Tikrit Journal of Engineering Sciences (2023) 30 (3): 174-189

DOI: http://doi.org/10.25130/tjes.30.3.16

IRAQI Academic Scientific Journals

College of Engineering

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Effect of Soil Bulk Density on Water Infiltration in Layered Soil

Ahmed A. M. Al-Ogaidi *[a], *Mohammad Tariq Mahmood* [b], *Abdulghani Khalaf Mohammed* [a], *Haqqi Ismail Yasin* [a]

a Dams and Water Resources Engineering Department, College of Engineering, University of Mosul, 41002, Mosul, Iraq.

b Dams and Water Resources Research Center, University of Mosul, 41002, Mosul, Iraq.

Keywords:

Bulk Density, Empirical Equations, Infiltration Rate, Soil Moisture, Kostiakov Equation.

ARTICLE INFO

Article history:

Received	11 May	2023
Received in revised form	18 July	2023
Accepted	22 Aug.	2023
Final Proofreading	06 Oct.	2023
Available online	08 Oct.	2023

Citation: Al-Ogaidi AAM, Mahmood MT, Mohammed AK, Yasin HI. **Effect of Soil Bulk Density on Water Infiltration in Layered Soil**. *Tikrit Journal of Engineering Sciences* 2023; **30**(3): 174-189.

http://doi.org/10.25130/tjes.30.3.16

Corresponding author:

Ahmed A. M. Al-Ogaidi

Dams and Water Resources Engineering Department, College of Engineering, University of Mosul, 41002, Mosul, Iraq.

Abstract: The optimal design of various irrigation systems requires knowledge and a deep understanding of various soil properties. Water infiltration in the soil is among the most prominent of these characteristics. Ten laboratory experiments were conducted to study the effect of the bulk density of stratified soils (two-layered soils), Where sandy loam soil, and clay soil were used. Three bulk density values were adopted for each soil, and experiments were conducted in different sequences. New empirical relationships were derived to calculate the cumulative infiltration depth and the depth of the wetting front in terms of time and the basic infiltration rate of the soil. The results revealed a high agreement between the values measured in the laboratory and those estimated from the proposed empirical equations for infiltration and wetting front depths with a coefficient of determination of 0.96 and 0.98, respectively. The results showed that the infiltration and wetting front depths increased with the cumulative infiltration time and the soil bulk density reduction, regardless of the soil location in the upper or lower layer within the stratified soil. It was also found that the infiltration rate was affected by the density of the upper stratum more than its influence by the change in the density of the lower stratum.

تأثير الكثافة الظاهرية للتربة على ارتشاح الماء في تربة طباقية

احمد علي محمد العكَيدي[1]، محمد طارق محمود[2]، عبدالغني خلف محمد[1]، حقي إسماعيل ياسين[1]
[1] قسم هندسة السدود والموارد المائية / كلية الهندسة / جامعة الموصل / الموصل - العراق.
[2] مركز بحوث السدود والموارد المائية / جامعة الموصل / الموصل - العراق.

الخلاصة
ان التصميم الأمثل لمختلف أنظمة الري يتطلب معرفة وفهم عميق لمختلف خصائص التربة وتعتبر عملية ارتشاح الماء في التربة من بين أبرز هذه الخصائص. تم اجراء 10 تجارب مختبرية لدراسة تأثير تغير الكثافة الظاهرية للترب الطباقية (ترب مكونة من طبقتين) حيث تم استخدام تربة مزيجية رملية وتربة طينية وتم اعتماد ثلاث قيم للكثافة الظاهرية لكل تربة وتم اجراء التجارب بتعاقبات مختلفة. تم اشتقاق علاقة تجريبية لعمق الارتشاح التراكمي ولعمق جبهة الابتلال بدلالة كل من الزمن ومعدل الارتشاح الأساس للتربة. بينت النتائج ان هنالك توافق عال بين القيم المقاسة مختبريا وتلك المخمنة من المعادلات التجريبية المقترحة لكل من عمق الارتشاح وعمق جبهة الابتلال وبمعامل تحديد مقداره 0.96 و0.98 على التوالي. أظهرت النتائج ان كل من عمق الارتشاح وعمق جبهة الابتلال يزداد مع زيادة زمن الارتشاح التراكمي وكذلك كلما قلت الكثافة الظاهرية للتربة بغض النظر عن موقع التربة في الطبقة العليا ام السفلى ضمن التربة الطباقية. كما تبين ان معدل الارتشاح يتأثر بكثافة الطبقة العليا أكثر من تأثره بتغير كثافة الطبقة السفلى.

الكلمات الدالة: الكثافة الظاهرية، معادلات تجريبية، معدل الارتشاح، رطوبة التربة، معادلة كوستياكوف.

1.INTRODUCTION

The study of water's downward vertical movement through the soil surface, which is called the process of infiltration, has an essential role from a practical point of view to reach the optimal design of the various irrigation systems. The infiltration occurs due to the clear and combined effect of the gravity and tension forces and the simple effect of the head of water above the soil surface. The infiltration process is affected by numerous factors, most notably the soil properties (texture, structure, and bulk density), its initial moisture, the condition of its surface, the rate of water application, physical and chemical properties of water, the temperature of the soil and water, and the condition of the soil profile (homogeneous or stratified) [1, 2]. Soil water dynamics play a significant role in the hydrological cycle [3, 4]. Ref. [5] showed that water infiltration into soils is not only important for agriculture but is also considered one of the two main functions of the ecosystem, i.e., garbage decomposition and infiltration. It was found that the different types of vegetation cover affect the infiltration process, as the infiltration rate is inversely related to the bulk density of the soil. The mulching also acts as a surface layer that impedes the process of water infiltration through the soil. Soil formations and extents in nature show heterogeneity more than homogeneity within porous media, such as vertical layers of various compositions [6]. These stratified soil profiles are widely spread in fields adjacent to rivers [7]. The field soils, in general, are heterogeneous and may be stratified soils, as the plowed soils may have the characteristics of two layers, i.e., the disturbed surface layer and the undisturbed subsurface layer [8]. A surface crust may also form on the barren plowed soil due to the direct impact of raindrops on the soil surface, which also produces the layering effect [9]. Studies showed that water movement in heterogeneous soils significantly differed from its movement in homogeneous soils [10]. Over the past decades, many studies have shown that precise quantification of soil hydraulic processes is vital for regulating restricted water resources in agriculture and delivering upcoming benefits [11-13]. Since soil water flow is affected by the soil's texture, porosity, and hydraulic properties, characterizing soil heterogeneity's effect on soil water movement is vital for the optimal use of water resources [14, 15]. Soil strata with contrasting properties form overlapping barriers that may reduce the porous contact and thus reduce the hydraulic conductivity of the soil [16]. This barrier has a positive impact as it increases the soil's water-holding capacity [17]. Previous studies also indicated that the sequence and succession of soil layers clearly affect water infiltration and sedimentation [18]. It was noted by [19] that the vertical arrangement of the soil strata from the finest at the surface down to the coarsest might lead to preferential or finger flow due to the forces of gravity and water repulsion in most cases. In contrast, it was noted by [20] that the vertical arrangement of the soil layers, from the coarsest down to the finest, plays a crucial role in storing water throughout the soil profile. Ref. [21] proposed an empirical equation to estimate the cumulative infiltration depth in the form of the Kostiakov equation as a function of some physical properties of the soil, such as initial moisture, bulk density, and the percentages of sand, silt, and clay of the soil. This equation was derived based on laboratory data gathered from published papers. The results showed a high agreement between the values estimated from the proposed empirical equation and those measured in the laboratory. The results also showed that the depth and rate of infiltration decreased as the soil's bulk density or initial moisture increased. In addition, the depth and rate of infiltration increased as the soil's percentage of sand increased. Ref. [22] indicated that the soil layer with high resistance to penetration was the one that controlled the movement of water entering the soil and reduced the infiltration rate, where the surface soil is compressed and compacted soil due to agricultural activities reducing soil porosity, which is the most important pathway in the process of water infiltration in the soil. Ref. [23] conducted a field experiment to measure soil infiltration at 25 points within a network of points 10 m apart. The results showed differences in the soil properties and changes in the basic infiltration rate values from 3 mm/h to 68 mm/h. The results showed that the percentage of sand, the particle density, and the organic carbon content of the soil directly related to the rate of infiltration, while it was found that there was an inverse relationship between each of the percentages of silt, clay, bulk density, moisture content, and the infiltration rate. The researchers also derived an empirical equation to estimate the infiltration rate in terms of the percentages of sand, silt, clay, soil moisture content, bulk and particle soil density, and organic carbon content, with a high coefficient of determination. The importance of studying water flow in stratified soils is evident. Accordingly, the present research aims to study the effect of changing the bulk density of stratified soils on the infiltration and progression of water through it.

2.METHODS AND MATERIALS

2.1.*General Description of Laboratory Experiments*

The laboratory experiments for the research were conducted in the Physics and Management of Soil Water Laboratory of the Department of Dams and Water Resources Engineering/ College of Engineering /University of Mosul /Mosul /Iraq. Five types of soils were prepared by air drying, crushing, and sieving them with a 2-mm sieve. Then, the soil passing through this sieve was collected, spread, and well mixed to obtain a homogeneous soil. After that, the initial moisture content of the soil samples was evaluated by selecting several random samples. After achieving minimum differences in the soil moisture values among the selected soil samples, the soil was packed in sealed plastic bags to keep its initial moisture constant and to ensure a homogeneous distribution of this moisture. A hydrometer was also used to determine the percentages of sand, silt and clay of the soils, and these percentages were used to find the soil texture using the USDA soil triangle. Table 1 shows these percentages in addition to the initial moisture content of the soils used in the research. To conduct laboratory experiments and monitor the infiltration depth and the wetting front advance, two symmetrical transparent cylinders were prepared with an inner diameter of 11 cm and a height of 63 cm. The cylinders were perforated from the bottom and sides with small holes with a distribution that ensures that the soil air exits smoothly and does not impede the water movement through the soil (Fig. 1).

Table 1 Some Physical Properties of the Considered Soils.

Soil Texture	Sand %	Silt %	Clay %	Gravimetric Initial Moisture %
Loam	42	34	24	2.40
Clay loam	44	24	32	2.65
Sandy loam A	61	27	12	3.60
Sandy loam B	68	16	16	1.23
Clay	22	34	44	8.00

Fig. 1 The Transparent Cylinders Considered in the Laboratory Experiments.

2.2.*Infiltration Tests for Different Soil Profiles*

The experiments of layered soils included the use of two soils: one of them was sandy loam soil (A), and the other was clayey soil. These two soils were adopted to study the effect of layering on water infiltration. The stratified soil profile was prepared with a total height of 50 cm, of which 20 cm was for the upper stratum and 30 cm for the lower stratum. Soils were compacted in cylinders in the form of strata with a thickness of 5 cm for each layer based on specific soil weights according to the bulk density and initial moisture for each soil. Ten laboratory tests were carried out with different sequences of layers and bulk densities, as shown in Table 2. For all laboratory tests, tap water was used at a constant temperature of 21 °C. Water was added to the soil after covering it with a thin plastic piece (nylon) to prevent surface erosion and control the start time of the infiltration process. The head of the water above the soil surface was 10 cm, and when the water head reached 5 cm, water was quickly added to return the head to 10 cm again, and so on until the end of the experiment. The experiment time began after removing the thin plastic piece, and the depth of the infiltrated water was monitored through the soil surface and the advance of the wetting front for specific times that were close at the beginning of the experiment and diverged with the progress of the experiment time.

Table 2 Details of the Laboratory Experiments of the Layered Profiles.

Experiment no.	Soil texture of the Upper Layer	Bulk density of the Upper Layer, g/cm³	Soil texture of the Lower Layer	Bulk Density of the lower layer, g/cm³
1	Clay	1.27	Sandy loam A	1.52
2	Clay	1.36	Sandy loam A	1.52
3	Clay	1.46	Sandy loam A	1.52
4	Clay	1.27	Sandy loam A	1.63
5	Clay	1.46	Sandy loam A	1.63
6	Sandy loam A	1.42	Clay	1.36
7	Sandy loam A	1.52	Clay	1.36
8	Sandy loam A	1.63	Clay	1.36
9	Sandy loam A	1.42	Clay	1.46
10	Sandy loam A	1.63	Clay	1.46

It is vital to refer that one of the simplest and most common equations used to represent the depth of cumulative infiltration with time adopted by many researchers such as [24] is the ordinary Kostiakov equation [25], which is represented by the following formula:

$$D = ct^{m} \qquad (1)$$

where D is the cumulative infiltration depth (mm), t is the cumulative infiltration time (min), and c and m are empirical constants. By deriving this equation with respect to time, the infiltration rate equation is obtained as follows:

$$I = kt^{n} \qquad (2)$$

where I is the infiltration rate (mm/min), and k and n are empirical constants, where $k = cm$ and $n = m$-1. The US Department of Agriculture (USDA) defines the basic infiltration rate as the value on the infiltration rate curve at which the change in the infiltration rate in one hour is not more than 10%. By adopting this definition, the following equation was developed to estimate the basic infiltration time, Tb:

$$Tb = |600n| \qquad (3)$$

The absolute value was used in Eq. (3) because the value of n is negative, and time cannot be negative. From knowing the basic infiltration time and substituting its value into the infiltration rate, Eq. (2), the value of the basic infiltration rate Ib can be obtained as follows:

$$Ib = kTb^{n} \qquad (4)$$

The infiltration test was carried out for five homogeneous soils shown in Table 1 and for three bulk densities for each soil. After completing these tests, the infiltration function constants and the basic infiltration rate for each soil were calculated, as shown in Table 3.

Table 3 Infiltration Characteristics for the Considered Soil.

Soil Texture	ρ_b, g/cm³	Ib, mm/h	c	m
Loam	1.34	8.18	8.127	0.439
	1.44	6.70	7.059	0.433
	1.54	5.03	4.976	0.439
Clay loam	1.44	13.90	9.095	0.486
	1.54	9.89	6.765	0.481
	1.64	5.20	7.644	0.397
Sandy loam (A)	1.42	32.13	6.812	0.620
	1.52	19.83	6.751	0.562
	1.63	13.57	4.722	0.559
Sandy loam (B)	1.56	25.27	10.934	0.534
	1.66	15.15	7.714	0.515
	1.77	7.63	9.635	0.413
Clay	1.27	19.76	5.778	0.580
	1.36	8.86	5.821	0.485
	1.46	6.14	3.019	0.519

* ρ_b: bulk density, Ib: basic infiltration rate, and c and m are coefficients of the infiltration equation.

3.RESULTS AND DISCUSSION

3.1.Basic Infiltration Rate

The values of bulk density, basic infiltration rate, sand, silt, and clay percentages were adopted for the five soils, shown in Tables 1 and 3, to find an empirical relationship to estimate the basic infiltration rate for homogeneous soils. The following equation was suggested:

$$Ib = 39.5\rho_b^{-7.36}(-8.48Sa^{1.77} + 0.28Si^{-2.25} + 0.003C^{-3.84}) \qquad (5)$$

where ρ_b is the soil bulk density (g/cm³), and Sa, Si, and C are the sand, silt, and clay percentages, respectively (decimal fraction). The statistical computer program SPSS was adopted to estimate the coefficients of Eq. (5) using the non-linear regression method with 15 values for each of the variables included in the equation. These coefficients were derived with a high coefficient of determination of 0.974. Eq. (5) can be used to know the influence of the bulk density of homogeneous soil on the basic infiltration rate, as an increase in the soil's bulk density decreases the soil's basic infiltration rate, as illustrated in Fig. 2. The initial soil moisture was neglected as it has no effect on the final infiltration rate, and its effect is very little on the basic infiltration rate [21]. It is imperative here to refer that Eq. (5) can be applied for a specific range of values for bulk density (1.27 – 1.77 g/cm3), sand (22 – 68%), silt (16 – 34%), clay (12 – 44%), and gravimetric initial moisture (1.23 – 8%).

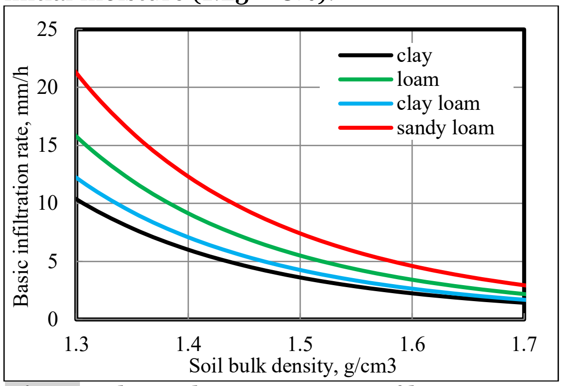


Fig. 2 Relation between Basic Infiltration Rate and Soil Bulk Density for Various Soil Textures.

3.2.Accumulated Infiltration Depth and Depth of Wetting Front

The depth of the cumulative infiltration and the depth of the wetting front is affected by numerous factors, including time, soil bulk density, the basic infiltration rate of the soil, the initial moisture of the soil, and other factors, such as the layering that has been studied in the current research. Accordingly, two empirical relationships were derived to estimate the cumulative infiltration depth and the wetting front depth for layered soils in terms of time and the basic soil infiltration rate, which is one of the soil characteristics that reflects its texture and structure [1]. The equations are as follows:

$$\boldsymbol{D} = \mathbf{100(18.9 + 1.35}\boldsymbol{Ibe} - \mathbf{10.57}\boldsymbol{Ibe}^{\mathbf{0.75}} + \mathbf{30.83}\boldsymbol{Ibe}^{\mathbf{0.5}} - \mathbf{39.6}\boldsymbol{Ibe}^{\mathbf{0.25}})\boldsymbol{t}^{\mathbf{0.576}} \qquad \textbf{(6)}$$

$$\boldsymbol{Z} = \mathbf{100(73.3 + 5.34}\boldsymbol{Ibe} - \mathbf{41.66}\boldsymbol{Ibe}^{\mathbf{0.75}} + \mathbf{120.89}\boldsymbol{Ibe}^{\mathbf{0.5}} - \mathbf{154.41}\boldsymbol{Ibe}^{\mathbf{0.25}})\boldsymbol{t}^{\mathbf{0.536}} \qquad \textbf{(7)}$$

Where Z is the wetting front depth (mm). The statistical computer program SPSS was adopted to estimate the coefficients Eqs. (6) and (7) using the non-linear regression method with 206 values for each variable included in the two equations. These coefficients were derived with a high determination coefficient of 0.96 and 0.98 for Eqs. (6) and (7), respectively. The values of another statistical criterion, i.e., the root mean square error RMSE, were considered, and they were 7.375 and 16.525 for Eqs. (6) and (7), respectively. Fig. 3 compares the laboratory-measured and predicted infiltration depth from Eq. (6) (Fig. 3A) and the laboratory-measured and estimated wetting front depth (Fig. 3B) from Eq. (7). The basic infiltration rate values were used for the layered soils so that its value is equal to the value of the basic infiltration rate for the soil of the upper layer until the wetting front reaches the boundary between the two layers, i.e., at a depth of 20 cm from the soil surface. After that, the equivalent basic infiltration rate value was used, which was calculated as computing the equivalent vertical hydraulic conductivity coefficient for layered soils because the basic infiltration rate is as close as possible to the saturated hydraulic conductivity coefficient of the soil. Therefore, the equivalent basic infiltration rate for the two layers was calculated as follows:

$$\boldsymbol{I_{be}} = \frac{\boldsymbol{h_1+h_2}}{\boldsymbol{h_1/I_{b1}+h_2/I_{b2}}} \qquad \textbf{(8)}$$

Where I_{be} is the equivalent basic infiltration rate (mm/h), I_{b1} and I_{b2} are the basic infiltration rates of the upper- and lower-layer soils, respectively (mm/h), and h_1 and h_2 are the thickness of the upper layer and the wetted depth of the lower layer (mm), respectively.

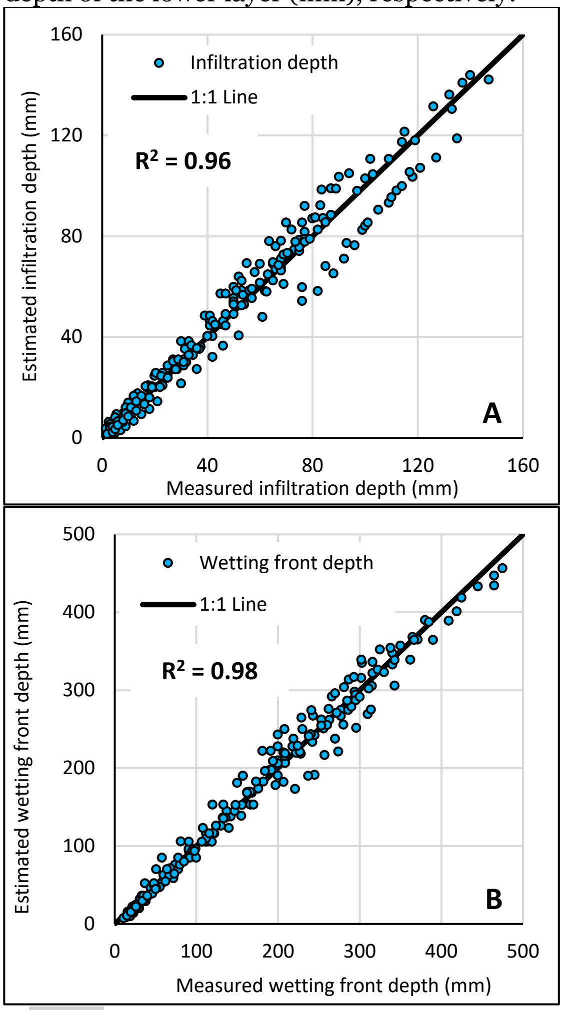


Fig. 3 Comparison between Measured and Estimated Values of Infiltration Depths (A) and Wetting Pattern Depths (B).

3.3.Accumulated Infiltration Rate

By deriving the empirical equation, i.e., Eq. (6), for estimating the cumulative infiltration depth with respect to time, the cumulative infiltration rate is obtained in the following formula:

$$I = 3456(18.9 + 1.35Ibe - 10.57Ibe^{0.75} + 30.83Ibe^{0.5} - 39.6Ibe^{0.25})t^{-0.424} \quad (9)$$

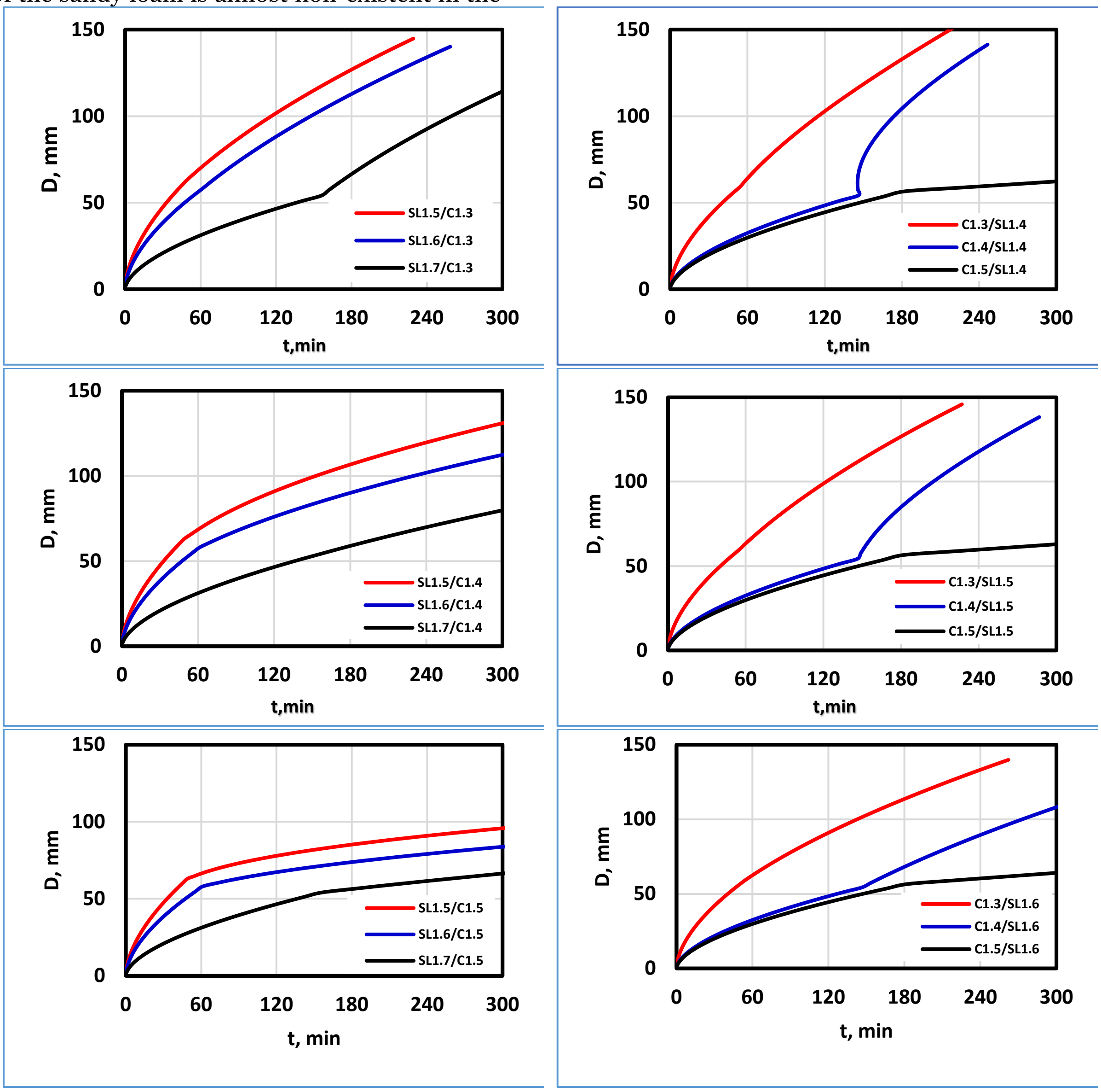
Eqs. (5) – (9) were considered for studying the effect of bulk density in layered soil on the cumulative infiltration depth, the wetting front depth, and the infiltration rate, as they were used in drawing all shapes in this section.

3.4.Effect of Bulk Density on the Cumulative Infiltration Depth

Fig. 4 shows the change of the cumulative infiltration depth with time under the influence of changing the bulk density of the upper layer while the bulk density of the lower layer was constant for various layering conditions. It is clear from Fig. 4 that there is an increase in the infiltration depth as a result of the decrease in bulk density. This increase seems to be uniform in case of layered soil profile of sandy loam soil over clay soil (Fig. 4A), while it looks non-uniform in case of layered soil profile of clay soil over sandy loam soil (Fig. 4A). In addition, the change in the slope of the infiltration depth curve with time at the interface between the two layers varied between increase, congruence, and decrease depending on the bulk density of the lower layer. From Fig. 4A, it is obvious that the depth of infiltration in the soil of the lower layer clearly reduced due to the increase in bulk density. From Fig. 4B, the effect of the bulk density change on the infiltration depth in the upper layer of clay soil appears more apparent at low values of bulk density. It is also obvious that the amount of change in the infiltration depth due to the change in bulk density in the lower layer of the sandy loam soil was apparent in the case of the low bulk density in the upper layer of clay soil. Furthermore, the amount of change in the infiltration depth due to the change in bulk density in the lower layer soil of the sandy loam was almost non-existent in the case of higher bulk density in the upper layer with clay soil. Fig. 5 depicts how the cumulative infiltration depth changes over time as a result of changing the bottom layer's bulk density, while the top layer's bulk density remains constant under varied stratification circumstances. It is clear from Fig. 5 that the infiltration in the upper layer in each of the three cases of bulk density is similar to the infiltration of water in homogeneous soil up to the interface between the two layers. Comparing the three cases, it is clear that the infiltration depth increased due to bulk density reduction, and the increase was more evident at low bulk density. In the lower layer, the increase of the infiltration depth due to the decrease in the bulk density was uniform in the case of sandy loam soil over clay soil (Fig. 5A), while it looked non-uniform in the case of sandy loam soil over clay soil (Fig. 5B). In general, the slope of the infiltration depth curve decreases, increases, or remains as it with time after the interface between the two layers depending on the bulk density of the soil in the lower layer. It is evident from all the graphs in Figs. 4 and 5, in general, that the depth of infiltration increased with the cumulative infiltration time and as the bulk density of the soil decreased, regardless of the soil location in the upper or lower layer within the stratified soil. It is also clear that there were cases in which there was a compatibility between the upper and lower strata soils, like the infiltration process was in a homogeneous and not stratified soil. This compatibility comes when sandy loam soil with a relatively high bulk density is used in one layer and clay soil with a relatively low bulk density in the other layer.

3.5.Effect of Bulk Density on Wetting Front Depth

Fig. 6 shows the wetting front depth change with time under the influence of changing the bulk density of the upper layer, while the bulk density of the lower layer was constant for various conditions of layering. It is clear from Fig. 6 that the change in the slope of the depth of the wetting front curve with time at the interface between the two layers varies between increase, congruence and decrease depending on the bulk density of the lower layer. The change in the increase of the wetting front depth due to the decrease in bulk density was approximately uniform for sandy loam soil over clay soil (Fig. 6A), while it was non-uniform for clay soil over sandy loam soil (Fig. 6B). From Fig. 6A, it is evident that the wetting front depth in the soil of the lower layer clearly reduced with the increase of bulk density. From Fig. 6B, the effect of the bulk density change on the wetting front depth in the upper layer of clay soil appears more apparent at low values of bulk density. It is also evident that the change in the wetting front depth with the change of bulk density in the lower layer of the sandy loam soil was apparent in the case of the low bulk density in the upper layer with clay soil. Furthermore, the amount of change in the wetting front depth due to the bulk density change in the lower layer soil of the sandy loam was almost non-existent in the case of higher bulk density in the upper layer with clay soil. Fig. 7 depicts how the wetting front depth changes over time due to changing the bottom layer's bulk density, while the top layer's bulk density remains constant under varied stratification circumstances. It is clear from Fig. 7 that the wetting front in the upper layer in each of the three cases of bulk density is similar to the wetting front of water in homogeneous soil up to the interface between the two layers. Comparing the three cases, it is clear that the wetting front depth increased due to bulk density reduction, and the increase was more evident at low bulk density. Moreover, the change in the slope of the wetting front depth curve at the interface between the two layers varied between congruence and decrease depending on the soil's bulk density in the lower layer. Awing to bulk density reduction in the lower layer, there was approximately a uniform change in the wetting front depth increase in the case of sandy loam over clay (Fig. 7A), while this change was non-uniform in the case of clay over sandy loam (Fig. 7B). From Fig. 7A, it is evident that the depth of the wetting front in the lower layer of soil decreases clearly and uniformly due to the increase in bulk density. From Fig. 7B, the amount of change in the wetting front depth as a result of the bulk density change in the lower layer soil of the sandy loam is almost non-existent in the case of higher bulk density in the upper layer with clay soil. It is evident from all the graphs in Figs. 6 and 7, in general, that the depth of the wetting front increased with the decrease of the soil's bulk density, regardless of the soil location in the upper or lower layer within the stratified soil. It is also clear that there were cases in which there was a compatibility between the upper and lower strata soils like the wetting front process is in a homogeneous and not stratified soil. This compatibility comes when sandy loam soil with one relatively high bulk density is used in one layer and clay soil with a relatively low bulk density in the other layer.

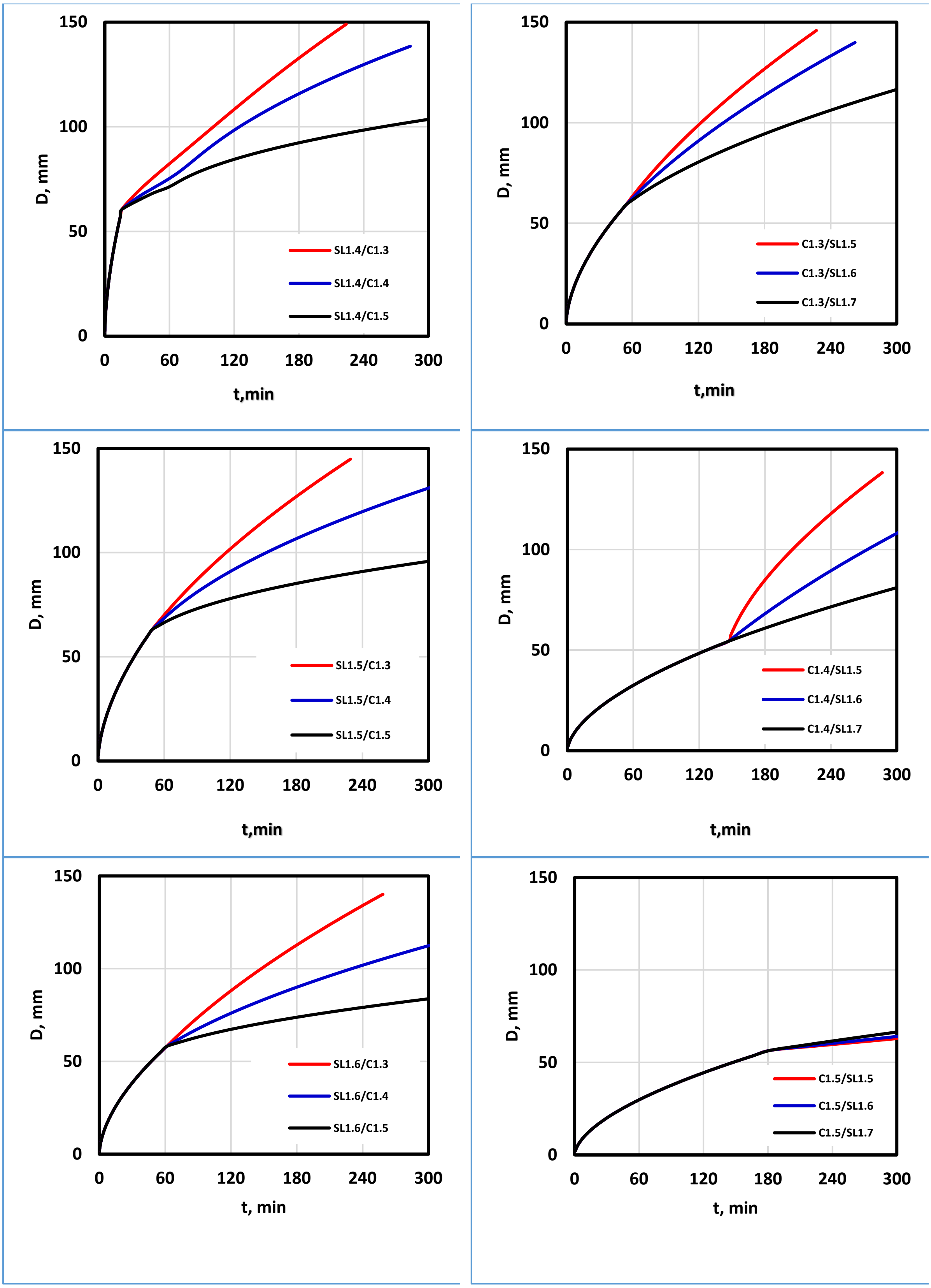


A. sandy loam soil as an upper layer in different bulk densities and clay soil as a lower layer with constant bulk density.

B. clay soil as an upper layer in different bulk densities and sandy loam soil as a lower layer with constant bulk density.

D and t are infiltration depth and time. C1.3/SL1.5 is a layered soil profile of clay soil of 1.3 g/cm^3 bulk density as the upper layer over sandy loam soil of 1.5 g/cm^3 bulk density as the lower layer, and so on.

Fig. 4 Change of Cumulative Infiltration Depth with Time for Layered Soil of Different Bulk Densities for the Upper Layer and Constant Bulk Density of the Lower Layer.

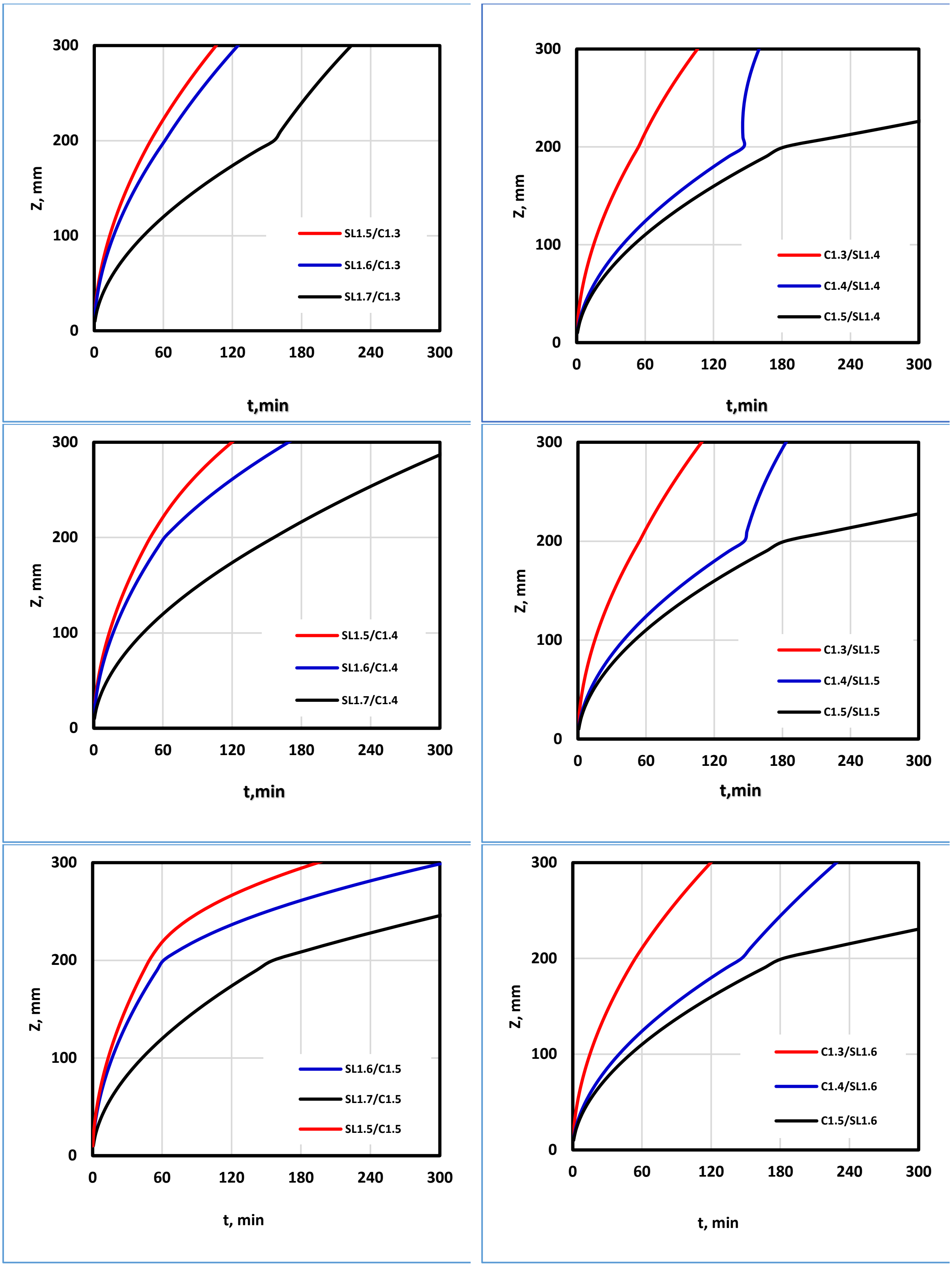


A. sandy loam soil as the upper layer with constant bulk density and clay soil as the lower in different bulk densities.

B. clay soil as the upper layer with constant bulk density and sandy loam soil as the lower in different bulk densities.

D and t are infiltration depth and time. C1.3/SL1.5 is a layered soil profile of clay soil of 1.3 g/cm^3 bulk density as the upper layer over sandy loam soil of 1.5 g/cm^3 bulk density as the lower layer, and so on.

Fig. 5 Change of Cumulative Infiltration Depth with Time for Layered Soil of Different Bulk Densities for the Lower Layer and Constant Bulk Density of the Upper Layer.

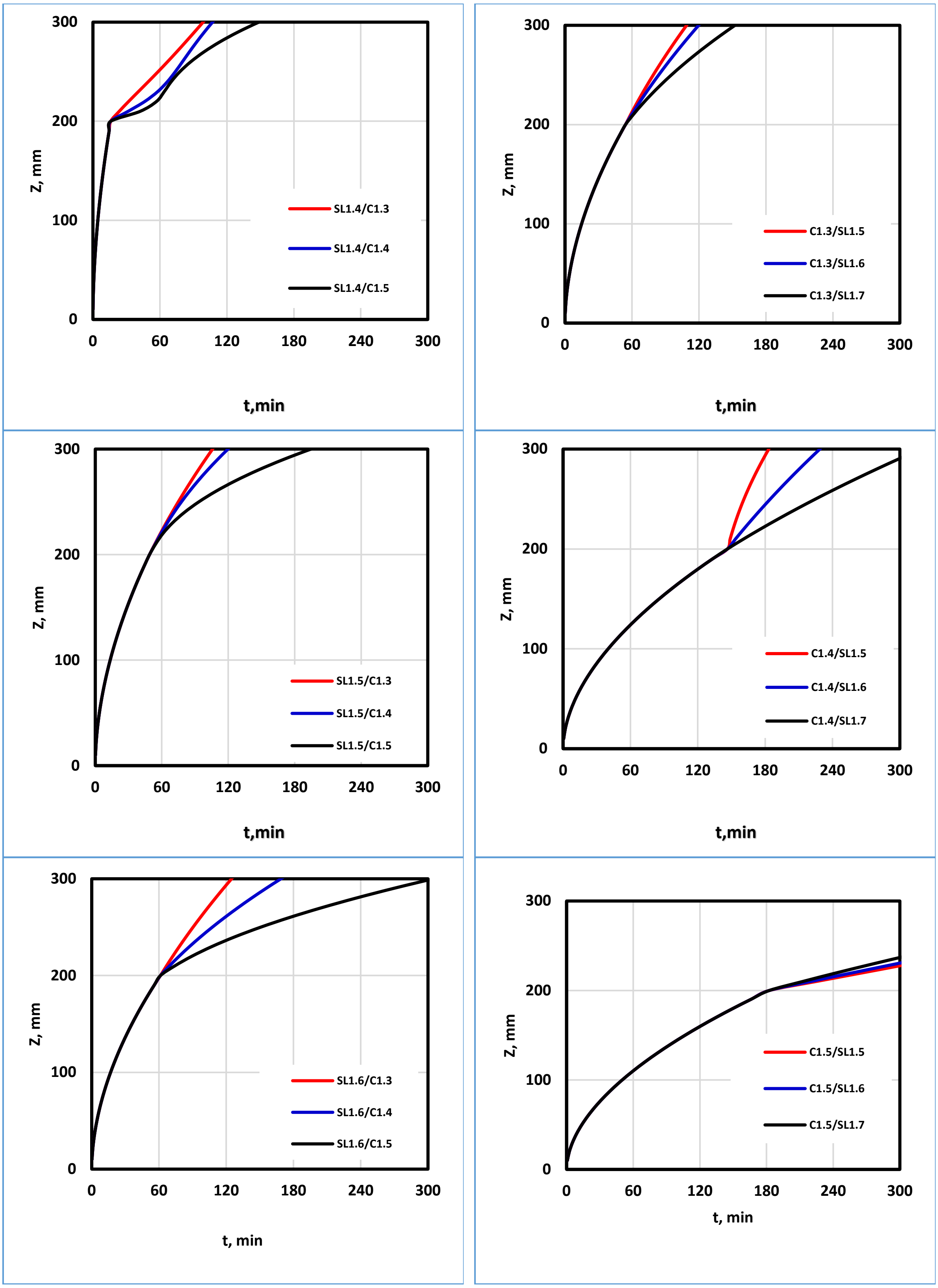


A. sandy loam soil as the upper layer in different bulk densities and clay soil as the lower layer with constant bulk density.

B. clay soil as the upper layer in different bulk densities and sandy loam soil as the lower layer with constant bulk density.

Z and t are wetting front depth and time. C1.3/SL1.5 is a layered soil profile of clay soil of 1.3 g/cm^3 bulk density as the upper layer over sandy loam soil of 1.5 g/cm^3 bulk density as the lower layer, and so on.

Fig. 6 Change of Wetting Front Depth with Time for Layered Soil of Different Bulk Densities for the Upper Layer and Constant Bulk Density of the Lower Layer.



A. sandy loam soil as the upper layer with constant bulk density and clay soil as the lower in different bulk densities.

B. clay soil as the upper layer with constant bulk density and sandy loam soil as the lower in different bulk densities.

Z and t are wetting front depth and time. C1.3/SL1.5 is a layered soil profile of clay soil of 1.3 g/cm^3 bulk density as the upper layer over sandy loam soil of 1.5 g/cm^3 bulk density as the lower layer, and so on.

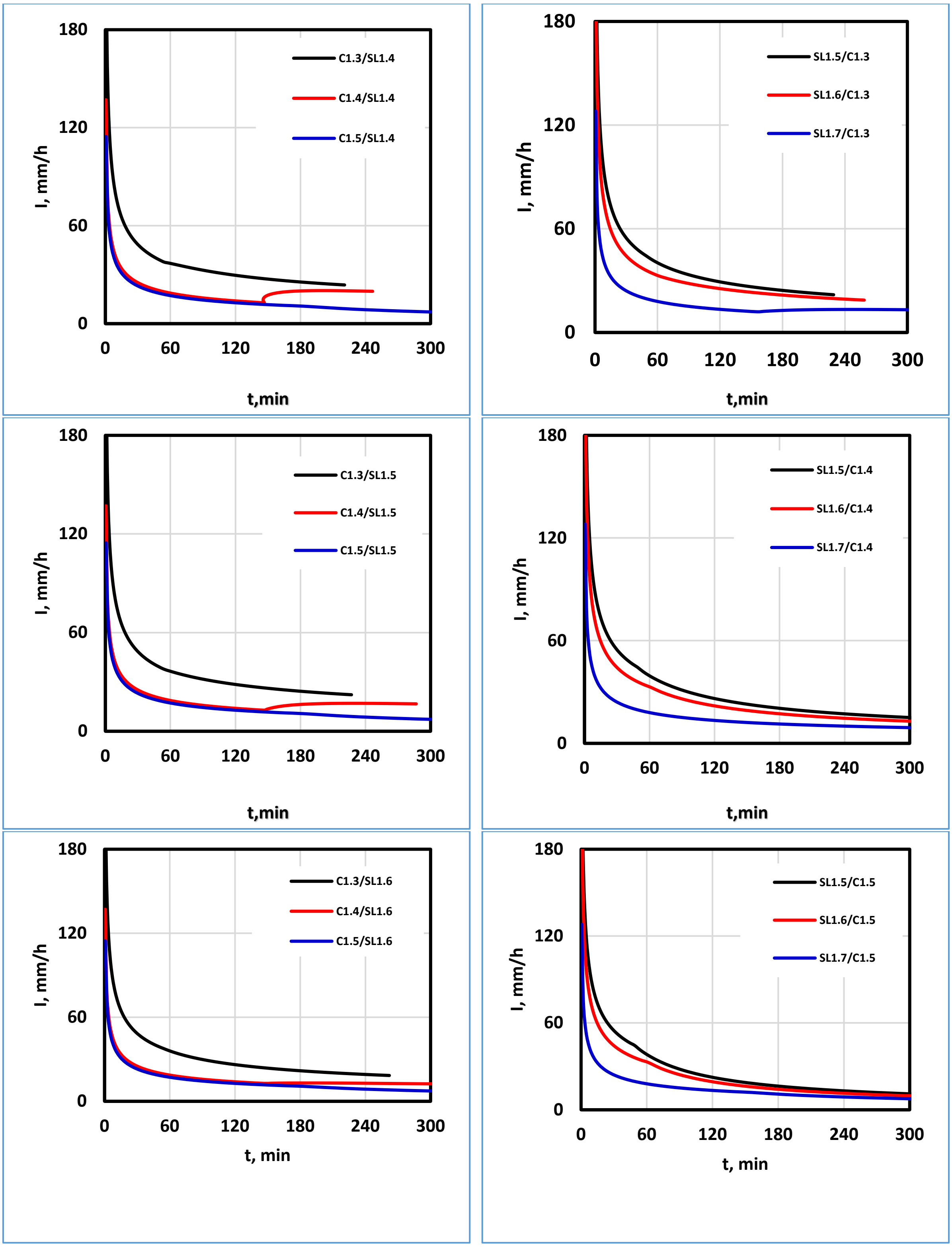
Fig. 7 Change of Wetting Front Depth with Time for Layered Soil of Different Bulk Densities for the Lower Layer and Constant Bulk Density of the Upper Layer.

3.6.Effect of Bulk Density on Infiltration Rate

The impact of bulk density variation of the top stratum with constant bulk density of the bottom layer is shown in Fig. 8 for various layering conditions. Fig. 8 shows that an increase in the soil's bulk density of the upper layer decreased the infiltration rate at any time of infiltration, whether before or after the wetting front passed the interface between the two layers and for all stratification cases. From Fig. 8, it is also noted that the infiltration rate curve moves from the clay soil in the upper layer to the sandy loam soil in the lower layer, as in Fig. 8A, where there is no apparent change in the infiltration rate when the density of the sandy loam soil in the lower layer increases, i.e., the infiltration rate was affected by the density of the upper layer more than the change in the density of the lower layer. The same applies to Fig. 8B, where the infiltration rate curve goes from the sandy loam soil in the upper layer to the clayey soil in the lower layer. As the water reached the cylinder end, it required passing through the upper layer, which remained the one controlling the infiltration rate. Fig. 9 illustrates the influence of bulk density of top stratum change with constant bulk density of the bottom layer under various situations of stratification. It is clear from Fig. 9A that the increase in the soil's bulk density of the lower layer insignificantly decreased the infiltration rate at any time of infiltration when the upper layer density was constant, whether before or after the wetting front passed the interface between the two layers and for all stratification cases. From Fig. 9A, it is also noted that the infiltration rate curve moves from the clay soil in the upper layer to the sandy loam soil in the lower layer, as in Fig. 9A, where there was no noteworthy change in the infiltration rate when the sandy loam soil density in the lower layer increased, i.e., the infiltration rate was affected by the density of the upper layer more than the change in the density of the lower layer. The same applies to Fig. 9B, where the infiltration rate curve goes from the sandy loam soil in the upper layer to the clay soil in the lower layer. As the water reached the cylinder's end, it required passing through the upper layer, which remained the one controlling the infiltration rate.

3.7. Effect of Changing the Upper- and Lower-Layers Thickness on the Cumulative Infiltration Depth, the Wetting Front Depth, and the Infiltration Rate

The effect of changing the upper- and lower-layers thickness of a stratified soil profile of 45 cm height (clay over sandy loam) on the infiltration and wetting front depths is presented in Figs. 10A and 10B. It is clear from Figs. 10A and 10B that there is an increase in the cumulative infiltration and the wetting front depths until the wetting front passes the interface between the two layers. Then, refraction occurs in the curve when passing the boundary between the two layers, and an increase in its slope and this increase in slope depends on the bulk density of both soils. The slope increases when the lower layer has a coarser texture than the upper layer due to the change in the physical properties of the soil. Figs. 10C and 10D show the impact of varying the top and bottom layer thicknesses on the infiltration and wetting front depths of a stratified soil profile of 45 cm height (sandy loam over clay). It is obvious from Figs. 10C and 10D, there is a decrease in the cumulative infiltration depth and the wetting front depth even after the wetting front passes the interface between the two layers, and this reduction in slope depends on the bulk density for both soils. The slope of the curve decreases when the lower layer has a finer texture than the upper layer due to the change in the physical properties of the soil. Fig. 10E shows the change of infiltration rate with time for a stratified soil with an upper layer of clay soil with a bulk density of 1.35 g/cm^3 and a thickness of 15 cm, 25 cm, and 35 cm, corresponding to a lower layer with sandy loam soil with a bulk density of 1.55 g/cm^3 and a thickness of 30 cm, 20 cm, and 10 cm. The curve is unaffected by the upper clay layer thickness, which remained the one controlling the infiltration rate for all stratification cases. Fig. 10F shows the infiltration rate change with time for stratified soil with an upper layer of sandy loam soil with a bulk density of 1.55 g/cm^3 and 5 cm, 15 cm, and 25 cm thick, and it corresponds to a lower layer of clay soil with a bulk density of 1.35 g/cm^3 and 40 cm, 30 cm, and 20 cm thick. It is clear from this figure that there is a change in the curve depending on the thickness of the upper layer, where the rate of infiltration is greater in the layering case SL-25/C-20 and the rate of infiltration is less in the layering case SL-5/C-40. The thickness of the upper layer has a clear role in this case.

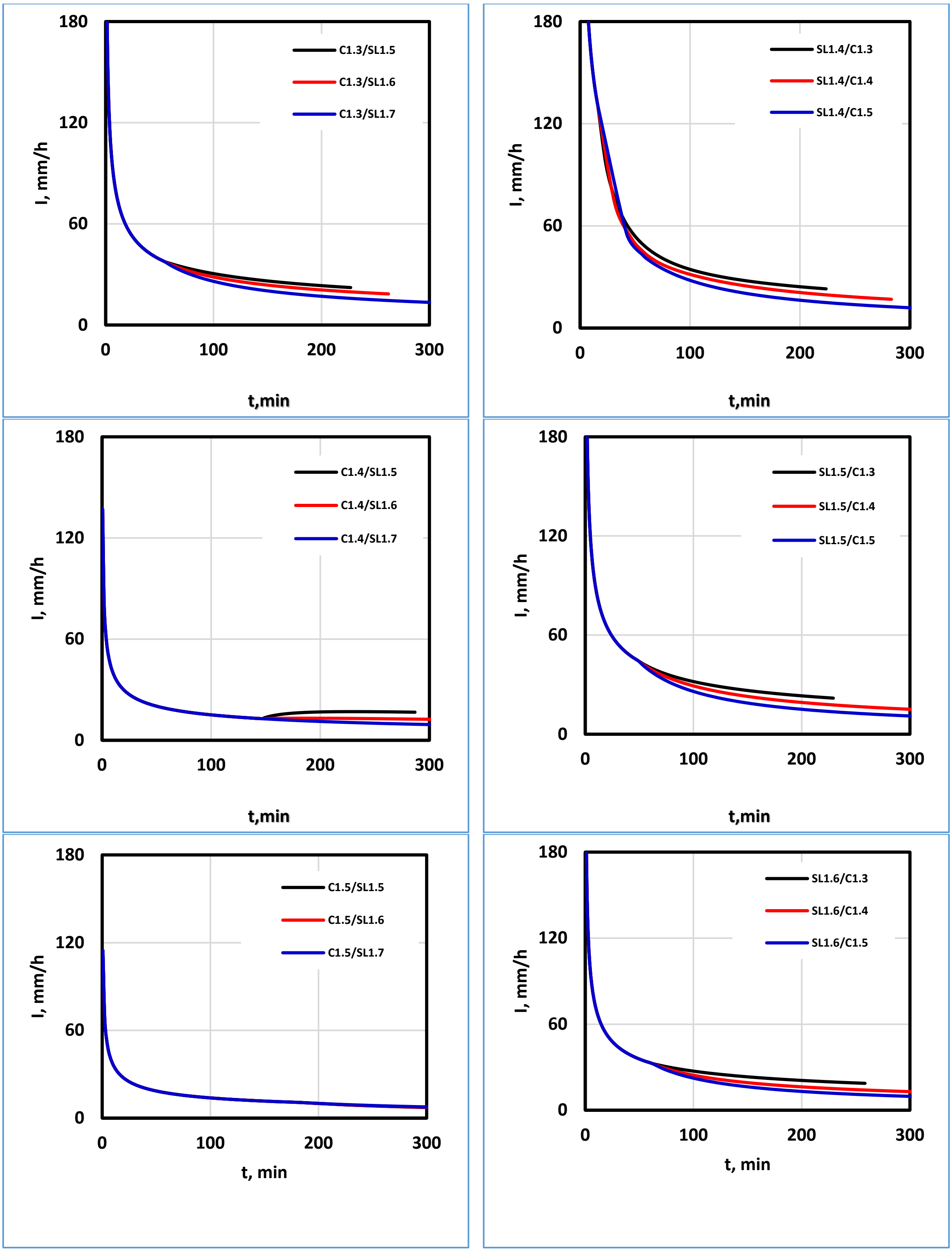


A. clay soil as the upper layer in different bulk densities and sandy loam soil as the lower layer with constant bulk density.

B. sandy loam soil as the upper layer in different bulk densities and clay soil as the lower layer with constant bulk density.

I and t are infiltration rate and time. C1.3/SL1.5 is a layered soil profile of clay soil of 1.3 g/cm^3 bulk density as the upper layer over sandy loam soil of 1.5 g/cm^3 bulk density as the lower layer, and so on.

Fig. 8 Change of Infiltration Rate with Time for Layered Soil of Different Bulk Densities for the Upper Layer and Constant Bulk Density of the Lower Layer.

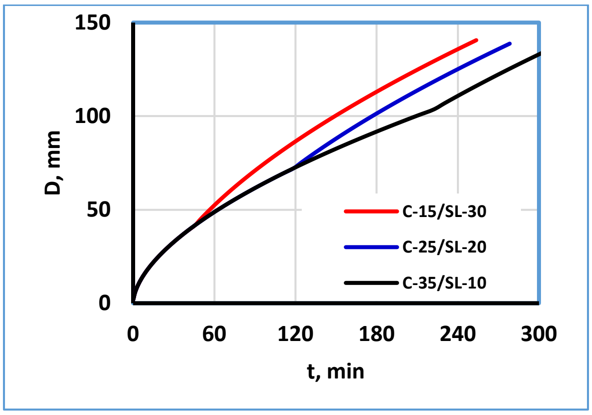


A. clay soil as the upper layer with constant bulk density and sandy loam soil as the lower in different bulk densities.

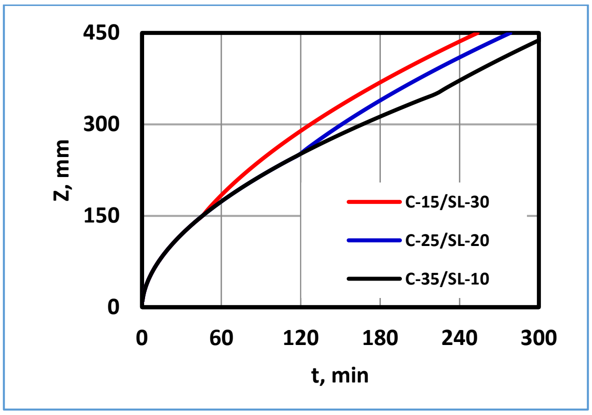
B. sandy loam soil as the upper layer with constant bulk density and clay soil as the lower in different bulk densities.

I and ***t*** are infiltration rate and time. C1.3/SL1.5 is a layered soil profile of clay soil of 1.3 g/cm^3 bulk density as the upper layer over sandy loam soil of 1.5 g/cm^3 bulk density as the lower layer, and so on.

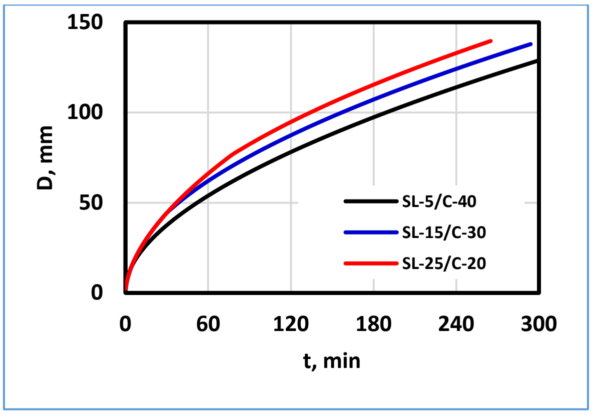
Fig. 9 Change of Infiltration Rate with Time for Layered Soil of Different Bulk Densities for the Lower Layer and Constant Bulk Density of the Upper Layer.



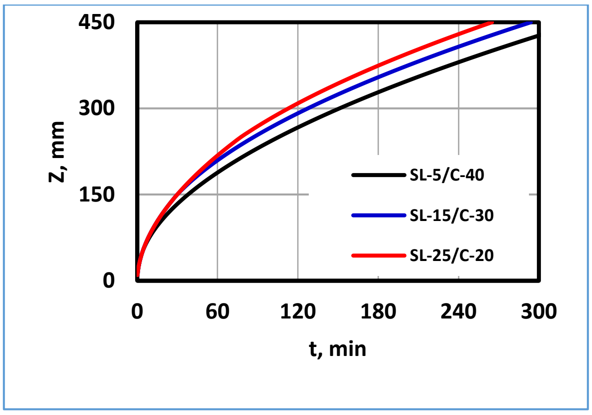
A. change of infiltration depth with time for layered soil of different thicknesses for each layer. Clay soil as the upper layer and sandy loam soil as the lower layer of bulk densities 1.35 and 1.55 g/cm^3, respectively.



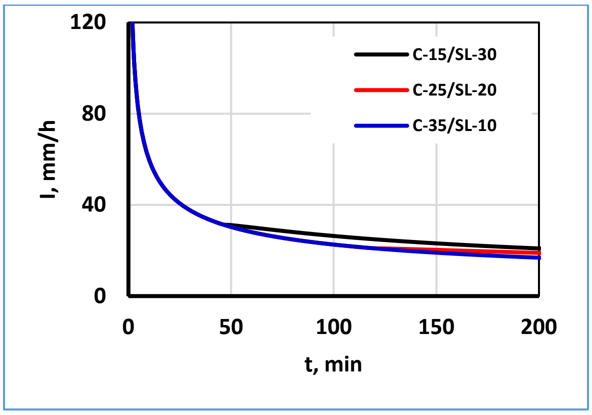
B. change of wetting front depth with time for layered soil of different thicknesses for each layer. Clay soil as the upper layer and sandy loam soil as the lower layer of bulk densities 1.35 and 1.55 g/cm^3, respectively.



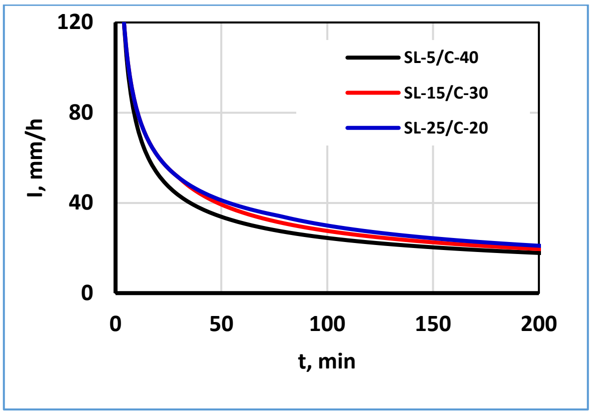
C. change of infiltration depth with time for layered soil of different thicknesses for each layer. A sandy loam soil as the upper layer and clay soil as the lower layer of bulk densities 1.55 and 1.35 g/cm^3, respectively.



D. change of wetting front depth with time for layered soil of different thicknesses for each layer. A sandy loam soil as the upper layer and clay soil as the lower layer of bulk densities 1.55 and 1.35 g/cm^3, respectively.



E. change of infiltration rate with time for layered soil of different thicknesses for each layer. Clay soil as the upper layer and sandy loam soil as the lower layer of bulk densities 1.35 and 1.55 g/cm^3, respectively.



F. change of infiltration rate with time for layered soil of different thicknesses for each layer. A sandy loam soil as the upper layer and clay soil as the lower layer of bulk densities 1.55 and 1.35 g/cm^3, respectively.

I, D, Z, and t are infiltration rate, infiltration depth, wetting front depth, and time. C-15/SL-30 is a layered soil profile of clay soil of 15 cm thickness as an upper layer over sandy loam soil of 30 cm thickness as a lower layer, and so on.

Fig. 10 Change of Infiltration Depth, Wetting Front Depth, and Infiltration Rate with Time for Layered Soil of Different Thicknesses for Each Layer.

4.CONCLUSION

Water infiltration in the soil is among the most important properties that must be well-known and understood, as it is considered a prerequisite for the optimal design of various irrigation systems. Ten laboratory experiments were conducted to study the effect of changing the bulk density of stratified soils (soils consisting of two layers), where clay soil was used as fine and heavy soil and sandy loam soil as light, coarse soil. Three bulk density values were considered for each soil, and the experiments were conducted in different layering sequences. A group of experiments was conducted for stratified soil consisting of coarse soil over fine soil and vice versa to study the effect of the soil texture, its location in the stratified soil, and the variation of bulk density of each layer on water infiltration. Empirical equations were derived for the cumulative infiltration depth and the wetting front depth in terms of time and the basic infiltration rate of the soil. The results of the present research confirmed that the infiltration depth increased with the cumulative infiltration time, and the cumulative infiltration and the wetting front depths increased as the soil bulk density decreased, regardless of the soil location in the upper or lower layer within the stratified soil. It was also found that there were cases in which there was a compatibility between the soil in the upper layer and the soil in the lower layer, seeming that the infiltration process looked like in a homogeneous and not stratified soil, which is evident in the curve of the infiltration depth with time or in the curve of the wetting front depth with time. The change in the depth of infiltration curve slope with time or the curve of the wetting front depth with time at the interface between the two layers varied between increase, congruence, and decrease depending on the soil bulk density in the lower layer. It was also shown that an increase in the bulk density of the upper layer soil decreased the infiltration rate at any time of infiltration, whether before or after the wetting front passed the interface between the two layers and for all stratification cases. The increase in the soil bulk density of the lower layer insignificantly decreased the infiltration rate at any time of infiltration when the upper layer density was constant, whether before or after the wetting front passed the boundary between the two layers and for all layering cases.

NOMENCLATURE:

Symbol	Description	Unit
D	cumulative infiltration depth	mm
c, m	empirical constants	--
t	cumulative infiltration time	min
I	infiltration rate	mm/min
k, n	empirical constants	--
T_b	basic infiltration time	min
I_b	basic infiltration rate	mm/min
ρ_b	bulk density	g/cm3
Z	depth of wetting front	mm
I_{be}	equivalent basic infiltration rate	mm/h

REFERENCES

[1] Hachum AY, Yasin HI. **On-farm Irrigation Systems Engineering**. *Dar Al Kuttb for Printing and Publishing, Mosul University, Mosul, Iraq*.1992.

[2] Qing X, Haojie H, Jinran X, Caixia Z, Zhiliang Z, Huiqiang H. **Research Progress of Soil Water Infiltration**. *E3S Web of Conferences* 2020; **189**: 01006, (1-9).

[3] Nakhaei M, Simůnek J. Estimating the Soil Hydraulic and Thermal Properties of Unsaturated Porous Media Using HYDRUS-2D. *In Proceedings of the 4th International Conference 2013; HYDRUS Software Applications to Subsurface Flow and Contaminant Transport Problems* (pp. 257-266).

[4] Govindaraju RS, Goyal A. **Rainfall and infiltration**. *In Rainfall* 2022; (pp. 367-396). Elsevier.

[5] Fung TK, et al. **Litter Decomposition and Infiltration Capacities in Soils of Different Tropical Urban Land Covers**. *Urban Ecosystems* 2022; **25**(1), 21-34.

[6] Smith RE, Diekkrüger B. **Effective Soil Water Characteristics and Ensemble Soil Water Profiles in Heterogeneous Soils**. *Water Resources Research* 1996; **32**(7): 1993-2002.

[7] Sadeghi M, Tuller M, Gohardoust MR, Jones SB. **Column-Scale Unsaturated Hydraulic Conductivity Estimates in Coarse-Textured Homogeneous and Layered Soils Derived Under Steady-State Evaporation from a Water Table**. *Journal of Hydrology* 2014; **519**: 1238-1248.

[8] Moore ID, Eigel JD. **Infiltration Into Two-Layered Soil Profiles**. *Transactions of the ASAE* 1981; **24**(6): 1496-1503.

[9] Morin J, Benyamini Y. **Rainfall Infiltration into Bare Soils**. *Water Resources Research* 1977; **13**(5): 813-817.

[10] Liu HT, Li BG, Ren TS. **Soil Profile Characteristics of High-Productivity Alluvial Cambisols in the North China Plain**. *Journal of Integrative Agriculture* 2015; **14**(4); 765-773.

[11] Deng XP, Shan L, Zhang H, Turner NC. **Improving Agricultural Water Use Efficiency in Arid and Semiarid Areas of China**. *Agricultural Water Management* 2006; **80**(1-3): 23-40.

[12] Evans RG, Sadler EJ. **Methods and Technologies to Improve Efficiency**

of Water Use. *Water Resources Research* 2008; **44**(7):1-15.

[13] Kresović B, et al. **Grain Yield and Water Use Efficiency of Maize as Influenced by Different Irrigation Regimes Through Sprinkler Irrigation under Temperate Climate**. *Agricultural Water Management* 2016; **169**: 34-43.

[14] Deng P, Zhu J**. Anisotropy of Unsaturated Layered Soils: Impact of Layer Composition and Domain Size**. *Soil Science Society of America Journal* 2015; **79**(2): 487-494.

[15] Gao H, Shao M. **Effects of Temperature Changes on Soil Hydraulic Properties**. *Soil and Tillage Research* 2015; **153**: 145-154.

[16] Fred Zhang Z, Strickland CE, Field JG, Parker DL, Clayton RE. **Evaluating the Performance of a Surface Barrier for Reducing Soil-Water Flow**. *Vadose Zone Journal* 2012; **11**(3): vzj2011-0117.

[17] Mantoglou A, Gelhar L. **Capillary Tension Head Variance, Mean Soil Moisture Content, and Effective Specific Soil Moisture Capacity of Transient Unsaturated Flow in Stratified Soils**. *Water Resources Research* 1987; **23**(1); 47-56.

[18] Romano N, Brunone B, Santini A. **Numerical Analysis of One-Dimensional Unsaturated Flow in Layered Soils**. *Advances in Water Resources* 1998; **21**(4): 315-324.

[19] Ritsema CJ, Dekker LW, Hendrickx JMH, Hamminga W. **Preferential Flow Mechanism in a Water Repellent Sandy Soil**. *Water Resources Research* 1993; **29**(7): 2183- 2193.

[20] Zettl J, Lee Barbour S, Huang M, Si B, Leskiw LA. **Influence of Textural Layering on Field Capacity of Coarse Soils**. *Canadian Journal of Soil Science* 2011; **91**(2): 133-147.

[21] Yasin HI, Ghazal EM. **Infiltration and Some Physical Properties of Soil.** *Al-Rafidain Engineering Journal (AREJ)* 2021; **26**(2): 249-258.

[22] Cleophas F, et al. **Effect of Soil Physical Properties on Soil Infiltration Rates**. *Journal of Physics: Conference Series* 2022; **2314**(1) :012020, (1-7).

[23] Patle GT, Sikar TT, Rawat KS, Singh SK. **Estimation of Infiltration Rate from Soil Properties Using Regression Model for Cultivated Land**. *Geology, Ecology, and Landscapes* 2019; **3**(1): 1-13.

[24] Patle G. T. **Estimation and Modelling of Infiltration Rate of Paddy Fields in a Hilly Micro Watershed of Sikkim (India)**. *Agricultural Engineering International: CIGR Journal* 2021; **23**(3): 13-20

[25] Kostiakov AN. On The Dynamics of the Coefficient of Water Percolation in Soils and the Necessity of Studying it from the Dynamic Point of View for the Purposes of Amelioration. *Transactions of 6th Committee International Society of Soil Science* 1932(pp. 7-21).