schema of Mini Disk Tension Infiltrometer is shown on Figure (7) (Decagon Devices, Inc., [online]).

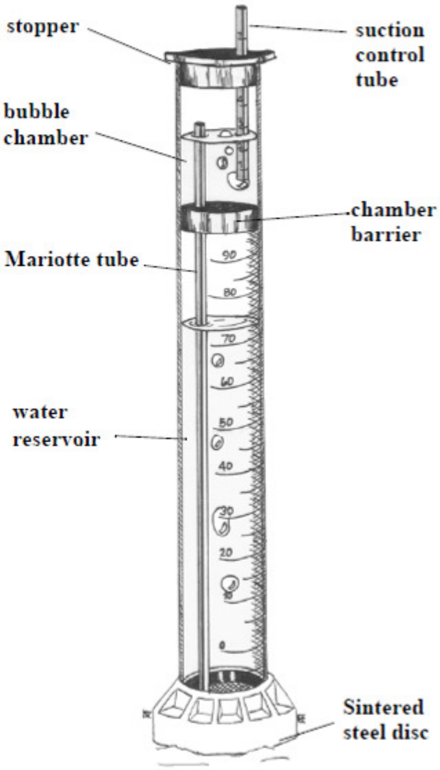


Figure 7 - Schema of Mini Disk Tension Infiltrometer, Decagon Devices, Inc. [online]

According to Decagon Devices, Inc. [online] it is usable for field and also laboratory measurements. The body is made from polycarbonate and the contact disk is a porous semi-permeable sintered stainless steel disk. Semipermeability means, that it allows water not air to go through (Decagon Devices, Inc., [online]).

The chamber for tension changes is visible in Figure (8)

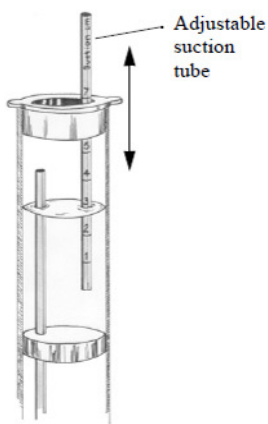


Figure 8 - Chamber for tension changes, Decagon Devices, Inc.

The size range of pores, cracks, etc. participating in the flow is determined by the tension set on the infiltrometer disk/membrane (Elrick and Reynolds 1992). The suction settings and corresponding pore diameter are shown later in Table 2.

Table 2 below shows the relation between suction settings and pore diameter for Mini Disk Tension Infiltrometer (MDTI). The chamber for changing the suctions is visible on Figure 7. Decagon Devices, Inc. recommends that if the bigger value of tension is used (e.g. 7 cm), only pores smaller than 0.41 mm will take part during infiltration and will be filled. If the suction is decreased to 1 cm, also pores up to 2.90 mm will take part during the infiltration. The suction settings are given in absolute values. In real values it is always a negative value.

Table 2 - Suction settings and corresponding pore diameter, Decagon Devices, Inc. [online]

Suction settings and corresponding pore diameter							
Suction Settings [cm]	1	2	3	4	5	6	7
Pore diameter [mm]	2.90	1.45	0.97	0.73	0.58	0.48	0.41

Špongrová et al. (2009) wrote that the tension infiltrometer method shows the infiltration capacity of different pore sizes by measuring the hydraulic conductivity using a range of water pressure heads. When the pressure head decreases, the hydraulic conductivity increases. Mohanty et al. (1994) show that by setting the suction head on the infiltrometer, we can limit the size of soil pores which will take part in conducting the water. Sequential increase of tension heads goes ahead to drain smaller and smaller pores. Infiltration rate then decreases when more water-conducting pores are emptied.

There are different times to read the values from MDTI for each soil type. For example for silty loam we need to make a measurement every 30 seconds, due to its high suction, in contrast, a reading for clay should be made every 30 minutes. These are just approximate values given by Decagon Devices, Inc. The real time has to be set on the field according to all the parameters.

For the MDTI there is an essential requirement for good and consistent hydraulic contact between the measuring device membrane and soil during the whole time (Perroux and White, 1988). They also recommend trimming of any vegetation down to ground level to avoid any influence of the grass cover. Excess contact sand outside the rim of the infiltrometer has to be added to avoid any horizontal wicks of sand. Reynolds and

Zebchuk (1996) made some measurements using the contact material for the tension infiltrometer and they stated, that the use of contact material is usually done by placing a layer of some contact material (e.g. sand) between the membrane and soil surface. Smettem and Clothier (1989) recommend that a circle of fine contact sand with a radius which corresponds to the contact membrane of tension infiltrometer is applied. Time zero is then set to the moment of the first contact or connection between the sand and infiltrometer membrane. They also obtained the first 30 s readings from infiltrometer due to wetting of contact material for the first moments.

For placing the infiltrometer on the contact material Close et al. (1998) suggest that the infiltrometer is gently rotated a few degrees clockwise and anticlockwise and then gently press down on the contact material (silica sand is suggested) while placing the device.

3.3.2 Hood Infiltrometer

According to Schwärzel and Punzel (2007) disc infiltrometers, (the category which Hood Infiltrometers also belongs to), are used to determine saturated and also near-saturated hydraulic conductivity of soil. The biggest advantage of Hood Infiltrometer (HI) is that it does not use any contact material unlike the MDTI. The contact material can affect the value of hydraulic conductivity. Instead of this there is direct contact between water held in the hood and the soil surface. This overcomes problems associated with the influence of contact material. They noted that soil hydraulic conductivity is soil structure dependant. On the other hand Buczko et al. (2006) recommend the use of contact material and recommend also that a good contact between the hemispherical hood and soil is sealed with a thin layer of contact sand.

A reason why to use the HI is that it places the water column directly on the soil surface and no need of contact material, membrane or plate is required. This is the biggest advantage over conventional infiltrometers. The only adjustment required to the terrain is to cut the vegetation to about 5 mm tall. The HI consists of three major components: hood, Mariotte water supply and manometer.

The hood is constructed from acrylic and the diameter is 12.4 cm. For measurement itself, it is placed open side down on the undisturbed soil surface with a retaining ring. The place between the hood and retaining ring is then covered by sand to overcome leaking of water to the sides and to seal up the hood. Then there is the Mariotte bottle with its diameter of 12 cm and length of 71.6 cm. This Marriotte is used for water supply of the hood during infiltration. The principle of setting up the tensions is the same as for ordinary tension infiltrometers. It means that inside the Mariotte water supply, there is a bubble tower with an adjustable pipe which controls the suction. The only peculiarity as opposed to the conventional disk infiltrometer is that there is an air outlet tube which connects head spaces of the water reservoir (Mariotte water supply) and the hood. From the hood, there also leads a standpipe which is joined to U- Tube manometer. The U-tube manometer can then measure effective pressure head created on the soil surface.

Schema of HI is shown in Figure (9).

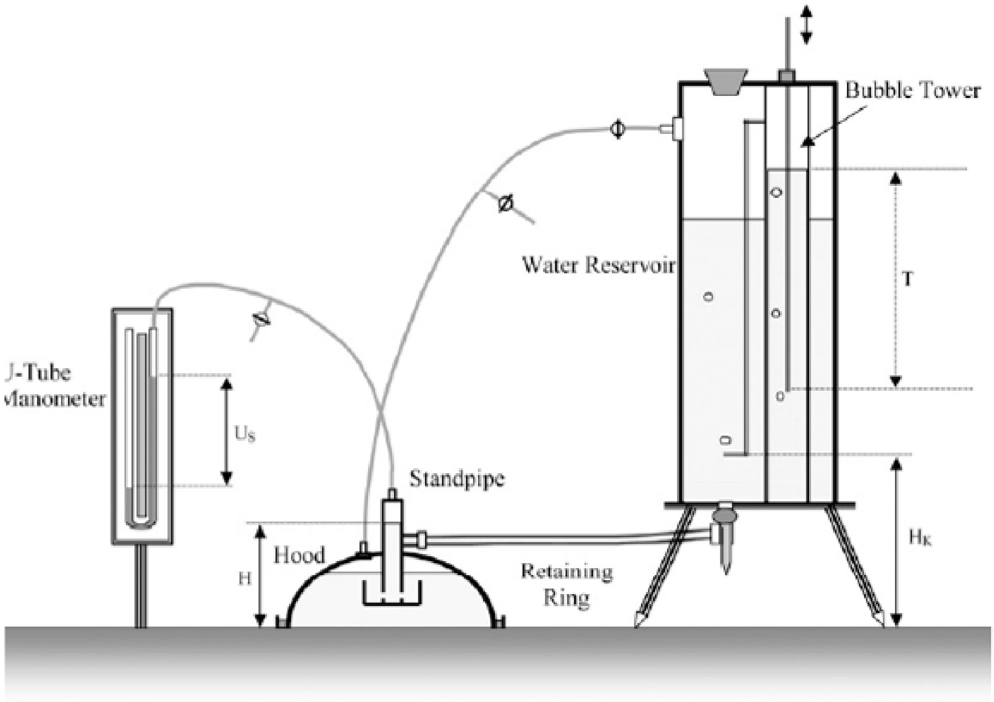


Figure 9 - Schema of HI device, UGT GmbH [online]

There is of course a need of filling in the hood. This is done by opening the connection tube between the hood and Mariotte water reservoir, which will cause water to move into the buffer cup inside of the hood. This filling of the buffer cup is needed to extract air from the connecting tube. After this procedure is made, the air outlet tube has to be slowly opened to fill in the hood. The outlet for air has to be closed after reaching the mark in the hood. Water inside the hood is then under negative pressure. As it was previously mentioned, the selected pressure head can be set up by the adjustable pipe. Then the measuring can start.

As Buczko et al. (2006) explained, the HI is a modified version of a closed-top infiltrometer. This type of infiltrometer was designed by Dixon (1975). Water is applied to the closed-top infiltrometer and this then applies negative pressure to the soil surface. This infiltrometer simulates heads from -3 to +1 cm of water. It is based on the principle, that "natural positive air pressure can be simulated by equivalent negative air pressure above ponded surface water" (Dixon, 1975, p. 755). If h_w is defined as the ponded water depth and actual or simulated soil air pressure head is h_a, then h_s is effective surface head, which is the difference between h_w and h_a.

So under the closed-top infiltrometer the equation is (equation 21):

$$h_a > h_w;\ h_s = h_w - h_a \tag{21}$$

where $h_s < 0$.

The principle of the closed-top infiltrometer is illustrated in Figure (10)

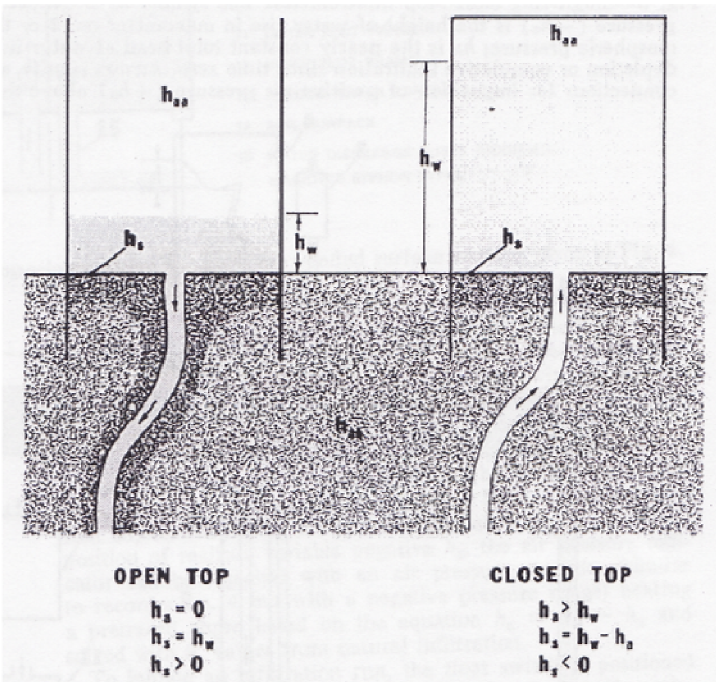


Figure 10 - Idealized water and air flow in hydrophylic bimodal porous media under open-top and closed-top infiltrometer, Dixon (1975)

The HI parameters are given in Table (3) below.

Table 3 - HI parameters, UGT GmbH [online]

Hood infiltrometer parameters	
Tension range	0 - 60 hPa
Measuring range	+/- 700 mm of water column
Time steps	choose
Tension of measurement	resolution 0.1 hPa
Infiltration rate	0.01 ml/min - 20 ml/min
Measuring range	1 000 cm/d - 0.01 cm/d
Water consumption	0.1 - 0.5 l per infiltration step
Measuring period	ca. 2 days

Hydraulic conductivity is then calculated as a function of water tension *h*. For this, Gardner`s equation is used (Decagon Devices, Inc.):

$$k_u = k_f \exp(\alpha h) \tag{22}$$

Where k_u is hydraulic conductivity under unsaturated conditions, k_f is saturated hydraulic conductivity, h is the pressure head, α is sorptive number.

Wooding`s equation for the steady state flow is written in this form:

$$Q = \pi a^2 k_u \left(1 + \frac{4}{\pi \alpha a}\right) \tag{23}$$

where a is the dimensionless length equal to ($\alpha r/2$), r is the radius of disc and other parameters are known from the previous equation (see equation 22).

The calculation of hydraulic conductivity of soil under different tensions is in details described in Chapter 4.4.1.

3.4 Factors affecting the determination of unsaturated hydraulic conductivity

There are many significant factors which can affect determination of hydraulic conductivity such as different tensions settings, different systems and different place. We can divide these factors to extrinsic (such as traffic, cropping and others) and intrinsic (like soil type, pore size distribution and others) properties. Factors associated with these properties affect infiltration ratio and runoff processes on agriculturally used soils (Mohanty et al., 1994). Knowledge of all these factors can then help with modelling of infiltration and runoff processes more precisely and accurately (Mohanty et al., 1994).

Some significant effects on the accuracy of measurement have been described according to Elrick and Reynolds (1992) as; soil heterogeneity, macrostructure collapse just under the infiltrometer during the measurement, changes in hydraulic contact during the measurement and also the contact material and its hydraulic properties and thickness. The wrong hydraulic contact can be caused by wind during the measurement and can also be caused by the decreasing weight of the infiltrometer itself.

A summary of the issues, which affect the hydraulic conductivity measurement was written by Johnson (1963) who wrote that the measurement is influenced by chemical-physical conditions of the soil profile and this property can vary with time. The rate is affected by texture and structure of soil, sediment surface and also the distribution of soil water content, chemical and physical nature of the water, length of application time, bioactivity, temperature of water, percentage of entrapped air in soil surface, atmospheric pressure and the type of equipment or method which is used. Unfortunately he did not make measurements with tension infiltrometers, but only with ring infiltrometers.

3.4.1 Tillage, crop effects

Schwärzel et al. (2009) suggest, that methods to determine the interactions between crop or soil management and its influence on soil structure and pore-size distribution are needed to improve knowledge about the overall impacts of agricultural processes on soil water regime and fertility. They wrote that saturated and near-saturated soil hydraulic properties are very sensitive to management practices such as tillage and other factors.

Tillage variances, which alter soil structure and also increase porosity of the upper layer of the soil, were measured by Ankeny et al. (1991), White et al. (1992) and Reynolds and

Zebchuk (1996). Effect of crop seasonality or as it can also be named as 'seasonal variability' due to factors such as soil compaction and water regime was studied by Chowdary at. al. (2006) and Buczko et al.(2006). The tillage and crop effect was also measured by Logsdon et al. (1993). They were measuring the effect of different tillage practices (no-tillage, chisel, moldboard plow and ridge till) and also different crop rotations at various dates (4 dates) between June 1991 and May 1992. They claimed that infiltration rates under no-tillage compared to tilled soils can be faster, slower or not significantly different. There is also the effect of traffic-induced compaction of the soil and dependence on soil canopy cover. The fauna activity (eg. earthworms) and root activity of flora can cause an increase in macroporosity and thus differences in infiltration rates. Soil cracking under dry conditions can also influence the rates considerably. Mohanty et al. (1994) wrote that hydraulic conductivity – both saturated and unsaturated – is much higher in the corn rows than in wheel track inter-rows. They also noted that infiltration of water depends on soil macroporosity. If soil has a lot of macropores, the runoff from the soil is smaller.

Kechavarzi et al. (2009) issued an article about tillage effect on nearly-saturated hydraulic conductivity. They examined 5 different tillage treatments (conventional and shallow plough, minimum tillage, direct drill and no-treatment). They found, that minimum tillage and no-treatment soil plotted higher hydraulic conductivity near saturation than tilled soils. However the results of hydraulic conductivity differ from author to author. For example Ankeny et al. (1990) didn't measured differences in hydraulic conductivity under different tillage of soils.

The effect of canopy roots was also studied by Shirmohammadi and Skaggs (1984). They reported that fescue roots loosen the soil and this then causes an increase in hydraulic conductivity. Mohanty et al. (1994) also mentioned in his article the impact of depth and size of the taproot system, which can then affect the hydraulic conductivity positively.

Matula (2003) wrote, that mouldboard plough often followed by secondary tillage operation, which has been applied since the Middle Ages, can cause soil compaction due to the repeated use of heavy traffic operations. He also made 2 measurements in 1997 and 2000 to compare the tillage effect on infiltration. He discovered that there were almost no effect for conventional ploughing, but he observed a decrease in infiltration between these two years for reduced tilled treatment and no-till treatment.

White and Perroux (1989) measured hydraulic conductivity from sorptivity measurements. Their method required air-drying of the sample every time between two measurements under different tensions. The air-drying caused a bad wetting/drying influence on the soil.

3.4.2 Time variability

Angulo-Jaramillo et al. (2000) also point out a time aspect with effect on hydraulic properties. They suggest, that there is a seasonal or temporal change caused by irrigation, tillage practices, rain and wind and also biological activity which can modify the soil structure.

3.4.3 Particle size distribution

The effect of particle size distribution was examined by Benson and Trast (1995). They performed an experiment which determined the influence of soil particles of 2 μm (clay) on hydraulic conductivity. An increase in the fraction of smaller particle sizes resulted in the decrease of hydraulic conductivity, but they concluded, that the trend was not significantly strong enough to say with confidence that content of fine soil particles does not significantly affect the hydraulic conductivity of given soil.

3.4.4 Air bubbles

Another factor, which affects the measuring of hydraulic conductivity, is the presence of air bubbles in the infiltrometer reservoir. Air bubbles causes a noise during the measurement and the measurement is not so precise because of bubbling-induced variability. This was studied by Casey et al. (2002) and also Ankeny et al. (1988).

3.4.5 Contact material

A factor measured by Reynolds and Zebchuk (1996) is the usage of contact material for tension infiltrometers. Good contact between infiltrometer and soil surface is required, but the contact material can cause some problems and can influence measurements. As the contact material sand is usually used, they observed incompatibility between pressure head of the soil surface and pressure head on the membrane of the tension infiltrometer within using the contact material. The discrepancy is depending on thickness, hydraulic conductivity and air entry value of the contact material. This discrepancy can then influence the accuracy or validity of tension infiltrometer measuring and thus the reliability of results are compromised.

Perroux and White (1988) established the 3 following criteria for contact material, which have to be fulfilled:

1, the hydraulic conductivity *K (h)* of the contact material should be greater or equal to the hydraulic conductivity of the soil over the range of pressure heads on the tension infiltrometer;

2, the pore water pressure head at which the contact layer (eg. sand) spontaneously saturates has to be less than the minimum value of pressure head which can be set on the given infiltrometer;

3, the contact layer should be as thin as it is possible to minimise the effects on hydraulic conductivity of the measured soil.

Perroux and White (1988) calculated, that the ideal thickness of contact material layer is about 3 – 5 mm with fine sand texture and its hydraulic conductivity *K (h)* of 10^{-5} ms^{-1}. These parameters should be usable for most soils with agricultural usage and also for the pressure heads of tension infiltrometers.

Elrick and Reynolds (1992) and Smettem and Clothier (1989) stated that the thickness and other properties of the contact material can affect the early-time transient flow measurements because of the time needed for the wetting front to move through the contact material to the soil layer. On the other hand, Bagarello et al. (2000) found that there is almost no influence on steady-state infiltration rates when using appropriate contact material with higher permeability than the soil surface.

Close et al. (1998) calculated that non-uniform wetting of the contact material can influence the measurements and cause them to fluctuate. Wang et al. (1998) said, that there is no need of use contact material for very smooth soil surface.

Bagarello et al. (2001) also refer to the importance of the use of contact material to establish proper hydraulic contact between the membrane of the tension infiltrometer and the soil surface. They determined the change in hydraulic properties using two types of contact material – natural sand contact material and glass spheres. If the sand is reused, the saturated hydraulic conductivity *K* is increasing due to a progressive loss of finer particles from the sand. However the second material used – the Spheriglass – maintained a stable hydraulic conductivity both in laboratory and also in the field.

3.4.6 Pressure heads

Bagarello et al. (2000) mentioned also the effect of descending (i.e. from low to high negative heads) or ascending pressure heads used on the tension infiltrometer. They wrote that some authors used the measurements from lower to higher suction – (ascending) as Ankeny et al. (1991); Logsdon (1993) and Mohanty et al. (1994) have experimented in this way.

On the other hand, there are some measurements (wet-to-dry measurements) which reduce the antecedent negative head effects at low infiltration rates (this theory is based on Mohanty et al., 1994). The disadvantage of the descending sequence can cause hysteresis. Experiments carried by Logsdon et al. (1993) on silt loam soil show higher infiltration under measurements taken under descending pressure heads than at ascending pressure head values.

Logsdon (1993) also made measurements for ascending heads. In his case pressure heads -150, -60 and -30 mm were used. It was determined that as the heads become less negative, the sorptivity and also hydraulic conductivity increases.

3.4.7 Initial water content

Benson and Trast (1995) performed an experiment measuring the hydraulic conductivity of soils which were prepared to various molding water contents. This measurement was held in a laboratory, so the samples were then compacted and permeated in the lab. They chose a compacted clay soil, which was used as an integral component of municipal and hazardous waste landfills.

Benson and Daniel (1990) also made measurements on highly plastic clay soil and found that hydraulic conductivity varied by six orders of magnitude. This was dependant on the molding water content and also compaction of the soil.

Benson et al. (1994) also made some other measurements for clay soils and they found that the hydraulic conductivity of soil is sensitive to molding water content and also the dry unit weight. It was concluded that the hydraulic conductivity is dependant on plasticity of soils. More plastic soils tend to have lower hydraulic conductivity. They also noted that soil with higher initial water content (saturation) has lower hydraulic conductivity.

Logsdon (1993) wrote in an article that measurements were made on seven dates during the year on clay loam soil where corn was planted. She found that K (hydraulic conductivity) and S (sorptivity) fluctuated over the growing season with no relation to water content, which fluctuated from 0.04 to 0.36 m/m during the measurements. The measurements were made under ascending pressure heads. Readings were taken every 15 and 25 minutes at each negative head for the clay loam. Initial and final water contents were measured using soil samples taken on the measuring places. The negative impact of bubbling time which causes a delay in infiltration was discussed. On non-compacted wet soil, the bubbling usually occurs within a few minutes, but on initially dry soil it can occur for 45 minutes.

Graphs on Figure (11) below show S and K as a function of initial soil water content (for -150 mm head or -60 mm when the higher pressure head did not wet the soil).

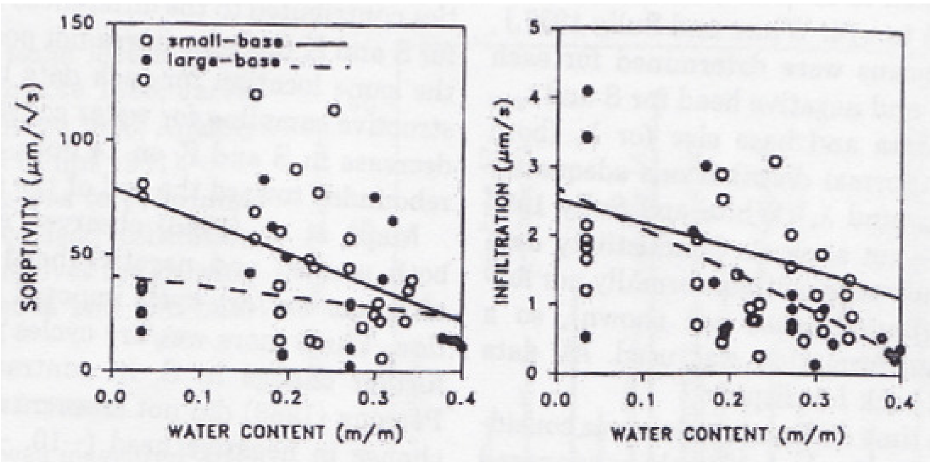


Figure 11 - Sorptivity and hydraulic conductivity as a function of initial soil water contents, Logsdon (1993)

Benson and Trast (1995) calculated the initial saturation of the soil using equation (24):

$$S_i = \frac{w}{\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}} \tag{24}$$

where w is molding water content, γ_d is dry unit weight, γ_w is the unit weight of water and G_s is the particle density.

The Figure (12) below shows the results from the experiment of Benson and Trast (1995). A trend of decreasing hydraulic conductivity when initial saturation increases is visible.

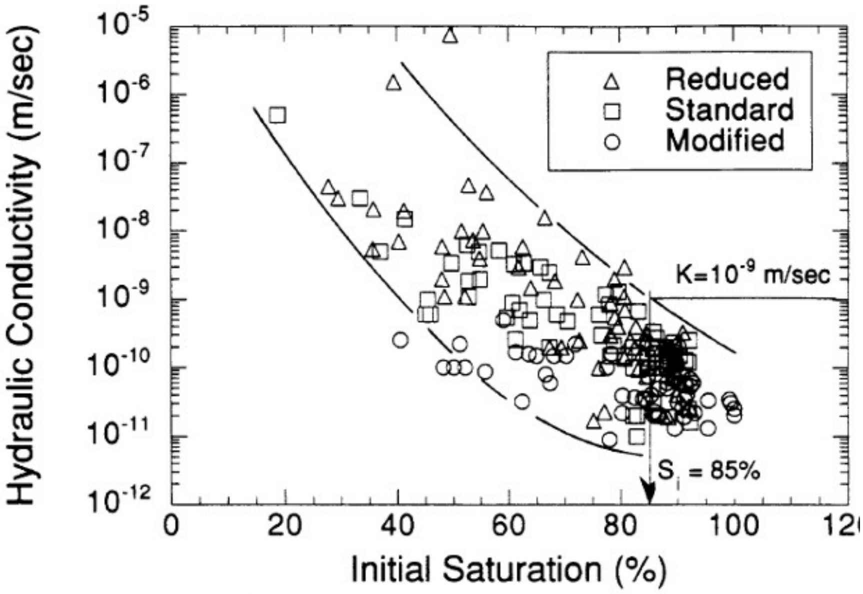


Figure 12 - Hydraulic conductivity versus initial water content, Benson and Trast (1995)

Other authors who made measurements about initial water content include El-Shafei and Al-Darby (1991) who studied the effect of initial soil water content on infiltration, but under a small positive head and with an initial water content of 28 – 48 % of saturation.

Hawke et al. (2006) described the influence of rainfall intensity and initial soil water content on changes in hydraulic conductivity measured by TDR – Time-Domain Reflectometer. They reported that rainfall can affect the matrix structure on the surface of soil. The compressive force of the rain can deform or even destroy the particle arrangement. Orientation or position of surface particles and aggregates can be affected by shear forces. Also, during the infiltration the pores may become clogged by detached particles.

Kim and Kim (2009) wrote that there is a significant difference between drying and wetting curve on the Soil Water Retention Curve. It means in other words, that the initial water content in soil can influence the behavior of unsaturated soils. They made their research with 3 types of granite soil sample. Dry (initial water content was 6.5 %), wet (18.5 %) and optimum water (11.6 %). They measured the time to reach the equilibrium state.

Figure (13) shows how water content corresponds to the matric suction. When the matric suction is over 300 kPa in this case, the changes in water content are equal almost to zero, although the matric suction still increases.

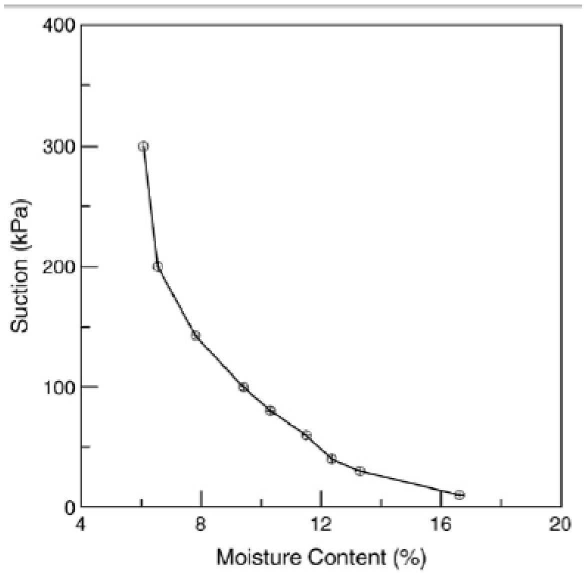


Figure 13 - Water content corresponding to matric suction, Kim and Kim (2009)

Angulo-Jaramillo et al. (2000) made an experiment on sandy soil in Spain and stony sandy loam in France. Both these experimental soils were cropped with maize and were under conventional tillage. The only difference was in the irrigation practice – one possibility was the furrow irrigation, the second one was gun irrigation. Two measurements were made (first before the irrigation period, the second at the end of growing period). The sandy soil under furrow irrigation showed a drastic reduction of hydraulic conductivity and also sorptivity between the two measuring periods. On the other hand, for the sandy loam there was almost no significant difference between two measuring periods and no linearity is shown for the hydraulic conductivity for this soil.

4 Materials and Methods

Factors affecting the determination of unsaturated hydraulic conductivity can be evaluated on the basis of the field experiments. The following devices were used:

Hood Infiltrometer IL-2700 (Umwelt Geräte Technik, GmbH.),

Mini Disk Tension Infiltrometer (Decagon Devices, Inc.).

The unsaturated hydraulic conductivity was measured using HI and MDTI at three applied pressure heads. The initial water content of the soil was chosen for investigation as this is the factor most affecting the estimation of *K(h).*

Three levels of the initial water content were investigated on the experimental field - dry, medium wet and wet conditions as it is explained in detail in the following Chapter 4.2. The initial water content was measured at an area closely surrounding the infiltrometer before the unsaturated hydraulic conductivity measurement using the disturbed samples and Theta Probe (Delta-T Devices, Ltd) method. This is discussed in Chapters 4.2.1 and 4.2.2. After the measurement the undisturbed soil samples were taken. From these samples additional calculations such as particle density, dry bulk density and porosity were made.

Methods and equations used for calculation of the unsaturated hydraulic conductivity from the HI and MDTI are described in Chapter 4.4.

4.1 Characterisation of the experimental locality

Experiments were held on Experimental field of University of Life Sciences Prague during August and September 2011. The soil is characterized by texture as loam or clay loam with about 20 % of clay, according to USDA textural classes. The type of soil is Chernozem modal.

Other soil characteristics such as the dry bulk density, particle density and total porosity are described in following Chapter 4.2.

There was a permanent grass cover on the experimental place (see Figure 14) and close to this experimental area was a treated field. Relatively homogeneous soil conditions are required to minimize the effect of soil heterogeneity and thus enabling evaluation of other factors.

Figure 14 - Grass cover on the experimental place

4.2 Water content and preparing the experiment

The unsaturated hydraulic conductivity *K(h)* was measured using HI and MDTI. The initial water content of the soil was chosen for investigation as this is the factor most affecting the estimation of *K(h)*. Three levels of the initial water content were investigated on the experimental field – dry, medium wet and wet conditions. It means that three levels of initial water content were maintained on the field. Five measurements for each of the three levels of initial water content were made by HI. After redistribution of infiltrated water and after the previous condition of initial water content was reached, measurement with the MDTI was made in the same place as the HI.

The places of measurement were named as D1 – D5 for the driest soil profile, MW1 – MW5 for the medium wet soil and W1 – W5 for the wettest soil profile. These abbreviations are used in the following text and tables. The layout of the experimental field is shown in Appendix (1)

If the proper value of the initial water content could not be provided by the natural weather condition, the soil had to be irrigated. Reaching the correct value of the initial water content was then achieved by irrigating the place for measurement with regular tap water, which was sprayed over the area of the infiltration and surrounding ~ 1 m^2. In the following days the place was monitored and the water content measured by Theta Probe to be able to reach the proper value of the initial water content. Thanks to these continual measurements, precautions such as covering the experimental field with foil to prevent the soil water from evaporation or irrigation was done. The measurement with HI or MDTI was then held after 6 days at the earliest, to be sure that the natural redistribution of the added tap water was reached.

The initial water content was measured at an area closely surrounding the infiltrometer using the calculation of water content by mass and volume. The measuring of water content by mass is done with the disturbed samples taken using the gouge soil sampler. The values of water content by volume are reached by Theta Probe method.

After the measurements with MDTI the undisturbed soil sample was taken to obtain the particle density and dry bulk density of the soil.

4.2.1 Water content by mass

Before measuring with HI, a disturbed sample from an area close to the infiltrometer was taken to establish the initial water content as Kechavarzi et al. (2009) also recommended. Methods for the determination of soil water content are described also by Klute (1986) and Topp et al. (1992).

The disturbed samples which were taken close to the place of measuring with HI were taken using the gouge soil sampler. These samples were ~ 0.9 - 1 m distance from the place of measurements to avoid influencing the tensiometer measurements and to avoid the destruction of pore distribution in the soil profile. The first 50 cm of the soil profile was examined for each hole and it was divided into 5 samples, each for 10 cm of the soil profile. For determining the water content gravimetrically, each sample was put into an aluminium sampling container with lid with known mass, and was immediately weighed on return to the lab. After at least 24 hours drying in oven at 105 °C to the constant mass, the containers with dry soil samples were weighted once more.

Then the water content by mass was calculated based on the equation (25):

$$w = \frac{m_w}{m_z} \tag{25}$$

where w is water content by mass, m_w is mass of water, calculated by subtracting the mass of dry soil sample from the mass of wet soil sample, and m_z is mass of dry soil sample.

The values of water content by mass are shown in the Table (4). Each spot has five values of the water content by mass. These five values correspond to each 10 cm of the soil profile from the surface (depth of 0 cm) down to the depth of 50 cm. For each spot one measurement of the water content by the gauge was done. However, if the spots were nearby, only one measurement of water content was taken for both spots. This can be seen e.g. on spots D1, D2, D4 and D5 for the dry place.

Table 4 - Water content by mass w [%] near HI measurement spots

Water content by mass w [%] near HI measurement spots					
	depth of the soil profile				
place	**0-10 cm**	**10-20 cm**	**20-30 cm**	**30-40 cm**	**40-50 cm**
D1	23.39	21.44	19.56	18.56	18.64
D2	23.39	21.44	19.56	18.56	18.64
D3	22.65	20.75	18.55	17.74	17.30
D4	23.62	23.00	20.84	17.79	17.36
D5	23.62	23.00	20.84	17.79	17.36
ø DRY	23.33	21.93	19.87	18.09	17.86
MW1	30.72	29.65	28.08	25.80	23.10
MW2	28.45	26.74	23.51	23.01	22.17
MW3	28.45	26.74	23.51	23.01	22.17
MW4	29.50	28.45	26.90	25.51	23.36
MW5	29.50	28.45	26.90	25.51	23.36
ø MEDIUM WET	29.32	28.01	25.78	24.57	22.83
W1	35.32	33.56	30.64	28.41	27.12
W2	35.32	33.56	30.64	28.41	27.12
W3	35.15	32.31	30.16	27.90	26.50
W4	35.15	32.31	30.16	27.90	26.50
W5	36.12	34.90	32.94	31.29	31.13
ø WET	35.41	33.33	30.91	28.78	27.67

4.2.2 Water content by volume

Also measurements of water content with Theta Probe Soil Moisture Sensor ML2X (Delta-T Devices) were taken, but these measurements are just for the first six centimeters of the soil profile.Theta-probe belongs to the capacitance methods. The Theta-probe is used to measure volumetric soil water content using a simple technique of standing wave. The volumetric soil water content can be described as the ratio between the volume of water present in the soil and the total volume of the sample. This can be expressed as equation (26):

$$\theta_r = \frac{V_w}{V} \qquad (26)$$

where θ_r is the volumetric water content as the dimensionless parameter expressed usually in % or as the ratio in m^3/m^3. V_w is the volume of water and V is total volume of the soil.

The Theta Probe soil moisture sensor schema is shown on Figure (15).

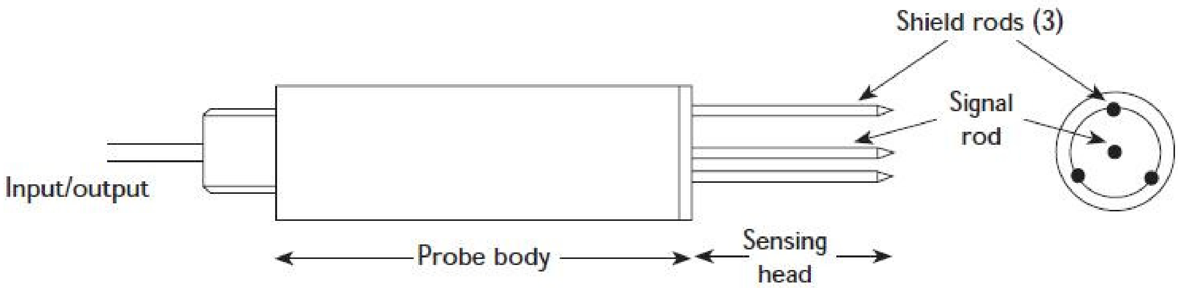


Figure 15 – Theta Probe Soil Moistre Sensor ML2X schema, Miller and Gaslein [online]

Usually the probe has to be calibrated for measurements. However, for the purposes of the experiment, only the difference between measured values was important and not the accurate values of the water content of the soil.

The biggest advantage of measuring with Theta Probe is that the results of water content are immediately visible. This is why this device was used before each measurement with infiltrometers. The Theta Probe Soil Moisture Sensor ML2X is visible in Figure (16).

Figure 16 - Theta Probe Soil Moistre Sensor ML2X; Wine Business.com [online]

Measurements were done under natural conditions on the experimental field. It means that there were some problems with obtaining very close values of initial water content for the two devices. The measurements with HI and also the MDTI needed to be made with very similar initial water conditions to be able to compare these two devices with respect to the initial water content of the soil. However, measuring under natural conditions has a big disadvantage due to varying weather and other factors which can affect measurements, such as sunshine, wind, rain and others. To avoid the influence of these environmental factors, a plastic foil was used which covered the field and protected it from rain or from evaporation of soil water. During the sunny days the beach umbrella was used to protect the soil and also water for infiltration from warming. Regular tap water was used for infiltration, which is in accordance with the manuals of these devices.

As it is shown in the Table (5) the average values for dry, medium wet and wet are 25.1, 32.5 and 38.3 % water content by volume for HI and 23.9, 31.7 and 35.4 % for MDTI. For each place of infiltration six measurements were made in the surrounding area with Theta Probe and the average of these six values was used in Table (5). The measurement with Theta Probe device has the disadvantage that they are only for a thin layer of the soil profile, because the length of the rods is about 6 cm. The abbreviation HI used in table is for HI.

It means that for the HI a step of 7.4 % was between the dry and medium wet soil and 5.8 % between the medium wet and the wet soils. For MDTI the differences were step of 7.8 % between dry and medium wet soil and 3.7 % between the medium wet and the wet soils.

Table 5 – Volumetric water content of experimental area from the Theta Probe device for HI and MDTI

	data for HI	**data for MDTI**
place	**θ [%]**	**θ [%]**
D1	25.4	25.2
D2	25.7	23.2
D3	21.9	23.0
D4	26.2	24.5
D5	26.1	23.7
ø DRY	25.1	23.9
MW1	33.6	32.7
MW2	32.4	31.3
MW3	31.5	31.1
MW4	33.0	32.2
MW5	32.0	31.2
ø MEDIUM WET	32.5	31.7
W1	38.5	35.4
W2	39.6	35.2
W3	37.5	36.7
W4	37.7	34.5
W5	38.0	35.0
ø WET	38.3	35.4

The minimum (min) and maximum (max) values of the volumetric water content are shown in Table (6). The minimum for dry place,, medium wet and wet place was measured on the same spot of measurement (D3, MW3 and D4) both for HI (HI) and MDTI and maximum values of volumetric water content for the medium wet soil profile is also on the same spot.

Table 6 - Minimum and maximum values of volumetric initial water content

		HI		**MDTI**	
		place	**value of θ [%]**	**place**	**value of θ [%]**
DRY	**min**	D3	21.9	D3	23.0
	max	D4	26.2	D1	25.4
MEDIUM WET	**min**	MW3	31.5	MW3	31.1
	max	MW1	33.6	MW1	32.7
WET	**min**	W4	37.7	W4	34.5
	max	W2	39.6	W1	35.4

The graph of volumetric water content is shown in Appendix (2).

4.2.3 Undisturbed soil samples

Immediately after the measurement was made with the MDTI, undisturbed soil samples with a volume of 100 cm^3 at a sampling depth of 0 - 6 cm were taken from below the infiltrometer surface with Kopecky`s sampling rings for analysis. The sampling rings with plastic lids are shown on Figure (17). This ring with 100 cm^3 of volume has an inner diameter of 57 mm. The diameter of sampling ring almost corresponds to the diameter of the MDTI disc. The soil sampler is 40.5 mm high and is made from stainless steel.

Figure 17 - Kopecky`s sampling rings, UGT GmbH [online]

Samples were wrapped from the bottom side with a geotextile to avoid any damages and losses of the soil. As Dane and Topp (2002) also recommended, the undisturbed samples were repacked to avoid any damage of the sample and to avoid evaporation. Samples were weighed and left to saturate on a saturation mat to the constant mass on arrival in the laboratory. Due to capillary forces, the Kopecky`s sampling rings were fully saturated. The saturated soil samples were then weighed.

The rings were then put into the oven to reach the constant dry weight at 105 °C as Kechavarzi et al. (2009) recommends. After this procedure, the determination of particle density ρ_z was carried out by using the water pycnometer method which is described in detail in the following text. The dry bulk density ρ_d was calculated and also the total porosity P of the soil. These calculations are also described in the following text.

Particle density

For calibration of the water pycnometer, the empty pycnometer was completely filled with distilled water. The pycnometer was then tempered by water to a temperature of 20 °C. After the temperature of the pycnometer reached exactly 20 °C the pycnometer was sealed with the glass stopper. No air bubbles can remain under the stopper. the pycnometer was then weighed. Then the water from pycnometer was emptied. Figure (18) shows the water pycnometer.

Figure 18 - Water pycnometer, Educational Technology Clearinghouse [online]

For the measurement of the particle density 15 - 17 grams of oven-dried fine soil were put into the ceramic cup and the distilled water was added. The amount of distilled water has to be enough to cover the soil. This mixture was then heated over a Bunsen burner to remove the air bubbles in the soil sample. Water was boiled for approximately 5 minutes.

The pycnometer was then filled with the mixture of soil and water which was prepared before. The pycnometer was filled completely with the distilled water and was again tempered to 20 °C. Then the pycnometer was weighted again. The particle density was calculated using equation (27):

$$\rho_z = \frac{m_z}{m_z + m_1 - m_2} \tag{27}$$

where ρ_z is the particle density of soil particles, m_1 is mass of pycnometer filled with water, m_2 is mass of pycnometer filled with soil suspension and m_z mass of dry soil sample. For each soil sample two measurements have to be done and the difference has to be smaller than 0.03 g/cm^3. Thus the measurements have to be very accurate and precise. The values were in the range between 2.57 – 2.60 g/cm^3 (the values of particle density for each measurement spot are shown in Appendix 3). So the soil specific weight was very homogenousely spread over the area. The value of particle density between 2.57 – 2.60 g/cm^3 corresponds according to Valla et al. (2008) to surface humic horizons.

Dry bulk density

The dry bulk density ρ_d of soil is calculated using equation (28):

$$\rho_d = \frac{m_s}{V_t} \tag{28}$$

where m_s is mass of soil dried at 105° C in the oven and V_t is the volume of soil under natural conditions. The dry bulk density of this soil was between 1.55 and 1.62 g/cm^3.

Total porosity

The total porosity P of the soil can be calculated using equation (29):

$$P = \frac{\rho_z - \rho_d}{\rho_z} \tag{29}$$

where ρ_d is dry bulk density and ρ_z particle density, as shown in the previous two Chapters.

The total porosity can be characterized as the relative volume of pores in soils. The results of the total porosity, such as the dry bulk density with respect to the place of measurement and initial water content are shown in Appendix (4). The total porosity of the soil was between 37.23 and 40.59 %.

The graph of total porosity, dry bulk density and particle density with respect to measuring spot are shown in Appendix (3; 4).

4.3 Experiment

An important step to be taken is the preparation of the place for infiltrometers. First the measurement with HI was held and after redistribution of infiltrated water and after the previous condition of initial water content was reached, measurement with the MDTI was made in the same place as the HI.

There are different procedures to prepare the place for HI and MDTI. HI places the water column directly on the soil surface and there is no need of contact material. The only adjustment required to the terrain is to cut the vegetation cover to about 5 mm tall. For the MDTI the vegetation has to be trimmed down to ground level and the contact silica sand is recommended to be used to ensure good contact between the infiltrometer and the ground surface. The silica sand used as the contact material for MDTI was silica sand ST56 (Sklopísek Střeleč). The grains of the silica sand have the diameter of 0.063 – 0.40 mm. The same silica sand was used also for HI but for a different purpose: to tighten the contact between the hood and soil as it is visible on Figure 20).

The place of measurement is visible also on Figure (19). In the left picture there is the prepared place for HI, and on the right image there is the same place after one week with the place for MDTI. On the right picture it is possible to see some residuals after used sand for the HI.

Figure 19 - Prepared place for measurements - trimmed grass on the place for the HI and for MDTI, which was put on the same place as the Hood after about a week when the soil water content had settled to the the previous conditions as much as possible

The excess of sand used to tighten the contact between the hood and HI is shown on Figure (20)

Figure 20 - Excess of sand between the hood and the outer ring of HI, UGT GmbH [online]

During the whole experiment there was no treatment of the grass or field on the experimental area. Only the exact place for measuring was prepared by trimming grass with scissors as it is recommended in manuals for the devices to ensure good contact between the device and soil surface.

The measurements of unsaturated hydraulic conductivity were performed under different pressure heads. They were performed for -3, -1, -0.5 cm of pressure head for the MDTI, -0.5, -1, -3 cm of pressure head for HI. It means that for MDTI the ascending values of pressure head were used and for HI the descending values, as it is recommended in the manuals.

The time given for infiltration was at least 40 minutes for each tension for HI. For HI that was enough to reach the steady-state flow and to prevent the effect of transient flow which occurs in the first moments of flow. It means that in total at least 120 minutes of infiltration were made under all three performed pressure heads. For MDTI the minimum of 15 minutes for each tension performed was used. The data were collected every 15 seconds for HI and every 30 seconds for the MDTI.

Figure (21) shows the MDTI in operation.

Figure 21 - MDTI in operation

Water to the MDTI was added just once for the infiltration as it has the water reservoir big enough for the infiltration. The amount of infiltrated water depends on the soil and also on the time for infiltration. Short intervals of 30 seconds were chosen for reading the values.

Water to the HI was added during the measurement. HI has a reservoir of ~ 630 millimeters of water column. The water has to be poured when there is still some water remaining in the reservoir (eg. 10 – 20 mililiters). The water had to be poured every 15 minutes. However, the time depended on the soil water content as the factor affecting the hydraulic conductivity and on the performed pressure head.The HI in operation can be seen on Figure (22).

Figure 22 - HI in operation

4.3.1 Layout of the experimental field

Five measurements with HI and MDTI were performed under three different levels of water content as it is discussed in detail in Chapter 4.2. It means that in total fifteen measurements were done for each infiltrometer.

The placement of the infiltration locations with respect to the initial water content is shown in the Appendix (1). The measuring points had a distance of 1.5 meters in between to be sure that there will be no influence in the water flow beneath the soil profile caused by previous measurements. During the measurements there was often the danger of compaction of the upper layers of the soil profile. It is caused by frequent walking around the devices to be able to read the values and to have access to operate and maintain the devices. To avoid compaction of the soil, a path for walking (~ 50 cm width) was laid out simply by the whipcord.

The measurements with MDTI were held on the same place as measurements with HI after at least six days (as it is discussed more in Chapter 4.2). To make it easier to find the right place for measurements, four spots were made with yellow spray paint around the place for measurements with HI. This can be seen on Figure (23). This picture was taken after measurement with MDTI.

Figure 23 - Yellow spots around the place for measurement

The infiltrations were made randomly according to the weather condition to have the proper initial water content, as discussed in Chapter 4.2. It means that the measurements were not made in order from the driest water condition to the wettest one, but in the way as the weather allowed. The whole layout of the experiment is shown in the Appendix (1).

4.4 Calculation of unsaturated hydraulic conductivity

4.4.1 Calculation of unsaturated hydraulic conductivity measured by HI

The measurements of unsaturated hydraulic conductivity with HI were performed under three different pressure heads. They were performed for -0.5, -1, -3 cm of pressure head for the HI. The infiltration time for each tension was at least 40 minutes and the data were collected every 15 seconds automatically by datelogger. The last three minutes of infiltration of each tension were used as it is discussed further in Chapter 5.1. An example of the Excel sheet used for calculation is in Appendix (5).

The calculation of the unsaturated hydraulic conductivity measured by HI is calculated using these equations (30 - 31):

$$\frac{Q_1}{\pi a^2} = k_f e^{a-h_1}\left(1+\frac{4}{\pi\alpha a}\right) \tag{30}$$

$$\frac{Q_2}{\pi a^2} = k_f e^{a-h_2}\left(1+\frac{4}{\pi\alpha a}\right) \tag{31}$$

where h_1 and h_2 are neighboring values of the chosen water tensions. The water tension should be chosen step by step by 1 or 2 cm up to the soil bubble point.

By simple division we will get equation (32) in this form:

$$\alpha = \frac{\ln\left(\frac{Q_1}{Q_2}\right)}{(h_1 - h_2)}\text{; where } (h_1, h_2 < 0). \tag{32}$$

Two α parameters were calculated. The first one from h_1, h_2 are then used for calculating hydraulic conductivity for tension -0.5, the second one from h_2 and h_3 are used for determination of hydraulic conductivity for tensions -1 and -3. Hydraulic conductivity was calculated in cm/min.

And for the hydraulic conductivity equations in this form were used (33 – 35):

$$k(h_1) = \frac{\frac{Q_1}{\pi a^2}}{\left(1 + \frac{4}{\pi a \alpha}\right)} \tag{33}$$

$$k(h_2) = \frac{\frac{Q_2}{\pi a^2}}{\left(1 + \frac{4}{\pi a \alpha}\right)} \tag{34}$$

$$k(h_3) = \frac{\frac{Q_3}{\pi a^2}}{\left(1 + \frac{4}{\pi a \alpha}\right)} \tag{35}$$

where h_1, h_2, h_3 is the pressure head applied. For the unsaturated hydraulic conductivity usually units of cm/min are used.

It is advised to start the test with water tension set to zero value and then increase the water tension step by step (1-2 cm in every step) up to the bubble point of a given soil.

4.4.2 Calculation of unsaturated hydraulic conductivity measured by Mini Disk Tension Infiltrometer

The measurements of unsaturated hydraulic conductivity with MDTI were held under three different pressure heads. They were performed for -3, -1 and -0.5 cm of pressure head. This range of values corresponds to the pressure heads used for the HI. The infiltration time for each of applied heads was 15 minutes with manual readings every 30 seconds, as it is also written in Chapter 5.2. For calculation all the values were used. The Excel sheet with calculations is shown in Appendix (6).

The hydraulic conductivity *K(h)* measured by MDTI can be then calculated by equation (36) proposed by Zhang (1997), which requires measuring cumulative infiltration versus time:

$$I = C_1 t + C_2 \sqrt{t} \tag{36}$$

where C_1 are C_2 are parameters calculated empirically. C_1 relates to hydraulic conductivity *K(h)* and C_2 is sorptivity of soil. *I* is cumulative infiltration, *t* time.

According to Decagon Devices, Inc., the hydraulic conductivity can then be simply calculated from equation (37):

$$K(h) = \frac{C_1}{A} \tag{37}$$

where C_1 is the slope of cumulative infiltration curve versus square root of time and *A* is a value, which can be determined from van Genuchten parameters (Table 4). The table is divided into 12 soil texture classes and for each texture class and suction height there is a given value.

A values can be taken from Table 3, or calculated from these equations (38) and (39):

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp\left[2.92(n-1.9)\alpha h\right]}{\left(ar_d\right)^{0.91}} \tag{38}$$

valid for $n \geq 1.9$; or

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp\left[7.5(n-1.9)\alpha h\right]}{\left(ar_d\right)^{0.91}} \tag{39}$$

valid for $n<1.9$. Where in both these equations n and α are van Genuchten parameters (values are given in Table 7), h is the tension applied and r with index d is radius of MDTI`s disk.

Table 7 - Van Genuchten parameters for 12 soil types and values of A for MDTI

			h_0						
	α		**-0.5**	**-1**	**-2**	**-3**	**-4**	**-5**	**-6**
texture		**n**							
sand	0.145	2.68	2.84	2.40	1.73	1.24	0.89	0.64	0.46
loamy sand	0.124	2.28	2.99	2.79	2.43	2.12	1.84	1.61	1.40
sandy loam	0.075	1.89	3.88	3.89	3.91	3.93	3.95	3.98	4.00
loam	0.036	1.56	5.46	5.72	6.27	6.87	7.53	8.25	9.05
silt	0.016	1.37	7.92	8.18	8.71	9.29	9.90	10.55	11.24
silt loam	0.020	1.41	7.10	7.37	7.93	8.53	9.19	9.89	10.64
sandy clay loam	0.059	1.48	3.21	3.52	4.24	5.11	6.15	7.41	8.92
clay loam	0.019	1.31	5.86	6.11	6.64	7.23	7.86	8.55	9.30
silty clay loam	0.010	1.23	7.89	8.09	8.51	8.59	9.41	9.90	10.41
sandy clay	0.027	1.23	3.34	3.57	4.09	4.68	5.36	6.14	7.04
silty clay	0.005	1.09	6.08	6.17	6.36	6.56	6.76	6.97	7.18
clay	0.008	1.09	4.00	4.10	4.30	4.51	4.74	4.98	5.22

Values of van Genuchten parameter *A* were taken from Table (7). For this experiment *A* values for tension -3 was stated as 6.87, for -1 it was 5.72 and for tension -0.5 the value of 5.46 for the loamy soil from the table.

5 Results

5.1 Hydraulic conductivity measured by HI

As it can be seen in Chapter 4.4.1, measurements with descending pressure heads were made with the HI, specifically with pressure heads of -0.5, -1 and -3 cm. The time used for infiltration was at least 40 minutes which was enough to reach the steady-state flow. The data were automatically collected by using a datalogger in 15 second intervals; it means that 12 numbers were used for the calculation of unsaturated hydraulic conductivity from HI.. The average value from the last 3 minutes was used for each tension step.

For this infiltration experiment the smaller hood radius (8 cm) was used.

Figure (24) shows the graph of the cumulative infiltration from HI versus time. The graph was created using just the last 3 minutes of infiltration from each pressure head. The first applied pressure head is -0.5 up to the vertical line at the time of 3:00 minutes. Then the -1 pressure head is applied up to 6:00 minutes and the last pressure head is -3. The tendency of decreasing hydraulic conductivity with increasing pressure head is visible.

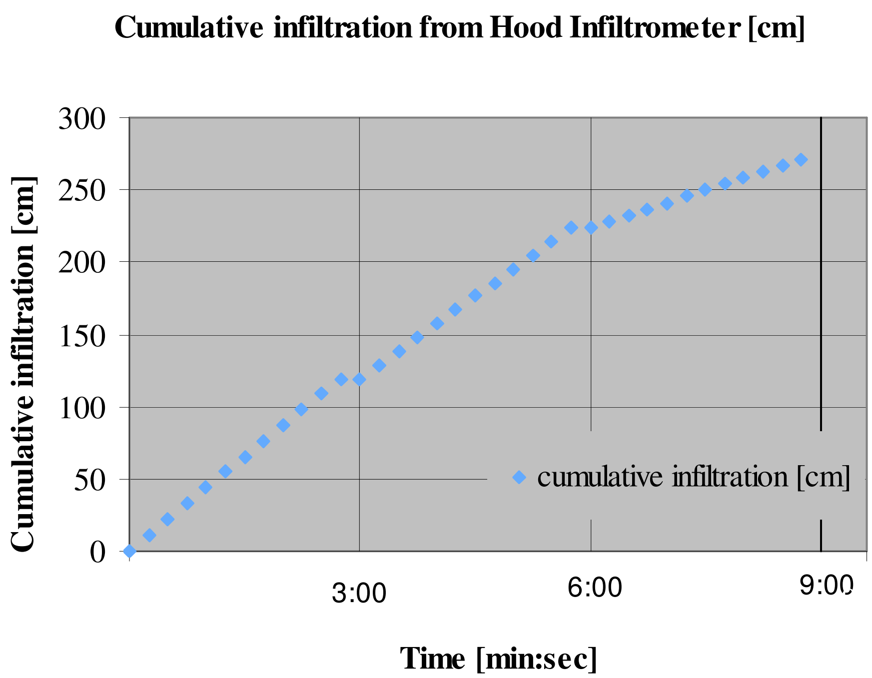


Figure 24 - Cumulative infiltration of HI under three different tensions

The unsaturated hydraulic conductivities calculated from the cumulative infiltrations of HI are shown in Table (8). From the table it is visible, that values of *K(h)* for dry and medium wet soil profiles were very similar, but the values of the wettest site is slightly smaller and this tendency is visible for all three pressure heads implemented. In the table below are the values of unsaturated hydraulic conductivities for all 15 measurements and also their arithmetic mean values are added for each pressure head step. The unsaturated hydraulic conductivity was measured in cm/min.

Table 8 - Values of K(h) from HI

applied pressure head	**-0.5**	**-1**	**-3**
place	**unsaturated hydraulic conductivity in cm/min**		
D1	1.022	0.900	0.441
D2	0.927	0.894	0.512
D3	1.062	0.903	0.447
D4	0.991	1.019	0.459
D5	0.796	0.601	0.449
Arithmetic mean value of DRY	0.960	0.864	0.461
MW1	1.082	0.677	0.276
MW2	0.941	0.908	0.405
MW3	1.041	0.806	0.345
MW4	1.050	0.945	0.600
MW5	0.996	0.948	0.600
Arithmetic mean value of MEDIUM WET	1.022	0.857	0.445
W1	1.016	0.850	0.537
W2	0.647	0.328	0.261
W3	0.770	0.560	0.459
W4	0.861	0.804	0.443
W5	0.985	0.592	0.470
Arithmetic mean value of WET	0.856	0.627	0.434

The graphs for each pressure head are shown below (Figures 25 – 28). Each water condition has its own graph and then the simple average values of each water condition are compared in one graph. It is visible, that the lines for dry and medium wet conditions are almost similar, but the line for the wet condition differ, especially for tension -1.

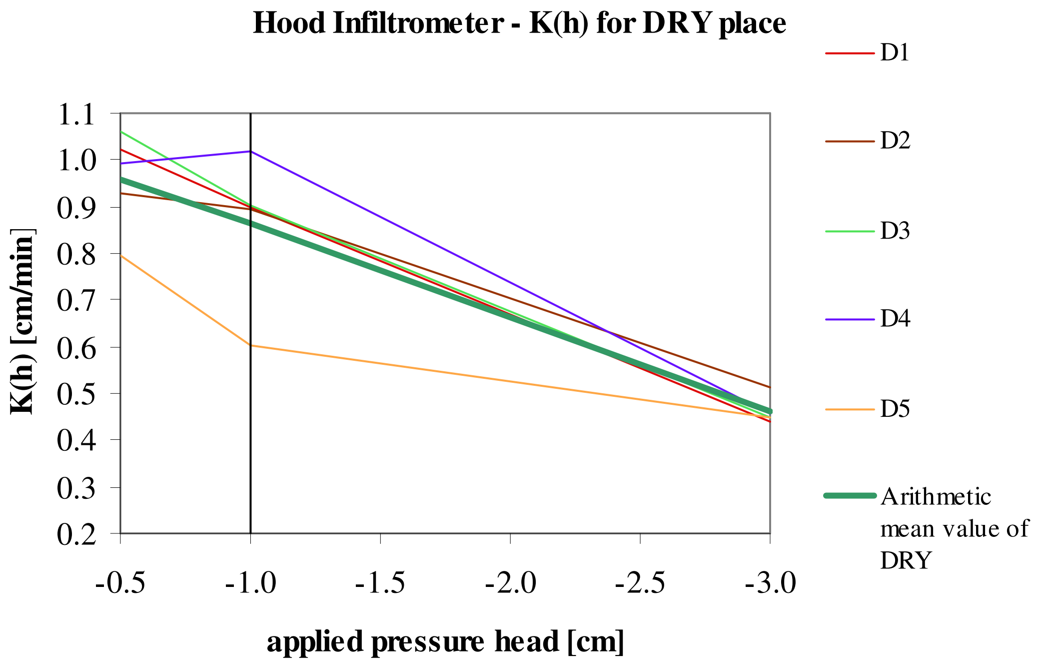


Figure 25 - HI K(h) for DRY place

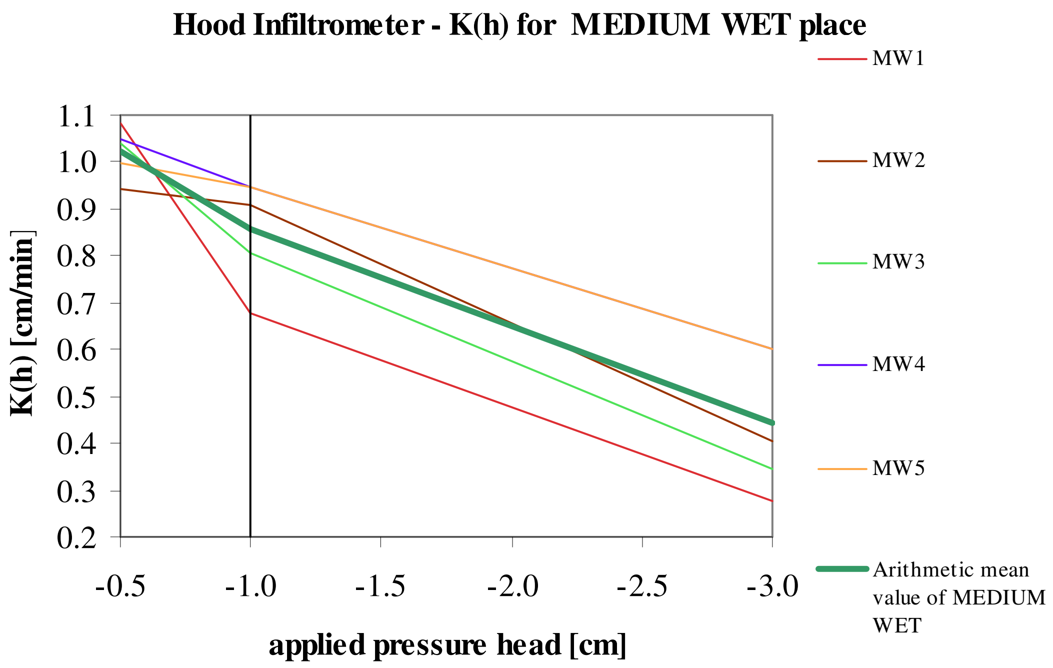


Figure 26 - HI K(h) for MEDIUM WET place

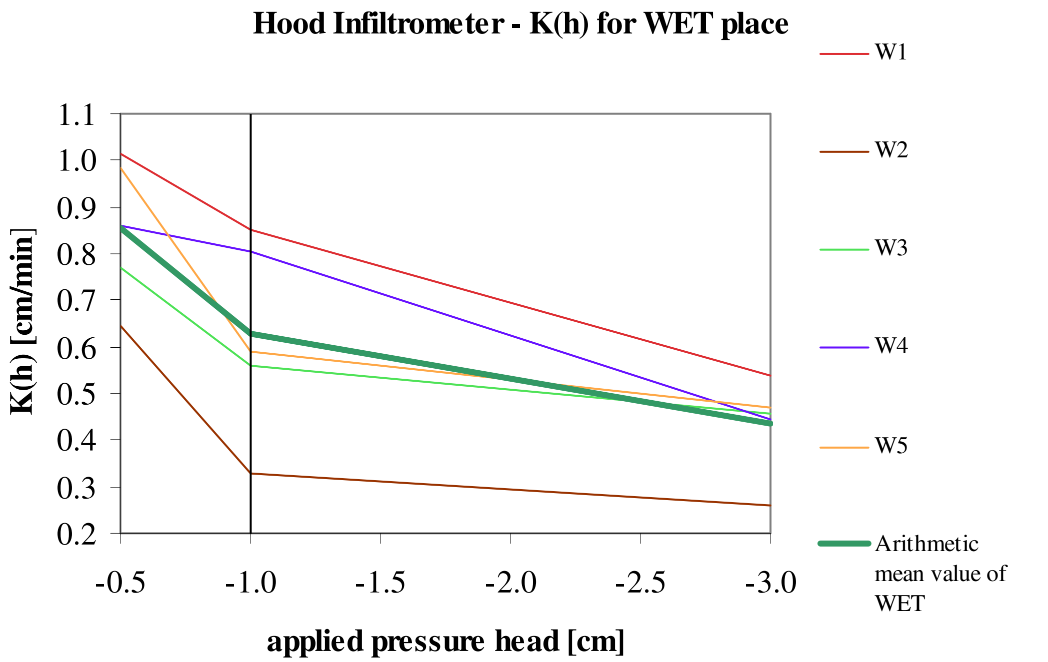


Figure 27 - HI K(h) for WET place

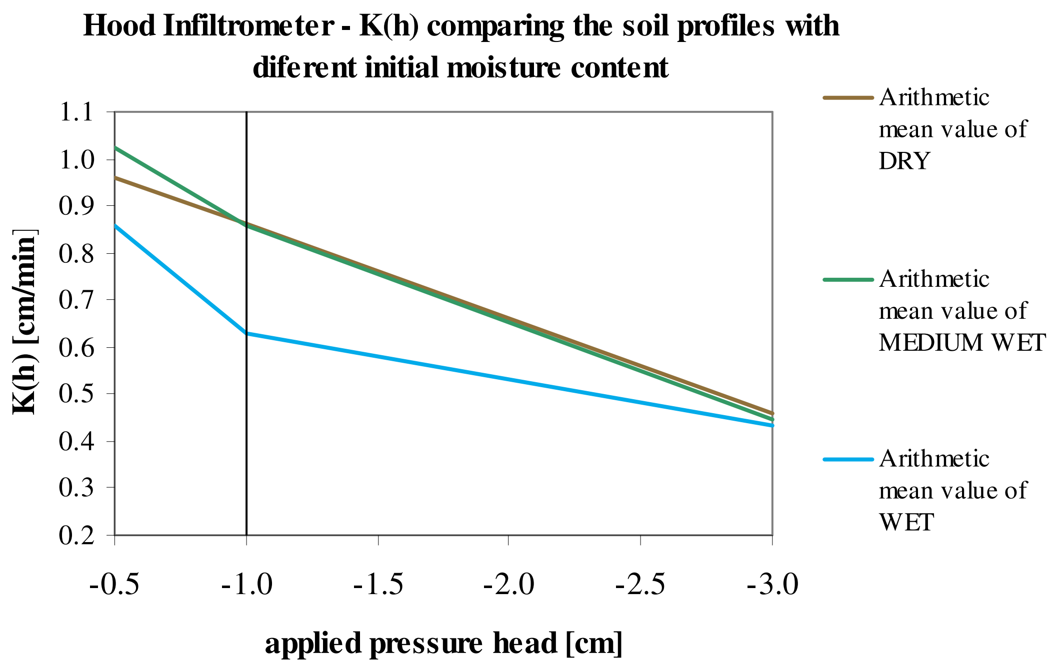


Figure 28 - HI K(h) - comparing the soil profiles with different initial water content

5.2 Calculation of hydraulic conductivity for Mini Disk Tension Infiltrometer

The measurements were performed for ascending -3, -1, -0,5 cm of pressure heads for MDTI and values were recorded manually every 30 seconds.

The good and consistent contact between soil surface and membrane of this device was achieved by using a thin layer of contact sand. Each tension step was held for 15 minutes. The graph of surface pressure head versus time of infiltration for MDTI is shown on Figure (29).

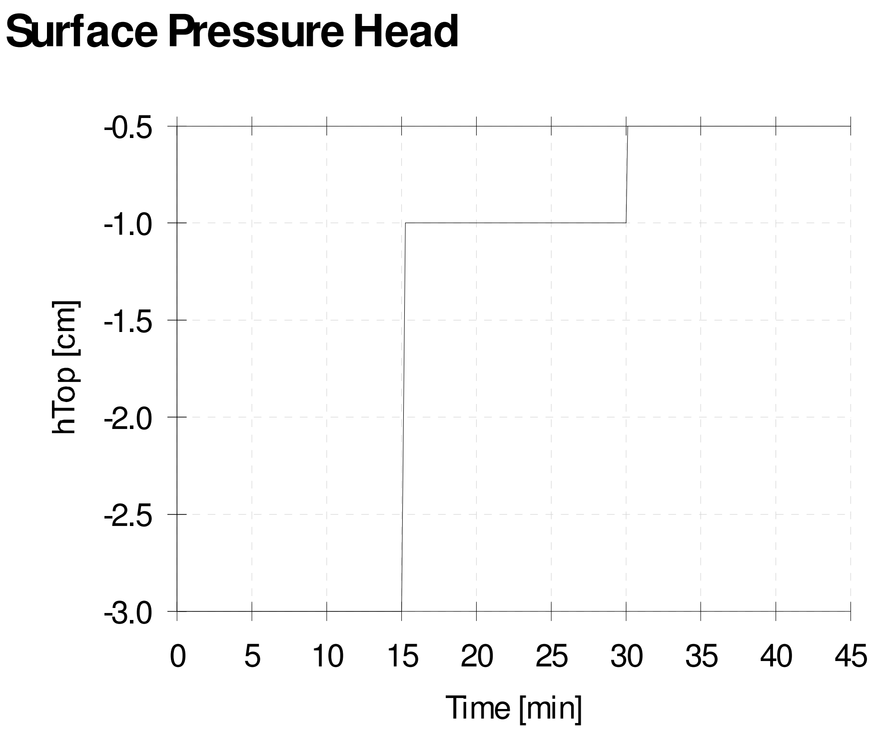


Figure 29 - Surface pressure head for MDTI

The calculated values of unsaturated hydraulic conductivities are shown in table below (Table 9) and also the graphs (Figures 30 - 33) to compare the cumulative infiltrations from each infiltrometer. The values of unsaturated hydraulic conductivities for MDTI are ordered from the lowest tension to the highest, despite that it was measured in the other order. It is done in this way to make this Table (9) consistent with the Table (8) for HI.

Table 9 - Values of K(h) from MDTI

applied pressure head	-0.5	-1	-3
place	unsaturated hydraulic conductivity in cm/min		
D1	0.023	0.024	0.006
D2	0.058	0.038	0.003
D3	0.033	0.014	0.007
D4	0.025	0.018	0.006
D5	0.027	0.021	0.004
Arithmetic mean value of DRY	0.033	0.023	0.005
MW1	0.004	0.003	0.003
MW2	0.029	0.01	0.002
MW3	0.041	0.023	0.004
MW4	0.006	0.005	0.003
MW5	0.029	0.014	0.003
Arithmetic mean value of MEDIUM WET	0.022	0.011	0.003
W1	0.045	0.029	0.001
W2	0.055	0.011	0.001
W3	0.018	0.011	0.001
W4	0.039	0.032	0.002
W5	0.036	0.016	0.002
Arithmetic mean value of WET	0.039	0.02	0.002

Graphs of cumulative infiltration from 45 minutes of infiltration from MDTI are shown in Figures (30 – 32). The vertical lines show the change of applied tension. The first applied pressure head for MDTI was -3, than -1 and the last one was -0.5. Each tension was performed for 15 minutes. The tendency of decreasing value of unsaturated hydraulic conductivity with increasing pressure head applied is visible on all three graphs.

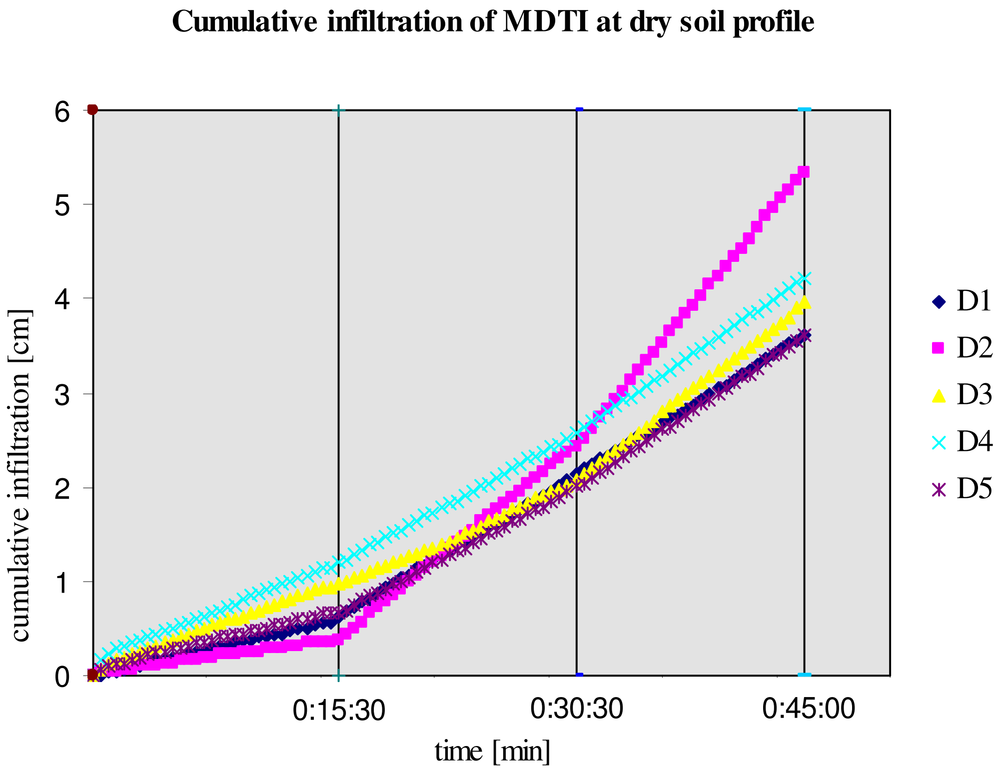


Figure 30 - Cumulative infiltration of MDTI at DRY soil profile

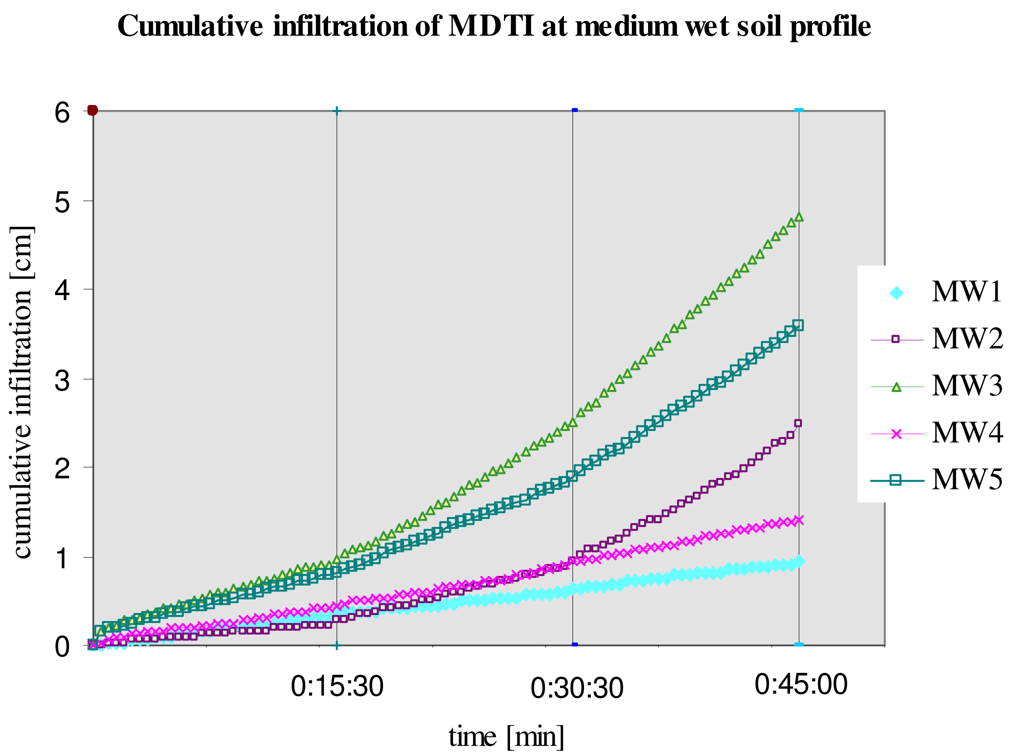


Figure 31 - Cumulative infiltration of MDTI at MEDIUM WET soil profile

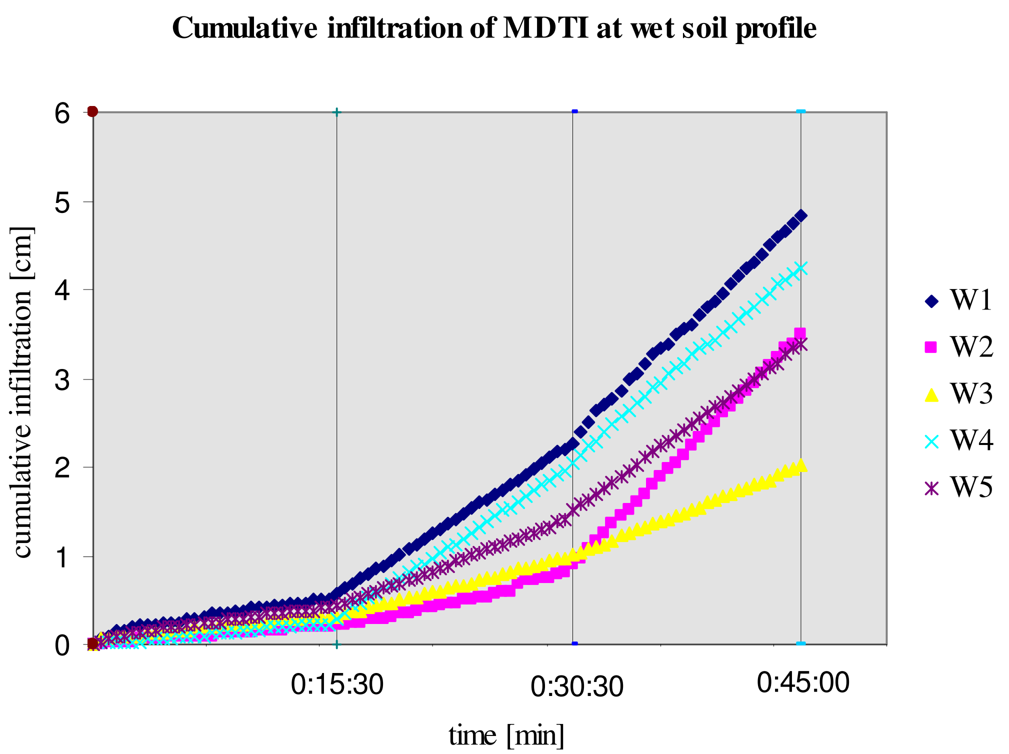


Figure 32 - Cumulative infiltration of MDTI at WET soil profile

Graphs of unsaturated hydraulic conductivity measured by MDTI are shown in Figures (33 – 36). Each initial water content has its own graph and then one graph with averages of K(h) under all the initial water contents is shown.

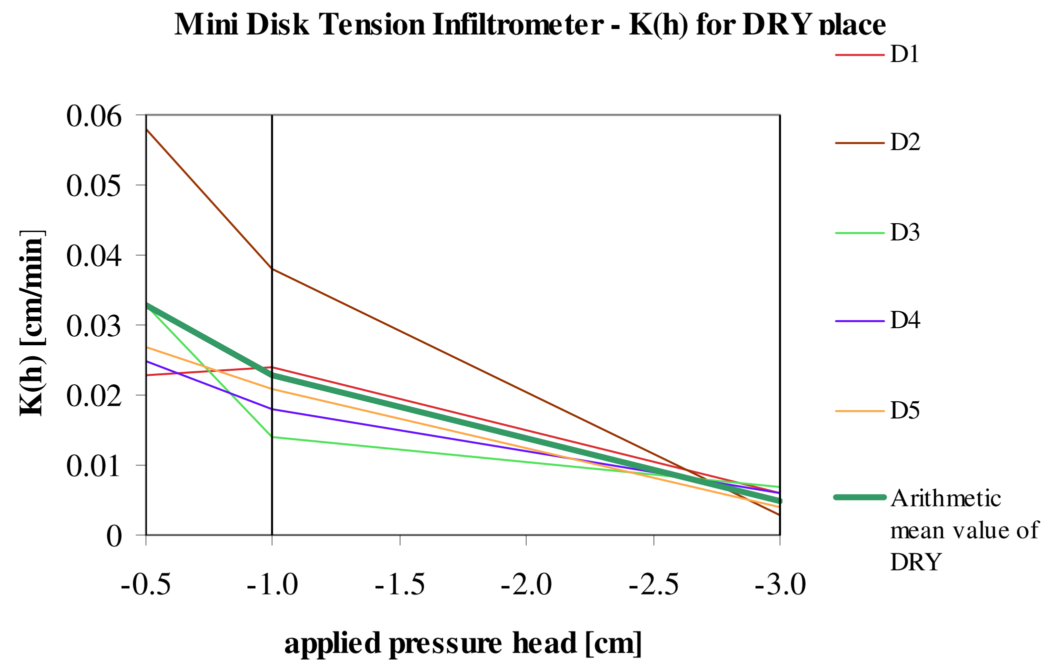


Figure 33 - MDTI K(h) for DRY place

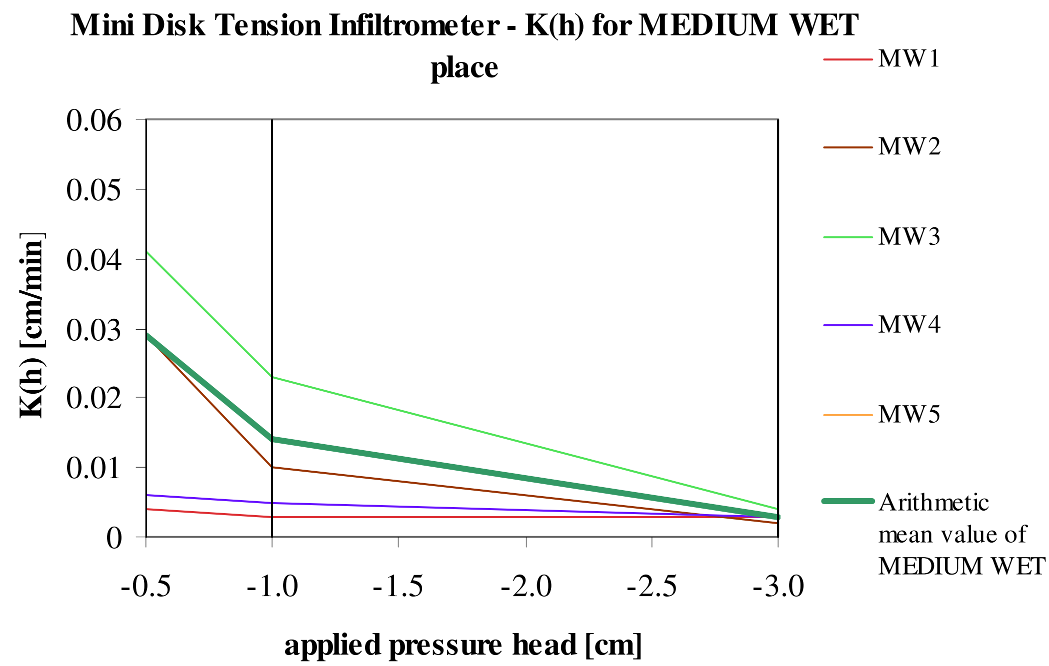


Figure 34 - MDTI K(h) for MEDIUM WET place

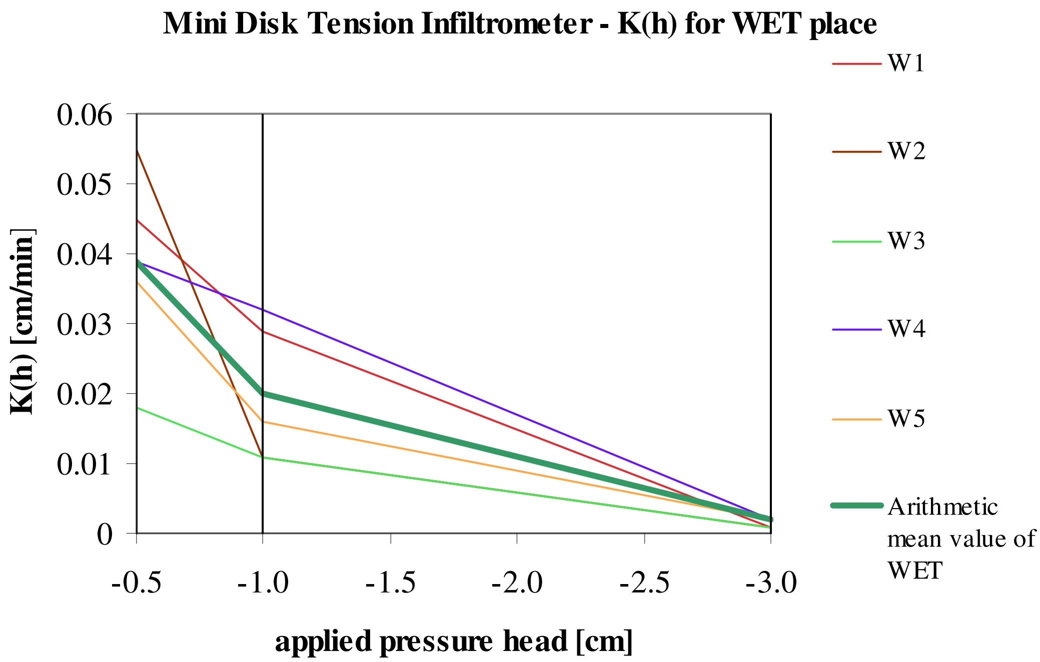


Figure 35 - MDTI K(h) for WET place

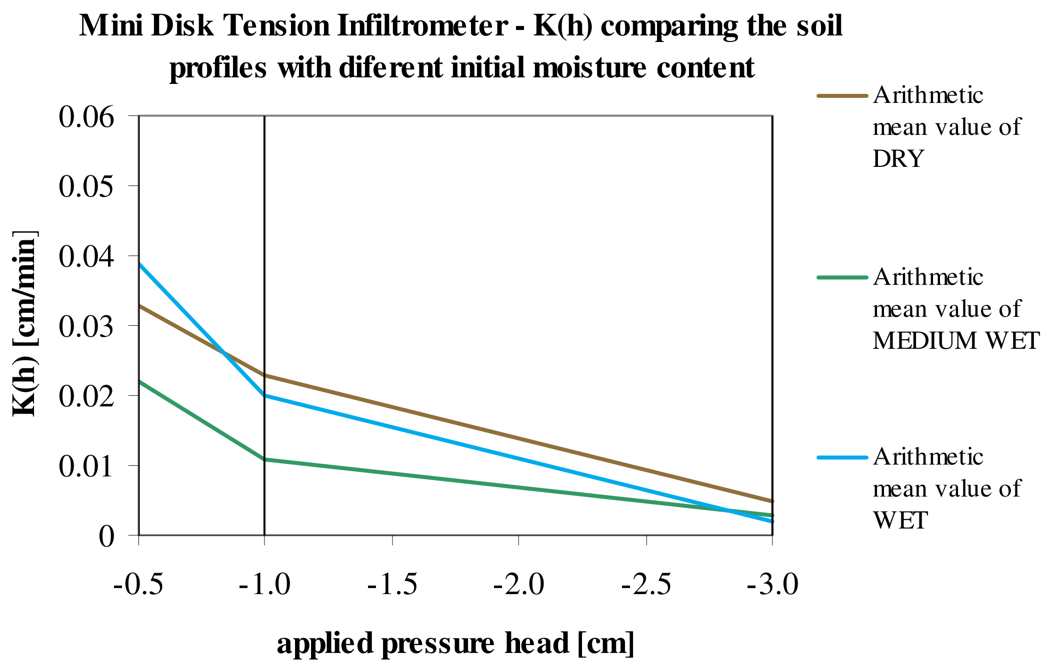


Figure 36 - MDTI K(h) - comparing the soil profiles with different initial water content

5.3 Correlation

The graphs of correlation are shown on Figures (37 – 38).

The first graph shows correlation of all values of unsaturated hydraulic conductivity measured by HI and MDTI for the first applied pressure head for both devices. It means the pressure head of -0.5 for HI and -3 for MDTI. The reason why only the first applied pressure head was used is that the initial water content is known only for these first tensions. The second graph shows medium values of K(h) measured by both devices.

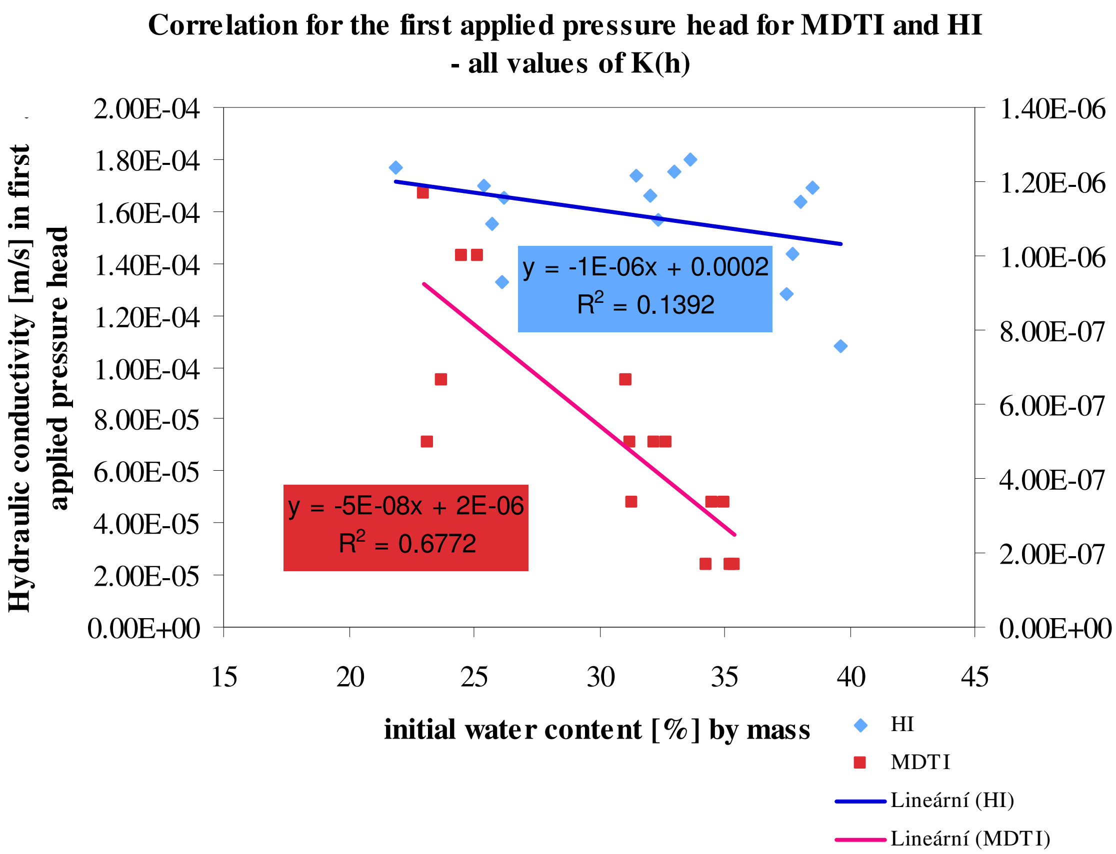


Figure 37 - Correlation for the first applied pressure head for MDTI and HI - all values of K(h)

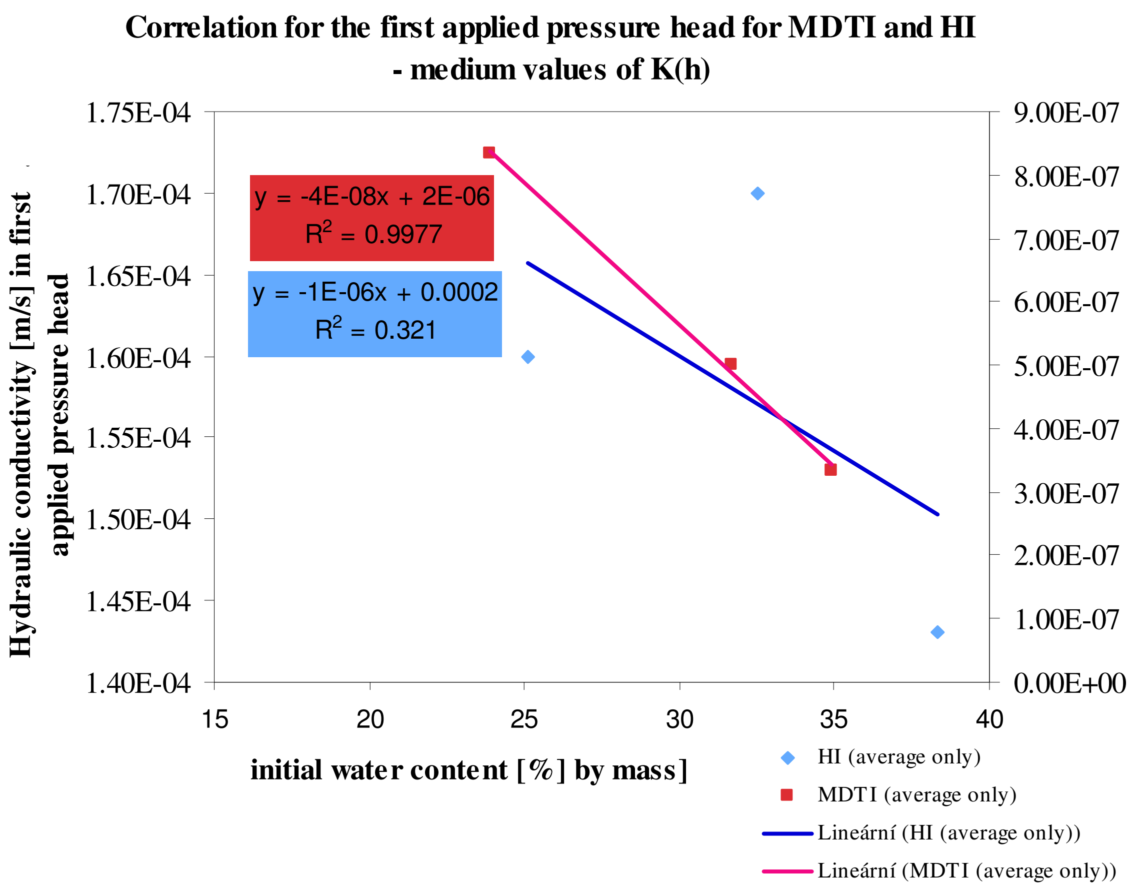


Figure 38 - Correlation for the first applied pressure head for MDTI and HI - medium values of K(h)

6 Discussion

With respect to the aims of the thesis, two devices for measuring the unsaturated hydraulic conductivity were compared. The results were evaluated with respect to initial water content of the soil profile as the factor affecting the determination of the unsaturated hydraulic conductivity and are discussed in following two Chapters 6.1 and 6.2. In the thesis two factors which influenced the measurements the most are evaluated – applied pressure head and the initial water content. Results of these issues are discussed in Chapters 6.4 and 6.5.

6.1 Hydraulic conductivity from HI measurement

The results of measured unsaturated hydraulic conductivity from HI measurements (see Table 8) were statistically evaluated. Table (10) shows the standard deviation (SD) and the coefficient of variance (CV).

Table 10 - Statistical evaluation of HI K(h)

	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]
	applied tension					
place	-0.5		-1		-3	
DRY	0.093	0.968	0.139	16.113	0.026	5.609
MEDIUM WET	0.049	5.099	0.104	11.986	0.133	28.812
WET	0.137	14.233	0.188	21.726	0.092	20.008

It is visible from Table (10) that differences of the hydraulic conductivity measured under pressure head of -0.5 cm are almost negligible as they have small values of CV. The hydraulic conductivities measured under wet conditions differ the most. Very variable results were also observed under the medium wet condition under the pressure head of -0.3 cm.

The unsaturated hydraulic conductivity of D1, D3, D5 and W1, W2 and W3 place differ from others. The conductivities of D1, D3 and W1 are higher than the others; on the other hand the unsaturated hydraulic conductivities of D5, W2, W3. This trend is visible in Table (8). It may be caused by lower total porosities of the D5, W2, W3 places and higher porosities for D1, D2 and W1 places in comparison with other measuring spots. There could be some biological activity under spots with higher hydraulic conductivities such as ants and earthworms.

The unsaturated hydraulic conductivities of dry and medium wet soils differ by only 1 – 6 percent for all three pressures applied, which is almost negligible. The values of dry and wet soil differ by 11 % for pressure head of -0.5, 27 % for pressure head of -1 cm and 6 % for pressure head of -3 cm. The trend of decreasing unsaturated hydraulic conductivity with increasing initial water content is visible.

Two correlation graphs (Figures 37 – 38) show that the measurement with HI of *K(h)* is not as much dependent on the initial water content as the measurement with MDTI. Only a weak dependence of *K(h)* measured by HI on the initial water content is visible.

6.2 Hydraulic conductivity from Mini Disk Tension Infiltrometer measurements

The standard deviation (SD) and coefficient of variance (CV) statistics was calculated also for the MDTI measurements (see Table 9). Results are visible in Table (11):

Table 11 - Statistical evaluation of MDTI K(h)

	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]
	applied tension					
place	-0.5		-1		-3	
DRY	0.013	1.338	0.008	0.949	0.001	0.319
MEDIUM WET	0.014	1.501	0.007	0.825	0.001	0.137
WET	0.012	1.268	0.009	1.039	0.000	0.106

The trend observed for HI is an opposite trend to the one observed for MDTI. The values measured under the pressure head of -3 cm vary the least and the values of -0.5 pressure head are significantly different. The differences between unsaturated hydraulic conductivities measurements under particular pressure head and initial water content are almost negligible as they have very small CV values.

Values obtained from MDTI are more homogenous than the values obtained from HI. The coefficient of variance is less than 1.51 %.

The trend of decreasing unsaturated hydraulic conductivity can be seen for the -3 cm pressure head applied the most. Other applied heads does not show any trend.

The correlation graphs (Figures 36 – 37) show that the measurement of *K(h)* with MDTI is significantly dependent on the initial water content. This dependence is visible especially for the mean values of *K(h)*. Thus the disadvantage of measurements with MDTI is that different values of *K(h)* are obtained with different weather conditions.

6.3 Comparison of HI and MDTI unsaturated hydraulic conductivities

The values for the hydraulic conductivity from MDTI and HI vary (see Table 12), but because there is still not any reference method to determine this, it is very difficult to say, which of these values is the correct one. Still there are not many comparison works to compare the measured values from these two devices in literature.

Table 12 - K(h) from MDTI and HI measurement

applied pressure head	-0.5		-1		-3	
used device	HI	MDTI	HI	MDTI	HI	MDTI
place	unsaturated hydraulic conductivity in cm/min					
D1	1.022	0.023	0.900	0.024	0.441	0.006
D2	0.927	0.058	0.894	0.038	0.512	0.003
D3	1.062	0.033	0.903	0.014	0.447	0.007
D4	0.991	0.025	1.019	0.018	0.459	0.006
D5	0.796	0.027	0.601	0.021	0.449	0.004
Arithmetic mean value of DRY	0.960	0.033	0.864	0.023	0.461	0.005
MW1	1.082	0.004	0.677	0.003	0.276	0.003
MW2	0.941	0.029	0.908	0.01	0.405	0.002
MW3	1.041	0.041	0.806	0.023	0.345	0.004
MW4	1.050	0.006	0.945	0.005	0.600	0.003
MW5	0.996	0.029	0.948	0.014	0.600	0.003
Arithmetic mean value of MEDIUM WET	1.022	0.022	0.857	0.011	0.445	0.003
W1	1.016	0.045	0.850	0.029	0.537	0.001
W2	0.647	0.055	0.328	0.011	0.261	0.001
W3	0.770	0.018	0.560	0.011	0.459	0.001
W4	0.861	0.039	0.804	0.032	0.443	0.002
W5	0.985	0.036	0.592	0.016	0.470	0.002
Arithmetic mean value of WET	0.856	0.039	0.627	0.020	0.434	0.002

The values of unsaturated hydraulic conductivity measured by HI are significantly higher than *K(h)* measured by MDTI. These results were also observed by Schwärzel and Punzel (2007) who observed the difference of measured values obtained by HI and MDTI.

They reported that values obtained from HI were almost one order of magnitude greater than the values of MDTI obtained under the corresponding pressure head applied.

The reason for smaller values of *K(h)* measured by MDTI could also be that the measurements with HI were done first and the soil profile was influenced by flooding with HI and thus the pores conducting water can be clogged by detached particles.

Some discrepancy in the measured data due to different infiltration areas of MDTI and HI is also visible. The infiltration area of the MDTI is much smaller and therefore can be influenced by the soil variability to a much greater extant than the HI. For this infiltration, the smaller radius (8 cm) of hood for HI was used to decrease this discrepancy. It can be said that it is hard to compare two devices which work on different principles, but the tendency of decreasing saturated hydraulic conductivity value with increasing water content in the soil profile for both devices is visible.

6.4 Pressure head

The results of the unsaturated hydraulic conductivity are in accordance with i.e. Logsdon (1993) with respect to the pressure heads. It was observed by the author, that as the heads become less negative, the sorptivity *S* and also hydraulic conductivity *K* increases. This tendency is visible also in the results (see Tables 8 and 9) of this thesis where with applied pressure heads -0,5; -1 and -3 for both devices the unsaturated hydraulic conductivity *K(h)* considerably decreases. This is visible for both MDTI and HI.

The results from both infiltrometers show that the values of unsaturated hydraulic conductivity fluctuate less for tension -0.5 applied for HI and for tension -3 performed for MDTI. This trend was discussed in Chapters 6.1 and 6.2. Both tension -0.5 for HI and -3 for MDTI are the first performed tensions for these devices. The reason could be that the following flow can be influenced by the flow under the first tension applied. The soil profile then has different water content and thus may behave in a different way and fluctuate more in the value of unsaturated hydraulic conductivity.

6.5 Initial water content

There are many authors who deal with the measurement of saturated and unsaturated hydraulic conductivity with respect to different initial water contents. Namely they are Angulo-Jaramillo et al. (2000), Benson and Trast (1995), Benson and Daniel (1990), Benson et al. (1994), El-Shafei and Al-Darby (1991), Hawke et al. (2006), Kim and Kim (2009) and Logsdon (1993) who are mentioned in Chapter 3.4.7.

First the authors with similar results are listed:

The lower unsaturated hydraulic conductivity with increasing initial water content was observed also by Benson et al. (1994) who made measurements for clay soils using permeameters. This trend is visible also in the work of Benson and Trast (1995) who, discovered strength dependence of the hydraulic conductivity on the initial water content.

Hawke et al. (2006) described the influence of rainfall intensity and initial soil water content on changes in hydraulic conductivity. For this measurement a different method to infiltrometry was used. They measured this property by using TDR method, the Time-Domain Reflectometer, which is a sensor for indirect soil water content determination. They discovered that the rainfall can affect the matrix structure on the surface of the soil. This can cause clogging of the pores by detached particles and influence the hydraulic conductivity. Thus the measured hydraulic conductivity decreases with increasing initial water content.

Angulo-Jaramillo et al. (2000) made an experiment on two types of soil – sandy soil and stony sandy loam with tension disk infiltrometer. They discovered that there is a big difference of the measured hydraulic conductivity with respect also to the type of irrigation. They observed that the furrow irrigation used on the sandy soil shows a drastic reduction of hydraulic conductivity. On the other hand for the sandy loam soil there was almost no significant difference in hydraulic conductivity.

On the other hand there is also an experiment with different results:

Extensive observations about the initial water content were also made by Logsdon (1993). Measurements on seven dates during the year on clay loam soil were made using tension infiltrometer. Other factors which were taken into account were canopy cover and different pressure heads. It was observed that the hydraulic conductivity fluctuated over the measurements with no relation to initial water content.

6.6 Evaluation of measurements and recommendations

The measurements of unsaturated hydraulic conductivity in this thesis were made under natural conditions on the experimental field of Czech University of Life Sciences Prague.

In the case of measuring in situ, it is difficult to reach homogenous conditions for all measurements.

The two devices – HI and MDTI – were compared with respect to initial water content of the soil profile. However, under the natural conditions there is an influence of weather – sunshine, wind, rain, temperature – on the measuring of the unsaturated hydraulic conductivity. The soil heterogeneity and biological activity also has a big effect on the measured values as they can be influenced by bigger pores caused by earthworms plus other factors. If these natural conditions are omitted the measuring can be more accurate.

As it was mentioned in one of the previous Chapters 6.3, there is also a visible discrepancy in the measured data for HI and MDTI. It is caused by different infiltration areas of these two devices. The infiltration area of MDTI is much smaller than the HI and thus the value of hydraulic conductivity can be influenced by the higher soil variability.

Another incompatibility which can be observed during comparison of these two infiltrometers is the different principles of measuring, and also the need to use the contact material for MDTI.

The recommendations for extended research are to hold this measurement under homogenous conditions which can probably only be achieved in the laboratory. This is possible to perform for the MDTI but problematic for the HI as more water is infiltrated in the soil profile. Also, maybe a higher number of measuring with just one device has a better predictive value and can compare the effect of initial water content of the soil. Another option is to hold these measurements under higher steps of different initial water content conditions and also make measurement on different soil types.

7 Conclusions

The most important factors affecting the determination of unsaturated hydraulic conductivity were described and compared from different authors. A particular focus is given to different initial water content conditions of the soil profile and the influence of this condition to the obtained data from the infiltrometers. The effect of applied pressure head is also studied.

The initial water content of the soil is widely discussed in the literature. The experiment was performed using two infiltrometers on the experimental field of Czech University of Life Sciences Prague. HI and MDTI were used for measuring the unsaturated hydraulic conductivity $K(h)$ with many replications. The HI is a relatively new device and thus it was chosen to be explored more. The results of the $K(h)$ values of this thesis correspond to results of other authors as mentioned.

The trend of decreasing $K(h)$ with increasing pressure head applied was observed for both devices used. The measurement with HI show that the measurement of $K(h)$ is not as much dependent on the initial water content as the measurement with MDTI. Only a weak dependence of $K(h)$ measured by HI on the initial water content is visible. The measurement of $K(h)$ with HI is not influenced so much by external conditions. The hypothesis was fulfilled for MDTI, but for HI it is not conclusive.

8 References

Angulo-Jaramillo, R., Vandervaere, J.-P., Roulier, S., Thony, J.-L., Gaudet, J.-P., Vauclin, M. (2000) Field measurement of soil surface hydraulic properties by disc and ring infiltrometers. A review and recent developments. Soil & Tillage Research, 55: 1-29.

Ankeny, M. D., Ahmed, M., Kaspar, T.C., and Horton, R. (1991) Simple field method for determining unsaturated hydraulic conductivity. Soil Science Society of America Journal, 55**,** 467-470.

Ankeny, M. D., Kaspar, K.C., and Horton, R. (1988) Design for an automated tension infiltrometer. Soil Science Society of America Journal, 52**,** 893-896.

Ankeny, M. D., Kaspar, T.C., Horton, R. (1990) Characterization of tillage and traffic effects on unconfined infiltration measurement. Soil Science Society of America Journal, 54, 810-837.

Bagarello, V., Iovino, M., Tusa, G. (2000) Factors affecting measurement of the near saturated soil hydraulic conductivity. Soil Science Society of America Journal, 64: 1203-1210.

Bagarello, V., Iovino, M., Tusa, G. (2001) Effect of contact material on tension infiltrometer measurements. Transactions of the ASAE, 44, 911-916.

Benson, C.H., Daniel, D. (1990) Influence of clods on hydraulic conductivity of compacted clay. Journal of Geotechnical Engineering, 116, 1231-1248.

Benson, C.H., Trast, J.M. (1995) Hydraulic conductivity of thirteen compacted clays. Clays and Clay Minerals, vol. 43, No. 6, 669-681.

Benson, C.H., Zhai, H., Wang, X. (1994) Estimating the hydraulic conductivity of compacted clay liners. Journal of Geotechnical Engineering, 120, 366-387.

Buczko, U., Bens, O., Hüttl, R.F. (2006) Water infiltration and hydrophobicity in forest soils of a pine-beech transformation chronosequence. Journal of Hydrology, 331, 383-395.

Casey, F. X. M., and Derby, N.E. (2002) Improved design for an automated pension infiltrometer. Soil Science Society of America Journal, 66**,** 64-67.

Close, K.R., Frasier, G., Dunn, G.H., Loftis, J.C. (1998) Tension infiltrometer contact interface evaluation by the use of potassium iodide tracer. Transactions of the ASAE, 41: 995-1004.

Dane, J.H., Topp, G.C. (Ed.) (2002) Methods of soil analysis; Part 4 - Physical methods, No.5, 1st edition, Soil Science Society of America, Inc., Madison, p. 1692 (chapters 3 and 4).

Dixon, R. M. (1975) Design and use of closed-top infiltrometers. Soil Science of American Proceedings, 39**,** 755-763.

Chowdary, V.M., Damodhara Rao, M., Jaiswal, C.S. (2006) Study of infiltration process under different experimental conditions. Agricultural water management, 83, 69-78.

El-Shafei, Y.Z., Al-Darby, A.M. (1991) Initial moisture content in relation to infiltration capacity of sandy soils. Agric. Sci., 2, 333-348.

Elrick, D.E., Reynolds, W.D. (1992) Infiltration from Constant-Head Well Permeameters and Infiltrometers. Soil Science Society of America, 677, 1-24

Hawke, R.M., Price, A.G., Bryan, R.B. (2006) The effect of initial soil water content and rainfall intensity on near-surface soil hydrologic conductivity: A laboratory investigation. Elsevier: Catena, 65, 237-246.

Hillel, D. (1998) Environmental Soil Physics. Academic Press, New York, USA, 771 p.

Johnson, A.I. (1963) A Field Method for Measurement of Infiltration, Washington, Geological Survey Water-Supply Paper 1544-F, United States Government Printing Office, 27 p.

Kechavarzi, C., Špongrová, K., Dresser, M., Matula, S., Godwin, R.J. (2009) Laboratory and field testing of an automated tension infiltrometer. Biosystems Engineering, 104: 266-277.

Kim, Ch., Kim, T. (2009) Behavior of unsaturated weathered residual granite soil with initial water contents. Elsevier: Engineering Geology 113, 1-10.

Klute, A. (Ed.) (1986) Methods of soil analysis; Part 1 - Physical and mineralogical methods, No.9, 2nd edition, American Society of Agronomy, Inc. and Soil Science Society of America, Inc., Madison, p. 1188 (chapter 26).

Kutílek, M. and Nielsen, D.R. (1994) Soil Hydrology . Catena Verlag, Cremlingen – Destedt, 370 p.

Lal, R., Shukla, M.K. (2004) Principles of Soil Physics, Marcel Dekker, Inc., New York, 716 p., ISBN: 0-8247-5324-0

Lin, H. S., Mc Innes, K.J. (1995) Water flow in clay soil beneath a pension infiltrometer. Soil Science*,* 159**,** 375-382.

Logsdon, S. D. (1993) Negative head hydraulic properties of the soil surface at different times. Soil Science, 156**,** 373-379.

Logsdon, S.D., Jordahl, J.L., Karlen, D.L. (1993) Tillage and crop effects on ponded and pension infiltration rates. Soil & Tillage Research, 28, 179-189.

Lohman, S.W., (1972) Ground-Water Hydraulics. Geological Survey Professional Paper 708, United States Government Printing Office, Washington.

Matula, S (2003) The influence of tillage treatments on water infiltration into soil profile. Plant soil environ., 49, 298-306.

Mohanty, B. P., Ankeny, M.D., Horton, R., Kanwar, R.S. (1994) Spatial analysis of hydraulic conductivity measured using disc infiltrometers. Water Resources Research*,* 30**,** 2489-2498.

Perroux, K. M., and White, I. (1988) Designs for disk permeameters. Soil Science Society of America Journal, 52, 1205-1215.

Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F., Tan, C.S. (2000) Comparison of pension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Science Society of America Journal, 64, 478-484.

Reynolds, W.D., Elrick, D.E. (1991) Determination of hydraulic conductivity using a tension infiltrometer. Soil Science Society of America Journal, 55, 633-639.

Reynolds, W. D., Zebchuk, W.D. (1996) Use of contact material in pension infiltrometer measurements. Soil Technology*,* 9**,** 141-159.

Shirmohammadi, A., Skaggs, R.W. (1985). Predicting infiltration for shallow water table soils with different surface covers. Transactions of American Society of Agricultural Engineers, 28(6), 1829-1837.

Schwärzel, K., Feger, K.-H., Carrick, S., Buchan, G. (2009) How does crop management control soil hydraulic properties? Deutsche Bodenkundliche Gesellschaft, online on http://www.ddbges.de, visited 7/2011.

Schwärzel, K., Punzel, J. (2007) Hood Infiltrometer – A new type of tension infiltrometer. Soil Science Society of America Journal, 71, 1438-1447.

Shouse, P. J., and Mohanty, B.P. (1998) Scaling of near-saturated hydraulic conductivity measured using disc infiltrometers. Water Resources Research, 34, 1195-1205.

Smettem, K. R. J., and Clothier, B.E. (1989) Measuring unsaturated sorptivity and hydraulic conductivity using multiple disc permeameters. Journal of Soil Science, 40, 563-568.

Šimůnek, J., Angulo-Jaramillo, R., Shaap, M.G., Vandervaere, J.P., van Genuchten, M.T. (1998) Using an inverse method to estimate the hydraulic properties of crusted soils from tension-disc infiltrometer data. Geoderma, 61-81.

Šimůnek, J., van Genuchten, M.Th. (1997) Parameter estimation of soil hydraulic properties from multiple tension disc infiltrometer data. Soil Science, 162, 383-398.

Špongrová, K., Kechavarzi, C., Dresser, M., Matula, S., Godwin, R.J. (2009) Development of an automated tension infiltrometer for field use. Vadose Zone Journal, 8, 810-817.

Topp, G.C., Reynolds, W.D., and Green, R.E. (1992) Advances in measurement of soil physical properties: Bringing theory into practice, SSSA Special Publication no. 30, Soil Science Society of America, Inc., Madison, USA. 288 p.

Valla, M., Kozák, J., Němeček, J., Matula, S., Borůvka, L., Drábek, O. (2008) Pedologické praktikum. Česká zemědělská univerzita, Praha. 155 p.

Vandervaere, J.-P., Vauclin, M., Elrick, D.E. (2000) Transient flow from tension infiltrometers: I. The two-parameter equation. Soil Science Society of America Journal, 64: 1263-1272.

Vandervaere, J.-P., Vauclin, M., Elrick, D.E. (2000) Transient flow from tension infiltrometers: II. Four methods to determine sorptivity and conductivity. Soil Science Society of America Journal, 64: 1272-1284.

Ventrella, D., Losavio, N., Vonella, A.V., Leij, F.J. (2005) Estimating hydraulic conductivity of a fine-textured soil using tension infiltrometry. Geoderma, 124, 267-277.

Walker, C., Lin, H.S., Fritton, D.D. (2006) Is the tension beneath a tension infiltrometer what we think it is? Vadose Zone Journal, 5, 860-866.

White, I., Perroux, K.M. (1989) Estimation of unsaturated hydraulic conductivity from field sorptivity measurements. Soil Science Society of America Journal, 53, 324-329.

White, I., Sully, M.J., and Perroux, K.M. (1992) Measurement of surface-soil hydraulic properties: disk permeameters, tension infiltrometers, and other techniques. In: G.C. Topp,

Zhang, R. (1997) Infiltration models for the disk infiltrometer. Soil Science Society of America Journal, 61, 1597-1603.

Decagon Devices, Inc: Mini Disk Tension Infiltrometer [online]. Accessed in 06/2011. Available at http://www.decagon.com/products/lysimeters-and-infiltrometers/mini-disk-tension-infiltrometer/.

Delta-T Devices, Ltd: ML2x ThetaProbe [online]. Accessed in 04/2012. Available at http://www.delta-t.co.uk/product-display.asp?id=ML2x Product&div=Irrigation and Horticulture.

Educational Technology Clearinghouse: Pycnometer [online]. Accessed in 04/2012. Available at http://etc.usf.edu/clipart/26800/26840/pycnometer_26840.htm.

Miller, J.D., Gaslein, G.J.: Theta Probe ML2x [online]. Accessed in 04/2012. Available at http://www.macaulay.ac.uk/MRCS/pdf/tprobe.pdf.

Sklopísek Střeleč: Produkty [online]. Accessed in 04/2012. Available at http://www.glassand.eu/index.php?page=katalog#skla.

UGT GmbH: HI IL 2700 [online]. Accessed in 06/2011. Available at http://ugt-online.de/en/produkte/bodenkunde/messgeraete-fuer-die-hydraulische-und-pneumatische-leitfaehigkeit/haubeninfiltrometer-il-2700.html.

Wine Business.com [online]. Accessed in 04/2012. Available at http://www.winebusiness.com/content/Image/theta-probe.jpg.

9 List of symbols

List of symbols			
Roman alphabet			
Symbol	**Description of symbol**	**Dimension**	**Unit**
a	dimensionless length		
A	value relating to Van Genuchten parameters		
A	cross section of intiltrometer	L	cm
$C1$, $C2$, $C3$	parameters		
d	radius	L	cm
G_s	particle density		
h	applied tension, soil water potential	L	cm
h_1, h_2	neighboring values of chosen water tensions	L	cm
h_0	pressure head, tension	L	cm
h_a	simulated soil air pressure head	L	cm
h_i	initial water potential	L	cm
h_s	effective surface head	L	cm
h_w	ponded water depth	L	cm
I	cummulative infiltration	L	cm
I_{1D}	cummulative infiltration during 1D process	L	cm
I_{3D}	cummulative infiltration during 3D process	L	cm
K	saturated hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
K_r	relative hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
K_S	saturated hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
$K(h)$	hydraulic conductivity function	$L\,T^{-1}$	$cm.min^{-1}$
k_f	saturated hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
k_u	hydraulic conductivity under unsaturated conditions	$L\,T^{-1}$	$cm.min^{-1}$
l	length	L	cm
m_1	mass of pycnometer filled with water	W	g
m_2	mass of pycnometer filled with soil suspension	W	g
m_s	mass of soil dried under 105 °C	W	g
m_w	mass of water	W	g
m_z	mass of dry sample	W	g
n	value relating to Van Genuchten parameters		
P	total porosity	%	%
q	steady-state infiltration rate	$L\,T^{-1}$	$cm.min^{-1}$
Q	steady-state infiltration flux	$L\,T^{-1}$	$cm.min^{-1}$

r	radius, radial coordinate	L	cm
r_0	disk radius	L	cm
R	disk radius	L	cm
S	sorptivity	L $T^{-1/2}$	cm.$min^{-1/2}$
t	time	T	min
V	total volume of soil	L^3	cm^3
V_t	volume of soil under natural conditions	L^3	cm^3
V_w	volume of water	L^3	cm^3
w	water content by mass, molding water content	L^3L^{-3}	cm^3cm^{-3}
z	vertical coordinate	L	cm

List of symbols

Greek alphabet

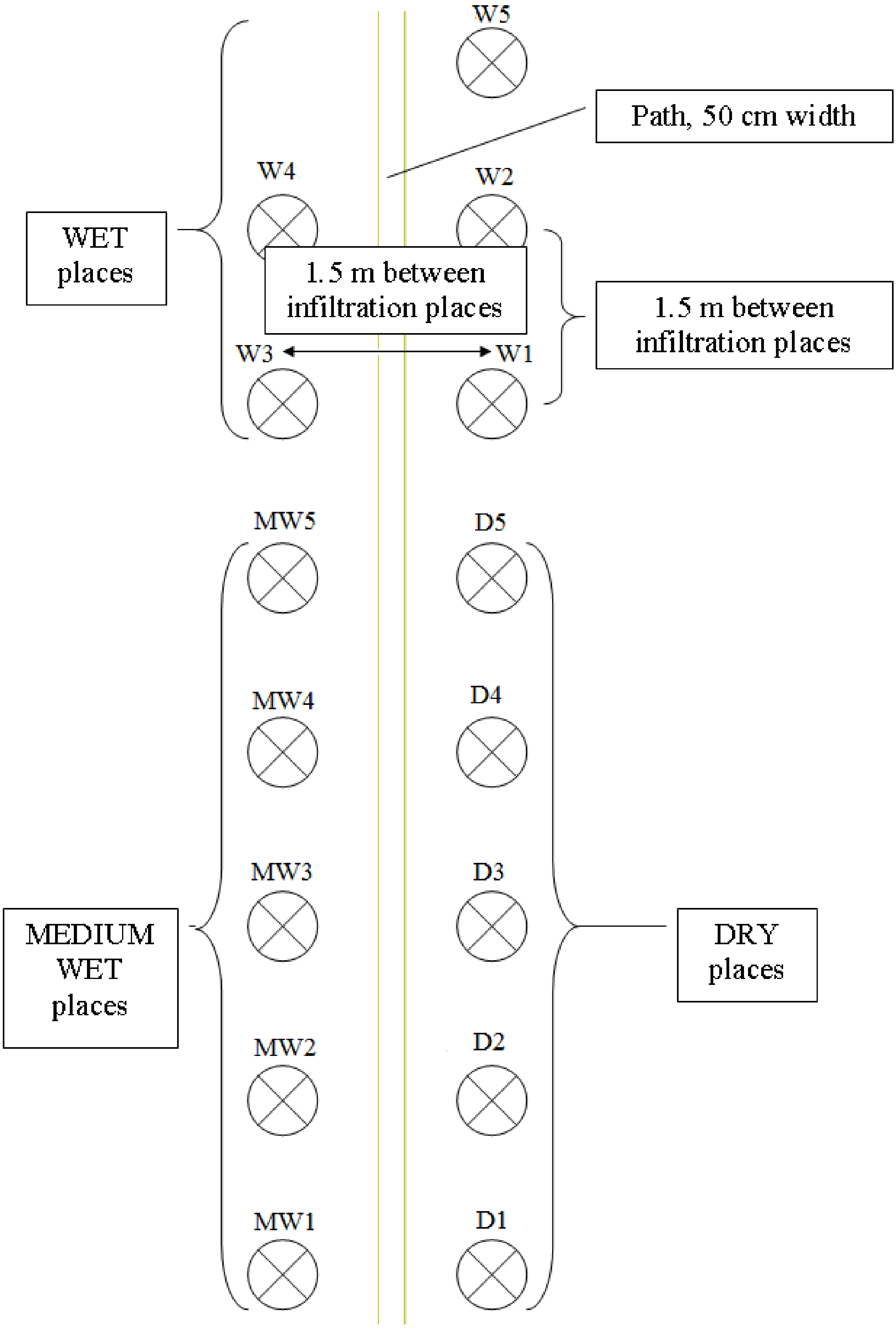
Symbol	Description of symbol
α	constant
α	sorptive number
β	constant
γ	constant
γ_d	dry unit weight
γ_w	unit weight of water
ψ	water potential
ψ_i	initial or background pore water potential
ψ_t	steady water potential
ϕ	matric flux potential
θ	volumetric water content
θ_r	volumetric water content
ρ_d	dry bulk density
ρ_z	specific weight of soil particles

Abbreviations

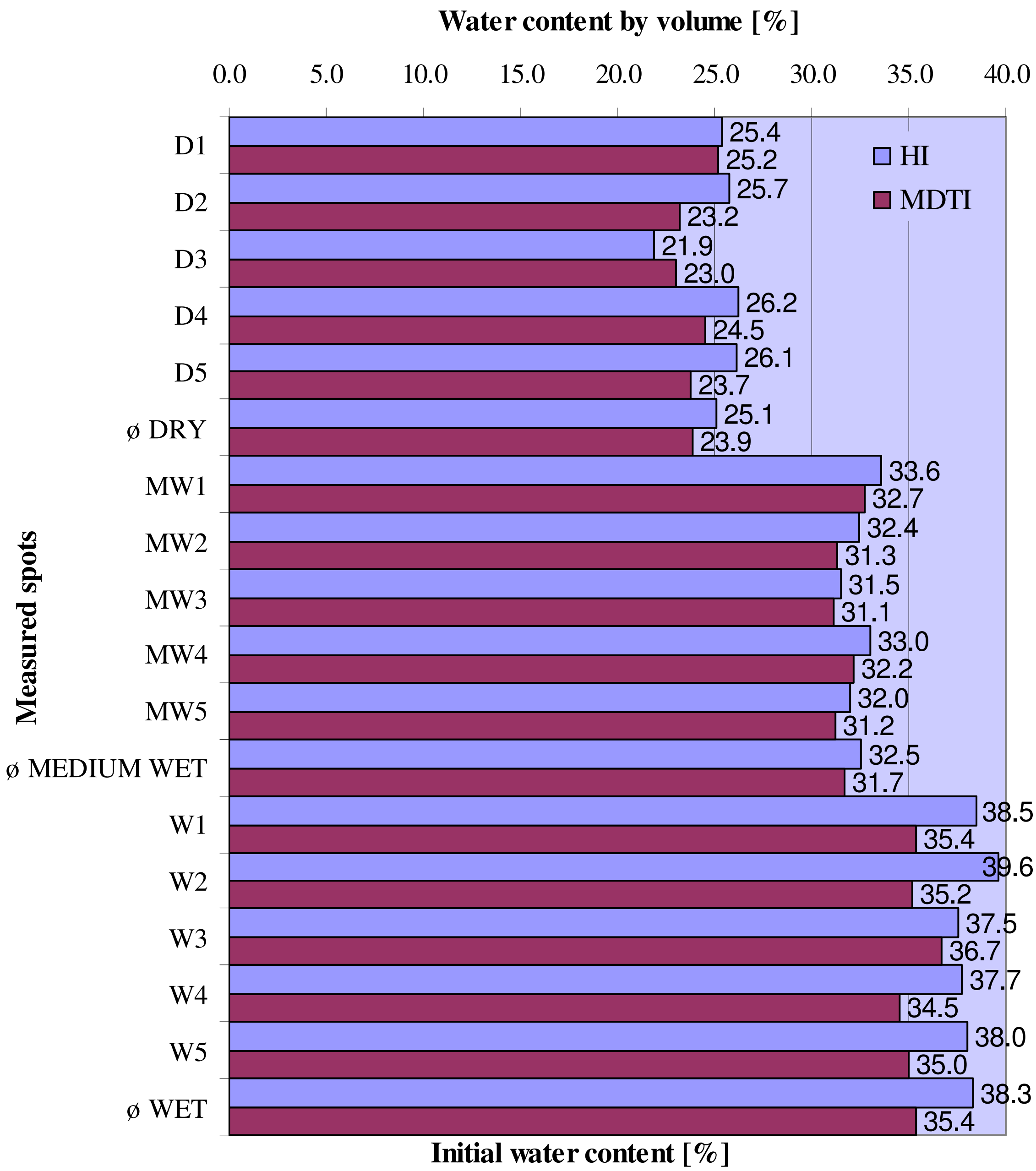
CV	coefficient of variance
HI	Hood Infiltrometer
max	maximum
min	minimum
MDTI	Midi Disk Tension Infiltrometer
SD	standart deviation
SWRT	Soil Water Retention Curve
TDR	Time-Domain reflectometry

10 Appendices

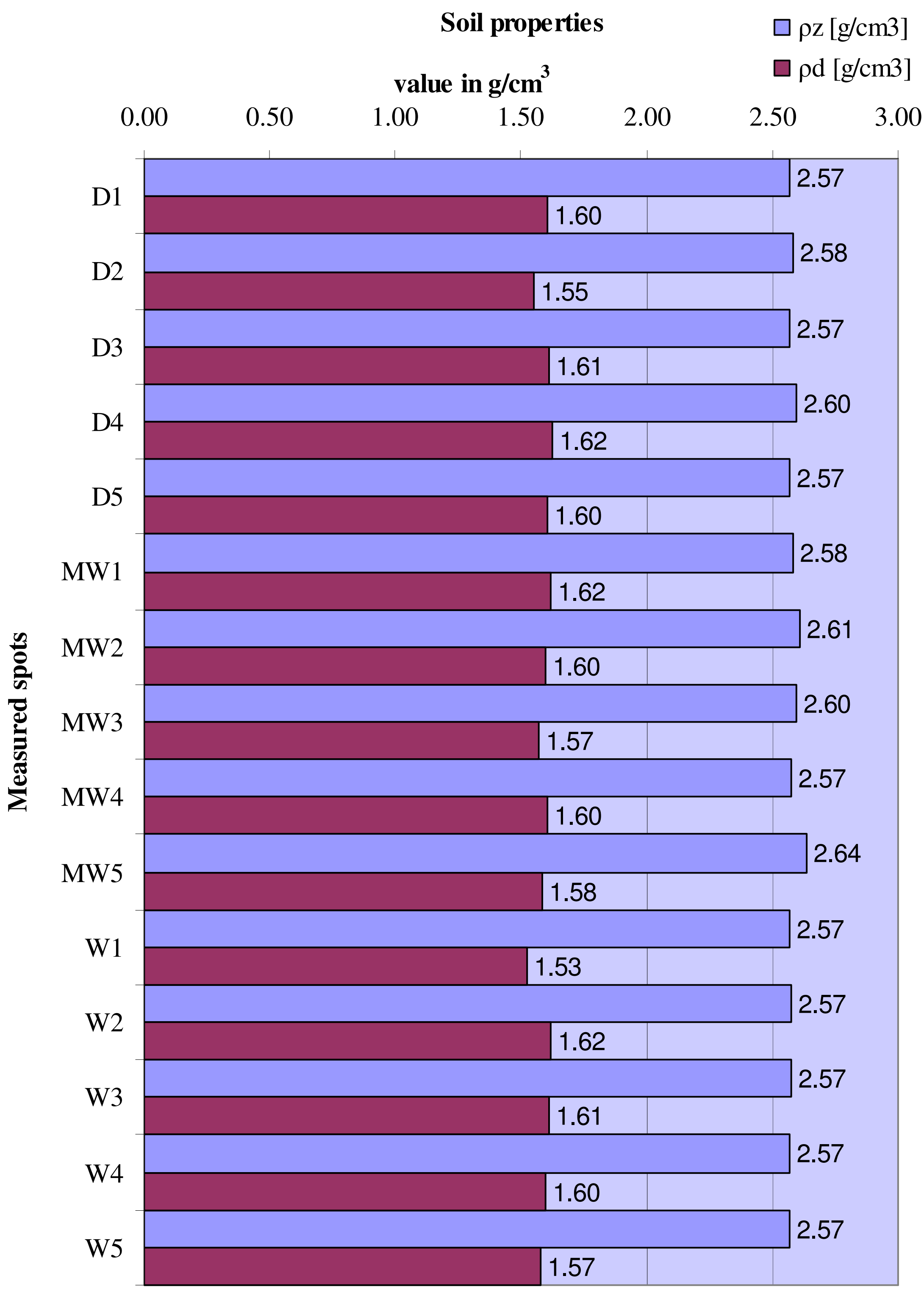
Appendix 1 - The layout of the field



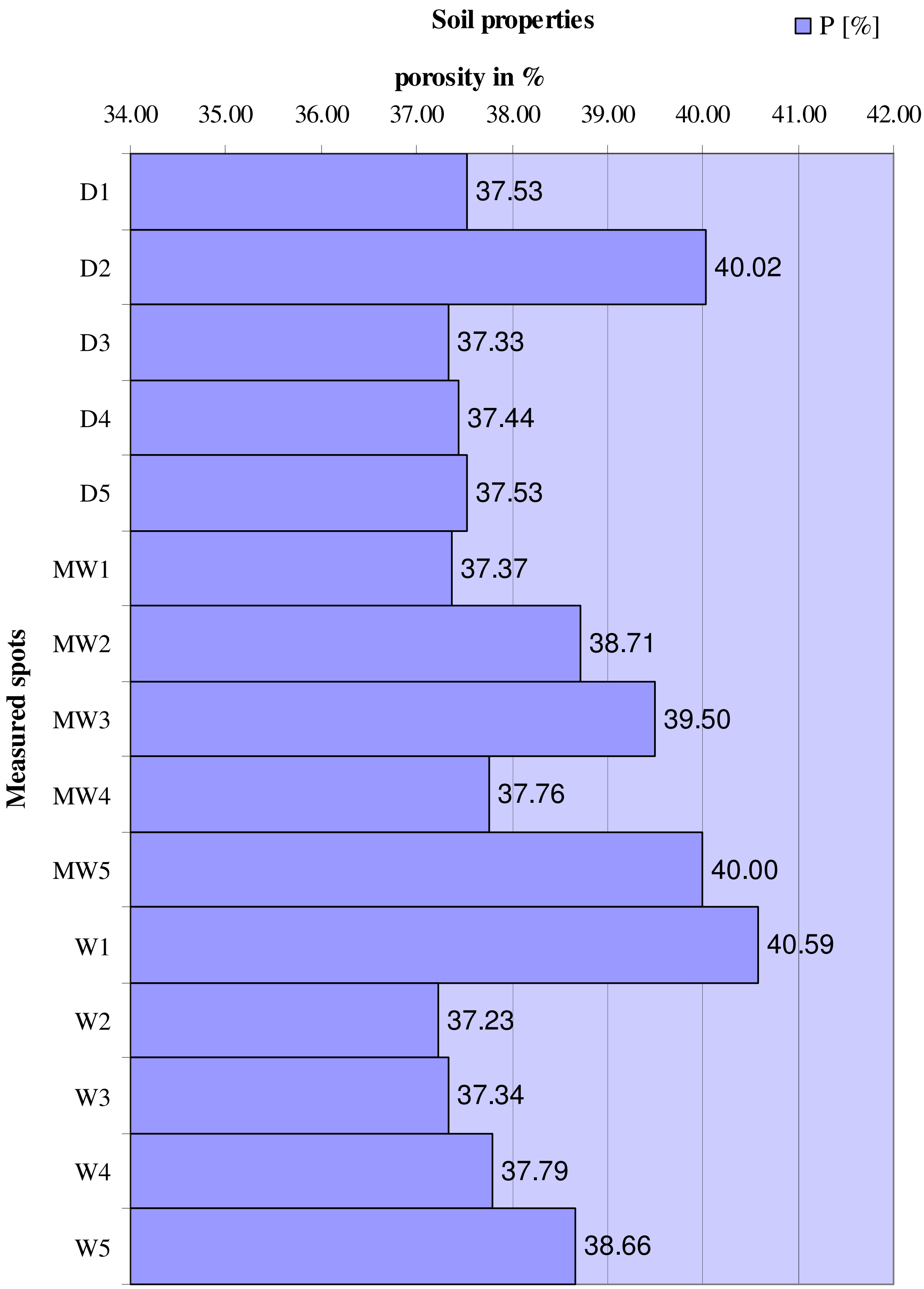
Appendix 2 - Initial water content by volume on each spot; data for HI and MDTI



Appendix 3 - Soil properties (particle density and dry bulk density) for each spot of measurement



Appendix 4 - Soil property (porosity) for each measurement spot



Appendix 5 - Calculation of K(h) for HI in Excel sheet

tension	Time of measurement [hr:min:sec]	Real values from reservoir [mm of water column]	Decrease of surface in water reservoir [cm]	Cumulative decrease of surface in water reservoir [cm]	Real infiltrated volume, V=75,10*deccrease of surface in water reservoir [cm3]	Q=V/t [cm/min]		calculation of parameter alfa from equation: alpha	K(h)	
-0.5	0:30:30	209.9	0	0	0	0			1.6176675	cm/min
	0:30:45	196.4	1.05	1.05	78.855	315.42	α	0.25201	1.6315517	m/s
	0:31:00	183	1.1	2.15	82.61	330.44				
	0:31:15	170.4	1.13	3.28	84.863	339.452				
	0:31:30	157.4	1.12	4.4	84.112	336.448				
	0:31:45	144.4	1.07	5.47	80.357	321.428				
	0:32:00	132	1.06	6.53	79.606	318.424				
	0:32:15	119.4	1.08	7.61	81.108	324.432				
	0:32:30	106.9	1.07	8.68	80.357	321.428				
	0:32:45	92	1.07	9.75	80.357	321.428	sum of Q	average of Q		
	0:33:00	79.7	1.11	10.86	83.361	333.444				
	0:33:15	67.6	1.05	11.91	78.855	315.42	3577.76	325.251		
-1	1:12:00	220.8	0	0	0	0				
	1:12:15	211.2	0.96	0.96	72.096	288.384			1.4261552	cm/min
	1:12:30	201.3	0.92	1.88	69.092	276.368	α	0.39873	1.3991597	m/s
	1:12:45	191.8	1.03	2.91	77.353	309.412				
	1:13:00	181.7	0.9	3.81	67.59	270.36				
	1:13:15	172.3	1	4.81	75.1	300.4				
	1:13:30	162.2	0.94	5.75	70.594	282.376				
	1:13:45	153.3	0.92	6.67	69.092	276.368				
	1:14:00	143.8	0.91	7.58	68.341	273.364				
	1:14:15	134.7	0.97	8.55	72.847	291.388				
	1:14:30	125.5	1.01	9.56	75.851	303.404				
	1:14:45	115.7	0.94	10.5	70.594	282.376	3154.2	286.745		
-3	2:00:15	259.4	0	0	0	0				
	2:00:30	254.9	0.45	0.45	33.795	135.18			0.642449	cm/min
	2:00:45	250.8	0.41	0.86	30.791	123.164	α	0.39873	1.3991597	m/s
	2:01:00	246.7	0.41	1.27	30.791	123.164				
	2:01:15	242.4	0.43	1.7	32.293	129.172				
	2:01:30	237.9	0.45	2.15	33.795	135.18				
	2:01:45	233.6	0.43	2.58	32.293	129.172				
	2:02:00	229.2	0.44	3.02	33.044	132.176				
	2:02:15	224.5	0.47	3.49	35.297	141.188				
	2:02:30	220.4	0.41	3.9	30.791	123.164				
	2:02:45	216.2	0.42	4.32	31.542	126.168				
	2:03:00	212.1	0.41	4.73	30.791	123.164	1420.89	129.172		

Appendix 6 - Calculation of K(h) for MDTI in Excel sheet

MDTI determination of K(h)

tension	time	square root of time	reading in cm3 = ml	infiltrated volume of water (cm3)	cumulative volume (cm3)	cumulative infiltration (cm)		
-3	0	0	84	0	0	0	**FOR TENSION -3**	
	0.5	0.707106781	83	1	1	0.062876027	**A from table**	**6.87**
	1	1	82	1	2	0.125752054	**C1 from equation**	**0.0471**
	1.5	1.224744871	81.5	0.5	2.5	0.157190067	**K=C1/A [cm/min]**	**0.006855895**
	2	1.414213562	81	0.5	3	0.188628081		
	2.5	1.58113883	80.5	0.5	3.5	0.220066094		
	3	1.732050808	80	0.5	4	0.251504108		
	3.5	1.870828693	79.5	0.5	4.5	0.282942121		
	4	2	79	0.5	5	0.314380135		
	4.5	2.121320344	78.5	0.5	5.5	0.345818148		
	5	2.236067977	78	0.5	6	0.377256161		
	5.5	2.34520788	77.5	0.5	6.5	0.408694175		
	6	2.449489743	77	0.5	7	0.440132188		
	6.5	2.549509757	76.5	0.5	7.5	0.471570202		
	7	2.645751311	76	0.5	8	0.503008215		
	7.5	2.738612788	75.5	0.5	8.5	0.534446229		
	8	2.828427125	75	0.5	9	0.565884242		
	8.5	2.915475947	74.5	0.5	9.5	0.597322256		
	9	3	74.5	0	9.5	0.597322256		
	9.5	3.082207001	74	0.5	10	0.628760269		
	10	3.16227766	73.5	0.5	10.5	0.660198282		
	10.5	3.240370349	73	0.5	11	0.691636296		
	11	3.31662479	72.5	0.5	11.5	0.723074309		
	11.5	3.391164992	72	0.5	12	0.754512323		
	12	3.464101615	71.5	0.5	12.5	0.785950336		
	12.5	3.535533906	71	0.5	13	0.81738835		
	13	3.605551275	70.5	0.5	13.5	0.848826363		
	13.5	3.674234614	70	0.5	14	0.880264377		
	14	3.741657387	69.5	0.5	14.5	0.91170239		
	14.5	3.807886553	69	0.5	15	0.943140404		
	15	3.872983346	68.5	0	15	0.943140404		
-1	15.5	3.937003937	68	0.5	15.5	0.974578417	**FOR TENSION -1**	
	16	4	67.5	0.5	16	1.00601643	**A from table**	**5.72**
	16.5	4.062019202	67	0.5	16.5	1.037454444	**C2 from graph**	**0.0822**
	17	4.123105626	66.5	0.5	17	1.068892457	**K=C1/A [cm/min]**	**0.014370629**
	17.5	4.183300133	66	0.5	17.5	1.100330471		
	18	4.242640687	65.5	0.5	18	1.131768484		
	18.5	4.301162634	65	0.5	18.5	1.163206498		
	19	4.358898944	64.5	0.5	19	1.194644511		
	19.5	4.415880433	64	0.5	19.5	1.226082525		
	20	4.472135955	63.5	0.5	20	1.257520538		
	20.5	4.527692569	63	0.5	20.5	1.288958551		
	21	4.582575695	62.5	0.5	21	1.320396565		
	21.5	4.636809248	62	0.5	21.5	1.351834578		
	22	4.69041576	61.5	0.5	22	1.383272592		
	22.5	4.74341649	61	0.5	22.5	1.414710605		
	23	4.795831523	60.5	0.5	23	1.446148619		
	23.5	4.847679857	59.5	1	24	1.509024646		
	24	4.898979486	59	0.5	24.5	1.540462659		
	24.5	4.949747468	58.5	0.5	25	1.571900673		
	25	5	57.5	1	26	1.634776699		
	25.5	5.049752469	57	0.5	26.5	1.666214713		
	26	5.099019514	56.5	0.5	27	1.697652726		
	26.5	5.14781507	55.5	1	28	1.760528753		
	27	5.196152423	55	0.5	28.5	1.791966767		
	27.5	5.244044241	54.5	0.5	29	1.82340478		
	28	5.291502622	53.5	1	30	1.886280807		
	28.5	5.338539126	53	0.5	30.5	1.91771882		
	29	5.385164807	52.5	0.5	31	1.949156834		
	29.5	5.431390246	52	0.5	31.5	1.980594847		
	30	5.477225575	51.5	0.5	32	2.012032861		
-0.5	30.5	5.522680509	50.5	1	33	2.074908888	**FOR TENSION -0,5**	
	31	5.567764363	49.5	1	34	2.137784915	**A from table**	**5.46**
	31.5	5.61248608	48.5	1	35	2.200660942	**C2 from graph**	**0.1796**
	32	5.656854249	47.5	1	36	2.263536968	**K=C1/A [cm/min]**	**0.032893773**
	32.5	5.700877125	46.5	1	37	2.326412995		
	33	5.744562647	45.5	1	38	2.389289022		
	33.5	5.787918451	44.5	1	39	2.452165049		
	34	5.830951895	43.5	1	40	2.515041076		
	34.5	5.873670062	42.5	1	41	2.577917103		
	35	5.916079783	41.5	1	42	2.64079313		
	35.5	5.958187644	40.5	1	43	2.703669157		
	36	6	39	1.5	44.5	2.797983197		
	36.5	6.041522987	38	1	45.5	2.860859224		
	37	6.08276253	37	1	46.5	2.923735251		
	37.5	6.123724357	36	1	47.5	2.986611278		
	38	6.164414003	35	1	48.5	3.049487305		
	38.5	6.204836823	34	1	49.5	3.112363332		
	39	6.244997998	33	1	50.5	3.175239358		
	39.5	6.284902545	32	1	51.5	3.238115385		
	40	6.32455532	31	1	52.5	3.300991412		
	40.5	6.363961031	30	1	53.5	3.363867439		
	41	6.403124237	29	1	54.5	3.426743466		
	41.5	6.442049363	28	1	55.5	3.489619493		
	42	6.480740698	27	1	56.5	3.55249552		
	42.5	6.519202405	26	1	57.5	3.615371547		
	43	6.557438524	25	1	58.5	3.678247574		
	43.5	6.595452979	24	1	59.5	3.741123601		
	44	6.633249581	23	1	60.5	3.803999627		
	44.5	6.670832032	21.5	1.5	62	3.898313668		
	45	6.708203932	20.5	1	63	3.961189695		
sum:	**420**	**93.64227899**		**11**	**422.5**	**26.56512137**		

Czech University of Life Sciences Prague
Faculty of Agrobiology, Food and Natural Resources
Department of Water Resources

Factors affecting determination of unsaturated soil hydraulic conductivity in situ using tension infiltrometer

Diploma Thesis

Supervisor: prof. Ing. Svatopluk Matula, CSc.
Author: Jana Lufinková
2012

Statement

I declare that I wrote my diploma thesis “Factors affecting determination of unsaturated soil hydraulic conductivity in situ using tension infiltrometer” by myself and I have used only the sources mentioned at the end of the thesis.

In Prague on 23rd April 2012

Jana Lufinková

Acknowledgment

Many thanks to my supervisors prof. Svatopluk Matula from Czech University of Life Sciences and prof. Willibald Loiskandl from University of Natural Resources and Life Sciences for their help and support.

Thanks to Markéta Miháliková, for her all round help and supervision, and for enabling me to measure in her laboratory.

Many thanks also to my home school Czech University of Life Sciences for lending me the measuring devices.

I wish to express a special thank you to my family – namely my mother, father, sister and all grandparents for their financial and moral support during my studies.

Summary

This Diploma Thesis focuses on the unsaturated hydraulic conductivity of soil and the performance of two different tension infiltrometer devices used in its measurement. Particular attention is given to different initial water content conditions of the soil profile and the influence of this condition to the measured data.

The two devices used in the measurement of hydraulic conductivity were Hood Infiltrometer IL-2700 (Umwelt Geräte Technik, GmbH.) and Mini Disk Tension Infiltrometer (Decagon Devices, Inc.). Results of the unsaturated hydraulic conductivity of these two devices were compared.

The Hood Infiltrometer was used because it is a relatively new device and not many articles have been published regarding the use of this infiltrometer. For comparison to the Hood Infiltrometer, the Mini Disk Tension Infiltrometer was used as it is a very simple and easy-to-use device. The comparison of these two devices is made with respect to the initial water content of the soil profile. The measurements were done under three different tensions (-0.5; -1 and -3 cm).

Three levels of initial water content – dry, medium wet and wet - and their influence on measured unsaturated hydraulic conductivity were investigated. The initial water content was measured at an area closely surrounding the infiltrometers using both gravimetric and an indirect method. The average values of initial water content by volume for dry, medium wet and wet measuring spot were 25.1, 32.5 and 38.3 % for Hood Infilrometer and 23.9, 31.7 and 35.4 % for Mini Disk Tension Infiltrometer.

The values for the hydraulic conductivity from Mini Disk Tension Infiltrometer and Hood Infiltrometer vary. The values of unsaturated hydraulic conductivity obtained by Hood Infiltrometer are significantly higher than values measured by Mini Disk Tension Infiltrometer.

The results from both devices show that there is an indirect dependence of the unsaturated hydraulic conductivity on the initial water content. It means that with increasing water content the unsaturated hydraulic conductivity measured with Hood Infiltrometer and Mini Disk Tension Infiltrometer decreases. This trend was conclusive especially for Mini Disk Tension Infiltrometer. For the Hood Infiltrometer a weaker dependence of unsaturated hydraulic conductivity on the initial water content is visible.

The tendency of decreasing hydraulic conductivity with increasing pressure head was observed for both devices. The results from both infiltrometers show that the values of unsaturated hydraulic conductivity fluctuate less for tension -0.5 applied for Hood Infiltrometer and for tension -3 performed for Mini Disk Tension Infiltrometer. Both tension -0.5 for Hood Infiltrometer and -3 for Mini Disk Tension Infiltrometer are the first performed tensions for these devices. The reason probably is that the following flow is influenced by the flow under the first tension applied.

Keywords

Unsaturated hydraulic conductivity, Infiltration, Mini Disk Tension Infiltrometer, Hood Infiltrometer

Content and list of figures

List of appendices

1 Introduction

Unsaturated hydraulic conductivity is a very important hydrophysical characteristic of a given soil profile. The unsaturated hydraulic conductivity can be described as the velocity with which the water flows through a porous media such as a soil profile. This characteristic should be measured preferably in situ as it gives more representative values than measuring in the laboratory. It is used for example to prevent or minimize the potential contamination of groundwater by soluble pollutants.

There are a variety of ways to measure the unsaturated hydraulic conductivity and this thesis deals with two devices – Hood Infiltrometer and Mini Disk Tension Infiltrometer. Both are tension infiltrometers. Despite the fact that it is a time consuming method, tension infiltrometry became very popular due to its accuracy and provision of more representative values of hydraulic conductivities.

Still there does not exist any reference method for measuring the unsaturated hydraulic conductivity. Thus two devices for estimation the hydraulic conductivity were used and compared. The conditions which in general affect the measurements of hydraulic conductivity are: tillage and crop effect, time variability, particle size distribution, contact material, pressure head and initial water content. This thesis focuses on different initial water contents of the soil profile. Three different levels of water content are used and measurements from two devices with three tension settings are then compared. The difference in time is neglected because all the measurements were made in a very small interval. The other conditions such as tillage and crop effect, contact material and particle size distribution are described only theoretically.

2 Objectives of the Thesis

There are two main objectives of the Thesis:

i) to summarize the most important factors affecting the determination of unsaturated hydraulic conductivity and final values of unsaturated hydraulic conductivity and to identify factor(s) which require more detailed investigation

ii) to evaluate the effects of the identified factor(s) based on this study.

Hypothesis

The objectives of the thesis were formulated on the basis of following hypotheses:

i) The measurement of unsaturated hydraulic conductivity is affected by different conditions during the measurement including common changes in soil, weather, season and vegetation. These factors can be identified and evaluated.

ii) The initial water content of soil has significant influence on the measured values of unsaturated hydraulic conductivity.

3 Literature review

3.1 Hydraulic conductivity and Infiltrometers

Hydraulic conductivity is a property describing the ease with which the water can move through the soil profile. The movement is influenced by many factors; e.g. porosity of the soil and saturation of the soil profile. The soil profile can be saturated or unsaturated.

Most of the natural processes involving the soil-water interaction occur under unsaturated conditions of the soil. Unsaturated flow has become a very important topic and much research has been made in recent times.

The difference between the saturated and unsaturated flow is that if the soil is saturated, all pores are filled with water and the hydraulic conductivity reaches its maximum value. When the soil profile is unsaturated, some of the pores are filled with air and the hydraulic conductivity usually decreases. The conductivity of unsaturated soils depends generally on the structure and texture of the soil profile, as Hillel (1998) and Kutílek (1994) reported.

The dependence of the unsaturated hydraulic conductivity of sandy and clayey soil versus suction is visible on Figure (1).

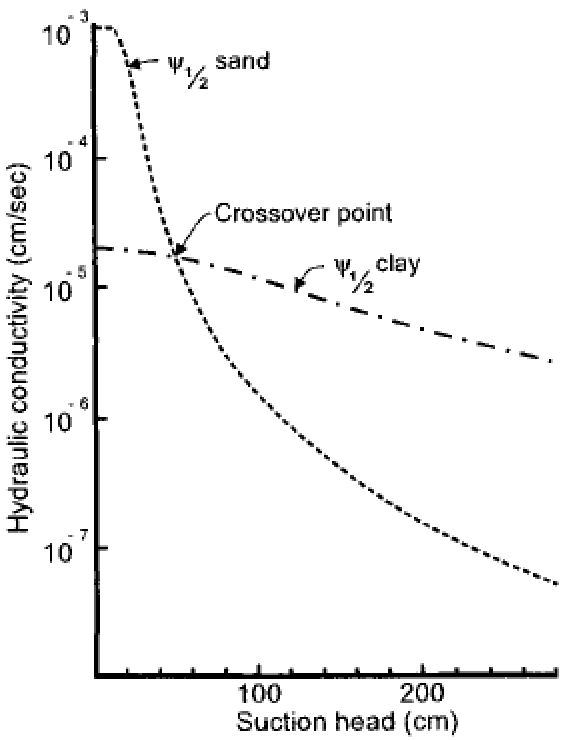


Figure 1 - Dependence of unsaturated hydraulic conductivity on suction in different soils, on log-log scale, Hillel (1998)

Both saturated and unsaturated hydraulic conductivities are important hydrophysical characteristics of the soil. The hydraulic conductivity is not constant for the given soil but it varies with time and this characteristic is unique for each soil type. Špongrová et al. (2009) mentioned that the rate in which the water moves through the soil profile and its pores can be characterized by hydraulic conductivity function *K* in relation to volumetric water content of the pressure head of soil water. These two properties (the water content and pressure head) have to be measured preferably in situ. Ankeny et al. (1991) showed that the values of water infiltration and water movement are very important to prevent or minimize potential contamination of groundwater by chemicals. Angulo-Jaramillo et al. (2000) also stress the importance of knowing hydrodynamic functions of soils for the management and prognosis of hydrodynamical flows in both natural and anthropogenic soils. Ankeny et al. (1991) continues, by stating that a simple (and if possible) fast measurement and determination of hydraulic conductivity is necessary.

Some possibilities on how to measure and determine hydraulic conductivity of the unsaturated zone exists. This thesis is focused on tension infiltrometers. Tension infiltrometry uses the near-saturated hydraulic conductivity, which is without the influence of preferential flow. The preferential flow affects the saturated flow. According to Špongrová et al. (2009) working in situ and especially with infiltrometers to determine the unsaturated hydraulic conductivity functions *K (h)* is time consuming and thus also costly. According to Kechavarzi et al. (2009) this was partially solved by automation of the measurement which was developed by many authors.

The time consumption and costs are also confirmed by Reynolds et al. (2000), who described hydraulic conductivity as being “difficult to measure”. Walker et al. (2006) wrote in their article that tension infiltrometers have started to become used for determination of saturated or unsaturated hydraulic conductivity, macropore flow and also sorptivity. They mentioned that the big advantage of this device is its nondestructive use and also its simplicity. Other advantages such as relatively low price of the device, minimal disturbance of the soil surface and also the replicability of the measurements are mentioned by Ventrella et al. (2005).

Elrick and Reynolds (1992) published an article which shows that infiltration in soil is three-dimensional and can be both transient and steady state. First there is the phase of transient flow which then gives way to steady state flow. According to Hillel (1998), steady-state flow is defined as a system where flux, gradient and water content are constant in time, whereas for transient flow these parameters vary. Elrick and Reynolds (1992) described that after the steady state phase is reached, the wetting zone increases in size. The determination of hydraulic conductivity can be done by positive or negative pressure heads. The tension infiltrometer which uses negative pressure head, can determine the early-time transient and steady-state flow rates just by the corresponding scale of the unsaturated hydraulic conductivity. As an example, the tension flux potential is given. According to these authors, the transient and steady infiltration of water into the vadose zone is dependent on pores and their position and network and also on soil particles. Lin and Mc Innes (1995) wrote that hydraulic conductivity can be determined from infiltration data from theoretical analyses of uniform water flow under the tension infiltrometer. Ankeny et al. (1991) observed that for measuring the unsaturated hydraulic conductivity, only steady-state infiltration measurements are needed and no initial water content knowledge is required. It is very important to be careful during installation of the infiltrometer because the soil structure should not be destroyed by placing or driving the contact ring to the soil surface. And – of course – the repetition of measurements should be done on identical surfaces.

Selecting the proper method to estimate the hydraulic properties of the soil is necessary to obtain representative values of hydraulic conductivity as presented by Bagarello et al. (2000) in their article.

Tension infiltrometry has become a popular tool for determination of unsaturated hydraulic conductivity and other near saturated hydraulic properties and also for examining the effects of macropores on infiltration. Traditionally, hydraulic conductivity is calculated from steady-state data using quasi-analytical solution of Wooding, which calculate *K* with steady infiltration from a circular source (Ventrella et al. 2005).

According to Lal and Shukla (2004) flow in the unsaturated zone is tortuous and for the flow descriptions usually the Darcy-Buckingham and Richards equations are used. But Darcy-Buckingham equation alone is usable only for a situation where the water content remains constant. This is seldom observed in natural conditions. There then has to be the continuity equation in combination with Darcy-Buckingham.

There are some equations which were mentioned by Elrick and Reynolds (1992). For the tension infiltrometers they wrote: “Water is applied to the infiltration surface under a steady water potential, ψ_t *[L]*, where $\psi_t \leq 0$. Consequently, only an unsaturated wetting zone develops, within which the water potential varies from $\psi = \psi_t \leq 0$ at the infiltration surface to $\psi = \psi_i$ at the wetting front", where ψ is water potential, ψ_i is initial or background pore water potential in surrounding unsaturated soil and ψ_t is characterized as steady water potential.

A simple schema of tension infiltrometer is shown in Figure (2). Wetting zone is drawn like a three-dimensional flow of water. The Mariotte bottle is designed so that a range of negative pressure heads which will then be applied via the disk or membrane can be set For the tension infiltrometer, water infiltrates under a steady state negative potential ψ_t, where $\psi_t \leq 0$. Only unsaturated wetting zone occurs were water potential varies from values $\psi \leq \psi_t \leq 0$ (at the infiltration surface) and $\psi = \psi_i$ (at the wetting front), where ψ_i is background water potential of the soil.

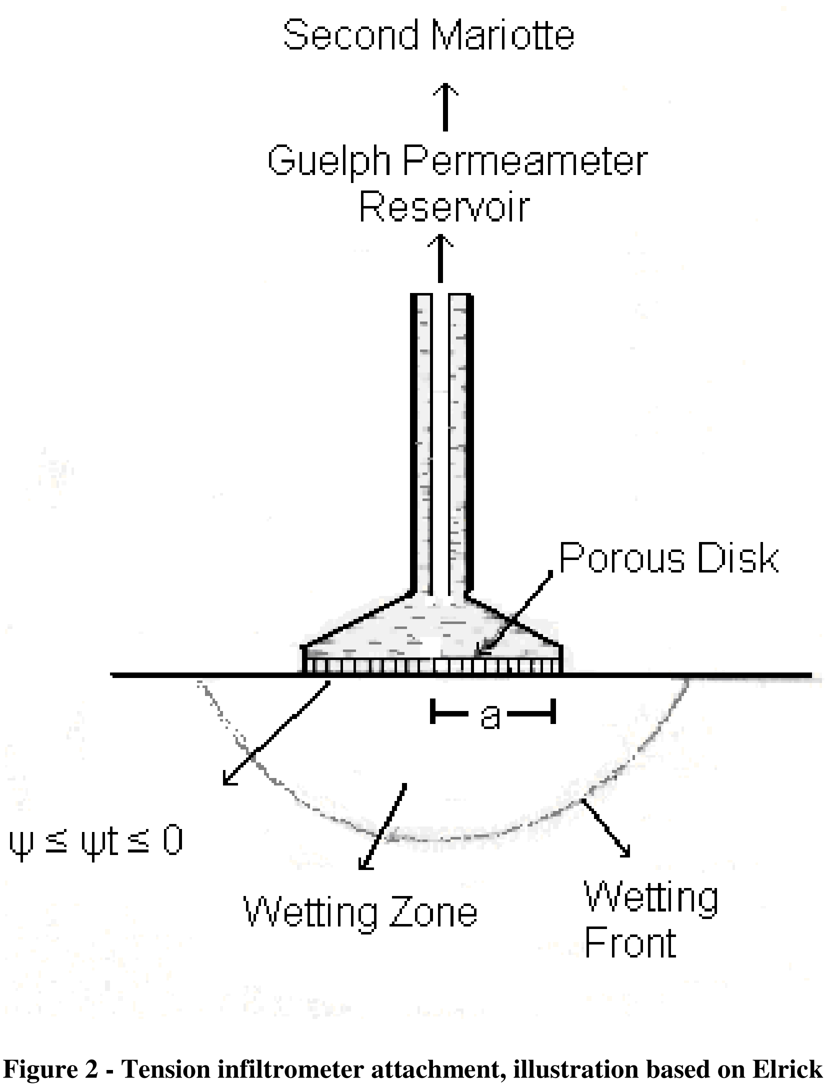


Figure 2 - Tension infiltrometer attachment, illustration based on Elrick and Reynolds (1992)

The schema of tension infiltrometer was drawn also by Gardner and Gardner (1939) and is shown on Figure (3).

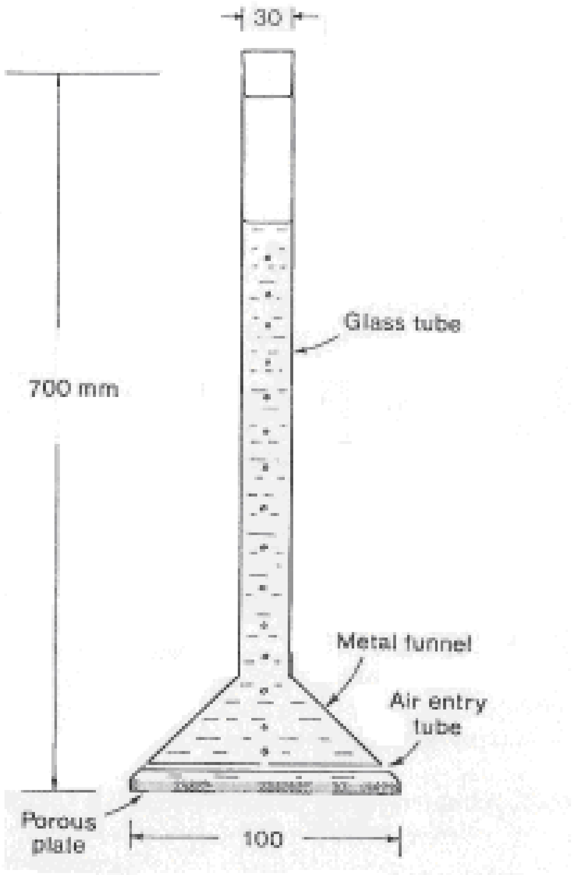


Figure 3 - The tension infiltrometer of Gardner published in 1939 with dimensions in milimetres (White et al. 1992)

According to Reynolds and Elrick (1991) the tension infiltrometer is basically built from a double Mariotte bottle which can be connected to a porous membrane or disk which has direct contact with soil surface. The first Mariotte bottle works like a water supply for the flow of water to the soil, the second is used to change the tensions caused on the membrane or disk. Many tension infiltrometers have been developed but they are all based on this principle. However, there is one special exception and it is the Hood Infiltrometer. This device does not consist of a membrane or disk. It has direct contact with soil surface what will be explained in the Chapter 3.3.2 dedicated to Hood Infiltrometers.

The cumulative infiltration from the tension infiltrometer can be expressed in length units (this can be also calculated as volume of water read from the Mariotte bottle and then divided by the cross section area *A* of the column) as reported by Lal and Shukla (2007).

Ankeny et al (1988) presented evidence that all tension infiltrometers are based on Clothier and White`s (1981) device which uses a sintered glass plate of 8.6 cm diameter as a contact disk and the tension is controlled simply by a hypodermic needle. The schema of this apparatus is illustrated in Figure (4).

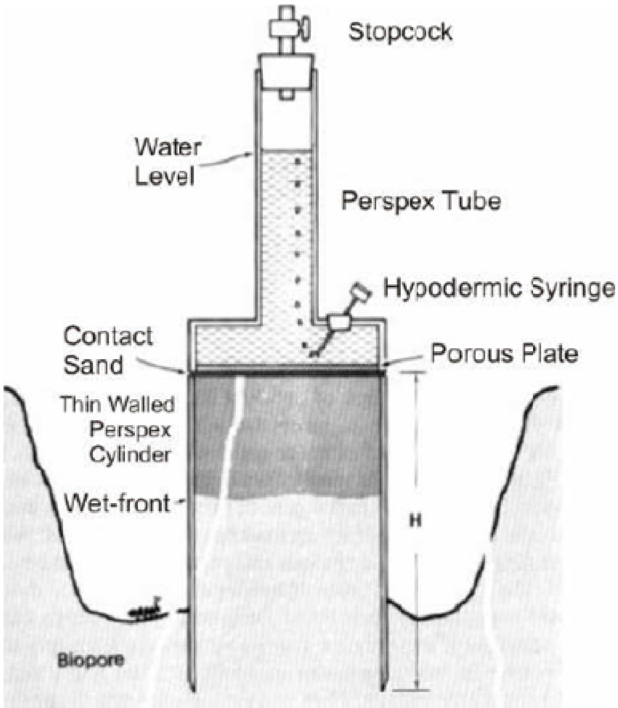


Figure 4 - The sorptivity tube tension infiltrometer of Clothier and White (White et al. 1992)

3.2 Forces and flow under tension disk infiltrometers

Infiltration or hydraulic conductivity can be described as the downward entry of water into the soil profile (Johnson 1963).

Hydraulic conductivity is usually described in unit length per unit time, usually in these units (by Lohman, 1972) as shown in equation (1):

$$K = -\frac{ft^3}{ft^2 day(-ft \cdot ft^{-1})} = ft \cdot day^{-1}\left[LT^{-1}\right] \tag{1}$$

where K is the hydraulic conductivity.

Equation (1) can be also rewritten as interpretation for SI units:

$$K = -\frac{m^3}{m^2 day(-m \cdot m^{-1})} = m \cdot day^{-1}\left[LT^{-1}\right] \qquad (2)$$

where 1 ft is 0.305 m.

Kim and Kim (2009) stated that unsaturated soil has a force which enables the soil to absorb water by capillary forces. This force can also be named as total suction. This force makes the behavior of unsaturated soil different from saturated soil.

The relationship between suction and saturation degree is visible on the Soil Water Retention Curve (SWRC) in Figure (5). Drying curve is the upper one, wetting curve is situated below as it is described also in the graph.

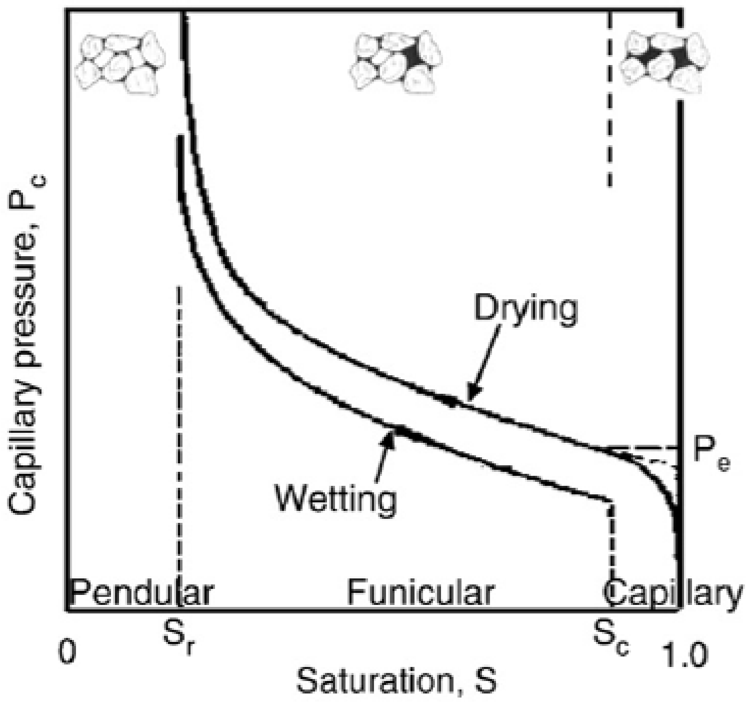


Figure 5 - SWRC curves according to states of saturation (pendular, funicular and capillary, Kim and Kim (2009)

The flow under tension infiltrometers is three-dimensional. This is presented in Figure (6).

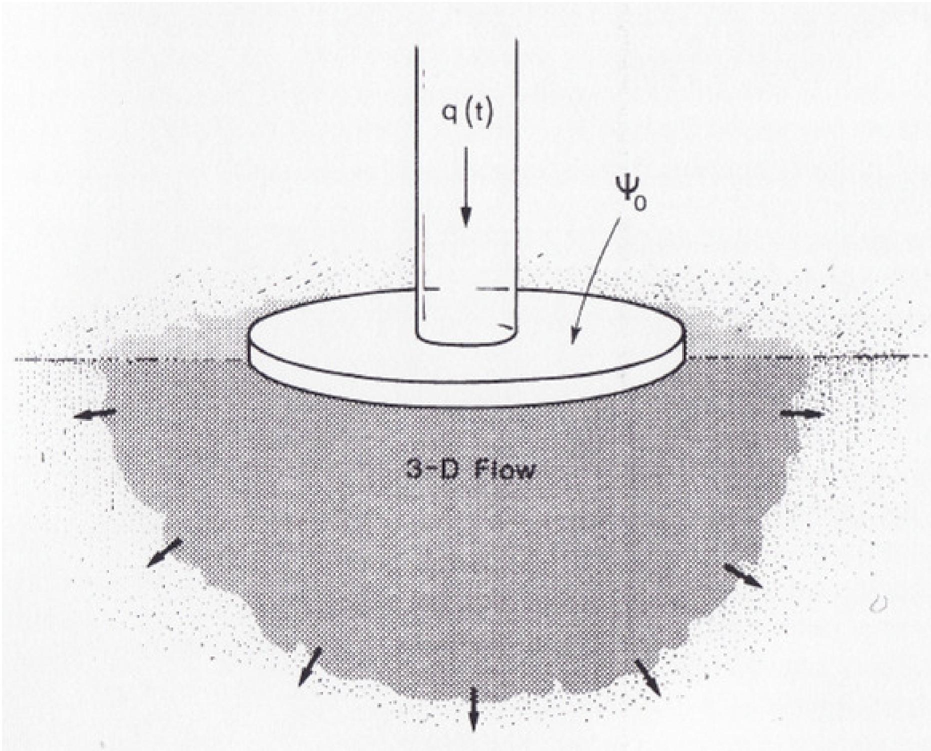


Figure 6 - Schema of unconfined three-dimensional flow from water source placed on the soil surface, White et al. (1992)

Angulo-Jaramillo et al. (2000) and Šimůnek and van Genuchten (1997) wrote that the methods to determine hydraulic properties of soil are based on steady state flow, transient flow or on numerical model and inverse parameter estimation techniques. Their description is as follows:

3.2.1 Steady-State flow equations

The steady state flow means that there is no change in pressure head with respect of time. This statement is mathematically symbolized by a simple equation $dh/dt=0$. It means that the change in head (*dh*) with respect to the change in time (*dt*), equals zero.

Steady state flow practically does not occur in nature, but it is used due to the fact that the flow in nature is closely approached in nature and in aquifer tests. This condition is usually symbolized by $dh/dt \rightarrow 0$. The steady-state flow equations are based on Darcy`s law, which says that the rate of laminar flow of water through porous media is proportional to the hydraulic gradient.

The Darcy Law is written in this form (equations 3 and 4):

$$q = \frac{Q}{A} = -\frac{Kdh}{dl}\left[LT^{-1}\right] \tag{3}$$

which is the same as the hydraulic conductivity equation in this form:

$$K = -\frac{q}{dh/dl}\left[LT^{-1}\right] \tag{4}$$

as presented by Lohman (1972).

As it was written by Ankeny et al. (1991), there is only a need to measure steady-state infiltration for determining the water flow in agricultural soils. Description of the steady-state infiltration equations are as follows:

Under the tension infiltrometer there is a three-dimensional steady-state infiltration of water. This was described by Wooding (1968) in a quasi-analytical equation (5) which counts with steady infiltration from a circular source (Ventrella et al. 2005):

$$Q = \pi r^2 K + 4r\phi \tag{5}$$

where Q is steady infiltration flux, K saturated hydraulic conductivity, ϕ matric flux potential and r radius of the disc permeameter. Using Kirchhoff integral transformation from Richard's equation, the soil water potential as matric flux potential can be calculated (Hillel, 1998) as shown in equation (6):

$$\Phi(\psi) = \int_{\psi_i}^{\psi} K(\psi) d\psi \tag{6}$$

where ψ is soil water pressure head.

Or for *h* as pressure head it stands in this form (Shouse and Mohanty, 1998), in equation (7):

$$\Phi(h_o) = \int_{h_i}^{h_0} K(h)dh \tag{7}$$

where $h_i \leq h_0 \leq 0$. Where h_i is initial pressure head of dry soil, h_0 is the arbitrary supply pressure head.

The hydraulic conductivity function can then be calculated from equation (8) according to Ankeny et al., (1991):

$$K(\psi) = K_s \exp(\alpha\psi) \tag{8}$$

where α is constant.

Based on equation (7) which can be rewritten also in this form (Lin and Mc Innes, 1995):

$$K(\psi) = K(\psi_0)\exp[\alpha(\psi - \psi_0)] \tag{9}$$

as we can assume that the steady-state infiltration rate *Q* calculated from circular tension infiltrometer is according to equation (10) approximately:

$$Q(\psi_0) = [\pi a r^2 + 4r] \cdot \int_{\psi_i}^{\psi_0} K(\psi)d\psi \tag{10}$$

where *r* is radius of infiltration surface depending on disk radius, ψ_i is initial pressure head, ψ_0 is surface pressure head, *K* is known hydraulic conductivity, where $K(\psi_0) >> K(\psi_i)$ is valid.

The previous equation (10) can then be rewritten in the form for hydraulic conductivity:

$$K(\psi_0) = Q(\psi_0)/\left[\pi r^2 + 4r/\alpha\right] \tag{11}$$

which is based on the equation described by Ankeny et al. (1991). In this equation the measurements of $Q(\psi_0)$ value at two supply water potentials (ψ_1 and ψ_2) both $K(\psi_0)$ and α as the constant may be determined.

For the multiple head devices, as published by Elrick and Reynolds (1992) two or more pressure heads are used sequentially to the soil surface to infiltrate and from this the unsaturated hydraulic conductivity are solved

1. using simultaneous equations (for two pressure heads applied sequentially);
2. least squares regression (also for more pressure heads);
3. piece wise fitting of exponential curves (also for more pressure heads).

3.2.2 Transient flow

Transient flow is described by many authors. Use of the transient flow equation (12) is based on the theory of transient axisymmetric infiltration from a circular source of water applied at the soil surface. Some authors showed, that additional term accounting for side effects, which occurs due to the axisymetric flow geometry, is linear in time (Vandervaere et al., 2000):

$$I_{3D} - I_{1D} = \frac{\gamma S^2}{R(\theta_0 - \theta_n)} t \tag{12}$$

where the indexes 3D and 1D stand for axisymmetric three dimensional and one-dimensional process and γ is a constant, which can be said to be equal to √3 when the gravity forces are neglected at the periphery of the disc, R is disc radius and S is sorptivity. Smetten et al. 1994, Vandervaere et al., 2000 set the value for γ as 0.75.

For short to medium times, the previous equation (12) can be rewritten into an infiltration equation in this form (13):

$$I_{3D} = S\sqrt{t} + \left[\frac{2-\beta}{3} K + \frac{\gamma S^2}{R(\theta_0 - \theta_n)} \right] \tag{13}$$

where β is a constant (0< β<1). This equation can be simply rewritten in form (14):

$$I = C_1\sqrt{t} + C_2 t \tag{14}$$

where the subscript for 3D flow is omitted and with:

$$C_1 = S;\ C_2 = \frac{2-\beta}{3} K + \frac{\gamma S^2}{R(\theta_0 - \theta_n)}. \tag{15}$$

3.2.3 Numerical model and Inverse Parameter Estimation

The numerical model and inverse parameter estimation procedure is well described by Schwärzel and Punzel (2007). They presented the Richard`s equation for symmetric isothermal Darcian flow in this form (equation 16):

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial h}{\partial r} \right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z} \right) + \frac{\partial K}{\partial z} \tag{16}$$

where θ is the volumetric water content, t is time, r is radial coordinate, h represents pressure head and K is unsaturated hydraulic conductivity. This equation was also used by Šimůnek et al. (1998), who suggested numerical modelling to estimate hydraulic conductivity from the disk infiltrometer, from cumulative infiltration data at several heads. Kodešová et al. (2006) wrote that the single Richard's equation for HYDRUS-1D is used for the single-porosity model, which describes one-dimensional isothermal Darcian flow in variably saturated soil.

"HYDRUS is a public domain Windows-based modeling environment for analysis of water flow and solute transport in variably saturated porous media. The software package (for HYDRUS 1D) includes the one-dimensional finite element model HYDRUS for simulating the movement of water, heat, and multiple solutes in variably saturated media. The model is supported by an interactive graphics-based interface for data-preprocessing, discretization of the soil profile, and graphic presentation of the results. HYDRUS 2D is a software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media" as written in manual of HYDRUS.

Using the HYDRUS-2D model, the previous Equation (16) was numerically solved for the following initial and boundary conditions $\theta_i(z)$. Equation (17) describes the initial water content condition:

$$\theta(r, z, t) = \theta_i(z); \; t = 0 \tag{17}$$

equation (18) describes the time-variable pressure head below the tension infiltrometer:

$$h(r, z, t) = h_0(t); \; 0 < r < r_0; \; z = 0 \tag{18}$$

This equation (19) prescribes the zero-flux condition at the surface of the soil:

$$\frac{\partial h(r, z, t)}{\partial z} = 1; \; r > r_0; \; z = 0 \tag{19}$$

The last equation (20) says that other boundaries are sufficiently distant from the infiltration source and that they have no influence on the flow process of tension infiltrometer.

$$h(r,z,t) = h_i; \quad r^2 + z^2 \to \infty \tag{20}$$

In equations (17) to (20) θ_i represents initial volumetric water content, h_0 is time-variable supply pressure head done by disk infiltrometer and h_i is initial pressure head, r_o is the disk radius, z is the vertical coordinate (in centimeters) and t is time.

3.3 Tension infiltrometers

3.3.1 Mini Disk Tension Infiltrometer

The Mini Disk Tension Infiltrometer is an infiltrometer with a single disk and multiple tensions (also called pressure heads) manufactured by Decagon Devices, Inc. This was described by Ankeny et al. (1991). This device has a great advantage due to being very small and portable. The total height of this infiltrometer is just over 32 cm and the volume of water required to operate with it is about 135 ml.

Table 1 below shows the decisive parameters of the Mini Disk Tension Infiltrometer.

Table 1 - Mini Disk Tension Infiltrometer parameters, Decagon Devices, Inc. [online]

Mini Disk Tension Infiltrometer parameters	
Total Length	32.7 cm
Diameter of Tube	3.1 cm
Volume of Water Required to Operate	135 ml
Sintered Stainless Steel Disc	4.5 cm diameter, 3 mm thick
Length of Water Reservoir	21.2 cm
Length of Suction Regulation Tube	10.2 cm
Length of Mariotte Tube	28 cm
Suction Range	0.5 to 7 cm of suction

The schema of Mini Disk Tension Infiltrometer is shown on Figure (7) (Decagon Devices, Inc., [online]).

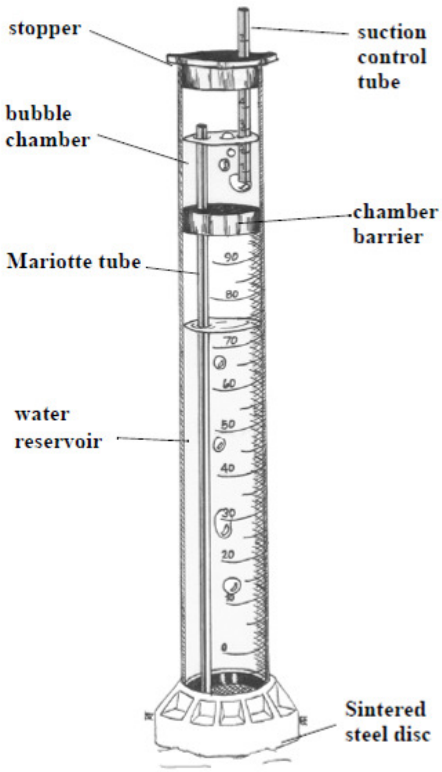


Figure 7 - Schema of Mini Disk Tension Infiltrometer, Decagon Devices, Inc. [online]

According to Decagon Devices, Inc. [online] it is usable for field and also laboratory measurements. The body is made from polycarbonate and the contact disk is a porous semi-permeable sintered stainless steel disk. Semipermeability means, that it allows water not air to go through (Decagon Devices, Inc., [online]).

The chamber for tension changes is visible in Figure (8)

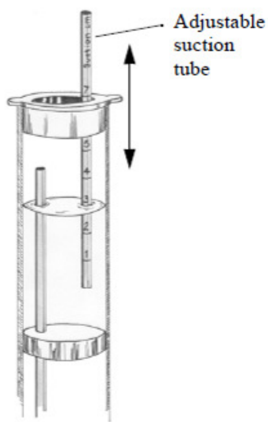


Figure 8 - Chamber for tension changes, Decagon Devices, Inc.

The size range of pores, cracks, etc. participating in the flow is determined by the tension set on the infiltrometer disk/membrane (Elrick and Reynolds 1992). The suction settings and corresponding pore diameter are shown later in Table 2.

Table 2 below shows the relation between suction settings and pore diameter for Mini Disk Tension Infiltrometer (MDTI). The chamber for changing the suctions is visible on Figure 7. Decagon Devices, Inc. recommends that if the bigger value of tension is used (e.g. 7 cm), only pores smaller than 0.41 mm will take part during infiltration and will be filled. If the suction is decreased to 1 cm, also pores up to 2.90 mm will take part during the infiltration. The suction settings are given in absolute values. In real values it is always a negative value.

Table 2 - Suction settings and corresponding pore diameter, Decagon Devices, Inc. [online]

Suction settings and corresponding pore diameter							
Suction Settings [cm]	1	2	3	4	5	6	7
Pore diameter [mm]	2.90	1.45	0.97	0.73	0.58	0.48	0.41

Špongrová et al. (2009) wrote that the tension infiltrometer method shows the infiltration capacity of different pore sizes by measuring the hydraulic conductivity using a range of water pressure heads. When the pressure head decreases, the hydraulic conductivity increases. Mohanty et al. (1994) show that by setting the suction head on the infiltrometer, we can limit the size of soil pores which will take part in conducting the water. Sequential increase of tension heads goes ahead to drain smaller and smaller pores. Infiltration rate then decreases when more water-conducting pores are emptied.

There are different times to read the values from MDTI for each soil type. For example for silty loam we need to make a measurement every 30 seconds, due to its high suction, in contrast, a reading for clay should be made every 30 minutes. These are just approximate values given by Decagon Devices, Inc. The real time has to be set on the field according to all the parameters.

For the MDTI there is an essential requirement for good and consistent hydraulic contact between the measuring device membrane and soil during the whole time (Perroux and White, 1988). They also recommend trimming of any vegetation down to ground level to avoid any influence of the grass cover. Excess contact sand outside the rim of the infiltrometer has to be added to avoid any horizontal wicks of sand. Reynolds and

Zebchuk (1996) made some measurements using the contact material for the tension infiltrometer and they stated, that the use of contact material is usually done by placing a layer of some contact material (e.g. sand) between the membrane and soil surface. Smettem and Clothier (1989) recommend that a circle of fine contact sand with a radius which corresponds to the contact membrane of tension infiltrometer is applied. Time zero is then set to the moment of the first contact or connection between the sand and infiltrometer membrane. They also obtained the first 30 s readings from infiltrometer due to wetting of contact material for the first moments.

For placing the infiltrometer on the contact material Close et al. (1998) suggest that the infiltrometer is gently rotated a few degrees clockwise and anticlockwise and then gently press down on the contact material (silica sand is suggested) while placing the device.

3.3.2 Hood Infiltrometer

According to Schwärzel and Punzel (2007) disc infiltrometers, (the category which Hood Infiltrometers also belongs to), are used to determine saturated and also near-saturated hydraulic conductivity of soil. The biggest advantage of Hood Infiltrometer (HI) is that it does not use any contact material unlike the MDTI. The contact material can affect the value of hydraulic conductivity. Instead of this there is direct contact between water held in the hood and the soil surface. This overcomes problems associated with the influence of contact material. They noted that soil hydraulic conductivity is soil structure dependant. On the other hand Buczko et al. (2006) recommend the use of contact material and recommend also that a good contact between the hemispherical hood and soil is sealed with a thin layer of contact sand.

A reason why to use the HI is that it places the water column directly on the soil surface and no need of contact material, membrane or plate is required. This is the biggest advantage over conventional infiltrometers. The only adjustment required to the terrain is to cut the vegetation to about 5 mm tall. The HI consists of three major components: hood, Mariotte water supply and manometer.

The hood is constructed from acrylic and the diameter is 12.4 cm. For measurement itself, it is placed open side down on the undisturbed soil surface with a retaining ring. The place between the hood and retaining ring is then covered by sand to overcome leaking of water to the sides and to seal up the hood. Then there is the Mariotte bottle with its diameter of 12 cm and length of 71.6 cm. This Marriotte is used for water supply of the hood during infiltration. The principle of setting up the tensions is the same as for ordinary tension infiltrometers. It means that inside the Mariotte water supply, there is a bubble tower with an adjustable pipe which controls the suction. The only peculiarity as opposed to the conventional disk infiltrometer is that there is an air outlet tube which connects head spaces of the water reservoir (Mariotte water supply) and the hood. From the hood, there also leads a standpipe which is joined to U- Tube manometer. The U-tube manometer can then measure effective pressure head created on the soil surface.

Schema of HI is shown in Figure (9).

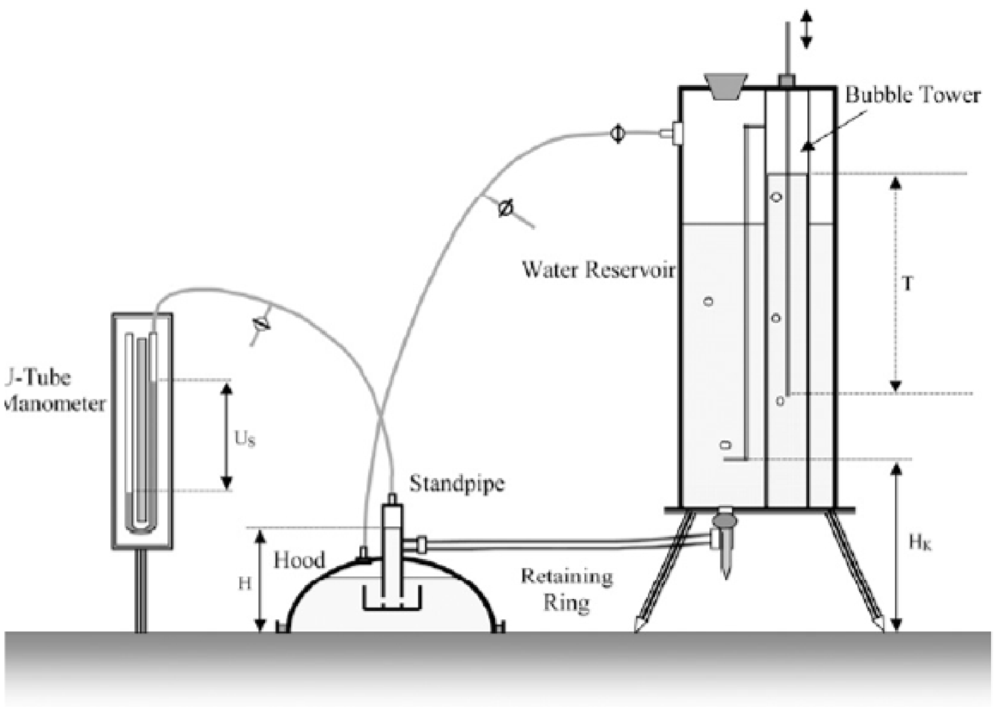


Figure 9 - Schema of HI device, UGT GmbH [online]

There is of course a need of filling in the hood. This is done by opening the connection tube between the hood and Mariotte water reservoir, which will cause water to move into the buffer cup inside of the hood. This filling of the buffer cup is needed to extract air from the connecting tube. After this procedure is made, the air outlet tube has to be slowly opened to fill in the hood. The outlet for air has to be closed after reaching the mark in the hood. Water inside the hood is then under negative pressure. As it was previously mentioned, the selected pressure head can be set up by the adjustable pipe. Then the measuring can start.

As Buczko et al. (2006) explained, the HI is a modified version of a closed-top infiltrometer. This type of infiltrometer was designed by Dixon (1975). Water is applied to the closed-top infiltrometer and this then applies negative pressure to the soil surface. This infiltrometer simulates heads from -3 to +1 cm of water. It is based on the principle, that "natural positive air pressure can be simulated by equivalent negative air pressure above ponded surface water" (Dixon, 1975, p. 755). If h_w is defined as the ponded water depth and actual or simulated soil air pressure head is h_a, then h_s is effective surface head, which is the difference between h_w and h_a.

So under the closed-top infiltrometer the equation is (equation 21):

$$h_a > h_w; \; h_s = h_w - h_a \tag{21}$$

where $h_s < 0$.

The principle of the closed-top infiltrometer is illustrated in Figure (10)

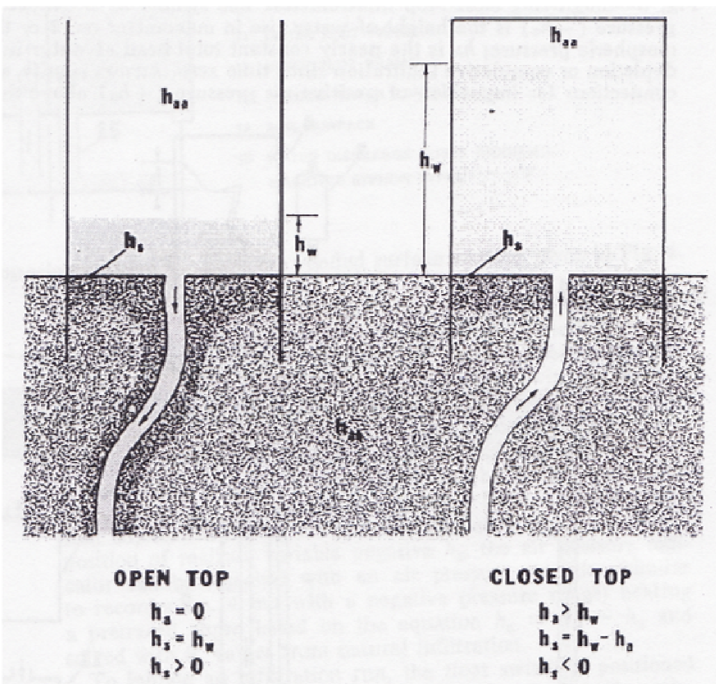


Figure 10 - Idealized water and air flow in hydrophylic bimodal porous media under open-top and closed-top infiltrometer, Dixon (1975)

The HI parameters are given in Table (3) below.

Table 3 - HI parameters, UGT GmbH [online]

Hood infiltrometer parameters	
Tension range	0 - 60 hPa
Measuring range	+/- 700 mm of water column
Time steps	choose
Tension of measurement	resolution 0.1 hPa
Infiltration rate	0.01 ml/min - 20 ml/min
Measuring range	1 000 cm/d - 0.01 cm/d
Water consumption	0.1 - 0.5 l per infiltration step
Measuring period	ca. 2 days

Hydraulic conductivity is then calculated as a function of water tension *h*. For this, Gardner`s equation is used (Decagon Devices, Inc.):

$$k_u = k_f \exp(\alpha h) \tag{22}$$

Where k_u is hydraulic conductivity under unsaturated conditions, k_f is saturated hydraulic conductivity, h is the pressure head, α is sorptive number.

Wooding`s equation for the steady state flow is written in this form:

$$Q = \pi a^2 k_u \left(1 + \frac{4}{\pi \alpha a}\right) \tag{23}$$

where a is the dimensionless length equal to ($\alpha r/2$), r is the radius of disc and other parameters are known from the previous equation (see equation 22).

The calculation of hydraulic conductivity of soil under different tensions is in details described in Chapter 4.4.1.

3.4 Factors affecting the determination of unsaturated hydraulic conductivity

There are many significant factors which can affect determination of hydraulic conductivity such as different tensions settings, different systems and different place. We can divide these factors to extrinsic (such as traffic, cropping and others) and intrinsic (like soil type, pore size distribution and others) properties. Factors associated with these properties affect infiltration ratio and runoff processes on agriculturally used soils (Mohanty et al., 1994). Knowledge of all these factors can then help with modelling of infiltration and runoff processes more precisely and accurately (Mohanty et al., 1994).

Some significant effects on the accuracy of measurement have been described according to Elrick and Reynolds (1992) as; soil heterogeneity, macrostructure collapse just under the infiltrometer during the measurement, changes in hydraulic contact during the measurement and also the contact material and its hydraulic properties and thickness. The wrong hydraulic contact can be caused by wind during the measurement and can also be caused by the decreasing weight of the infiltrometer itself.

A summary of the issues, which affect the hydraulic conductivity measurement was written by Johnson (1963) who wrote that the measurement is influenced by chemical-physical conditions of the soil profile and this property can vary with time. The rate is affected by texture and structure of soil, sediment surface and also the distribution of soil water content, chemical and physical nature of the water, length of application time, bioactivity, temperature of water, percentage of entrapped air in soil surface, atmospheric pressure and the type of equipment or method which is used. Unfortunately he did not make measurements with tension infiltrometers, but only with ring infiltrometers.

3.4.1 Tillage, crop effects

Schwärzel et al. (2009) suggest, that methods to determine the interactions between crop or soil management and its influence on soil structure and pore-size distribution are needed to improve knowledge about the overall impacts of agricultural processes on soil water regime and fertility. They wrote that saturated and near-saturated soil hydraulic properties are very sensitive to management practices such as tillage and other factors.

Tillage variances, which alter soil structure and also increase porosity of the upper layer of the soil, were measured by Ankeny et al. (1991), White et al. (1992) and Reynolds and

Zebchuk (1996). Effect of crop seasonality or as it can also be named as ‘seasonal variability’ due to factors such as soil compaction and water regime was studied by Chowdary at. al. (2006) and Buczko et al.(2006). The tillage and crop effect was also measured by Logsdon et al. (1993). They were measuring the effect of different tillage practices (no-tillage, chisel, moldboard plow and ridge till) and also different crop rotations at various dates (4 dates) between June 1991 and May 1992. They claimed that infiltration rates under no-tillage compared to tilled soils can be faster, slower or not significantly different. There is also the effect of traffic-induced compaction of the soil and dependence on soil canopy cover. The fauna activity (eg. earthworms) and root activity of flora can cause an increase in macroporosity and thus differences in infiltration rates. Soil cracking under dry conditions can also influence the rates considerably. Mohanty et al. (1994) wrote that hydraulic conductivity – both saturated and unsaturated – is much higher in the corn rows than in wheel track inter-rows. They also noted that infiltration of water depends on soil macroporosity. If soil has a lot of macropores, the runoff from the soil is smaller.

Kechavarzi et al. (2009) issued an article about tillage effect on nearly-saturated hydraulic conductivity. They examined 5 different tillage treatments (conventional and shallow plough, minimum tillage, direct drill and no-treatment). They found, that minimum tillage and no-treatment soil plotted higher hydraulic conductivity near saturation than tilled soils. However the results of hydraulic conductivity differ from author to author. For example Ankeny et al. (1990) didn’t measured differences in hydraulic conductivity under different tillage of soils.

The effect of canopy roots was also studied by Shirmohammadi and Skaggs (1984). They reported that fescue roots loosen the soil and this then causes an increase in hydraulic conductivity. Mohanty et al. (1994) also mentioned in his article the impact of depth and size of the taproot system, which can then affect the hydraulic conductivity positively.

Matula (2003) wrote, that mouldboard plough often followed by secondary tillage operation, which has been applied since the Middle Ages, can cause soil compaction due to the repeated use of heavy traffic operations. He also made 2 measurements in 1997 and 2000 to compare the tillage effect on infiltration. He discovered that there were almost no effect for conventional ploughing, but he observed a decrease in infiltration between these two years for reduced tilled treatment and no-till treatment.

White and Perroux (1989) measured hydraulic conductivity from sorptivity measurements. Their method required air-drying of the sample every time between two measurements under different tensions. The air-drying caused a bad wetting/drying influence on the soil.

3.4.2 Time variability

Angulo-Jaramillo et al. (2000) also point out a time aspect with effect on hydraulic properties. They suggest, that there is a seasonal or temporal change caused by irrigation, tillage practices, rain and wind and also biological activity which can modify the soil structure.

3.4.3 Particle size distribution

The effect of particle size distribution was examined by Benson and Trast (1995). They performed an experiment which determined the influence of soil particles of 2 μm (clay) on hydraulic conductivity. An increase in the fraction of smaller particle sizes resulted in the decrease of hydraulic conductivity, but they concluded, that the trend was not significantly strong enough to say with confidence that content of fine soil particles does not significantly affect the hydraulic conductivity of given soil.

3.4.4 Air bubbles

Another factor, which affects the measuring of hydraulic conductivity, is the presence of air bubbles in the infiltrometer reservoir. Air bubbles causes a noise during the measurement and the measurement is not so precise because of bubbling-induced variability. This was studied by Casey et al. (2002) and also Ankeny et al. (1988).

3.4.5 Contact material

A factor measured by Reynolds and Zebchuk (1996) is the usage of contact material for tension infiltrometers. Good contact between infiltrometer and soil surface is required, but the contact material can cause some problems and can influence measurements. As the contact material sand is usually used, they observed incompatibility between pressure head of the soil surface and pressure head on the membrane of the tension infiltrometer within using the contact material. The discrepancy is depending on thickness, hydraulic conductivity and air entry value of the contact material. This discrepancy can then influence the accuracy or validity of tension infiltrometer measuring and thus the reliability of results are compromised.

Perroux and White (1988) established the 3 following criteria for contact material, which have to be fulfilled:

1, the hydraulic conductivity *K (h)* of the contact material should be greater or equal to the hydraulic conductivity of the soil over the range of pressure heads on the tension infiltrometer;

2, the pore water pressure head at which the contact layer (eg. sand) spontaneously saturates has to be less than the minimum value of pressure head which can be set on the given infiltrometer;

3, the contact layer should be as thin as it is possible to minimise the effects on hydraulic conductivity of the measured soil.

Perroux and White (1988) calculated, that the ideal thickness of contact material layer is about 3 – 5 mm with fine sand texture and its hydraulic conductivity *K (h)* of 10^{-5} ms^{-1}. These parameters should be usable for most soils with agricultural usage and also for the pressure heads of tension infiltrometers.

Elrick and Reynolds (1992) and Smettem and Clothier (1989) stated that the thickness and other properties of the contact material can affect the early-time transient flow measurements because of the time needed for the wetting front to move through the contact material to the soil layer. On the other hand, Bagarello et al. (2000) found that there is almost no influence on steady-state infiltration rates when using appropriate contact material with higher permeability than the soil surface.

Close et al. (1998) calculated that non-uniform wetting of the contact material can influence the measurements and cause them to fluctuate. Wang et al. (1998) said, that there is no need of use contact material for very smooth soil surface.

Bagarello et al. (2001) also refer to the importance of the use of contact material to establish proper hydraulic contact between the membrane of the tension infiltrometer and the soil surface. They determined the change in hydraulic properties using two types of contact material – natural sand contact material and glass spheres. If the sand is reused, the saturated hydraulic conductivity *K* is increasing due to a progressive loss of finer particles from the sand. However the second material used – the Spheriglass – maintained a stable hydraulic conductivity both in laboratory and also in the field.

3.4.6 Pressure heads

Bagarello et al. (2000) mentioned also the effect of descending (i.e. from low to high negative heads) or ascending pressure heads used on the tension infiltrometer. They wrote that some authors used the measurements from lower to higher suction – (ascending) as Ankeny et al. (1991); Logsdon (1993) and Mohanty et al. (1994) have experimented in this way.

On the other hand, there are some measurements (wet-to-dry measurements) which reduce the antecedent negative head effects at low infiltration rates (this theory is based on Mohanty et al., 1994). The disadvantage of the descending sequence can cause hysteresis. Experiments carried by Logsdon et al. (1993) on silt loam soil show higher infiltration under measurements taken under descending pressure heads than at ascending pressure head values.

Logsdon (1993) also made measurements for ascending heads. In his case pressure heads -150, -60 and -30 mm were used. It was determined that as the heads become less negative, the sorptivity and also hydraulic conductivity increases.

3.4.7 Initial water content

Benson and Trast (1995) performed an experiment measuring the hydraulic conductivity of soils which were prepared to various molding water contents. This measurement was held in a laboratory, so the samples were then compacted and permeated in the lab. They chose a compacted clay soil, which was used as an integral component of municipal and hazardous waste landfills.

Benson and Daniel (1990) also made measurements on highly plastic clay soil and found that hydraulic conductivity varied by six orders of magnitude. This was dependant on the molding water content and also compaction of the soil.

Benson et al. (1994) also made some other measurements for clay soils and they found that the hydraulic conductivity of soil is sensitive to molding water content and also the dry unit weight. It was concluded that the hydraulic conductivity is dependant on plasticity of soils. More plastic soils tend to have lower hydraulic conductivity. They also noted that soil with higher initial water content (saturation) has lower hydraulic conductivity.

Logsdon (1993) wrote in an article that measurements were made on seven dates during the year on clay loam soil where corn was planted. She found that K (hydraulic conductivity) and S (sorptivity) fluctuated over the growing season with no relation to water content, which fluctuated from 0.04 to 0.36 m/m during the measurements. The measurements were made under ascending pressure heads. Readings were taken every 15 and 25 minutes at each negative head for the clay loam. Initial and final water contents were measured using soil samples taken on the measuring places. The negative impact of bubbling time which causes a delay in infiltration was discussed. On non-compacted wet soil, the bubbling usually occurs within a few minutes, but on initially dry soil it can occur for 45 minutes.

Graphs on Figure (11) below show S and K as a function of initial soil water content (for -150 mm head or -60 mm when the higher pressure head did not wet the soil).

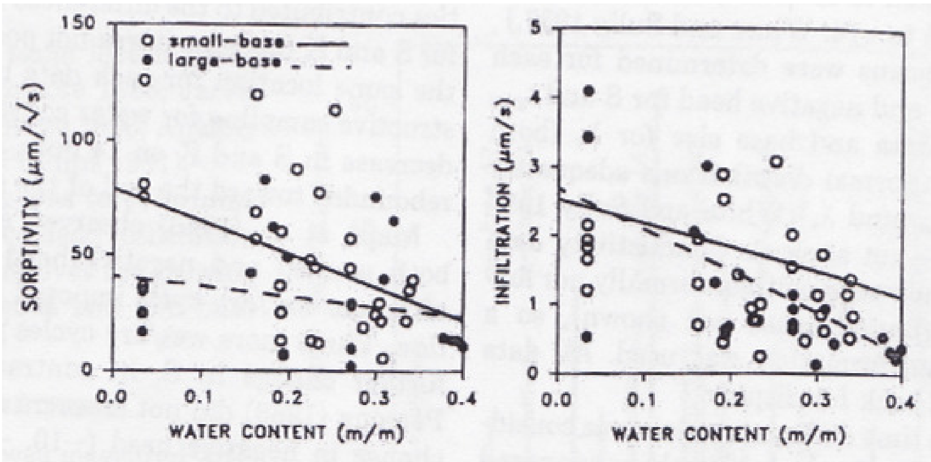


Figure 11 - Sorptivity and hydraulic conductivity as a function of initial soil water contents, Logsdon (1993)

Benson and Trast (1995) calculated the initial saturation of the soil using equation (24):

$$S_i = \frac{w}{\dfrac{\gamma_w}{\gamma_d} - \dfrac{1}{G_s}} \tag{24}$$

where w is molding water content, γ_d is dry unit weight, γ_w is the unit weight of water and G_s is the particle density.

The Figure (12) below shows the results from the experiment of Benson and Trast (1995). A trend of decreasing hydraulic conductivity when initial saturation increases is visible.

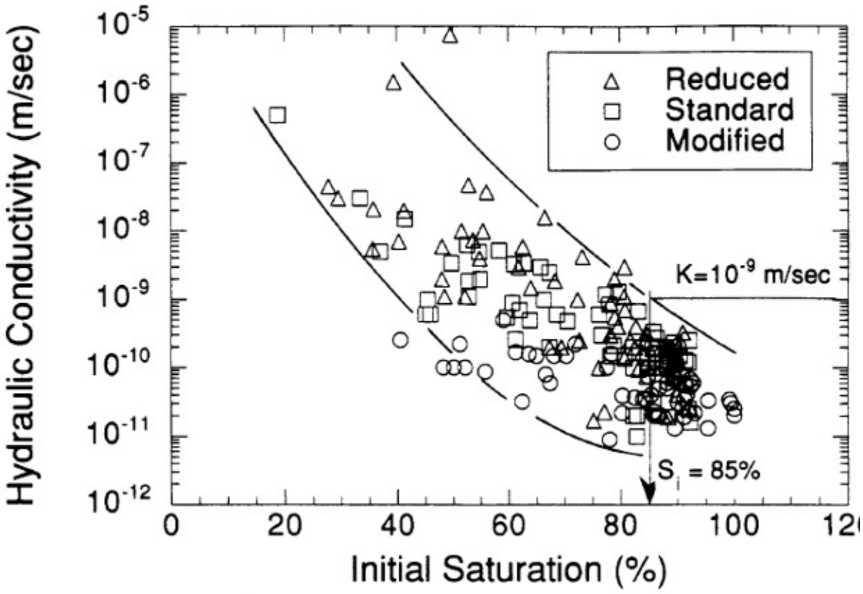


Figure 12 - Hydraulic conductivity versus initial water content, Benson and Trast (1995)

Other authors who made measurements about initial water content include El-Shafei and Al-Darby (1991) who studied the effect of initial soil water content on infiltration, but under a small positive head and with an initial water content of 28 – 48 % of saturation.

Hawke et al. (2006) described the influence of rainfall intensity and initial soil water content on changes in hydraulic conductivity measured by TDR – Time-Domain Reflectometer. They reported that rainfall can affect the matrix structure on the surface of soil. The compressive force of the rain can deform or even destroy the particle arrangement. Orientation or position of surface particles and aggregates can be affected by shear forces. Also, during the infiltration the pores may become clogged by detached particles.

Kim and Kim (2009) wrote that there is a significant difference between drying and wetting curve on the Soil Water Retention Curve. It means in other words, that the initial water content in soil can influence the behavior of unsaturated soils. They made their research with 3 types of granite soil sample. Dry (initial water content was 6.5 %), wet (18.5 %) and optimum water (11.6 %). They measured the time to reach the equilibrium state.

Figure (13) shows how water content corresponds to the matric suction. When the matric suction is over 300 kPa in this case, the changes in water content are equal almost to zero, although the matric suction still increases.

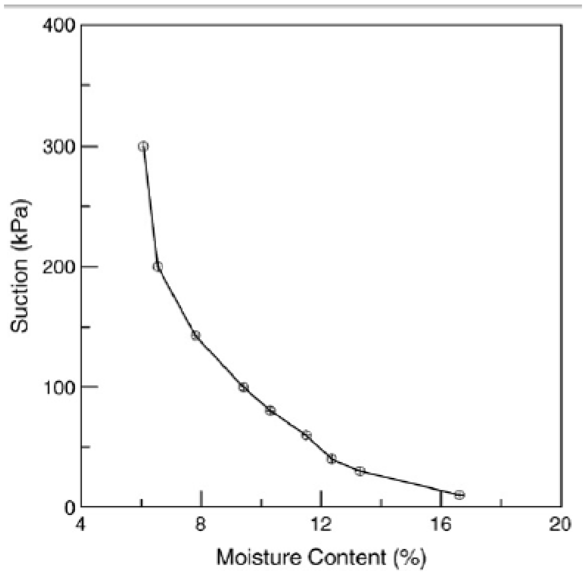


Figure 13 - Water content corresponding to matric suction, Kim and Kim (2009)

Angulo-Jaramillo et al. (2000) made an experiment on sandy soil in Spain and stony sandy loam in France. Both these experimental soils were cropped with maize and were under conventional tillage. The only difference was in the irrigation practice – one possibility was the furrow irrigation, the second one was gun irrigation. Two measurements were made (first before the irrigation period, the second at the end of growing period). The sandy soil under furrow irrigation showed a drastic reduction of hydraulic conductivity and also sorptivity between the two measuring periods. On the other hand, for the sandy loam there was almost no significant difference between two measuring periods and no linearity is shown for the hydraulic conductivity for this soil.

4 Materials and Methods

Factors affecting the determination of unsaturated hydraulic conductivity can be evaluated on the basis of the field experiments. The following devices were used:

Hood Infiltrometer IL-2700 (Umwelt Geräte Technik, GmbH.),

Mini Disk Tension Infiltrometer (Decagon Devices, Inc.).

The unsaturated hydraulic conductivity was measured using HI and MDTI at three applied pressure heads. The initial water content of the soil was chosen for investigation as this is the factor most affecting the estimation of *K(h)*.

Three levels of the initial water content were investigated on the experimental field - dry, medium wet and wet conditions as it is explained in detail in the following Chapter 4.2. The initial water content was measured at an area closely surrounding the infiltrometer before the unsaturated hydraulic conductivity measurement using the disturbed samples and Theta Probe (Delta-T Devices, Ltd) method. This is discussed in Chapters 4.2.1 and 4.2.2. After the measurement the undisturbed soil samples were taken. From these samples additional calculations such as particle density, dry bulk density and porosity were made.

Methods and equations used for calculation of the unsaturated hydraulic conductivity from the HI and MDTI are described in Chapter 4.4.

4.1 Characterisation of the experimental locality

Experiments were held on Experimental field of University of Life Sciences Prague during August and September 2011. The soil is characterized by texture as loam or clay loam with about 20 % of clay, according to USDA textural classes. The type of soil is Chernozem modal.

Other soil characteristics such as the dry bulk density, particle density and total porosity are described in following Chapter 4.2.

There was a permanent grass cover on the experimental place (see Figure 14) and close to this experimental area was a treated field. Relatively homogeneous soil conditions are required to minimize the effect of soil heterogeneity and thus enabling evaluation of other factors.

Figure 14 - Grass cover on the experimental place

4.2 Water content and preparing the experiment

The unsaturated hydraulic conductivity $K(h)$ was measured using HI and MDTI. The initial water content of the soil was chosen for investigation as this is the factor most affecting the estimation of $K(h)$. Three levels of the initial water content were investigated on the experimental field – dry, medium wet and wet conditions. It means that three levels of initial water content were maintained on the field. Five measurements for each of the three levels of initial water content were made by HI. After redistribution of infiltrated water and after the previous condition of initial water content was reached, measurement with the MDTI was made in the same place as the HI.

The places of measurement were named as D1 – D5 for the driest soil profile, MW1 – MW5 for the medium wet soil and W1 – W5 for the wettest soil profile. These abbreviations are used in the following text and tables. The layout of the experimental field is shown in Appendix (1)

If the proper value of the initial water content could not be provided by the natural weather condition, the soil had to be irrigated. Reaching the correct value of the initial water content was then achieved by irrigating the place for measurement with regular tap water, which was sprayed over the area of the infiltration and surrounding ~ 1 m^2. In the following days the place was monitored and the water content measured by Theta Probe to be able to reach the proper value of the initial water content. Thanks to these continual measurements, precautions such as covering the experimental field with foil to prevent the soil water from evaporation or irrigation was done. The measurement with HI or MDTI was then held after 6 days at the earliest, to be sure that the natural redistribution of the added tap water was reached.

The initial water content was measured at an area closely surrounding the infiltrometer using the calculation of water content by mass and volume. The measuring of water content by mass is done with the disturbed samples taken using the gouge soil sampler. The values of water content by volume are reached by Theta Probe method.

After the measurements with MDTI the undisturbed soil sample was taken to obtain the particle density and dry bulk density of the soil.

4.2.1 Water content by mass

Before measuring with HI, a disturbed sample from an area close to the infiltrometer was taken to establish the initial water content as Kechavarzi et al. (2009) also recommended. Methods for the determination of soil water content are described also by Klute (1986) and Topp et al. (1992).

The disturbed samples which were taken close to the place of measuring with HI were taken using the gouge soil sampler. These samples were ~ 0.9 - 1 m distance from the place of measurements to avoid influencing the tensiometer measurements and to avoid the destruction of pore distribution in the soil profile. The first 50 cm of the soil profile was examined for each hole and it was divided into 5 samples, each for 10 cm of the soil profile. For determining the water content gravimetrically, each sample was put into an aluminium sampling container with lid with known mass, and was immediately weighed on return to the lab. After at least 24 hours drying in oven at 105 °C to the constant mass, the containers with dry soil samples were weighted once more.

Then the water content by mass was calculated based on the equation (25):

$$w = \frac{m_w}{m_z} \tag{25}$$

where w is water content by mass, m_w is mass of water, calculated by subtracting the mass of dry soil sample from the mass of wet soil sample, and m_z is mass of dry soil sample.

The values of water content by mass are shown in the Table (4). Each spot has five values of the water content by mass. These five values correspond to each 10 cm of the soil profile from the surface (depth of 0 cm) down to the depth of 50 cm. For each spot one measurement of the water content by the gauge was done. However, if the spots were nearby, only one measurement of water content was taken for both spots. This can be seen e.g. on spots D1, D2, D4 and D5 for the dry place.

Table 4 - Water content by mass w [%] near HI measurement spots

Water content by mass w [%] near HI measurement spots					
	depth of the soil profile				
place	**0-10 cm**	**10-20 cm**	**20-30 cm**	**30-40 cm**	**40-50 cm**
D1	23.39	21.44	19.56	18.56	18.64
D2	23.39	21.44	19.56	18.56	18.64
D3	22.65	20.75	18.55	17.74	17.30
D4	23.62	23.00	20.84	17.79	17.36
D5	23.62	23.00	20.84	17.79	17.36
ø DRY	23.33	21.93	19.87	18.09	17.86
MW1	30.72	29.65	28.08	25.80	23.10
MW2	28.45	26.74	23.51	23.01	22.17
MW3	28.45	26.74	23.51	23.01	22.17
MW4	29.50	28.45	26.90	25.51	23.36
MW5	29.50	28.45	26.90	25.51	23.36
ø MEDIUM WET	29.32	28.01	25.78	24.57	22.83
W1	35.32	33.56	30.64	28.41	27.12
W2	35.32	33.56	30.64	28.41	27.12
W3	35.15	32.31	30.16	27.90	26.50
W4	35.15	32.31	30.16	27.90	26.50
W5	36.12	34.90	32.94	31.29	31.13
ø WET	35.41	33.33	30.91	28.78	27.67

4.2.2 Water content by volume

Also measurements of water content with Theta Probe Soil Moisture Sensor ML2X (Delta-T Devices) were taken, but these measurements are just for the first six centimeters of the soil profile.Theta-probe belongs to the capacitance methods. The Theta-probe is used to measure volumetric soil water content using a simple technique of standing wave. The volumetric soil water content can be described as the ratio between the volume of water present in the soil and the total volume of the sample. This can be expressed as equation (26):

$$\theta_r = \frac{V_w}{V} \tag{26}$$

where θ_r is the volumetric water content as the dimensionless parameter expressed usually in % or as the ratio in m^3/m^3. V_w is the volume of water and V is total volume of the soil.

The Theta Probe soil moisture sensor schema is shown on Figure (15).

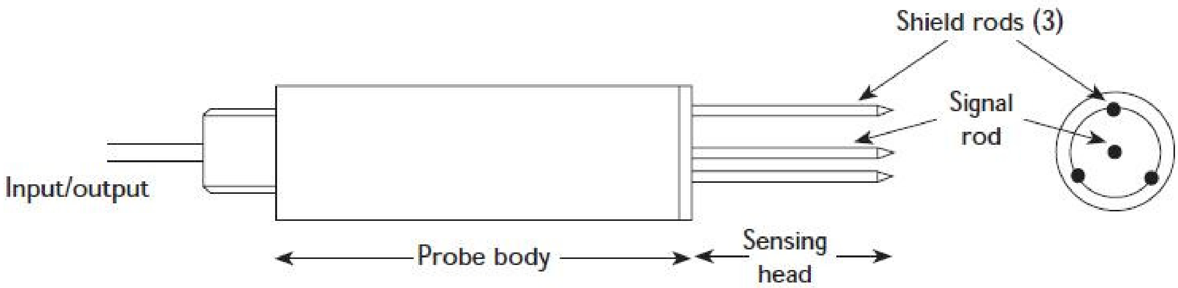


Figure 15 – Theta Probe Soil Moistre Sensor ML2X schema, Miller and Gaslein [online]

Usually the probe has to be calibrated for measurements. However, for the purposes of the experiment, only the difference between measured values was important and not the accurate values of the water content of the soil.

The biggest advantage of measuring with Theta Probe is that the results of water content are immediately visible. This is why this device was used before each measurement with infiltrometers. The Theta Probe Soil Moisture Sensor ML2X is visible in Figure (16).

Figure 16 - Theta Probe Soil Moistre Sensor ML2X; Wine Business.com [online]

Measurements were done under natural conditions on the experimental field. It means that there were some problems with obtaining very close values of initial water content for the two devices. The measurements with HI and also the MDTI needed to be made with very similar initial water conditions to be able to compare these two devices with respect to the initial water content of the soil. However, measuring under natural conditions has a big disadvantage due to varying weather and other factors which can affect measurements, such as sunshine, wind, rain and others. To avoid the influence of these environmental factors, a plastic foil was used which covered the field and protected it from rain or from evaporation of soil water. During the sunny days the beach umbrella was used to protect the soil and also water for infiltration from warming. Regular tap water was used for infiltration, which is in accordance with the manuals of these devices.

As it is shown in the Table (5) the average values for dry, medium wet and wet are 25.1, 32.5 and 38.3 % water content by volume for HI and 23.9, 31.7 and 35.4 % for MDTI. For each place of infiltration six measurements were made in the surrounding area with Theta Probe and the average of these six values was used in Table (5). The measurement with Theta Probe device has the disadvantage that they are only for a thin layer of the soil profile, because the length of the rods is about 6 cm. The abbreviation HI used in table is for HI.

It means that for the HI a step of 7.4 % was between the dry and medium wet soil and 5.8 % between the medium wet and the wet soils. For MDTI the differences were step of 7.8 % between dry and medium wet soil and 3.7 % between the medium wet and the wet soils.

Table 5 – Volumetric water content of experimental area from the Theta Probe device for HI and MDTI

	data for HI	data for MDTI
place	θ [%]	θ [%]
D1	25.4	25.2
D2	25.7	23.2
D3	21.9	23.0
D4	26.2	24.5
D5	26.1	23.7
ø DRY	25.1	23.9
MW1	33.6	32.7
MW2	32.4	31.3
MW3	31.5	31.1
MW4	33.0	32.2
MW5	32.0	31.2
ø MEDIUM WET	32.5	31.7
W1	38.5	35.4
W2	39.6	35.2
W3	37.5	36.7
W4	37.7	34.5
W5	38.0	35.0
ø WET	38.3	35.4

The minimum (min) and maximum (max) values of the volumetric water content are shown in Table (6). The minimum for dry place,, medium wet and wet place was measured on the same spot of measurement (D3, MW3 and D4) both for HI (HI) and MDTI and maximum values of volumetric water content for the medium wet soil profile is also on the same spot.

Table 6 - Minimum and maximum values of volumetric initial water content

		HI		MDTI	
		place	**value of θ [%]**	**place**	**value of θ [%]**
DRY	**min**	D3	21.9	D3	23.0
	max	D4	26.2	D1	25.4
MEDIUM WET	**min**	MW3	31.5	MW3	31.1
	max	MW1	33.6	MW1	32.7
WET	**min**	W4	37.7	W4	34.5
	max	W2	39.6	W1	35.4

The graph of volumetric water content is shown in Appendix (2).

4.2.3 Undisturbed soil samples

Immediately after the measurement was made with the MDTI, undisturbed soil samples with a volume of 100 cm^3 at a sampling depth of 0 - 6 cm were taken from below the infiltrometer surface with Kopecky`s sampling rings for analysis. The sampling rings with plastic lids are shown on Figure (17). This ring with 100 cm^3 of volume has an inner diameter of 57 mm. The diameter of sampling ring almost corresponds to the diameter of the MDTI disc. The soil sampler is 40.5 mm high and is made from stainless steel.

Figure 17 - Kopecky`s sampling rings, UGT GmbH [online]

Samples were wrapped from the bottom side with a geotextile to avoid any damages and losses of the soil. As Dane and Topp (2002) also recommended, the undisturbed samples were repacked to avoid any damage of the sample and to avoid evaporation. Samples were weighed and left to saturate on a saturation mat to the constant mass on arrival in the laboratory. Due to capillary forces, the Kopecky`s sampling rings were fully saturated. The saturated soil samples were then weighed.

The rings were then put into the oven to reach the constant dry weight at 105 °C as Kechavarzi et al. (2009) recommends. After this procedure, the determination of particle density ρ_z was carried out by using the water pycnometer method which is described in detail in the following text. The dry bulk density ρ_d was calculated and also the total porosity P of the soil. These calculations are also described in the following text.

Particle density

For calibration of the water pycnometer, the empty pycnometer was completely filled with distilled water. The pycnometer was then tempered by water to a temperature of 20 °C. After the temperature of the pycnometer reached exactly 20 °C the pycnometer was sealed with the glass stopper. No air bubbles can remain under the stopper. the pycnometer was then weighed. Then the water from pycnometer was emptied. Figure (18) shows the water pycnometer.

Figure 18 - Water pycnometer, Educational Technology Clearinghouse [online]

For the measurement of the particle density 15 - 17 grams of oven-dried fine soil were put into the ceramic cup and the distilled water was added. The amount of distilled water has to be enough to cover the soil. This mixture was then heated over a Bunsen burner to remove the air bubbles in the soil sample. Water was boiled for approximately 5 minutes.

The pycnometer was then filled with the mixture of soil and water which was prepared before. The pycnometer was filled completely with the distilled water and was again tempered to 20 °C. Then the pycnometer was weighted again. The particle density was calculated using equation (27):

$$\rho_z = \frac{m_z}{m_z + m_1 - m_2} \tag{27}$$

where ρ_z is the particle density of soil particles, m_1 is mass of pycnometer filled with water, m_2 is mass of pycnometer filled with soil suspension and m_z mass of dry soil sample. For each soil sample two measurements have to be done and the difference has to be smaller than 0.03 g/cm^3. Thus the measurements have to be very accurate and precise. The values were in the range between 2.57 – 2.60 g/cm^3 (the values of particle density for each measurement spot are shown in Appendix 3). So the soil specific weight was very homogenousely spread over the area. The value of particle density between 2.57 – 2.60 g/cm^3 corresponds according to Valla et al. (2008) to surface humic horizons.

Dry bulk density

The dry bulk density ρ_d of soil is calculated using equation (28):

$$\rho_d = \frac{m_s}{V_t} \tag{28}$$

where m_s is mass of soil dried at 105° C in the oven and V_t is the volume of soil under natural conditions. The dry bulk density of this soil was between 1.55 and 1.62 g/cm^3.

Total porosity

The total porosity P of the soil can be calculated using equation (29):

$$P = \frac{\rho_z - \rho_d}{\rho_z} \qquad (29)$$

where ρ_d is dry bulk density and ρ_z particle density, as shown in the previous two Chapters.

The total porosity can be characterized as the relative volume of pores in soils. The results of the total porosity, such as the dry bulk density with respect to the place of measurement and initial water content are shown in Appendix (4). The total porosity of the soil was between 37.23 and 40.59 %.

The graph of total porosity, dry bulk density and particle density with respect to measuring spot are shown in Appendix (3; 4).

4.3 Experiment

An important step to be taken is the preparation of the place for infiltrometers. First the measurement with HI was held and after redistribution of infiltrated water and after the previous condition of initial water content was reached, measurement with the MDTI was made in the same place as the HI.

There are different procedures to prepare the place for HI and MDTI. HI places the water column directly on the soil surface and there is no need of contact material. The only adjustment required to the terrain is to cut the vegetation cover to about 5 mm tall. For the MDTI the vegetation has to be trimmed down to ground level and the contact silica sand is recommended to be used to ensure good contact between the infiltrometer and the ground surface. The silica sand used as the contact material for MDTI was silica sand ST56 (Sklopísek Střeleč). The grains of the silica sand have the diameter of 0.063 – 0.40 mm. The same silica sand was used also for HI but for a different purpose: to tighten the contact between the hood and soil as it is visible on Figure 20).

The place of measurement is visible also on Figure (19). In the left picture there is the prepared place for HI, and on the right image there is the same place after one week with the place for MDTI. On the right picture it is possible to see some residuals after used sand for the HI.

Figure 19 - Prepared place for measurements - trimmed grass on the place for the HI and for MDTI, which was put on the same place as the Hood after about a week when the soil water content had settled to the the previous conditions as much as possible

The excess of sand used to tighten the contact between the hood and HI is shown on Figure (20)

Figure 20 - Excess of sand between the hood and the outer ring of HI, UGT GmbH [online]

During the whole experiment there was no treatment of the grass or field on the experimental area. Only the exact place for measuring was prepared by trimming grass with scissors as it is recommended in manuals for the devices to ensure good contact between the device and soil surface.

The measurements of unsaturated hydraulic conductivity were performed under different pressure heads. They were performed for -3, -1, -0.5 cm of pressure head for the MDTI, -0.5, -1, -3 cm of pressure head for HI. It means that for MDTI the ascending values of pressure head were used and for HI the descending values, as it is recommended in the manuals.

The time given for infiltration was at least 40 minutes for each tension for HI. For HI that was enough to reach the steady-state flow and to prevent the effect of transient flow which occurs in the first moments of flow. It means that in total at least 120 minutes of infiltration were made under all three performed pressure heads. For MDTI the minimum of 15 minutes for each tension performed was used. The data were collected every 15 seconds for HI and every 30 seconds for the MDTI.

Figure (21) shows the MDTI in operation.

Figure 21 - MDTI in operation

Water to the MDTI was added just once for the infiltration as it has the water reservoir big enough for the infiltration. The amount of infiltrated water depends on the soil and also on the time for infiltration. Short intervals of 30 seconds were chosen for reading the values.

Water to the HI was added during the measurement. HI has a reservoir of ~ 630 millimeters of water column. The water has to be poured when there is still some water remaining in the reservoir (eg. 10 – 20 mililiters). The water had to be poured every 15 minutes. However, the time depended on the soil water content as the factor affecting the hydraulic conductivity and on the performed pressure head.The HI in operation can be seen on Figure (22).

Figure 22 - HI in operation

4.3.1 Layout of the experimental field

Five measurements with HI and MDTI were performed under three different levels of water content as it is discussed in detail in Chapter 4.2. It means that in total fifteen measurements were done for each infiltrometer.

The placement of the infiltration locations with respect to the initial water content is shown in the Appendix (1). The measuring points had a distance of 1.5 meters in between to be sure that there will be no influence in the water flow beneath the soil profile caused by previous measurements. During the measurements there was often the danger of compaction of the upper layers of the soil profile. It is caused by frequent walking around the devices to be able to read the values and to have access to operate and maintain the devices. To avoid compaction of the soil, a path for walking (~ 50 cm width) was laid out simply by the whipcord.

The measurements with MDTI were held on the same place as measurements with HI after at least six days (as it is discussed more in Chapter 4.2). To make it easier to find the right place for measurements, four spots were made with yellow spray paint around the place for measurements with HI. This can be seen on Figure (23). This picture was taken after measurement with MDTI.

Figure 23 - Yellow spots around the place for measurement

The infiltrations were made randomly according to the weather condition to have the proper initial water content, as discussed in Chapter 4.2. It means that the measurements were not made in order from the driest water condition to the wettest one, but in the way as the weather allowed. The whole layout of the experiment is shown in the Appendix (1).

4.4 Calculation of unsaturated hydraulic conductivity

4.4.1 Calculation of unsaturated hydraulic conductivity measured by HI

The measurements of unsaturated hydraulic conductivity with HI were performed under three different pressure heads. They were performed for -0.5, -1, -3 cm of pressure head for the HI. The infiltration time for each tension was at least 40 minutes and the data were collected every 15 seconds automatically by datelogger. The last three minutes of infiltration of each tension were used as it is discussed further in Chapter 5.1. An example of the Excel sheet used for calculation is in Appendix (5).

The calculation of the unsaturated hydraulic conductivity measured by HI is calculated using these equations (30 - 31):

$$\frac{Q_1}{\pi a^2} = k_f e^{a-h_1}\left(1+\frac{4}{\pi \alpha a}\right) \tag{30}$$

$$\frac{Q_2}{\pi a^2} = k_f e^{a-h_2}\left(1+\frac{4}{\pi \alpha a}\right) \tag{31}$$

where h_1 and h_2 are neighboring values of the chosen water tensions. The water tension should be chosen step by step by 1 or 2 cm up to the soil bubble point.

By simple division we will get equation (32) in this form:

$$\alpha = \frac{\ln\left(\frac{Q_1}{Q_2}\right)}{(h_1 - h_2)}\text{; where } (h_1, h_2 < 0)\,. \tag{32}$$

Two α parameters were calculated. The first one from h_1, h_2 are then used for calculating hydraulic conductivity for tension -0.5, the second one from h_2 and h_3 are used for determination of hydraulic conductivity for tensions -1 and -3. Hydraulic conductivity was calculated in cm/min.

And for the hydraulic conductivity equations in this form were used (33 – 35):

$$k(h_1) = \frac{\frac{Q_1}{\pi a^2}}{\left(1 + \frac{4}{\pi a \alpha}\right)} \tag{33}$$

$$k(h_2) = \frac{\frac{Q_2}{\pi a^2}}{\left(1 + \frac{4}{\pi a \alpha}\right)} \tag{34}$$

$$k(h_3) = \frac{\frac{Q_3}{\pi a^2}}{\left(1 + \frac{4}{\pi a \alpha}\right)} \tag{35}$$

where h_1, h_2, h_3 is the pressure head applied. For the unsaturated hydraulic conductivity usually units of cm/min are used.

It is advised to start the test with water tension set to zero value and then increase the water tension step by step (1-2 cm in every step) up to the bubble point of a given soil.

4.4.2 Calculation of unsaturated hydraulic conductivity measured by Mini Disk Tension Infiltrometer

The measurements of unsaturated hydraulic conductivity with MDTI were held under three different pressure heads. They were performed for -3, -1 and -0.5 cm of pressure head. This range of values corresponds to the pressure heads used for the HI. The infiltration time for each of applied heads was 15 minutes with manual readings every 30 seconds, as it is also written in Chapter 5.2. For calculation all the values were used. The Excel sheet with calculations is shown in Appendix (6).

The hydraulic conductivity *K(h)* measured by MDTI can be then calculated by equation (36) proposed by Zhang (1997), which requires measuring cumulative infiltration versus time:

$$I = C_1 t + C_2 \sqrt{t} \tag{36}$$

where C_1 are C_2 are parameters calculated empirically. C_1 relates to hydraulic conductivity *K(h)* and C_2 is sorptivity of soil. *I* is cumulative infiltration, *t* time.

According to Decagon Devices, Inc., the hydraulic conductivity can then be simply calculated from equation (37):

$$K(h) = \frac{C_1}{A} \tag{37}$$

where C_1 is the slope of cumulative infiltration curve versus square root of time and *A* is a value, which can be determined from van Genuchten parameters (Table 4). The table is divided into 12 soil texture classes and for each texture class and suction height there is a given value.

A values can be taken from Table 3, or calculated from these equations (38) and (39):

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp\left[2.92(n-1.9)\alpha h\right]}{\left(ar_d\right)^{0.91}} \tag{38}$$

valid for $n \geq 1.9$; or

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp\left[7.5(n-1.9)\alpha h\right]}{\left(ar_d\right)^{0.91}} \tag{39}$$

valid for $n<1.9$. Where in both these equations n and α are van Genuchten parameters (values are given in Table 7), h is the tension applied and r with index d is radius of MDTI`s disk.

Table 7 - Van Genuchten parameters for 12 soil types and values of A for MDTI

			h_0						
	α		**-0.5**	**-1**	**-2**	**-3**	**-4**	**-5**	**-6**
texture		**n**							
sand	0.145	2.68	2.84	2.40	1.73	1.24	0.89	0.64	0.46
loamy sand	0.124	2.28	2.99	2.79	2.43	2.12	1.84	1.61	1.40
sandy loam	0.075	1.89	3.88	3.89	3.91	3.93	3.95	3.98	4.00
loam	0.036	1.56	5.46	5.72	6.27	6.87	7.53	8.25	9.05
silt	0.016	1.37	7.92	8.18	8.71	9.29	9.90	10.55	11.24
silt loam	0.020	1.41	7.10	7.37	7.93	8.53	9.19	9.89	10.64
sandy clay loam	0.059	1.48	3.21	3.52	4.24	5.11	6.15	7.41	8.92
clay loam	0.019	1.31	5.86	6.11	6.64	7.23	7.86	8.55	9.30
silty clay loam	0.010	1.23	7.89	8.09	8.51	8.59	9.41	9.90	10.41
sandy clay	0.027	1.23	3.34	3.57	4.09	4.68	5.36	6.14	7.04
silty clay	0.005	1.09	6.08	6.17	6.36	6.56	6.76	6.97	7.18
clay	0.008	1.09	4.00	4.10	4.30	4.51	4.74	4.98	5.22

Values of van Genuchten parameter *A* were taken from Table (7). For this experiment *A* values for tension -3 was stated as 6.87, for -1 it was 5.72 and for tension -0.5 the value of 5.46 for the loamy soil from the table.

5 Results

5.1 Hydraulic conductivity measured by HI

As it can be seen in Chapter 4.4.1, measurements with descending pressure heads were made with the HI, specifically with pressure heads of -0.5, -1 and -3 cm. The time used for infiltration was at least 40 minutes which was enough to reach the steady-state flow. The data were automatically collected by using a datalogger in 15 second intervals; it means that 12 numbers were used for the calculation of unsaturated hydraulic conductivity from HI.. The average value from the last 3 minutes was used for each tension step.

For this infiltration experiment the smaller hood radius (8 cm) was used.

Figure (24) shows the graph of the cumulative infiltration from HI versus time. The graph was created using just the last 3 minutes of infiltration from each pressure head. The first applied pressure head is -0.5 up to the vertical line at the time of 3:00 minutes. Then the -1 pressure head is applied up to 6:00 minutes and the last pressure head is -3. The tendency of decreasing hydraulic conductivity with increasing pressure head is visible.

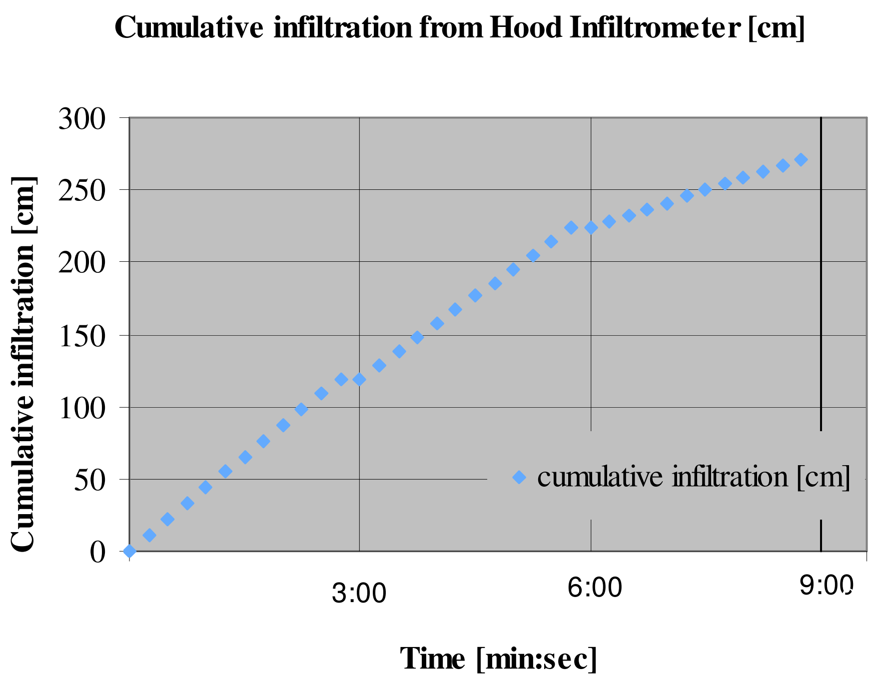


Figure 24 - Cumulative infiltration of HI under three different tensions

The unsaturated hydraulic conductivities calculated from the cumulative infiltrations of HI are shown in Table (8). From the table it is visible, that values of *K(h)* for dry and medium wet soil profiles were very similar, but the values of the wettest site is slightly smaller and this tendency is visible for all three pressure heads implemented. In the table below are the values of unsaturated hydraulic conductivities for all 15 measurements and also their arithmetic mean values are added for each pressure head step. The unsaturated hydraulic conductivity was measured in cm/min.

Table 8 - Values of K(h) from HI

applied pressure head	**-0.5**	**-1**	**-3**
place	**unsaturated hydraulic conductivity in cm/min**		
D1	1.022	0.900	0.441
D2	0.927	0.894	0.512
D3	1.062	0.903	0.447
D4	0.991	1.019	0.459
D5	0.796	0.601	0.449
Arithmetic mean value of DRY	0.960	0.864	0.461
MW1	1.082	0.677	0.276
MW2	0.941	0.908	0.405
MW3	1.041	0.806	0.345
MW4	1.050	0.945	0.600
MW5	0.996	0.948	0.600
Arithmetic mean value of MEDIUM WET	1.022	0.857	0.445
W1	1.016	0.850	0.537
W2	0.647	0.328	0.261
W3	0.770	0.560	0.459
W4	0.861	0.804	0.443
W5	0.985	0.592	0.470
Arithmetic mean value of WET	0.856	0.627	0.434

The graphs for each pressure head are shown below (Figures 25 – 28). Each water condition has its own graph and then the simple average values of each water condition are compared in one graph. It is visible, that the lines for dry and medium wet conditions are almost similar, but the line for the wet condition differ, especially for tension -1.

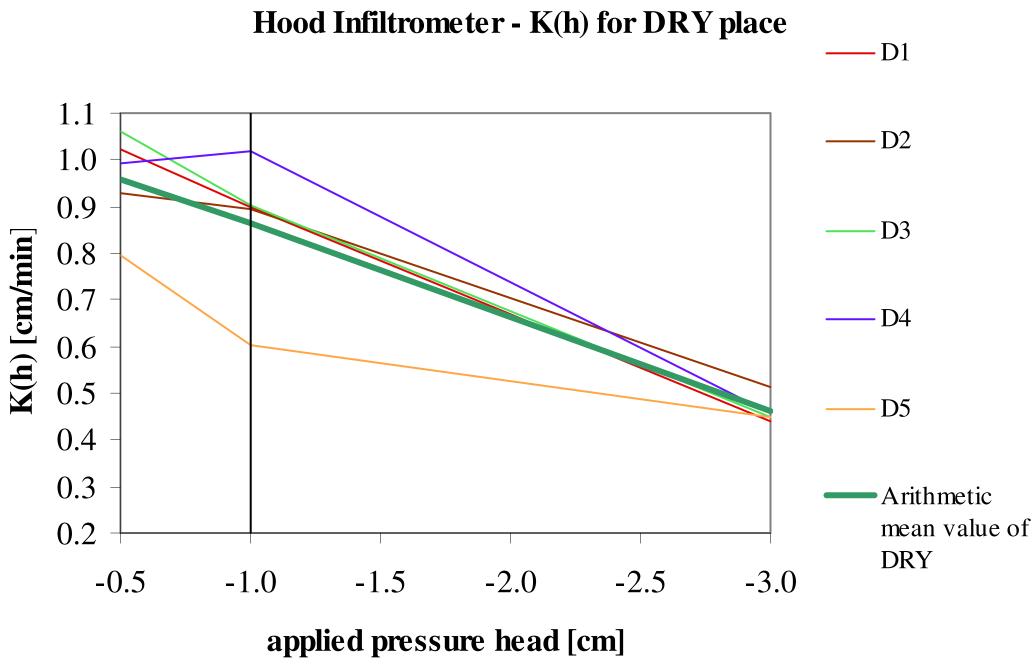


Figure 25 - HI K(h) for DRY place

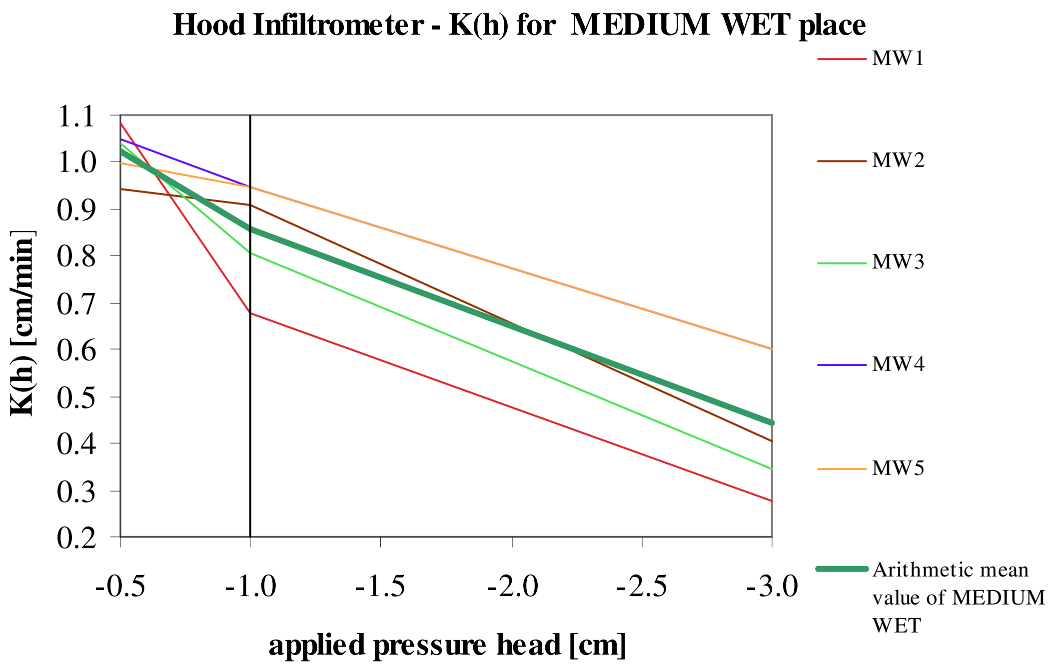


Figure 26 - HI K(h) for MEDIUM WET place

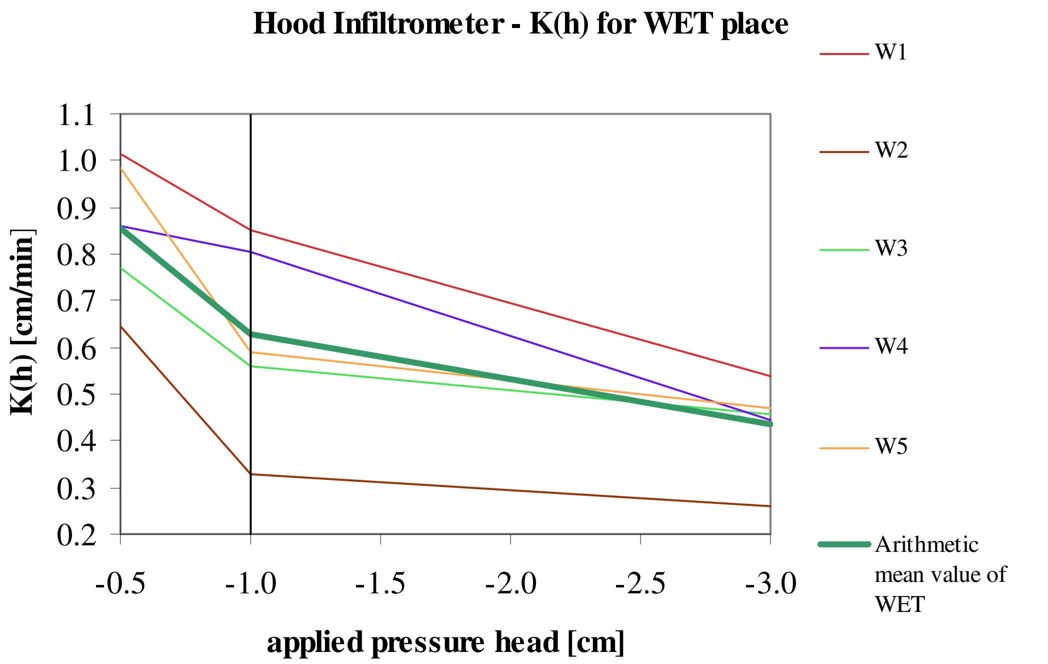


Figure 27 - HI K(h) for WET place

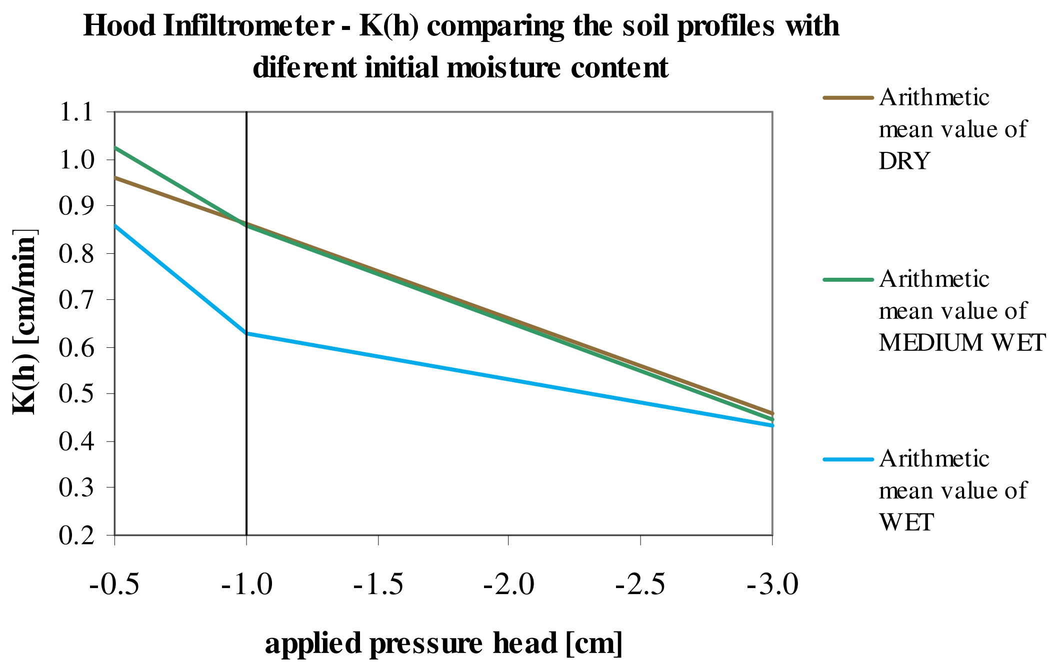


Figure 28 - HI K(h) - comparing the soil profiles with different initial water content

5.2 Calculation of hydraulic conductivity for Mini Disk Tension Infiltrometer

The measurements were performed for ascending -3, -1, -0,5 cm of pressure heads for MDTI and values were recorded manually every 30 seconds.

The good and consistent contact between soil surface and membrane of this device was achieved by using a thin layer of contact sand. Each tension step was held for 15 minutes. The graph of surface pressure head versus time of infiltration for MDTI is shown on Figure (29).

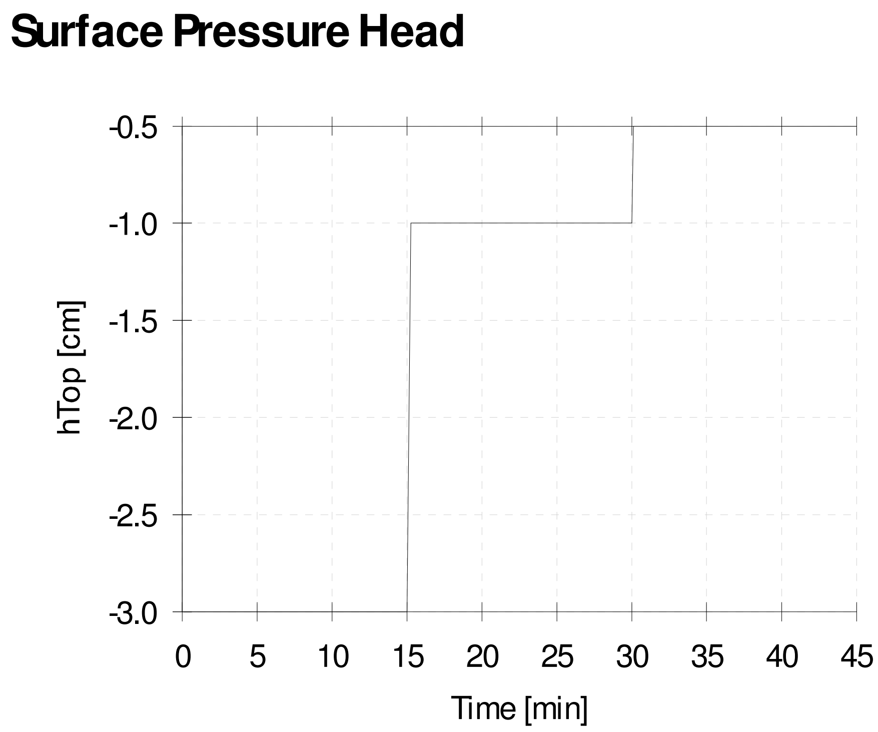


Figure 29 - Surface pressure head for MDTI

The calculated values of unsaturated hydraulic conductivities are shown in table below (Table 9) and also the graphs (Figures 30 - 33) to compare the cumulative infiltrations from each infiltrometer. The values of unsaturated hydraulic conductivities for MDTI are ordered from the lowest tension to the highest, despite that it was measured in the other order. It is done in this way to make this Table (9) consistent with the Table (8) for HI.

Table 9 - Values of K(h) from MDTI

applied pressure head	-0.5	-1	-3
place	unsaturated hydraulic conductivity in cm/min		
D1	0.023	0.024	0.006
D2	0.058	0.038	0.003
D3	0.033	0.014	0.007
D4	0.025	0.018	0.006
D5	0.027	0.021	0.004
Arithmetic mean value of DRY	0.033	0.023	0.005
MW1	0.004	0.003	0.003
MW2	0.029	0.01	0.002
MW3	0.041	0.023	0.004
MW4	0.006	0.005	0.003
MW5	0.029	0.014	0.003
Arithmetic mean value of MEDIUM WET	0.022	0.011	0.003
W1	0.045	0.029	0.001
W2	0.055	0.011	0.001
W3	0.018	0.011	0.001
W4	0.039	0.032	0.002
W5	0.036	0.016	0.002
Arithmetic mean value of WET	0.039	0.02	0.002

Graphs of cumulative infiltration from 45 minutes of infiltration from MDTI are shown in Figures (30 – 32). The vertical lines show the change of applied tension. The first applied pressure head for MDTI was -3, than -1 and the last one was -0.5. Each tension was performed for 15 minutes. The tendency of decreasing value of unsaturated hydraulic conductivity with increasing pressure head applied is visible on all three graphs.

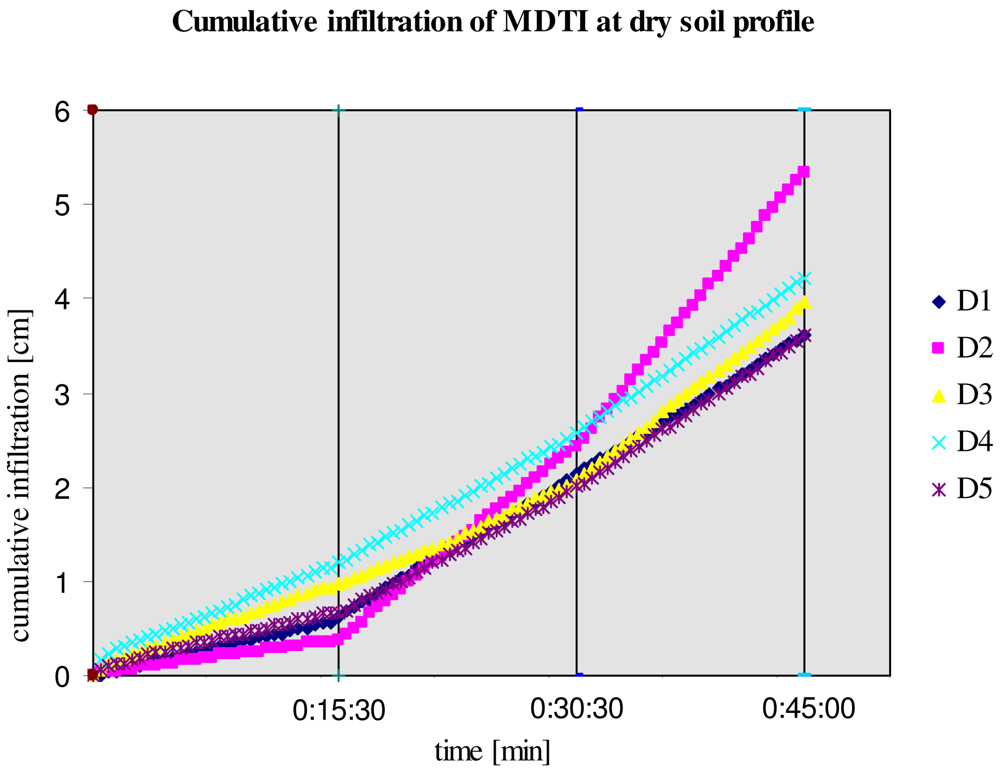


Figure 30 - Cumulative infiltration of MDTI at DRY soil profile

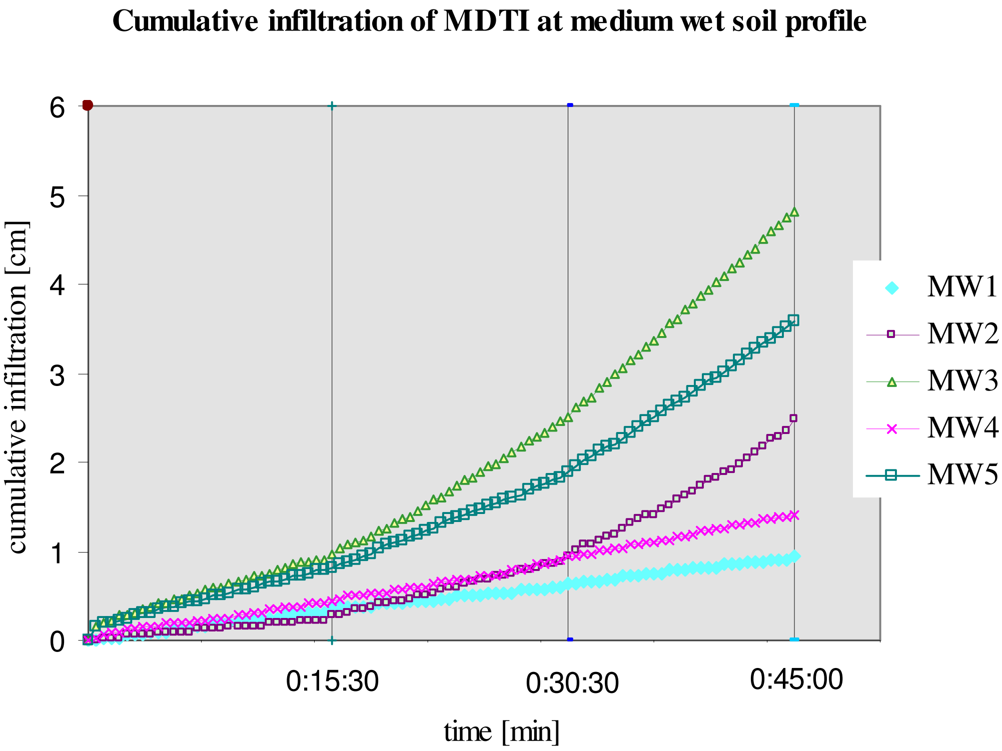


Figure 31 - Cumulative infiltration of MDTI at MEDIUM WET soil profile

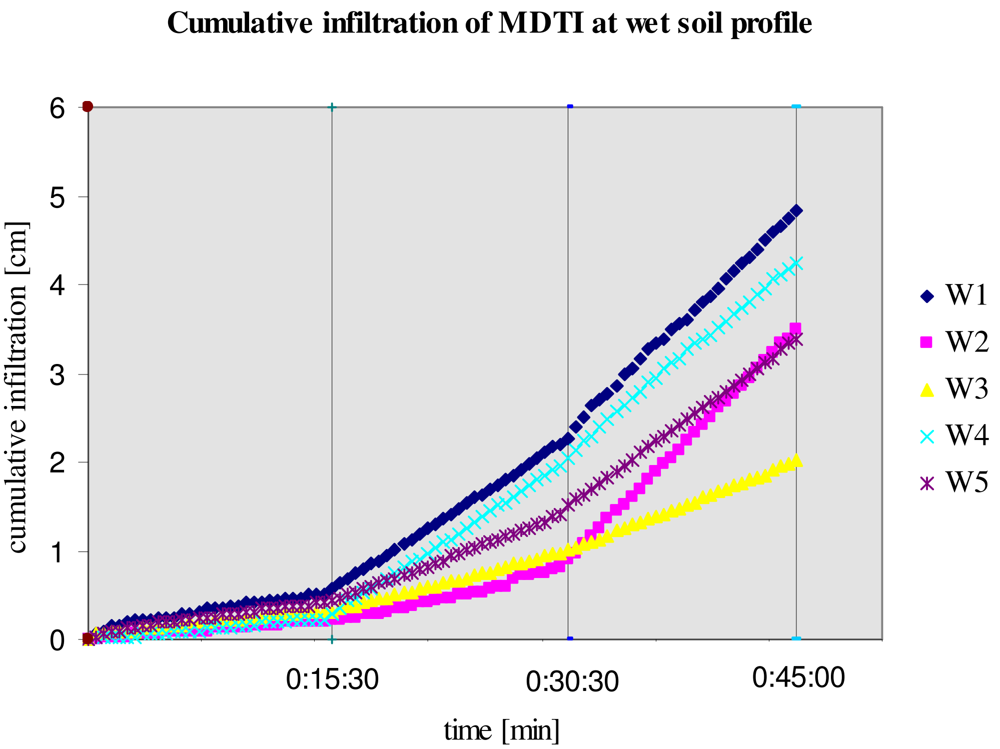


Figure 32 - Cumulative infiltration of MDTI at WET soil profile

Graphs of unsaturated hydraulic conductivity measured by MDTI are shown in Figures (33 – 36). Each initial water content has its own graph and then one graph with averages of K(h) under all the initial water contents is shown.

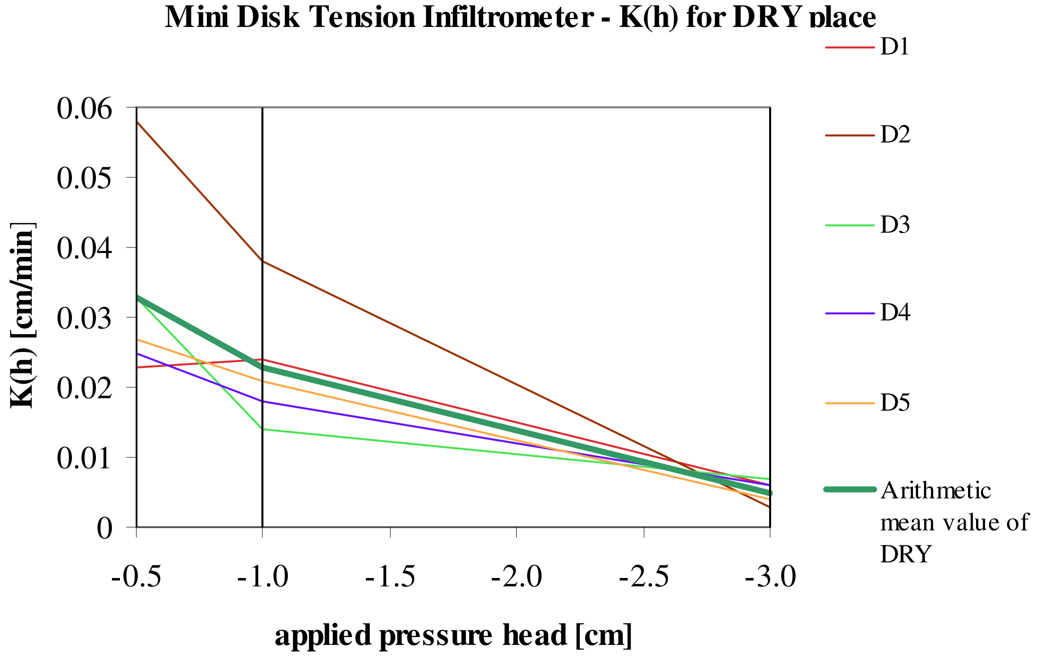


Figure 33 - MDTI K(h) for DRY place

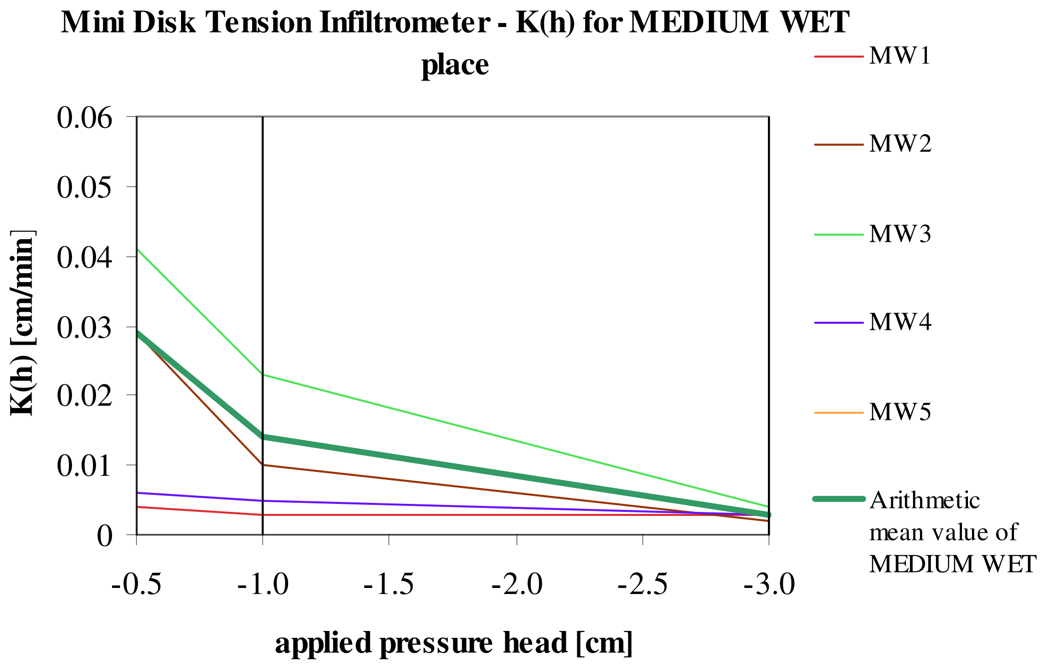


Figure 34 - MDTI K(h) for MEDIUM WET place

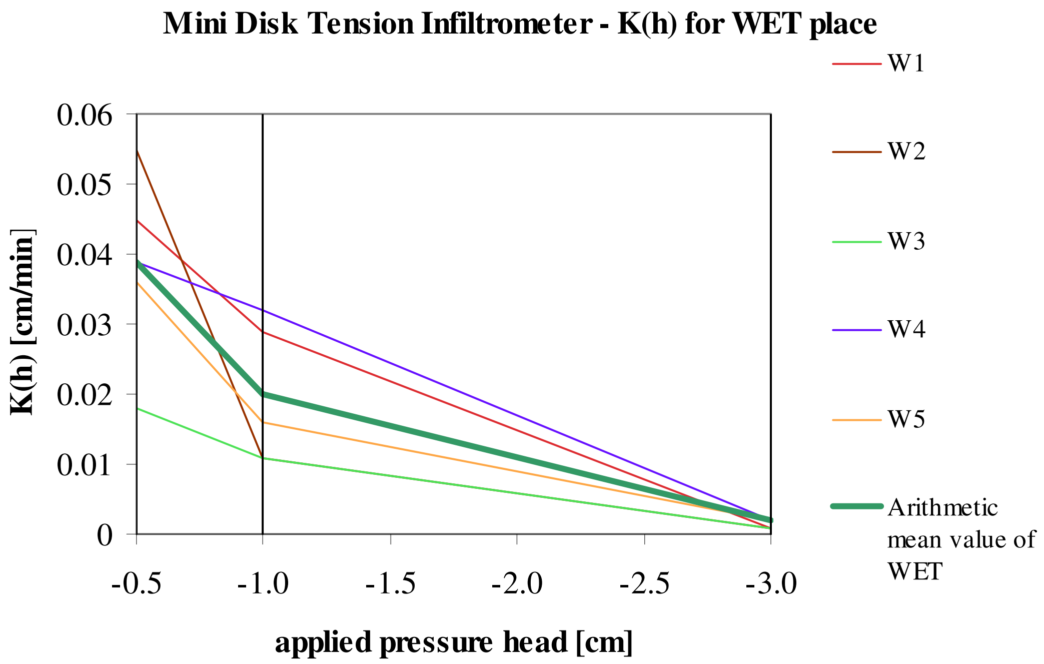


Figure 35 - MDTI K(h) for WET place

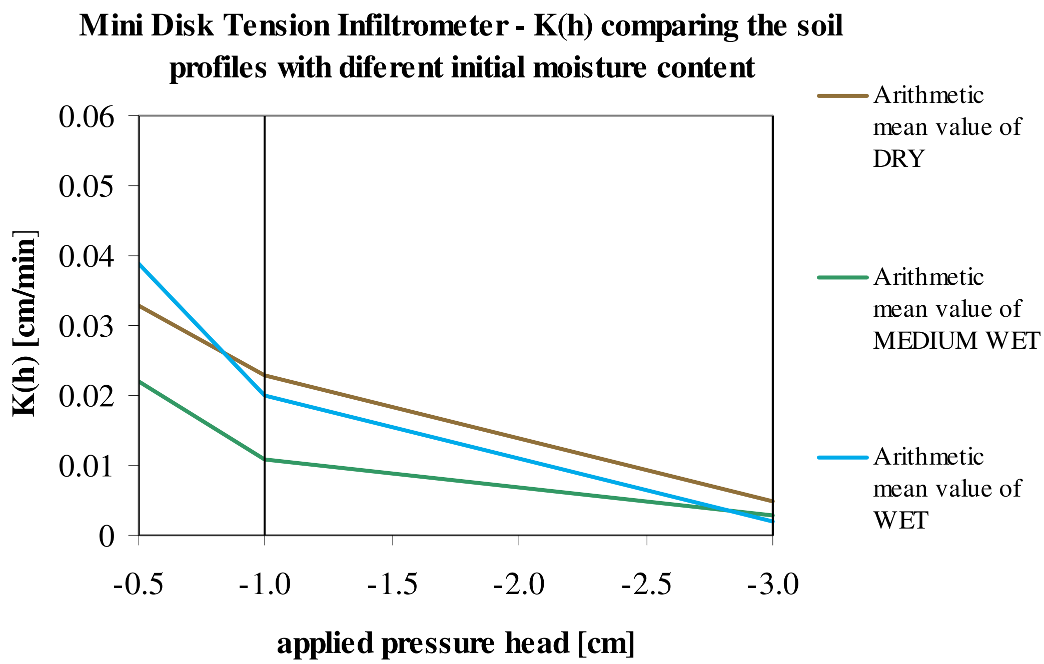


Figure 36 - MDTI K(h) - comparing the soil profiles with different initial water content

5.3 Correlation

The graphs of correlation are shown on Figures (37 – 38).

The first graph shows correlation of all values of unsaturated hydraulic conductivity measured by HI and MDTI for the first applied pressure head for both devices. It means the pressure head of -0.5 for HI and -3 for MDTI. The reason why only the first applied pressure head was used is that the initial water content is known only for these first tensions. The second graph shows medium values of K(h) measured by both devices.

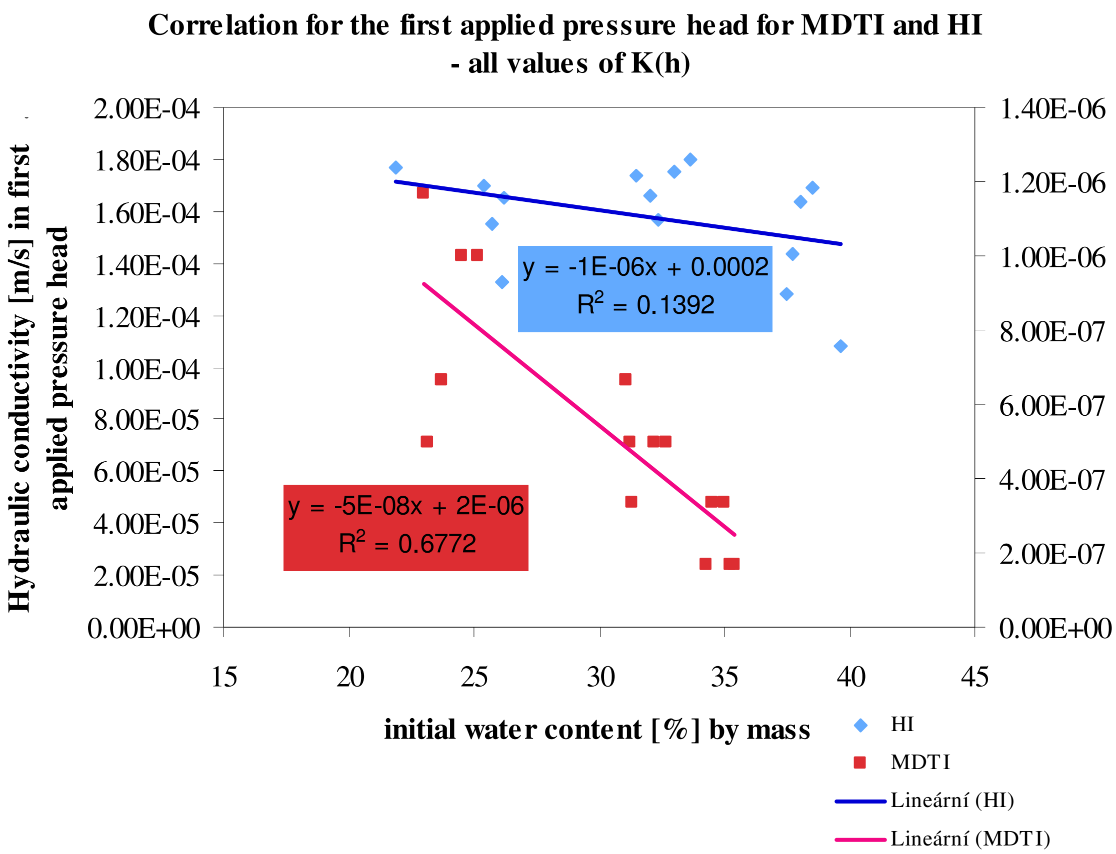


Figure 37 - Correlation for the first applied pressure head for MDTI and HI - all values of K(h)

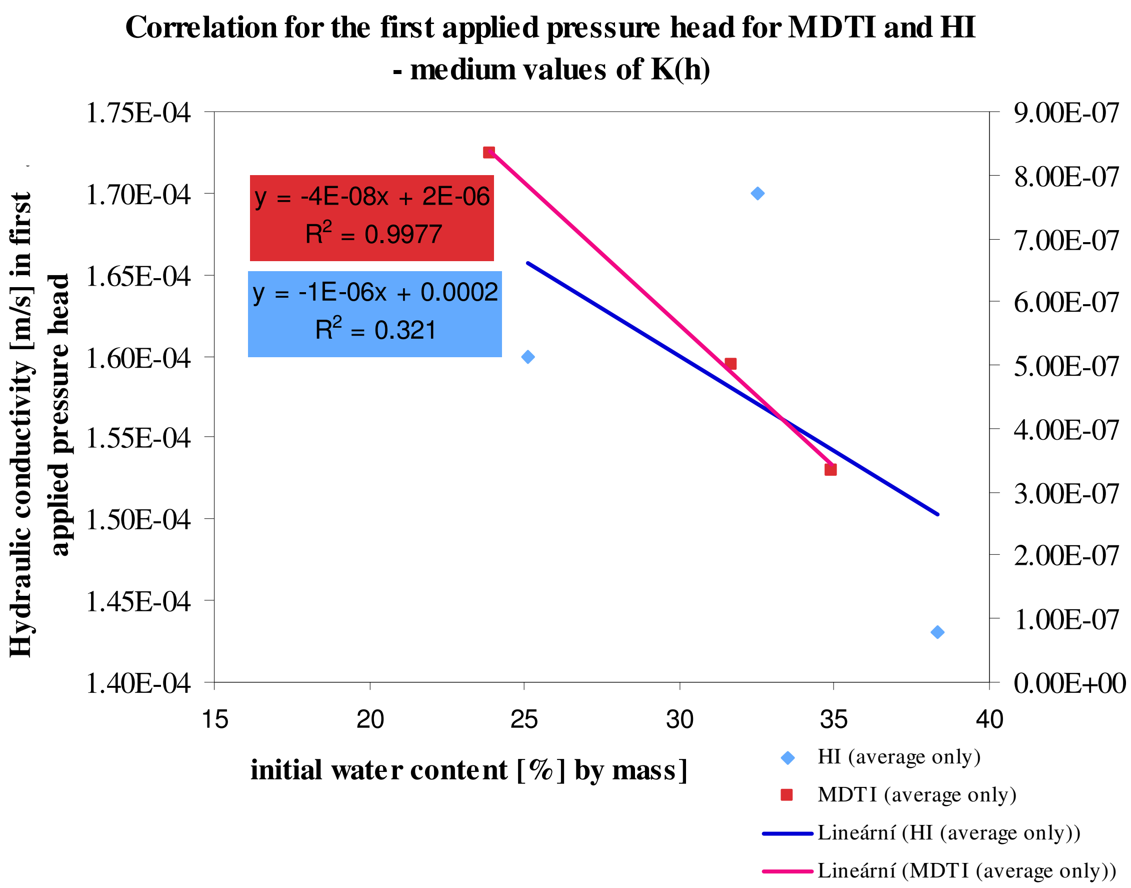


Figure 38 - Correlation for the first applied pressure head for MDTI and HI - medium values of K(h)

6 Discussion

With respect to the aims of the thesis, two devices for measuring the unsaturated hydraulic conductivity were compared. The results were evaluated with respect to initial water content of the soil profile as the factor affecting the determination of the unsaturated hydraulic conductivity and are discussed in following two Chapters 6.1 and 6.2. In the thesis two factors which influenced the measurements the most are evaluated – applied pressure head and the initial water content. Results of these issues are discussed in Chapters 6.4 and 6.5.

6.1 Hydraulic conductivity from HI measurement

The results of measured unsaturated hydraulic conductivity from HI measurements (see Table 8) were statistically evaluated. Table (10) shows the standard deviation (SD) and the coefficient of variance (CV).

Table 10 - Statistical evaluation of HI K(h)

	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]
	applied tension					
place	-0.5		-1		-3	
DRY	0.093	0.968	0.139	16.113	0.026	5.609
MEDIUM WET	0.049	5.099	0.104	11.986	0.133	28.812
WET	0.137	14.233	0.188	21.726	0.092	20.008

It is visible from Table (10) that differences of the hydraulic conductivity measured under pressure head of -0.5 cm are almost negligible as they have small values of CV. The hydraulic conductivities measured under wet conditions differ the most. Very variable results were also observed under the medium wet condition under the pressure head of -0.3 cm.

The unsaturated hydraulic conductivity of D1, D3, D5 and W1, W2 and W3 place differ from others. The conductivities of D1, D3 and W1 are higher than the others; on the other hand the unsaturated hydraulic conductivities of D5, W2, W3. This trend is visible in Table (8). It may be caused by lower total porosities of the D5, W2, W3 places and higher porosities for D1, D2 and W1 places in comparison with other measuring spots. There could be some biological activity under spots with higher hydraulic conductivities such as ants and earthworms.

The unsaturated hydraulic conductivities of dry and medium wet soils differ by only 1 – 6 percent for all three pressures applied, which is almost negligible. The values of dry and wet soil differ by 11 % for pressure head of -0.5, 27 % for pressure head of -1 cm and 6 % for pressure head of -3 cm. The trend of decreasing unsaturated hydraulic conductivity with increasing initial water content is visible.

Two correlation graphs (Figures 37 – 38) show that the measurement with HI of *K(h)* is not as much dependent on the initial water content as the measurement with MDTI. Only a weak dependence of *K(h)* measured by HI on the initial water content is visible.

6.2 Hydraulic conductivity from Mini Disk Tension Infiltrometer measurements

The standard deviation (SD) and coefficient of variance (CV) statistics was calculated also for the MDTI measurements (see Table 9). Results are visible in Table (11):

Table 11 - Statistical evaluation of MDTI K(h)

	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]	SD [cm/min]	CV [%]
			applied tension			
place	-0.5		-1		-3	
DRY	0.013	1.338	0.008	0.949	0.001	0.319
MEDIUM WET	0.014	1.501	0.007	0.825	0.001	0.137
WET	0.012	1.268	0.009	1.039	0.000	0.106

The trend observed for HI is an opposite trend to the one observed for MDTI. The values measured under the pressure head of -3 cm vary the least and the values of -0.5 pressure head are significantly different. The differences between unsaturated hydraulic conductivities measurements under particular pressure head and initial water content are almost negligible as they have very small CV values.

Values obtained from MDTI are more homogenous than the values obtained from HI. The coefficient of variance is less than 1.51 %.

The trend of decreasing unsaturated hydraulic conductivity can be seen for the -3 cm pressure head applied the most. Other applied heads does not show any trend.

The correlation graphs (Figures 36 – 37) show that the measurement of *K(h)* with MDTI is significantly dependent on the initial water content. This dependence is visible especially for the mean values of *K(h)*. Thus the disadvantage of measurements with MDTI is that different values of *K(h)* are obtained with different weather conditions.

6.3 Comparison of HI and MDTI unsaturated hydraulic conductivities

The values for the hydraulic conductivity from MDTI and HI vary (see Table 12), but because there is still not any reference method to determine this, it is very difficult to say, which of these values is the correct one. Still there are not many comparison works to compare the measured values from these two devices in literature.

Table 12 - K(h) from MDTI and HI measurement

applied pressure head	**-0.5**		**-1**		**-3**	
used device	**HI**	**MDTI**	**HI**	**MDTI**	**HI**	**MDTI**
place	**unsaturated hydraulic conductivity in cm/min**					
D1	1.022	0.023	0.900	0.024	0.441	0.006
D2	0.927	0.058	0.894	0.038	0.512	0.003
D3	1.062	0.033	0.903	0.014	0.447	0.007
D4	0.991	0.025	1.019	0.018	0.459	0.006
D5	0.796	0.027	0.601	0.021	0.449	0.004
Arithmetic mean value of DRY	0.960	0.033	0.864	0.023	0.461	0.005
MW1	1.082	0.004	0.677	0.003	0.276	0.003
MW2	0.941	0.029	0.908	0.01	0.405	0.002
MW3	1.041	0.041	0.806	0.023	0.345	0.004
MW4	1.050	0.006	0.945	0.005	0.600	0.003
MW5	0.996	0.029	0.948	0.014	0.600	0.003
Arithmetic mean value of MEDIUM WET	1.022	0.022	0.857	0.011	0.445	0.003
W1	1.016	0.045	0.850	0.029	0.537	0.001
W2	0.647	0.055	0.328	0.011	0.261	0.001
W3	0.770	0.018	0.560	0.011	0.459	0.001
W4	0.861	0.039	0.804	0.032	0.443	0.002
W5	0.985	0.036	0.592	0.016	0.470	0.002
Arithmetic mean value of WET	0.856	0.039	0.627	0.020	0.434	0.002

The values of unsaturated hydraulic conductivity measured by HI are significantly higher than *K(h)* measured by MDTI. These results were also observed by Schwärzel and Punzel (2007) who observed the difference of measured values obtained by HI and MDTI.

They reported that values obtained from HI were almost one order of magnitude greater than the values of MDTI obtained under the corresponding pressure head applied.

The reason for smaller values of *K(h)* measured by MDTI could also be that the measurements with HI were done first and the soil profile was influenced by flooding with HI and thus the pores conducting water can be clogged by detached particles.

Some discrepancy in the measured data due to different infiltration areas of MDTI and HI is also visible. The infiltration area of the MDTI is much smaller and therefore can be influenced by the soil variability to a much greater extant than the HI. For this infiltration, the smaller radius (8 cm) of hood for HI was used to decrease this discrepancy. It can be said that it is hard to compare two devices which work on different principles, but the tendency of decreasing saturated hydraulic conductivity value with increasing water content in the soil profile for both devices is visible.

6.4 Pressure head

The results of the unsaturated hydraulic conductivity are in accordance with i.e. Logsdon (1993) with respect to the pressure heads. It was observed by the author, that as the heads become less negative, the sorptivity *S* and also hydraulic conductivity *K* increases. This tendency is visible also in the results (see Tables 8 and 9) of this thesis where with applied pressure heads -0,5; -1 and -3 for both devices the unsaturated hydraulic conductivity *K(h)* considerably decreases. This is visible for both MDTI and HI.

The results from both infiltrometers show that the values of unsaturated hydraulic conductivity fluctuate less for tension -0.5 applied for HI and for tension -3 performed for MDTI. This trend was discussed in Chapters 6.1 and 6.2. Both tension -0.5 for HI and -3 for MDTI are the first performed tensions for these devices. The reason could be that the following flow can be influenced by the flow under the first tension applied. The soil profile then has different water content and thus may behave in a different way and fluctuate more in the value of unsaturated hydraulic conductivity.

6.5 Initial water content

There are many authors who deal with the measurement of saturated and unsaturated hydraulic conductivity with respect to different initial water contents. Namely they are Angulo-Jaramillo et al. (2000), Benson and Trast (1995), Benson and Daniel (1990), Benson et al. (1994), El-Shafei and Al-Darby (1991), Hawke et al. (2006), Kim and Kim (2009) and Logsdon (1993) who are mentioned in Chapter 3.4.7.

First the authors with similar results are listed:

The lower unsaturated hydraulic conductivity with increasing initial water content was observed also by Benson et al. (1994) who made measurements for clay soils using permeameters. This trend is visible also in the work of Benson and Trast (1995) who, discovered strength dependence of the hydraulic conductivity on the initial water content.

Hawke et al. (2006) described the influence of rainfall intensity and initial soil water content on changes in hydraulic conductivity. For this measurement a different method to infiltrometry was used. They measured this property by using TDR method, the Time-Domain Reflectometer, which is a sensor for indirect soil water content determination. They discovered that the rainfall can affect the matrix structure on the surface of the soil. This can cause clogging of the pores by detached particles and influence the hydraulic conductivity. Thus the measured hydraulic conductivity decreases with increasing initial water content.

Angulo-Jaramillo et al. (2000) made an experiment on two types of soil – sandy soil and stony sandy loam with tension disk infiltrometer. They discovered that there is a big difference of the measured hydraulic conductivity with respect also to the type of irrigation. They observed that the furrow irrigation used on the sandy soil shows a drastic reduction of hydraulic conductivity. On the other hand for the sandy loam soil there was almost no significant difference in hydraulic conductivity.

On the other hand there is also an experiment with different results:

Extensive observations about the initial water content were also made by Logsdon (1993). Measurements on seven dates during the year on clay loam soil were made using tension infiltrometer. Other factors which were taken into account were canopy cover and different pressure heads. It was observed that the hydraulic conductivity fluctuated over the measurements with no relation to initial water content.

6.6 Evaluation of measurements and recommendations

The measurements of unsaturated hydraulic conductivity in this thesis were made under natural conditions on the experimental field of Czech University of Life Sciences Prague.

In the case of measuring in situ, it is difficult to reach homogenous conditions for all measurements.

The two devices – HI and MDTI – were compared with respect to initial water content of the soil profile. However, under the natural conditions there is an influence of weather – sunshine, wind, rain, temperature – on the measuring of the unsaturated hydraulic conductivity. The soil heterogeneity and biological activity also has a big effect on the measured values as they can be influenced by bigger pores caused by earthworms plus other factors. If these natural conditions are omitted the measuring can be more accurate.

As it was mentioned in one of the previous Chapters 6.3, there is also a visible discrepancy in the measured data for HI and MDTI. It is caused by different infiltration areas of these two devices. The infiltration area of MDTI is much smaller than the HI and thus the value of hydraulic conductivity can be influenced by the higher soil variability.

Another incompatibility which can be observed during comparison of these two infiltrometers is the different principles of measuring, and also the need to use the contact material for MDTI.

The recommendations for extended research are to hold this measurement under homogenous conditions which can probably only be achieved in the laboratory. This is possible to perform for the MDTI but problematic for the HI as more water is infiltrated in the soil profile. Also, maybe a higher number of measuring with just one device has a better predictive value and can compare the effect of initial water content of the soil. Another option is to hold these measurements under higher steps of different initial water content conditions and also make measurement on different soil types.

7 Conclusions

The most important factors affecting the determination of unsaturated hydraulic conductivity were described and compared from different authors. A particular focus is given to different initial water content conditions of the soil profile and the influence of this condition to the obtained data from the infiltrometers. The effect of applied pressure head is also studied.

The initial water content of the soil is widely discussed in the literature. The experiment was performed using two infiltrometers on the experimental field of Czech University of Life Sciences Prague. HI and MDTI were used for measuring the unsaturated hydraulic conductivity *K(h)* with many replications. The HI is a relatively new device and thus it was chosen to be explored more. The results of the *K(h)* values of this thesis correspond to results of other authors as mentioned.

The trend of decreasing *K(h)* with increasing pressure head applied was observed for both devices used. The measurement with HI show that the measurement of *K(h)* is not as much dependent on the initial water content as the measurement with MDTI. Only a weak dependence of *K(h)* measured by HI on the initial water content is visible. The measurement of *K(h)* with HI is not influenced so much by external conditions. The hypothesis was fulfilled for MDTI, but for HI it is not conclusive.

8 References

Angulo-Jaramillo, R., Vandervaere, J.-P., Roulier, S., Thony, J.-L., Gaudet, J.-P., Vauclin, M. (2000) Field measurement of soil surface hydraulic properties by disc and ring infiltrometers. A review and recent developments. Soil & Tillage Research, 55: 1-29.

Ankeny, M. D., Ahmed, M., Kaspar, T.C., and Horton, R. (1991) Simple field method for determining unsaturated hydraulic conductivity. Soil Science Society of America Journal, 55**,** 467-470.

Ankeny, M. D., Kaspar, K.C., and Horton, R. (1988) Design for an automated tension infiltrometer. Soil Science Society of America Journal, 52**,** 893-896.

Ankeny, M. D., Kaspar, T.C., Horton, R. (1990) Characterization of tillage and traffic effects on unconfined infiltration measurement. Soil Science Society of America Journal, 54, 810-837.

Bagarello, V., Iovino, M., Tusa, G. (2000) Factors affecting measurement of the near saturated soil hydraulic conductivity. Soil Science Society of America Journal, 64: 1203-1210.

Bagarello, V., Iovino, M., Tusa, G. (2001) Effect of contact material on tension infiltrometer measurements. Transactions of the ASAE, 44, 911-916.

Benson, C.H., Daniel, D. (1990) Influence of clods on hydraulic conductivity of compacted clay. Journal of Geotechnical Engineering, 116, 1231-1248.

Benson, C.H., Trast, J.M. (1995) Hydraulic conductivity of thirteen compacted clays. Clays and Clay Minerals, vol. 43, No. 6, 669-681.

Benson, C.H., Zhai, H., Wang, X. (1994) Estimating the hydraulic conductivity of compacted clay liners. Journal of Geotechnical Engineering, 120, 366-387.

Buczko, U., Bens, O., Hüttl, R.F. (2006) Water infiltration and hydrophobicity in forest soils of a pine-beech transformation chronosequence. Journal of Hydrology, 331, 383-395.

Casey, F. X. M., and Derby, N.E. (2002) Improved design for an automated pension infiltrometer. Soil Science Society of America Journal, 66**,** 64-67.

Close, K.R., Frasier, G., Dunn, G.H., Loftis, J.C. (1998) Tension infiltrometer contact interface evaluation by the use of potassium iodide tracer. Transactions of the ASAE, 41: 995-1004.

Dane, J.H., Topp, G.C. (Ed.) (2002) Methods of soil analysis; Part 4 - Physical methods, No.5, 1st edition, Soil Science Society of America, Inc., Madison, p. 1692 (chapters 3 and 4).

Dixon, R. M. (1975) Design and use of closed-top infiltrometers. Soil Science of American Proceedings, 39**,** 755-763.

Chowdary, V.M., Damodhara Rao, M., Jaiswal, C.S. (2006) Study of infiltration process under different experimental conditions. Agricultural water management, 83, 69-78.

El-Shafei, Y.Z., Al-Darby, A.M. (1991) Initial moisture content in relation to infiltration capacity of sandy soils. Agric. Sci., 2, 333-348.

Elrick, D.E., Reynolds, W.D. (1992) Infiltration from Constant-Head Well Permeameters and Infiltrometers. Soil Science Society of America, 677, 1-24

Hawke, R.M., Price, A.G., Bryan, R.B. (2006) The effect of initial soil water content and rainfall intensity on near-surface soil hydrologic conductivity: A laboratory investigation. Elsevier: Catena, 65, 237-246.

Hillel, D. (1998) Environmental Soil Physics. Academic Press, New York, USA, 771 p.

Johnson, A.I. (1963) A Field Method for Measurement of Infiltration, Washington, Geological Survey Water-Supply Paper 1544-F, United States Government Printing Office, 27 p.

Kechavarzi, C., Špongrová, K., Dresser, M., Matula, S., Godwin, R.J. (2009) Laboratory and field testing of an automated tension infiltrometer. Biosystems Engineering, 104: 266-277.

Kim, Ch., Kim, T. (2009) Behavior of unsaturated weathered residual granite soil with initial water contents. Elsevier: Engineering Geology 113, 1-10.

Klute, A. (Ed.) (1986) Methods of soil analysis; Part 1 - Physical and mineralogical methods, No.9, 2nd edition, American Society of Agronomy, Inc. and Soil Science Society of America, Inc., Madison, p. 1188 (chapter 26).

Kutílek, M. and Nielsen, D.R. (1994) Soil Hydrology . Catena Verlag, Cremlingen – Destedt, 370 p.

Lal, R., Shukla, M.K. (2004) Principles of Soil Physics, Marcel Dekker, Inc., New York, 716 p., ISBN: 0-8247-5324-0

Lin, H. S., Mc Innes, K.J. (1995) Water flow in clay soil beneath a pension infiltrometer. Soil Science, 159**,** 375-382.

Logsdon, S. D. (1993) Negative head hydraulic properties of the soil surface at different times. Soil Science, 156**,** 373-379.

Logsdon, S.D., Jordahl, J.L., Karlen, D.L. (1993) Tillage and crop effects on ponded and pension infiltration rates. Soil & Tillage Research, 28, 179-189.

Lohman, S.W., (1972) Ground-Water Hydraulics. Geological Survey Professional Paper 708, United States Government Printing Office, Washington.

Matula, S (2003) The influence of tillage treatments on water infiltration into soil profile. Plant soil environ., 49, 298-306.

Mohanty, B. P., Ankeny, M.D., Horton, R., Kanwar, R.S. (1994) Spatial analysis of hydraulic conductivity measured using disc infiltrometers. Water Resources Research, 30**,** 2489-2498.

Perroux, K. M., and White, I. (1988) Designs for disk permeameters. Soil Science Society of America Journal, 52, 1205-1215.

Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F., Tan, C.S. (2000) Comparison of pension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Science Society of America Journal, 64, 478-484.

Reynolds, W.D., Elrick, D.E. (1991) Determination of hydraulic conductivity using a tension infiltrometer. Soil Science Society of America Journal, 55, 633-639.

Reynolds, W. D., Zebchuk, W.D. (1996) Use of contact material in pension infiltrometer measurements. Soil Technology, 9**,** 141-159.

Shirmohammadi, A., Skaggs, R.W. (1985). Predicting infiltration for shallow water table soils with different surface covers. Transactions of American Society of Agricultural Engineers, 28(6), 1829-1837.

Schwärzel, K., Feger, K.-H., Carrick, S., Buchan, G. (2009) How does crop management control soil hydraulic properties? Deutsche Bodenkundliche Gesellschaft, online on http://www.ddbges.de, visited 7/2011.

Schwärzel, K., Punzel, J. (2007) Hood Infiltrometer – A new type of tension infiltrometer. Soil Science Society of America Journal, 71, 1438-1447.

Shouse, P. J., and Mohanty, B.P. (1998) Scaling of near-saturated hydraulic conductivity measured using disc infiltrometers. Water Resources Research, 34**,** 1195-1205.

Smettem, K. R. J., and Clothier, B.E. (1989) Measuring unsaturated sorptivity and hydraulic conductivity using multiple disc permeameters. Journal of Soil Science*,* 40**,** 563-568.

Šimůnek, J., Angulo-Jaramillo, R., Shaap, M.G., Vandervaere, J.P., van Genuchten, M.T. (1998) Using an inverse method to estimate the hydraulic properties of crusted soils from tension-disc infiltrometer data. Geoderma, 61-81.

Šimůnek, J., van Genuchten, M.Th. (1997) Parameter estimation of soil hydraulic properties from multiple tension disc infiltrometer data. Soil Science, 162, 383-398.

Špongrová, K., Kechavarzi, C., Dresser, M., Matula, S., Godwin, R.J. (2009) Development of an automated tension infiltrometer for field use. Vadose Zone Journal, 8, 810-817.

Topp, G.C., Reynolds, W.D., and Green, R.E. (1992) Advances in measurement of soil physical properties: Bringing theory into practice, SSSA Special Publication no. 30, Soil Science Society of America, Inc., Madison, USA. 288 p.

Valla, M., Kozák, J., Němeček, J., Matula, S., Borůvka, L., Drábek, O. (2008) Pedologické praktikum. Česká zemědělská univerzita, Praha. 155 p.

Vandervaere, J.-P., Vauclin, M., Elrick, D.E. (2000) Transient flow from tension infiltrometers: I. The two-parameter equation. Soil Science Society of America Journal, 64: 1263-1272.

Vandervaere, J.-P., Vauclin, M., Elrick, D.E. (2000) Transient flow from tension infiltrometers: II. Four methods to determine sorptivity and conductivity. Soil Science Society of America Journal, 64: 1272-1284.

Ventrella, D., Losavio, N., Vonella, A.V., Leij, F.J. (2005) Estimating hydraulic conductivity of a fine-textured soil using tension infiltrometry. Geoderma, 124, 267-277.

Walker, C., Lin, H.S., Fritton, D.D. (2006) Is the tension beneath a tension infiltrometer what we think it is? Vadose Zone Journal, 5, 860-866.

White, I., Perroux, K.M. (1989) Estimation of unsaturated hydraulic conductivity from field sorptivity measurements. Soil Science Society of America Journal, 53, 324-329.

White, I., Sully, M.J., and Perroux, K.M. (1992) Measurement of surface-soil hydraulic properties: disk permeameters, tension infiltrometers, and other techniques. In: G.C. Topp,

Zhang, R. (1997) Infiltration models for the disk infiltrometer. Soil Science Society of America Journal, 61, 1597-1603.

Decagon Devices, Inc: Mini Disk Tension Infiltrometer [online]. Accessed in 06/2011. Available at http://www.decagon.com/products/lysimeters-and-infiltrometers/mini-disk-tension-infiltrometer/.

Delta-T Devices, Ltd: ML2x ThetaProbe [online]. Accessed in 04/2012. Available at http://www.delta-t.co.uk/product-display.asp?id=ML2x Product&div=Irrigation and Horticulture.

Educational Technology Clearinghouse: Pycnometer [online]. Accessed in 04/2012. Available at http://etc.usf.edu/clipart/26800/26840/pycnometer_26840.htm.

Miller, J.D., Gaslein, G.J.: Theta Probe ML2x [online]. Accessed in 04/2012. Available at http://www.macaulay.ac.uk/MRCS/pdf/tprobe.pdf.

Sklopísek Střelеč: Produkty [online]. Accessed in 04/2012. Available at http://www.glassand.eu/index.php?page=katalog#skla.

UGT GmbH: HI IL 2700 [online]. Accessed in 06/2011. Available at http://ugt-online.de/en/produkte/bodenkunde/messgeraete-fuer-die-hydraulische-und-pneumatische-leitfaehigkeit/haubeninfiltrometer-il-2700.html.

Wine Business.com [online]. Accessed in 04/2012. Available at http://www.winebusiness.com/content/Image/theta-probe.jpg.

9 List of symbols

List of symbols			
Roman alphabet			
Symbol	**Description of symbol**	**Dimension**	**Unit**
a	dimensionless length		
A	value relating to Van Genuchten parameters		
A	cross section of intiltrometer	L	cm
$C1$, $C2$, $C3$	parameters		
d	radius	L	cm
G_s	particle density		
h	applied tension, soil water potential	L	cm
h_1, h_2	neighboring values of chosen water tensions	L	cm
h_0	pressure head, tension	L	cm
h_a	simulated soil air pressure head	L	cm
h_i	initial water potential	L	cm
h_s	effective surface head	L	cm
h_w	ponded water depth	L	cm
I	cummulative infiltration	L	cm
I_{1D}	cummulative infiltration during 1D process	L	cm
I_{3D}	cummulative infiltration during 3D process	L	cm
K	saturated hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
K_r	relative hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
K_S	saturated hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
$K(h)$	hydraulic conductivity function	$L\,T^{-1}$	$cm.min^{-1}$
k_f	saturated hydraulic conductivity	$L\,T^{-1}$	$cm.min^{-1}$
k_u	hydraulic conductivity under unsaturated conditions	$L\,T^{-1}$	$cm.min^{-1}$
l	length	L	cm
m_1	mass of pycnometer filled with water	W	g
m_2	mass of pycnometer filled with soil suspension	W	g
m_s	mass of soil dried under 105 °C	W	g
m_w	mass of water	W	g
m_z	mass of dry sample	W	g
n	value relating to Van Genuchten parameters		
P	total porosity	%	%
q	steady-state infiltration rate	$L\,T^{-1}$	$cm.min^{-1}$
Q	steady-state infiltration flux	$L\,T^{-1}$	$cm.min^{-1}$

r	radius, radial coordinate	L	cm
r_0	disk radius	L	cm
R	disk radius	L	cm
S	sorptivity	$L\ T^{-1/2}$	$cm.min^{-1/2}$
t	time	T	min
V	total volume of soil	L^3	cm^3
V_t	volume of soil under natural conditions	L^3	cm^3
V_w	volume of water	L^3	cm^3
w	water content by mass, molding water content	L^3L^{-3}	cm^3cm^{-3}
z	vertical coordinate	L	cm

List of symbols

Greek alphabet

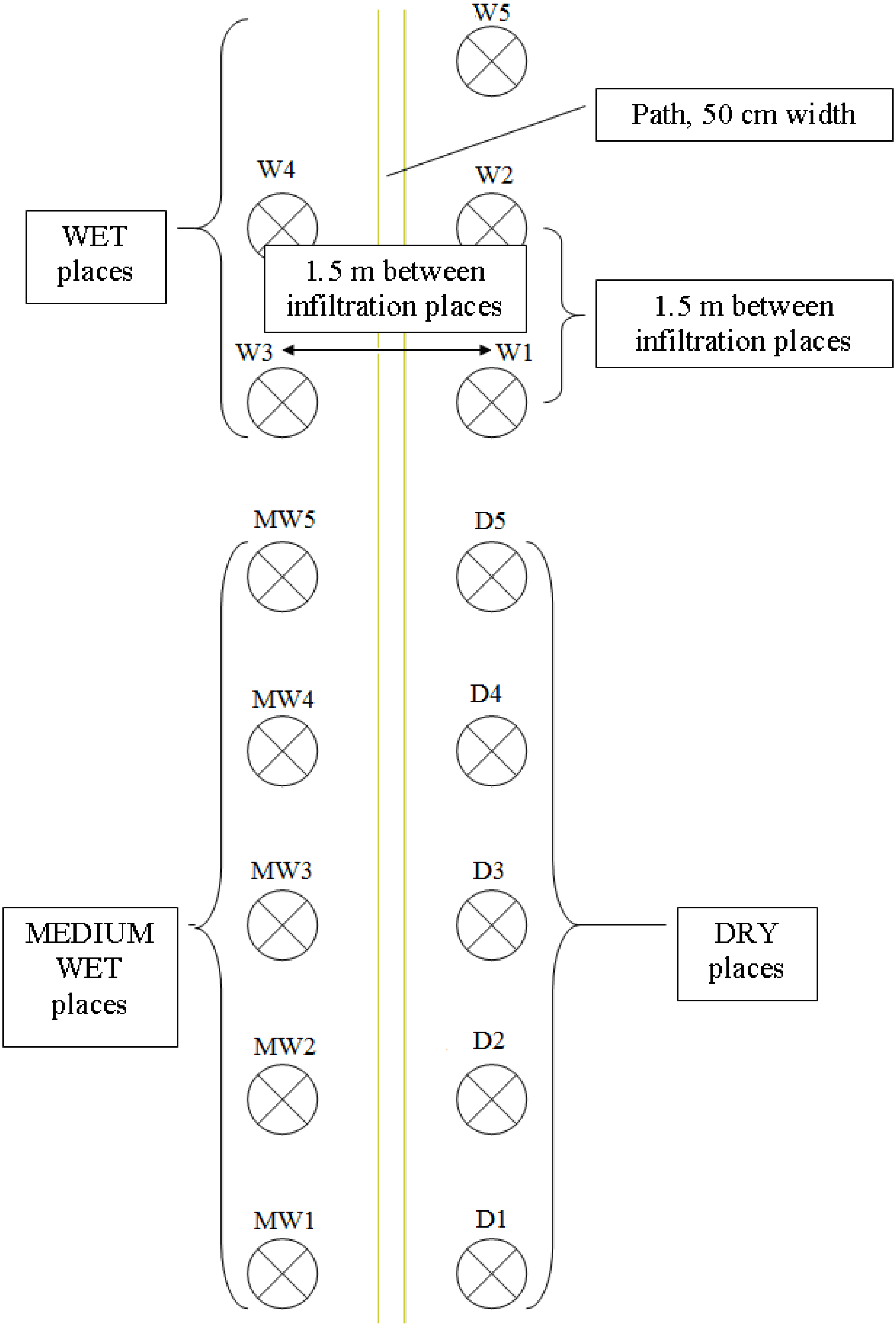
Symbol	Description of symbol
α	constant
α	sorptive number
β	constant
γ	constant
γ_d	dry unit weight
γ_w	unit weight of water
ψ	water potential
ψ_i	initial or background pore water potential
ψ_t	steady water potential
ϕ	matric flux potential
θ	volumetric water content
θ_r	volumetric water content
ρ_d	dry bulk density
ρ_z	specific weight of soil particles

Abbreviations

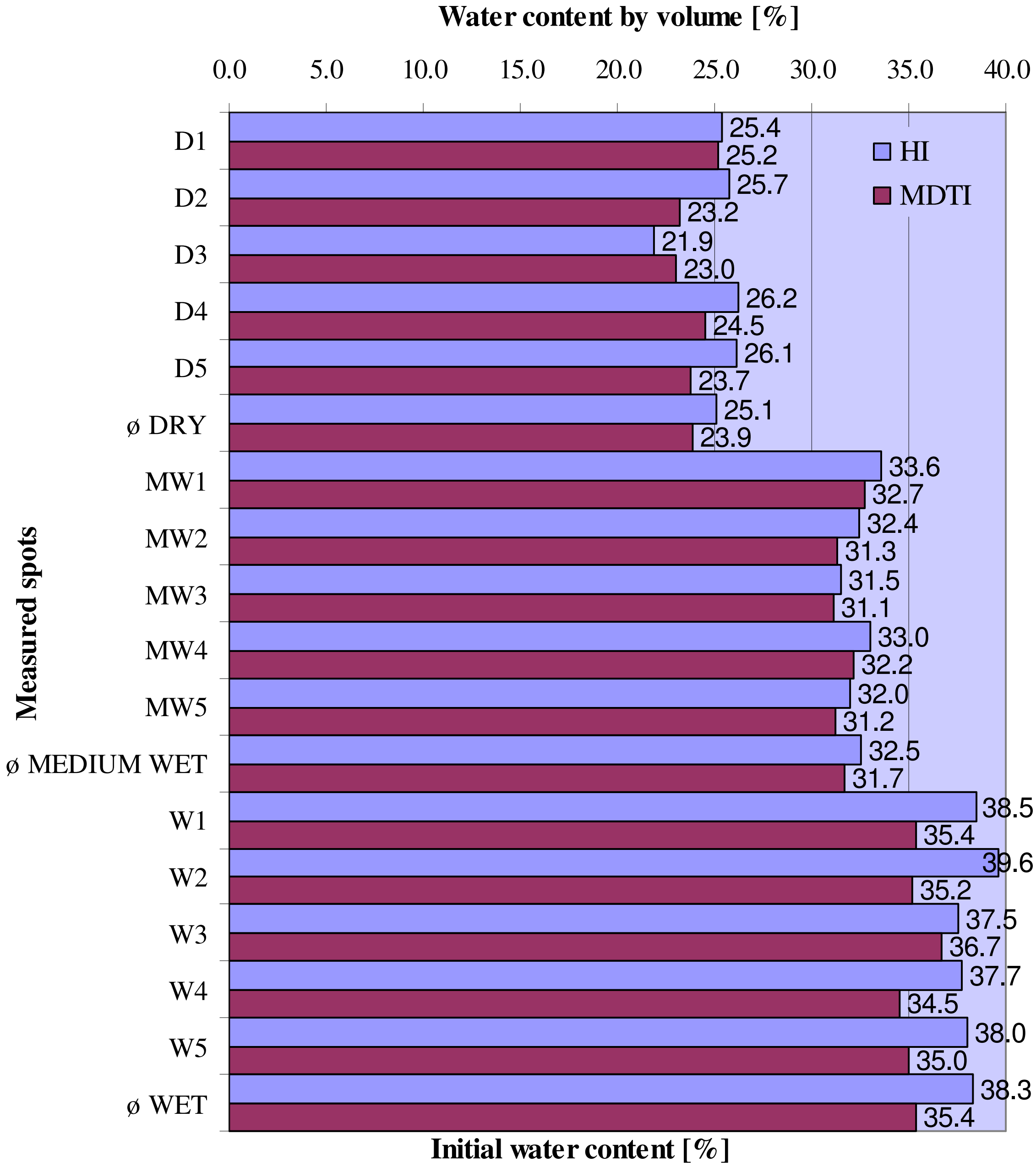
CV	coefficient of variance
HI	Hood Infiltrometer
max	maximum
min	minimum
MDTI	Midi Disk Tension Infiltrometer
SD	standart deviation
SWRT	Soil Water Retention Curve
TDR	Time-Domain reflectometry

10 Appendices

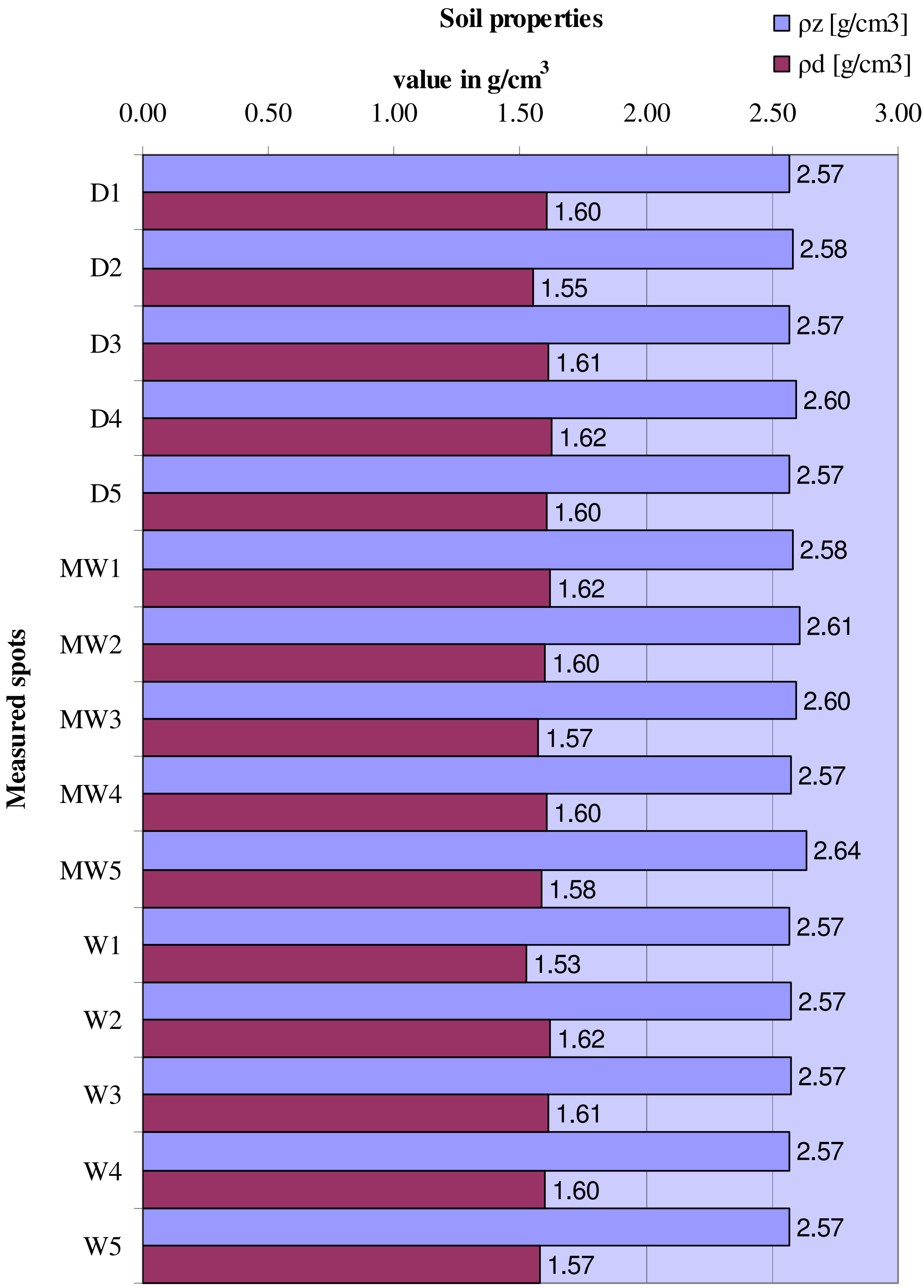
Appendix 1 - The layout of the field



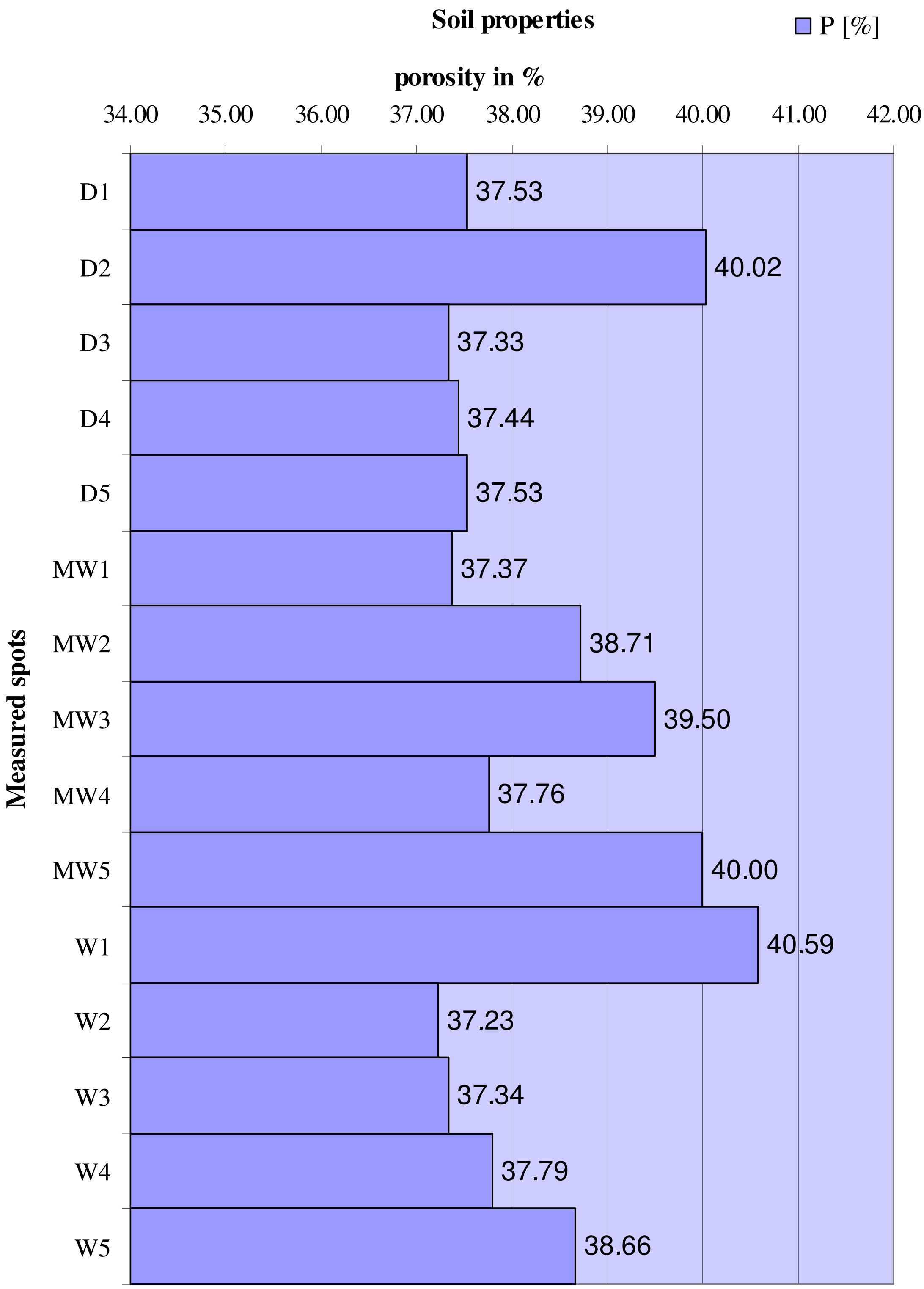
Appendix 2 - Initial water content by volume on each spot; data for HI and MDTI



Appendix 3 - Soil properties (particle density and dry bulk density) for each spot of measurement



Appendix 4 - Soil property (porosity) for each measurement spot



Appendix 5 - Calculation of K(h) for HI in Excel sheet

tension	Time of measurement [hr:min:sec]	Real values from reservoir [mm of water column]	Decrease of surface in water reservoir [cm]	Cumulative decrease of surface in water reservoir [cm]	Real infiltrated volume, V=75,10*decrease of surface in water reservoir [cm3]	Q=V/t [cm/min]		calculation of parameter alfa from equation: alpha	K(h)	
-0.5	0:30:30	209.9	0	0	0	0			1.6176675	cm/min
	0:30:45	196.4	1.05	1.05	78.855	315.42	α	0.25201	1.6315517	m/s
	0:31:00	183	1.1	2.15	82.61	330.44				
	0:31:15	170.4	1.13	3.28	84.863	339.452				
	0:31:30	157.4	1.12	4.4	84.112	336.448				
	0:31:45	144.4	1.07	5.47	80.357	321.428				
	0:32:00	132	1.06	6.53	79.606	318.424				
	0:32:15	119.4	1.08	7.61	81.108	324.432				
	0:32:30	106.9	1.07	8.68	80.357	321.428				
	0:32:45	92	1.07	9.75	80.357	321.428	sum of Q	average of Q		
	0:33:00	79.7	1.11	10.86	83.361	333.444				
	0:33:15	67.6	1.05	11.91	78.855	315.42	3577.76	325.251		
-1	1:12:00	220.8	0	0	0	0				
	1:12:15	211.2	0.96	0.96	72.096	288.384			1.4261552	cm/min
	1:12:30	201.3	0.92	1.88	69.092	276.368	α	0.39873	1.3991597	m/s
	1:12:45	191.8	1.03	2.91	77.353	309.412				
	1:13:00	181.7	0.9	3.81	67.59	270.36				
	1:13:15	172.3	1	4.81	75.1	300.4				
	1:13:30	162.2	0.94	5.75	70.594	282.376				
	1:13:45	153.3	0.92	6.67	69.092	276.368				
	1:14:00	143.8	0.91	7.58	68.341	273.364				
	1:14:15	134.7	0.97	8.55	72.847	291.388				
	1:14:30	125.5	1.01	9.56	75.851	303.404				
	1:14:45	115.7	0.94	10.5	70.594	282.376	3154.2	286.745		
-3	2:00:15	259.4	0	0	0	0				
	2:00:30	254.9	0.45	0.45	33.795	135.18			0.642449	cm/min
	2:00:45	250.8	0.41	0.86	30.791	123.164	α	0.39873	1.3991597	m/s
	2:01:00	246.7	0.41	1.27	30.791	123.164				
	2:01:15	242.4	0.43	1.7	32.293	129.172				
	2:01:30	237.9	0.45	2.15	33.795	135.18				
	2:01:45	233.6	0.43	2.58	32.293	129.172				
	2:02:00	229.2	0.44	3.02	33.044	132.176				
	2:02:15	224.5	0.47	3.49	35.297	141.188				
	2:02:30	220.4	0.41	3.9	30.791	123.164				
	2:02:45	216.2	0.42	4.32	31.542	126.168				
	2:03:00	212.1	0.41	4.73	30.791	123.164	1420.89	129.172		

Appendix 6 - Calculation of K(h) for MDTI in Excel sheet

MDTI determination of K(h)

tension	time	square root of time	reading in cm3 = ml	infiltrated volume of water (cm3)	cumulative volume (cm3)	cumulative infiltration (cm)		
-3	0	0	84	0	0	0	**FOR TENSION -3**	
	0.5	0.707106781	83	1	1	0.062876027	**A from table**	**6.87**
	1	1	82	1	2	0.125752054	**C1 from equation**	**0.0471**
	1.5	1.224744871	81.5	0.5	2.5	0.157190067	**K=C1/A [cm/min]**	**0.006855895**
	2	1.414213562	81	0.5	3	0.188628081		
	2.5	1.58113883	80.5	0.5	3.5	0.220066094		
	3	1.732050808	80	0.5	4	0.251504108		
	3.5	1.870828693	79.5	0.5	4.5	0.282942121		
	4	2	79	0.5	5	0.314380135		
	4.5	2.121320344	78.5	0.5	5.5	0.345818148		
	5	2.236067977	78	0.5	6	0.377256161		
	5.5	2.34520788	77.5	0.5	6.5	0.408694175		
	6	2.449489743	77	0.5	7	0.440132188		
	6.5	2.549509757	76.5	0.5	7.5	0.471570202		
	7	2.645751311	76	0.5	8	0.503008215		
	7.5	2.738612788	75.5	0.5	8.5	0.534446229		
	8	2.828427125	75	0.5	9	0.565884242		
	8.5	2.915475947	74.5	0.5	9.5	0.597322256		
	9	3	74.5	0	9.5	0.597322256		
	9.5	3.082207001	74	0.5	10	0.628760269		
	10	3.16227766	73.5	0.5	10.5	0.660198282		
	10.5	3.240370349	73	0.5	11	0.691636296		
	11	3.31662479	72.5	0.5	11.5	0.723074309		
	11.5	3.391164992	72	0.5	12	0.754512323		
	12	3.464101615	71.5	0.5	12.5	0.785950336		
	12.5	3.535533906	71	0.5	13	0.81738835		
	13	3.605551275	70.5	0.5	13.5	0.848826363		
	13.5	3.674234614	70	0.5	14	0.880264377		
	14	3.741657387	69.5	0.5	14.5	0.91170239		
	14.5	3.807886553	69	0.5	15	0.943140404		
	15	3.872983346	68.5	0	15	0.943140404		
-1	15.5	3.937003937	68	0.5	15.5	0.974578417	**FOR TENSION -1**	
	16	4	67.5	0.5	16	1.00601643	**A from table**	**5.72**
	16.5	4.062019202	67	0.5	16.5	1.037454444	**C2 from graph**	**0.0822**
	17	4.123105626	66.5	0.5	17	1.068892457	**K=C1/A [cm/min]**	**0.014370629**
	17.5	4.183300133	66	0.5	17.5	1.100330471		
	18	4.242640687	65.5	0.5	18	1.131768484		
	18.5	4.301162634	65	0.5	18.5	1.163206498		
	19	4.358898944	64.5	0.5	19	1.194644511		
	19.5	4.415880433	64	0.5	19.5	1.226082525		
	20	4.472135955	63.5	0.5	20	1.257520538		
	20.5	4.527692569	63	0.5	20.5	1.288958551		
	21	4.582575695	62.5	0.5	21	1.320396565		
	21.5	4.636809248	62	0.5	21.5	1.351834578		
	22	4.69041576	61.5	0.5	22	1.383272592		
	22.5	4.74341649	61	0.5	22.5	1.414710605		
	23	4.795831523	60.5	0.5	23	1.446148619		
	23.5	4.847679857	59.5	1	24	1.509024646		
	24	4.898979486	59	0.5	24.5	1.540462659		
	24.5	4.949747468	58.5	0.5	25	1.571900673		
	25	5	57.5	1	26	1.634776699		
	25.5	5.049752469	57	0.5	26.5	1.666214713		
	26	5.099019514	56.5	0.5	27	1.697652726		
	26.5	5.14781507	55.5	1	28	1.760528753		
	27	5.196152423	55	0.5	28.5	1.791966767		
	27.5	5.244044241	54.5	0.5	29	1.82340478		
	28	5.291502622	53.5	1	30	1.886280807		
	28.5	5.338539126	53	0.5	30.5	1.91771882		
	29	5.385164807	52.5	0.5	31	1.949156834		
	29.5	5.431390246	52	0.5	31.5	1.980594847		
	30	5.477225575	51.5	0.5	32	2.012032861		
-0.5	30.5	5.522680509	50.5	1	33	2.074908888	**FOR TENSION -0,5**	
	31	5.567764363	49.5	1	34	2.137784915	**A from table**	**5.46**
	31.5	5.61248608	48.5	1	35	2.200660942	**C2 from graph**	**0.1796**
	32	5.656854249	47.5	1	36	2.263536968	**K=C1/A [cm/min]**	**0.032893773**
	32.5	5.700877125	46.5	1	37	2.326412995		
	33	5.744562647	45.5	1	38	2.389289022		
	33.5	5.787918451	44.5	1	39	2.452165049		
	34	5.830951895	43.5	1	40	2.515041076		
	34.5	5.873670062	42.5	1	41	2.577917103		
	35	5.916079783	41.5	1	42	2.64079313		
	35.5	5.958187644	40.5	1	43	2.703669157		
	36	6	39	1.5	44.5	2.797983197		
	36.5	6.041522987	38	1	45.5	2.860859224		
	37	6.08276253	37	1	46.5	2.923735251		
	37.5	6.123724357	36	1	47.5	2.986611278		
	38	6.164414003	35	1	48.5	3.049487305		
	38.5	6.204836823	34	1	49.5	3.112363332		
	39	6.244997998	33	1	50.5	3.175239358		
	39.5	6.284902545	32	1	51.5	3.238115385		
	40	6.32455532	31	1	52.5	3.300991412		
	40.5	6.363961031	30	1	53.5	3.363867439		
	41	6.403124237	29	1	54.5	3.426743466		
	41.5	6.442049363	28	1	55.5	3.489619493		
	42	6.480740698	27	1	56.5	3.55249552		
	42.5	6.519202405	26	1	57.5	3.615371547		
	43	6.557438524	25	1	58.5	3.678247574		
	43.5	6.595452979	24	1	59.5	3.741123601		
	44	6.633249581	23	1	60.5	3.803999627		
	44.5	6.670832032	21.5	1.5	62	3.898313668		
	45	6.708203932	20.5	1	63	3.961189695		
sum:	**420**	**93.64227899**		**11**	**422.5**	**26.56512137**		