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Initial Moisture Content in Relation to Infiltration Capacity of Sandy Soils

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Abstract. The effect of initial wetness on infiltration, under a small positive head, into a fine sand soil (typic torripsamments) was investigated on long soil columns. The sprinkling technique was applied to obtain a uniform initial moisture content in the soil profile ranging from 28 to 48% saturation.

The saturation and transition zones were not observed, but rather a zone of almost constant moisture content (transmission zone) with 81% saturation extended from the soil surface. The same transmission zone was obtained under ponded infiltration, regardless of the initial wetness, within the range used which was considered a practical one. The matric suction head at the wetting front was of the order of 21 to 57 cm, depending on the intial wetness. The infiltration rate decreased with increase of the initial wetness due to the decrease of the initial moisture deficit in the soil and the matric suction at the wetting front.

A Darcy-type equation, based on the physical features of the moisture profile, was derived to predict the change of the infiltration rate as a result of change of the initial wetness of the soil. The derived equation has been found in good agreement with both the experimental measurements and Kostiakov- type (exponential) equation. However, the exponent (n) of time (t) in Kostiakov's equation was not equal to 0.5, but tended towards 0.7 for sandy soils. A relation between the constant of proportionality (C), in the exponential equation, and the initial moisture content in the soil was found to facilitate the predictive computation of the infiltration rate for practical purposes.

Introduction

Modeling infiltration is necessary to predict runoff and, therefore, erosion and sediment yield. Infiltration models also provide information for predicting soil water penetration and moisture levels for a variety of purposes, including irrigation scheduling and groundwater recharge.

Considerable progress has been made in modeling ponded infiltration into homogeneous or layered soils with stable surfaces [1-5]. Green and Ampt [6] derived an infiltration equation (Eq. 1) that was based upon a very simple physical model of the soil.

$$L - \phi_e \ln (1 + (L/\phi_e)) = K_s t/f \qquad (1)$$

where L is the depth to the wetting front, ϕ_e is the effective matric potential at the wetting front, K_s is the saturated hydraulic conductivity of the soil, f is the soil porosity and t is the time. The cumulative infiltration rate (D) is just D = fL which, unfortunately, cannot be solved explicity from Eq. 1. Physically, Green and Ampt assumed that the soil was saturated behind the wetting front. Although Eq 1 has parameters that can be related to physical properties of the soil, it is considered empirical since the value of ϕ_e must be found experimentally. Bodman and Colman [7] identified five features in the moisture content profiles under ponded infiltration, subsequently named the saturation zone, transition zone, transmission zone, wetting zone, and wetting front. Other references indicated that the transition zone was not observed, and it was reported that the porous media were saturated throughout the transmission zone [8, 9]. The saturation, transition and transmission zones have been observed [10-12]. Hansen [13] utilized Darcy's law and introduced an equation to determine the wetting front advance during infiltration, depending mainly on the characteristics of the transmission zone. He also observed that the rate of entry in moist soils was less than in dryer soils, but the wetting front advanced more rapidly when the soil was wet. The same results, regarding wetting front advance, were also obtained by El-Shafei [14]. Slack *et al.* [15] used the Green- Ampt- Mein- Larson infiltration model to predict infiltration on soils having different initial moisture contents (θ_i). Their regression analysis indicated that the correlation coefficient (r) of the predicted and observed infiltration rates was 0.72. Reduced infiltration increases runoff, thus affecting a wide variety of water management and resource problems. The consideration of the factors that influence infiltration may then be considered in turn as factors which affect the soil hydraulics and water retention functions.

The goal of this study was to develop a mathematical equation, based on Darcy's law and the physical features of the moisture content profile, to predict the infiltration rate under shallow ponding at different initial soil moisture contents.

Materials and Methods

The sandy soil (typic torripsamments) used in the experiments was sampled from the 30 cm surface layer from the College Experimental and Research Farm at Dierab, Saudi Arabia. The particle- size analysis of the samples by hydrometer method [16, pp. 383-411] showed that the percentages of clay, silt and sand were 2, 3 and 95. However, the direct dry sieving [17, pp. 545-567] indicated that the soil had 25% very fine sand (0.05 – 0.1 mm), 73.5% fine sand (0.1 – 0.25 mm) and 0.5% medium sand (0.25 – 0.50 mm). Accordingly, the soil can be considered as a fine sand soil. The soil contained low soluble salts ($EC_e = 1.2\ dSm^{-1}$), high $CaCo_3$ (20%), very low organic matter (0.1%) and low SAR (0.9). The water used had $EC = 0.44\ dSm^{-1}$ and SAR = 0.96. The saturated hydraulic conductivity (K_s) and the saturation percentage on volume basis (θ_s) of the soil were 25 cm h^{-1} and 42.5, respectively.

The experiments were conducted on long soil columns (70 cm) fabricated from sections of cylindrical transparent lucite tubing 4 cm inside diameter and 5 cm long. The soil was air dried, sieved through 2 mm- screen and the initial air dry moisture content was determined. Soil samples were placed in the cylinders by 5 cm increments and loosely compacted to a bulk density (D_b) equal to 1.5 g cm^{-3} which was the average field bulk density.

A flooding apparatus (Fig. 1) was designed to make the collection of accurate infiltration data as a function of time possible throughout the experiment, and to maintain constant head (2 cm) above soil surface by means of the bubbler (mariotte) tube.

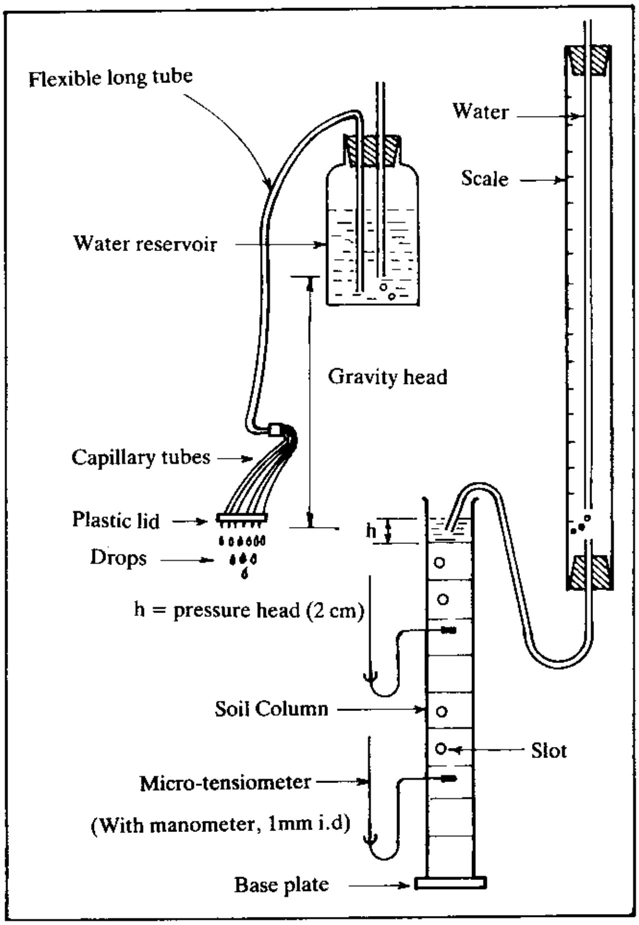

Fig. 1. Schematic diagram of the experimental set up, showing the soil column with sprinkler simulator and flooding apparatus.

From a practical point of view, it was usually difficult to obtain completely uniform initial moisture content (θ_i). El-Shafei [14] applied the ice moisturizing technique, which requires a deep-freeze room, to bring the soil uniformly to the desired θ_i. In this study, the sprinkling technique [18, 19, p. 159, 20] was applied to obtain a good uniform moisture profile. The principle of the method is to continuously supply water to the soil under sprinkling at a constant rate lower than the saturated hydraulic conductivity of the soil, eventually resulting in the establishment of a steady moisture in the conducting profile. A simple sprinkler simulator (water applicator) was designed to uniformly sprinkle the soil surface at constant rate (R). It consisted of a water supply reservoir with a constant head siphon (gravity head) connected to many capillary tubes (Fig. 1). Thus, the water was applied to the surface of each soil column through 20 polyethylene capillary tubes (0.27 mm i. d.) which were held 5 cm above the surface by means of the plastic lid. The falling distance 5 cm was small enough to minimize the impact or kinetic energy associated with the falling drops. The desired application rate (R) was adjusted by varying the gravity head. The sprinkler simulator was able to supply water at rate (R) ranges from 0.05 to 20 cm h^{-1}. Five constant rates (R) ranging from 0.06 to 1.20 cm $^{-1}$ were used to produce five different initial moisture contents (θ_i) ranging from 12% to 20.5%. When the wetting front passed 50 cm depth under sprinkling, the soil column was then transferred to the flooding apparatus to be subjected to the ponded infiltration. At the end of each ponded infiltration run, the moisture profile was determined gravimetrically for each 5 cm increment and a fast response micro-tensiometer [21] with water manometer (1 mm i. d.) was inserted in the last 1.0 centimeter near the wetting front to determine the matric suction head (S).

The sprinkling technique was also implemented to directly measure the hydraulic conductivity (K) as a funciton of the moisture content (θ) since a unit hydraulic gradiant existed in the established moisture profile. The wetting front advance (L) versus time (t) was accurately traced for the case in which θ_i equalled 0.12 by visual observation and 6 micro- tensiometers (as sensors) which were installed along the soil columns through small slots (Fig. 1).

Results and Discussion

During the sprinkler infiltration under the sprinkler simulator (Fig. 1), the sandy soil was wetted by drops of water applied at rate (R) sufficient to prevent surface ponding. Thus the soil surface became nearly- saturated and then tended to drain down until the next drop of water was incident on the surface. Additional drops of water incident on the surface wet the soil to a greater depth. When the depth of wetting became sufficiently great, the potential distribution down the profile was such as to permit the drainage of water from the nearly- saturated zone near the surface. At this stage, the zone near the surface was draining while that near the moisture front was wetting. The initial zone of high moisture content near the surface gradually disappeared to form a moisture profile of fairly uniform moisture content (θ_T). This zone of constant moisture content is usually called the transmission zone which is behind the wetting front (Fig. 2), and the wetting front moves with constant velocity (V) downwards. The constant moisture content in the transmission zone (θ_T) was taken as an overall average of the moisture contents (θ) throughout the profile from 0 to 40 cm depth. Fig. 2 shows the soil moisture profiles under five different sprinkler rates (R); 0.06, 0.15, 0.30, 0.60 and 1.2 cm h^{-1}, which produced five initial moisture contents (θ_i) which were subjected to ponded infiltration. The five θ_i were 0.12, 0.135, 0.17, 0.185 and 0.205 $cm^3 cm^{-3}$ which corresponded to 28.24, 31.76, 40, 43.53 and 48.24% saturation, respectively.

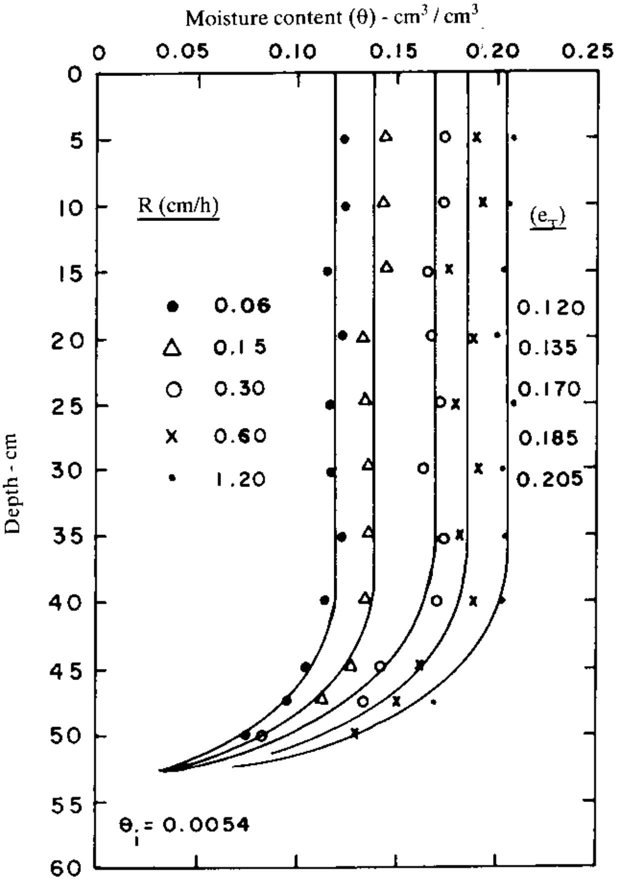

Fig. 2. Moisture profiles under sprinkler infiltration and different application rates (R) for obtaining different initial moisture content (θ_i) which correspond to the constant moisture contents in the transmission zone (θ_T).

The infiltration rate under sprinkling was constant and was equal to application rate (R). Since there was a unit hydraulic gradient in the transmission zone, it can be concluded that the hydraulic conductivity (K) has a value equal to R that corresponds to the uniform moisture content (θ_T).

$$R = K(\theta_T) \tag{2}$$

Thus, one can obtain five points in the K- θ relationship. Another five points in the K- θ relationships were obtained by applying another series of R; 2.15, 5.3, 10, 13.7 and 19.2 cm h^{-1} which are less than K_s. Fig. 3 shows the measured values of the hydraulic conductivity (K) plotted as a function of moisture content (θ) for the sandy soil. These results obtained under sprinkler infiltration are in agreement with several researchers [19-23]. It might be pointed out that the relation between K and θ can be considered unique for sandy soils where the soil particles are not aggregated and gen-

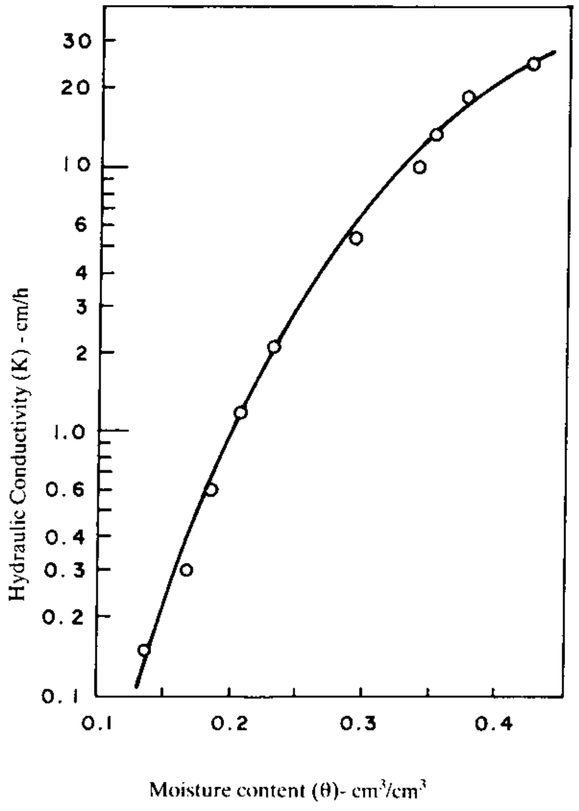

Fig. 3. Hydraulic conductivity as a function of moisture content for fine sand soil.

erally stable. Fig. 4 presents both the advance of the wetting front (L) and the cumulative infiltration rate (D) as a function of time (t) for θ_i equals 0.12 $cm^3\ cm^{-3}$. The results in Fig. 4 confirmed the following realtionships:

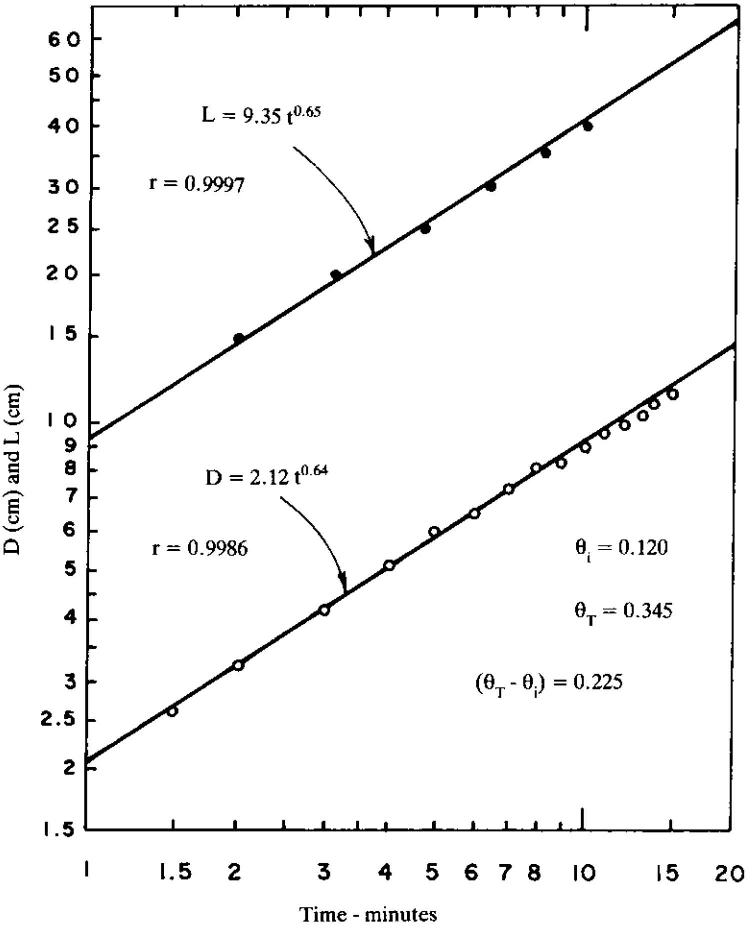

Fig. 4. Cumulative infiltration (D) and wetting front advance (L) as a function of time, at initial moisture content (θ_i) equals 0.12 $cm^3\ cm^{-3}$.

$$D = C\,t^n \tag{3}$$

$$L = (C / (\theta_T - \theta_i))\,t^n = (C / D_i)\,t^n = D / D_i \tag{4}$$

where, D_i is the initial moisture deficit (pore space available for infiltration) and equal to $(\theta_T - \theta_i)$, and C and n are constants. It can be deduced from Fig. 4 that the infiltration equation in a sandy soil is an exponential type but the exponent (n) of the time (t) is not equal or close to 0.5 which is in contrast to Kostiakov [24]. However, Baver *et al.* [25, p. 498] mentioned that both equations of infiltration rate and of the wetting front advance are exponential for time intervals of a few hours and for uniform materials but the exponent (n) is not always 0.5. Through an extensive infiltration study on different sand fractions, El-Shafei and Fahmy [26] found that the exponent (n) tends towards 0.7. The exponent (n) and constant of proportionality (C) are mainly empirical and have no physical meaning.

For obtaining an infiltration equation containing physically sound parameters, a simplified approach which depends on a Darcy-type equation was applied as follows.

Under shallow ponded infiltration through a uniform stable material such as sandy soils, a zone of almost constant moisture content (transmission zone) extends immediately from the soil surface (Fig. 5). If the ponding depth is negligible and the surface is thus maintained at zero pressure head, the advance rate of the wetting front (dL/dt) obeys Darcy's law:

$$dL / dt = K_T / D_i \, ((L+S) / L) \tag{5}$$

in which

L = penetration depth of the wetting front, having a positive value downward.

t = time

K_T = hydraulic conductivity of the transmission zone which is dependent on θ_T

D_i = initial moisture deficit as a fraction ($cm^3 \, cm^{-3}$) and equal to ($\theta_T - \theta_i$).

S = matric suction head near the wetting front and is assumed to have a constant value for each initial moisture content (θ_i).

Eq. 5 can be rewritten,

$$dt = D_i / K_T \, (LdL / (L+S)) \tag{6}$$

If the wetting zone which is a zone of decreasing moisture content (Fig. 5) is introduced between the transmission zone and the wetting front, Eq. 6 becomes:

$$dt = D_i \, ((Z/L)(1/K_w) + ((L-Z)/L) \, (1/K_T)) \, (LdL/(L+S)) \tag{7}$$

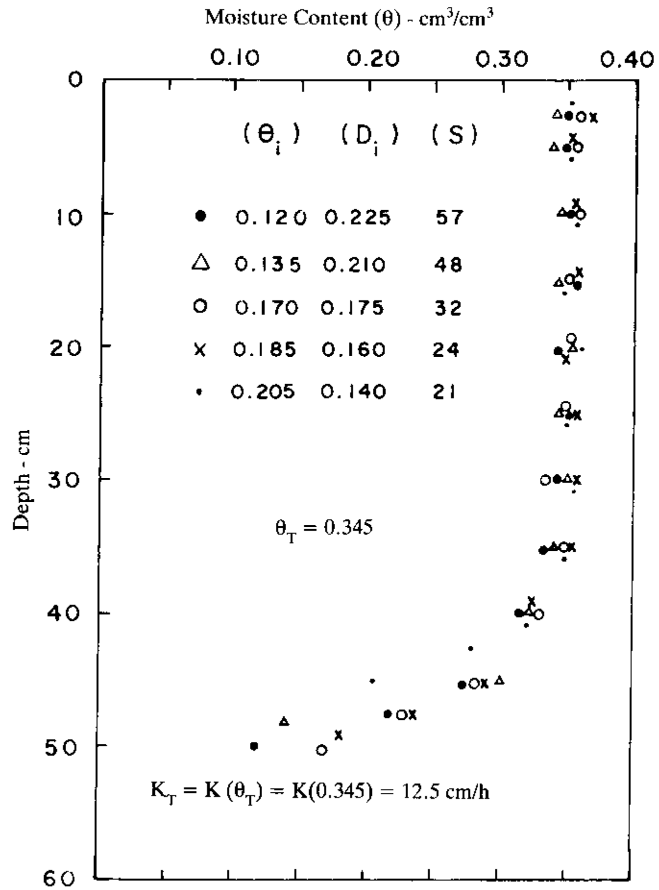

Fig. 5. **Moisture content distributions under ponded infiltration at different initial wetness of the soil (θ_i). D_i is the initial moisture deficit ($cm^3\ cm^{-3}$), S is the matric suction at the wetting front (cm) and K_T is the hydraulic conductivity of the transmission zone ($cm\ h^{-1}$).**

where, z is the depth of the wetting zone and K_w is the hydraulic conductivity of the wetting zone.

$$dt = D_i/K_T((Z/L)(K_T/K_w) + ((L–Z)/L))\ (LdL/(L+S))$$

$$dt = D_i/K_T((Z/L)(K_T/K_w)(LdL/(L+ S)) + ((L–Z)/L)(LdL/(L+S)))$$

$$dt = D_i/K_T\ ((Z\ (K_T/K_w)(dL/(L+S))) + (((L–Z)/(L+S))dL))$$

By integration with the initial condition:

$$\int_0^t dt = D_i/K_T \int_0^L Z\,(K_T/K_w)(dL/(L+S)) + D_i/K_T \int_0^L ((L-Z)/(L+S))dL \tag{8}$$

$$\int_0^L Z\,(K_T/K_w)(dL/(L+S)) = Z[\ln(L+S)]_0^L = Z\,(K_T/K_w)(\ln(L+S)-\ln S)$$

$$= Z\,(K_T/K_w)(\ln((L+S)/S))$$

$$\int_0^L ((L-Z)/(L+S))dL = \int_0^L (L/(L+S))dL - \int_0^L (Z/(L+S))dL$$

$$= \int_0^L ((L+S-S)/(L+S))dL - Z \int_0^L dL/(L+S)$$

$$= \int_0^L (1-(S/(L+S)))dL - Z \int_0^L dL/(L+S)$$

$$= (L-S)\ln((L+S)/S) - Z\ln((L+S)/S)$$

The integration of Eq. 8 yields:

$$\int_0^t dt = (D_i/K_T)\,\{Z\,(K_T/K_w)\ln((L+S)/S)]$$

$$+\ (D_i/K_T)[(L-S)\ln((L+S)/S) - Z\ln((L+S)/S)]$$

$$t = (D_i/K_T)[(L-S)\ln((L+S)/S) + ((K_T/K_w)-1)\,Z\ln((L+S)/S] \tag{9}$$

By introducing Eq. 4 into Eq. 9, the following equation is obtained.

$$t = (1/K_T)[D-(D_iS\ln((D/D_iS)+((K_T/K_w)\,Z\ln((D/D_iS)+1))]$$

$$t = (1/K_T)[\ D-(\ln((D/D_iS)+1)(D_iS - Z((K_{T/Kw})-1))] \tag{10}$$

Eq. 10 describes the infiltration process under shallow ponding taking into consideration the complete feature of the resultant moisture profiles; transmission zone, wetting zone and wetting front. However, it is impractical especially for obtaining a reliable value of K_w since the wetting zone has no constant moisture content (θ_w). Moore *et al.* [27] defined the average suction at the wetting front as the average suction between the limits θ_i and θ_m, where θ_m is the maximum volumetric moisture content attained in the wetting zone. Nevertheless, by examining Eq. 10, one might deduce that the term $z((K_T/K_w)-1)$ approaches zero when K_w approaches K_T. Also, the value of Z depends on the penetration depth (L) and consequently on (D/D_i). This suggests that the term $z((K_T/K_w)-1)$ does not determine infiltration properties of the soil but depends on them. As a result, one may consider the previous term of secondary importance, and thus Eq. 10 can be reduced to Eq. 11 without significant error.

$$t = (60/K_T)[D - D_iS \ln((D/D_iS)+1))] \tag{11}$$

The constant 60 in Eq. 11 is equivalent to 60 min/hr to make the units dimensionally inconsistent where t in min., K in cm h^{-1}, D and S in cm, and D_i is a fraction.

The experimental results of ponded infiltration (Fig. 5) demonstrate that almost the same transmision zone is obtained regardless of the initial moisture content (θ_i) within the experimental range from θ_i = 0.12 to 0.205 cm_3 cm_{-3} which is equivalent to 28.24 and 48.24% saturation, repectively. The value 0.345 for θ which was taken as an average over the 40 cm depth corresponds to 81.2% saturation. It has been recognized that the actual moisture content in the transmission zone is often less than saturation owing to air entrapped in the soil pores during the infiltration process [28-30, 31, pp. 433-449]. Many investigators reported that the air entrapment generally ranges from 10 to 30% of porosity depending on the pore size distribution [5, 31, pp. 433-499, 32-34]. Consequently, the value of K_T is equal to 12.5 cm h^{-1} (Fig. 3). The values of D_i and S at different θ_i are also recorded in Fig. 5. The folowing example will illustrate the use of Eq. 11.

Determine the time (t) required for 5 cm depth of water to infiltrate into a sandy soil (D_b = 1.5 g cm^{-3}) for θ_i = 0.135 and 0.170 cm^3 cm^{-3}:

By applying Eq. 11 on the data in Fig. 5, we obtain for the case of θ_i = 0.135:

$$t = (60/12.5)[5-(0.21\times48 \ln(5/0.21\times48) + 1))] = 4.4 \text{ min}$$

for the case of θ_i = 0.170:

$$t = (60/12.5)[5-(0.175\times32 \ln((5/0.175\times32) + 1))] = 6.9 \text{ min}$$

The computed values 4.4 and 6.9 min. for t coincide with measured ones (Fig. 6). Consequently, the infiltration rate is decreased by increasing θ_i and the reverse is true for wetting front advance. The inset data in Fig. 5 indicate that the matric suction head at the wetting front (S) ranges from 21 to 57 cm depending on θ_i. Hillel and Gardner [35] found that S was of the order of 50–100 cm for infiltration into initially dry soil. Fig. 6 shows a good agreement between the measured and computed infiltration rate by Eq. 11. This good agreement is attributed to the accurate measurement of the matric suction head (S) by the sensitive micro- tensiometers, and the hydraulic

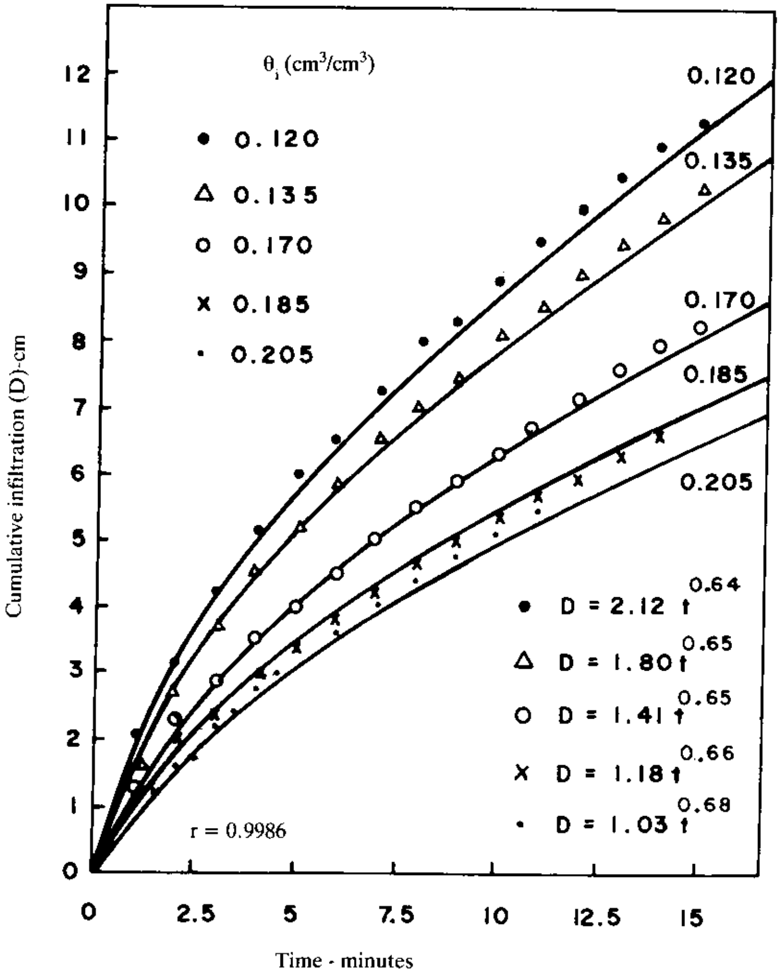

Fig. 6. Cumulative infiltration as a function of time for different initial wetness (θ_i); comparing measured (points) and computed values (solid lines). the equations are the regression of the measured data.

conductivity in the transmission zone (K_T) by the sprinkling method. It is clear that the infiltration rate diminishes by increasing the initial wetness of the soil due to the reduction of soil pore space available for water movement. One can also conclude from Fig. 6 that the exponential relation is verfied and in good agreement with Eq. 11 for infiltraiton into sandy soils which often needs a short time interval. Individual experimental infiltration data were fitted by Kostiakov's equation using non-linear least squares regression [36] to obtain Eq. 3 and the results are presented in Fig. 6 where all $r > 0.9986$. The regression parameters C and n (Eq. 3) are not correlated with any other measured variable and are merely fitting coefficients (2, 37]. Accordingly, the cumulative infiltration rate (D) into sandy soils can be reasonably described by the following Eq. 12.

$$D = C\,t^{0.66} \tag{12}$$

Where C is a parameter that mainly depends on the initial moisture content (θ_i). Fig. 7 presents the relationship between the parameter (C) and θ_i which was found exponential with correlation coefficient (r) = 0.9965.

$$C = 0.128\,\theta_i^{-1.326} \tag{13}$$

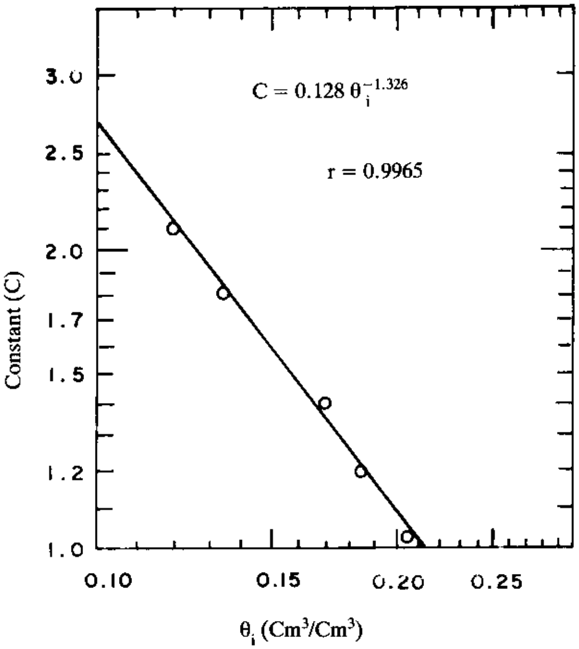

Fig. 7. The parameter (C) in the exponential infiltration equation as a function of the initial wetness (θ_i) for sandy soils.

Eqs. 12 and 13 can be used with Eq. 4 to predict the infiltration rate and wetting front advance in sandy soils within or close to the practical range of initial wetness, 28 to 48% saturation.

In conclusion, the infiltration rate was greatly affected by the initial moisture content of the sandy soil. The presented sprinkler simulator was found to be efficient in producing the different uniform initial moisture profiles, by varying the water application rates. The derived equations, which were in good agreement with Darcy-type equation, are useful as well as practicable to manage the water applciation on sandy soils. The range of the initial moisture content used in the experiments (28 to 48% saturation) is considered practical for sandy soil. However, a further study might be suggested to investigate the effect of initial moisture content, within and beyond that range, on the infiltration characteristics of fine-textured soils.

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الرطوبة الابتدائية وعلاقتها بالسعة المائية التسربية للتربة الرملية

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ملخص البحث. في معظم الأحيان تتم عملية الري على التربة وهي تحتوي على درجة من الرطوبة الابتدائية (درجة من التشبع). وقد تمت دراسة تأثير الرطوبة الابتدائية للتربة على السعة التسربية لها باستخدام أعمدة طويلة من التربة الرملية تحت ضاغط مائي صغير على السطح.

وقد استخدمت طريقة الرش المائي للحصول على رطوبة ابتدائية منتظمة في قطاع التربة حيث استعمل خمسة معدلات لشدة الرش للحصول على خمس قيم مختلفة للرطوبة الابتدائية تتراوح بين ٢٨ إلى ٤٨٪ من درجة التشبع.

وأظهرت النتائج عدم وجود كلٍّ من منطقة التشبع (Saturation zone) أو المنطقة الاجتيازية (Transition Zone) في القطاع الرطوبي، ولكن وجود منطقة انتقالية (Transmission zone) ثابتة المحتوى الرطوبي تقريبًا وتمتد من السطح إلى أسفل ولها درجة تشبع قدرها ٨١٪. وقد تم الحصول على المنطقة الانتقالية نفسها تقريبًا، تحت التسرب المائي الغمري (ضاغط مائي على السطح) بغض النظر عن قيمة الرطوبة الابتدائية في التربة. وقد كانت شدة الامتصاص الرطوبي (الشد الرطوبي) عند جبهة الابتلال في حدود ٢١ إلى ٥٧سم تبعًا للرطوبة الابتدائية.

وقد حدث انخفاض في التسرب المائي مع زيادة الرطوبة الابتدائية في التربة نتيجة للانخفاض في العجز الرطوبي الابتدائي (Moisture deficit) وشدة الامتصاص الرطوبي (الشد الرطوبي) عند جبهة الابتلال.

وتم استنباط معادلة من النوع الدارسي (Darcy) تعتمد على أسس فيزيائية لقطاع التربة الرطوبي وذلك للتنبؤ بالتغير في معدل التسرب المائي نتيجة للتغير في الرطوبة الابتدائية للتربة. وقد اتفقت حسابات المعادلة المستنبطة بصورة جيدة مع كل من القياسات العملية والمعادلات الأسية (Kostiakov - type). ووجد أن قيمة الأس (n) للزمن (t) في معادلة كوستياكوف لا تساوي ٠,٥ (كما هو الغالب في التربة الطميية) ولكنها تميل نحو ٠,٧ للتربة الرملية. ووجد أيضًا أن العلاقة (المستنتجة) بين ثابت التناسب (C) في المعادلة الأسية والرطوبة الابتدائية للتربة تتيح إمكانية حساب معدل التسرب المائي للأغراض العملية التطبيقية.