Iranian Journal of Science and Technology, Transactions of Civil Engineering (2024) 48:1599–1607
https://doi.org/10.1007/s40996-023-01254-z

RESEARCH PAPER

Evaluation of Unsaturated Water Flow Features of Compacted Soil Subjected to Horizontal and Vertical Water Infiltration

Chahira Sayad Gaidi[1] · **Laouni Gaidi**[2] · **Ali Merdji**[3] · **Sandipan Roy**[4]

Received: 18 March 2023 / Accepted: 30 September 2023 / Published online: 23 October 2023

Abstract
The objective of this study is to compare the unsaturated water flow features during horizontal and vertical infiltration. To follow the moisture variation (water content θ (z, t)), the time domain reflectometry method is used. The retention curve is obtained by the filter paper method. The suction test results are interpreted by the Van Genuchten (Soil Sci Soc Am J 44(5):892–898, 1980) model. These results allow the determination of the relationships between diffusivity and water content ($D(\theta)$) and hydraulic conductivity and water content ($K(\theta)$) by applying the instantaneous profiles method. The results showed that the unsaturated water flow parameters are influenced by the flow direction and the gravity effect. The diffusivity values in the vertical infiltration column are higher than those measured in the horizontal infiltration column. The experimental points calibrated with the models of Brooks and Corey (J Irrig Drain Div 92(2):61–88, 1966) and Campbell (Soil Sci 117(6):311–314, 1974) have shown that this model fairly well describes the hydraulic conductivity evolution versus water content.

Keywords Unsaturated soil · Infiltration · Water content · Diffusivity · Hydraulic conductivity

1 Introduction

The issue of availability and access to water is undoubtedly one of the major problems that humanity will have to face during this century. Today, it is estimated that one in five inhabitants of the planet does not have access to sufficient water, and only one in three has good water quality. In this context, it may be useful to recall that "the quantitative and qualitative measurement of the elements of the hydrological and hydrogeological cycles and the measurement of other environmental characteristics that influence water constitute an essential basis for effective water management (Affeltranger and Lasserre 2003)". Understanding and analyzing the water cycle are the basis of any study or reflection on the subject of water management.

Water infiltration into soils is a major component of the water cycle. Knowledge of the mechanisms governing infiltration flows makes it possible to estimate the unsaturated water flow features in the soil. Among these, hydraulic conductivity represents a fundamental parameter in water transfers, the estimation of which finds numerous applications in the following fields (Velly 2000): (a) in agriculture for the choice of the type of crop and the methods of drainage and irrigation; (b) in sanitation in order to size a spreading network; (c) in the environment for forecasting the risks of recurrent or accidental contamination of groundwater by surface activities; and (d) in geotechnics within the framework of erodibility and slope stability studies.

Infiltration is an essential part of the hydrological cycle. It is defined by the proportion between the surface flow, also called runoff, and the underground flow. The estimation of the importance of the infiltration process makes it possible to determine what fraction of the rain will participate in surface runoff and what fraction will participate in the recharge of groundwater.

✉ Sandipan Roy
sandipan888roy@gmail.com

[1] Laboratory of Water Sciences & Techniques, Faculty of Science & Technology, University Mustapha Stambouli of Mascara, Mascara 29000, Algeria

[2] Laboratory for the Study of Structures and Mechanics of Materials, Faculty of Science & Technology, University Mustapha Stambouli of Mascara, Mascara 29000, Algeria

[3] Faculty of Science & Technology, University Mustapha Stambouli of Mascara, Mascara 29000, Algeria

[4] Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur 603203, India

The hydraulic conductivity values and the water transfer qualification parameters can be determined in the laboratory on test specimens taken from the field or directly in place by means of in situ tests. However, it is often difficult to access this conductivity with the only information that can be conveniently obtained from these tests.

Two soil columns were put through standard infiltration tests in the laboratory to find out how water moves through unsaturated soil and how gravity affects the water parameters of this soil. During infiltration tests, soil water content (moisture) and soil suction were measured to monitor water transfer. Infiltration curves were used to describe the water flow and the infiltration rate. The water content profiles were used to observe the soil saturation process and to determine the soil column transit time.

The transient analysis of moisture and effective pressure profiles, measured during infiltration in an unsaturated soil layer, makes it possible to establish the relationships between the unsaturated water flow parameters (Hamilton et al. 1981). These parameters are obtained by applying the generalized Darcy law (Vachaud 1966; Vauclin 1971; Wesseling et al. 1966). Knowledge of the phenomenological relationships between the unsaturated water flow features in the soil is an essential prerequisite for any quantification, by experimental means and by modeling, of water transfers in unsaturated porous media. These relationships make it possible to evaluate the unsaturated water flow parameter values in a saturated state. These relationships cannot be inferred from fundamental soil properties but must be determined by experimental procedures. Often, these relationships are inferred from the water balance during soil wetting or drainage.

Results from all studies seem to be conflicting because they consider only the morphology of structure rather than the hydrodynamic functionalities. In summary, the studies show the necessity: (a) to take into account matrix pores and macropores; (b) to consider the field scale of soil profiles rather than the laboratory scale of cores to also assess the heterogeneity induced by compaction; and (c) to directly consider the hydrodynamic functionality of the pores in conducting water and air rather than dwelling on the morphology of soil structure.

Hamilton et al. (1981) measured the hydraulic conductivity–suction relationship using a permeameter and a thermocouple psychrometer. They found that the instantaneous profile method works well for clays, which have a degree of saturation varying between 30 and 90%, and for sands, which have a degree of saturation lower than 50%. Tensiometers should be used to measure suction at higher saturation levels. In addition, Daniel (1983) used the method of instantaneous profiles to measure the unsaturated hydraulic conductivity of fine silty sand with the simultaneous use of tensiometers and psychrometers. The method requires several weeks per test, and the time allocated to the calibration of psychrometers and tensiometers must be added (Hamilton et al. 1981; Daniel 1983). Krisdani et al. (2009) adopted the instantaneous profile method for the calculation of residual soil permeability functions in laboratory slope models. These instantaneous profiles were calculated using pore pressure measured with tensiometers along the slope models and independently measured soil–water characteristic curves. The instantaneous results of the profile were adjusted by the statistical method to obtain a continuous permeability function. The instantaneous profile method is commonly used for compacted clay soils (Cui et al. 2008). The determination of the water content profile during water infiltration is an important part of using this method. In several studies, the water retention test is carried out in parallel with the infiltration test, which allows the indirect establishment of the water content profile from the measured suction profile (Ye et al. 2009; Wang et al. 2013). Wei Su et al. (2018) worked on rigid Teguline clay collected from the Albian Bassin Paris region. They discovered that hydraulic conductivity decreases with increasing suction and that the extrapolated value of hydraulic conductivity at zero suction is very similar to the value obtained directly using the constant head method. The successful incorporation of miniature TDR probes and tough filament tape extends the common instantaneous profile method to small laboratory samples and rigid materials (Wei Su et al. 2018). Even though it has been shown that structural changes affect hydraulic properties, the way the raw experimental data are interpreted has a big impact on how the calculated changes in water permeability and suction are made (Dieudonne and Charlier 2017).

Da Silva et al. (2020) used the new version of the Splintex model (Splintex 2.0) to figure out the unsaturated soil hydraulic conductivity (SHCC) as a function of volumetric water content () and saturated permeability (Ks). The Splintex 2.0 model assumes that soil pores are represented by equivalent capillary tubes and that water flow is a function of pore size distribution. Then, the $K(\theta)$ data estimates are fitted to the unsaturated soil hydraulic conductivity described by Van Genuchten (1980) and Mualem's equation (1976) (VGM). The goodness of fit of $K(\theta)$ was assessed with a selection of 198 SHCCs measured by the instantaneous profiles method. The used data contain measured information on textural composition, bulk and solid densities, total porosity, and $K(\theta)$ data. Splintex 2.0 provided mean values close to the VGM parameters fitted to the data measured by the instantaneous profile method. For the analyzed texture groups, the SHCC estimates were highly correlated ($r = 0.852$).

To calculate diffusivity and hydraulic conductivity, soil moisture and suction profiles are indispensable. By applying the instantaneous profiles method to moisture profiles, different unsaturated water flow parameters are calculated.

The instantaneous profile method is used to determine diffusivity and hydraulic conductivity versus water content or suction (Alimi-Ichola and Gaidi 2006). Volumetric water profiles are determined using TDR (time domain reflectometry) measurements.

2 Instantaneous Profiles Method

The instantaneous profiles method consists in imposing an infiltration at one end of soil column and measuring the moisture spatio-temporal variations θ (z, t) or water potential ϕ (z, t). We calculate the flow that crosses a section at depth z. Then, we use Darcy's generalized law to determine the diffusivity and hydraulic conductivity values (Hamilton et al. 1981). The obtained results allow the determination of following relationships: hydraulic conductivity—water content (K (θ)); hydraulic conductivity—suction “pF” (K(pF)) and diffusivity—water content ($D(\theta)$), using the instantaneous profile method. It is possible to demonstrate the gravity influence on the hydraulic conductivity and diffusivity.

Darcy's law applied to an unsaturated soil is written:

$$q = -K(\theta)\frac{\partial\varphi}{\partial z}, \quad (1)$$

with: $\phi = \psi - z$, q: water flow, ψ: soil suction

$$\text{So,}\quad q = -K(\theta)\left(\frac{\partial\psi}{\partial z} - 1\right) \quad (2)$$

If we suppose that at section $z = H$ (H: height of column) the outing flow is zero, the flow $q(t)$ which crosses a section at the given position z is determined from the profiles $\theta(z, t)$ at time t by the equation:

$$q(t)|_z = \frac{1}{\Delta t}\int_z^H (\theta(z, t + \Delta t) - \theta(z, t))\mathrm{d}z = \left.\frac{\partial I(t)}{\partial t}\right|_z$$

$I(t)|_z$ represents the water layer flowing through the section z between the instant t at $t + \Delta t$.

The retention curve ψ (θ) makes it possible to evaluate the potential gradient $\partial\psi/\partial z$ at time t and at section z.

The hydraulic conductivity $K(\theta)$ evolution at an instant t and the section z is calculated from the equation:

$$K(t)|_z = -\frac{q(t)|_z}{\left.\left(\frac{\partial\psi(t)}{\partial z} - 1\right)\right|_z} \quad (3)$$

At the instant t and the section of given depth z corresponds an average volumetric water content θ or an average value of pF. We can therefore associate at any time t with Eq. 3 terms the values of θ or of pF. We can write:

$$K(\theta)|_{z,t} = -\frac{q(\theta)|_{z,t}}{\left.\left(\frac{\partial\psi(\theta)}{\partial z} - 1\right)\right|_{z,t}} \quad (4)$$

or

$$K(pF)|_{z,t} = -\frac{q(pF)|_{z,t}}{\left.\left(\frac{\partial\psi(pF)}{\partial z} - 1\right)\right|_{z,t}} \quad (5)$$

The relation $D(\theta)$ is obtained from Eq. 6 (Childs and Collis-George 1948):

$$D(\theta)|_{z,t} = K(\theta)|_{z,t}\left.\frac{\partial\psi}{\partial\theta}\right|_{z,t} \quad (6)$$

By neglecting gravity and adopting the flow to horizontal flow, Eqs. 4 and 5 reduce to:

$$K(\theta)|_{z,t} = -\frac{q(\theta)|_{z,t}}{\left.\left(\frac{\partial\psi(\theta)}{\partial z}\right)\right|_{z,t}} \quad (7)$$

$$K(pF)|_{z,t} = -\frac{q(pF)|_{z,t}}{\left.\left(\frac{\partial\psi(pF)}{\partial z}\right)\right|_{z,t}} \quad (8)$$

The relation $D(\theta)$ is obtained from the flow measurements and the volumetric water content gradient:

$$D(\theta)|_{z,t} = -\frac{q(\theta)|_{z,t}}{\left.\left(\frac{\partial\theta}{\partial z}\right)\right|_{z,t}} \quad (9)$$

The moisture profiles integration makes it possible to determine the flowing layer evolution $I(z,t)$. We can then draw the water flowing layer curves evolution with time from the moisture profiles. The slopes of these curves at different times give the flow that crosses the section over time.

2.1 Empirical Models of Hydraulic Conductivity

Several empirical models have been proposed to describe the variation of hydraulic conductivity versus volumetric water content or suction. These models are necessary for water transfer modeling in unsaturated porous media. We have wanted from existing models those who better represent the experimental results. We have chosen the Brooks and Corey (1966) and Campbell (1974) models.

2.2 Model of Brooks and Corey (1966) and Campbell (1974)

The experimentally measured permeability coefficient value K_s of the studied soil is equal to 6×10^{-8} m/s. The model of Brooks and Corey (1966) and Campbell (1974) describes the variation of hydraulic conductivity with volumetric water content. The hydraulic conductivity according to this model is written:

$$K(\theta) = K_S\left(\frac{\theta}{\theta_S}\right)^m \quad \text{when} \quad Y > Y_e \tag{10}$$

θ_s volumetric water content at saturation, ψ_e inlet air pressure, $K(\theta)$ hydraulic conductivity at the water content θ, K_s hydraulic conductivity at $\theta=\theta_{s,}$ m: empirical constant

We try to find the values of parameters θ_s, K_s and m which permit to this model to represent well the experimental results.

2.3 TDR Method

Time domain reflectometry (TDR) is based on measuring the transit time and the amplitude attenuation of an electromagnetic pulse launched along a transmission line (TL) implanted in the soil. The measurement method was developed by Topp et al. (1980), who showed that for many soil materials, there exists an empirical relationship between volumetric water content and soil dielectric constant. The electromagnetic wave attenuation that is propagated along the transmission line is related to the bulk electrical conductivity of the soil (Nadler et al. 1991). Topp et al. (1980) proposed to determine the soil volumetric water content θ, this relationship:

$$\theta = -0.053 + 0.29\varepsilon - 5.5\,10^{-4}\varepsilon^2 + 4.3\,10^{-6}\varepsilon^3 \tag{11}$$

where ε, the soil dielectric constant, is measured from the transit time t of an electromagnetic pulse through the soil by:

$$\varepsilon = (ct/2L)^2 \tag{12}$$

where $c=$ velocity of light in free space, L: length of the used probe rod.

To improve volumetric water content measurement, TDR probes were calibrated with water and different soils. So the measurement of the soil water content during this study is obtained from the relationship (Gaidi and Alimi-Ichola 2000):

$$\theta = 0.0548 + 0.0153\varepsilon - 5\times10^{-5}\varepsilon^2 + 8\times10^{-8}\varepsilon^3 \tag{13}$$

2.4 Infiltration Test

Simultaneous infiltration tests on two soil columns are carried out. So, the water flow parameters of unsaturated soil for vertical and horizontal water percolation can be compared.

The infiltration tests are performed in a PEHD column with a 600-mm height. The column is composed of rings of 40 mm height and 100 mm diameter. The soil was wetted at a fixed water content and compacted at the desired bulk density in each ring (Alimi-Ichola and Gaidi 2006). Before soil compaction, TDR probes are inserted in eight rings, which compose each test column. The probes consisted of three steel rods of 75 mm in length. After the column setting, TDR probes are located at depths of 2, 10, 18, 26, 34, 42, 50, and 58 mm. The used soil material is clayey sand.

The experimental setup for this study is illustrated in Fig. 1. The TDR probes are connected to a multiplexer for sequential measurement. A computer program is used to drive the multiplexer and the two balances. So, infiltration flow and TDR measurements are recorded according to the data acquisition program. Cumulative infiltration curves are obtained from balance measurements. These balances are placed on heavy supports to absorb any possible vibrations. Balances are reported to have a precision of 1/100 g and are sensitive to vibration. Mariotte's bottles are filled with water and provide the hydraulic load. The effect of the flux mode on the infiltration curve and the soil's hydraulic conductivity is measured by figuring out the initial and steady flow rates.

The carried-out test allows a comparison between a vertical and horizontal flows under the same initial conditions.

Van Genuchten (1980) model is used to describe the experimental water retention curve (14).

$$\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right) = \left[\frac{1}{1+(\alpha h)^n}\right]^m \tag{14}$$

where θ_r: residual volumetric water content, θ_s: saturated volumetric water content ($h=0$), α, n and m: model parameters

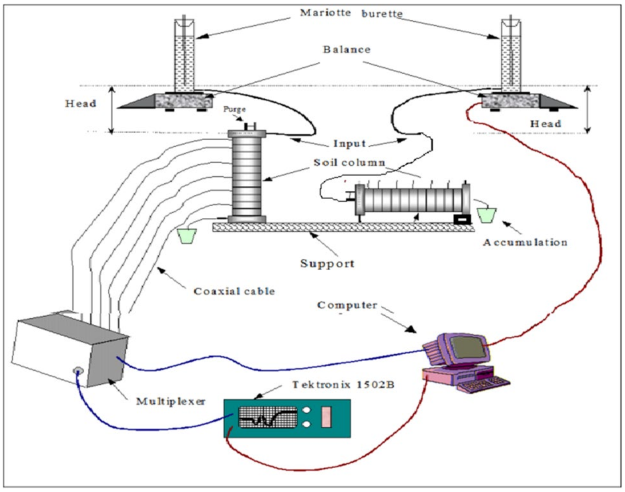


Fig. 1 The experimental device

Table 1 Van Genuchten parameters

	θ_r	θ_s	α cm^{-1}	m	n
Clayey sand	0.0025	0.34	0.35	0.11	1.1236

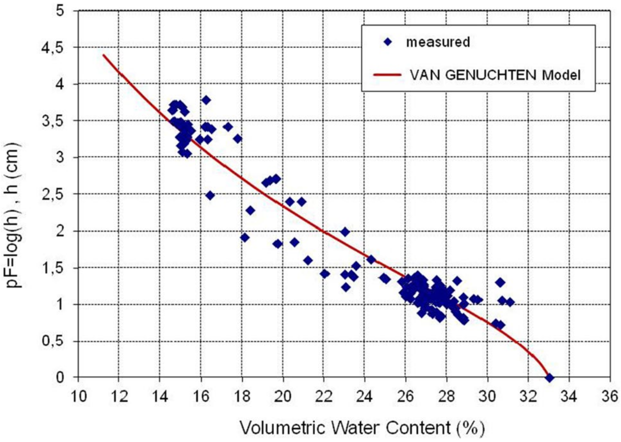


Fig. 2 Retention curve of the soil

The parameters of this model are computed from measured suctions versus volumetric water contents. These parameter values are shown in Table 1. Bentoumi (1995) have shown that the function h(θ) derived from Eq. 10 represents the evolution of the effective head pressure in the soil during infiltration. So Eq. 10 can be used to compute suction profiles from volumetric water content profiles.

Measured suction points and Eq. (10) are represented in Fig. 2.

The infiltration is performed at constant water head supply $h_0 = 25$ cm and at an initial water content equal to 10%. The soil in the two columns is compacted to dry bulk density equal to 1.55 g/cm^3.

3 Results and Discussion

3.1 Infiltration Curve Analysis

Curves of cumulative infiltration versus time are determined from the variation of the Mariotte burette weight. By using the acquisition software, the balances directly provide the infiltrated volumes (in text format). The TDR curves obtained from the Tektronix 1502B cable tester unit are recorded on the computer for further analysis.

Infiltrated volumes in soil columns are plotted versus time (Fig. 3). This figure shows that water flow is the same during one day of infiltration. After this time, the infiltrated volume in the vertical column becomes higher than the infiltrated volume in the horizontal column. This difference shows the gravity influence on the infiltration process. After 6 days of infiltration, the volume of water infiltrated into the vertical column is approximately 153 ml, and that of the horizontal column is only 135 ml. From this time on, the two infiltration curves increase in parallel with the same velocity.

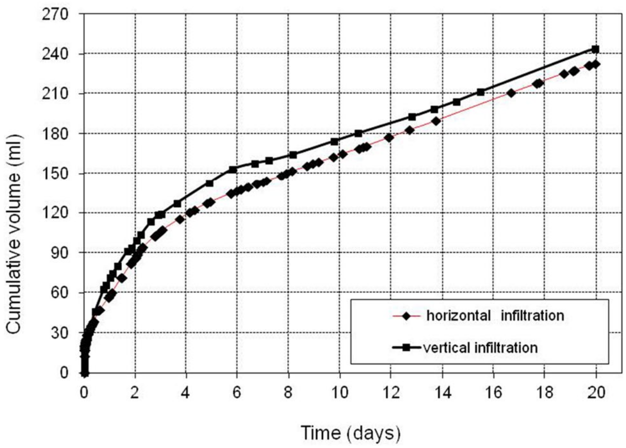


Fig. 3 Infiltration curve

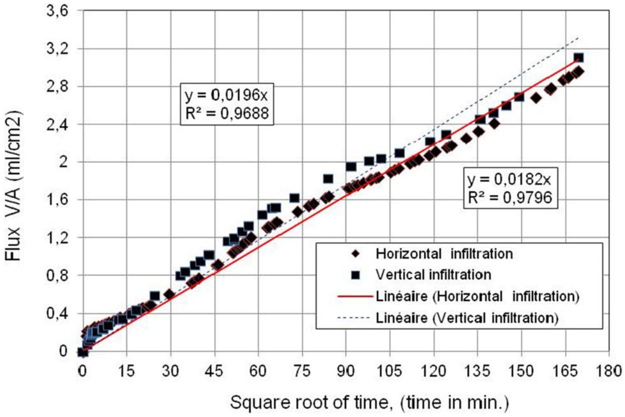


Fig. 4 Infiltration curve

The infiltration curves of the two columns represented in square root of time $I = S\sqrt{t}$ (Model of Philip 1969) are represented in Fig. 4.

The experimental points regression lines offer a good correlations coefficient. In Philip model, S (cm/s$^{1/2}$) is the sorptivity and I the cumulative infiltration ($I = $ V/A).

Table 2 contains the sorptivity values (S) calculated from the two lines slopes (Fig. 4).

The sorptivity value reflects the capacity of the soil to retain liquid. The sorptivity value in the vertical column is slightly higher than that obtained in the horizontal column. This result explains the fact that the propagation velocity in a vertical column is higher than that in a horizontal column.

Table 2 Sorptivity measurement

	S (cm/s$^{1/2}$)
Horiz. column	2.35E-03
Vertical COLUMN	2.53E-03

3.2 Moisture Profiles Analysis

The soil moisture profile, which represents its volumetric water content distribution at a chosen time t, makes it possible to explain and quantify the process of water infiltration in soil. During vertical infiltration, moisture propagates through unsaturated soil under gravity forces on the one hand and capillary forces on the other. If the soil capillary forces become too weak, the diffusion will be negligible, and the hydraulic load imposed on the soil surface will remain the sole motor of flow (Bentoumi 1995).

Figure 5a and b represents the moisture profiles $\theta = f(z,t)$ in the tow soil columns. By comparing these moisture profiles, we notice that:

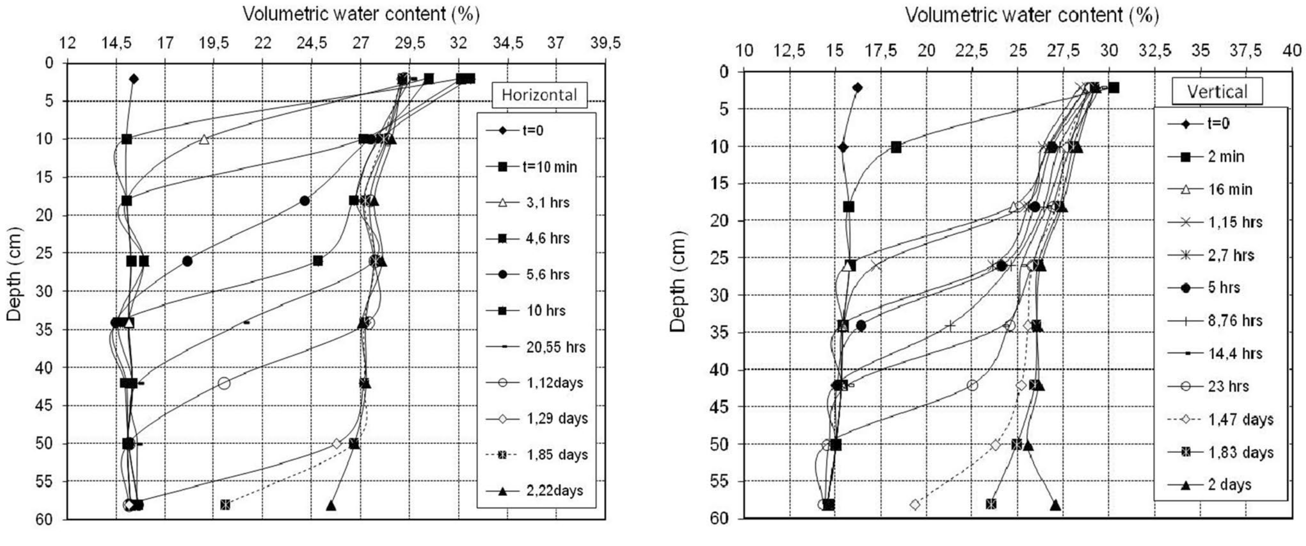
- The transfer in the two columns begins always with a diffusion phenomenon followed by convection.
- At test beginning, the moisture progression in two soil columns is done with same manner.
- An acceleration of flow in vertical column compared to horizontal one.
- The sixth ring in vertical column (probe 6) is reached by liquid after 23 h of infiltration. On the other hand, the sixth ring (probe 6 of the horizontal column) is reached by liquid after 1.12 days of flow.
- Water came out from horizontal column bottom after 1.85 days. This duration is only 1.47 days in vertical infiltration.
- A global overview of the two moisture profiles groups allows concluding that the propagation in vertical column is faster than that in horizontal case. This rapidity in volumetric water content propagation reflects the gravity effect on the infiltration velocity.

3.3 Suction Profiles Analysis

The Van Genuchten model will make it possible to trace the suction profiles from volumetric water content profiles (Fig. 6). We notice that the soil suction follows the moisture variation. When volumetric water content is high, the suction value (pF) becomes low. Any decrease in volumetric water content is followed by suction increase. Generally, in the two columns, there is not an immense difference in suction profiles.

3.4 Diffusivity and Hydraulic Conductivity Study

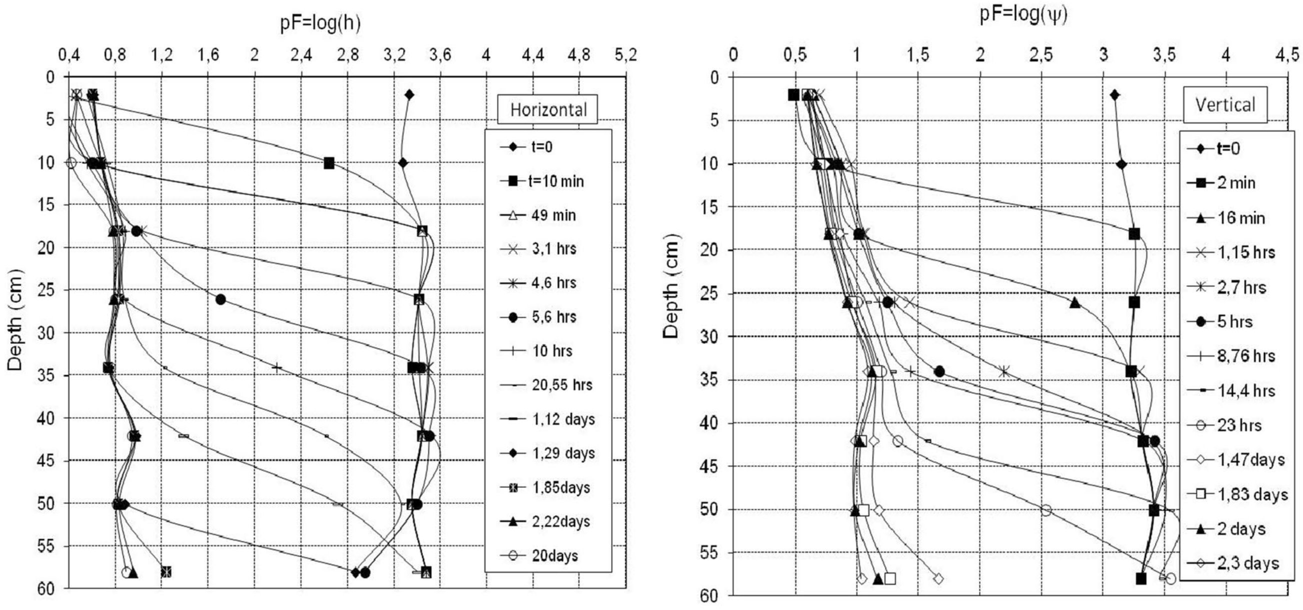
The diffusivity variation curves versus the volumetric water content $D(\theta)$ obtained by the instantaneous profiles method are shown in Fig. 7. The diffusivity values of vertical column are higher than those of horizontal column. Therefore, Eq. (6) overestimates the values of diffusivity. This difference further proves gravity influence on water flow. Despite this difference, the values of the diffusivities remain in the same order of magnitude ($\times 10^{-7}$).



(a)

(b)

Fig. 5 Moisture profiles



(a) **(b)**

Fig. 6 Suction profiles

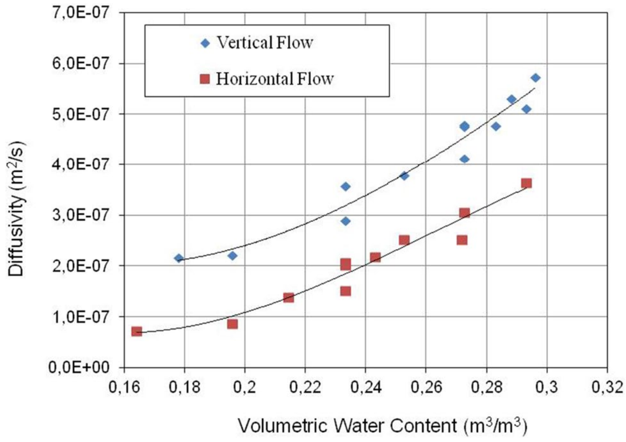


Fig. 7 Diffusivity variation curves vs. volumetric water content

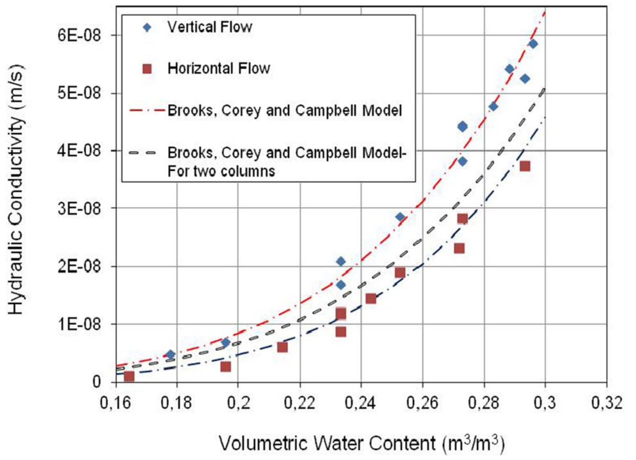


Fig. 8 Model of Brooks and Corey (1966) and Campbell (1974): $K(\theta)$

The soil hydraulic conductivity variation versus volumetric water content is plotted in Fig. 8. The hydraulic conductivities in the two columns vary with the same manner. These curves show an increase of hydraulic conductivity according to volumetric water content (horizontal flow and vertical flow cases). For given volumetric water content, the hydraulic conductivity of vertical column is always slightly superior than that of horizontal column. When the water content increases, the difference between the measured hydraulic conductivities increases (in vertical and horizontal flow).

Since the two soil columns contain the same soil compacted at the same conditions, the two hydraulic conductivity curves must be very close or even superimposed. But in our case, we notice a slight difference between the two curves. This difference probably results from the high velocity of vertical infiltration noted in the water profiles and the difference in velocity in the infiltration curve. In the vertical column, when water saturates a layer causes a slight increase in the hydraulic head in the soil which is not the case in the horizontal column. These variations led to a slight dysfunction in the theoretical framework of the instantaneous profile method.

3.5 Model *K*(*θ*)—Model of Brooks and Corey (1966) and Campbell (1974)

The measured soil permeability coefficient at saturation K_s is equal to 6×10^{-8} m/s. The model of Brooks and Corey (1966) and Campbell (1974) describes the variation of hydraulic conductivity vs. water content. The hydraulic conductivity of this model is written according to Eq. 10. We seek the parameters θ_s, K_s and *m* values which permit at this model to represent well the experimental results.

Figure 8 shows the experimental points of the horizontal and vertical columns. We also represent the curve given by the model of Brooks and Corey (1966) and Campbell (1974) obtained after the model parameters determination. These parameters make it possible to obtain a curve which represents the experimental points. The parameters of this model change depending on the studied case.

Figure 8 shows the experimental points of the horizontal and vertical columns. We also represent the curve given by the model of Brooks & Corey (1966) and Campbell (1974), obtained after the model parameter determination. These parameters make it possible to obtain a curve, which represents the experimental points. The parameters of this model change depending on the studied case.

The saturation water content value in vertical flow is close to that obtained in the horizontal flow case. We also note that the saturation permeability coefficient in the vertical column is slightly higher than that obtained in the horizontal column. The saturation permeability coefficient of the vertical column is 15% higher than the permeability coefficient obtained in the horizontal column. The used model well represents the experimental points of a vertical or horizontal flow. Since the soil in the two columns is the same, we propose to establish a global model representing the measurement points in the two columns (Fig. 8). The global parameters of the model are presented in Table 3.

Table 3 Parameters of the Brooks and Corey (1966) and Campbell (1974) model

	K_s (m/s)	θ_s (m^3/m^3)	*m*
Vertical column	6.4e−8	0.3	5
Horizontal column	5.5e−8	0.31	5.6
Global curve	6.0e−8	0.31	5

4 Conclusion

The study presented in this paper mainly concerns the analysis and interpretation of water infiltration tests carried out in the laboratory on unsaturated soil. This study permits some understanding of elements of soil water transfer in vertical and horizontal flow. To follow this transfer in real time and continuously, we used TDR probes. These probes make it possible to measure the soil water content and the electrical conductivity. The developed experimental device allowed for the evolution of moisture profiles during infiltration. This water content measurement made it possible to assess the infiltration rate and soil water flow. The experimental device allowed following the spatiotemporal distributions of water content and soil suction during infiltration using TDR probes. During water infiltration, there is a progressive propagation of moisture in the soil. The liquid movement by diffusion in the unsaturated soil has the same importance as the convection movement under the gravity effect. The convection movement is predominant during horizontal infiltration. The unsaturated water flow characteristics are slightly influenced by the nature of infiltration. The diffusivity values in the vertical column are higher than those measured in the horizontal column. Also, the hydraulic conductivities are slightly higher in the vertical column. The nature of infiltration must therefore be taken into account when dimensioning impermeable barriers. It is especially necessary to be careful when applying the theory of instantaneous profiles, it is preferable and sufficient to carry out tests on vertical soil columns to avoid any malfunction of the theoretical framework of the method. This research should be complemented by another study carried out on soil columns percolated by leachate. This research will allow for studying the influence pollutants on unsaturated water flow features and on soil structure.

References

Affeltranger B, Lasserre F (2003) La gestion par bassin versant: du principe écologique à la contrainte politique–le cas du Mékong. VertigO-la revue électronique en sciences de l'environnement 4(3)

Alimi-Ichola I, Gaidi L (2006) Influence of the unsaturated zone of soil layer on the solute migration. Eng Geol 85(1–2):2–8

Bentoumi O (1995). Transfert par infiltration de l'eau dans les sols fins compactes non saturés: Etude de la diffusivité et de la conductivité hydraulique. Doctoral dissertation, Lyon, INSA

Brooks RH, Corey AT (1966) Properties of porous media affecting fluid flow. J Irrig Drain Div 92(2):61–88

Campbell GS (1974) A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci 117(6):311–314

Childs EC, Collis-george N (1948) Interaction of water and porous materials. Soil Geom Soil Water Equilib 3:78–85

Cui YJ, Ferrari A, Gallipoli D, Jommi C, Laloui L, Pirone M et al (2004) Unsaturated soil mechanics. Int Soc Soil Mech Geotech Eng

Cui YJ, Tang AM, Loiseau C, Delage P (2008) Determining the unsaturated hydraulic conductivity of a compacted sand–bentonite mixture under constant-volume and free-swell conditions. Phys Chemof Earth, Parts a/b/c 33:S462–S471

da Silva AC, Armindo RA, Prevedello CL (2020) Utilizing Splintex 2.0 for estimating the soil hydraulic conductivity curve measured with instantaneous profile method. Soil Tillage Res 204:104722

Daniel DE (1983) Permeability test for unsaturated soil. Geotech Test J 6(2):81–86

Dieudonné AC, Charlier R (2017) Evaluation of the instantaneous profile method for the determination of the relative permeability function. In: Advances in laboratory testing and modelling of soils and shales (ATMSS). Springer, pp 181–188

Gaidi L, Alimi-Ichola I (2000) Etude des caractéristiques hydrodynamiques des sols par la méthode TDR (time domain reflectometry). Bull Eng Geol Environ 59(3):247–255

Hamilton JM, Daniel DE, Olson RE (1981) Measurement of hydraulic conductivity of partially saturated soils. Permeability and groundwater contaminant transport. ASTM STP 746:182–196

Krisdani H, Rahardjo H, Leong EC (2009) Use of instantaneous profile and statistical methods to determine permeability functions of unsaturated soils. Can Geotech J 46(7):869–874

Mualem Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour Res 12(3):513–522

Nadler A, Dasberg S, Lapid I (1991) Time domain reflectometry measurements of water content and electrical conductivity of layered soil columns. Soil Sci Soc Am J 55(4):938–943

Philip JR (1969) Theory of infiltration. In: Advances in hydroscience, vol 5. Elsevier, pp 215–296

Su W, Cui YJ, Qin PJ, Zhang F, Ye WM, Conil N (2018) Application of instantaneous profile method to determine the hydraulic conductivity of unsaturated natural stiff clay. Eng Geol 243:111–117

Topp GC, Davis JL, Annan AP (1980) Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour Res 16(3):574–582

Vachaud G (1966) Vérification de la loi de Darcy généralisée et détermination de la conductivité capillaire à partir d’une infiltration horizontale

Van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44(5):892–898

Vauclin M (1971) Effets dynamiques sur la relation succion-teneur en eau lors d'écoulements en milieu non saturé. Doctoral dissertation, Université scientifique et médicale de Grenoble

Velly N (2000) Etude des méthodes d'interprétation des essais d'infiltration in situ dans les sols non saturés. These De Docteur De L'ecole Nationale Des Ponts Et Chaussees En Geologie De L'ingenieur

Wang Q, Cui YJ, Tang AM, Barnichon JD, Saba S, Ye WM (2013) Hydraulic conductivity and microstructure changes of compacted bentonite/sand mixture during hydration. Eng Geol 164:67–76

Wesseling J, Wit KE (1966) An infiltration method for the determination of the capillary conductivity of undisturbed soil cores (no. 81)

Ye WM, Cui YJ, Qian LX, Chen B (2009) An experimental study of the water transfer through confined compacted GMZ bentonite. Eng Geol 108(3–4):169–176