Bulk Density in Relation to Infiltration Capacity of Loam Soils

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ABSTRACT. An Infiltration experiment was carried out on columns of a loam soil (Fluventic Camborthids) packed to five bulk densities. Equations based on physical parameters were derived to compute the advance of the wetting front and cumulative infiltration. These parameters were bulk density (D_b), initial moisture content (θ_o), the moisture content in the transmission zone (θ_T), the hydraulic conductivity of the transmission zone (K_T), and the matric suction head of the wetting front (ψ). The equations mainly utilized Darcy's law and the physical characteristics of the transmission and the wetting front zones. The derived equations have been found to be in good agreement with the experimental results and also with empirical power type equations which often used for practical purposes. The empirical equations were taken into account D_b, θ_o, and θ_T. A relation between an empirical constant (A) and bulk density (D_b) was found. This may be used as tentative guide for predicting the infiltration capacity of loam soils which are subjected to seasonal volume changes as result of cultivation and heavy agricultural machinery.

Seasonal soil volume changes usually take place particularly in the plowed layer. They are caused by both vertical displacement of the soil particles as a result of cultivation, gravity, precipitation, and irrigation, and by the horizontal displacement of individual portions of soil due to shrinkage and cracking. Voronin (1982) observed an increase in bulk density due to the use of heavy agricultural machinery and irrigation. Atamanyuk and Moldavian (1970) found a relationship between soil bulk density (D_b) and moisture content (θ). Rigorous mathematical techniques have been developed in recent years for the analysis of infiltration into

uniform as well as composite profiles. These techniques are generally based upon numerical methods for the solution of the partial differential equation of unsaturated soil-water flow (Philip 1954, Hanks and Bowers 1962, Rubin and Steinhardt 1963, Parlange 1972, Clothier *et al.* 1981, and Boulier *et al.* 1987). However, most of them are still too formidable for practical routine use. Hansen (1955) utilized Darcy's law and introduced an equation to determine the wetting front advance (L) during infiltration which depends mainly on the characteristics of the transmission zone.

In many cases it is desirable to seek a simplified approach based upon physical parameters and specific assumptions which may apply adequately to particular problems. Thus, the main objective of this study was to develop mathematical equations based on physical parameters to predict the rate of wetting front advance and infiltration during ponded infiltration, taking into account the effect of soil bulk density.

Materials and Methods

A laboratory experiment was carried out on soil columns contained in transparent lucite cylinders, 6-cm i.d. by 60-cm long, and packed to five fulk densities (1.35, 1.40, 1.45, 1.50, and 1.55 g cm^{-3}). The cylinders were assembled from 5-cm sections joined together by grooving and tongue jointing around the circumference. The soil used was a loam (Fluventic Camborthids) with 20% clay, 30% silt, and 50% sand, sampled from the 30-cm top layer at College Experimental and Research Farm, Dierab, Saudi Arabia. It contains moderate soluble salts (EC$_e$ = 4.5 dSm^{-1}), high CaCO$_3$ (36%), and low organic matter (0.5%). The soil hydraulic conductivity at saturation (K$_s$) and its saturation percentage on weight basis (θ_s) were 2 cm h^{-1} and 31.6%, respectively. The soil was air dried, sieved through 2 mm-screen, and packed to the desired bulk density, in increments of 5-cm at a time. The water used has EC = 0.44 dSm^{-1}. The hydraulic conductivity (K)– moisture content (θ) relationship was obtained by using sprinkling technique (El-Shafei 1988) and by applying Jackson's formula (1972). The sprinkling technique depends on the existence of a unit hydraulic gradient in the established moisture profile under an application rate (q) supplied by sprinkler (rain) simulator. Thus K(θ) = q. The sprinkler simulator was constructed by water supply reservoir with a constant head syphon connected to 24 capillary tubes (0.27-mm i.d.) which were held 5-cm above the soil surface to minimize the impact energy of the falling drops. For more details, the reader is referred to El-Shafei (1988). Many sensitive micro-tensiometers (1-mm i.d.) with mercury manometers, were inserted along the soil column through slots to obtain

the matric suction (ψ) - moisture content (θ) relationship. The Jackson's formula (1972) is presented as follows:

$$K_i = K_s \ (\theta_i/\theta_s)^c \sum_{j=i}^{m} \ [(2j+1 \ - \ 2i) \ \psi_j^{-2}]/ \sum_{j=1}^{m} \ [(2j-1) \ \psi_j^{-2}] \qquad (1)$$

where K_i is the hydraulic conductivity at moisture content θ_i, m is the number of increments of θ (16 equal intervals was used from $\theta = 0$ to $\theta = \theta_s$), ψ is the matric suction at the midpoint of each θ increment, j and i are summation indices, and c is an arbitrary constant and was assumed equal to unity. A wide range of moisture contents (θ) were obtained by distribution and redistribution of moisture in the soil column after an infiltration process, then matric suctions (ψ) were measured by the sensitive microtensiometers (El-Shafei and El-Naggar 1981), to get ψ-θ relationship. The moisture content (θ) was determined gravimetrically (on weight basis) for each 2.5 cm depth along the soil column after each infiltration run. Each measured point is an average of two determinations.

Results and Discussion

The results obtained from the infiltration experiments are given in Figures 1, 2 and 3. It can be deduced from Fig. 1 that below the surface saturation zone, there exists a lengthening unsaturated zone (transmission zone) with uniform moisture content (θ_T). The transmission zone is followed by a wetting zone where the moisture content sharply decreases with depth, then a wetting front which forms a sharp boundary between the wet and dry soil. These soil moisture profiles are in accordance with those observed by Bodman and Coleman (1943), and later presented by others (*e.g.*, Cannel and Stolzy 1962, Gupta and Staple 1964, Bridge and Collis-George 1973, El-Shafei and Fahmy 1975, and Bond and Collis-George 1981). The θ_T value was taken as an average of the moisture contents between 5 to 30 cm depths. The θ_w value (Fig. 1) was determined in the one centimeter ahead of the wetting front. Fig. 2 shows how the advance of the wetting front (L) decreases as the bulk density (D_b) increases. However, there was a substantial decrease in L when D_b increased from 1.35 to 1.40 g cm^{-3}. The cumulative infiltration (D) showed the same trend (Fig. 3). The computed power regression equations for L and D as a function of t are presented in Figures 2 and 3 which yield a correlation coefficient (r) = 0.9990. The results obtained are in good agreement with Kostiakov (1932) and Baver *et al.* (1972) who stated that for time intervals of a few hours and for uniform materials, the equations of L and D are in the form of power type with an exponent (n) close to but not always 0.5. The
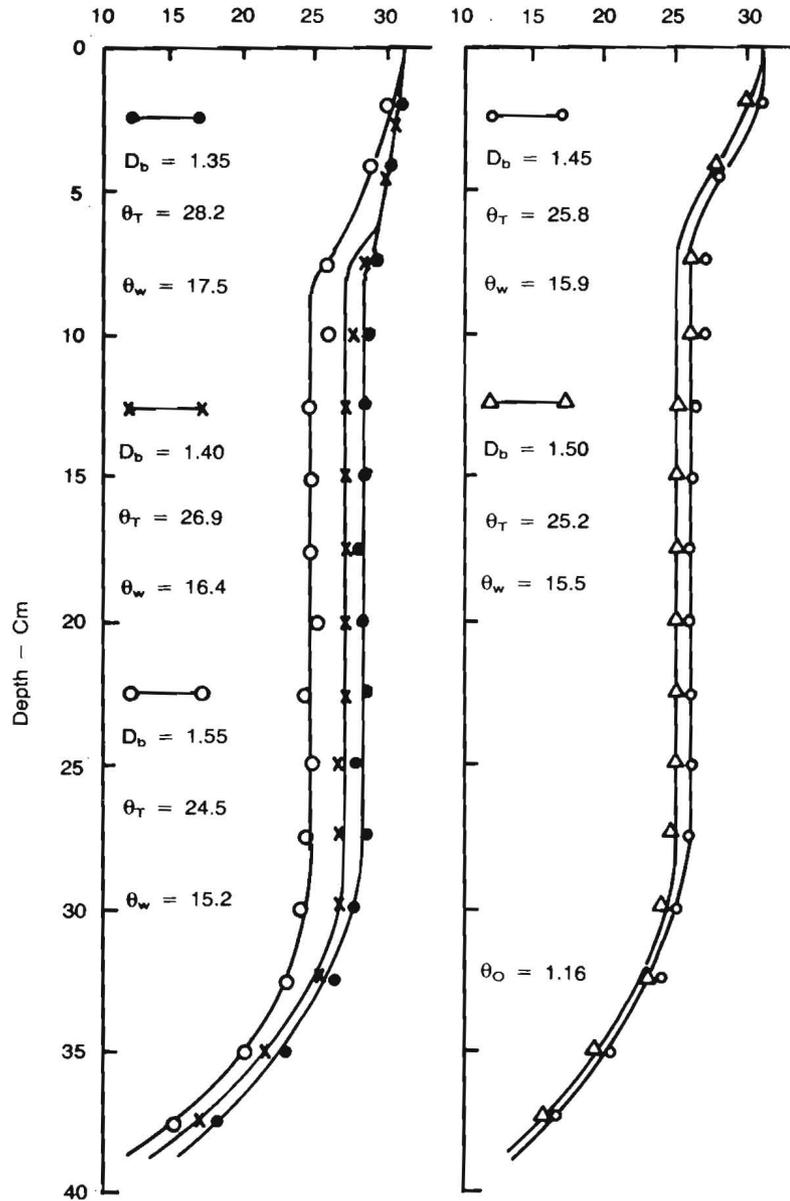
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Moisture content (θ) — % w/w

Fig. 1. Moisture profile in uniform loam soil after termination of the infiltration run for different bulk densities (D_b); showing the values of moisture contents in the transmission zone (θ_T) and near the wetting front (θ_w).
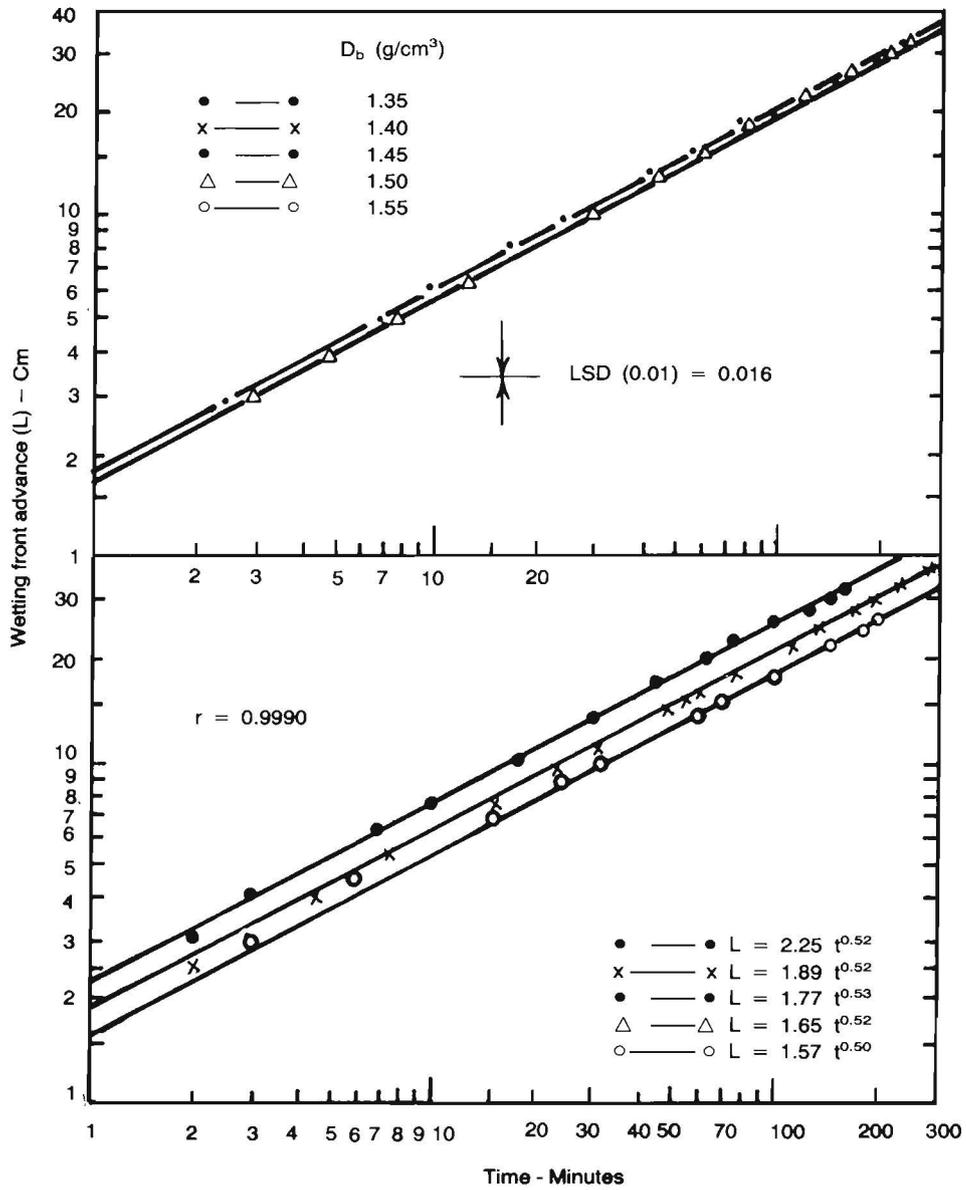
Fig. 2. Wetting front advance for different bulk densities (D_b).

analysis of the transmission zones (Fig. 1), and the depicted data in Figures 2 and 3 lead to the following relationships:

$$L = A\ t^n \qquad\qquad\qquad\qquad (2)$$
$$D = B\ t^n \qquad\qquad\qquad\qquad (3)$$
$$D = A\ D_b\ (\theta_T - \theta_o)\ t^n \qquad\qquad (4)$$

where A and B are constants have no particular physical meaning and are interrelated by soil bulk density (D_b), soil moisture content in the transmission zone (θ_T) and initial moisture content (θ_o). The exponent (n) is close to 0.5. The difference ($\theta_T - \theta_o$) is expressed as a fraction (g g^{-1}). The power type equations 2 and 3 can be converted to linear relationship if are plotted on a log-log scale.
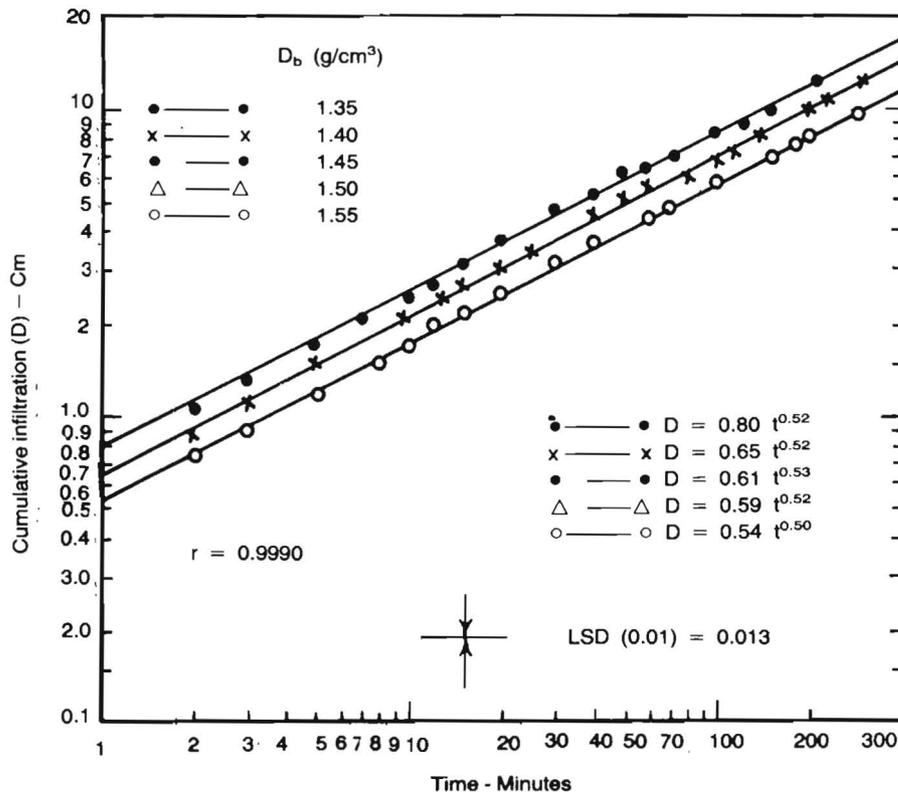

Fig. 3. Cumulative infiltration for different bulk densities (D_b). The lines for D_b 1.45 and 1.50 g cm^{-3} were omitted to avoid overlapping.

Thus, the logarithms of the data were taken and analyzed by using the General Linear Model (SAS User's Guide, 1986). The statistical analysis (Table 1) revealed the high significant effect of the soil bulk density on the advance of wetting front and the cumulative infiltration.
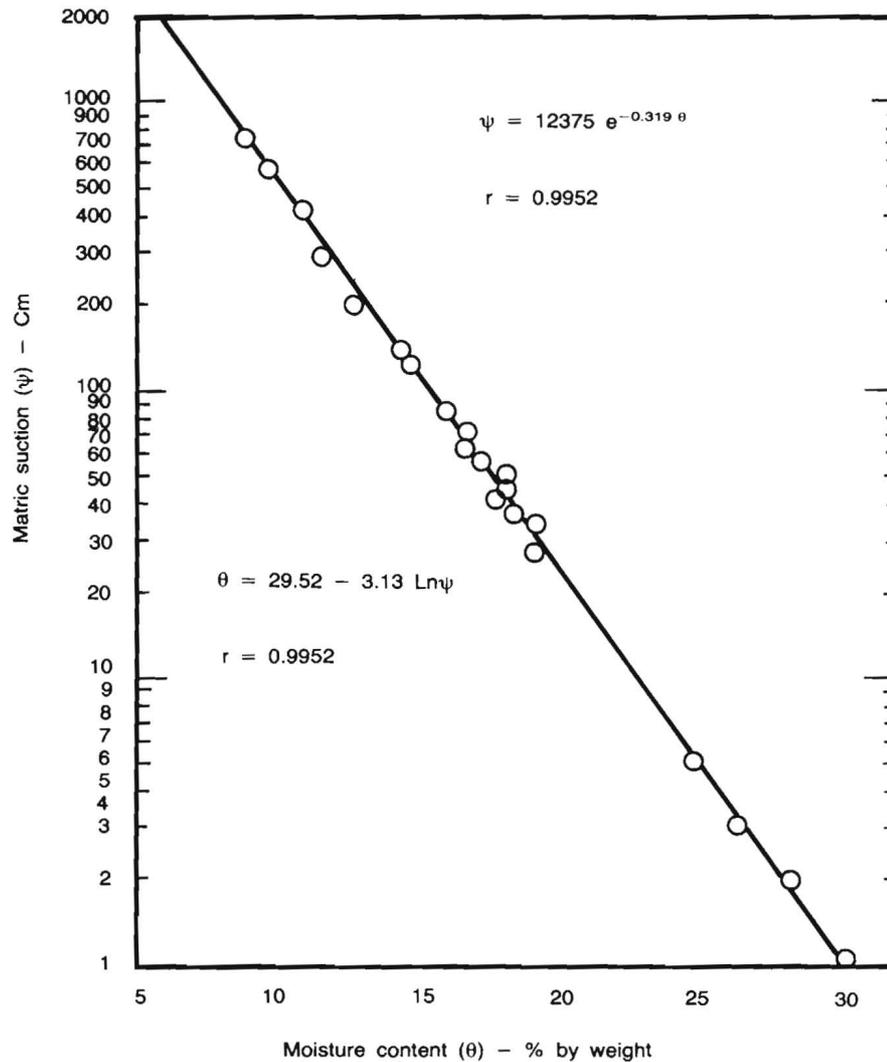

$$\psi = 12375 \, e^{-0.319 \, \theta}$$

$$r = 0.9952$$

$$\theta = 29.52 - 3.13 \, Ln\psi$$

$$r = 0.9952$$

Moisture content (θ) — % by weight

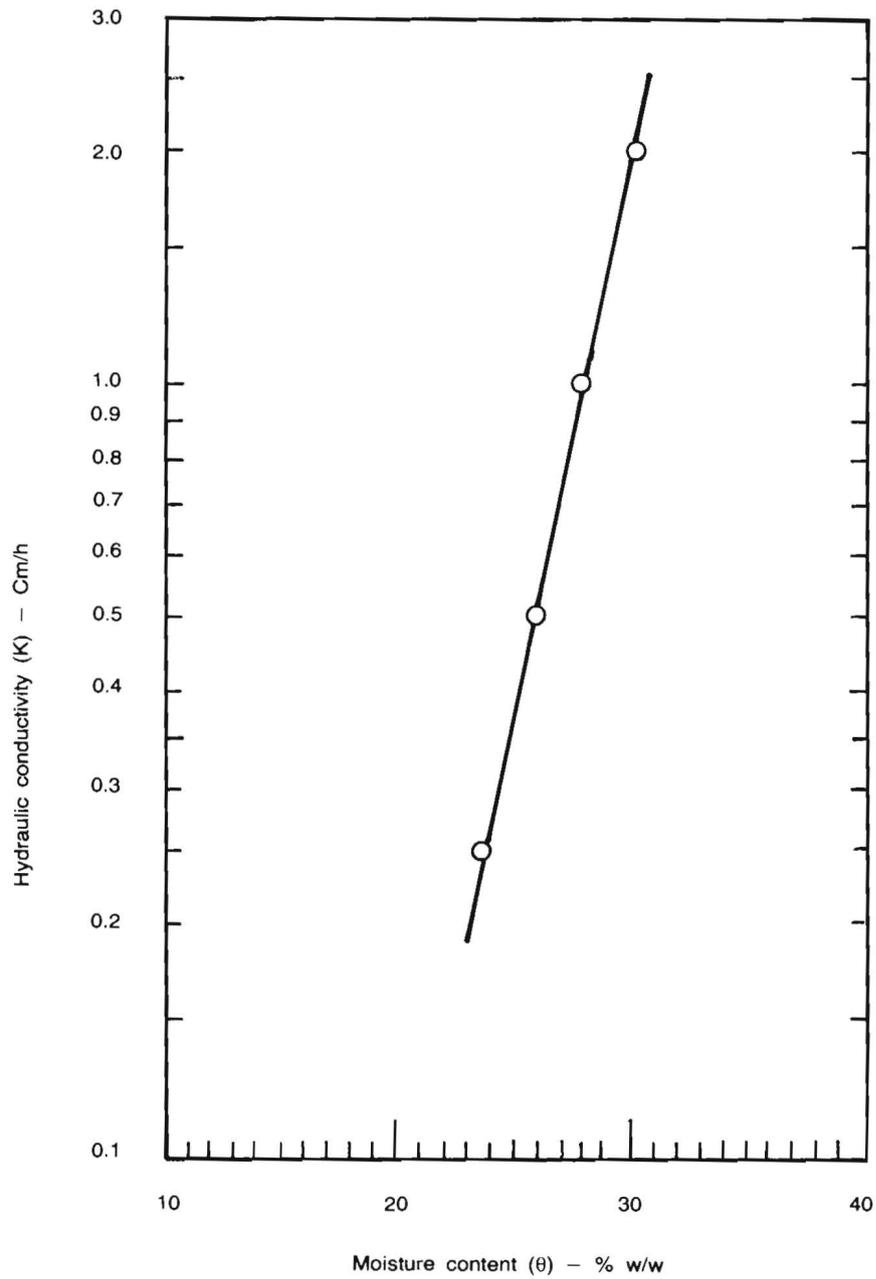**Fig. 4.** Matric suction of loam soil as a function of moisture content.

Fig. 5. Hydraulic conductivity of loam soil as a function of moisture content.

Table 1. The parameters A in equation 2 and B in equation 3 as affected by soil bulk density (D_b, g cm^{-3})*

D_b	A	B
1.35	2.25 a	0.80 a
1.40	1.89 b	0.65 b
1.45	1.77 c	0.61 c
1.50	1.65 d	0.59 d
1.55	1.57 e	0.54 e
LSD (0.01)	0.016	0.013

* Values followed by the same letter are not significantly different at 1% level.

For developing an infiltration equation accounting for soil bulk density and based on physical parameters, the following few assumptions can be made:

1. The bulk density (D_b) is uniform throughout the profile and remains constant during watering.
2. The initial moisture content (θ_o) is uniform throughout the profile.
3. The hydraulic conductivity of the transmission zone (K_T) remains constant for each D_b.
4. The soil matric suction (ψ) that depends on the curvature of the menisci near the wetting front, is constant for each D_b.

The advance rate of the wetting front (V) can obey Darcy's law as follows:

$$V = dL/dt = [K_T/ (D_b(\theta_T - \theta_o))] [(L + \psi)/L]$$

$$D_b (\theta_T - \theta_o)/K_T \int_0^L LdL/(L + \psi) = \int_0^t dt$$

$$D_b (\theta_T - \theta_o)/K_T \int_0^L \{[(L + \psi)/(L + \psi)] - [\psi/(L + \psi)]\} dL = \int_0^t dt$$

$$t = 60 D_b (\theta_T - \theta_o)/K_T [L - \psi \ln (L + \psi)/\psi] \tag{5}$$
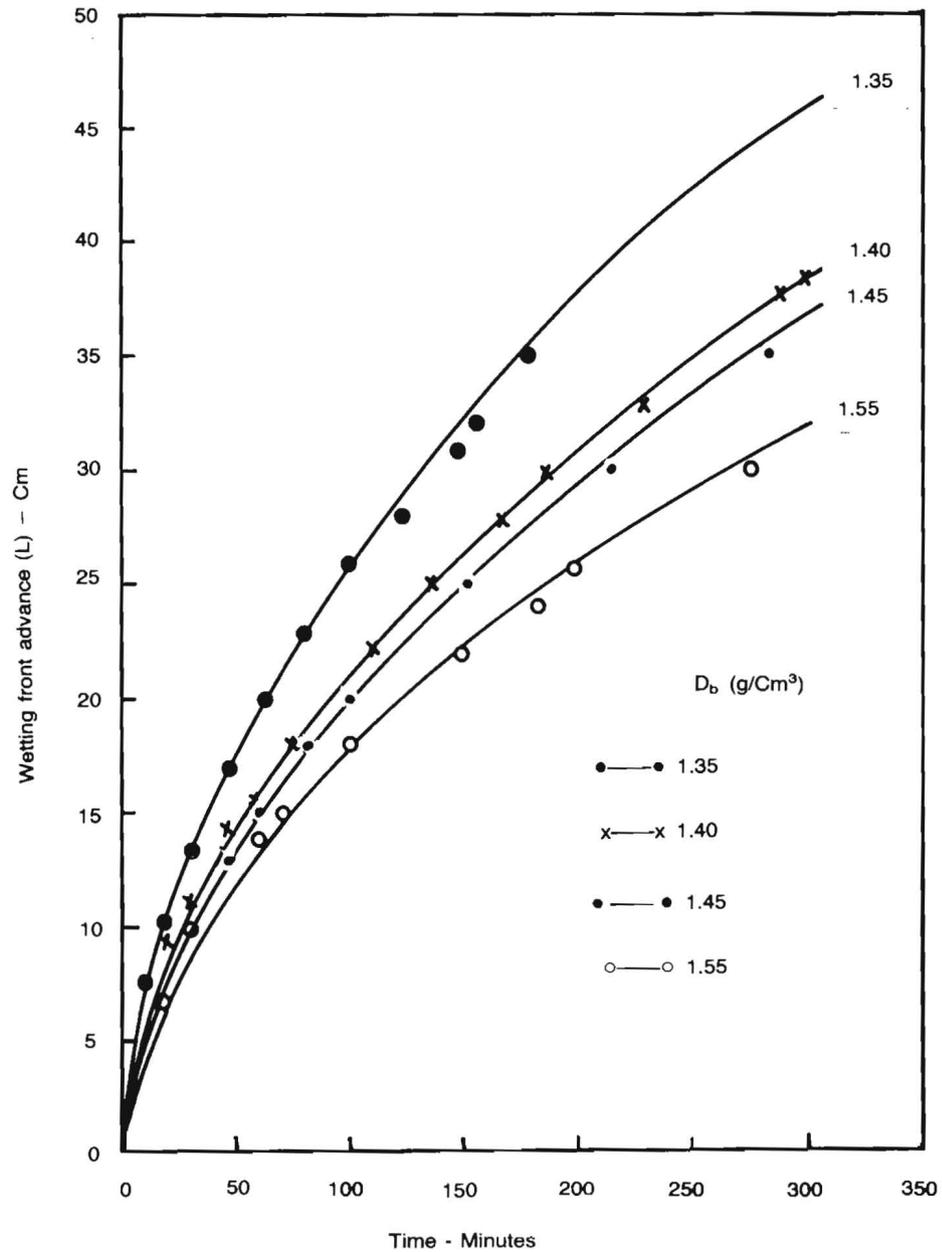
Fig. 6. Wetting front advance for different bulk densities; comparing computed values by the derived equation 5 (solid lines) with measured ones (points).

in which, t in min., $(\theta_T - \theta_o)$ in g g^{-1}, L in cm, ψ in cm and K$_T$ in cm h^{-1}. The parameters K$_T$ and ψ are functions of θ. Fig. 4 shows the measured values for ψ plotted as a function of θ which produced the following relationship for loam soil:

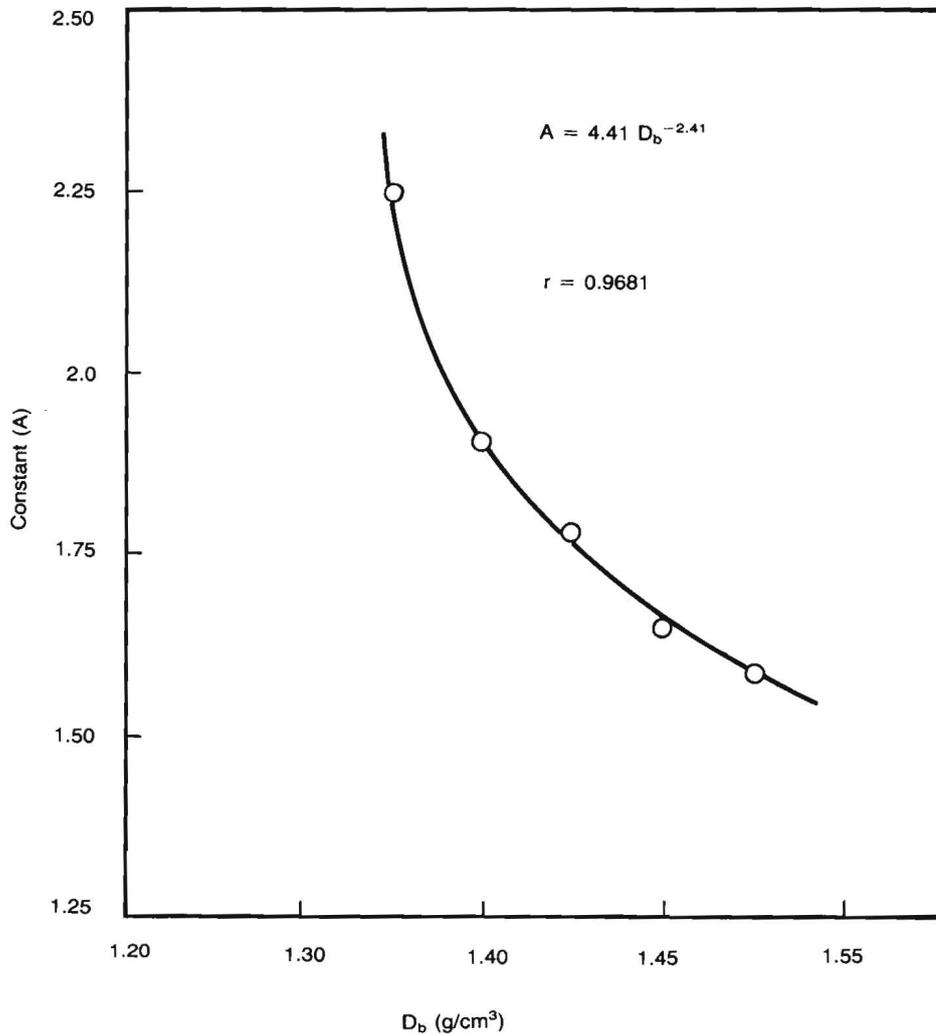$$\theta = 29.52 - 3.13 \ln \psi \qquad (r = 0.9952) \qquad (6)$$

Fig. 7. The parameter (A) in equation 4 as a function of bulk density (D$_b$).

Since the lowest value of θ_T obtained was 24.5% (81% of saturation) for $D_b = 1.55$ g cm^{-3}, it was found that three water rates (1, 0.50 and 0.25 cm h^{-1}) applied by a rain simulator (El-Shafei 1988) were quite enough to cover the needed values of K_T. Fig. 5 shows the measured hydraulic conductivity (K) plotted as a function of θ. However, a good approximation for $K-\theta$ relationship over the whole range of θ (0 to 32%) was calculated by implementing Fig. 4 and applying Jackson's formulation (Eq. 1). The resulted $K-\theta$ relationship conformed to the following exponential equation for loam soil:

$$K = 7.82 \times 10^{-10}\, e^{-0.75\theta} \qquad (r = 0.997) \tag{7}$$

Fig. 6 shows a good agreement between the computed L by the derived equation (5) and the measured ones. The good agreement is attributed to the accurate measurement of $K-\theta$ and $\psi-\theta$ relationships which were taken under infiltration process (wetting cycle). One can conclude from equations 2 and 4 that:

$$D = D_b\,(\theta_T - \theta_o)\, L \tag{8}$$

Accordingly, equation (5) can be converted to equation (9) which implies the cumulative infiltration (D).

$$t = 60/K_T\,[D - D_b(\theta_T - \theta_o)\,\psi\, \ln(1 + (D/D_b(\theta_T - \theta_o)\psi))] \tag{9}$$

Although equations 5 and 9 give greater insight into the physics of infiltration, however, the empirical equations 2 and 4 still have considerable currency because they contain parameters that can be adjusted for different bulk densities. Fig. 7 presents the relationship between the parameter (A) and D_b.

$$A = 4.41\, D_b^{2.41} \qquad (r = 0.968) \tag{10}$$

It should be mentioned here that equation (10) is only valid for loam soil and within the range of $D_b = 1.35$ to 1.55 g cm^{-3}.

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علاقة الكثافة الظاهرية بالسعة المائية التسربية لتربة طميية

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ص . ب : ٢٤٦٠ ـ الرياض ١١٤٥١ ـ المملكة العربية السعودية

أجريت تجربة معملية لـدراسة التسرب المـائي في أعمدة تـربة طميـية (قطر ٦ سم وطـول ٦٠ سم) تحت ضاغط مـائي ٢ سم علـى السـطح وخمس كثـافات ظاهرية للتربة (١,٣٥، ١,٤٠، ١,٤٥، ١,٥٠، ١,٥٥ جم/سم٣) حيث أن متوسط الكثافة الظاهرية في الحقل ١,٤٠ جم/سم٣ .

وقد إستخدمت طريقة الرش المائي (المعتمـدة على وجـود وحدة من التـدرج الهيدروليكي في المنطقة الإنتقاليـة لقطاع تـوزيع الـرطوبة) بواسطة نموذج مبسط للرش (يعـطي تصرفات ميـاه مختلفة) بـالإضافة إلى تـطبيق معـادلـة جاكسـون (١٩٧٢) وذلك بهدف الحصول على العـلاقة بـين معـامـل التوصيل الهيدروليكي والمحتوى الرطوبي للتربة ، كما إستخدمت مشدادات دقيقة ذات حساسية عـاليـة في قياسات الشد الرطوبي (شدة الإمتصاص الرطوبي) في التربـة وإيجاد العـلاقة بـين الشد الرطوبي والمحتوى الرطوبي في التربة .

وقد أظهرت النتائج أن كلا من معدل تقـدم جبهة الإبتـلال ومعدّل التسرب المائي التراكمي في التربة ينخفض معنوياً بإزدياد قيمة الكثافة الظاهـرية في حـدود مدى الكثافة المستعمل .

وقـد تم إستنباط معـادلات عامـة مبنية علـى عوامـل فيزيـائية للتربـة وذلك لحسـاب معدل تقـدم جبهة الإبتـلال ومعـدل التسرب المـائي التـراكمي . وهـذه

العوامل هي الكثافة الظاهرية، الرطوبة الإبتدائية، المحتوى الرطوبي في المنطقة الإنتقالية لقطاع توزيع الرطوبة، التوصيل الهيدروليكي للمنطقة الإنتقالية والشد الرطوبي (شدة الإمتصاص الرطوبي) عند جبهة الإبتلال. وتستخدم المعادلات أساساً قانون دارسي والصفات الفيزيائية لمنطقة الرطوبة الإنتقالية وجبهة الإبتلال لحركة المياه الرأسية.

وقد أجريت مقارنة بين قيم التسرب المائي المحسوبة بالمعادلات المستنبطة وبين القياسات المتحصل عليها ووجد أن هناك إتفاقاً جيداً بينهما.

وقد إستنبطت أيضاً معادلات تجريبية أسية (الشائعة الإستعمال للأغراض التطبيقية) متوافقة مع النتائج والمعادلات التحليلية السابقة وتعتمد أساساً على الكثافة الظاهرية، الرطوبة الإبتدائية، المحتوى الرطوبي في المنطقة الإنتقالية وثابت (معامل)، لحساب تقدم جبهة الإبتلال، والتسرب المائي في التربة. وقد وجدت علاقة بين الثابت (المعامل) الداخل في المعادلات التجريبية والكثافة الظاهرية للتربة وذلك للتنبؤ بالتغير في السعة المائية التسربية للتربة الطميية والخاضعة للتغيرات الحجمية الموسمية نتيجة لعمليات الحرث وإستخدام الآلات الزراعية الثقيلة.