SATURATED HYDRAULIC CONDUCTIVITY OF A REPEATEDLY USED LOAM SOIL PACKED WITH VARIOUS METHODS

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ABSTRACT

Performing laboratory measurement of saturated hydraulic conductivity, K_s, of sieved soil is important for many scientific purposes but little is known on the dependence of the K_s measurements on both the applied packing method and the reuse of a given soil mass. Four packing methods were tested on an initially dry loam soil by measuring K_s with the simplified falling head (SFH) technique. The four methods differed by the used compacting procedure (dropping from a given height, pestle imparting vertical and radial solicitations on the pressed soil surface) and the number of soil layers disposed at each step of the procedure. Changes in K_s due to the reuse of the same soil mass were also determined. Depending on the packing method and the number of times a given soil mass was used, the means of K_s varied from 51 to 110 mm h^{-1}, with a ratio between these two extremes of 2.2, and the coefficients of variation, *CV*s, ranged between 10 and 36%, depending on the developed dataset (sample size, $N = 15$ for each dataset). Therefore, the packing method and the reuse of the same soil had a moderate effect on determination of K_s. For a given pre-treatment of the soil mass, the lowest variability of K_s was detected by using the pestle, probably because this simple device favored homogenization of the soil and enhanced the contact with the walls of the cylinder. With the pestle, reusing the soil once was enough to pass from a medium ($CV = 23$-27%) to a low ($CV = 12\%$) variation of K_s. Taking into account that the best procedure yields the lowest variability of the individual K_s measurements, the conclusion was that the pestle and a previously wetted soil should be used. In the future, additional experiments should be carried out on other soils, in different antecedent soil water conditions and with other laboratory measurement methods of K_s. Developing simple procedures for preparing different samples with similar K_s values appears possible.

Keywords: Saturated soil hydraulic conductivity; Simplified falling head technique; Sieved soil; Packing procedures; Soil reuse.

1. INTRODUCTION

Laboratory determination of saturated, K_s, or near-saturated, K, hydraulic conductivity of repacked soil samples represents the connecting link between the studies dealing with purely ideal data, such as those generated numerically or analytically, and the investigations performed in the laboratory or the field on real and nearly undisturbed soil. Therefore, working on a repacked, and presumably homogeneous, porous medium allows the soil scientist to gradually move from theory to practice. Repacked soil samples have been used, and still continue to be used, for a large variety of scientific purposes that include, as an example, testing theories, devices and procedures for determining K_s (Reynolds and Elrick, 1987; Bagarello et al., 2004, 2006; Concialdi et al., 2020), studying factors influencing the K_s values of specific types of soil (Moutier et al., 1998), establishing wastewater reuse effects on K_s (Viviani and Iovino, 2004; Assouline and Narkis, 2011), relating K_s or K with the bulk soil physical properties (Assouline, 2006; Ghosh and Pekkat, 2019), testing soil seal development effects on K (Armenise et al., 2018), determining the relationship between K_s and the soil microstructure (Xu et al., 2021), evaluating the effects of rock fragments on K_s (Wu et al., 2021).

Working on repacked soil samples implies making a decision on the packing method to be applied, also depending on the available equipment and the size of the sample that has to be prepared. A variety of choices can be made at this purpose. For example, Laliberte et al. (1966) obtained different densities by vibrating the soil columns after packing them with air-dried soil. Reicovsky et al. (1980) obtained various degrees of compaction by means of a standard laboratory press with pistons that pressed moist soil samples slightly from both ends simultaneously. Bagarello et al. (2004) prepared samples of 5 cm in diameter and 4 or 5 cm in height with a step-by-step procedure, pouring at each step 1 cm of soil that was then manually compacted. The soil samples used by Bagarello et al. (2006) and Concialdi et al. (2020) had a diameter of nearly 9 cm and a height of 32 cm or more. They were prepared by filling a column with 40 cm of soil that was then dropped repeatedly from a height of 5 cm until compaction ceased. Soil samples of 5.1 cm × 20 cm and 10 cm × 12 cm were prepared by Moody et al. (2009) by introducing soil in 5-10 increments. Even Zhang et al. (2017) prepared 30 cm × 60 cm samples with a step-by-step procedure. In this case, each step involved pouring 5 cm of soil followed by compaction. The soil samples by Ghosh and Pekkat (2019), having a diameter of 20 cm and a height of 30 cm, were obtained by packing the soil in three layers and imparting an equal number of blows on each layer, depending on the desired state of compaction. In some investigations, however, the applied packing method was not described (Moutier et al., 1998; Assouline and Narkis, 2011; Armenise et al., 2018; Di Prima et al., 2018).

The link between the applied method to prepare repacked soil samples and the determination of K_s has rarely been considered although a recent investigation has demonstrated that the packing procedure can have a large impact on the K_s results. In particular, Teng et al. (2019) recognized that K_s can vary by even an order of magnitude due to the dependence of the pore size distribution on the applied packing method. Other investigations dealing with packing methods can be found in the literature but they are not expressly focused on measurement of K_s (Oliviera et al., 1996; Lewis and Sjöstrom, 2010; Gilbert et al., 2014; Banzhaf and Hebig, 2016). Therefore, the knowledge of the effect of the applied packing method on laboratory determination of K_s is still incomplete and additional investigations are necessary to fill this gap.

Another factor to be considered is the possibility to reuse the same sieved soil for different experiments. Using a mass of soil twice or more times has the practical advantage that less efforts have to be made to collect soil in the field and to perform the initial pre-treatment, such as removal of stones or vegetation residues. However, when a sieved soil mass is used for the first time, it is subjected to several solicitations. For example, a mechanical breakdown of the small aggregates in the sieved soil could occur during packing, depending on the applied forces. Changes in the soil are also possible during the K_s measurement stage due, for example, to slaking when the initially dry soil is suddenly wetted or to weakening of the interparticle binding forces promoted by a prolonged contact with water (Le Bissonnais, 1996; Ben-Hur and Lado, 2008; Dikinya et al., 2008), depending on the applied K_s measurement method. Generally, no detailed information is provided in the investigations making use of repacked soil samples about the history of the used soil mass for a given experiment although there are a few exceptions. For example, Moody et al. (2009, 2019) reused the same soil for subsequent experiments while Ryżak et al. (2015) reported that a given soil sample was only used once in their experiments. To the best of our knowledge, the impact of the repeated use of a sieved soil mass for determination of K_s has still to be investigated.

An interest of the scientific community for the simplified falling head (SFH) technique for determining K_s (Bagarello et al., 2004) is documented in the literature (Keller et al., 2012; Angulo-Jaramillo et al., 2016; Biddoccu et al., 2016, 2017; Kovář et al., 2017; Preti et al., 2018; Castellini et al., 2021). Probably, a point of attractiveness of this technique is that it is simple, rapid and usable both in the laboratory and the field. Part of the potential and limitations of the SFH technique have been investigated in the laboratory, working on repacked soil samples (Bagarello et al., 2006; Concialdi et al., 2020). However, the effects of the packing method and the soil reuse were not considered. Therefore, the sensitivity of the K_s

values obtained with the SFH technique to both the applied packing method and the reuse of a given mass of soil is still unknown.

The objective of this investigation was to establish the impact of both the applied packing method and the repeated use of the same soil mass for the preparation of a soil sample on determination of saturated hydraulic conductivity of a loam soil with the simplified falling head technique. The specific objectives were to i) determine changes in K_s among four different packing methods that do not require specialized equipment; and ii) determine if and how K_s changes when the same soil mass is used more than once.

2. MATERIALS AND METHODS

2.1. Soil

On November 2019, approximately 100 kg of soil were collected from the surface layer in an orchard established at the Department of Agricultural, Food and Forest Sciences of the Palermo (Italy) University (38°06’24’’ N, 13°21’06’’ E). The mean organic carbon content, *OC* (%), of the upper few centimeters of the soil, determined with the Walkley-Black method, was equal to 3.1%.

Eight soil samples were collected from the upper 0.1 m of the profile to determine the soil textural characteristics in the sampled zone for this investigation. For four samples, the soil particle size distribution was determined using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation with sodium hexametaphosphate and mechanical agitation. Soil was classified as loam in all cases (mean sand, silt and clay percentages equal to 50.7%, 30.3% and 19.0%, respectively). Soil of the other four samples was not pre-treated with H_2O_2 and sodium hexametaphosphate and the sand, silt and clay percentages were equal to 58.1%, 38.8% and 3.2%, respectively. Therefore, a part of the particles smaller than 2 mm was constituted by small aggregates of elementary particles, in agreement with other soils (Dikinya et al., 2008).

Loamy soils have been used for many experiments with repacked porous media (Viviani and Iovino, 2004; Assouline, 2006; Bagarello et al., 2006; Armenise et al., 2018; Di Prima et al., 2018; Kargas et al., 2018). Consequently, this investigation was expected to have a rather general interest.

2.2. Experimental methods

The soil was transported to the laboratory where it was spread on plastic sheeting and manually stirred every two days. After approximately a week of air drying, the soil was passed through a 5 mm sieve and placed in an oven at 60 °C for 24 hours. After that, the soil was passed through a 2 mm sieve and left exposed to air in the laboratory until use.

Plexiglas cylinders of 9.3 cm in diameter and 15 cm in height were used to prepare the soil columns for this investigation. Initially, the amount of air-dried soil needed to completely fill the cylinder without any compaction was found to be equal to 1100 g. Therefore, 1100 g of soil were used each time to prepare a soil column. Four different packing methods were used. In particular, with the P1 method, the cylinder was filled up to its upper rim by simply pouring soil. The soil was then compacted manually by dropping the cylinder repeatedly from a height of approximately 5 cm. With the P2 method, the soil mass was subdivided into three equal parts. One third of the soil mass was poured in the cylinder and the soil was compacted manually by dropping the cylinder repeatedly from a height of approximately 5 cm. The second part was then poured and the same compaction procedure was applied again. Finally, the last part of soil was poured into the cylinder and compacted by dropping. Even the P3 method was based on a partition of the soil mass into three equal parts. In this case, however, one third of the soil mass was poured in the cylinder and the soil was compacted manually by a wood pestle that was pressed downward and rotated around its vertical axis. The second part was then added and the same compaction procedure was applied again. Finally, the last part of soil was poured and compacted. The P4 method was similar to the P3 method but soil packing was carried out in six subsequent steps. The final height of all soil columns was equal to 12.5 cm since this was the smallest height practically attainable with the P1 method. A total of nearly 150 drops were required to reach this height and performing more drops of the soil column did no longer alter its height.

Fifteen soil columns were prepared with each packing method. For each column, the saturated soil hydraulic conductivity, K_s (mm h^{-1}), was determined with the simplified falling head (SFH) technique (Bagarello et al., 2004). A fixed water volume was used for each K_s test to nearly sample all the soil column while avoiding seepage, that is appearance of free water at the bottom of the column at the end of the infiltration run. Three estimates of the infiltration time, t_a (h), were obtained for each run. In particular, the t_{a1} infiltration time was defined as the time from application of water to the instant when the first point of the infiltration surface was exposed by the falling water. The t_{a2} infiltration time was defined by considering the instant when half the soil surface was visually exposed to air. The t_{a3} infiltration time, representing the standard protocol for a SFH experiment (Bagarello et al., 2004), was determined by considering total disappearance of free water from the soil surface. At the end of each run, the final length of the soil sample, l_f (cm), was measured to detect possible vertical swelling phenomena promoted by wetting. The depth of the wetting front, d_{wf} (cm), with respect to the final position of the soil surface was also measured. Final height and wetting front measurements were performed along four verticals established at a radial distance of 90° and the four values were averaged to characterize a soil sample.

The first infiltration experiment, denoted as R0 (reuse 0, soil never used before), was performed from February to June 2020. The period was rather long as a consequence of the limitations imposed by the covid-19 pandemic. On a given working day, four columns were prepared with the tested methods (P1, P2, P3, P4) and the antecedent gravimetric soil water content, w_i, was determined by placing eight replicated samples of 80 g of air-dry soil in an oven at 105 °C for 24 h. The SFH experiment was performed the day after. With the exception of the first set of four measurements, for which a water volume of 330 mL was used, all runs were carried out 300 mL of water. In no case did the wetting front reach the bottom of the soil column. After the SFH test, the soil was recovered and it was placed in a container exposed to air. Different containers were used for the four packing methods so that the soil prepared with the, e.g., P1 method was not mixed with that prepared with another method. The recovered soil mass in a container was periodically mixed by hands during this storage period to make air-drying more rapid.

The second infiltration experiment, denoted as R1 (reuse 1, soil already used once), was performed at the end of July and the beginning of August 2020 since a monitoring of w_i indicated that the soil returned to a water content close to that before the R0 experiment. The experimental methodology did not change as compared with the R0 experiment. The consistency between packing methods was maintained in the sense that a given packing method was applied on the same soil mass. The soil was passed through a 2 mm sieve before preparing a column. Very small amounts of soil never used before (i.e., in total, a few hundreds of grams) were added to the available soil mass to be sure that the soil was enough to prepare another set of 15 columns for each packing method. After the R1 experiment, the used soil for the P1 packing method was placed again in a container and it remained exposed to air without any periodic mixing due to the summer closure of the laboratory.

A third infiltration experiment, denoted as R2 (reuse 2, soil already used twice) was performed at the beginning of September 2020 by only considering the P1 packing method. The soil in the container appeared rather damp. Therefore, soil drying was forced by placing it in an oven at 60 °C for three days. The oven-dried soil was passed through a sieve with openings of 2 mm and it was left to attain the ambient temperature for 24 h before proceeding further with determination of w_i, preparation of the soil samples and SFH infiltration run. For the R2 experiment, 40-50 drops were enough to reach a height of the soil sample of 12.5 cm.

2.3. Calculations and data analysis

The saturated soil hydraulic conductivity, K_s (L T^{-1}), was calculated with the SFH equation (Bagarello et al., 2004):

$$K_s = \frac{\Delta\theta}{t_a(1-\Delta\theta)}\left[\frac{D}{\Delta\theta} - \frac{\left(D+\frac{1}{\alpha^*}\right)}{1-\Delta\theta} ln\left(1 + \frac{(1-\Delta\theta)D}{\Delta\theta\left(D+\frac{1}{\alpha^*}\right)}\right)\right] \quad (1)$$

in which t_a (T) is the infiltration time of the applied water volume, V (L^3), $\Delta\theta$ (L^{3}L^{-3}) is the difference between the saturated (θ_s) and the initial (θ_i) volumetric soil water content, $D = V/A$ (L) is the height of the ponded head of water at $t = 0$, A (L^2) is the infiltration surface, and α^* (L^{-1}) is a soil texture/structure that was fixed at 0.012 mm^{-1} in this investigation (Elrick and Reynolds, 1992; Concialdi et al., 2020). In this investigation, θ_i and θ_s were determined using the antecedent gravimetric soil water content, w_i (g g^{-1}), and the dry soil bulk density, ρ_b (g cm^{-3}), assuming that θ_s coincided with the porosity. 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:

$$\rho_b = \frac{m_s}{V_t} = \frac{m_{ad}}{V_t(1+w_i)} \quad (2)$$

where m_s (g) is the mass of the dry soil, V_t (cm^3) is the bulk volume of the soil sample, and m_{ad} (g) is the mass of the air-dry soil.

A comparison among the nine developed datasets (P1, P2, P3 and P4 packing methods for the R0 and R1 experiments plus P1 method for the R2 experiment) was initially made with reference to both the length of the soil column after the SFH run, l_f (L), and the final depth of the wetting front, d_{wf} (L). The experimental d_{wf} values were also compared with those predicted theoretically according to Bagarello et al. (2004):

$$d_{wf} = \frac{V}{A\,\Delta\theta} = \frac{D}{\Delta\theta} \tag{3}$$

The effect of the infiltration time criterion (t_{a1}, t_{a2}, t_{a3}) on calculation of K_s was then tested by comparing the K_s values obtained with the former two criteria ($K_s(t_{a1})$ and $K_s(t_{a2})$, respectively) with those obtained with the standard SFH protocol, $K_s(t_{a3})$.

A comparison among the nine K_s datasets obtained with the different packing methods and soil reuse experiments was finally carried out.

The arithmetic mean and the associated coefficient of variation, *CV*, were used to summarize a given dataset. Several comparisons were established between two datasets by performing F and two-tailed t tests at $P = 0.05$. A pairwise comparison was preferred to other alternative statistical tests since establishing differences between, e.g., the P1 and P3 data does not depend on the information collected with the P2 or P4 packing methods. Unpaired t tests were performed since a given soil sample was used only once in this investigation. A two tailed t test at $P = 0.05$ was also performed to establish statistical significance of the correlation between two variables. The 95% confidence intervals, *ci*, for both the intercept and the slope were also calculated to check departure of the calculated regression line from the identity line.

3. RESULTS AND DISCUSSION

3.1. Dry soil bulk density and antecedent soil water content

The soil columns prepared for this investigation had a dry bulk density, ρ_b, varying from 1.24 to 1.27 g cm^{-3} (sample size, $N = 135$; mean = 1.25 g cm^{-3}; coefficient of variation, $CV = 0.6\%$) and an antecedent soil water content, θ_i, ranging between 0.028 and 0.045 m^{3}m^{-3} (mean =

0.041 m^3m^{-3}; CV = 11.7%). The ρ_b and θ_i values were nearly constant for the first two experiments since, for the eight developed datasets (R0 and R1 experiments; P1, P2, P3 and P4 packing methods; N = 15 for each dataset), the means of ρ_b and θ_i fell in the 1.24-1.25 g cm^{-3} and 0.041-0.042 m^3m^{-3} ranges, respectively. The soil was a little more compacted (1.27 g cm^{-3}) and drier (0.028 m^3m^{-3}) for the R2 experiment since it was maintained in the oven for some time before exposure to air. Without this last dataset, the mean and the CV of the individual ρ_b values were 1.25 and 0.4%, respectively, and those of θ_i were 0.042 m^3m^{-3} and 4.2% (N = 120 in this case).

Therefore, the K_s values corresponding to different packing methods for the R0 and R1 experiments were determined under nearly identical ρ_b and θ_i conditions. Similarly, ρ_b and θ_i did not change when a soil never used before (R0) and a soil already used once (R1) were compared for a given packing method.

3.2. Length of the soil column

At the end of the SFH infiltration run, the length, l_f, of the soil column increased on average by 8 to 12 mm (initial l_f = 12.5 cm), depending on the packing method and the number of times a given soil mass was used (**Table 1**). Using the pestle for compacting the soil (P3 and P4 packing methods) determined less vertical swelling as compared with repeatedly dropping the cylinder from a small height (P1 and P2 methods). Some differences between the pestle and the dropping methods were significant but they were always small since they did not exceed 2 mm regardless of the experiment (R0, R1). Reusing the same mass of soil once (R1) implied a minimal decrease of l_f as compared with a soil that was never used before (R0), regardless of the packing method (differences by $\leq$ 3 mm). However, these changes in l_f were statistically significant only for the P2 method. Moreover, the tendency to a decrease of l_f was not perceivable by considering the R0, R1 and R2 experiments for the P1 packing method since l_f did not change significantly in this case.

Vertical swelling upon wetting is expected in initially dry clay soils (Moutier et al., 1998) and it was also signaled by Bagarello et al. (2006) and Concialdi et al. (2020), applying the SFH technique on the same soil of this investigation. According to this experiment, the packing method influenced the length of the soil column upon wetting only moderately. In particular, a dry soil sample prepared with a pestle appeared minimally more rigid than that prepared by dropping. Reusing the soil made the sample length less sensitive to wetting but this last perception was supported statistically only once. Therefore, the pestle and a soil that has been subjected to a wetting-drying treatment seem usable to prepare a more rigid sample as compared with the other considered methodologies (dropping method, soil never used before). However, the signs leading to this suggestion were overall weak and an equally plausible alternative interpretation of the data could be that neither the packing method nor the reuse of a given soil mass should be expected to have a great impact on the final length of the soil sample.

3.3. Depth of the wetting front

On average, the depth of the wetting front at the end of the run varied from 10.2 to 10.6 cm, depending on the packing method and the number of times the same material was reused (**Table 1**). The d_{wf} values did not differ among the P1, P3 and P4 methods, regardless of the used soil (R0, R1), but significantly larger values, at the most by 3 mm, were obtained with the P2 method for some of the established comparisons. With the pestle, d_{wf} did not change between the R0 and R1 experiments. With the dropping procedure, d_{wf} increased with the reuse by a nearly imperceptible and also non-significant amount (1 mm). Applying the P1 packing method three times (R0, R1, R2) yielded some weak sign that d_{wf} could moderately increase with additional reuses.

The means of the measured d_{wf} values were 10-15 mm or 11-17% greater than those expected theoretically according to eq.(3), depending on the packing method and the number of times the same soil was reused (**Fig. 1**). The difference between the experimental and the theoretical means of d_{wf} decreased appreciably when the measured vertical swelling was subtracted from the experimental d_{wf} value. In particular, differences between means decreased to -1 to 5 mm, depending on the considered treatment, denoting that the increase of the soil sample length upon wetting influenced the experimental vs. theoretical comparison of d_{wf}. Even the corrected d_{wf} value was generally greater than that obtained theoretically (**Fig. 1**). This result was not surprising since other investigations suggested that air entrapment in the sampled soil volume or diffusion of the wetting front can induce a greater depth of wetting than theoretically predicted (Concialdi et al., 2020).

According to Wells et al. (2007), differences by 4 mm in wetting front depths of approximately 2 to 6 cm can be considered small and nearly negligible. Adapting the conclusion by Wells et al. (2007) to this investigation, the effects of the packing method and the soil reuse on d_{wf} were nearly negligible in practice since differences did never exceed 4 mm. Moreover, the theoretical prediction of d_{wf} by eq.(3) can be considered as a sufficiently reliable approximation of the vertical distance between the soil surface at the beginning of the experiment and the final position of the wetting front. This information has practical importance to determine in advance the amount of water that should be used to explore a soil layer of a pre-established thickness or to be confident that a one-dimensional infiltration process is established in the field.

3.4. Infiltration time criterion

The mean infiltration time increased from ~7 min with the t_{a1} criterion to ~12 min with the t_{a3} criterion. Both $K_s(\mathrm{t_{a1}})$ and $K_s(\mathrm{t_{a2}})$ were significantly related with $K_s(\mathrm{t_{a3}})$, with coefficients of determination, R^2, equal to 0.76 for the $K_s(\mathrm{t_{a1}})$ vs. $K_s(\mathrm{t_{a3}})$ relationship (*ci* for the intercept and the slope from -40.8 to -8.8 and 1.98-2.41, respectively) and 0.88 for the $K_s(\mathrm{t_{a2}})$ vs. $K_s(\mathrm{t_{a3}})$ relationship (*ci* for the intercept and the slope from -15.2 to -1.3 and 1.38-1.56, respectively) (**Fig. 2**). Of course, the calculated K_s values were highest with the t_{a1} criterion and lowest with the t_{a3} criterion (**Table 2**) since the considered run duration for the K_s calculation increased between these two extremes. On average, the $K_s(t_{a1})/K_s(t_{a3})$ and $K_s(t_{a2})/K_s(t_{a3})$ ratios were equal to 1.81 and 1.34, respectively.

According to Elrick and Reynolds (1992), differences in the K_s estimates by a factor of two or three could be considered small and perhaps negligible for some practical purposes. Therefore, the applied infiltration time criterion had a minor effect on the K_s values obtained with the SFH technique, in agreement with Bagarello et al. (2004) concluding that minor measurement errors in the duration of the infiltration process do not affect appreciably the determination of K_s. However, the *CV* of K_s decreased according to the sequence $t_{a1} > t_{a2} > t_{a3}$ (**Table 2**). Less variability implies more confidence in the reliability of a mean value as a representative parameter for a given situation (Picciafuoco et al., 2019; Bagarello et al., 2021). Therefore, the original infiltration time criterion by Bagarello et al. (2004) yielded the most representative mean value of K_s. Consequently, the recommendation is to use the original infiltration time criterion. More variable, and hence less representative, and slightly higher estimates of K_s can be expected if alternative criteria are used. In the following, the $K_s(t_{a3})$ data were considered and they were denoted for simplicity as K_s.

3.5. Saturated soil hydraulic conductivity

The 135 K_s values obtained in this investigation varied from 30 to 189 mm h^{-1}, that is by 6.3 times, with a mean and a coefficient of variation, *CV*, equal to 72 mm h^{-1} and 34%, respectively. Depending on the packing method and the number of times a given soil mass was used, the means of K_s varied from 50.8 to 109.7 mm h^{-1}, with a ratio between these two extremes of 2.2, and the *CV* values ranged between 10 and 36% (**Table 1**). This initial check suggested that the packing method and the reuse of the same soil mass moderately influenced determination of K_s (Elrick and Reynolds, 1992). However, several differences were statistically significant (**Table 1**).

With the soil never used before (R0), the mean of K_s decreased by 2.2 times according to the sequence P2 > P1 > P3 = P4. Using the pestle instead of the dropping method reduced variability of K_s but the *CV* values of the four datasets (from 23% to 36%) remained in the range denoting a medium variation (Warrick, 1998). The minimum and, especially, the maximum K_s values of a dataset were smaller with the pestle than by repeatedly dropping the soil column (**Fig. 3a**). In particular, the largest discrepancy between the four highest K_s values was by 2.5 times and it was detected between the P2 and P3 methods. For the four lowest K_s values, the largest discrepancy was by 1.6 times and it was noticed between the P1 and P4 methods.

With the P1 and P2 methods, solicitations are exclusively oriented downward and compaction mainly depends on the particle's vertical mobility into the soil mass. No specific attention is paid with these packing methods to the contact between the soil and the cylinder. With the P3 and P4 methods, solicitations occur both downward and radially, close to the pressed soil layer. It appears plausible to believe that the rubbing action by the pestle promoted some crushing of the small aggregates and it also had a spreading effect that likely improved the contact between the soil and the cylinder. Therefore, a soil compaction in both the vertical and the radial direction yielded a more homogeneous sample and also improved the contact between the porous medium and the cylinder as compared with a compaction exclusively performed in the vertical direction.

While the P3 and P4 packing methods yielded equivalent K_s results, a statistically significant difference was detected between the P1 and P2 methods although the differences were small and perhaps negligible in practice (means differing by 1.5 times and very similar *CV* values, **Table 1**). Probably, the P2 method yielded higher K_s values than the P1 method because the soil was added step by step in the former case but all at once in the latter one. Therefore, the first third of the soil mass was dropped 150 times, the second third was dropped 100 times and the last third was dropped 50 times. In other terms, parts of the soil mass used to prepare the sample with the P2 method received less solicitations as compared with the soil treated with the P1 method. Consequently, compaction was less complete.

Applying the four packing methods on the reused soil (R1) yielded similar means, since they differed at the most by 1.3 times (**Table 1**), and more similar distributions of K_s as compared with the R0 experiment (**Fig. 3b**). However, the cumulative distribution for the P1 and P2 methods remained slightly shifted to the right of those for the P3 and P4 methods. In addition, some differences were statistically significant. In particular, K_s decreased according to the sequence P2 = P1 $\geq$ P4 = P3. Even with the R1 experiment, using the pestle instead of the dropping method reduced the variability of K_s. All means obtained in this second step of the experiment (61-77 mm h^{-1}) fell into the range of the means of K_s obtained with the R0 soil (51-110 mm h^{-1}). Therefore, the effect of the packing method on the determination of K_s was less noticeable when the experiment was carried out with the R1 soil.

As compared with the R0 experiment, the K_s values obtained on the R1 soil were stable with the P1 packing method, significantly smaller by 1.4 times with the P2 method and significantly larger by 1.2-1.3 times with the P3 and P4 methods (**Table 1**). Therefore, the P1 method was the most appropriate method to minimize the effect of the reuse of a given soil mass on detection of the mean K_s value. The reduced sensitivity of this packing method to the soil pre-treatment was not a fortuitous result since it was confirmed when the same soil mass was used once again (R2 experiment, **Table 1** and **Fig. 4a**). However, even the significant differences detected for the other methods were practically small (Elrick and Reynolds, 1992). In all cases, reusing the same soil mass implied obtaining less variable K_s data. In particular, reusing the same soil mass determined development of K_s datasets characterized by a low variation ($CV < 15\%$) in accordance with Warrick (1998).

The soil used for the R1 experiment appeared finer to both the eye and the touch as compared with the soil of the R0 experiment. Formation of a finer material as a consequence of the first experiment (R0) appeared plausible since the particle size distribution analysis indicated that some particles were aggregates of elementary particles and the R0 experiment was carried out by suddenly wetting an initially dry medium. Therefore, the conditions were favorable to the occurrence of slaking or other wetting induced soil alteration phenomena (Le Bissonnais, 1996; Martínez-Mena et al., 1998). Homogenization of the soil was also indicated by the decrease of the CV values of K_s from the R0 to the R1 experiment for all packing methods. Therefore, the impact of the packing method on the determination of K_s was less noticeable with a more homogeneous porous medium.

Regardless of the packing method, all K_s values obtained with the R1 experiment fell in the range of the K_s data obtained with the R0 experiment (**Fig. 4**). In other words, reusing the soil consistently implied disappearance of both the lowest and the highest K_s values of a soil never used before. For the P1 and P2 methods, the K_s distribution for the R1 experiment was located towards the left end of the corresponding distribution for the R0 experiment. For the P3 and P4 methods, the distribution for the reused soil was located towards the right end of the corresponding distribution for the non-previously used soil. Therefore, the former two packing methods mainly induced a decrease of the highest measurable values of K_s while the latter two methods mainly determined an increase of the lowest measureable values of K_s. The absence of particularly high K_s values could be due to a better contact between the soil and the cylinder walls promoted by the use of an overall finer soil mass. The lack of particularly low K_s values could be due to the fact that a finer soil condition did not favor development of low permeability zones since there was less material that could be destroyed as a consequence of the rubbing action by the pestle during preparation of the soil column.

Homogeneity of the replicated measurements of K_s represents the logical expectation of any investigation carried out in the laboratory on an ideally homogeneous porous medium. Ideally, nearly constant K_s values should be obtained, regardless of the soil sample, and hence the *CV* of the individual measurements should be equal or close to zero. This investigation showed that the applied procedure to prepare a repacked soil sample has to be taken into account to reach or to get closer to this objective since the applied packing method and the pre-treatment of the soil mass can be expected to have a moderate but statistically significant impact on the K_s values measured in the laboratory with the SFH technique. Using a pestle to compact the soil is better than repeatedly dropping the soil column since lower *CV*s were obtained in the former case than the latter one. It also appears advisable to include, during pre-treatment of the dry soil, a pre-wetting phase under ponding since it seems to have a homogenizing effect, likely as a consequence of slaking of the small aggregates that are present in the sieved soil mass. Moreover, the use of a previously wetted and dried soil mass makes the packing method a less important experimental factor in the sense that the means of K_s become more similar among different packing methods as compared with the case of a sieved but non previously wetted soil. Even in this case, however, the recommendation is to use the pestle since it assures the highest uniformity of the results. Of course, a development of this investigation should be to establish if, for a given packing method, the mean and the variability of the K_s values stabilize after a certain number of reuses of the same soil mass.

This investigation also suggested that using a given soil mass more than once could not preclude detection of stable means of K_s, since this result was clear with the P1 packing method. Therefore, another development should be to verify if dropping repeatedly a cylinder filled with soil from a small height generally minimizes any reuse effect, at least in terms of mean results.

An appreciably greater impact of sample preparation with repacked soil on K_s was signaled by Teng et al. (2019). In particular, these authors concluded that differences in K_s caused by different soil column preparation methods can be as large as one order of magnitude. The discrepancy in sample preparation effects between this investigation and that by Teng et al. (2019) could have different explanations such as differences in the considered soils (loam in this investigation against silty-clay-loam in that by Teng et al., 2019), the antecedent soil water content (air-dry against a higher and controlled value), the applied methods to prepare the soil columns (dropping- and pestle-based methods against Proctor compaction, static compaction and consolidation) or the K_s measurement technique (SFH against another falling head technique). In any case, this investigation reinforced the conclusion by Teng et al. (2019) that the influence of the sample preparation procedure on K_s should not be ignored.

4. CONCLUSIONS

Performing laboratory measurement of saturated hydraulic conductivity, K_s, of sieved and packed soil is important for many scientific purposes. The expectation of an experiment with a nearly homogeneous porous medium is to obtain nearly stable data between replicates since the variability typical of real soils is purposely removed or minimized in this kind of experiments. Packing procedures should be as simple as possible, also considering that the available equipment and personnel are often scarce in many laboratories.

For a loam soil, this investigation demonstrated that both the packing method and the number of times a given soil mass is used to prepare a soil sample influence determination of K_s with the simplified falling head (SFH) technique.

Among the tested packing methods, the suggestion was to use a pestle instead of repeatedly dropping the soil column from a small height. The pestle establishes both vertical and radial forces that likely favor rupture of the small soil aggregates present in the sieved soil mass and also enhance the contact between the soil and the inner walls of the cylinder. Therefore, the use of this simple device can be expected to improve homogeneity of the measured K_s values as compared with the dropping method that only exerts a compaction action in the vertical direction.

Another suggestion was that the soil should be subjected to wetting during the pre-treatment stage. The soil becomes finer after wetting, probably as a consequence of slaking processes that destroy, at least in part, the small aggregates. Consequently, variability of the individual determinations of K_s is reduced.

In this investigations there were also signs that a very stable mean of K_s and homogenization of the individual data could be expected if the soil is wetted more than once. In particular, if an experiment is planned with the objective to obtain stable means of K_s regardless of the recent history of a soil mass, repeatedly dropping the soil column from a small height could be an appropriate procedure. However, this information is currently limited to a single packing method. Further tests should be aimed to verify if stabilization of both the mean and the variability of K_s occurs after a certain number of reuses regardless of the applied packing method.

In conclusion, using a pestle and a previously wetted soil could be a good procedure to obtain reproducible K_s data in the laboratory with the SFH technique. This conclusion applies to an initially dry loam soil that remains in contact with flowing water for a few minutes after being suddenly wetted. Therefore, it cannot be generalized to any soil, antecedent soil water content or laboratory measurement method. In the future, additional experiments on packing and reuse effects on determination of K_s should be carried out in different experimental conditions. These tests are necessary since packing a sieved soil mass in a column gives rise to a pore system that could be expected to easily change depending on the applied solicitations during both the pre-treatment of the sample and the K_s measurement stage.

According to this investigation, it could be possible to develop simple procedures for preparing different samples with similar K_s values.

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Table 1. Mean and coefficient of variation, *CV* (%), of saturated soil hydraulic conductivity, K_s (mm h^{-1}), final length of the soil sample, l_f (cm), and depth of the wetting front with respect to the final position of the soil surface, d_{wf} (cm), for the P1, P2, P3 and P4 packing methods applied to soil that was never used before (reuse 0) or it was used once (reuse 1) or twice (reuse 2) (sample size, N = 15 for given reuse, variable and packing method)

Variable	Reuse	Statistic	P1	P2	P3	P4
l_f	0	Min	13.2	13.5	13.1	13.1
		Max	13.9	14.0	14.0	13.8
		Mean	13.6 ab A	13.7 a A	13.5 b A	13.5 b A
		CV	1.5	0.9	1.7	1.1
	1	Min	13.2	13.1	13.1	12.7
		Max	13.8	13.9	13.7	14.1
		Mean	13.5 a A	13.4 ab B	13.3 b A	13.4 ab A
		CV	1.4	1.6	1.6	2.4
	2	Min	13.2	-	-	-
		Max	13.8	-	-	-
		Mean	13.6 A	-	-	-
		CV	1.4	-	-	-
d_{wf}	0	Min	9.2	10.1	10.0	9.9
		Max	11.2	11.6	11.3	11.6
		Mean	10.2 a A	10.5 b A	10.3 ab A	10.3 ab A
		CV	4.4	3.4	3.1	3.9
	1	Min	9.9	10.2	10.0	9.9
		Max	10.8	11.2	10.5	10.9
		Mean	10.3 a AB	10.6 b A	10.3 a A	10.3 a A
		CV	2.5	2.6	1.6	2.8
	2	Min	10.0	-	-	-
		Max	10.7	-	-	-
		Mean	10.4 B	-	-	-
		CV	1.9	-	-	-
K_s	0	Min	47.1	44.5	35.4	30.3
		Max	136.9	189.4	76.0	88.5
		Mean	75.1 a A	109.7 b A	53.0 c A	50.8 c A
		CV	31.5	35.8	22.6	26.7
	1	Min	50.5	58.7	49.4	52.3
		Max	104.8	103.2	72.8	79.5
		Mean	73.9 ac A	77.3 a B	61.1 b B	66.6 bc B
		CV	20.4	16.0	12.3	11.7
	2	Min	66.3	-	-	-
		Max	93.6	-	-	-
		Mean	76.6 A	-	-	-
		CV	9.9	-	-	-

P1 method: cylinder filled up to its upper rim and compaction by repeatedly dropping the cylinder. P2 method: similar to the P1 method but with the soil added in three subsequent steps. P3 method: soil added in three subsequent steps but compacted with a wood pestle. P4 method: similar to the P3 method but with the soil added in six subsequent steps. K_s determined with the t_{a3} infiltration time, representing the suggested infiltration time for an experiment with the Simplified Falling Head technique (Bagarello et al., 2004). For given reuse and variable, means followed by a different lower case letter are significantly different according to a two-tailed t test at P = 0.05. Means followed by the same lower case letter are not significantly different. For given packing method and variable, means followed by a different upper case letter are significantly different according to a two-tailed t test at P = 0.05. Means followed by the same upper case letter are not significantly different.

Table 2. Minimum, *min*, maximum, *max*, mean and coefficient of variation, *CV* (%), of saturated soil hydraulic conductivity, K_s (mm h^{-1}), obtained by different total infiltration time criteria (sample size, $N = 135$)

Statistic	**t_{a1} criterion**	**t_{a2} criterion**	**t_{a3} criterion**
Min	37.4	34.2	30.3
Max	367.1	247.5	189.4
Mean	132.5	97.0	71.6
CV	46.0	39.0	33.8

t_{a1} = time from application of water to the instant when the first point of the infiltration surface was exposed by the falling water. t_{a2} = time from application of water to the instant when the half the soil surface was exposed to air. t_{a3} = time from application of water to the instant when all free water disappeared from the soil surface.

Figure 1. Comparison between the mean values of the experimental and the theoretical depths of the wetting front, d_{wf}, at the end of infiltration for the four packing methods (P1, P2, P3, P4) and the replicated experiments with the same soil mass (R0, R1, R2)

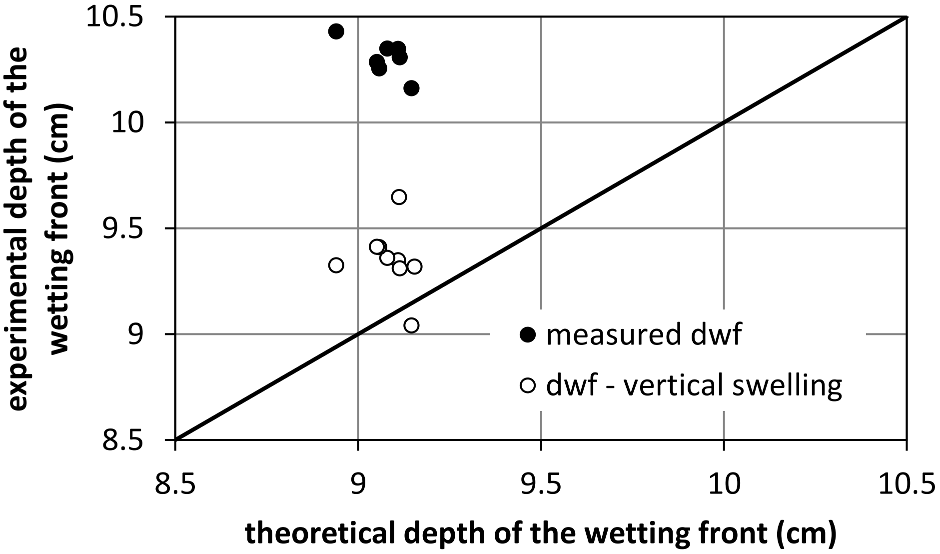

Figure 2. Comparison between the saturated soil hydraulic conductivity, K_s, values obtained with different infiltration time criteria (t_{a1}: from application of water to the instant when the first point of the infiltration surface is exposed by the falling water; t_{a2}: the instant when half the soil surface is exposed to air is considered; t_{a3}: total disappearance of free water from the soil surface is considered; sample size, N = 135)

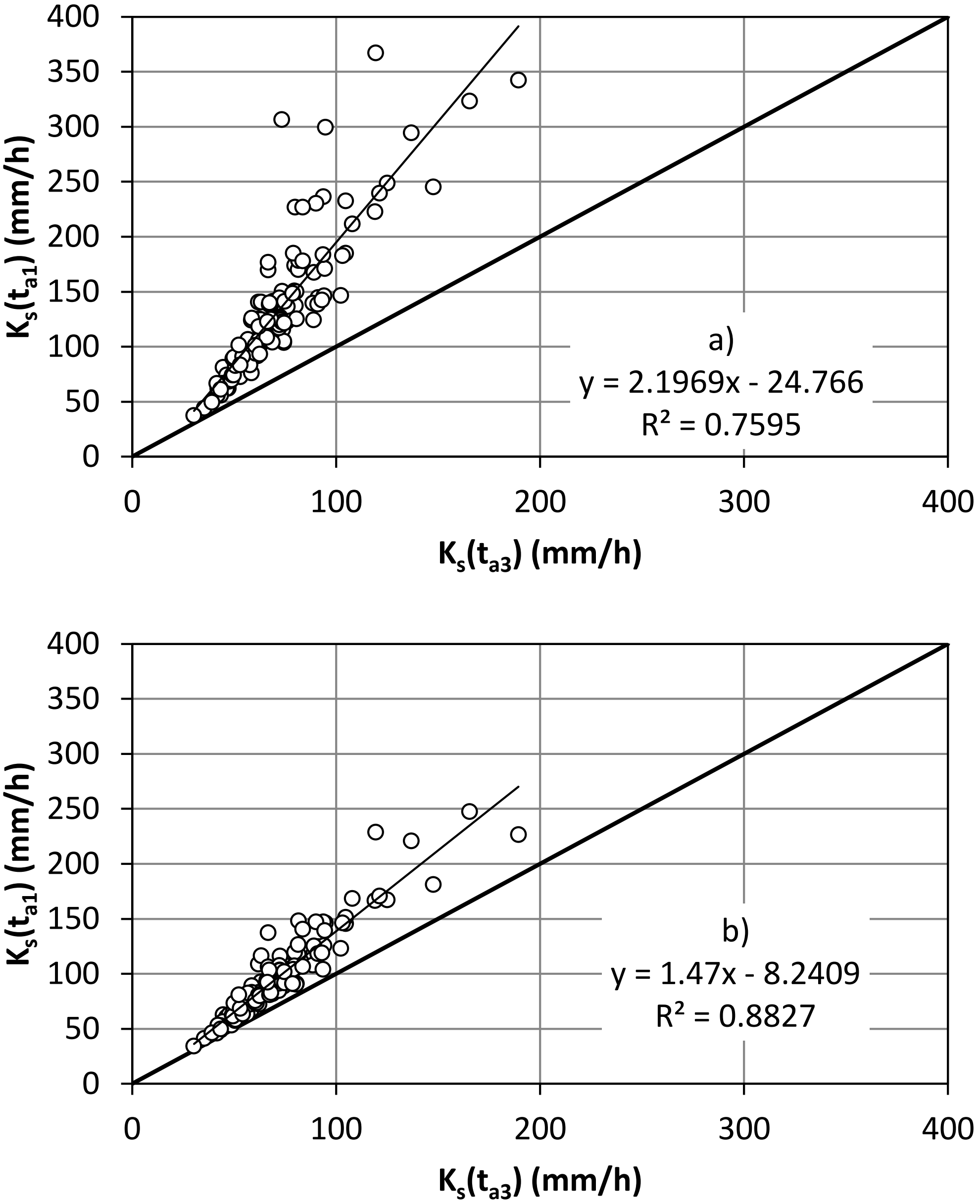

Figure 3. Cumulative empirical frequency distribution of the saturated soil hydraulic conductivity, K_s, values obtained with four packing methods (P1, P2, P3, P4) and a soil that a) was never used before (R0) and b) was previously used once (R1)

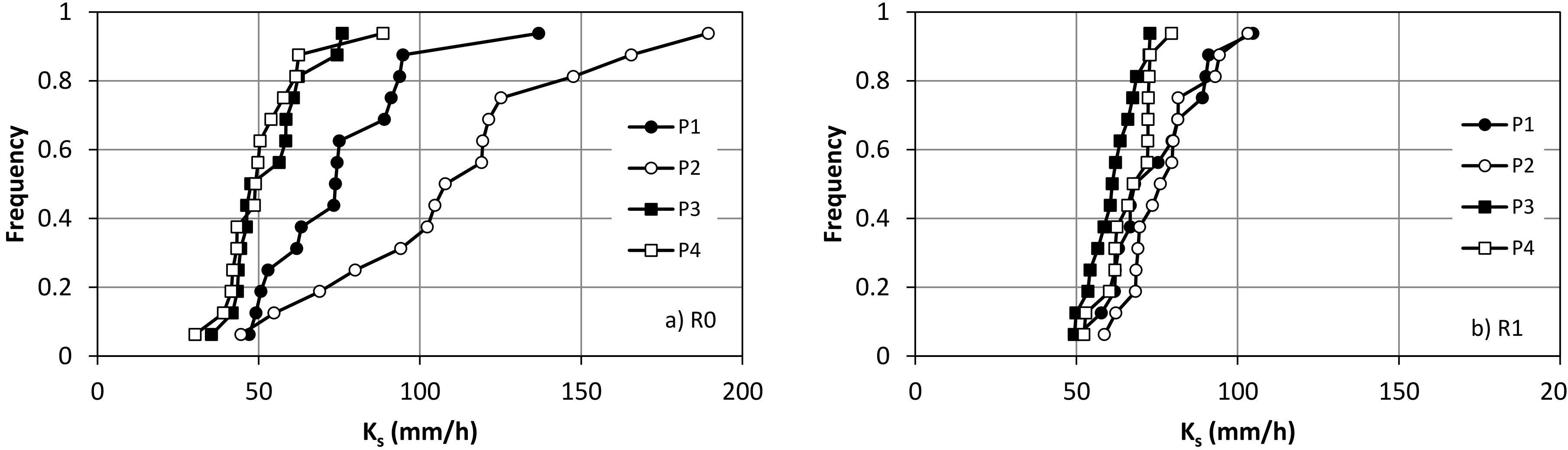

Figure 4. Cumulative empirical frequency distribution of the saturated soil hydraulic conductivity, K_s, values obtained with a soil that was never used before (R0) or it was previously used once (R1) or twice (R2) and the a) P1, b) P2, c) P3, and d) P4 packing methods