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A Test of Factors Influencing One-Dimensional Mini-Disk Infiltrometer Experiments on Repacked Loam Soil Columns

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Abstract: Performing infiltration experiments on sieved and repacked soil columns seems a generally underrated topic from a methodological point of view. This study assessed how the descriptive parameters of the infiltration process were influenced by (i) the operator; (ii) the number of replicated runs; and (iii) the soil sample preparation method. A total of 135 loam soil columns, each 20 cm high were prepared by two operators. Four packing methods, differing by the number of steps required to prepare the sample, were applied. One-dimensional infiltration runs were carried out on each soil column using a Mini-Disk Infiltrometer set at a pressure head of −3 cm. A statistical, or at least practical, similarity of the infiltration parameters obtained by the two operators was detected. Six replicated runs were found to be enough to obtain an acceptable description of the entire infiltration process. Differences between the packing methods were noticeable since infiltration parameters differed by up to 2.7 times, probably because soil compaction energy varied with the applied packing method. Two operators can achieve consistent and reproducible results using the same equipment and packing method since the number of steps in which the soil column is prepared has an appreciable effect on its hydrodynamic response.

Keywords: repacked soil columns; infiltration; replicability; operator; sample size; packing method

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1. Introduction

Laboratory infiltration experiments on sieved and repacked soil columns are carried out for many purposes, including studying soil sealing under controlled rainfall events [1], establishing the effects of water quality [2,3] or amendments of various nature [4–7] on the soil hydrodynamic response. Performing experiments on sieved and repacked soil columns seems a generally underrated topic [8], even if it presents several critical issues [9–11]. Factors to be considered include the following: (i) the operator preparing the soil column and performing the infiltration run; (ii) the number of replicated runs; and (iii) the method applied to prepare the soil sample.

An experiment can be carried out by a single operator or by two or more operators, who may have different abilities in applying experimental methods. The operator-to-operator variation is a common aspect of all experimental methods [12,13]. Such variation affects replicability of the experiment and hence its scientific robustness. Variation induced during the sample preparation stage and the subsequent measurement phase can stem from several factors, including the level of experience of the operator. In particular, more experienced operators can be expected to prepare the sample with higher precision and consistency than less experienced operators. However, even duly trained operators can prepare a soil sample in a different manner due to their physical prowess or perhaps fatigue. Although the literature occasionally mentions operator-induced variability [12,14,15], it does not seem that the impact of this type of variability has been extensively tested in relation to measurement of soil hydrodynamic properties.

Notably, a sample has to be representative of the target population. Larger sample sizes are expected to better represent the population, but too large sample sizes lead to a loss of time, human resources and money. On the other hand, the risk with too small sample sizes is that they do not satisfactorily represent the sampled population [16,17]. Choosing an appropriate sample size requires considering the actual data variability [18]. Hydrodynamic properties of field or undisturbed soil generally show a noticeable variability, and this circumstance implies that the measurement has to be replicated many times [18,19]. Instead, working in the laboratory with sieved and repacked soil can be expected to require less replications of the measurement since a more homogeneous porous medium is used in this case [20]. To the best of our knowledge, however, large datasets providing realistic estimates of the actual data variability have not been developed with reference to hydrodynamic properties of repacked soil columns. Therefore, the usability of small sample sizes for these types of investigations still needs support.

When working with repacked soil samples, it is necessary to choose an appropriate packing method. This choice depends on the purpose of the investigation, but also on several practical constraints, such as the equipment available to researchers and the size of the sample that can be prepared in a laboratory. Several methodologies are, in principle, usable, such as vibrating devices [21] or press pistons [22]. In other cases, soil columns are prepared by manual methods involving a step-by-step procedure [7,23,24]. At each step, a mass of soil is poured into the cylinder, and this mass is then compacted by a pestle or by repeatedly dropping the soil column from a certain height. Packing method effects on measurement of soil hydrodynamic properties can be significant [25], and hence, they should be taken into account when the experiment is planned.

The Mini-Disk Infiltrometer, MDI [26], is a compact tension infiltrometer, designed for quick and straightforward measurement of the infiltration process under unsaturated conditions. In particular, pressure head values, h_0, ranging from -0.5 cm to -7 cm can be established at the infiltration surface. Typically, this device is employed in the field for measuring three-dimensional (3D) infiltration processes for a specific h_0 value [27,28]. However, the MDI is also usable for measuring one-dimensional (1D) infiltration on small-diameter repacked soil columns [3,29]. Many investigations, some of which are mentioned in Table 1 as an example, have been carried out in the laboratory by applying the MDI on sieved and repacked soil samples. In general, the number of operators performing the experiment is not indicated, the number of replicates varies with the experiment—settling, however, on rather small values—and soil packing methods change from one investigation to another or they are not described. The fact that experimental methods differ with the investigation, or they are not described at all, makes the interpretation of the data difficult and hinders comparison between different investigations [30]. The general objective of this investigation was to test factors influencing 1D infiltration experiments with the MDI on sieved and repacked soil columns. The specific objectives were to establish—for loam soil and a given pressure head on the soil surface—the dependence of the measured infiltration parameters on (i) the operator performing the experiment; (ii) the considered sample size; and (iii) the applied packing method to prepare the soil column.

Table 1. Examples of experiments performed with the Mini-Disk Infiltrometer (MDI) on repacked soil columns.

Reference	Soils	Aims of the MDI Application	Size of the Columns	Soil Column Preparation	N *
Assouline and Narkis [3]	Clayey	Evaluating the impact of 15 years of irrigation with treated wastewater on soil hydraulic properties and flow processes compared to the use of freshwater	10 cm long × 5.2 cm in diameter	Air-dried, crushed and sieved soil. The <2 mm fraction of the aggregates was kept for the study. Packing method not described	2
Fatehnia et al. [31]	Poorly graded sand	Comparing methods to determine soil hydraulic conductivity from infiltration data	Not described	Not described	3
Bordoloi et al. [32]	Inorganic low plastic silt	Determining infiltration rates in compacted natural fiber-reinforced soil composite	17 cm long × 15.5 cm in diameter	Static compaction of the soil at a fixed moisture content. Compaction in three equal layers along the longitudinal axis of the mold at established densities	3
Alghamdi et al. [33]	Sandy	Testing the impact of biochar, bentonite and compost on soil physical characteristics	30 cm long × 5 cm in diameter	Soil hand-mixed, air-dried and sieved at 2 mm. Columns filled to obtain a given bulk density value. Packing method not described	3
Kargas et al. [29]	Sandy-loam; Loam; Silty-clay-loam	Investigating differences between three- (3D) and one- (1D) dimensional infiltration and determining the γ parameter of the Haverkamp et al.'s [34] infiltration model	30 cm long × 30 cm in diameter (3D experiment) and 50 cm long × 4.5 cm in diameter (1D experiment)	Air-dried soil, passed through a 2 mm sieve. Packing method not described	1
Ghosh et al. [35]	Sand; Clay-loam	Testing the effect of the initial compaction state on near-saturated soil hydraulic conductivity	30 cm long × 20 cm in diameter	Mass of air-dried soil mixed with a given amount of water to obtain the desired soil water content. Soil packed in three layers by an equal number of blows with a 1.7 kg rammer on each layer. Number of blows varying with the state of compaction for a particular soil	4
Roy et al. [36]	Silty-clay-loam; Silty-clay; Sandy-loam	Determining hydraulic conductivity of three types of soil in both frozen and unfrozen conditions with five initial soil water contents	17.8 cm long × 20.3 cm in diameter	Use of fixed amounts of soil and water to obtain a given initial water content. Soil columns prepared layer by layer to attain a pre-established bulk density value	3
Naik and Pekkat [37]	Loam; Silt-loam	Using the MDI for estimating water retention characteristic curve parameters	25 cm long × 30 cm in diameter	Nearly dry soil. Soil compacted in three layers by maintaining a uniform bulk density	6
Autovino et al. [38]	Loam; Clay	Determining the impact of soil layering on 1D infiltration processes established with the MDI	20–23 cm long × 5.3 cm in diameter	Air-dried and passed through a 2 mm sieve. Partition of the soil mass into three equal parts. First third poured in the cylinder and soil compacted by a wood pestle. Then, the rotation of the pestle around its vertical axis. Application of the same procedure with the second and third parts	9

* Number of replicates for a given treatment.

2. Materials and Methods

2.1. Soil

The investigation was carried out on a soil collected in Sicily (Italy), in an orchard of the Department of Agricultural, Food and Forest Sciences of the Palermo University (38°06′24′′ N, 13°21′06′′ E). The soil (Typic Rhodoxeralf) has a relatively high gravel content, an organic carbon content of 27 g/kg [39] and it is mostly sandy-loam or loam down to a depth of at least 0.30 m. Average values of saturated soil hydraulic conductivity determined in the field using the so-called BEST procedure [40] vary during the year between 16 and 194 mm/h [41]. For this investigation, an area where the texture was loam (clay = 19.0%, silt = 30.3%, sand = 50.7%; USDA classification system) was sampled [39]. The soil, collected from approximately the upper 10 cm of the profile, was transported to the laboratory and spread on plastic sheets for natural drying at room temperature. This process lasted about 40 days, during which the soil was manually stirred every 2–3 days to facilitate drying. Once the soil was air-dry, it was sieved for 5 min through a 2 mm mesh sieve and the fine fraction was retained for the experiment.

2.2. Experimental Methods

Soil columns were prepared in 25 cm long Plexiglas cylinders having an inner diameter, d, of 5.3 cm. Two different operators (V and Z) prepared the soil columns and performed the infiltration runs. The V operator was a master student whereas the Z operator was a PhD student. Soil columns were prepared by pouring the soil into the cylinder and manually pressing the poured soil using a wood pestle with a circular disc with a diameter of 5.0 cm at its bottom. The diameter of the disc was a little smaller (by 3 mm) than that of the cylinder to make it easier to slide the pestle into the cylinder. After concluding pressing, the pestle was rotated clockwise and counter-clockwise around its vertical axis for a few times.

Different packing methods (P1, P2, P3 and P4) were applied in this investigation to prepare soil columns with a final length of 20 cm using 537 g of air-dry soil. For P1, all the air-dry soil was poured into the cylinder at once and pressed 200–220 times. For P2, 268.5 g of soil was poured and pressed 80–100 times. Then, another 268.5 g of soil was added and compacted another 80–100 times. For P3, the soil was added in three steps (179 g of air-dry soil at each step), and it was pressed 30 times at each step. For P4, the soil was added in four steps (134.25 g of soil at each step) and pressed 10–15 times after each soil addition. The fact that an operator manually compacted the soil impeded the determination of the dissipated energy for preparing the sample. However, assuming that the pressing action did not vary appreciably between two pestle applications, it can be suggested that 3.3–5.5 times higher energy was required to prepare the soil column using the P1 method than the P4 method.

A direct measurement of the dry bulk density, ρ_b (g/cm^3), of a soil column was not available since the soil used to fill the cylinder was air-dry and not oven-dry. Therefore, ρ_b was determined by the following relationship [20]:

$$\rho_b = \frac{m_s}{V_t} = \frac{m_{ad}}{V_t \times (1 + w_{ad})} \quad (1)$$

where m_s (g) is the mass of the dry soil, V_t (cm^3) is the bulk volume of the soil sample, m_{ad} (g) is the mass of the air-dry soil and w_{ad} (g/g) is the gravimetric soil water content of the air-dry soil that was measured each working day.

Each operator (V and Z) prepared N = 45 soil columns using the P3 packing method. A single operator (Z) prepared N = 15 columns with each of the four packing methods, namely P1, P2, P3 and P4. On average, ρ_b was equal to 1.17 g/cm^3 (coefficient of variation, CV = 0.8%; N = 135), and the volumetric air-dry soil water content, θ_{ad}, obtained by ρ_b and w_{ad}, was equal to 0.051 m^3/m^3 (CV = 5.4%). Therefore, the soil columns were overall homogeneous with reference to both ρ_b and θ_{ad}.

A Mini-Disk Infiltrometer, MDI, was used to measure 1D infiltration in a laboratory where approximately constant temperature and humidity conditions are maintained. For each run, the MDI was filled with tap water at room temperature. A pressure head, h_0, equal to -3 cm, was established at the base of the device. This choice was made to avoid flow along pores with an equivalent diameter > 1.0 mm [42] and, hence, to only consider flow through the soil matrix. Before each test, the soil column was placed on a perforated support that allowed air to easily escape from the bottom of the sample. For each run, the infiltrated volumes were measured every 10 s for the first minute, 15 s for the subsequent minute, 30 s for another two minutes and then every minute until the complete emptying of the MDI reservoir occurred. Cumulative infiltration, I (mm), at a given time, t (h), was obtained by dividing the cumulative infiltrated volume by the cross-sectional area of the soil column.

A risk of obtaining inaccurate data with the MDI, as with all tension infiltrometers, is linked to poor hydraulic contact between the rough soil surface and the base of the device [43]. This risk was likely minimal in this investigation since using the pestle implied preparing the smoothest possible infiltration surface.

The depth of the wetting front, d_{wf} (cm), with respect to the soil surface, was also measured at the end of the infiltration run. These measurements were performed along four verticals established at a radial distance of 90° and the four values were averaged to characterize the soil sample.

2.3. Infiltration Parameters

The mean infiltration rate, ir_{med} (mm/h), was calculated for each run as the ratio between cumulative infiltration by the end of the run and its total duration.

In addition, the empirical Horton [44] infiltration model was fitted to the I vs. t data by minimizing the sum of the squared residuals between the measured and the predicted I values [45]:

$$I = i_{fH}t + \frac{i_{0H} - i_{fH}}{k_H}\left(1 - e^{-k_H t}\right) \tag{2}$$

where $i_{0\text{H}}$ (mm/h) is the initial infiltration rate (t = 0), $i_{f\text{H}}$ (mm/h) is the final infiltration rate and the constant k_{H} (1/h) describes the rate at which $i_{0\text{H}}$ approaches $i_{f\text{H}}$. For given $i_{0\text{H}}$ and $i_{f\text{H}}$ values, the smaller the $k_{\text{H},}$ the more gradual the transition from the initial to the final conditions [46]. The quality of the fitting was evaluated by calculating the relative error, Er (%), in agreement with Lassabatere et al. [45]. The Er values varied from 1.2% to 5.2%, with a mean value of 3.2%. According to Lassabatere et al. [45] a relative error that does not exceed 5.5% denotes an acceptable fitting of an infiltration model to the data. Therefore, the fitting of the model to the infiltration data was satisfactory for all individual runs.

The model developed by Horton was chosen since it describes the infiltration curve in some detail, that is by three different parameters expressive of the initial and the final stages of the process and also of the transition between these two stages.

2.4. Data Analysis

Five response variables, that is ir_{med}, $i_{0\text{H}}$, $i_{f\text{H}}$, k_{H} and d_{wf}, were considered in this investigation.

Initially, a comparison was established between the experiments performed by the two operators.

Taking into account that the operators V and Z yielded similar results, a single dataset of ir_{med}, $i_{0\text{H}}$, $i_{f\text{H}}$, k_{H} and d_{wf}, values (N = 90 for each variable) was developed by pooling the data obtained by these two operators. The number of samples, N_r, required to estimate the mean of a variable with a given tolerance, d, for a given confidence level (95% in this investigation) was then calculated according to Warrick [19]:

$$N_r = \frac{z_{0.5\alpha}^2\, SD^2}{d^2} = \frac{z_{0.5\alpha}^2 CV^2}{a^2} \tag{3}$$

where $z_{0.5\alpha}$ is the normalized difference from the mean, *SD* is the standard deviation, *CV* is the coefficient of variation and *a* is a fraction of the mean, *Me*, such that $d = a \times Me$. According to Warrick [19], the sample coefficient of variation was used in the calculations. Using large sample sizes (i.e., $N = 90$) for estimating *CV* was considered advantageous in the perspective to obtaining reliable N_r values. Using Equation (3) with *a* (fraction of the mean) values ranging between 0.05 and 0.25 to estimate appropriate sample sizes is common in investigations on soil hydrodynamic parameters (e.g., [47–50]).

Finally, a comparison was performed between the four packing methods.

Variability of the data was considered low, medium and high for $CV \leq 15\%$, $15\% < CV \leq 50\%$ and $CV > 50\%$, respectively [19]. All comparisons were carried out by using F and *t* tests at $p = 0.05$. Percentage differences between two means, Δ, were also calculated as

$$\Delta = 100 \times \frac{highest\ mean - lowest\ mean}{lowest\ mean} \quad (4)$$

3. Results and Discussion

3.1. Operator

With reference to ir_{med}, the means obtained by the two operators differed by a not statistically significant Δ value of 8.8% (Table 2). Considering the fitted parameters of the Horton model, $\Delta = 8.1\%$ was obtained for $i_{0\mathrm{H}}$, $\Delta = 5.5\%$ for $i_{f\mathrm{H}}$ and $\Delta = 1.9\%$ for k_{H}, and no difference between two corresponding means was significant. For d_{wf}, Δ was equal to 1.4% and differences were statistically significant in this case. Following Warrick [19], variability of ir_{med}, $i_{0\mathrm{H}}$, $i_{f\mathrm{H}}$ and k_{H} was medium. A low variability was instead detected for d_{wf}.

Table 2. Statistics of the ir_{med}, $i_{0\mathrm{H}}$, $i_{f\mathrm{H}}$, k_{H} and d_{wf} values obtained by the two operators (V and Z) (sample size, $N = 45$ for each operator).

Parameter	Operator	Min	Max	Mean	CV (%)
ir_{med} (mm/h)	V	68.4	169.0	109.9 a	21.0
	Z	89.3	180.6	119.6 a	19.5
$i_{0\mathrm{H}}$ (mm/h)	V	381.5	1304.3	685.6 a	29.1
	Z	342.0	1398.4	741.3 a	33.0
$i_{f\mathrm{H}}$ (mm/h)	V	56.0	122.8	81.1 a	20.6
	Z	63.9	128.5	85.6 a	18.5
k_{H} (1/h)	V	21.0	85.8	48.1 a	29.5
	Z	21.7	97.1	49.1 a	34.6
d_{wf} (cm)	V	10.5	11.6	11.0 a	2.6
	Z	10.5	11.3	10.9 b	2.1

ir_{med} = mean infiltration rate; $i_{0\mathrm{H}}$ = initial infiltration rate; $i_{f\mathrm{H}}$ = final infiltration rate; k_{H} = decay constant; d_{wf} = depth of the wetting front; *Min* = minimum value; *Max* = maximum value; *CV* = coefficient of variation. For a given parameter, two means in a column followed by the same lowercase letter were not significantly different according to an F test and a two-tailed *t* test at $p = 0.05$. Means followed by a different lowercase letter were significantly different.

According to Wells et al. [51], differences of 0.4 cm in wetting front depths of approximately 2 to 6 cm can be considered small and nearly negligible. Adapting the conclusion by Wells et al. [51] to this investigation, the difference between the two means of d_{wf} obtained by the V and Z operators (Table 2) was significant but negligible in practice, since it was <0.2 cm.

Therefore, differences between the two corresponding means were small and not significant or small and practically negligible. Consequently, the results of the experiment did not depend on the operator, or they differed only marginally. In other words, two different operators repeating the same experiment with exactly the same equipment and applying the same manual packing method yielded results that were consistent with each other.

3.2. Sample Size

Table 3 summarizes the ir_{med}, i_{0H}, i_{fH}, k_H and d_{wf} values obtained by pooling the data by the V and Z operators (N = 90) and it lists the sample sizes, N_r, required to estimate the mean value of each considered parameter within +5%, +10%, +15% and +25% at the 95% confidence level.

Table 3. Statistics of the ir_{med}, i_{0H}, i_{fH}, k_H and d_{wf} values overall obtained by the V and Z operators (sample size, N = 90) and required sample size, N_r, to obtain sample means differing at the most by a fraction, a, from the true mean with a 95% confidence level.

Parameter	Min	Max	Mean	CV (%)	N_r			
					a = 0.05	a = 0.1	a = 0.15	a = 0.25
ir_{med} (mm/h)	68.4	180.6	114.8	20.5	64.6	16.1	7.2	2.6
i_{0H} (mm/h)	342.0	1398.4	713.5	31.4	151.4	37.8	16.8	6.1
i_{fH} (mm/h)	56.0	128.5	83.4	19.6	59.0	14.8	6.6	2.4
k_H (1/h)	21.0	97.1	48.6	32.0	157.7	39.4	17.5	6.3
d_{wf} (cm)	10.5	11.6	10.9	2.5	0.9	0.2	0.1	0.04

ir_{med} = mean infiltration rate; i_{0H} = initial infiltration rate; i_{fH} = final infiltration rate; k_H = decay constant; d_{wf} = depth of the wetting front; *Min* = minimum value; *Max* = maximum value; *CV* = coefficient of variation.

For a given a value, the required number of replicates was minimal, and also very small (<1 regardless of a), for d_{wf}, intermediate for ir_{med} and i_{fH} and largest for i_{0H} and k_H. Therefore, a very limited experimental information was enough to reliably determine the depth of the wetting front. For a given sample size, the mean and the final infiltration rates were generally more reliable than the initial infiltration rate and the decay constant. In other words, the infiltration process was one, but it was easier to characterize this process in terms of ir_{med} and i_{fH} than i_{0H} and i_{fH}. Taking into account that the actual sample size was N = 90, the means of ir_{med}, i_{fH} and d_{wf} reported in Table 3 differed by even less than 5% from the true mean with a 95% confidence level. Instead, the estimates of i_{0H} and k_H differed a little more, that is by 5% to 10%.

This investigation contributed to giving an answer to two different questions. One question was whether a small number of replicates can be used in practice, as is common (Table 1). Another question was if the experiment could be improved to substantially reduce uncertainties of the estimated means for all parameters.

Working with numerically simulated data, Reynolds [52] suggested that an individual estimate of saturated soil hydraulic conductivity is accurate if it differs from the true value by no more than 25%. Reynolds [52] suggested such a stringent accuracy criterion since, in his analysis, the data were free of the perturbations embedded in field and laboratory measurements. If a criterion of this type can be accepted under ideal conditions, it can be even more so with reference to experimental data. Therefore, assuming that a difference of 25% can be considered practically negligible for other soil hydrodynamic parameters and with reference to the mean value of a soil hydrodynamic parameter, this investigation supported the usability of small sample sizes in experiments on repacked soil columns with the MDI. The reason was that N_r = 6 was enough to obtain sample means differing at the most by +25% from the true mean with a 95% confidence level for all considered parameters (Table 3). Therefore, the answer to the first question was that small sample sizes can indeed be used. The uncertainties are larger for the parameters expressive of the transient stage of the infiltration process but practically acceptable.

With reference to the second question, the analysis suggested that 150–160 individual determinations of i_{0H} and k_H should be carried out to obtain an accurate estimate of the mean (i.e., a = 0.05 in Equation (3)). This is likely an impractically large number. Therefore, the answer in this case was that there is a practical limit to the reliability of a given parameter. The reason is that substantially improving the quality of the estimated mean of this parameter would imply an experiment that cannot be carried out in practice.

3.3. Packing Method

Infiltration rates (ir_{med}, $i_{0\mathrm{H}}$ and $i_{f\mathrm{H}}$) decreased monotonically from the P4 to the P1 packing methods (Table 4). The ir_{med} and $i_{f\mathrm{H}}$ values decreased according to the P4 = P3 > P2 > P1 sequence. The largest difference, detected between the P1 and P4 methods, was by a factor of 2.7 for ir_{med} and 2.4 for $i_{f\mathrm{H}}$. The $i_{0\mathrm{H}}$ values differed according to the P4 = P3 > P2 = P1 sequence and the largest difference, also detected between the P1 and P4 methods, was by 1.8 times. Variability was medium in ten of the twelve cases considered (three parameters × four packing methods) and low in the other two cases. The lowest CV values were obtained with the P4 method for ir_{med} and $i_{f\mathrm{H}}$ and with the P2 method for $i_{0\mathrm{H}}$, yielding, however, a very similar result to that obtained with the P4 method. The means of k_H decreased according to the P4 = P1 = P3 > P2 sequence since the only significant difference (Δ = 27.6%) was detected between the P2 and P4 methods. Even in this case, the variability of the data was medium regardless of the packing method, and the lowest CV value was obtained with the P4 method. Finally, d_{wf} decreased according to the P2 > P1 > P3 > P4 sequence. Two means differed by 2.3% to 15.6%, depending on the established comparison. The variability of the data was low for all packing methods and the highest CV value was obtained for the P4 method.

Table 4. Statistics of the ir_{med}, $i_{0\mathrm{H}}$, $i_{f\mathrm{H}}$, k_H and d_{wf} values obtained by four different packing methods (P1, P2, P3, P4).

Parameter	Statistic	Packing Method			
		P1	P2	P3	P4
ir_{med} (mm/h)	Min	31.2	36.4	93.5	104.8
	Max	70.8	113.9	180.6	154.1
	Mean	48.5 a	81.8 b	123.9 c	132.4 c
	CV (%)	27.0	31.2	20.8	9.7
$i_{0\mathrm{H}}$ (mm/h)	Min	277.7	435.7	408.6	556.8
	Max	957.4	856.3	1398.4	1280.2
	Mean	519.9 a	590.9 a	805.1 b	939.5 b
	CV (%)	31.9	21.0	36.5	21.9
$i_{f\mathrm{H}}$ (mm/h)	Min	30.3	33.0	63.9	83.1
	Max	55.1	89.0	128.5	109.8
	Mean	40.9 a	64.4 b	88.4 c	97.8 c
	CV (%)	20.1	30.2	20.9	8.2
k_H (1/h)	Min	28.1	28.9	23.3	36.0
	Max	108.4	76.2	97.1	86.5
	Mean	54.8 ab	52.6 a	53.7 ab	67.1 b
	CV (%)	39.9	24.1	40.6	22.0
d_{wf} (cm)	Min	10.7	11.6	10.5	8.3
	Max	11.4	13.1	11.3	11.0
	Mean	11.1 a	12.0 b	10.9 c	10.4 d
	CV (%)	1.6	3.1	1.8	5.8

ir_{med} = mean infiltration rate; $i_{0\mathrm{H}}$ = initial infiltration rate; $i_{f\mathrm{H}}$ = final infiltration rate; k_H = decay constant; d_{wf} = depth of the wetting front; *Min* = minimum value; *Max* = maximum value; *CV* = coefficient of variation. For a given parameter, the means followed by the same lowercase letter were not significantly different according to an F test and a two-tailed t test at p = 0.05. Means followed by a different lowercase letter were significantly different.

Overall, the effect of the used packing method was noticeable for the infiltration rates and the depth of the wetting front, and it was relatively small with reference to the decay constant of the infiltration model.

As reported by Lewis and Sjöstrom [10], homogeneous packing requires adding soil in very small increments, at least in case of sand [9], but relatively large increments are commonly used [53,54]. According to this investigation, the greater the number of layers, the higher the infiltration rates. This result likely occurred because, as the number of layers increased, the efforts made to compact the soil were overall smaller and more evenly distributed along the soil column. Reducing and distributing these efforts along the vertical axis of the column gave rise to the formation of a more permeable and homogeneous soil sample than that obtained when these efforts were concentrated on a single or a few exposed soil surfaces. In other words, it seems that the infiltration data obtained on a soil column prepared with a multi-layering method tends to be expressive of an infiltration process that occurs in an overall rather homogeneous soil column. Instead, if the soil is poured into the cylinder only once, the upper soil layer is appreciably more compacted than the subsoil, and this circumstance makes the infiltration process slower. In particular, infiltration is mainly controlled by the upper soil layer.

In this investigation, the applied packing procedure did not appreciably influence the decay constant, k_{H}. Therefore, not all parameters that describe the dynamics of the infiltration process show the same sensitivity to the applied packing method. In particular, this sensitivity is appreciable for the parameters expressive of the rate at which infiltration occurs (ir_{med}, $i_{0\mathrm{H}}$, $i_{f\mathrm{H}}$), but it is smaller with reference to the rate at which $i_{0\mathrm{H}}$ approaches $i_{f\mathrm{H}}$.

Using a relatively large number of layers to prepare the soil column appears advantageous for improving reproducibility of the infiltration experiment. This suggestion was based on the fact that the *CV* values for ir_{med}, $i_{0\mathrm{H}}$, $i_{f\mathrm{H}}$ and k_{H} were lowest, or almost so, with the P4 packing method. However, some word of caution is necessary with reference to this finding since *CV* did not decrease monotonically from the P1 to the P4 methods. In other words, other investigations should be performed to verify the suggestion that more layers imply less variability in the data.

It also seems that the larger the number of layers, the smaller the thickness of the wetted soil volume tends to be, although the decrease in d_{wf} from the P1 to P4 methods was not monotonic either. Perhaps this was a consequence of the fact that, with a multi-layering packing method, pores were overall larger, as also suggested by the higher infiltration rates. Filling these pores required relatively large amounts of water. Consequently, there was not enough water to also fill the pores of the deepest zone of the soil column.

To improve the interpretation of packing effects on infiltration, future investigations could also include an accurate characterization of the pore structure in soil samples prepared with different methods. The expectation could be to better understand the link between soil hydrodynamic response and pore system characteristics, including pore volume, size and tortuosity (e.g., [55,56]). Moreover, simple packing devices, such as the one recently developed by Bagarello et al. [57], could be used with a double potential advantage: (i) the dissipated energy to compact the soil could be expressed quantitatively, and (ii) exactly the same experimental method could be applied in different laboratories.

4. Conclusions

This investigation tested factors influencing 1D infiltration experiments with the MDI on columns of a sieved and repacked loam soil. According to this investigation, it appears reasonable to believe that two operators who apply the same manual method to prepare a soil column and perform an experiment with the Mini-Disk Infiltrometer can collect comparable infiltration data.

Obtaining a mean value differing from the true mean by no more than a fixed percentage at a given confidence level requires less replicates of the run for mean and final infiltration rates than for the parameters describing the initial stage of the process. In general, however, a relatively small number of replicated runs is enough to obtain an acceptable description of the entire infiltration process.

With a manual packing method to prepare a soil column, the number of steps in which soil is added from time to time has an appreciable effect on the hydrodynamic response of the tested soil column.

Therefore, an experiment carried out by one or two operators applying a given packing method could be considered replicable in other circumstances. In particular, preparing a soil column in subsequent steps is recommended since this choice seems appropriate for reducing variability of the individual measurements of the infiltration parameters.

This conclusion is valid for this experiment, and therefore it cannot be considered general unless, perhaps, with reference to other loam soils and an infiltration process that excludes the largest pores, i.e., one that only occurs through the soil matrix. The experiment should be repeated with other soils and other established pressure heads at the infiltration surface, with the goal of collecting experimental information that can be used to reach general conclusions. The methodology applied in this investigation, using simple devices and laboratory methods, could easily be extended to other scenarios.

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