J. Hydrol. Hydromech., 72, 2024, 2, 149–157
https://doi.org/10.2478/johh-2024-0001

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

One-dimensional infiltration in a layered soil measured in the laboratory with the mini-disk infiltrometer

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Abstract: Layered soils can consist of a thin little permeable upper layer over a more permeable subsoil. There are not many experimental data on the influence of this upper layer on infiltration. The mini-disk infiltrometer set at a pressure head of –3 cm was used to compare infiltration of nearly 40 mm of water in homogeneous loam and clay soil columns with that in columns made by a thin layer (1 and 3 cm) of clay soil over the loam soil. For each run, the Horton infiltration model was fitted to the data and the soil sorptivity was also estimated by considering the complete infiltration run. For the two layered soils, the estimates of initial infiltration rate and decay constant were similar but a thicker upper layer induced 2.4 times smaller final infiltration rates. Depending on the infiltration parameter and the thickness of the upper layer, the layered soils were characterized by 2.2–6.3 times smaller values than the loam soil and 2.2–6.6 higher values than the clay soil. Sorptivity did not differ between the homogeneous clay soil and the layered soil with a thick upper layer and a thin layer was enough to induce a decrease of this hydrodynamic parameter by 2.5 times as compared with that of the homogeneous loam soil. Even a thin upper layer influences appreciably infiltration and hydrodynamic parameters. Layering effects vary with the thickness of the upper layer and the considered parameter. The applied experimental methodology could be used with other soils and soil combinations.

Keywords: One-dimensional infiltration; Homogeneous soils; Layered soils; Mini-disk infiltrometer.

INTRODUCTION

Infiltration in layered soils, that are frequent in different environments and situations (Wang et al., 2014; Yang et al., 2006), can differ appreciably from infiltration in non-layered soils (Hillel, 1998). A special case of layered soil is when a seal layer is formed at the surface, yielding a less permeable upper layer as compared with the subsoil (Assouline, 2013). The thickness of this upper layer can be very variable but in a rather narrow range since it should not exceed a few centimeters at the most (Armenise et al., 2018; Assouline, 2004). Even such a thin layer can have a large impact on the hydrological response of a field or a watershed (Assouline and Mualem, 2002, 2006). According to some investigations, when the soil is layered and the upper layer is the less permeable, water infiltration should be more representative of the upper layer (Bagarello et al., 2023; da Silva Ribas et al., 2021; Lassabatere et al., 2010; Yilmaz et al., 2013). To our knowledge, however, there are not many experimental investigations on the actual correspondence between homogeneous and layered soils (Di Prima et al., 2018). Testing the similarity between these two kinds of soils is advisable to improve our ability to interpret soil hydrologic processes and also in the perspective to use the infiltration data for estimating soil hydrodynamic properties (Assouline and Mualem, 2002; Moret-Fernández et al., 2021).

These experiments should preferably be performed on layered soils with thin or relatively thin little permeable upper layers given that, with large thicknesses, a similarity between the homogeneous and layered soils is expected more since infiltration occurs in porous media with similar characteristics for relatively long times. Performing these checks with as simple as possible experimental methods is advisable to make the experiment easily reproducible and also considering that the experiment is inherently complex even if a single layered soil is considered. The reason is that replicated experiments have to be performed on soil columns made with this layered soil but also with each of the two homogeneous soils that are combined with each other to form the layered porous medium. An infiltration model, such as that by Horton (1940), could be fitted to the data to characterize a run by a limited number of relevant parameters.

Performing laboratory infiltration experiments on layered soil columns made with sieved and repacked soil is rather common for a variety of purposes such as improving knowledge of the process in particular situations (Wang et al., 2014), establishing if the data allow to recognize the presence of layering (Moret-Fernández et al., 2021), testing predictive infiltration models for these non-homogeneous porous media (Chen et al., 2019; Mohammadzadeh-Habili and Heidarpour, 2015; Moore and Eigel, 1981). Investigations differ by several factors, depending on their specific objectives. For example, simulated rainfall was used in some cases (Yang et al., 2006) whereas a ponded depth of water was established on the infiltration surface in other cases (Wang et al., 2014). The total length of the soil column and the thickness of the tested soil layers also change, even if investigations considering layers of at least a few tens of centimeters seem to be more frequent. For example, total length was 21 cm (Al-Maktoumi et al., 2015), 100 cm (Yang et al., 2006) or 300 cm (Ma et al., 2011). The columns by Yang et al. (2006) were made of 60–65 cm of an upper layer over 35–40 cm of a subsoil. The experiment by Ma et al. (2011) was performed on a soil column filled with five layers of 120, 20, 30, 30 and 120 cm. A 20 cm thick upper layer over a 40 cm thick subsoil was considered by Chen and Hsu (2012). The columns by Wang et al. (2014) and Chen et al. (2019) were made by layers of 22.5–25, 20 and 20–22.5 cm. In the experiment by Batsilas et al. (2023), the height of the upper and lower layers was 45 and 48 cm, respectively. However, experiments with thinner upper layers have also been performed. For example, Young et al. (2002) considered a two layered soil made of 7.5 cm thick layers. In the experiment by Al-Maktoumi et al. (2015), 15 cm of a soil were overlaid with 6 cm of another soil.

A rather simple and cheap method to obtain infiltration data in layered soils with thin little permeable upper layers is performing one-dimensional (1D) experiments with the mini-disk infiltrometer (MDI) on relatively small soil columns, that is on the order of 20–25 cm in length by 5 cm in diameter. With the MDI, a negative but close to zero pressure head is established on the soil surface. The infiltration data are therefore representative of a nearly saturated soil matrix (Assouline and Narkis, 2011). The device has already been used in the laboratory to perform different 1D experiments on repacked soil, such as those testing the effects of treated wastewater on the hydraulic properties of a clayey soil (Assouline and Narkis, 2011) or performing comparisons with three-dimensional infiltration (Kargas et al., 2018).

The general objective of this investigation was to determine the impact of soil layering on one-dimensional infiltration processes established with the mini-disk infiltrometer. The specific objectives were to i) compare infiltration in homogeneous loam and clay soil columns with that measured in columns made by a thin layer of clay soil over the loam soil; ii) test the effect of the thickness of the upper clay soil on infiltration in a rather narrow range of small thickness values; and iii) establish layering effects on the fitted parameters of a three-parameter infiltration model and also on the estimated soil sorptivity.

MATERIALS AND METHODS

Experiment

The infiltration experiment was carried out with two soils differing by texture collected in Sicily (Italy). In particular, a site was the orchard of the Department of Agricultural, Food and Forest Sciences of the Palermo University (38°06’24’’ N, 13°21’06’’ E). The other site was the experimental station for soil erosion measurement Sparacia (37°38’46’’ N, 13°45’43’’ E), located approximately 100 km south of Palermo. The soil at the Palermo site (Typic Rhodoxeralf) has a relatively high gravel content and it is mostly sandy-loam or loam down to a depth of at least 0.30 m. For this investigation, the soil was collected in an area where the texture was loam (clay = 15.4%, silt = 36.2%, sand = 48.4%; USDA classification system) (Agosta et al., 2023). The soil of Sparacia (Vertic Xerocrept) has a clay texture (clay = 62% silt = 33%, sand = 5%) and a negligible gravel content (Pampalone et al., 2022).

The soil collected from approximately the upper 10 cm of the profile (nearly 100 kg for each soil) was transported to the laboratory and it was spread on plastic sheets for natural drying at room temperature. This process lasted about 40 days, during which the soil was shuffled every 2–3 days to facilitate drying. Once the condition of air-dry soil was reached, the soil was sieved through a 2 mm mesh sieve and the fine fraction was retained for the experiment.

Soil columns were prepared in 25 cm long plexiglass cylinders having an inner diameter of 5.3 cm, equipped with a nylon guard cloth and a thin wire mesh at the base to support the weight of the soil. A total of 36 soil columns were used in this experiments. In particular, nine columns were prepared with the homogeneous loam soil (AO soil) and nine columns were prepared with the homogeneous clay soil (SO). The final length of these soil columns was 20 cm. A layered soil with a little permeable upper layer and a more permeable subsoil was prepared using these fine clay and coarser loam soils. In particular, nine columns were composed of 1 cm of clay soil over 20 cm of the loam soil (L1 soil). The other nine columns were prepared by placing 3 cm of clay soil on 20 cm of the loam soil (L3 soil). Each soil column was prepared with a soil mass that was never used before.

The so-called P3 packing method by Bagarello et al. (2022) was used to prepare the homogeneous soil columns and also the subsoil layer of the layered soil columns. This packing method is based on the partition of the air-dry soil mass used to fill the cylinder into three equal parts. One third is poured in the cylinder and the soil is compacted manually by a wood pestle that is pressed downward repeatedly. After concluding pressing, the pestle is rotated clockwise and counter-clockwise around its vertical axis for a few times. The second part is then added and the same compaction procedure is applied again. Finally, the last part of soil is poured and compacted. In this investigation, all interfaces in packing were gently scarified after compaction and before adding another increment to improve the hydraulic contact between the layers (Wang et al., 2014).

The AO soil columns were packed in order to obtain a nearly constant dry soil bulk density, ρ_b, equal to 1.18 g/cm^3. For each step of the packing procedure, 179 g of air-dry soil were poured into the cylinder and this soil was pressed 30 times. Therefore, a total of 537 g of air-dry soil was used. The final length of the soil column and the number of compactions for each layer did not change for the homogeneous SO soil columns. In this case, a total of 600 g of air-dry soil was used and the ρ_b value was equal to 1.25 g/cm^3. With reference to the layered soils, an established amount of air-dry clay soil (nearly 30 g for the L1 soil and 90 g for the L3 soil) was placed on the top of the sample and it was pressed with the pestle 10 times to obtain for these upper layers the same dry soil bulk density of the homogeneous SO soil columns (1.25 g/cm^3).

A direct measurement of ρ_b was not available since the soil used to fill the cylinder was air-dry. Therefore, ρ_b was determined by the following relationship (Bagarello et al., 2022):

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

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 on six samples during the experiment. The volumetric air-dry soil water content, obtained by ρ_b and w_{ad}, was equal to 0.05 m^3/m^3 for the loam soil and 0.12 m^3/m^3 for the clay soil.

A mini-disk infiltrometer, MDI (manufactured by Decagon Devices, Pullman, WA, USA, Infiltrometer User's Manual, Decagon Devices Inc., 2014), was used to measure infiltration. For each infiltration run, the MDI was filled with tap water at room temperature. A pressure head equal to –3 cm was established at the base of the device. A slightly negative pressure head was used in this investigation to avoid flow along possible large voids resulting from packing or at the contact between the soil and the wall of the column (Assouline and Narkis, 2011). Before each 1D 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 (95 mL for the A0, L1 and L3 soil runs and 90 mL for the SO soil runs, with differences related to the used device). For the SO soil, the run lasted long and infiltrated water volumes were measured every 5 min after the first 4 hours of infiltration. 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.

Data analysis

A check of the laboratory data was first performed by visually examining the I vs. t curves to verify if they were initially concave and then smoothly described a linear relationship, as expected (Pachepsky and Karahan, 2022).

The mean infiltration rate, ir_{med} (mm/h), was then calculated for each run. In addition, the empirical Horton (1940) 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 (Lassabatere et al., 2006):

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

where i_{0H} (mm/h) is the initial infiltration rate (t = 0), i_{fH} (mm/h) is the final infiltration rate and the constant k_H (1/h) describes the rate at which i_{0H} approaches i_{fH}. For given i_{0H} and i_{fH} values, the smaller k_H the more gradual the transition from the initial to the final conditions (Tindall et al., 1999). The quality of the fitting was evaluated by the relative error, Er (%), in agreement with Lassabatere et al. (2006). The model by Horton was chosen since it describes the infiltration curve by three different parameters expressive of the initial and the final stages of the process and also of the transition between these two stages. Another reason was that this model gave a good representation of the experimentally determined I v. t relationships in other investigations (Agosta et al., 2023; Iovino et al., 2021; Shukla et al., 2003).

According to Ndiaye et al. (2005), infiltration measured by a one-dimensional tension infiltrometer experiment can be used to estimate the sorptivity, S (mm/h$^{0.5}$), and the soil hydraulic conductivity, K (mm/h), corresponding to the imposed pressure head at the soil surface. In particular, the two-term infiltration equation (Philip, 1957) is fitted to the data to obtain S and the A (mm/h) parameter:

$$I = St^{0.5} + At \quad (3)$$

Hydraulic conductivity is then calculated from A. For each infiltration run, S and A were also estimated by fitting a quadratic equation with a null constant coefficient to the (I, $t^{0.5}$) data (Minasny and McBratney, 2000). Each soil column was characterized by a value of S but not of K. The reason was that S was directly obtained by fitting Eq. (3) to the data collected during the entire duration of the run. Therefore, the estimates of S were usable to detect differences between the two homogeneous soils and also to verify how layering influenced the sorptivity estimates. Calculation of K was not performed for a twofold reason: i) the procedure by Ndiaye et al. (2005) is based on the infiltration model by Haverkamp et al. (1994) that is valid for homogeneous soils and hence is not usable for layered soils; ii) even considering, perhaps forcedly, a sort of equivalent conductivity for the layered soil, calculating K was not possible since these calculations require an estimate of the so-called β parameter that, according to recent investigations on three-dimensional infiltration, is soil-dependent (Yilmaz et al., 2023). This circumstance precluded defining a single β value for a soil column made by two texturally different layers.

A comparison was then performed between the AO, SO, L1 and L3 soils. Initially, all the experimental infiltration rate, ir (mm/h) vs. I and I vs. t relationships for these soils were reported on a single ir vs. I plot and a single I vs. t plot and they were visually examined to recognize clear differences among the four soils. The ir vs. I plot was considered, also according to other investigations (Morin and Benyamini, 1977), since durations changed from run to run, making representation of all data on a single ir vs. t plot confuse. Then, a statistical comparison between the infiltration (ir_{med}, i_{0H}, i_{fH}, k_H) and hydrodynamic (S) parameters for the four soils was carried out. A pairwise approach was applied to compare two datasets at a time. In particular, F and unpaired, two-tailed t tests were used. The statistical tests were carried out at P = 0.05.

RESULTS

Generally, the experimental infiltration processes appeared consistent with theory since the concavity of the I vs. t curves was faced downwards, denoting that the infiltration rates initially decreased during the run, and the I vs. t relationship assumed a nearly linear shape at longer times (Fig. 1).

However, some curves obtained in the SO soil exhibited a change in slope in an advanced stage of the run. In particular, they appeared to become flatter, denoting smaller infiltration rates. This shape was relatively similar to one of the possible shapes of cumulative infiltration curves recently described by Pachepsky and Karahan (2022), and particularly to the shape shown in their figure 2J. A possible reason why this shape was detected was that the initially air-dry clay soil swelled during wetting, which lasted several hours (on average, 5.85 h), and the consequence was a decrease of the volume of the largest pores (Kalnin et al., 2021) and hence of infiltration rates. According to Lassabatere et al. (2006), a relative error, Er, that does not exceed 5.5% denotes an acceptable fitting of an infiltration model to the data. With reference to the SO soil, adapting the Horton model to the complete infiltration curves yielded a mean value of Er equal to 4.4% and the threshold of 5.5% was exceeded in a single case (Er = 6.6%; Table 1). Therefore, this check, suggesting that the fitting of the model to the complete infiltration curve was overall satisfactory, did not raise any particular concern regarding the possibility to consider the entire infiltration curve for estimating the infiltration parameters.

In order to make comparison between homogeneous and layered soils easier to follow, all infiltration rates (AO, SO, L1, L3 soils) were reported on a single ir vs. I plot (Fig. 2a) but the data were also presented by showing the two homogeneous soils and only one of the two layered soils (Figs. 2b and 2c). The homogeneous AO and SO soils were characterized by the highest and the lowest infiltration rates, respectively, whereas the two layered soils showed intermediate ir values, that were generally higher for the L1 soil than the L3 soil. Notwithstanding some data scattering, that was not surprising (e.g., Wang et al., 2014; Xiao et al., 2019), no contact points were recognized between the two homogeneous soils on the ir vs. I plot.

At the beginning of the process, a certain overlap between the infiltration rate curves for the homogeneous SO soil and some curves for the layered soils was evident. This overlap appeared more complete and persisted longer in the case of the L3 soil than for the L1 soil, as logical. In a later stage of the experiment, the difference between the two layered soils became clearer, with the L1 soil yielding higher ir values than the L3 soil. As the applied water volume increased, the infiltration rates of the AO and L1 soils tended to become more similar and the infiltration rates of the SO and L3 soils tended to become more dissimilar on the representation of Fig. 2. The AO vs. L1 soils similarity appeared to be a consequence of decreasing infiltration rates for the former soil and stabilized rates for the latter one. Even the increasing deviation between the SO and L3 soils occurred because infiltration rates for the former soil decreased while those of the latter soil stabilized. Therefore, infiltration rates stabilized after applying a relatively small water volume in the layered soils but not in the homogeneous soils.

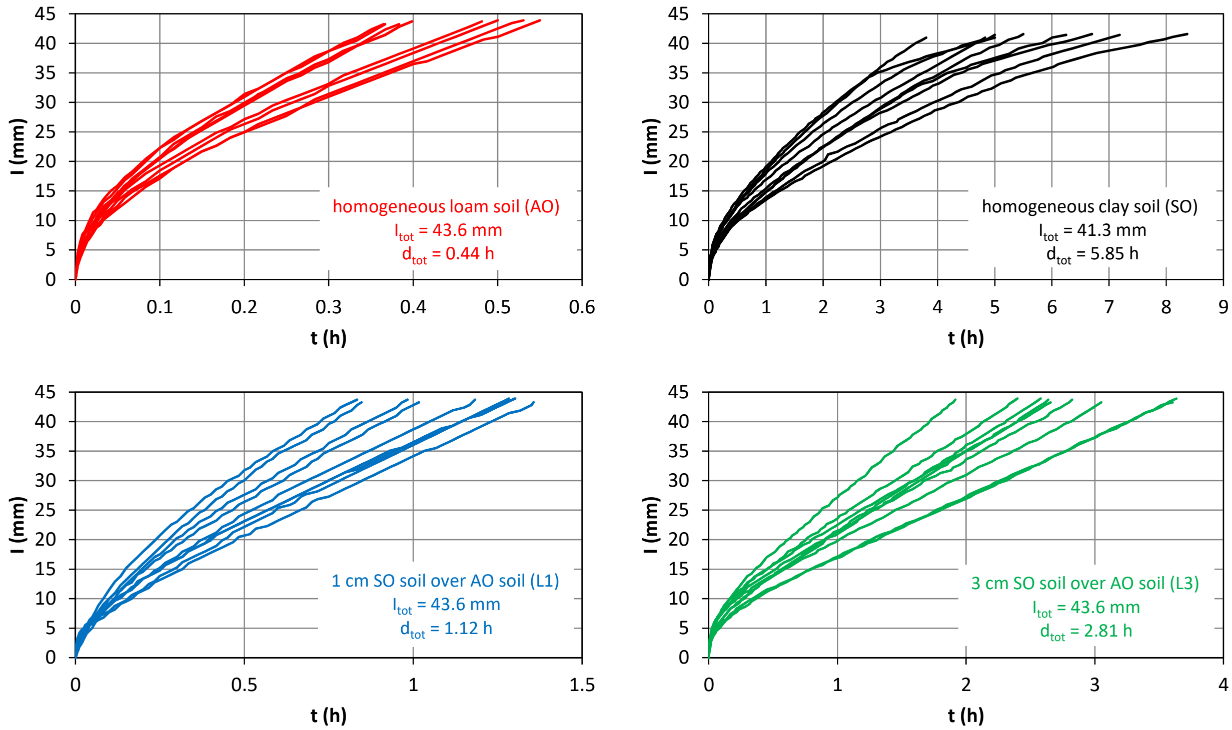

Fig. 1. Cumulative infiltration curves obtained in the four tested soils (I = cumulative infiltration; t = time; the mean values of the cumulative infiltration by the end of the run, I_{tot}, and of the total duration of the run, d_{tot}, are reported for each soil).

Table 1. Summary statistics of the mean infiltration rate, ir_{med}, the infiltration parameters of the Horton model (i_{0H} = initial infiltration rate; i_{fH} = final infiltration rate; k_H = decay constant; Er = relative error) and the soil sorptivity, S (sample size, N = 9 for each soil and parameter with the exception of S for the AO soil for which N was equal to 8).

Parameter	Statistic	SO soil	AO soil	L1 soil	L3 soil
ir_{med} (mm/h)	min	4.97	79.8	31.9	12.0
	max	10.8	118.5	52.5	22.8
	mean	7.43 (a)(c)(e)	101.1 (a)(d)(f)	40.1 (b)(c)(d)	16.1 (b)(e)(f)
	CV (%)	23.6	15.4	19.5	20.6
i_{0H} (mm/h)	min	28.8	476.3	116.6	105.9
	max	72.5	933.0	232.7	261.9
	mean	42.9 (a)(c)(e)	671.5 (a)(d)(f)	166.6 b(c)(d)	171.5 b(e)(f)
	CV (%)	32.8	21.1	22.0	31.7
i_{fH} (mm/h)	min	3.87	59.8	27.2	10.3
	max	8.48	85.1	38.7	18.6
	mean	5.59 (a)(c)(e)	73.4 (a)(d)(f)	31.8 (b)(c)(d)	13.3 (b)(e)(f)
	CV (%)	24.7	14.0	14.4	19.7
k_H (1/h)	min	1.77	34.1	7.24	14.0
	max	6.15	62.9	32.4	31.5
	mean	3.12 (a)(c)(e)	46.1 (a)(d)(f)	16.1 b(c)(d)	20.7 b(e)(f)
	CV (%)	45.9	20.9	51.3	29.6
Er (%)	min	2.36	2.53	0.88	1.25
	max	6.57	3.39	2.85	2.33
	mean	4.40 (a)(c)(e)	3.05 (a)(d)(f)	2.03 b(c)(d)	1.75 b(e)(f)
	CV (%)	27.4	10.2	29.7	22.2
S ($mm/h^{0.5}$)	min	12.8	50.5	18.3	12.0
	max	18.4	69.2	31.5	19.7
	mean	15.0 (a)(c)e	59.8 (a)(d)(f)	23.8 (b)(c)(d)	15.9 (b)e(f)
	CV (%)	13.6	9.7	15.9	19.0

For a given parameter, two means followed by the same letter not enclosed in parenthesis were not significantly different according to an F test and a two-tailed t test at P = 0.05. Means followed by the same letter enclosed in parenthesis are significantly different.

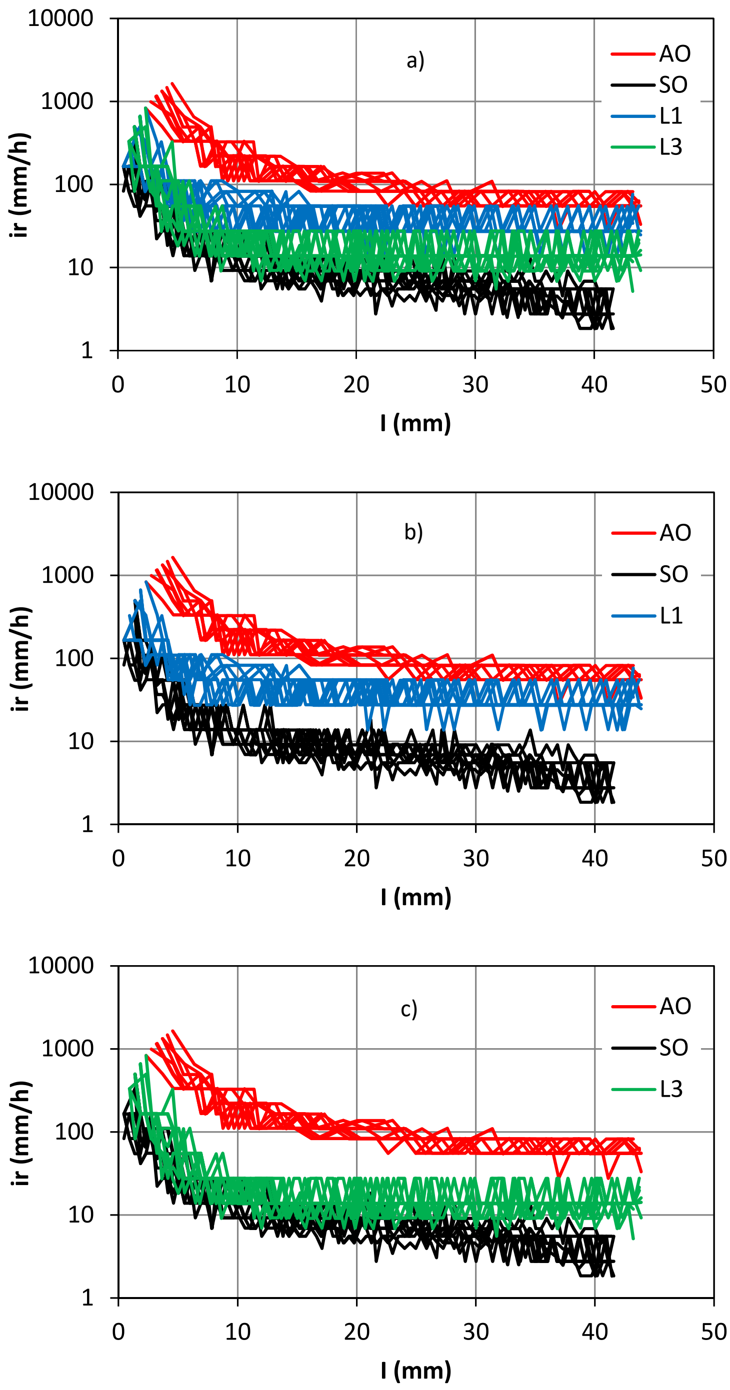

Fig. 2. Infiltration rate, *ir*, vs. cumulative infiltration, *I*, relationships for a) the four tested soils (AO: homogeneous loam soil; SO: homogeneous clay soil; L1: 1 cm of SO soil over the AO soil; L3: 3 cm of SO soil over the AO soil), b) the two homogeneous soils and the L1 layered soil, and c) the two homogeneous soils and the L3 layered soil.

On the *I* vs. *t* plot, the results for the two homogeneous soils defined an empty space that was filled by the data for the two layered soils (Fig. 3). The data of the L1 soil were closer to those of the homogeneous loam soil. The data of the L3 soil were closer to those of the homogenous clay soil.

The statistical analysis of the data indicated that the mean infiltration rates, ir_{med}, varied according to the AO > L1 > L3 > SO sequence (Table 1). The two homogeneous soils differed by more than an order of magnitude, that is by 13.6 times. Instead, the two layered soils differed by 2.5 times. The L1 soil yielded a 5.4 times higher ir_{med} value than the SO soil and a 2.5 times smaller value than the AO soil. The ir_{med} value of the L3 soil was 2.2 times greater than that obtained with the SO soil and 6.3 times smaller than the corresponding value for the AO soil. Therefore, with reference to ir_{med}, the four soils differed significantly from each other and the layered soils were characterized by intermediate values as compared with those of the two homogeneous soils that were combined one with the

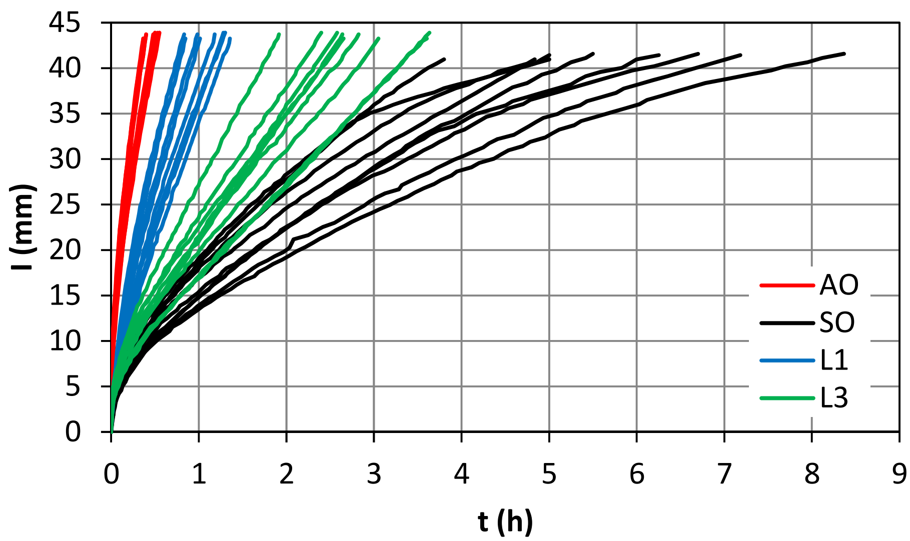

Fig. 3. Cumulative infiltration curves for the four tested soils (I = cumulative infiltration, t = time) for the AO (homogeneous loam soil), SO (homogeneous clay soil), L1 (1 cm of SO soil over the AO soil) and L3 (3 cm of SO soil over the AO soil) soils.

other to form the layered system. The L1 soil was more similar to the AO soil than to the SO soil. Instead, the L3 soil was more similar to the SO soil than to the AO soil.

The initial infiltration rates, i_{0H}, varied according to the AO > L3 = L1 > SO sequence (Table 1). The two homogeneous soils differed by more than an order of magnitude, that is by 15.7 times. Instead, the two layered soils were characterized by statistically similar values that only differed by 1.03 times. The L1 soil yielded a 3.9 times higher i_{0H} value than the SO soil and a 4.0 times smaller value than the AO soil. The i_{0H} value of the L3 soil was 4.0 times greater than that obtained with the SO soil and 3.9 times smaller than the corresponding value for the AO soil. Therefore, with reference to i_{0H}, the two homogeneous soils differed significantly from each other and also from the two layered soils. The results of these last two soils were similar to each other and nearly exactly intermediate as compared with those of the two homogeneous soils. In this case, the thickness of the little permeable upper layer did not have any impact on the comparison between the layered and the homogeneous soils.

The final infiltration rates, i_{fH}, varied according to the AO > L1 > L3 > SO sequence. The two homogeneous soils differed by 13.1 times while the two layered soils differed by 2.4 times. The L1 soil yielded a 5.7 times higher i_{fH} value than the SO soil and a 2.3 times smaller value than the AO soil. The i_{fH} value of the L3 soil was 2.4 times greater than that obtained with the SO soil and 5.5 times smaller than the corresponding value for the AO soil. Therefore, even with reference to i_{fH}, the four soils differed significantly from each other and the results for the layered soils were intermediate as compared with those of the two homogeneous soils. The L1 soil was more similar to the AO soil than to the SO soil. Instead, the L3 soil was more similar to the SO soil than to the AO soil. In both cases, more similar meant that means differed by 2.3–2.4 times instead of 5.5–5.7 times.

The decay constant, k_H, decreased according to the AO > L3 = L1 > SO sequence. The two homogeneous soils differed by 14.8 times while the two layered soils differed by 1.3 times. The L1 soil yielded a 5.2 times higher k_H value than the SO soil and a 2.9 times smaller value than the AO soil. The k_H value of the L3 soil was 6.6 times greater than that obtained with the SO soil and 2.2 times smaller than the corresponding value for the AO soil. Therefore, with reference to k_H, the two homogeneous soils differed significantly from each other and also from the two layered soils. However, the results for these last two soils were similar. Regardless of the thickness of the upper layer, the k_H values of the layered soils were closer to those of the AO soil (differences by 2.2–2.9 times) than to the k_H values of the SO soil (differences by 5.2–6.6 times).

The fitting error of the Horton model to the data, Er, varied according to the SO > AR > L1 = L3 sequence. Therefore, the quality of the fitting was better for the layered soils than the homogeneous ones but it was satisfactory in general since the means did never exceed the threshold of 5.5% and this threshold was exceeded for only one of the 36 infiltration runs.

Finally, an estimate of soil sorptivity, S, was obtained for 35 of the 36 infiltration runs (Table 1). The single failure occurred for a run with the AO soil that gave a negative estimate of A. The estimates of S obtained in the homogeneous soil columns (coefficient of variation, CV = 9.7 – 13.6%) were a little less variable than those obtained in the layered soil columns (CV = 15.9 – 19.0%). The statistical analysis of the data indicated that S varied according to the AO > L1 > L3 > SO sequence. Sorptivity differed by 4.0 times between the two homogeneous soils and by 1.5 times between the two layered soils. The L1 soil was closer to the SO soil than the AO one since the layered soil had a 1.6 times higher S value than the SO soil and a 2.5 times smaller value than the AO soil. The S value of the L3 soil was 3.8 times smaller than that obtained with the AO soil and it was statistically equal to the sorptivity determined for the SO soil. In particular, the two estimates of S differed by 6.3% in this last case. Therefore, with reference to S, the two homogeneous soils differed significantly. The L1 soil differed significantly from the two homogeneous soils but it was more similar to the SO soil than the AO soil. The L3 soil was significantly less sorptive than the AO soil but it had the same sorptivity as the SO soil.

DISCUSSION

Infiltration in a layered soil can be qualitatively similar to that of non-layered soils since infiltration rates decrease with time and then tend to stabilize (Bagarello et al., 2023; Wu et al., 1997). However, infiltration in a layered soil with a less permeable upper layer is expected to be more representative of the upper layer (da Silva Ribas et al., 2021; Lassabatere et al., 2010). This investigation contributed to better establish what is meant in practice when one speaks of an infiltration curve being more representative of the upper layer in a context of qualitative similarity of infiltration rate curves for homogeneous and layered soils.

In particular, the investigation tested soil layering effects on one-dimensional infiltration when the upper soil layer is relatively thin and has a finer texture than the subsoil. The check performed in this study was strictly valid for i) a layered soil in which the infiltration parameters of the upper layer, 1 to 3 cm thick, were a little more than an order of magnitude smaller than those of the subsoil (by 13.1–15.7 times, depending on the parameter), ii) a 1D infiltration process under a negative but close to zero pressure head (–3 cm), and iii) an experiment performed by supplying nearly the same total amount of water to each sampled soil column (41.3–43.6 mm), that is infiltration runs having a different duration depending on the sampled porous medium.

The data suggested that, at the beginning of the process, the layered soils actually show some similarity with the homogeneous clay soil, the more clearly the thicker this upper layer (Fig. 2). The presence of a loam subsoil then determines higher infiltration rates for the layered soil than the homogeneous clay soil, the sooner and the more appreciably the thinner the upper layer. Moreover, infiltration rates appear to stabilize earlier in the layered soils than in the homogeneous ones, in accordance with other findings (Wang et al., 2014).

Therefore, with reference to this specific experiment, the similarity between the homogeneous and the layered soils (da Silva Ribas et al., 2021; Lassabetere et al., 2010) appears to depend on the thickness of the upper layer, being more appreciable with thick upper layers, and also on the characteristics of the infiltration run, being stronger for relatively small applied water volumes. In any case, even an upper layer of only 1 cm determines an appreciable slowdown of the process as compared with that occurring in the homogeneous loam soil (Fig. 2). According to the data of this investigation (Figs. 1 and 3), in this case the total water volume supplied with the MDI will take 2.5 times longer to infiltrate completely. With an upper layer of 3 cm, it will take 6.4 times longer for its full infiltration to occur as compared with the homogeneous loam soil. These slowdowns will effectively make the infiltration process more and more similar to that occurring in the homogeneous clay soil (Lassabatere et al., 2010).

The investigation also allowed to establish the impact of the detected differences between the tested soils in terms of the three fitted parameters of the Horton infiltration model, that summarize the entire infiltration process, and of the estimated soil sorptivity (Table 1). In particular, two layered soils differing by the thickness of the upper layer can be expected not to differ by the estimated values of both the initial infiltration rate and the decay constant. The presence of a thicker layer at the soil surface is only signalled by a lower final infiltration rate. Regardless of the thickness of the upper layer, each infiltration parameter for the layered soil will be smaller than that obtained in the homogeneous coarser soil and higher than the one for the homogeneous fine soil. Soil sorptivity of the layered soil can be expected to be similar or also statistically identical to that of the homogeneous fine soil, depending on the thickness of the upper layer, even if the used data for estimating S are not limited to the early stage of the infiltration process (Minasny and McBratney, 2000).

To summarize, a relatively thick upper layer determines an equality between the layered and the fine homogeneous soils limited to sorptivity. Some parameters (ir_{med}, i_{fH}) are closer to the fine soil than the coarse one. Other parameters (i_{0H}) are intermediate between the two homogeneous soils. Still other parameters (k_H) are closer to the coarse soil than the fine one. The thinning of the upper layer maintains a greater similarity between layered and fine soils only with reference to sorptivity.

Evidently, trying to obtain general conclusions requires testing soil layering effects by considering different soils, initial soil water conditions and established pressure heads and, hence, water conducting pore sizes (Reynolds et al., 1995). A way to obtain an extensive information without necessarily performing extremely long and demanding laboratory experiments could consist of using numerical simulation of the processes of interest (e.g., Dohnal et al., 2016). Infiltration experiments performed in the laboratory on homogeneous soil columns could be used to derive the hydraulic parameters of the tested soils necessary for the simulations (Wang et al., 2014). In addition, some of the numerically considered scenarios for a layered soil system could be reproduced experimentally to also establish a comparison between numerical and experimental results. However, a homogeneous soil column and the upper layer of a layered soil column differ by their length and they have likely to be prepared with packing methods that differ to some extent. Packing method effects on the soil sample characteristics are expected (Bagarello et al., 2022; Lewis and Sjöstrom, 2010; Nimmo and Akstin, 1988; Oliviera et al., 1996). For example, a relatively long soil column could be less uniform than a relatively thin layer of the same soil since the soil compacting force decays gradually from the top to the base of any layer (Gao et al., 2018). Therefore, before performing extensive numerical simulations with laboratory determined soil hydraulic functions, it seems advisable to verify if the hydraulic functions obtained experimentally in a column of a homogeneous fine-textured soil are representative for the upper layer of a layered soil.

CONCLUSIONS

In this investigation, a MDI set at –3 cm and columns of sieved and repacked soil were used in the laboratory to measure one-dimensional infiltration in a layered soil with a clay upper layer and a loam subsoil.

Even a thin layer of a little permeable soil at the surface should be expected to appreciably increase the time required by a given water volume to infiltrate. In the early stages of the process, some overlap can actually be detected between infiltration rates in the layered and the homogeneous clay soils but not between the layered and the homogeneous loam soils, regardless of the thickness of the upper layer. The presence of a coarser subsoil makes the infiltration process in the layered soil more rapid than that of the homogeneous fine soil. Two layered soils differing by the thickness of the upper layer can be expected not to differ by both the initial infiltration rate and the decay constant of the Horton infiltration model. Instead, the presence of a thicker layer at the soil surface is signalled by a lower final infiltration rate. Regardless of the thickness of the upper layer, the layered soil is expected to yield smaller infiltration parameters as compared with the homogeneous coarser soil and higher as compared with the homogeneous finer soil. If the upper layer is relatively thick, the sorptivity of the layered soil estimated by considering the complete infiltration run can be expected to coincide with that of the homogeneous fine-textured soil.

A single investigation is incompatible with any general conclusion but it can be viewed as a step towards developments of an extensive experimental information that will make general conclusions possible. Other experiments should be carried out, by also considering soils that differ more from each other as compared with those of this investigation, different pressure heads established at the infiltration surface, and also including small positive pressure heads. The same experimental setup used in this investigation could be used to perform most of these additional experiments since combining the MDI with relatively small soil columns guarantees a certain cost-effectiveness of the experiment. Methodological improvements can be suggested, such as i) automatically recording the infiltration data, that could reduce the experimental efforts and the noise in the data, and ii) monitoring wetting front advancement during the run and soil water pressure head at different depths of the column, that could make physical interpretation of the process easier and stronger. The experimental data could be used to numerically simulate infiltration and also to establish comparisons between numerical and laboratory experiments.

Funding. This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

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Received 11 September 2023
Accepted 19 January 2024