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A simple method for correcting the effects of initial soil moisture on Modified Philip-Dunne Infiltrometer drawdown curves

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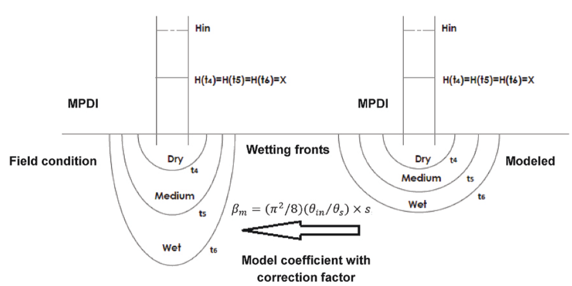
HIGHLIGHTS

- The drawdown curve measured using the MPDI for a given soil varies with θ_{in}.
- Different K_s value of a given soil is estimated using the MPDI when θ_{in} was varied.
- A correction factor is proposed to help in yielding a unique value of K_s.
- The Minidisk infiltrometer was used to benchmark the results.
- After applying the correction factor the MPDI method yield better results.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of varying initial soil moisture (θ_{in}) of a given soil on the drawdown curve measured using the Modified Philip-Dunne Infiltrometer (MPDI) and consequently on the estimated saturated hydraulic conductivity (K_s) value, was investigated. The laboratory tests completed using three different types of soil show that the drawdown curve was sensitive to θ_{in} for all three soils. This resulted in yielding K_s values that are sensitive to the values of θ_{in}. The lowest value of K_s was observed when the MPDI was used under wet conditions. To obtain a consistent estimate of K_s, a new correction factor was developed. This factor can be multiplied with the geometrical coefficient used in the governing equations of the MPDI to make appropriate corrections. After employing the correction factor, the variations in K_s values for all three tested soils decreased from 66%, 61% and 59%, to 26%, 16% and 26%, respectively. In situ experimental tests also show similar results and the coefficient of variation decreased from 81% to 61% after applying the correction factor. The performance was further validated by testing the relative performance of the MPDI against the results obtained using Minidisk Infiltrometer (MDI) under varying θ_{in} values. Results from the MDI show that the coefficient of variation for the K_s values of the three soils were 20%, 28%, and 32%, which are similar to the variations obtained after applying the correction factor in the MPDI model calculations. The aforementioned results indicate that the correction method proposed in this study is a useful method for improving the overall performance of MPDI.

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1. Introduction

Water movement into the soil is the most important factor that affects many hydrological processes including groundwater recharge and surface water runoff (Liu et al., 2011; Schiff and Dreibelbis 1949). Soil properties such as the amount of fines, initial moisture content θ_{in}, and saturated hydraulic conductivity K_s can greatly impact water transport rate through soil-water systems.

The rate at which water infiltrates into an unsaturated soil varies between a maximum value when the soil is dry, and to a minimum value when the soil is wet (Horton 1933; Philip 1957; Ruggenthaler et al., 2016). Ruggenthaler et al. (2016) investigated the infiltration behavior in eight sites under dry, moist, and wet soil moisture conditions using the Double-Ring Infiltrometer. The dry run was performed at the wilting point, the moist run was performed at the field capacity. The wet run used an artificial sprinkler to produce wet soil conditions. Results showed that the infiltration rate decreased with increasing θ_{in}. Hino et al. (1988) investigated the effect of θ_{in} on the vertical movement of water through a one-dimensional vertical infiltration system. The system was a small cylindrical lysimeter that was supplied with artificial rainfall with two tensiometers placed at different depths. Results showed that as θ_{in} increased, the water movement through the soil became faster. The slower movement of water in drier soil is related to the increased volume of water to fill in the voids of soil. Fan et al. (2018) investigated the wetting front patterns of different types of soil for θ_{in} values of 40%, 50%, and 60% of field capacity. A vertical line-source moistube, which contained uniformly distributed nano-pores, which worked as a subsurface source of water, was used to introduce a constant amount of water. Results showed that the rate of the downward movement of the wetting front increased with the increase in θ_{in}. The acceleration of the wetting front movement with the increase in θ_{in} is related to the reduced amount of water that is needed to fill in the voids in the soil.

The soil property that quantifies the ease at which water can move through the soil is the hydraulic conductivity K value (Mays, 2010). The value of K for a given soil increase with the increase in the soil moisture content and it eventually reaches the maximum and a constant value when the soil is fully saturated. This constant value is the saturated hydraulic conductivity K_s which is one of the crucial parameters that govern water transport in soil-water systems. Under saturated conditions, the soil with higher K_s can transmit water faster than the soil with lower K_s. Accurate measurement of K_s is important for the investigation of the hydrological processes and their relationship with groundwater recharge processes (Alagna et al., 2016; Alakayleh et al., 2018; McKenzie and Jacquier 1997; Mohanty et al., 1994; Reynolds et al., 2000; Zhang and Schaap 2019). Many field and laboratory methods for measuring K_s are available. However, measuring K_s variations over a large-field scale would require multiple tests using samples collected at many locations, which could be time-consuming. Therefore, a variety of field methods have been developed to measure in situ K_s values. The methods include the Guelph Permeameter (Reynolds and Elrick 1986), the Tension Infiltrometer (Perroux and White 1988), the Minidisk Infiltrometer (MDI) (Zhang 1997), the Double-Ring Infiltrometer (ASTM 2009), the Philip–Dunne Permeameter (Philip 1993), and the Modified Philip–Dunne Infiltrometer (MPDI) (Ahmed et al., 2014). The MPDI is a relatively simple measurement system, where a tube is inserted 5 cm into the soil and then filled with water. The user will measure the water drawdown data over time, the soil moisture levels at the beginning (i.e., the initial soil moisture content θ_{in}), and at the end of the test (i.e., the final soil moisture content θ_{sf}). These values are used to determine the in situ K_s and the Green-Ampt suction head Ψ at the wetting front (Green and Ampt, 1911).

Previous studies have shown that under natural conditions water moves into the soil by the effect of two major forces: gravity and capillary forces (Gray and Norum, 1967). The coarser the soil texture, the greater the influence of the gravitational force. On the contrary, the finer the soil texture, the stronger the capillary forces. When a soil has a high moisture content value (wet condition), then the influence of capillary forces will decrease and the effect of gravitational force will increase (Fan et al., 2018; Gray and Norum 1967; Hino et al., 1988; Regalado et al., 2005). The drawdown data collected using the MPDI under wet conditions (or low suction head conditions) should be carefully evaluated since the assumption that the flow is mostly driven by capillarity pressure force is no longer valid. Regalado et al. (2005) study pointed out that when low suction head conditions (or wet conditions) are present near the wetting front, results from the Philip Dunne Permeameter must be analyzed with care since the predominant force transporting water will be the gravitational force.

Alakayleh et al. (2019) investigated the performance of the MPDI using a forward modeling algorithm. Their study showed that the K_s and Ψ values estimated using the MPDI are insensitive to the soil moisture deficit ($\Delta\theta = \theta_{sf} - \theta_{in}$) assumed in the data analysis procedure (Ahmed et al., 2014). Therefore, the users of MPDI can independently estimate $\Delta\theta$ based on the field observations. Consequently, the estimated K_s and Ψ are only sensitive to the drawdown data measured using the MPDI. Regalado et al. (2005) found similar results and demonstrated the high level of sensitivity of K_s and Ψ values estimated using the Philip–Dunne Permeameter to the measured drawdown data, and relatively less sensitivity to $\Delta\theta$. Since the drawdown curve patterns for a given soil can vary under different field conditions (i.e., wet or dry soil), one has to carefully analyze the drawdown data after considering the variations in θ_{in} to evaluate the best estimates of K_s and Ψ values.

While several published studies (Alakayleh 2019; Garza et al., 2017; Nestingen et al., 2018) have used the MPDI method and compared its performance with other techniques; however, none of them have tested the performance under varying θ_{in}. In this study, we performed several experiments under both laboratory and field conditions using different types of soil to investigate the effects of varying θ_{in} on the drawdown curves measured using the MPDI and its implication on estimating K_s and Ψ values. The soil parameter values obtained from MPDI were compared against those obtained using MDI under similar test conditions. Based on these experimental datasets, we developed a correction factor that can be used to improve the performance of the MPDI when it is used under varying initial soil moisture conditions.

2. Materials and methods

2.1. Background

The MPDI (Ahmed et al., 2014) is a modified version of the Philip–Dunne Permeameter (Philip, 1993). It is an efficient field technique that can be used to quickly measure the near-surface soil K_s at multiple points. The method involves collecting the unsteady infiltration data over a short period rather than waiting for the steady state infiltration as in the Double-Ring Infiltrometer method. Therefore, MPDI tests are quick and they also require a minimal amount of water.

The original Philip–Dunne Permeameter is an open tube that is tightly inserted into a 15-cm borehole. However, the modified version, MPDI, developed by Ahmed et al. (2014), uses a transparent open-ended tube with a radius of 5 cm, which is beveled from one side for vertically inserting the tube into the soil (the radius and inserting depth can be varied based on user needs). Water is rapidly poured into the device to an initial height H_{in} and the height of water in the tube with time, $H(t)$, above the soil surface is monitored. The initial and final soil moisture contents (θ_{in} and θ_{sf}) are also measured using an in situ method (soil moisture probe) or a laboratory method (e.g., gravimetric measurements).

The data analysis method is developed based on the Green-Ampt theory (Green and Ampt 1911) to estimate K_s and Ψ by modeling the water level variations observed inside the MPDI, i.e., $H(t)$ versus t data. The Green-Ampt model assumes a homogenous and isotropic soil profile and a uniform distribution of θ_{in} at $t = 0$. Also, the wetting front is assumed to be a sharp region with an upper zone that is fully saturated and a lower zone that is always maintained at θ_{in}.

The actual disc-shaped infiltration surface of the MPDI (with a radius r_1 of 5 cm, see Fig. 1) is substituted by a sphere with an equivalent surface area (with a radius $r_0 = 0.5r_1$). The flow from the tube into the soil is assumed to be a capillarity-pressure driven flow. Ignoring the gravity component would result in the spherically symmetrical flow system. The assumed spherically symmetrical configuration is approximated to the actual three-dimensional flow configuration by applying a geometrical coefficient. Based on exploratory calculations using conformal mapping, Philip (1993) (see Fig. 1) and later Ahmed et al. (2014) have used a factor $\beta = \pi^2/8$ in the governing equations used to analyze the MPDI's drawdown data. Equation (1) below shows the governing equation of the MPDI model, as presented by Ahmed et al. (2014).

$$\Delta H(t) = \frac{K_s}{L_{max}}\Delta t\left[\beta\left(\theta_{sf}-\theta_{in}\right)\frac{R^2(t)+R(t)L_{max}}{K_s}\frac{\Delta R(t)}{\Delta t}\frac{\ln\frac{R(t)(r_o+L_{max})}{r_o(R(t)+L_{max})}}{L_{max}} - 2\beta r_o^2\frac{\ln\frac{R(t)(r_o+L_{max})}{r_o(R(t)+L_{max})}}{L_{max}} - \Psi + H(t) + L_{max}\right] \quad (1)$$

where $R(t)$ is the radius of the sharp wetting front at time t. L_{max} is the depth of insertion of the MPDI into the soil.

Ahmed et al. (2014) used Equation (1) to solve for K_s and Ψ by minimizing the absolute difference between $\Delta H(t)$ determined using Equation (1) and the measured change of head from the drawdown data. Another method for setting the optimization is to fit K_s and Ψ values by minimizing the absolute difference between Δt determined by rearranging Equation (1) and measured time intervals data.

2.2. Laboratory experiments

A mini MPDI with a radius of 1.27 cm (a tube of 1-inch diameter) that can be driven 1.27 cm into the soil was constructed and was used in our laboratory experiments. The device was provided with a support base to stabilize the system (Fig. 2a). The drawdown data for a series of experiments were measured using the mini MPDI to determine K_s and Ψ values. Three different types of soil were used in our laboratory study. For each soil, several experiments were performed by changing the θ_{in} value of the soil. The three types of soil were prepared by mixing fine sand with a varying amount (percent dry weights 8%, 15%, and 30%) of No. 52 SilCoSil silt. The silt was made of ground quartz purchased from the U.S. Silica Company. The Mastersizer 3000 made by Malvern Panalytical (2018) was used to determine the percentage of clay, silt, and sand in all three soils. These percentage values were used in the textural triangle (USDA, 2014) to determine the soil texture classes. After the soil mix was prepared by mixing the fine sand with silt at a specific percentage level, the mixture was packed in a testing bucket with a diameter of 29 cm and a depth of 37 cm. θ_{in} was measured gravimetrically by analyzing three soil samples taken during the packing of the middle and surface parts of the bucket where infiltration would occur. The MPDI was inserted 1.27 cm into the soil near the center of the bucket. Water was rapidly poured to fill the MPDI to an initial height H_{in} at time $t = 0$. During the infiltration period, the water level changes occurring inside the MPDI were recorded with time. Immediately after all the water has infiltrated into the soil, the infiltrometer tube was removed from the bucket and soil samples were collected from the location where the tube was inserted to measure the final soil moisture content θ_{sf}. Then the soil dry bulk density was measured by taking a soil core, closely following the procedure described in ASTM-F1815-11 (2011), to convert the gravimetric moisture content into volumetric soil moisture content. The collected data were analyzed using the procedure developed by Ahmed et al. (2014) to estimate K_s and Ψ. The soil was then removed and transferred to a bigger bucket and was mixed with additional water to obtain a higher θ_{in}. The soil was then repacked into the original test bucket using the same packing procedure to maintain a similar dry bulk density value. The MPDI testing procedure was repeated to conduct the drawdown experiments under different (wetter) θ_{in}. Fig. 2 shows the mini MPDI and the experimental testing setup that were used in this study. The mini MPDI was used in the laboratory since the soil is more homogenous than in the field, where a standard MPDI with a radius of 5 cm was used. Water infiltrated from the standard MPDI can cover a volume of soil greater than the one that the mini MPDI would cover. Note a larger well-representative sample volume is required to test a heterogeneous field system; however, a relatively smaller volume is sufficient for testing a homogenous experimental system.

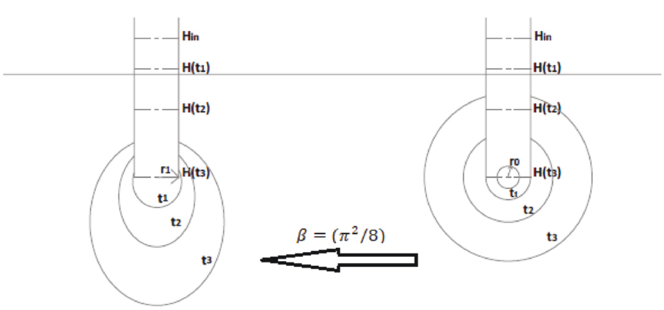


Fig. 1. Geometrical analog of the wetting fronts of water infiltrated from the Philip-Dunne Permeameter (revised from (Regalado et al., 2005)) where H_{in}, $H(t_1)$, $H(t_2)$, and $H(t_3)$ are the water levels inside the permeameter at times t_0, t_1, t_2, and t_3, respectively.

For comparison, a MDI made by Meter Group Inc (2018) was used to estimate the value of K_s of the three soils that were tested using the mini MPDI. The same packing and mixing procedures that were used for the MPDI were also used for MDI experiments. The Minidisk device is a transparent tube with a radius of 1.55 cm that is divided into two chambers. The lower chamber contains a water volume of about 90 cm^3 that is allowed to infiltrate into the soil. The upper chamber controlled the suction and therefore the water infiltration rate. A stainless-steel porous disk is attached to the bottom of the infiltrometer to prevent water from leaking in the open air. After both chambers were filled with water, the suction was set to 6 cm and the bottom of the infiltrometer was placed on the soil and then water started to infiltrate into the soil. During infiltration, the volume of water inside the infiltrometer was recorded at regular time intervals. Then the volume of cumulative water infiltrated with time was calculated. The test was repeated for different θ_{in} for all the soils. The procedures for data collection and analysis were performed following the methods described in Meter Group Inc (2018). The user manual (Meter Group Inc, 2018) includes a basic Microsoft Excel spreadsheet that was utilized in this study to calculate the K value based on Equations (2)–(4) described below.

The measured cumulative infiltration data from MDI were analyzed using the analysis procedure proposed by Zhang (1997) to estimate K. The cumulative infiltration data and the square root of time are fitted with the following equation (Philip 1957):

(a) Mini MPDI. (b) Experimental setup.

Fig. 2. (a) Mini MPDI, and (b) laboratory experimental setup used to test the three different soils.

$$I = C_1 t^{0.5} + C_2 t \tag{2}$$

where I is the cumulative infiltration, t is time, C_1 and C_2 are parameters related to the sorptivity and K, respectively. Then the K value of the soil is calculated using the equation:

$$K = \frac{C_2}{A_2} \tag{3}$$

where A_2 is a dimensionless coefficient that can be obtained using the equation:

$$A_2 = \frac{11.65(n^{0.1} - 1)exp[c(n - 1.9)\alpha h]}{(\alpha r_0)^{0.91}} \quad (c = 2.92 \ if \ n \geq 1.9; c = 7.5 \ if \ n < 1.9) \tag{4}$$

where n and α are the van Genuchten moisture retention parameters for the soil, r_0 is the radius of the infiltration disk, h is the suction at the soil surface, and c is constant.

As the suction applied at the soil surface resulted in near saturated hydraulic conductivity (Kargas et al., 2017; Radinja et al., 2019), the following equation was used to estimate K_s (Gardner 1958):

$$K_s = K / exp(\alpha_G h) \tag{5}$$

where α_G is the Gardner parameter reported in Létourneau and Caron (2019).

2.3. Field experiments

A standard MPDI with a radius of 5 cm that can be driven up to 5 cm into the soil was used to estimate the in situ K_s and Ψ values of a silt loam soil. The site is an agriculture field located in Auburn, Alabama, USA. Data were collected in situ for the water-level drop observed inside the tube at various times. The values of initial and final gravimetric soil moisture contents, and soil dry bulk density were also estimated. The drawdown data were collected at the same location using the MPDI for the same soil under both dry and wet conditions. Data for the dry condition were collected after several sunny days, and data for wet conditions were collected after a rainy day.

The MDI was also used to estimate the in situ K_s at the same location where the MPDI was used. The MDI's suction head was set to 5 cm for both dry and wet field conditions.

Table 1
The percentages of clay, silt, and sand in the 8%, 15%, and 30% silt-sand mixes used in the laboratory experiments.

	% Clay	% Silt	% Sand
Fine sand mixed with 8% silt	4.6	20.6	74.8
Fine sand mixed with 15% silt	6.4	49.4	44.2
Fine sand mixed with 30% silt	14.8	73.8	10.8

3. Results and discussion

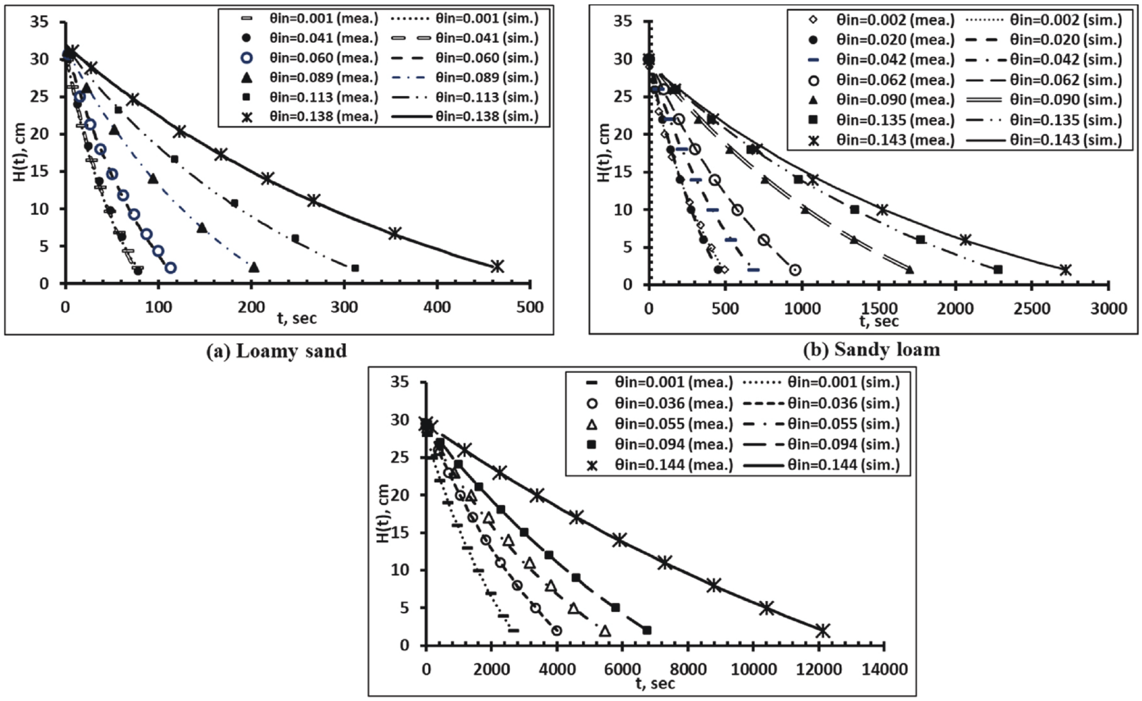
3.1. Laboratory experiments

The percentages of clay, silt, and sand measured using the Mastersizer 3000 analysis for the sand mixes with 8%, 15%, and 30% silt are presented in Table 1. Using these data the three soils were classified as loamy sand, sandy loam, and silt loam, respectively.

Fig. 3 shows the drawdown data points (symbols) measured using the mini MPDI for the three soils under varying θ_{in} versus the simulated drawdown curves (lines) using the Modified Philip–Dunne theory proposed by Ahmed et al. (2014). The simulated drawdown curves fit the measured drawdown data well with R^2 values very close to 1. The drawdown curves start from the initial water height H_{in} to the lowest height $H(t) = 2$ cm that can be read in the device. The support base of the mini MPDI would not allow us to read the depths close to a completely empty tube. The H_{in} values were 32, 30, and 29.5 cm for loamy sand, sandy loam, and silt loam, respectively.

Results show that the total drawdown time t_2, which was recorded when $H(t) = 2$ cm, varied with the soil type. For example, under dry conditions (where θ_{in} was maintained at 0.001, 0.002, and 0.001 for the three soils), t_2 values were 78, 492, and 2652 s for the loamy sand, sandy loam, and silt loam, respectively.

Our results show that the measured drawdown curves are significantly different for the same soil under varying θ_{in}. For every soil, the t_2 values are greater under wet than dry conditions. The t_2 values under wet conditions (Fig. 3) were 465, 2722, and 12118 s for loamy sand,



(c) Silt loam

Fig. 3. Laboratory-measured drawdown data (symbols) for the three soils under varying initial soil moisture content θ_{in} versus the simulated drawdown curves (lines) using the Modified Philip–Dunne theory proposed by Ahmed et al. (2014): (a) loamy sand, (b) sandy loam, and (c) silt loam.

sandy loam, and silt loam, respectively. The corresponding t_2 values under dry conditions were 78, 492, and 2652 s. The wet conditions had an initial water content of 0.138, 0.143, and 0.144 (which are 68%, 62%, and 58%, of the final measured water content of 0.204, 0.230, and 0.250 for the three soils). The three soils were not able to hold additional water after reaching these final measured water content levels. Therefore, very high θ_{in} values were not tested in this study. Ahmed et al. (2014) performed the field infiltration measurements in grassed roadside drainage ditches using their MPDIs at 32 sites and had θ_{in} with the percent of saturation ranging from 7.7% to 90.7% (54.2% ± 18.2%) and 90.6% sites with the percent initial saturation ≥30%.

The aforementioned results indicated that the rate of water infiltration into dry soil can be higher than in wet soil, which is similar to the observations made by others including Gray and Norum (1967); Philip (1957a,b); Ruggenthaler et al. (2016). This is because there are more voids in dry soil that allow water to fill relatively fast, but wet soil has much fewer voids to allow water to fill and therefore takes more time for the water to infiltrate.

Table 2
The saturated hydraulic conductivity K_s and Green-Ampt suction head Ψ at the wetting front estimated using the Modified Philip-Dunne theory for all the laboratory experimental tests performed in this study on three soils under varying initial soil moisture content θ_{in} with and without the correction factor.

Soil type	θ_{in}	θ_{sf}	Dry bulk density	K_s	Ψ	K_s ^{corrected}	Ψ ^{corrected}	$(\theta_{in}/\theta_{sf}) \times s$
	%	%	g/cm^3	cm/s	cm	cm/s	cm	
Loamy sand	0.12	20.4	1.58	3.15×10^{-2}	−9	2.29×10^{-2}	−9	0.1
	4.10	20.4	1.58	2.60×10^{-2}	−15	1.74×10^{-2}	−15	1.7
	6.00	20.4	1.59	1.80×10^{-2}	−15	2.68×10^{-2}	−17	2.6
	8.90	20.4	1.58	1.05×10^{-2}	−13	2.04×10^{-2}	−14	3.8
	11.3	20.4	1.59	7.09×10^{-3}	−13	1.67×10^{-2}	−16	4.8
	13.8	20.4	1.58	4.63×10^{-3}	−13	1.26×10^{-2}	−18	5.9
Sandy loam	0.18	23.0	1.64	4.01×10^{-3}	−13	2.89×10^{-3}	−11	0.1
	2.00	23.0	1.65	3.79×10^{-3}	−18	4.13×10^{-3}	−19	1.3
	4.20	23.0	1.65	2.76×10^{-3}	−18	4.14×10^{-3}	−18	2.7
	6.20	23.0	1.64	1.96×10^{-3}	−16	3.87×10^{-3}	−19	4.0
	9.00	23.0	1.65	1.10×10^{-3}	−16	2.83×10^{-3}	−21	5.7
	13.5	23.0	1.65	9.01×10^{-4}	−13	3.27×10^{-3}	−20	8.6
	14.3	23.0	1.64	8.92×10^{-4}	−10	3.44×10^{-3}	−16	9.1
Silt loam	0.14	25.0	1.72	5.66×10^{-4}	−20	4.08×10^{-4}	−18	0.1
	3.60	25.0	1.71	4.28×10^{-4}	−18	7.00×10^{-4}	−21	2.6
	5.50	25.0	1.71	3.35×10^{-4}	−16	7.16×10^{-4}	−20	4.6
	9.35	25.0	1.72	1.78×10^{-4}	−31	5.55×10^{-4}	−40	7.8
	14.4	25.0	1.72	9.49×10^{-5}	−33	4.33×10^{-4}	−45	12.0

Note: K_s ^{corrected} and Ψ ^{corrected} were estimated when $\beta_m = (\pi^2/8)(\theta_{in}/\theta_{sf}) \times s$ was used in the governing equations of the MPDI rather than using $\beta = (\pi^2/8)$. The estimated s values are 9, 15, and 21 for loamy sand, sandy loam, and silt loam, respectively, which linearly correlated with the bubbling pressure for these soils reported in Rawls et al. (1982).

The collected drawdown data for the three soils under varying θ_{in} and the corresponding θ_{in} and θ_{sf} were analyzed using the procedure proposed by Ahmed et al. (2014) and the estimated K_s and Ψ are reported in Table 2.

Table 2 shows that the overall trend of K_s values estimated using the MPDI was decreasing with increasing the fine content, which is as expected. This trend was also observed by Nestingen et al. (2018) for the K_s values estimated using the MPDI for three types of sand with different grain size distributions.

The MPDI data did not provide a unique value for K_s when measured under varying θ_{in} conditions; however, in reality, K_s should remain the same for a given soil whatever the value of θ_{in} at the time of performing the test. This difference in K_s is caused by the difference in measured drawdown curve as the K_s value estimated using the MPDI theory is highly sensitive to the drawdown curve and less sensitive to $\Delta\theta$. Therefore, the estimated K_s values of every soil (Table 2) varied with θ_{in}. The mean values and standard deviations of K_s are 1.63×10^{-2} and 1.08×10^{-2} cm/s, 2.20×10^{-3} and 1.34×10^{-3} cm/s, and 3.23×10^{-4} and 1.90×10^{-4} cm/s for loamy sand, sandy loam, and silt loam, respectively. The coefficients of variation of K_s for the loamy sand, sandy loam, and silt loam were 66%, 61%, and 59%, respectively.

The lowest K_s value of every soil was observed when the MPDI was used under wet conditions. Note that the flow of water from the MPDI into the soil is assumed to be primarily driven by capillarity-pressure force after ignoring the gravity effects. Previous studies have shown that the higher the θ_{in} the lower the effect of the capillary force and the greater the effect of gravity force (Hino et al., 1988). That means an underestimation of K_s is the consequence of neglecting the effects of the gravity force as the water infiltrated from MPDI is transported through the soil. The estimated Ψ values (see Table 2) were arbitrary and did not reflect the changes in the soil texture class and θ_{in}. This is similar to the results from Alakayleh et al. (2019) who concluded that the MPDI is not a robust method to estimate Ψ values.

3.1.1. Development of a correction factor to estimate a unique value for K_s

It is desirable to somehow account for the effect of θ_{in} in the MPDI model to provide a better estimate of K_s and possibly correct Ψ values that reflect the variation in θ_{in} of a given soil. We hypothesized that the constant coefficient β used in the MPDI governing equations should be allowed to vary with the soil texture class and also with the variation in θ_{in} values. To accomplish this, we proposed a correction factor $((\theta_{in}/\theta_{sf}) \times s)$ that can be multiplied by $\beta(=\pi^2/8)$ to get the modified geometrical coefficient $\beta_m(=(\pi^2/8)(\theta_{in}/\theta_{sf}) \times s)$. Then the corrected value β_m can be used in Equation (1), rather than using β. In the correction factor, s is an empirical constant that will vary with the soil textural class and it appears to be correlated to the value of the bubbling pressure. The estimated s values are 9, 15, and 21 for loamy sand, sandy loam, and silt loam, respectively, which are linearly correlated with the bubbling pressure values reported in Rawls et al. (1982).

The proposed correction in the geometrical coefficient β reflects the changes in the actual three-dimensional flow configuration of a given soil for varying θ_{in}. Fig. 4 shows the geometrical analog of the MPDI for a given soil considering varying θ_{in}. This figure shows the shape of the wetting fronts when the gravity effects are ignored (the right side of the figure), and when the gravity is taken into account (the left side of the figure) for a given value of θ_{in} (note that the water head drop, $\Delta H = H_{in} - H(t)$, is maintained the same). Previous studies have shown that the wetting front could advance to a deeper depth with the increase in θ_{in}. Also, the finer the soil texture is the greater the effect of θ_{in} (Fan et al., 2018; Hino et al., 1988).

The correction factor (see Table 2) varies with θ_{in} for the same soil texture class (since θ_{sf} and s remain the same) and is much greater for the wet condition than for dry condition to account for the effect of θ_{in} within a given soil. For example, when the θ_{in} value of the loamy sand (Table 2) is changed from 0.12% to 13.8%, a 115 times increase, the correction factor has the same level of increase. Also, the correction factor varies with the soil texture class because of the change in θ_{sf} and s. The correction factor increases with the increase in the fine content of the soil. This will account for the greater effect of θ_{in} on the drawdown data of fine soil than coarse soil. For example, when θ_{in} is the same for the three soil ($\theta_{in} \approx 0.09$) the correction factor equals 3.8, 5.7, and 7.8 for loamy sand, sandy loam, and silt loam, respectively. Note that Regalado et al. (2005) have shown that the sensitivity of estimated K_s using the Philip-Dunne Permeameter to the factor β is small. Therefore, a large difference in β value is needed to correct the large variation of K_s when estimated under varying θ_{in} in a fine soil.

After using the correction factor, the MPDI model can yield an almost unique estimate of K_s for a given soil regardless of the value of θ_{in}. The K_s and Ψ values estimated using the MPDI theory when the correction factor was used in the governing equation are also reported in Table 2. Results show that K_s values of every soil measured under varying θ_{in} were relatively uniform after applying the correction factor, but the Ψ values still appear to be arbitrary. The mean values and standard deviations of K_s are 1.95×10^{-2} and 5.01×10^{-3} cm/s, 3.51×10^{-3} and 5.51×10^{-4} cm/s, and 5.62×10^{-4} and 1.44×10^{-4} cm/s for loamy sand, sandy loam, and silt loam, respectively. The mean K_s values increased by 20–76% but the standard deviations decreased by 24–59% in comparison to ones before applying the correction factor. The coefficients of variation decreased to 26%, 16%, and 26% for the loamy sand, sandy loam, and silt loam, respectively. Fig. 5 shows K_s values

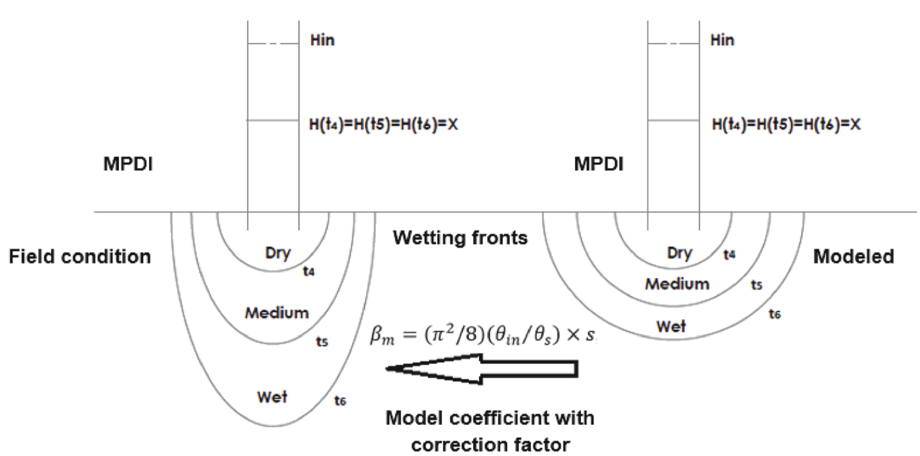


Fig. 4. Geometrical analog of the wetting fronts of water infiltrated from the MPDI into a given soil under three different θ_{in} values (dry, moist, and wet). The left figure shows realistic water flow patterns after accounting for gravity effects, and the right figure shows idealistic spherically symmetrical flow patterns that ignore gravity effects. Note that the corresponding water level in the tube is the same $H(t_4) = H(t_5) = H(t_6) = X$ cm but occurs at different times t_4, t_5, and t_6, respectively.

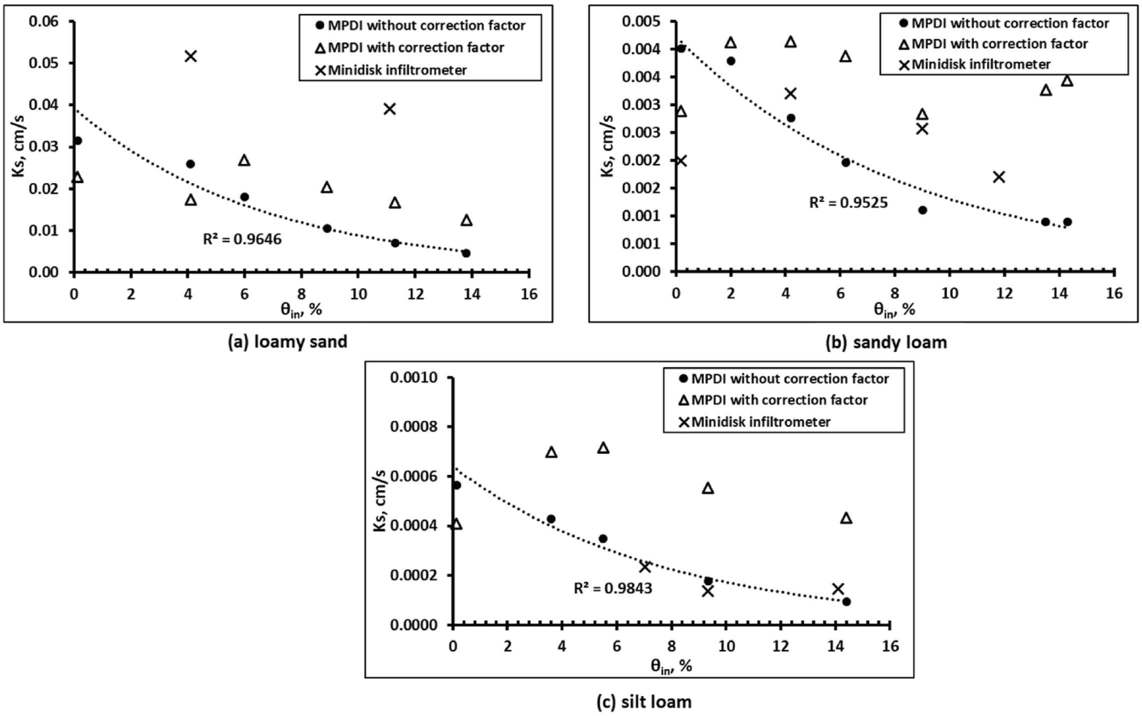


Fig. 5. Comparison of the saturated hydraulic conductivity K_s estimated using the Modified Philip-Dunne theory under varying initial soil moisture content θ_{in} before and after applying the correction factor and also the K_s values estimated using the Minidisk Infiltrometer. Note: the scales for K_s in the y-axis are different for each of the three soils. The dotted lines are the exponential trendlines fitted based on the K_s values before applying the correction factor. The coefficients of determination R^2 for the trendlines ranged between 0.95 and 0.98.

Table 3
Saturated hydraulic conductivity K_s estimated using the Minidisk infiltrometer under varying initial soil moisture content θ_{in}.

Soil type	θ_{in}	K_s
	%	cm/s
Loamy sand	4.1	5.17×10^{-2}
	11.1	3.92×10^{-2}
Sandy loam	0.18	2.0×10^{-3}
	4.2	3.2×10^{-3}
	9	2.57×10^{-3}
	11.8	2.36×10^{-3}
Silt loam	7.04	2.36×10^{-4}
	9.35	1.37×10^{-4}
	14.1	1.46×10^{-4}

before and after applying the correction factor with the corresponding θ_{in} values.

3.1.2. Comparing the relative performance of MPDI estimates against MDI measurements

The MPDI results were compared against the MDI results for the three soils measured under varying θ_{in}, and the estimated K_s values are summarized in Table 3. Since the K_s values estimated using both methods have not been compared against any true reference values, such as falling or constant head test results, we did not complete any error analysis to quantify the accuracy of the method. Instead, the coefficient of variation was used as a metric to compare the precision (variations in K_s) and therefore the relative performance of the MPDI against the MDI when both methods were used under varying θ_{in}conditions. The coefficients of variation of K_s estimated using the MDI were 20%, 28%, and 32% for the loamy sand, sandy loam, and silt loam, respectively, which are similar to the coefficients of variation after applying the correction factor (section 3.1.1) in the MPDI equations.

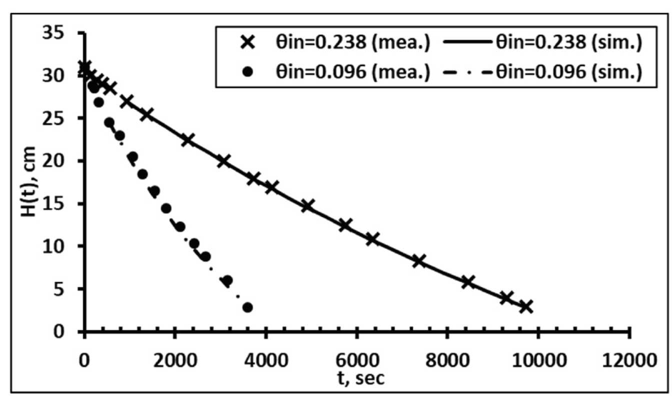


Fig. 6. Field-measured drawdown data for a silt loam soil under dry and wet conditions versus the simulated drawdown curves using the Modified Philip-Dunne theory proposed by Ahmed et al. (2014).

Table 4
Saturated hydraulic conductivity K_s and Green-Ampt suction head Ψ at the wetting front estimated using the Modified Philip-Dunne theory for a field soil under dry and wet conditions with and without the correction factor.

θ_{in}	θ_{sf}	K_s	Ψ	K_s ^{Corrected}	Ψ ^{Corrected}	$(\theta_{in}/\theta_{sf}) \times s$
%	%	cm/s	cm	cm/s	cm	
9.57	44.4	1.40×10^{-3}	−20	2.59×10^{-3}	−32	4.5
23.8	44.9	3.80×10^{-4}	−37	1.03×10^{-3}	−90	11.0

Note: K_s ^{corrected} and Ψ ^{corrected} were estimated when $\beta_m = (\pi^2/8)(\theta_{in}/\theta_{sf}) \times s$ was used in the governing equations of the MPDI rather than using $\beta = (\pi^2/8)$. Where $s = 21$ for the silt loam.

3.2. Assessment of modified MPDI performance using field experiments

Fig. 6 shows the measured drawdown data, which starts from H_{in} = 31 cm to $H(t_3)$ = 3 cm.

Similar to the laboratory results, the field measured drawdown curves are significantly different for the same soil under varying θ_{in}. The total drawdown time t_3, which was recorded at $H(t_3)$ = 3 cm, increased with θ_{in}. The t_3 values were 3600 and 9720 s under the dry and wet conditions, respectively. The dry soil has θ_{in} of 0.096 and the wet soil has θ_{in} of 0.238 with about 21.5 and 53.2% of θ_{sf}, respectively, which were similar to two laboratory tests (Tables 2 and 3) for the MPDI and the MDI. The collected drawdown data under the dry and wet conditions and the corresponding θ_{in} and θ_{sf} were analyzed using the analysis procedure proposed by Ahmed et al. (2014) and the obtained K_s and Ψ are reported in Table 4. Results (Table 4) show a similar trend to the laboratory experimental results of decreasing K_s value when the test was conducted under the relatively wet condition and the arbitrary Ψ values.

Then K_s and Ψ values were estimated after applying the correction factor and the results are reported in Table 4. Where the *s* value that was used in the correction factor is equal to 21 for the silt loam soil. The coefficients of variation before and after applying the correction factor were 81% and 61%, respectively. The coefficient of variation value of the in situ tested soil is higher than the one of the laboratory tested soil reported in Section 3.1.2. This could be related to the variations in the soil heterogeneity under laboratory and in situ conditions (Nestingen et al., 2018).

The MDI was then used under in situ conditions to measure K_s on the same location under dry and wet conditions. The measured K_s values were 3.59×10^{-3} and 3.17×10^{-3} cm/s for the dry and wet conditions, respectively. These values are of the same order of magnitude as the values estimated using the MPDI under the dry condition.

4. Conclusions

We have investigated the effects of varying soil moisture levels, θ_{in}, on the drawdown data measured using the MPDI and its impacts on the estimated values of K_s and Ψ. Laboratory experiments were conducted using three types of soil including loamy sand, sandy loam, and silt loam. Results show that the overall trend of K_s values estimated using the MPDI was decreasing with increasing the fine content. However, for a given soil, the drawdown curve was different when we varied the value of θ_{in}, and this resulted in estimating different K_s values. The lowest K_s values were observed when the MPDI was used in wet soils. Results from the MPDI were compared against the ones estimated using the MDI which was also used under varying θ_{in} conditions. Overall, the coefficients of variation in the MDI-estimated values of K_s were less than the ones estimated using the MPDI.

We proposed a correction factor to modify the MPDI equations to account for the effects of θ_{in}. The correction factor helped obtain a unique value of K_s. The correction factor accounted for variations in θ_{in}, and it also accounted for variations in soil texture. When the proposed correction factor was used, the coefficient of variation in the estimated values of K_s decreased from 66%, 61%, and 59%–26%, 16%, and 26% for the three soils. The effectiveness of the correction factor was also tested by collecting in situ drawdown data under dry and wet conditions at a silt loam field site. The coefficient of variation of K_s for this soil decreased from 81% to 61%. In all our laboratory and in situ experiments, the K_s values estimated using the MPDI after applying the correction factor were of the same order of magnitude as the ones estimated using the MDI. Our results show that the estimated Ψ values in all the experiments were rather arbitrary and they did not reflect the changes in soil texture classes and the soil moisture content, and this continues to be a major shortcoming of MPDI.

It should be noted that the MPDI was originally developed to evaluate the surface infiltration rate of stormwater infiltration practices at sites that are designed to have relatively high K_s values. We have tested the MPDI on three different soils that cover a wide range of soil textural classes used in the infiltration practices, and have developed a correction factor to account for variations in soil type and initial moisture content. Although the correction factor yielded promising results, we recommend further studies to test the performance of the MPDI with the correction factor under different types of field condition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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