Wetting Front Velocity Determination in Soil Infiltration Processes: An Experimental Sensitivity Analysis

Eduardo Rubio 1,*, María del Socorro Rubio-Alfaro 2 and Martín Hernández-Marín 2

1 Centro de Ciencias de la Ingeniería, Universidad Autónoma de Aguascalientes, Av. Universidad 940, Ciudad Universitaria, Aguascalientes 20100, Mexico
2 Centro de Ciencias del Diseño y de la Construcción, Universidad Autónoma de Aguascalientes, Av. Universidad 940, Ciudad Universitaria, Aguascalientes 20100, Mexico; rubio.socorro@hotmail.com (M.d.S.R.-A.); mhernandez@correo.uaa.mx (M.H.-M.)
* Correspondence: erubio@correo.uaa.mx; Tel.: +52-(449)-9107400

Abstract: An experimental approach for measuring the wetting front velocity in soils during water infiltration processes is presented. This experimental research is developed to test the sensitivity of the measurement technique in the detection of differences in the dynamics of the wetting front advancement in different soil testing scenarios. Experimental scenarios include undisturbed and artificially compacted soils, square and circular cross-sections of soil samples, water flowing in both directions downward and horizontal, and water infiltration in a block soil sample. The measurement technique is based on wetting front detection employing moisture sensors that measure the soil’s electrical conductivity. The technique was able to detect differences in wetting front in contrasting scenarios. Two-dimensional wetting front advancement experiments carried out on a block sample confirmed the results obtained for the one-dimensional case.

Keywords: experimental; moisture sensor; soil infiltration; wetting front dynamics; compacted soil; undisturbed soil; one-dimensional; two-dimensional

1. Introduction

Soil moisture is a key parameter for understanding processes in agronomy, biology, and hydrology and plays an important role in the organization of natural ecosystems and biodiversity. It is very dynamic and depends on factors such as the amount of rainfall, water consumption by plants, air, and soil temperature, among others. In practice, the moisture content of soils is usually determined by weight differences between wet and dry soil samples, but this can be considered an impractical process. Modern techniques developed nowadays allow the continuous monitoring of soil water content. There are reports in the literature that provide a deep review of the techniques for soil moisture measurement [1,2].

The use of the wetting front advancing method in the characterization of various soil types has also been reported. An example is an experimental work carried out in sand to silty clay soils, where acrylic columns with soil samples, instrumented with soil moisture meters and tensiometers, are used to conduct capillary rise tests and downward infiltration tests [3]. The determination of moisture contents, infiltration processes, and water dynamics in soils are subjects that have received great attention. Thus, various laboratory experimental approaches can be found. Among these is the study of mulched furrows with a cuboid soil chamber made from Flexiglas material, where the dynamic position of the moving wetting front in horizontal and vertical directions was recorded with a marker on the surfaces of the chamber [4]. Other studies showed that soil infiltration measurements, with point source methods made on an equilateral triangle cross-section box and a transparent film sheet for the measurement of the surface wet radius advancement, are useful in the design of drip irrigation systems [5].
Even though this paper is aimed to experimentally observe and measure the dynamics of the wetting front in initially dry soil, modeling may complement integral investigations on flow in rigid porous unsaturated material. On this matter, the classical Richards’ equation [6] and some derivatives such as the van Genuchten equation [7] are typically used, as well as methods such as the finite element that represent the base for analytical development and simulations involving parameters such as infiltration and hydraulic conductivity of unsaturated soil (i.e., [8,9]).

New methodologies have been explored to study critical zone water displacements in hydrological and agricultural fields of applications through the determination of the Darcy velocity from temperature measurements. Pt100 thermistors can be used to determine water flux through the soil on the basis that these sensors are sensitive to water flux. The limitations imposed using conventional low-sensitivity temperature sensors (0.1 K) are overcome by using high-precision sensors (0.001 K). This is achieved through the application of numerical models of convective and conductive heat transfer as a function of depth and time [10]. Models for predicting the wetted volume in soils by finger or preferential flows are reported. Finger flows development is studied with a two-dimensional apparatus composed of an acrylic chamber with a rainfall simulator. Measurements are made with a ruler, photographs, and tensiometers. The approach can get a downward growth model of a finger with subsequent lateral expansion and estimation of the wetted fraction [11].

Preferential flows in loess studied in the field have also been reported, where complete soil columns of 105 cm diameter and 160 cm depth were excavated in the field and instrumented with moisture and water potential sensors. Changes in the wetting front were measured with fixed rules and recorded with photographs. It is reported that vertical cracks distribute the water heterogeneously in the soil, with a positive linear relationship between the infiltration rate and the reciprocal of the wetting front depth under homogeneous infiltration but non-linear under preferential infiltration [12].

A linear source method is suggested for measuring soil infiltrability on sloping land, intended to overcome the problems of the conventional sprinkler method in measuring high initial infiltration rates and its applicability in sloping soils. A flume with a measuring tape, a linear water distributor for water supply of constant flow rate, a digital camera to record the advancement of the wetted areas, and measurement tapes attached to both sides of the flume are used. Mathematical models are used to compute the soil infiltrability-time function from the wetted soil surface area in accordance with the measured data [13]. Horizontal absorption tests in loess soil have also been conducted, where moisture sensors are used in an acrylic column with compacted loess soil for the measurement of hydraulic conductivity [14].

Empirical models are proposed to improve the design of drip irrigation systems. These models are developed for predicting the wetted radius on the soil surface and its corresponding wetted depth, as well as the wetted radius at different soil depths, to predict the full wetting pattern. Models are obtained from experiments made in a soil container with sides of Plexiglas sheets to monitor the advance of the wetting patterns. A moveable tank is used to provide a variable hydraulic head of water, and a ruler and webcam are used to measure the amount of applied water and the change in water elevation. A constant hydraulic head is provided with a float [15].

Two-dimensional maps of water content in unsaturated porous media can be determined by non-invasive imaging techniques. No tracer, dye injection, or calibration experiment is needed in this approach. This technique uses a rectangular flow tank with Plexiglas walls for visual observation of water content changes. Water flow is monitored with a bottle on a digital balance and a peristaltic pump. The photometric methodology that uses images recorded and processed with a digital camera system enables the representation of water content evolution over time. This technique has advantages compared with conventional procedures, which measure water content only at specific locations in the soil [16].
Advanced imaging techniques like Synchrotron X-rays are useful in the study of the wetting front characteristics. Experiments are reported where this technique is used to measure water content in a polycarbonate chamber filled with quartz sand. Miniature tensiometers are used to measure matric potential, and patterns are recorded with a CCD camera, where blue dye is used for better visualization of the infiltrating water. Source point infiltration is performed with distilled water through a hypodermic needle. With this approach, it can be observed that the wetting front changes from unstable to a stable Richards’ type. The stable Richards’ flow was characterized by a front moving both sideways and downward, with pressure and water content increasing behind the unsaturated wetting front [17].

Real-time imaging systems with neutron radioscopy to investigate the finger diameter and propagation velocity dependence on soil and wetting phase properties can also be found. Experiments are conducted in an infiltration column fabricated with an aluminum sheet. Quartz sand is placed into the column with a finer porous medium on top to control the rate of infiltration into the column. Aluminum oxides are used for the fine layer. A funnel is used to maintain a constant water depth at the top of the infiltration column. Neutron radioscopy is like X-ray imaging, and it is based on the fact that water has a high affinity for neutrons and will absorb them when subjected to a neutron beam. Quartz sand and aluminum allow neutrons to pass through unattenuated. It is considered a very accurate and reliable method to produce reliable finger diameter and velocity data [18].

The objective of this research is to demonstrate the sensitivity of a measurement technique for detecting small differences in moisture dynamics in soils under laboratory experimental conditions and, therefore, to be able to delineate a wetting front in porous media. Other physical properties of soils and their relationship with water dynamics are beyond the scope of this research.

2. Materials and Methods

The wetting front velocity determination is based on the use of soil moisture sensors. Soil moisture was measured at several points in the soil samples. For that, a computer-based multi-channel data acquisition system was implemented (Figure 1). The output signal of the sensors was coupled to signal conditioners and fed to a data acquisition system to be processed by a computer program. Data processing and recording were implemented by a program developed in LabVIEW software.

![Figure 1. General scheme of the data acquisition and processing system.](image)

Details for each channel of the sensor circuit are shown in Figure 2. Moisture detection is based on the dependence of the soil’s electrical conductivity on water content. For a high-water content in the soil, the electrical resistivity is low, while for low water content, the electrical resistivity is high. A fork-shaped sensor is nailed into the soil sample to get a measurement of the electrical conductivity. The signal is connected to an electronic circuit with analog and digital outputs. Analog output is processed with a voltage follower for which the output voltage is equal to the input voltage. For the case of the digital output, the signal of the sensor is compared with an adjustable reference voltage to set the threshold for moisture detection. This circuit offers a binary output voltage between 0 V and +Vcc.
For the experiments reported in the present work, a binary output was used as an indicator of the wetting front detection. Total measurement uncertainties are a result of fixed and random errors. In this case, the electrical signal at the input of the active circuits that drives the binary result (wet/not wet) defines the precision of the instrument. For dry soil, a high-level electrical signal with variations between successive measurements is obtained. Once the wetting front reaches the sensor, the signal changes to low. If these variations are large, a false wetting front can be detected. The standard deviation of this signal is a measure of the amount of dispersion of the set of values. For the proposed approach, a standard deviation of 0.0142 V was obtained for a signal with a span of 2.93 V. The use of several sensors along the soil sample gives the information to plot a time-position graph of the wetting front.

Laboratory experiments were conducted with two dry soil types. The first type was undisturbed soil collected nearby the San Pedro River, inside the city of Aguascalientes, Mexico. The second type of soil sample was composed of compacted gravel prepared in the laboratory with a hand soil compactor after being sieved by #4 and #10 meshes. For the present work, the latter will be named compacted soil. Undisturbed soil was hand-carved to get 19 cm high cylindrical samples ∅12 cm and square cross-section blocks 9 cm × 9 cm × 22.5 cm, while disturbed soil was compacted to get only cylindrical samples with the dimensions indicated earlier. Different shape samples, material types, and orientations were used to test the sensitivity of the measurement methodology.

Figure 3 shows the components of the experimental set-up with the soil sample. Moisture sensors were distributed along the soil sample to detect the wetting front advancement. A latex membrane was used to confine the water in the soil, and multi-purpose lithium grease was used as a seal to prevent the water from taking a preferential flow along the walls of the assembly. Sidewall leakage is an important aspect that needs to be addressed. In this regard, other authors have treated clay loam soil with glue and sprayed it with sand to create a coarse surface [19], Vaseline lubricating jelly on the edges of soil chambers [20], or soil specimens tightly wrapped with a resistant filament tape [21]. The arrangement of the soil sample for experiments with horizontal wetting front advancement is shown in Figure 4.

A two-dimensional characterization of the wetting front was also carried out in an undisturbed soil sample of 35 cm × 17.5 cm × 9.5 cm. Figure 5 shows the location of the moisture sensors distributed in a matrix structure in the undisturbed soil block sample. For this case, the water source was a point type at the top center of the block.
Figure 3. Set-up of the soil sample column with water source on top for moisture transfer in the vertically downward direction.

Figure 4. Sketch of the soil sample column for experiments with moisture transfer in the horizontal direction.

Figure 5. Block soil sample for experiments to get a two-dimensional plot of the wetting front advancement.
3. Results

Under the described methodology, the time the wetting front took to reach each sensing point from the surface was measured, and a time vs. distance plot was obtained, as shown in Figure 6. The points in this plot represent the location of the sensors, while the continuous line is a data interpolation.

![Position-time plot](image)

**Figure 6.** Position-time plot for the wetting front advancement.

As can be seen in Figure 6, the wetting front advancement shows a non-linear trend. Sensors are equally spaced. However, the wetting front takes 119 s to travel the distance between the first and the second sensor, while for deeper sensors, for example, between the fourth and fifth sensors, the wetting front takes 568 s. The wetting front moves faster near the surface of the soil sample. It can be noted that the velocity of the wetting front at a given point can be calculated from this plot.

3.1. Vertical Wetting Front Advancement for a Cylindrical Sample

This case analyzes a comparison of results between cylindrical cross-section soil samples for artificially compacted and undisturbed soils placed in a vertical position, as shown in Figure 3. Results for wetting front velocity vs. distance plots were also obtained (Figure 7).

![Wetting front velocity profile](image)

**Figure 7.** Wetting front velocity profile for the cylindrical soil sample in vertical position for compacted and undisturbed soil.

In this figure, the non-linear nature of the velocity of the water infiltration can be observed. However, infiltration velocities are higher for the compacted soil since near the surface, the compacted soil wetting front travels to a velocity of 490 mm/h, while for the undisturbed soil, the velocity is 346 mm/h. This response can be attributed to the different soil structures between compacted soil, which was prepared of sieved gravel, and undisturbed soil, which was basically clay. Therefore, the porosity of both materials is contrasting. However, at greater depths, both traces tend to be asymptotic to the same
wetting front velocity. That is the case because, as the soil is fully saturated, the suction characteristics tend to be more uniform in both soils.

3.2. Wetting Front Advancement Dependence on Orientation for Undisturbed and Square Cross-Section Soil Sample

This case analyzes a comparison of results of the wetting front dynamics between the samples positioned vertically (Figure 3) and horizontally (Figure 4) for undisturbed soil. Results are shown in Figure 8. As can be seen, the wetting front moves faster in the horizontal direction than in the vertical direction. This trend is observed by the higher velocity values obtained throughout the experiment. The non-linear trend in the velocity profile in both cases is also observed, as well as a higher velocity of the wetting front near the water source. The asymptotic trend at points far from the water source is also present but at different velocity values. For this case, the slower wetting front advancement in the vertical soil sample can be attributed to suction forces that slow down the water movement. Nevertheless, the difference between both hydraulic head directions may influence the response.

![Figure 8](image1.png)

**Figure 8.** Wetting front velocity profile for the undisturbed soil sample for horizontal and vertical moisture transfer.

3.3. Wetting Front Advancement Dependence on Cross-Section Shape for Undisturbed Soil Sample

In this section, a comparison of the wetting front dynamics under square and cylindrical cross-section shapes for undisturbed soil samples positioned vertically is shown in Figure 9.

![Figure 9](image2.png)

**Figure 9.** Undisturbed soil wetting front velocity profiles for square and cylindrical cross-section soil samples.
This graph shows that the methodology approach of the present work is sensitive to the wetting front velocity differences between both geometries. Major differences are observed near the surface of the soil samples, while the wetting front velocity values are the same at a distance of 70 mm from the water source. From this point on, measurements do not offer a wetting front velocity difference based on the cross-section for the tested geometries. In fact, velocity trends are reversed after this point, showing a strong dependence of the wetting front velocity on the cross-section of the soil sample.

3.4. Two-Dimensional Wetting Front Advancement for an Undisturbed Block Soil Sample

Results for the block soil sample with a water source at the top center are shown in a two-dimensional plot in Figure 10. Isolines are marked with the displacement time of the wetting front.

![Figure 10. Two-dimensional time-position profile of the wetting front advancement for undisturbed block soil sample.](image)

Results shown in Figure 10 (as in Figure 8) also suggest that the wetting front travels faster in the samples positioned in a horizontal direction. This fact is more evident near the water source, where the wetted distance from the water source is higher in the horizontal direction than in the vertical direction. This is in concordance with Figure 8, where the wetting front velocity difference is more evident near the soil sample surface. As expected, as the wetting front travels deeper into the soil sample, velocity values are far more different.

3.5. Visual Soil Moisture Distribution on a Square Cross-Section Soil Sample

Figure 11 shows results for the undisturbed square cross-section soil sample with water flowing in the horizontal direction, as shown in Figure 4. This figure shows the wetting patterns’ evolution in time on the face of the soil sample opposite to the water source. Wetted soil can be observed in a darker tone.

The soil moisture distribution observed in these images shows a preferential flow on the right side of the soil sample. Additionally, as observed, fissures directly influence the flow pattern since water first follows their traces. Gravity forces would force water to flow downward and start moistening the soil in the lower portion of the sample. This fact would be more pronounced in sandy soil where macropores dominate. However, this is not the case for the clay soil studied, where capillary forces prevail, avoiding the accumulation of water on the bottom of the sample.
4. Conclusions

An experimental approach has been developed to measure the wetting front velocity in infiltration processes for undisturbed and compacted soil samples, using square and circular cross-section geometries and vertical and horizontal water flow directions. The methodology was implemented with soil moisture sensors that detected the wetting front based on the electrical conductivity of the water content. One-dimensional and two-dimensional experiments were carried out.

The applied methodology was able to characterize the small differences in the wetting fronts for the soil samples subjected to different soil types, as well as different shapes and orientations of the tested samples. For all the experiments conducted, the non-linear nature of the wetting front velocity evolution during the infiltration of water was observed, with higher values of the wetting front advancement on the surface near the water source. As the wetting front advanced, its velocity was gradually decreasing showing an asymptotic trend.

For large grain-size and artificially compacted soil samples, the wetting front velocities were higher than those obtained from the undisturbed soil. For the case of water transport in the horizontal direction, wetting front velocities were higher than velocities obtained for the downward direction, explained by the faster water saturation of the soil with the sample standing vertical, although the different hydraulic heads must be considered. Concerning the geometry of the cross-section of the samples, higher wetting front velocities were obtained for the square geometry, although after the wetting front reached the halfway point of the sample, measurements did not report geometry appreciable differences. Two-dimensional measurements confirmed higher wetting front velocities in the horizontal direction, and camera image recordings showed a moistening process dominated more by fissure flow and capillarity than by gravity forces in the clay soil. Based on these results, the measurement approach can be used with confidence in the research of wetting front dynamics.

Author Contributions: Conceptualization, E.R. and M.H.-M.; methodology, E.R. and M.d.S.R.-A.; software, E.R.; validation, E.R., M.H.-M. and M.d.S.R.-A.; formal analysis, E.R. and M.H.-M.; investigation, E.R., M.H.-M. and M.d.S.R.-A.; resources, E.R. and M.H.-M.; data curation, E.R. and M.d.S.R.-A.; writing—original draft preparation, E.R.; writing—review and editing, M.H.-M. and M.d.S.R.-A.; visualization, E.R. and M.d.S.R.-A.; supervision, M.H.-M.; project administration, E.R.

All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare no conflict of interest.

References
1. Vereecken, H.; Huisman, J.A.; Bogena, H.; Vanderborght, J.; Vrugt, J.A.; Hopmans, J.W. On the value of soil moisture measurements in vadose zone hydrology: A review. Water Resour. Res. 2008, 44. [CrossRef]
2. Su, S.L.; Singh, D.N.; Baghini, M.S. A critical review of soil moisture measurement. Measurement 2014, 54, 92–105. [CrossRef]
3. Liu, Q.; Xi, P.; Miao, J.; Li, X.; Wang, K. Applicability of wetting front advancing method in the sand to silty clay soils. Soils Found. 2020, 60, 1215–1225. [CrossRef]
4. Zhang, Y.; Wu, P.; Zhao, X.; Zhao, W. Measuring and modeling two-dimensional irrigation infiltration under film-mulched furrows. Sci. Cold Arid. Reg. 2016, 8, 419–431.
5. Mao, L.; Li, Y.; Hao, W.; Mei, X.; Bralts, V.F.; Li, H.; Guo, R.; Lei, T. An approximate point source method for soil infiltration process measurement. Geoderma 2016, 264, 10–16. [CrossRef]
6. Richards, L.A. Capillary conduction of liquids through porous mediums. Physics 1931, 1, 318–333. [CrossRef]
7. Van Genuchten, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 1980, 44, 892–898. [CrossRef]
8. Berardi, M.; Difonzo, F.; Notarnicola, F.; Vurro, M. A transversal method of lines for the numerical modeling of vertical infiltration into the vadose zone. Appl. Numer. Math. 2021, 161, 131–145. [CrossRef]
9. Zhu, S.R.; Wu, L.Z.; Huang, J. Application of an improved P(m)-SOR iteration method for flow in partially saturated soils. Computat. Geosci. 2021, 26, 131–145. [CrossRef]
10. Tabbagh, A.; Cheviron, B.; Henine, H.; Guérin, R.; Bechkit, M.A. Numerical determination of vertical water flux based on soil temperature profiles. Adv. Water Resour. 2017, 105, 217–226. [CrossRef]
11. Kawamoto, K.; Mashino, S.; Oda, M.; Miyazaki, T. Moisture structures of laterally expanding fingering flows in sandy soils. Geoderma 2004, 119, 197–217. [CrossRef]
12. Ma, J.; Zeng, R.; Yao, Y.; Meng, X.; Meng, X.; Zhang, Z.; Wang, H.; Zhao, S. Characterization and quantitative evaluation of preferential infiltration in loess, based on a soil column field test. CATENA 2022, 213, 106164. [CrossRef]
13. Mao, L.L.; Lei, T.W.; Li, X.; Liu, H.; Huang, X.F.; Zhang, Y.N. A linear source method for soil infiltrability measurement and model representations. J. Hydrol. 2008, 353, 49–58. [CrossRef]
14. Hu, H.; Cui, Y.; Li, C.; Su, W.; Wang, Z. Improvement of three common methods for determining hydraulic conductivity curve of unsaturated soil upon wetting. J. Hydrol. 2021, 594, 125947. [CrossRef]
15. Al-Ogaidi, A.A.; Wayayok, A.; Rowshon, M.K.; Abdullah, A.F. Wetting patterns estimation under drip irrigation systems using an enhanced empirical model. Agric. Water Manag. 2016, 176, 203–213. [CrossRef]
16. Belfort, B.; Weill, S.; Lehmann, F. Image analysis method for the measurement of water saturation in a two-dimensional experimental flow tank. J. Hydrol. 2017, 550, 343–354. [CrossRef]
17. Bauters, T.W.J.; DiCarlo, D.A.; Steenhuis, T.S.; Parlange, J.Y. Soil water content dependent wetting front characteristics in sands. J. Hydrol. 2000, 231–232, 244–254. [CrossRef]
18. Tullis, B.P.; Wright, S.J. Wetting front instabilities: A three-dimensional experimental investigation. Transp. Porous Media 2007, 70, 335–333. [CrossRef]
19. Kandolus, M.M.; Šimůnek, J. Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. Agric. Water Manag. 2010, 97, 1070–1076. [CrossRef]
20. Wang, Y.; Li, Y.; Wang, X.; Chau, H.W. Finger flow development in layered water-repellent soils. Vadose Zone J. 2018, 17, 1–11. [CrossRef]
21. Su, W.; Cui, Y.J.; Qin, P.J.; Zhang, F.; Ye, W.M.; Conil, N. Application of instantaneous profile method to determine the hydraulic conductivity of unsaturated natural stiff clay. Eng. Geol. 2018, 243, 111–117. [CrossRef]