CHEMICAL ENGINEERING TRANSACTIONS
VOL. 58, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Remigio Berruto, Pietro Catania, Mariangela Vallone

ISBN 978-88-95608-52-5; **ISSN** 2283-9216

DOI: 10.3303/CET1758121

Height of Water Pouring Effects on Infiltration Runs Carried Out in an Initially Wet Sandy-loam Soil

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Ring infiltration methods are widely used for field soil hydraulic characterization. Establishing factors affecting these methods is necessary to interpret the collected data. The height from which water is poured on the soil surface is known to influence infiltration in a sandy-loam soil, since low (L, height of water pouring 0.03 m) runs yielded higher infiltration rates than high (H, 1.5 m) runs in previous investigations. The impact of water pouring height on infiltration rates seems to vary with the antecedent soil water content, θ_i. In this investigation, height effects on infiltration were tested for an initially very wet sandy-loam soil. Two-stage infiltration runs differing by the height of water pouring in the second stage of the run (L1L2 and L1H2 runs) were carried out. With the L1L2 runs, the final infiltration rate and the duration of the second stage were 2.2 times lower and longer, respectively, than the corresponding values of the first stage. With the L1H2 runs, the corresponding factors of difference were 5.5 and 4.5, respectively. Therefore, the perturbation due to a high height of water pouring was also detectable in initially wet soil conditions. Disturbance due to a high height of pouring was reduced in more compact soil conditions. In conclusion, the low-high infiltration run methodology seems usable in general to detect the effects of the water application procedure on infiltration. The dry soil bulk density appears useful to predict disturbance effects caused by the infiltration run.

1. Introduction

Interpreting and simulating hydrological processes need considering that the soil is not rigid. For this reason, the physical and hydraulic characteristics of the soil surface can differ, even greatly, from those of the deeper layers since only the surface soil is directly impacted by rainfall (Assouline, 2004). Measurements of soil hydraulic properties have to be consistent with the hydrological process of interest and therefore depth dependent soil data should be collected to predict infiltration and runoff (Assouline and Mualem, 2006, 2002).
Measuring soil hydraulic properties directly in the field assure functional connection between the sampled soil volume and the surrounding soil (Bouma, 1982). Single-ring infiltration methods are widely applied for hydraulic characterization of saturated soil in the field (e.g., Bagarello and Iovino, 1999; Lassabatere et al., 2006; Reynolds et al., 2000; Vauclin et al., 1994). Knowing what factors affect soil hydraulic properties determined with a particular ring method should allow to apply appropriate experimental methodologies in relation to the intended use of the data (e.g., Reynolds et al., 2000; Verbist et al., 2013).
According to some recent investigations on the BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization (Lassabatere et al., 2006), the height from which water is poured on the soil surface can influence appreciably the measured infiltration rates and hence determination of saturated soil hydraulic conductivity, K_s, since low runs (i.e., small height of water pouring) can yield even an order of magnitude higher values than high runs (Alagna et al., 2016; Bagarello et al., 2014).
According to Alagna et al. (2016), the impact of water pouring height on the K_s values of a sandy-loam soil decreases as the initial, or antecedent, soil water content increases. However, this conclusion was drawn by considering a relatively dry range of soil moistures. Therefore, additional tests should be carried out under

Please cite this article as: Bagarello V., Cecere N., Di Prima S., Giordano G., Iovino M., 2017, Height of water pouring effects on infiltration runs carried out in an initially wet sandy-loam soil, Chemical Engineering Transactions, 58, 721-726 DOI: 10.3303/CET1758121

initially high soil water content conditions since the interest for the low-high run methodology also depends on the knowledge of what happens in wet or very wet soil.
The general objective of this investigation was to improve assessment of antecedent soil water content effects on infiltration runs carried out with two heights of water pouring. At this aim, height effects on the measured infiltration were checked for an initially pre-wetted sandy-loam soil. An additional objective was to establish if soil physical properties allow to explain height effects.

2. Materials and methods

The field experiment was carried out at the so-called AR site, that was established at the Dipartimento Scienze Agrarie, Alimentari e Forestali of the Palermo (Italy) University. An approximately 100 m^2 flat area of a citrus orchard, with trees spaced 4 m × 4 m apart, was selected. The soil texture of the upper part of the profile, 0.1 m thick, was sandy-loam according to the USDA classification (Alagna et al., 2016).
Field infiltration experiments of the beerkan type (Lassabatere et al., 2006) were carried out on selected dates during the period 24 March to 12 May 2015. The main characteristics of these experiments were: i) insertion of 0.08-m-diam. rings to a depth of 0.01 m; ii) filling of 15 plastic glasses with 57 mL of water for each glass; iii) infiltration runs carried out by successively pouring the water contained in a glass on the confined infiltration surface. In particular, a given volume of water was poured in the ring in 3-5 s at the start of the measurement and the elapsed time during infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the ring, and the time needed for the water to infiltrate was logged. The procedure was repeated 15 times (Lassabatere et al., 2006); iv) low (L) infiltration runs, carried out by applying water close to the infiltration surface, i.e. from approximately a height, h_w, of 0.03 m, and dissipating its energy on the fingers of the hand, in an attempt to minimize soil disturbance due to water application; v) high (H) infiltration runs, meaning that water was applied from h_w = 1.5 m and the soil surface was not shielded to maximize possible damaging effects of water impact. To ensure flow verticality and prevent wind effects, the device by Bagarello et al. (2014) was used to pour water on the confined infiltration surface.
Two types of two-stage infiltration runs were carried out in this investigation, namely L1L2 and L1H2. In the former case, 15 volumes of water were applied by the L procedure and then the sampled soil was allowed to drain for a short time. Subsequently, the L procedure was used to pour other 15 volumes of water. With reference to the L1H2 runs, the H procedure was used for the second stage of the infiltration experiment. A total of 10 L1L2 runs and 10 L1H2 runs were carried out at 20 randomly selected sampling points. A L1L2 run and a L1H2 run were carried out close to one another and almost simultaneously on each sampling occasion, to sample a soil having similar characteristics in terms of dry bulk density, ρ_b (g cm^{-3}), and volumetric water content at the time of the run, θ_i (m^3m^{-3}). In particular, two rings were inserted at a distance of 1.0-1.5 m each other and two undisturbed soil cores (0.05 m in height by 0.05 m in diameter) were collected at the 0 to 0.05 m and 0.05 to 0.10 m depths at an intermediate distance between the two rings. These cores were used to determine ρ_b and θ_i in the laboratory. The following sequence of infiltration runs was applied: i) L run in ring no.1; ii) L run in ring no.2; iii) H run in ring no.1; iv) L run in ring no.2. The infiltration rates, i_r, were calculated as the ratio between the applied water depth by a single pouring and the corresponding duration of the infiltration process. The mean time interval between the first and the second stage of an infiltration run was longer for the L1L2 runs (62 min) than the L1H2 runs (16 min). However, it was short in both cases, i.e. it did not exceed approximately one hour, suggesting that the two types of experiments did not differ substantially with respect to the interval between two sequences of water application in a given ring.
Each stage of the two-stage infiltration runs was characterized by the final infiltration rate, *FIR* (mm s^{-1}), that was set equal to the last measured i_r value, and the total duration of the infiltration process, d_t (s). Working with final rates implies that all possible disturbance has occurred (Dohnal et al., 2016; Le Bissonnais and Singer, 1992). Run duration was also considered since it was a good indicator of soil disturbance phenomena in previous investigations (Alagna et al., 2016; Bagarello et al., 2014).
Four *FIR* and d_t datasets were developed by considering the L1 stage of the L1L2 run ($L1_{(L2)}$ dataset), the L1 stage of the L1H2 run ($L1_{(H2)}$), the L2 stage of the L1L2 run (L2) and the H2 stage of the L1H2 run (H2) (sample size, N = 10 for each dataset). For each L1L2 and L1H2 run, the ratio, *StF* (Second to First), between the value corresponding to the second stage and that for the first stage was calculated with reference to both *FIR* and d_t.
The Lilliefors (1967) test was applied to check the normal and the ln-normal distribution hypothesis for each variable considered in this investigation. The $L1_{(L2)}$ and $L1_{(H2)}$ datasets were initially compared to establish if the L1L2 and L1H2 experiments were carried out under initially similar conditions. A two-tailed t test at P = 0.05 was used at this aim. The four developed datasets for both *FIR* and d_t and the two datasets for *StF* were then used to establish the relation between the second and the first stage of the infiltration run and then to

detect height of water pouring effects on infiltration under initially wet soil conditions. Statistical comparison between means and regression analysis procedures were applied at this purpose.

3. Results and discussion

All the experimentally determined infiltration rate, i_r, vs. time, t, relationships indicated a decrease of i_r as t increased during the first stage of the two-stage infiltration run, which was theoretically expected. Moreover, the *FIR* for the second stage was smaller than the *FIR* for the first run in all but one cases concerning a L1L2 run. For half of the two-stage infiltration runs, the i_r value at the beginning of the second stage was 0.72-0.91 (L1L2 runs) or 0.38-0.83 (L1H2) times the *FIR* of the first stage. In the other cases, and particularly for six runs of the L1L2 type and four L1H2 runs, the infiltration rate at the beginning of the second stage was 1.45-5.37 (L1L2 runs) and 1.15-2.50 (L1H2) times higher than the *FIR* of the first stage and then it decreased.

Infiltration rates could be high at the beginning of a subsequent water application (Fohrer et al., 1999) but an infiltration rate in the initial phase of the second run similar to the *FIR* value of the first run is another possibility (Dohnal et al., 2016). Moreover, changes in the soil surface occur very soon after starting water application (Alagna et al., 2016; Bagarello et al., 2014; Thompson and James, 1985), which could explain why the mentioned i_r/*FIR* ratios were generally lower for the L1H2 runs than the L1L2 ones, regardless of the fact that they were greater or smaller than one. Therefore, this initial check of the experimental infiltration rates did not indicate anomalous results. Instead, it suggested that the height of water pouring had an effect on the results of the second infiltration stage.

Table 1: Summary statistics of the final infiltration rates, FIR (mm s^{-1}), total duration of a given stage of the run, d_t (s), StF (Second to First) ratios for both FIR, StF(FIR), and d_t, StF(d_t), determined for the different datasets (sample size, N = 10 for each dataset)

Statistic	Dataset	$L1_{(L2)}$	$L1_{(H2)}$	L2	H2	L1L2	L1H2
	Variable			FIR		StF(FIR)	
Min		0.025	0.032	0.013	0.015	0.097	0.041
Max		0.597	2.268	0.378	0.354	1.13	0.462
Mean		0.189	0.228	0.086	0.042	0.587	0.223
		a(b)	a(c)	(b)d	(c)d	(e)	(e)
CV (%)		105	184.7	160.8	108	62	62
	Variable			d_t		StF(d_t)	
Min		184	60	303	243	0.83	1.85
Max		4225	2710	11872	13025	7.9	10.8
Mean		644.3	539.7	1429	2448	2.22	4.54
		a(b)	a(c)	(b)d	(c)d	(e)	(e)
CV (%)		104.9	162.1	159.5	141.6	95.9	53.5

For a given variable, mean values followed by the same lower case letter enclosed in parenthesis are significantly different according to a two-tailed t test at P = 0.05 (paired for the $L1_{(L2)}$ vs. L2 and $L1_{(H2)}$ vs. H2 comparisons). Two means followed by the same lower case letter not enclosed in parenthesis are not significantly different.

Taking into account the results of the Lilliefors (1967) test, *FIR*, d_t and *StF*(d_t) were assumed to be ln-normally distributed and, consequently, the geometric mean (*M*) and the associated coefficient of variation (*CV*) were calculated to summarize these data (Lee et al., 1985). Moreover, statistical tests were performed on the ln-transformed data. The *StF*(*FIR*) data were assumed to be normally distributed. The arithmetic mean and the associated *CV* were calculated in this case and untransformed data were used for statistical testing.

Considering the $L1_{(L2)}$ and $L1_{(H2)}$ datasets, not statistically significant differences were detected for *FIR* and d_t (Table 1). Therefore, the two types of two-stage experiments (L1L2 and L1H2) were carried out under initially similar conditions and they were comparable. In other terms, it was expected to obtain similar results with the L2 and H2 experiments in the absence of a pouring height effect on infiltration.

For the L1L2 experiments, the *FIR* and d_t values of the second stage were 2.2 times lower and longer, respectively, than the corresponding values for the first stage, and the differences between the two stages were statistically significant for both variables (Table 1). Statistical significance of the differences was also detected for the L1H2 experiments but, in this case, the second stage yielded 5.5 times lower *FIR* values and 4.5 times longer d_t values than the first stage. The H2 runs yielded 2.1 times lower *FIR* values and 1.7 times longer d_t values as compared with the L2 runs but the differences were not significant in these cases. However, the differences between the L1L2 and L1H2 datasets were significant for both *FIR* and d_t when the comparison was developed in terms of *StF* ratios (Table 1). In particular, the mean *StF*(*FIR*) and *StF*(d_t)

values of 0.22 and 4.5 (L1H2 runs) were significantly lower and higher, respectively, than the corresponding mean values for the L1L2 runs (*StF*(*FIR*) = 0.59, *StF*(d_t) = 2.2).
Therefore, both the $L1_{(L2)}$ vs. L2 and $L1_{(H2)}$ vs. H2 comparisons suggested that the second stage yielded lower *FIR* values and longer infiltration times, regardless of the height of water pouring. However, the differences between the first and the second stage were smaller for the former comparison (L1L2 dataset) than the latter one (L1H2 dataset). An effect of the height of water pouring was also statistically detectable when comparisons were carried out in terms of *StF* ratios. Therefore, this investigation indicated that *FIR* decreased and d_t increased during the second stage of the infiltration run with a low height of water pouring. A higher height implied a larger decrease of *FIR* and an additional increase of d_t.
More water impact energy is expected to determine more alteration of the soil surface (Thompson and James, 1985), lower infiltration rates (Assouline and Mualem, 2006, 2002) and smaller K_s values (Alagna et al., 2016; Bagarello et al., 2014). Therefore, changes in *FIR* and d_t between the two stages of the run were more noticeable for the L1H2 experiment than the L1L2 one since, in the second stage of the infiltration run, more energy was supplied to the soil with the former experiment than the latter one. In other words, a high height of water pouring had a detectable impact on both *FIR* and d_t in initially very wet soil conditions.

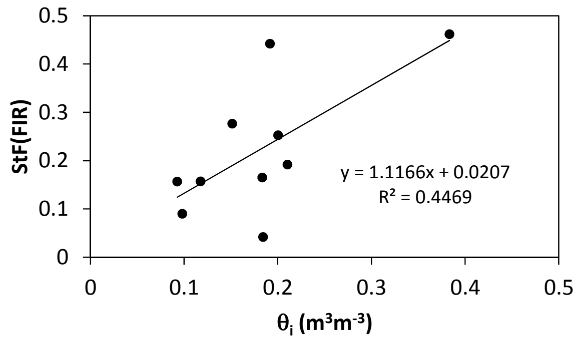

Figure 1: Relationship between the StF (Second to First) final infiltration rate, FIR, ratio and the antecedent soil water content, θ_i, for the L1H2 runs.

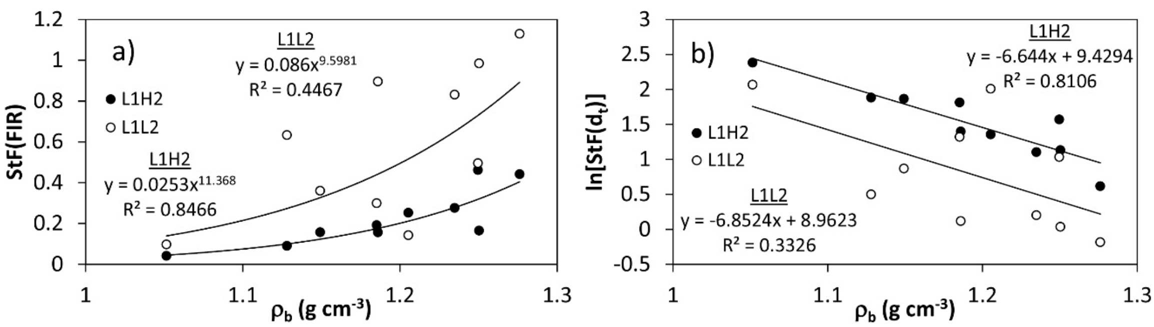

Figure 2: Relationship between the StF (Second to First) ratio for a) final infiltration rate, FIR, and b) total duration of a stage, d_t, and the dry soil bulk density, ρ_b, for the L1L2 and L1H2 runs.

The three high run experiments by Alagna et al. (2016) were carried out, with experimental methodologies similar to those applied in this investigation, in relatively dry initial soil conditions since the means of θ_i varied with the experiment from 0.12 to 0.20 m^3m^{-3}. The associated means of *FIR* varied from the 0.020 to 0.027 mm s^{-1} and those of d_t were in the range 3255-4854 s. In this investigation, the mean *FIR* and d_t values were equal to 0.042 mm s^{-1} and 2448 s, respectively, and the mean of θ_i was surely higher than 0.20 m^3m^{-3} since the soil porosity was of 0.55 m^3m^{-3} and the high run was carried out 16 min after the low ponding infiltration run. Therefore, this investigation supported the suggestion by Alagna et al. (2016) that the height of water pouring should have a less noticeable effect on both *FIR* and d_t in initially wet soil conditions.
A statistically significant effect of θ_i on *StF* was only detected with reference to *FIR* and the L1H2 runs (Figure 1) among the four considered *StF* datasets (L1L2 and L1H2 runs; *FIR* and d_t). In particular, even the fitted *StF*(*FIR*) vs. θ_i relationship suggested that the height effect on the final infiltration rate was less noticeable in

initially wetter soil conditions. This suggestion was rather weak since the coefficient of determination was low (R^2 = 0.45) and the fitting was largely governed by a single data point. However, there was not any reason to believe that this point was wrong.
The effect of dry soil bulk density on *StF* was statistically significant with reference to both types of experiment and both *FIR* and d_t (Figure 2). For a given variable, a higher R^2 value was obtained with the L1H2 runs than the L1L2 runs. Initially more compacted soil implied less differences between *FIR* for the two stages of the run and also more similar durations of these two stages. For both variables, the fitted regression lines suggested that, for a given ρ_b value, changes in *FIR* and d_t were more noticeable when the second stage was carried out from a relatively large distance from the infiltration surface.
Therefore, the soil bulk density can be viewed as a diagnostic parameter to predict the disturbance effect related to the height of water pouring. A less compacted soil is more sensitive to the height of water pouring, probably because the porous medium contains more macropores, that dominate flow under saturated or close to saturation conditions but are known to be particularly fragile and unstable (Jarvis et al., 2013).
In this investigation, height effects were detectable but infiltration rates decreased in the passage from the first to the second stage of the infiltration run regardless of the height of water pouring. Explaining this decrease needs additional investigations that should take into account different possible alternatives, including non-attainment of near steady conditions at the end of the first stage (Elrick and Reynolds, 1992), air entrapment effects (Dohnal et al., 2016; Le Bissonnais, 1996; Reynolds, 2008), and enhanced weakening of particle bonds with longer infiltration runs (Dikinya et al., 2008). The device by Di Prima (2015) could be used to check air entrapment effects due to repeated water pouring on the infiltration surface.

4. Conclusions

For the sandy-loam soil sampled in this investigation, the height of water pouring influenced the infiltration process when the soil was initially very wet. This effect, evaluated in terms of both final infiltration rates and total duration of the infiltration process, was less noticeable when the soil was initially wet than under initially drier conditions. A less compact soil was found to be more sensitive to the height of water pouring than a more compact porous medium, probably because less macropores were present in this case.
These results could perhaps help to better interpret hydrological processes occurring at the soil surface. For example, it could be suggested that excess rainfall during intense and prolonged events can be noticeable under both initially dry and wet conditions. In the former case, the reason is that an altered soil surface develops under wetting. In the latter case, this last phenomenon occurs at a lower rate but matric forces have a reduced effect on water infiltration. A similar reasoning can be made with reference to soil bulk density. Rainfall excess can be noticeable in an initially compact soil since it has a reduced ability to transmit water. However it can also be noticeable in a soil that is not initially compacted since an altered soil surface develops under wetting.
The developed methodology, including an infiltration run in two stages and both low and high runs during the second stage, appears appropriate to identify effects of water height application on infiltration parameters. Additional investigations could probably make the methodology more robust in general. In particular, it seems advisable to establish with more confidence what are the physical factors that operate when a two-stage infiltration run is carried out by preventing soil perturbing effects. Long duration runs should also be performed to better establish how the infiltration process evolves over time and to improve our knowledge on detection of quasi steady conditions.

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