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Water Infiltration into Uniform and Stratified Soils
II. Experimental Evaluation of an Approximate Theory[1]

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ABSTRACT

Downward infiltration of water into laboratory flow columns was studied experimentally for two different sand-silt mixtures designated as 'coarse' and 'fine'. Packing of the columns within a given stratum was held reasonably uniform. A special device was used to apply a 1-cm depth (head) of water instantaneously to the inlet end of a porous column without turbulent disturbance of the porous surface. Data were taken to assess the validity of infiltration equations derived by the Green and Ampt approach for both uniform and stratified columns.

For uniform columns, the equation for cumulative water infiltrated versus time accommodated the experimental data very well, and was fitted by least squares. Two characterizing constants are C, which is akin to a hydraulic conductivity, and P, which arises from the capillarity of the porous material. Although both C and P exhibited as much as a 2-fold variation for a given material, their respective mean values distinguished very well between the coarse and fine mixtures, and also provided the correct sense of C being markedly smaller for the fine material than for coarse, and of P being larger for fine material than for coarse.

For stratified columns, the corresponding equations were tested by predicting cumulative water infiltration versus time, based upon such parameters as C and P determined from uniform columns. These predictions agreed reasonably well with the direct measurements on the stratified columns, with one exception for a fine-over-coarse stratification after the wet front had penetrated into the coarse substratum relatively deeply in comparison with the thickness of the fine upper stratum. Also, the mean water content behind the wet front when in the substratum was distinctly less for fine over coarse than for a uniform coarse column.

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INTRODUCTION

In the first paper of this series (Asseed and Swartzendruber, 1), the approximate infiltration theory of Green and Ampt (4) was considered for both uniform and stratified soils. In the present paper, principal equations of this theory will be investigated experimentally. For a uniform soil

$$(y/a) - \ln(1 + y/a) = Ct/a \tag{1}$$

where y is the volume of water infiltrated per unit cross sectional area in time t after the constant depth H of water is ponded on the soil surface, C is a soil parameter akin to the hydraulic conductivity of nearly saturated soil, while the parameter a is given by

$$a = (\overline{\theta} - \theta_0)(H + P) = M(H + P) \tag{2}$$

where $\overline{\theta}$ is the constant mean water content behind the wet front, θ_0 is the constant initial water content of the soil, $M = \overline{\theta} - \theta_0$, and P is an equivalent constant head difference associated with the capillary properties of the soil. In terms of the wet-front depth z

$$y = (\overline{\theta} - \theta_0)z = Mz \tag{3}$$

Consider next the stratified case of an upper stratum of soil of thickness L_1 and properties C_1, P_1, and M_1 resting upon an infinitely deep stratum of properties C_2, P_2, and M_2. While the wet front is in the upper stratum, the equation will be the properly subscripted form of Eq. (1), namely

$$(y/a_1) - \ln(1 + y/a_1) = C_1t/a_1 \tag{4}$$

wherein y and t become y_0 and t_0 when the wet front strikes the stratum junction ($z = L_1$). When the wet front is in the lower stratum (wet-front depth $z > L_1$), the form of the equation becomes

$$(y_2/b) - (1 - c/b)\ln(1 + y_2/b) = C_2t_2/b \tag{5}$$

where y_2 and t_2 are reckoned from the stage at which the wet front strikes the stratum junction ($z = L_1$); also

$$b = M_2(H + P_2 + L_1) = a_2 + M_2L_1 \tag{6}$$

and

$$c = L_1M_2C_2/C_1 \tag{7}$$

Using the same origin as in Eq. (4) means that the overall cumulative infiltration curve is $y_0 + y_2$ versus $t_0 + t_2$, for $z > L_1$. In terms of wet-front depth

$$y_2 = (\overline{\theta}_2 - \theta_{02})(z - L_1) = M_2(z - L_1) \tag{8}$$

EXPERIMENTAL MATERIALS AND METHODS

Measurements were obtained on vertical laboratory columns of two mixtures of granular quartz, hereinafter referred to as 'coarse' and 'fine'. The coarse was a weight-basis mixture of 93.75% banding sand[3] and 6.25% of ground silica (No. 290)[3], while the fine was 75% banding sand and 25% ground silica. The banding sand has 90% of its

[3]Supplied by Ottawa Silica Company, Ottawa, Illinois, U.S.A.

particles in the size range 0.10 to 0.30 mm, while the ground silica has a size range 2 μ to 105 μ. The airdry water content of both the coarse and fine mixtures was essentially zero.

Uniformity of packing is usually somewhat of a problem in column studies, and absolute uniformity can be very difficult to obtain. Hence, the degree of control attempted here was to obtain a reasonable rather than perfect uniformity, and, particularly, to avoid distinct trends in bulk density change from one end to the other of a packed column. To achieve this, the empty confining columns, consisting of Plexiglas tubing of 6-mm wall and 3.8 cm inside diameter, were circumferentially scribed at 2-cm intervals of column length. Equal masses of porous material were then packed into each 2-cm section, the amount depending on the bulk density desired. Each individual section was tamped with a large rubber stopper fastened to the end of a long rod. The gamma-ray attenuation technique (3) was employed to measure the bulk density distribution in the packed columns. The dry bulk density was found to be within $\pm 5\%$ of the mean value, and there was no consistent trend from one end of the column to the other. This was considered to be satisfactory uniformity for the purposes of the present study.

The special water applicator of Swartzendruber and Asseed (6) was used to apply free water to the top end of each vertical column in a precise and controlled fashion without turbulent disturbance of the porous surface, with the H of Eqs. (2) and (6) generally being 1.1 cm. The bottom end of each vertical porous column was supported by several sheets of glass wool placed on a perforated Plexiglas end-disc that was open to the atmosphere at all times. At time zero, the column of porous medium was lifted quickly to bring its top surface into contact with the water applicator. Lapsed time t (or $t_0 + t_2$) was recorded with a stop watch. The downward progress of the wet front through the porous medium was recorded by means of the circumferential scribe marks placed every 2 cm on the exterior of the Plexiglas tubing. The volumes of water infiltrated were determined periodically by readings on the Mariotte-tube supply burette (6). These volumes were divided by the cross sectional area of the porous-medium column, to obtain the experimental values of y. Air temperatures were observed in the vicinity of each column, and remained constant within $\pm 0.5°C$ for any given experiment.

Water-infiltration measurements were obtained for two columns each as filled with only coarse and only fine material (uniform-column experiments). In other columns, a portion of coarse material was placed upon fine, and vice versa, with different lengths of coarse and fine (stratified-column experiments). A summary of these several combinations is given in Table 1. In all cases, the initial water contents θ_0, θ_{01}, or θ_{02} [of Eqs. (2) through (8)] were zero.

RESULTS AND DISCUSSION

Uniform Columns

For the four uniform columns of experiments 1 and 2 of Table 1, the y-versus-t data were analyzed by the least-squares method of Asseed and Swartzendruber (1), to evaluate the C and a of Eq. (1) as listed in Table 2. Experiment 1 is labelled in Table 2 as 1A and 1B for the two replicates on coarse material, while experiment 2 is labelled as 2A and 2B for the two replicates on fine material. For each column, data were taken until the wet-front depth z arrived at the bottom end of the 56.2-cm column. Results for these complete sets of data are identified in Table 2 as having a maximum wet-front depth of 56.2 cm. Least-squares fits for different sub-ranges of the data were also calculated, to determine the effect on the fitted C and a. These sub-ranges were chosen as the y-versus-t

Table 1 Porous-medium columns used for infiltration experiments.

Experiment No.	Type[1] and material	No. of determinations	Bulk density $\overline{\rho}_s$	Column length Overall	Column length L_1
			g/cc	cm	cm
1	Uniform, coarse	2	1.75	56.2	—
2	Uniform, fine	2	1.90	56.2	—
3	Stratified, coarse/fine	1	1.75/ 1.90	56.2	10.2
4	Stratified, coarse/fine	1	1.75/ 1.90	56.2	20.2
5	Stratified, coarse/fine	1	1.75/ 1.90	56.2	30.2
6	Stratfied, coarse/fine	1	1.75/ 1.90	56.2	40.2
7	Stratified, fine/coarse	1	1.90/ 1.75	56.2	10.2
8	Stratified, fine/coarse	1	1.90/ 1.75	56.2	20.2
9	Stratified, fine/coarse	1	1.90/ 1.75	56.2	30.2
10	Stratified fine/coarse	1	1.90/ 1.75	56.2	40.2

[1]Refers to whether column is uniform or stratified.

data for z intervals of 0 to 10.2, 0 to 20.2, 0 to 30.2, and 0 to 40.2 cm, corresponding with the values of L_1 of the stratified columns of Table 1.

Inspection of C and a in Table 2 does not seem to reveal any marked trends with size of sub-range. In contrast, it is seen for any given column that the mean-square deviation does increase progressively as the sub-range changes from a maximum z of 10.2 cm up to the full-range value of 56.2 cm. The mean-square deviation, shown for each sub-range and full range of data in Table 2, gives an indication of goodness of fit of Eq. (1), and would be zero if the data points fell perfectly on the theoretical curve. The largest mean-square deviation (18.31 min^2) in Table 2, occurring in experiment 2B for the full range (maximum z = 56.2 cm) of data, should represent the poorest fit of any set of data in the table. It is this set of data that was shown graphically in Fig. 2 of Asseed and Swartzendruber (1). Even for this so-called poorest fit, the least-squares curve of Eq. (1) was found to pass through the points very acceptably.

Experiment 1B for a maximum z of 10.2 cm does present behaviour worthy of special description. The least-squares method of Asseed and Swartzendruber (1) yielded a = 7,677 cm and $C = 8.23 \times 10^{-5}$ cm/min, both values being far out of line with all the other values of a and C for experiments 1A and 1B. Nevertheless, the product aC = 0.632 cm^2/min did compare very reasonably with the other values of aC in these two experiments. To account for such behaviour, let us note that for small y/a Eq. (1) becomes

$$y^2 = 2aCt \tag{9}$$

which, if solved for y, expresses the familiar square-root-of-time relationship for horizontal water absorption, as can also be derived directly for a horizontal porous-medium

Table 2 Fitted infiltration parameters for duplicate columns of coarse and fine material, $\theta_0 = 0$ (air-dry).

Description	Max. z	M.S. deviation[1]	C	a	aC	M	P	C_{20}
	cm	10^{-2} min^2	10^{-3} cm/min	cm	10^{-2} cm^2/min	cc/cc	cm H_2O	10^{-3} cm/min
Exp. No. 1A	10.2	0.20	84.1	6.47	54.4	0.246	25.	76.7
coarse, $\overline{\rho}_s$ =	20.2	0.40	52.2	11.07	57.8	0.246	43.9	47.6
1.75 g/cc,	30.2	2.38	71.7	7.41	53.1	0.248	28.8	65.4
23.9 °C	40.2	4.33	79.9	6.33	50.6	0.249	24.3	72.9
	56.2	11.06	90.4	5.14	46.5	0.252	19.3	82.4
						Means:	28.3	69.0
Exp. No. 1B	10.2	—	73.4[2]	8.61[3]	63.2	0.249	33.5	66.1
coarse, $\overline{\rho}_s$ =	20.2	1.99	67.8	8.40	57.0	0.249	32.6	61.0
1.75 g/cc,	30.2	4.44	58.2	10.06	58.5	0.249	39.3	52.4
24.4 °C	40.2	34.71	88.8	5.55	49.3	0.255	20.6	80.0
	56.2	57.62	78.8	6.66	52.5	0.255	25.0	71.0
						Means:	30.2	66.1
Exp. No. 2A	10.2	6.5	7.36	7.23	5.32	0.197	35.6	6.89
fine, $\overline{\rho}_s$ =	20.2	28.8	5.21	10.65	5.55	0.206	50.5	4.88
1.90 g/cc,	30.2	41.3	5.42	10.18	5.52	0.212	46.8	5.07
22.8 °C	40.2	411.1	4.15	14.26	5.92	0.212	66.0	3.88
	56.2	637.6	4.77	11.94	5.70	0.212	55.1	4.46
						Means:	50.8	5.04
Exp. No. 2B	10.2	1	6.39	9.38	5.99	0.192	47.7	5.90
fine, $\overline{\rho}_s$ =	20.2	32	3.60	17.02	6.13	0.202	82.9	3.33
1.90 g/cc,	30.2	70	3.66	16.66	6.10	0.204	80.4	3.38
23.3 °C	40.2	112	3.91	15.42	6.03	0.203	74.9	3.61
	56.2	1,831	5.59	9.52	5.32	0.215	43.2	5.17
						Means:	65.8	4.28

[1]Mean-square deviation $= \sum_{j=1}^{p} (t_j - \hat{t}_j)^2/p$, from Asseed and Swartzendruber (1975).
[2]Mean of four C's immediately following.
[3]Calculated as aC/(mean C) = (0.632)/(0.0734).

column by the Green and Ampt approach employed by Asseed and Swartzendruber (1). Hence, the mathematical solution for horizontal flow, as given by Eq. (9), may be viewed as a first-stage solution for vertical infiltration at sufficiently small times. From data of y versus t, or vice versa, it is then impossible to determine a and C separately — only the product aC can be evaluated. Thus, for a given set of (y, t) data which appears to be parabolic in the sense of Eq. (9), whether because of small times or experimental error or both, the least-squares method of Asseed and Swartzendruber can only operate by letting a become large. This, then, makes y/a small, as required to make Eq. (1) degenerate into Eq. (9). So, even though the large a and small C would be meaningless individually, their product could still be meaningful in the sense of Eq. (9). If these arguments are correct, then an alternative and more direct least-squares fitting method could be devised on the basis of Eq. (9) by choosing $\hat{t}_j = y_j^2/2aC$ for use in Asseed and Swartzendruber's (1) Eq. (14). When this was done and the calculations carried out, the resulting aC agreed perfectly with the 0.632 cm^2/min as found earlier. In view of all of the foregoing, more realistic individual estimates of a and C for this particular 10.2-cm sub-range (experiment 1B) were sought as follows: C was taken as the mean of the four C's determined for the full range and the three remaining sub-ranges of experiment 1B. This mean C (0.0734 cm/min) was then divided into the least-squares aC (of 0.632 cm^2/min) to obtain a = 8.61 cm.

The values of M in Table 2 were calculated on the basis of Eq. (3) from experimental plots of y against z. In general, the proportionality of these plots was quite good, and straight lines through the origin were drawn through the points by eye. Lines of different slope were drawn for the different sub-ranges if required, but it is clear from the table that these differences are very slight within a given material. From a, M, and H (= 1.1 cm in most cases), P was calculated by Eq. (2). Corrections of C for temperature effects on water viscosity were made by assuming C to be inversely proportional to viscosity η at the temperature of the experiment. If C_{20} and η_{20} are the respective values of C and η at 20°C, the correction takes the form

$$C_{20} = C\eta/\eta_{20} \tag{10}$$

which is the basis on which the C_{20} values in Table 2 were calculated.

Perusal of Table 2 shows that M varies but slightly within sub-ranges or duplications, whereas between coarse and fine materials there is a small difference that is correctly related to the difference in bulk density. In contrast, P and C_{20} exhibit almost 2-fold variations within sub-ranges. Such variations within a fairly uniform material may not be excessive, however, in view of a recent finding (Nofziger, Ahuja, and Swartzendruber, (5)) that relatively small random fluctuations in data can give rise to 2-fold variations in soil-water diffusivity. Furthermore, the means of both P and C_{20} within duplications are reasonably close, and the means for coarse and fine materials are distinctly separated in the proper sense. That is, the coarse would be expected to have a smaller P than the fine, and this indeed is actually found. Also, C_{20} distinguishes very well between coarse and fine, with at least a 13-fold difference in values, and also does so in the correct sense of designating the coarse material to be more permeable than the fine. Overall, it is felt that the results in Table 2 are encouragingly in support of Green and Ampt approach as represented by Eqs. (1), (2), and (3).

Finally, it is pertinent to consider the behaviour of aC (Table 2), since this quantity from Eq. (9) could be made the basis for characterizing water absorption by a horizontal column. Clearly, aC is nicely stable within sub-ranges and duplications, and still distinguishes properly and quite markedly between coarse and fine materials. Hence, the use of aC in establishing a and C would appear to have merit, but for fullest utilization would require an independent and more precise means of determining either C alone or a alone, so that the remaining undetermined parameter could in turn be calculated more precisely from aC.

Stratified Columns

We now consider the results for experiments 3 through 10 of Table 1, involving stratified columns. First to be assessed is whether the mean water content behind the wet front is the same for a given material whether in uniform [M of Eq. (3)] or stratified [M_2 of Eq. (8)] conditions. Graphical illustrations of how M_1 and M_2 for stratified columns were obtained are shown in Fig. 1 for experiments 5 and 9, for an upper layer of L_1 = 30.2 cm for both coarse above fine and fine above coarse. For coarse above fine, the shift from M_1 to M_2 is just a very simple break in the slope of the two straight lines at z = L_1 = 30.2 cm. But for fine above coarse, the transition from one major straight line to the other is somewhat more complex.

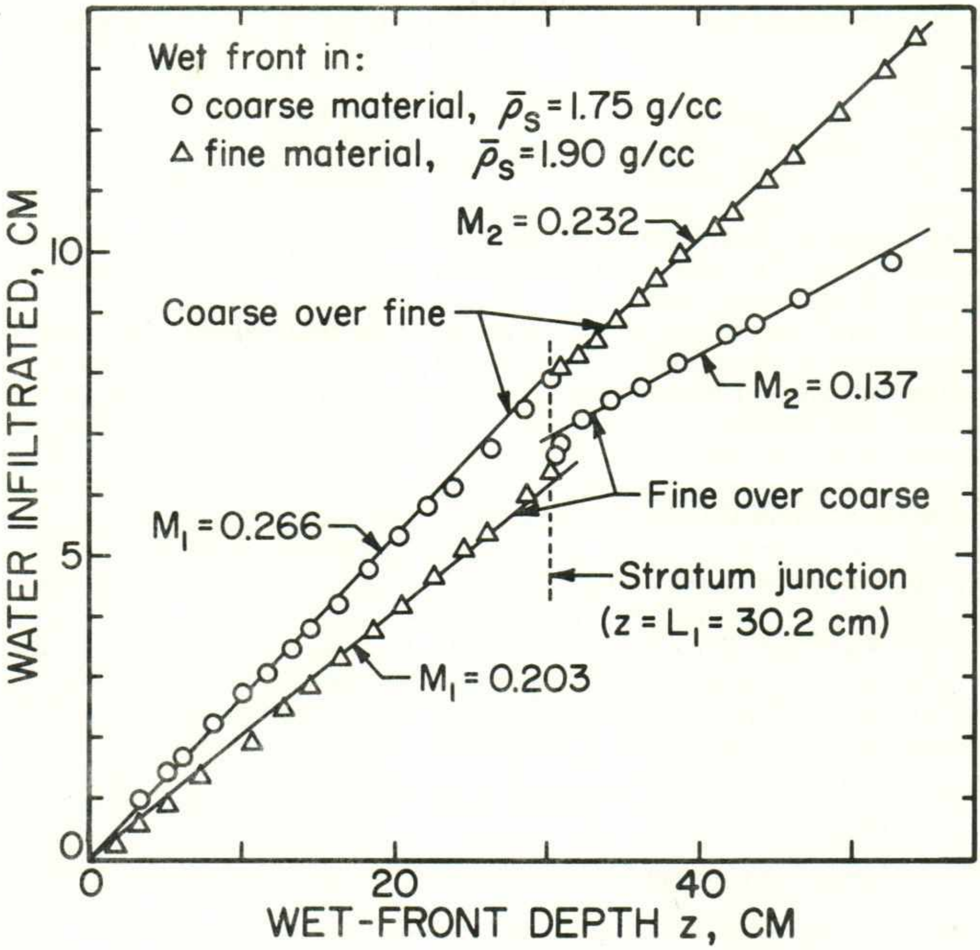

Fig. 1. Water infiltrated versus wet-front advance, for stratified columns of coarse over fine and fine over coarse, with depth of upper stratum $L_1 = 30.2$ cm in both instances.

When the wet front is in the upper (subscript 1) stratum of a stratified column, there is little reason to expect that the resulting M_1 should be different from the M of the same material in a completely uniform column. This is well verified in Table 3, where in every case M_1 agrees very well with the corresponding M. The same is true when M_2 [Eq. (8)] is compared with M for all of the stratifications in which the coarse material is above the fine (experiments 3 through 6). But when the fine material is above the coarse, M_2 for the underlying coarser material is distinctly less than M, and tends to become progressively smaller as the length L_1 of the upper (fine) stratum increases (experiments 7 through 10). This implies that if a finer textured material is interposed between a given porous material and the free-water depth H on the surface, the given (coarser) material will not wet to as great a $\bar{\theta}$ as it would if it were itself extended all the way to the free water, or as it would if the interposed stratum were even more coarse than the given material. Hence, this suggests that Eq. (5) might be less applicable for fine-over-coarse than for coarse-over-fine stratifications, particularly if M_2 in Eq. (6) were taken as the M determined from uniform-column experiments. This general difficulty has been discussed previously by Childs and Bybordi (2).

We next consider the use of Eqs. (4) and (5) to predict the actual stratified-column behaviour as observed in experiments 3 through 10. Two schemes were employed for arriving at the constants to be used in the equations. In the first scheme, the duplicate determinations for each coarse and each fine material of uniform experiments 1 and 2 were averaged to obtain the necessary values of M_1 and P_1 to calculate a_1, of M_2 and P_2 for calculating b and c, and of C_1 and C_2 to be used directly and in calculating c. C_1 and C_2 were also corrected to the temperature of the stratified-column experiments by a calculation similar to Eq. (10). It should be noted that the foregoing scheme is the one which would likely be employed in any practical utilization of Eqs. (4) and (5) for predicting infiltration into stratified systems.

Nevertheless, the foregoing scheme is subjec to any discrepancies involved in predicting the behaviour of even a single uniform column from the mean characterization of two uniform columns, and the variations of C and P within sub-ranges in Table 2 suggest that such discrepancies might be appreciable. To attempt to remove such error, a second scheme was devised in which as many as possible of the constants in Eqs. (4), (5), (6), and (7) were obtained from experimental observations on the stratified column itself. Hence, M_1, P_1, and C_1 were determined for the stratified column while the wet front was within the upper (subscript 1) stratum, C_1 and a_1 being the constants of the least-squares fit of Eq. (4). When the wet front was in the lower (subscript 2) stratum, M_2 was determined by plotting y_2 against z in accord with Eq. (8) (the M_2 values of Table 3). Effort also was made to determine b, c, and C_2 while the wet front was in the lower stratum, but without success. Hence, to enable a calculation of b and c from Eqs. (6) and (7), the values of C_2 and a_2 [second of Eqs. (6)] as computed in the first scheme were retained for use in the second scheme also. The parameters as used in both schemes are summarized in Table 4.

Table 3 Comparison of M_1 and M_2 of stratified columns with corresponding values of M for uniform columns.

Stratified Columns						Uniform Columns		
Exp.[1] No.	Stratum Subscript[2]	Stratum Length	Material	M_1	M_2	M[3]	Max. z	Exp.[1] No.
		cm		cc/cc	cc/cc	cc/cc	cm	
3	1	10.2	coarse	0.249	—	0.248	10.2	1
	2	46.0	fine	—	0.216	0.214	56.2	2
4	1	20.2	coarse	0.267	—	0.248	20.2	1
	2	36.0	fine	—	0.230	0.208	40.2	2
5	1	30.2	coarse	0.266	—	0.248	30.2	1
	2	26.0	fine	—	0.232	0.208	30.2	2
6	1	40.2	coarse	0.255	—	0.252	40.2	1
	2	16.0	fine	—	0.230	0.204	20.2	2
7	1	10.2	fine	0.182	—	0.194	10.2	2
	2	46.0	coarse	—	0.185	0.253	56.2	1
8	1	20.2	fine	0.204	—	0.204	20.2	2
	2	36.0	coarse	—	0.155	0.252	40.2	1
9	1	30.2	fine	0.203	—	0.208	30.2	2
	2	26.0	coarse	—	0.137	0.248	30.2	1
10	1	40.2	fine	0.204	—	0.208	40.2	2
	2	16.0	coarse	—	0.138	0.248	20.2	1

[1]From Table 1.

[2]Subscript 1 denotes upper stratum and subscript 2 denotes lower stratum.

[3]Mean of two determinations.

Table 4 Parameters used in Eqs. (4) and (5) for predicting cumulative infiltration into stratified columns.

For Exp. No.	L_1	Scheme[1]	y_0[2]	a_1	C_1	b	C_2	c
					10^{-3}		10^{-3}	
	cm		cm	cm	cm/min	cm	cm/min	cm
3	10.2	first	2.515	7.54	80.3	12.91	5.42	0.1465
		second	2.530	5.51	73.3	12.93	5.42	0.1619
4	20.2	first	4.990	9.74	61.0	19.06	4.22	0.2899
		second	5.383	10.25	46.0	19.51	4.22	0.4257
5	30.2	first	7.495	8.73	66.2	19.78	4.75	0.4512
		second	8.022	5.22	87.1	20.49	4.75	0.3817
6	40.2	first	10.132	5.94	86.0	22.07	4.61	0.4401
		second	10.241	5.38	86.8	23.10	4.61	0.4906
7	10.2	first	1.976	8.31	6.84	8.46	82.0	30.84
		second	1.849	9.05	5.84	7.77	82.0	26.40
8	20.2	first	4.123	13.86	4.44	11.03	82.7	94.77
		second	4.113	13.02	4.60	9.06	82.7	56.10
9	30.2	first	6.288	13.49	4.52	16.22	63.0	104.41
		second	6.132	7.54	6.84	12.85	63.0	37.95
10	40.2	first	8.345	14.87	4.00	19.68	58.0	144.14
		second	8.205	6.96	7.10	15.27	58.0	45.17

[1]In the first scheme, tabular values are derived from averages determined from uniform columns; in the second scheme, values are derived from the stratified column itself, inasmuch as possible.

[2]Calculated as L_1M_1, where M_1 is an average for the first scheme, and a single value for the second scheme.

The results of the two foregoing prediction schemes, along with the experimentally observed infiltration data for the stratified columns of experiments 3 through 10, are shown in Figs. 2 through 5. Results for both coarse-over-fine and fine-over-coarse for a given L_1 are shown on the same graph, with the solid-line curve representing the first-scheme prediction, and the broken-line curve the second scheme. The origin of coordinates is that of Eq. (4), the ordinate and abscissa becoming $y_0 + y_2$ and $t_0 + t_2$, respectively, when the wet front moves into the lower stratum, as discussed previously following Eq. (7). Where no broken-line curve is shown, it is essentially the same as the solid-line curve. The theoretical points at which the wet front strikes the stratum junction are indicated by arrows on the curves.

For all coarse-over-fine cases, the agreement between experiment and theoretical prediction is reasonably good, and in two cases (Figs. 3 and 4) is somewhat improved by the second-scheme prediction which involves more infiltration characterizations derived from the stratified columns themselves. In no instance is the second-scheme prediction poorer than the first scheme.

For the fine-over-coarse cases, the agreement between experiment and first-scheme prediction is also reasonably good in three instances out of four (Fig. 3 through 5), and for the most part the second-scheme prediction is worse than the first scheme, except that in two of these three instances (Figs. 3 and 5) the experimental points fall between the two predictions when the wet front is in the lower stratum. The poorest agreement is in Fig. 2 when the wet front is in the lower stratum, and again the second-scheme prediction is poorer than the first scheme. This suggests that Eq. (5) is least valid in fine-over-

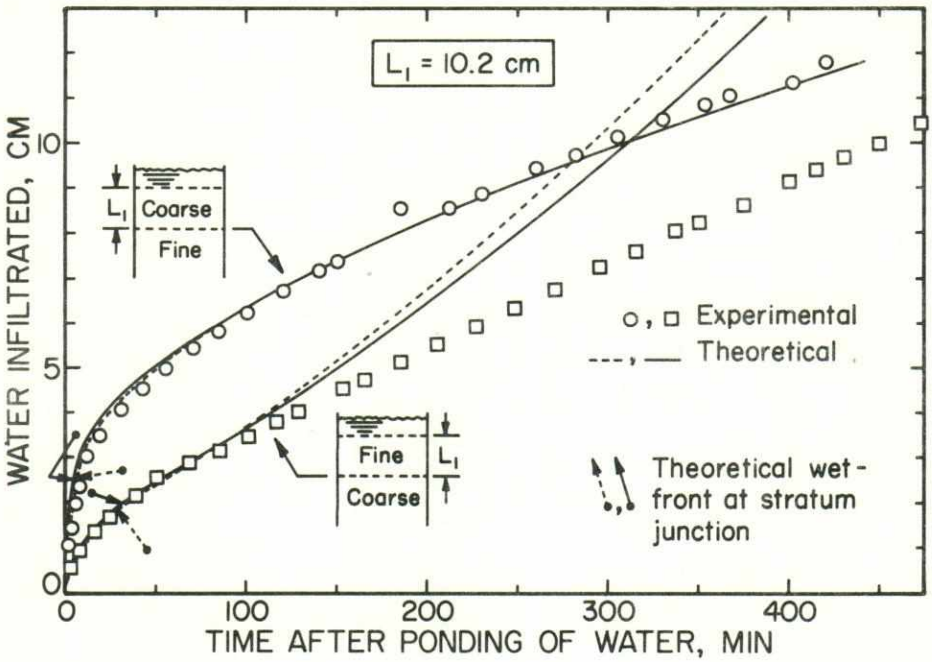

Fig. 2. Water infiltrated versus time, experimental and predicted [Eqs. (4) and (5)] for coarse-over-fine and fine-over-coarse stratifications, upper stratum $L_1 = 10.2$ cm. See text for explanation of theoretical curves.

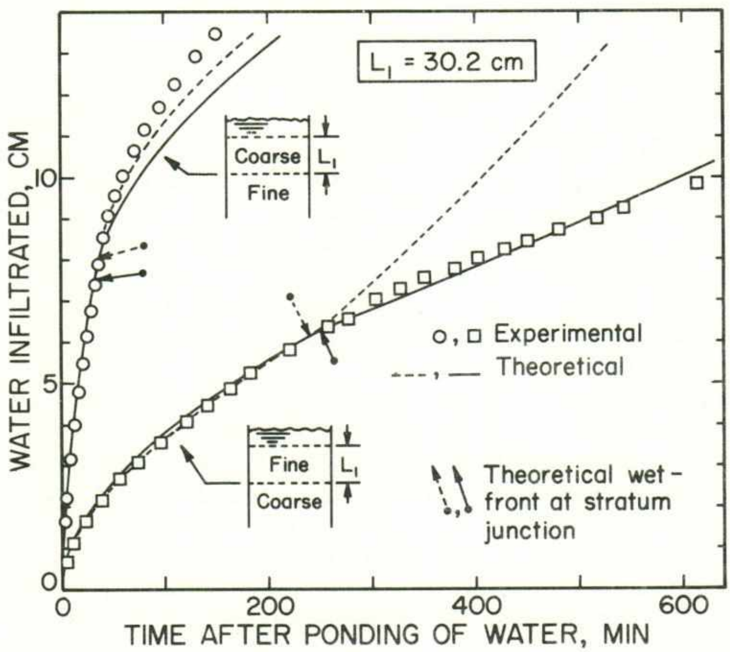

Fig. 3. Water infiltrated versus time, experimental and predicted [Eqs. (4) and (5)] for coarse-over-fine and fine-over-coarse stratifications, upper stratum $L_1 = 20.2$ cm. See text for explanation of theoretical curves.

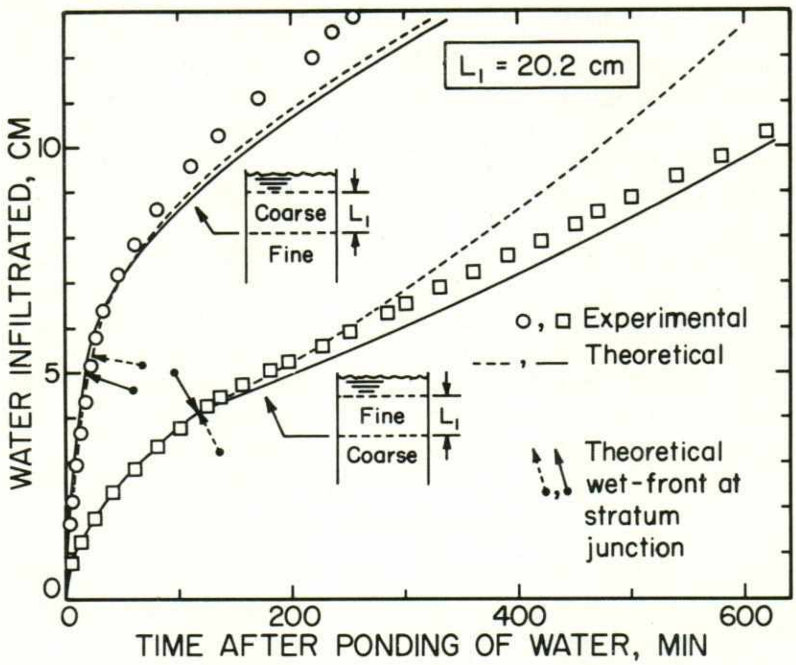

Fig. 4. Water infiltrated versus time, experimental and predicted [Eqs. (4) and (5)] for coarse-over-fine and fine-over-coarse stratifications, with upper stratum $L_1 = 30.2$ cm. See text for explanation of theoretical curves.

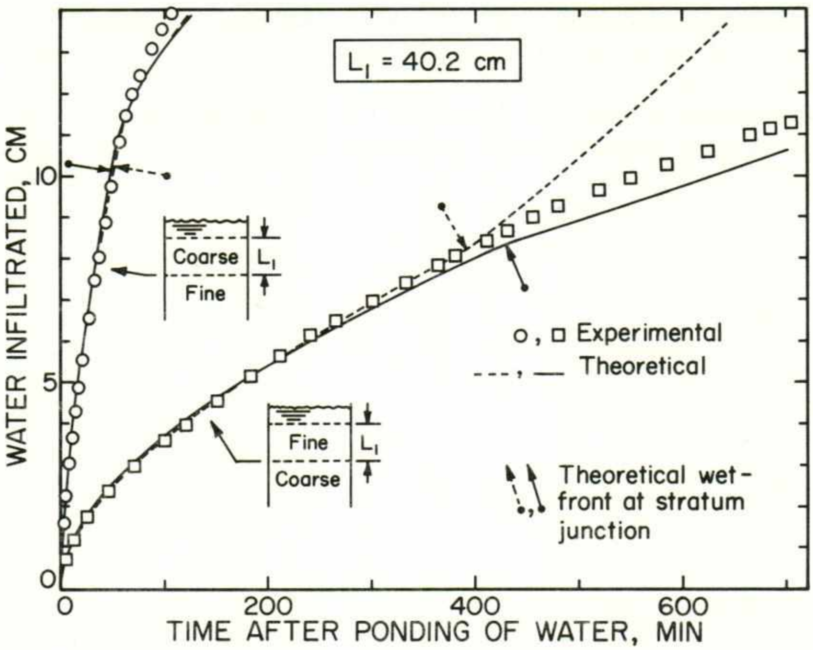

Fig. 5. Water infiltrated versus time, experimental and predicted [Eqs. (4) and (5)] for coarse-over-fine and fine-over-coarse stratifications, with upper stratum $L_1 = 40.2$ cm. See text for explanation of theoretical curves.

coarse systems where the fine stratum is short and the penetration of the wet front into the second stratum is a number of multiples of the length of the short upper stratum. On this basis, it might be argued that the fine-over-coarse experiments in Figs. 3, 4, and 5 would become more deviant if continued to deeper wet-front penetrations, but in two of these cases the solid-line curves are actually below the data points, rather than above them as in Fig. 2.

In an overall sense, it is felt that the data of Figs. 2 through 5 portray a reasonable conformity with the Green and Ampt approach for stratified soils as embodied in Eqs. (4) through (8), with the exception of the fine-over-coarse case in Fig. 2 when the wet front is in the substratum. In fact, for the fine-over-coarse cases in Figs. 3, 4, and 5, the agreement between experiment and theory actually seems very much better than would have been expected on the basis of the statement of Childs and Bybordi (2, p. 447) that the Green and Ampt approach has no relevance for such situations.

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