Unstable Flow during Redistribution in Homogeneous Soil

Zhi Wang,* Atac Tuli, and William A. Jury

ABSTRACT

Two- and three-dimensional laboratory experiments were conducted in a large 1 by 1 m^2 Hele–Shaw cell and a 10-cm cylinder column to study the stability of the redistribution process in a uniformly packed porous medium of coarse sand. Our results demonstrate that fingers form and propagate rapidly as soon as infiltration stops when the soil is initially dry, but form more slowly and are larger when the soil is wet. Finger widths ranged from about 4.5 cm when the soil was dry to 17 cm when the soil was very wet, and the fraction of the cross-sectional area occupied by fingers also increased (from 36 to 66%). Finger velocities declined with time in all studies, with averages ranging from 3.6 to 9.6 cm min^{-1}. We demonstrated that ponded infiltration was stable and uniform in our system, so that the fingering we observed was not due to soil heterogeneity. The porous medium retained a memory of the fingers formed in the first experiment, so fingers formed in subsequent redistribution cycles followed the old finger paths, even after 28 d had elapsed. Fingers provide channels for rapid drainage of previously infiltrated water, especially when the soil ahead of the front is dry. Our findings clearly contradict predictions made by the Richards equation, which calculates stable flow during redistribution in homogeneous soil.

Although unstable fluid flow has been acknowledged to exist in field soils, it has generally been associated with specific conditions that interfere with the normal surface tension and viscous flow that stabilizes water as it moves through a porous medium. Aside from these extreme conditions, preferential flow of water and chemicals has generally been attributed to soil heterogeneity and not to instability within the fluid phase (White, 1985). However, it has long been known in fluid mechanics and petroleum engineering (e.g., Taylor, 1950; Saffman and Taylor, 1958, Chuoke et al., 1959) that under certain conditions fluid flow can become unstable in a perfectly uniform porous medium or even when one fluid flows through another in a medium without a porous solid framework. These concepts have been extended to hydrologic applications (e.g., Raats, 1973; Philip, 1975; Parlange and Hill, 1976) to predict the conditions under which unstable flow might occur in porous media. Once the flow becomes unstable, fingering will bypass a significant portion of the matrix and transport the invading fluid much faster and deeper than would occur under stable flow conditions. A thorough review of experimental and theoretical studies of unstable flow in the vadose zone is given in de Rooij (2000) and Nieber (2001).

Previous research on unstable flow in vadose zone hydrology has identified some of the important, necessary conditions for the onset of fluid instability. The most widely studied and documented occurrences of unstable flow in the vadose zone are of two types: vertical flow from a fine-textured layer into a coarse one (Hill and Parlange, 1972; Starr et al., 1978, 1986; Glass et al., 1988, 1989a,b; Hillel and Baker, 1988; Baker and Hillel, 1990, Nieber, 1996; Wang et al., 1998b) and infiltration into a hydrophobic medium (Van Ommen et al., 1988; Hendrickx et al., 1993; Ritsema et al., 1993; Burcar et al., 1994; Carrillo et al., 2000; Wang et al., 1998b, 2000b). Because so much of the attention has been focused on these cases, it is commonly believed that unstable flow is a result either of heterogeneity or soil water repellence. However, infiltration experiments in perfectly uniform porous media have also shown unstable flow induced by air compression ahead of the wetting front (White et al., 1976, 1977; Wang et al., 1997, 1998c) or unsaturated infiltration under low rates (Selker et al., 1992; Wang et al., 1998b; Geiger and Durnford, 2000). Another condition predicted by Raats (1973) and Philip (1975) to cause unstable flow in uniform porous media is redistribution following the cessation of infiltration. It has received relatively little attention in the literature, presumably because the redistribution water front is not considered to be very different from an infiltration front. However, because redistribution is one of the most common natural hydrologic processes, it is important to understand the extent to which the process may be unstable, and what factors influence its occurrence.

Although Nicholl et al. (1994) observed fingering during redistribution in initially dry fractures, Diment and Watson (1985) and Tamai et al. (1987) seem to be the only researchers who have demonstrated that redistribution causes unstable flow in extremely coarse-textured uniform materials. However, these authors concluded that instability only occurs when the medium ahead of the draining front is extremely dry. Diment and Watson's experiments, which were performed in a small Hele–Shaw cell (80 cm high, 40 cm wide, and 1.5 cm thick), showed that redistribution "stabilized" when the initial water content was increased to only a few percent of saturation. In addition, they performed a stability analysis on the Richards flow equation and showed that instability was extremely rare during redistribution (Diment and Watson 1985). It is possible, however, that their experimental apparatus might have been too small to observe unstable flow under a range of conditions. Fluid stability analyses (Saffman and Taylor, 1958; Chuoke et al., 1959; Philip, 1975) have shown that unstable flow fingers have a characteristic width and spatial frequency or wavelength, and, therefore, that their development might be suppressed if the lateral extent of the experimental apparatus is not sufficiently large. This might explain why studies of redistribution conducted in small columns have not produced unstable flow, because

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Published in Vadose Zone Journal 2:52–60 (2003).

the cross-sectional area may have been too small to display several finger wavelengths. In addition, since fingers are predicted to widen when the initial soil water content increases (Jury et al., 2003), the spatial scale required to observe fingering in moist soil will also increase. Our recent study of redistribution in nonstructured field soils (Wang et al., 2003) showed that instabilities developed after infiltration ceased and that the fingers we observed were quite large (≈13-cm diam.) and had a mean wavelength of nearly 30 cm. Therefore, it appears to be necessary to use a large observation frame to study unstable flow during redistribution.

The objectives of the study reported here were (i) to conduct experiments in a large Hele–Shaw cell to observe the flow patterns during redistribution following infiltration, (ii) to observe the appearance of fingering during subsequent cycles of redistribution if flow was unstable, (iii) to study the effects of high initial water content on the development of fingers, and (iv) to compare the results of two-dimensional experiments with three-dimensional observations. We also report digital pictures of fingering during redistribution. Detailed measurements of the processes and theoretical analyses of the mechanisms of fingering are presented in a companion paper (Jury et al., 2003).

MATERIALS AND METHODS

Laboratory Setup and Materials

A Hele–Shaw cell with transparent walls was constructed using two sheets of 100 by 100 cm^2 Plexiglas bolted together with 1-cm spacing. Gridlines creating 10 by 10 cm^2 squares were drawn on the front and back panels for delineating the wetting patterns. The bottom of the cell was open to the atmosphere through nine 3-mm holes to prevent air compression. The cell was filled with commercial silica sand that was first sieved to obtain a uniform 0.5- to 0.8-mm particle size. Before packing, the slab box was laid horizontal with the front (top) panel removed, and dry sand was poured directly on top of the bottom panel using a flat pan. After filling the sand to about 1-cm thickness over 99 cm of the panel, the front panel was mounted and bolted, and the slab box was set vertically upright. The box was then gently tapped using a rubber hammer until the sand was consolidated to 95 cm. The nonuniform surface layer of loose sand was removed using a vacuum, and the remaining sand was leveled to its final height of 91 cm.

The saturated hydraulic conductivity of the sand, estimated using a constant head permeameter, was K_s = 682 cm h^{-1}. The water-entry value of the sand was about h_{we} = 3 cm, measured using a tension-pressure permeameter (Wang et al.,

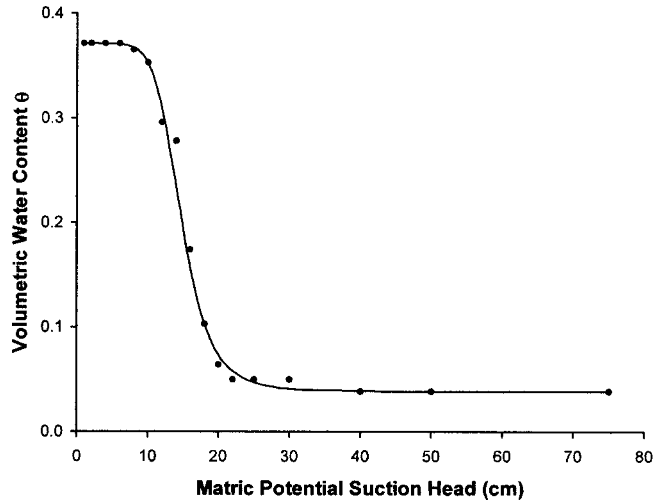

Fig. 1. Drying loop of the water characteristic curve. Circles are data points and curve is best fit of Eq. [3].

2000a). We measured the drying loop of the moisture release curve of the sand used in our experiments with a hanging water column (Jury et al., 1991), as shown in Fig. 1. A V-shaped funnel flume was constructed to hold and release a maximum of 2000 mL of water through a slotted tube attached to the bottom of the flume, which produced a uniform application of ponded water to the sand surface in 2 to 5 s.

Experimental Design

We conducted six experiments on various aspects of the redistribution process in our study (Table 1). In the first, we applied 500 mL (equivalent to a 5-cm irrigation) of deaired water onto the dry sand surface through a funnel flume to create ponded infiltration, then allowed water to redistribute without air entrapment ahead of the wetting front. In Exp. 2 through 4, we studied the effect of repeated infiltration cycles of 5 cm on the flow patterns that developed during redistribution. The second and third experiments were conducted 3 and 6 d (on Days 4 and 8, respectively) after the previous cycle's drainage from the bottom of the cell ceased. The fourth experiment was conducted 28 d after the previous experiment ended. We used a dye tracer (1% weight of the anionic compound Acid Red in the deaired water) in Exp. 4 to visualize the newest flow patterns. In the fifth experiment, the surface was ponded until the wetting front reached the bottom and the dye tracer was completely flushed out of the box. The purpose of this procedure was to observe the shape of the wetting front during an extended period of ponding and to eliminate the sand's memory of the previous flow patterns. The sixth experiment was conducted 24 h after Exp. 5, when the sand was still very wet,

Table 1. Experimental arrangements and part of the results in a large Hele–Shaw cell.†

Exp.	Time	Initial moisture	Tracer	Infiltration volume	Drainage volume	Water retention	Finger width‡	Finger velocity§	Finger area fraction
				mL			cm	cm min^{-1}	
Exp. 1	Day 1	dry	non	500	150	340	4.5 ± 0.9	9.6 ± 2.2	0.36
Exp. 2	Day 4	fingered	non	500	180	320	5.1 ± 1.4	5.8 ± 2.8	0.46
Exp. 3	Day 8	fingered	non	500	180	320	6.8 ± 2.0	5.8 ± 3.2	0.54
Exp. 4	Day 36	slight	dye¶	500	60	440	9.2 ± 2.3	3.6 ± 2.0	0.66
Exp. 5	Day 49	fingered	non	–	–	–	–	24.1 ± 3.1	1.0
Exp. 6	Day 50	wet	dye	500	50	450	16.3 ± 6.4	2.9 ± 1.4	0.65

† 100 cm deep, 100 cm wide, with 1-cm spacing.
‡ Average taken at midpoint of cell.
§ Average of all fingers.
¶ Acid red (1%).

to observe the effects of high initial water content on the development of flow instability. The various flow patterns that developed during each of the infiltration and redistribution experiments were photographed using a 35-mm digital camera and downloaded into the computer for analysis.

Three-dimensional experiments were conducted using a cylindrical column of 10-cm i.d. with transparent walls. The purpose of this phase of the study was to preserve the shape of the fingers by freezing the column rapidly once the fingers were fully developed. Initially dry sand was poured into the column using a mesh randomizer (a 2.50-cm-diam. tube with 3-mm mesh screens at 10- and 30-cm heights above the bottom). The sand was consolidated using a shaker, after which the surface was leveled and covered with cheesecloth. Predetermined irrigation amounts of 3 and 5 cm were applied uniformly to the sand surface in separate experiments using a pump and shower-head assembly. The application rate was high enough to create ponding on the surface during infiltration. The infiltrated water was allowed to redistribute until the wetting front reached the bottom of the column. The column was then placed in a cold room with a fixed temperature of −20°C. After 24 h, the column was retrieved from the cold room. Several holes were then drilled through the bottom crust of frozen sand, allowing the unwetted sand to spill out. The frozen fingers remaining inside the column were photographed using a digital camera. For detailed finger characterization in the future, a mold was made of the fingers using liquid components of the Foam System (S & W Plastics, Ontario, CA).

RESULTS

Figures 2 and 3 show photographs of the wetting front taken at different times during each of the experiments. The redistribution time is indexed from $t = 0$, defined as the moment when ponded water first disappeared from the sand surface. By comparing these photographs and relating the observations to the experimental conditions, we can draw a number of inferences about the nature of the flow process during infiltration and redistribution.

Unstable Flow during Redistribution

Figures 2a through 2f show pictures at six different times of the transition from infiltration to redistribution in an initially dry soil. At the end of infiltration ($t = 0$), the wetting front had penetrated to a depth of about 9 cm and was quite flat, indicating that the flow process was stable. Approximately 1 cm of residual water remained in the funnel valve's dead reservoirs, and was released during redistribution. After about 30 s of redistribution, fingers had formed at several locations that were visible at the front and back panels of the cell. These fingers, as well as several others not visible at 0.5 min, grew and propagated ahead of the front, which remained stationary during the rest of the draining process (Fig. 2d–2f). The fingers ranged in width from 3.5 to 5.5 cm, and occupied roughly 36% of the cross-sectional area. These fingers served as "short-circuiting" paths that drained most of the water initially present in the top layer. They moved downward at an average speed of 9.6 ± 2.2 cm min^{-1} averaged over the entire journey from wetting front to cell bottom (Table 1). After 24 h of drainage, 32% of the total application had drained from the cell. Therefore, if drainage had been unrestricted, the fingers would have been significantly longer.

The finger widths we observed are consistent with sizes predicted by the equation

$$d = a\sqrt{\frac{R^*|h_{we}|}{1 - i/K_s}} \qquad [1]$$

where d (cm) is finger diameter, $a = 3.14$ (two-dimensional) and 4.8 (two-dimensional), R^* (cm) is the hydraulic radius, and i is drainage rate. Equation [1] was derived by Wang et al. (1998a) and used in Wang et al. (2003) and Jury et al. (2003) to describe observed finger sizes. In our study, if we use our measured values $h_{we} = -3$ cm, $K_s = 682$ cm h^{-1}, the observed range of $0.3 < R^* < 0.7$ cm estimated from data reported in Wang et al. (1998a). Then Eq. [1] predicts 3 cm $< d <$ 4.5 cm (assuming $i = 0$) and 3.75 cm $< d <$ 5.5 cm (assuming $i/K_s = 0.3$, our best estimate of the maximum drainage flux just after fingers formed).

The great depths reached by the fingers following such a small water application (5 cm) are also understandable from the soil properties. As shown in Jury et al. (2003), maximum finger depth can be estimated approximately by assuming that the final profile is in hydrostatic equilibrium. The initial water infiltration I produces a water application W to the fingers that increases to I/ξ, where ξ is the fraction of the area covered by fingers. In our study, $\xi \approx 0.36$, so $I/\xi = W = 8.3$ cm. At equilibrium, the finger will have a water content distribution at heights z above the tip which is given by $\theta_{eq}[h^* - z]$, where $\theta_{eq}[h]$ is the equilibrium drying loop of the water characteristic function, and h^* is the matric potential of the drying loop corresponding to the water-entry value of the wetting loop. Thus, the finger will reach a depth z_{max}, which is given by

$$W = \int_0^{z_{max}} \theta_{eq}[h^* - z']dz' \qquad [2]$$

The drying loop of the water characteristic function of our coarse sand is shown in Fig. 1, along with the best fit ($\theta_s = 0.371$, $\theta_r = 0.039$, $\alpha = 0.07$, $N = 7.5$) of the van Genuchten (1980) parameters

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (-\alpha h)^N]^{1-1/N}} \qquad [3]$$

Using our best estimate $h^* \sim 12$ cm, we calculated that 5 cm of water would penetrate to a depth z_{max} approximately 115 cm below the depth where the fingers first form. Thus, the small amount of water storage behind the tip of the finger is responsible for its deep penetration. Fingers formed in a finer-textured soil might penetrate only a few centimeters following a 5-cm water application, both because of the higher water storage in the finger and because the fingers would be wider (Jury et al., 2003).

Finger Recurrence

The second experiment, shown in Fig. 2g through 2l, was designed to see how the residual traces of the fingers formed in the previous irrigation cycle would affect the

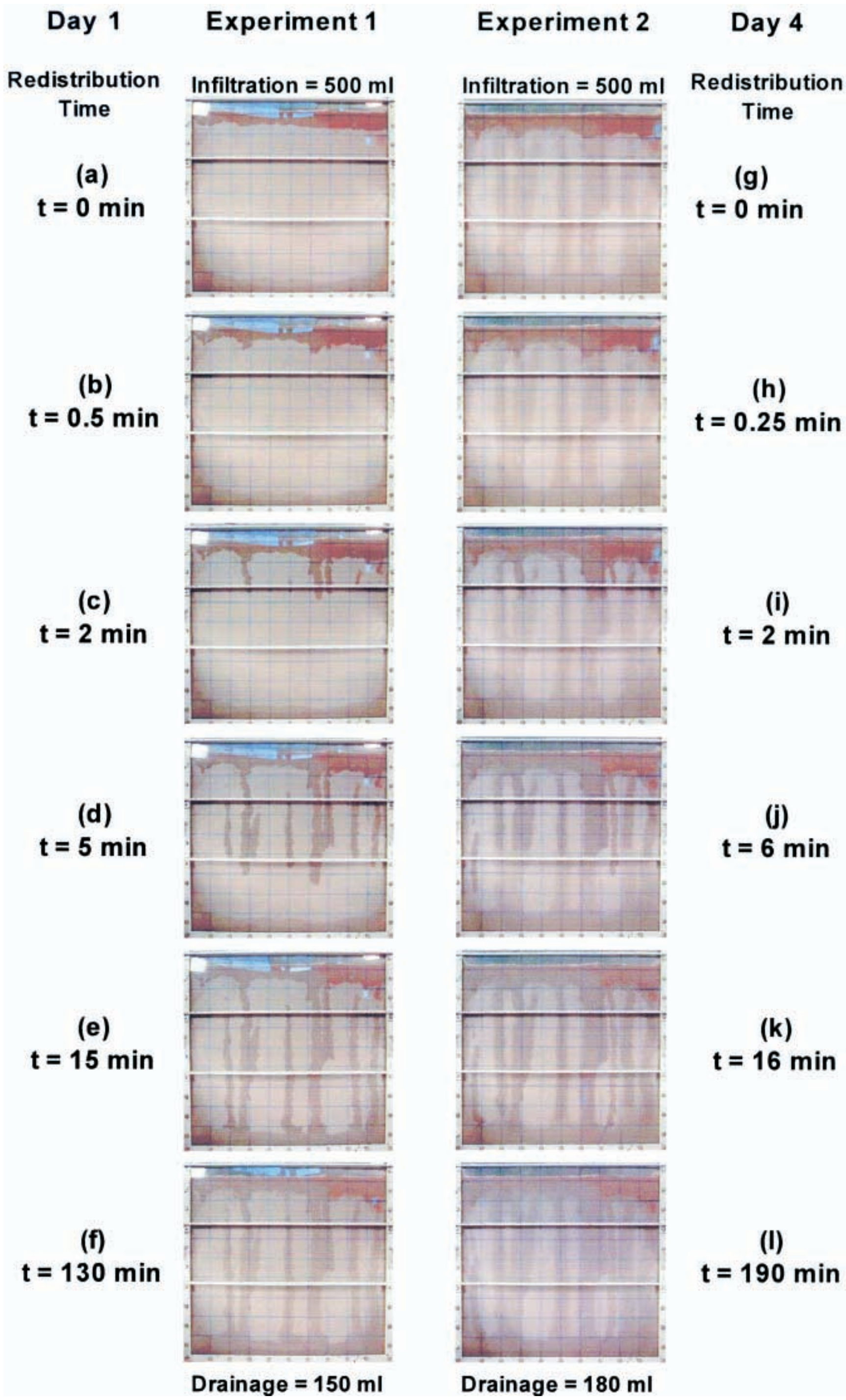

Fig. 2. Photographs of the wetting front taken at different times (a–f) during redistribution in dry sand and (g–l) during second cycle of redistribution with fingers in the sand. The redistribution time is indexed from $t = 0$, defined as the moment when ponded water first disappeared from the sand surface.

wetting front during a subsequent irrigation. As soon as infiltration ended at $t = 0$, water started to funnel into the old finger paths. The wetting front of the region between the fingers moved only a small distance below the point reached by the first cycle, and once again halted its advance as soon as the fingers were reached. Two additional fingers were created in this cycle, one nearest the left side of the box and the other at the third position from the right side. Also, the area fraction occupied by fingers rose to about 46%. The finger size increased slightly to a mean of 5.1 ± 2.2 cm, and the finger speed decreased by nearly 50%, as shown in Table 1. More water drained out of the box through the fingers in this study than in the first one.

Porous Medium Memory of Fingers

The third study (Fig. 3) was virtually a replication of the second, conducted 4 d after Exp. 2 ended. The development, location, and speed of the fingers were all quite

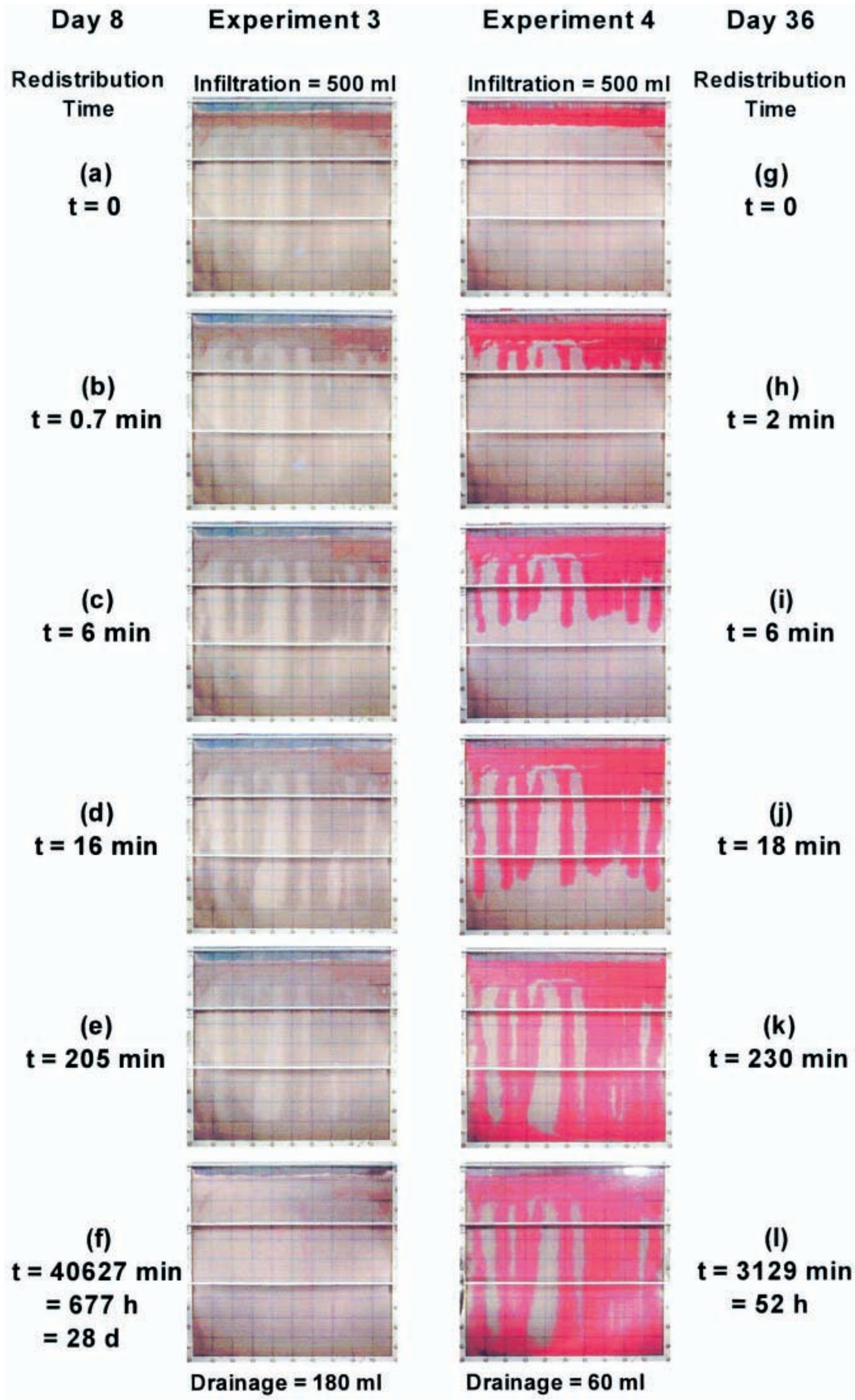

Fig. 3. Wetting front patterns (a–f) during the third cycle of redistribution with fingers in the sand and (g–l) during the fourth cycle of redistribution with diffused fingers in the sand.

similar to the processes observed in Exp. 2, except for an increase (to 6.8 ± 2.2 cm) in the mean size of the fingers, and a growth (to 54%) in the finger area fraction (Table 1). The fourth experiment was conducted to determine if the porous medium retained a memory of the fingered flow paths for an extensive period of time. During the 28 d that elapsed between the end of Exp. 3 and the beginning of Exp. 4, water in the finger domains gradually diffused into the surrounding profile, erasing the visual memory of the flow paths, as shown in Fig. 3f. Despite the apparent homogeneity of the soil ahead of the front, however, the 5-cm irrigation added in Exp. 4 followed virtually the same flow paths that had been produced by the fingers in the previous cycles. Figure 4 shows a closeup view of the infiltration pattern from Fig. 3d at 16 min of the third cycle, and from Fig. 3j at 18 min into the cycle conducted 28 d later. The fingers from the second cycle were slightly larger (9.2 ± 2.3 cm) and occupied about 66% of the cross-sectional area. Consequently, the finger speed (see Table 1) was re-

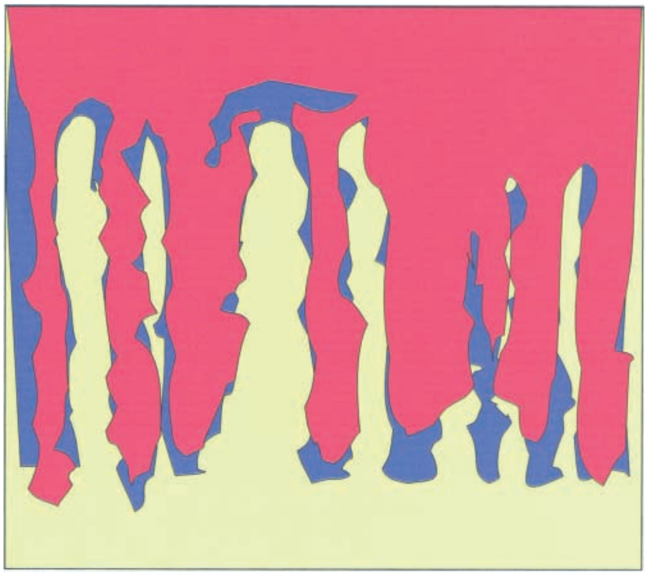

Fig. 4. Superposition of the draining front 16 min into the third cycle (blue), and 18 minutes into the fourth cycle conducted 28 d later in the same column. (red)

duced significantly compared with earlier experiments. Thus, the effect of the long redistribution time was to widen the finger pathways but not to eliminate them.

Stable Flow during Ponded Infiltration

The fifth experiment (Fig. 5) had several objectives. We first sought to demonstrate that the finger pathways established in the first experiment and faithfully followed in later experiments were not caused by soil heterogeneity, but rather were a random consequence of perturbations in wetting front position when the fluid was unstable. We also wanted to demonstrate that infiltration would be stable and uniform in this soil, and that fingering memory could be erased. To that end we continuously ponded water on the surface until all traces of the dye were removed from the profile (Fig. 5a–5f). As seen in the time sequence, the infiltrating front remained quite uniform during its transit through the cell, gaining a negligible advantage from encountering the fingered pathways remaining from Exp. 4 concluded several days earlier. Moreover, the soil matrix between the fingers that had remained dry in previous studies was now invaded by the advancing front, and the entire profile wetted up as the front exited the cell. This clearly establishes that the fingered locations were not consequences of permeability variations, as these would have shown up as wetting front irregularities in ponded infiltration.

Effects of High Initial Water Content

The sixth experiment was designed to see if fingering would occur in soil that was initially and uniformly quite wet. To this end we added 5 cm of dyed water only 1 d after Exp. 5 ended, when the entire soil profile was saturated. The redistribution flow was stable during the first minute (Fig. 5g and 5h), but became quite irregular as time progressed. For the next 3 min, the wetting front was oscillatory (Fig. 5i and 5j) and finally developed large (17 ± 1 cm) fingers, indicating the onset of instability. Three important characteristics of fingered flow in the wet sand can be identified (see Table 1), as compared with that in dry sand:

1. Finger size increased more than threefold compared with what was observed in Exp. 1 through 4.
2. Water retention in the wet sand increased by 53% in Exp. 6 and 34% in Exp. 4, compared with the average retention observed in Exp. 1 through 3.
3. Finger speed decreased to 30 to 50% of that in Exp. 1 through 3, but was comparable to that observed in Exp. 4, which had a relatively low initial water content in the fingers and a dry matrix in between.

The behavior in experiments 4 and 6 directly contradicts the results observed by Diment and Watson (1985) in their smaller Hele–Shaw cell; they noted that an increase to only a few percent water content eliminated the instability they had observed in oven-dry soil. According to their stability analysis, our results also contradict the predictions of the Richards equation.

Finger Speed

The dynamic changes of the wetting front velocity in all the experiments are shown in Fig. 6. The finger velocity, even in the earliest stages, is significantly less than the velocity of the ponded wetting front, indicating that the fingers are unsaturated. Finger velocity declined with time, as predicted by the model of Jury et al. (2003), and indicates that the rate of supply from the matrix is controlling the advance of the fingers. Velocity decreased as initial water content increased (Exp. 4 and 6), which may reflect the increase in area fraction associated with these studies. During redistribution, the downward flow in the matrix region between the fingers essentially stopped, which indicates that the pressure at the wetting front has dropped below the water-entry value required to continue its advance. Once the fingers fully develop, water behind the matrix front between the fingers experiences a lateral pressure gradient and reinforces the finger flow, thereby lowering the matrix water pressure below the threshold for downward movement (Jury et al., 2003). When the soil was initially dry, the wetted matrix region between the fingers did not move beyond 10 cm below the surface, and the fingers moved to the bottom of the cell, producing significant drainage (see Table 1). However, for the initially wet sand in Exp. 6, the wetting front remained stable for a longer time and moved to 42 cm below the surface before splitting.

Three-Dimensional Fingers

Figure 7 shows the results of the three-dimensional experiments. Three centimeters of water was applied to Column A and 5 cm to Column B. Water was allowed to redistribute for about 10 min before the column was put into a freezer. The bottom of column A was allowed to sit in a box containing the same kind of sand in the column, while the bottom of column B was in contact

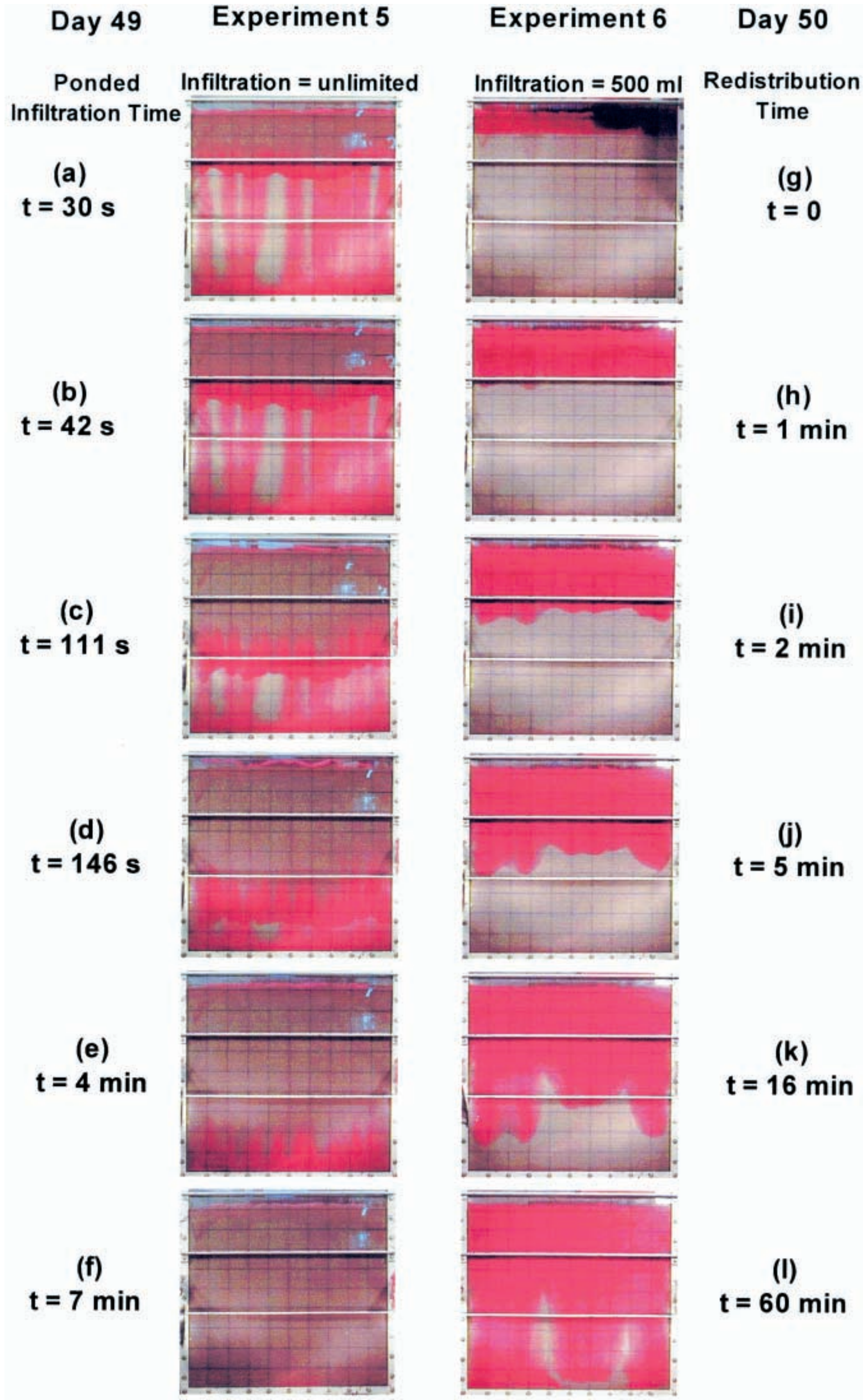

Fig. 5. Wetting front patterns (a–f) during ponded infiltration with fingers in the sand and (g–l) during redistribution in the sand with very high moisture contents.

with open air. This treatment was designed to reveal the shape of the zone wetted by the finger, and to provide a comparison with the two-dimensional patterns.

The wetting front in the 3-cm irrigation of Column A was stable during the infiltration period, as shown by the fully wetted 10-cm zone in the upper part of the column. However, the redistribution front was unstable, producing a 55-cm-long finger whose diameter decreased from 9 to 4 cm with depth. The size of the finger is compatible with Eq. [1], which predicts that three-dimensional fingers will be 1.52 times as large as two-dimensional ones. The shrinking diameter is a consequence of the decline of flux with time, as predicted by Jury et al. (2003). Since the column was placed atop a box containing the same kind of sand, the finger extended out of the column, producing about 1 L of frozen sand. In Column B, a larger application of water (5 cm) produced a uniform flow region of about 40 cm during infiltration. The flow was then destabilized during redistribution, producing a reduced cross-sectional area of fingered

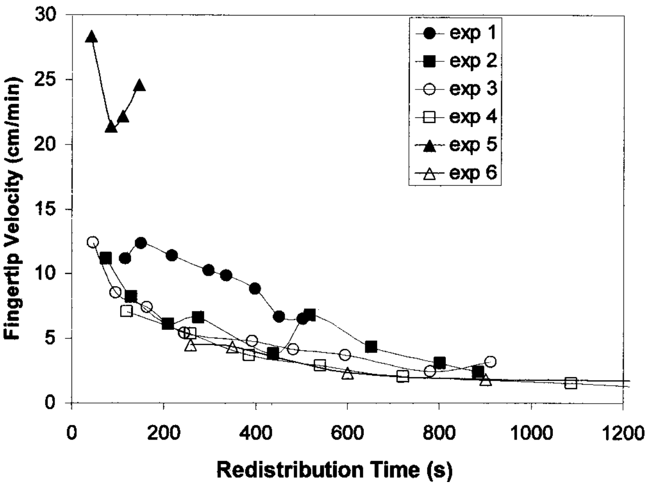

Fig. 6. Wetting front speed during ponded infiltration (Exp. 5) and redistribution in other experiments.

flow traveling along the wall of the column and occupying slightly less than one-half of the total cross-sectional area. It is probable that the shift of the finger toward the wall was caused by a slight inclination of the column during infiltration. Since the water table formed at the bottom air exit instead of producing free water, it follows that the finger tip was not fully saturated when it reached the bottom.

CONCLUSION

Our laboratory experiments showed that the redistribution process following the cessation of infiltration is unstable in homogeneous soil, producing a series of fingers that move far ahead of the original front. We demonstrated that ponded infiltration is stable and uniform in our system, so that the fingering observed is not due to soil heterogeneity. The porous medium retained a memory of the fingers formed in the first experiment, so that fingers formed in subsequent redistribution cycles followed the old finger paths, even after 28 d had elapsed. Fingers provide channels for rapid drainage of previously infiltrated water, especially when the soil ahead of the front is dry.

Contrary to a previous observation by Diment and Watson (1985) that the wetting front is stabilized during redistribution when the initial moisture content was raised above 1%, our experiment in very wet sand that had been saturated 24 h earlier still resulted in unstable flow. The fingers observed in this case were significantly larger than when the soil was dry. In the three-dimensional experiments, we also witnessed unstable flow during redistribution after the cessation of saturated infiltration, resulting in fingers propagating in the center or along the wall of a small column.

Our findings clearly contradict predictions made by Richards equation, which calculates stable flow during redistribution in homogeneous soil. We speculate (Jury et al., 2003) that the reason for this failure is the absence of a water-entry matric potential in the continuum description of flow.

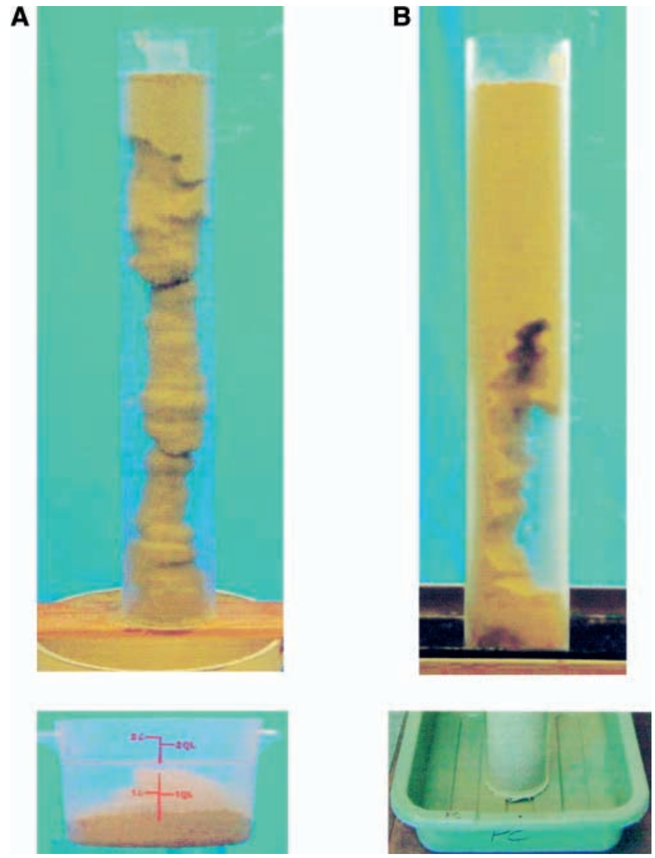

Fig. 7. Three-dimensional fingers formed in a 10-cm cylindrical column with different depths of water application: (A) 3 cm, (B) 5 cm. The boxes under the columns show the respective lower boundary conditions and the collected drainage effluent.

ACKNOWLEDGMENTS

The research was supported by Research Grant No. IS-2859-97 from BARD, the U.S.-Israel Binational Agricultural Research and Development Fund.

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