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Formation and persistence of fingered flow fields in coarse grained soils under different moisture contents

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Abstract

Fingers in homogeneous coarse-grained soils form from an instability in the wetting front and result in bypass flow which shortens the residence time in the vadose zone. Once formed, these fingers persist over a long period. In this paper, the formation of fingers and their persistence in initially uniform dry or wet soils are examined. Using fast-responding tensiometers in conjunction with rapid moisture measurements, it is shown that the matric potential at the finger tip and the position of the wetting curve relative to the drying curve are key factors in the persistence of the fingers. In accordance with the earlier observation, the tip and the fringes of the finger are on a wetting curve, while the remaining core of the finger is on a drying branch. This explains why large differences in moisture content can co-exist. This study also shows that the initial water content in and around the finger is crucially important in relation to which particular scanning curve is followed and, thus, to the water contents during infiltration.

1. Introduction

Most research on solute movement through individual flow paths has been primarily concerned with cracks, macropores, and biopores (Edwards et al., 1990). In addition, field and laboratory evidence has shown that flow variability occurs in coarse-grained sandy soils where heterogeneities in horizontal planes are minimal (Hill and Parlange, 1972; Glass et al., 1987, 1989; Hillel and Baker, 1988; Baker and Hillel, 1990; Selker et al., 1992a). In such soils, when rainfall intensity is much lower than saturated conductivity, the wetting front is not stable and water and pollutants move in fingers to the groundwater. These fingers persist over long periods

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of time (Glass et al., 1987). Persistence has two aspects. First, once the finger is formed, its core is preserved as a wet zone, which carries water downwards while slow lateral diffusion takes place in the fringe until the water potential is equal horizontally (but not the water content). Secondly, when infiltration halts and water is drained from the finger, and if water is reapplied, it enters the soil primarily in the finger core areas established previously. Thus, both aspects of persistence mean that most of the water entering flows only through a small portion of the soil. By analyzing the distribution of water content (but not the matric potential) within and around fingers in initially air-dried soil, Glass et al. (1989) hypothesized that persistence was a direct consequence of hysteresis in the soil characteristic curve. The objective of this paper is to test, through simultaneous measurement of both water content and potential over a wide range of moisture contents, the proposed theory of persistence of Glass et al. (1989).

2. Material and methods

A thin chamber with glass sides, 51 cm wide, 80 cm high and 1 cm thick, was filled with washed and dried white silica sand with grain diameters between 0.59 and 0.85 mm. To ensure uniform packing, sand was poured into the chamber through an extension with two coarse screens on top of the chamber. A full description of the sand cleaning process, filling procedures and experimental apparatus is given by Selker et al. (1992a).

To study the effect of uniform initial water content on flow in fingers, two sections with different water contents were established in the chamber. The top 40 cm of sand in the chamber was kept dry, while the bottom 40 cm of sand was saturated with water through the bottom of the chamber and then drained to a volumetric moisture content of approximately 5%. Two parts of the soil profile were represented in the laboratory. The initially dry sand was similar to the dry soil near the surface of a field after a period of little rain and high evaporation. The prewetted sand was similar to the capillary fringe of a receding groundwater table where all traces of previous fingers have been erased.

Fingers were simulated by dripping water at a rate of $10 \text{ cm}^3 \text{ min}^{-1}$ through a tube located just above the sand surface. This technique resulted in fingers similar, in an asymptotic sense, to those from unstable wetting fronts (Glass et al., 1987; Selker et al., 1992b,c). The finger passed through both the initially dry and prewetted sections of the slab chamber (cycle 1). Once outflow equalled the inflow, the application of water was halted. After water was drained from the finger and outflow from the chamber stopped, water application was resumed with the same flow rate of $10 \text{ cm}^3 \text{ min}^{-1}$ until a new steady-state condition was reached. This procedure was repeated twice on the same day (cycles 2 and 3) before the sand in the chamber was removed, dried, replaced and the cycles repeated. Five complete experiments were carried out.

The water content of the fingers was measured using the full field moisture visualization technique based on the transmission of light that was developed by

Glass et al. (1989). A uniform light source, consisting of a bank of 40 kHz fluorescent lamps, was placed on one side of the chamber. The light transmitted through the chamber was recorded on the other side using standard VHS video equipment. Changes in light intensity with time were quantified by digital analysis of the video images on an IBM compatible microcomputer. Since the intention was to study the formation of the finger above and below the dry/wet interface, the image was taken in the middle of the chamber. Water content and normalized light intensity were related as

$$\theta = -0.0066 + 0.3392 I_n - 0.5838 I_n^2 + 0.6043 I_n^3 \quad (1)$$

where θ is the water content ($\text{cm}^3 \text{cm}^{-3}$) and I_n is the normalized light intensity which varies for each point between 0 and 1: 0 for the dry sand and 1 for the saturated sand. An image of the dry sand was taken before the experiment started, and the image at saturation was measured at the end of the experiment after the chamber had been saturated by filling with water through the bottom of the chamber. Eq. (1), which is valid only when I_n is between 0.2 and 1, was obtained empirically by measuring the light intensity in the chamber and moisture content for a separate segmented column at the same height after both were fully drained after saturation.

Matric potential starting at 1.5 cm above and 1.5 cm below the interface of the dry and wet sand was measured with solid-state tensiometers flush with the wall, 1 cm in diameter, and with a response time of less than 1 s (Selker et al., 1992b). Tensiometers were connected to a computer through pressure transducers. Voltage readings were sampled and stored at 5 s intervals with a Tecmar analogue to digital conversion board in an IBM XT computer.

Primary and secondary soil characteristic curves in situ were determined by plotting the matric potential obtained with the tensiometers against the water content, calculated from Eq. (1) by taking the averaged value of I_n over a $0.5 \text{ cm} \times 0.6 \text{ cm}$ area near the tensiometer. The interface between the dry and wet sand was very sharp so that the measurements were representative for two areas.

3. Results and discussion

The average velocities of the tips of the fingers and their standard deviation for five infiltration tests are given in Table 1. For each cycle, the rate of downward movement was nearly equal. The velocity of the fingers in the dry sand was always faster than in

Table 1
The average and standard deviation for velocity (in cm s^{-1}) of the finger tip for the five experiments

Section	Cycle 1		Cycle 2		Cycle 3		Cycle 4	
	Average	St. dev.	Average	St. dev.	Average	St. dev.	Average	St. dev.
Dry	0.28	0.03	0.35	0.05	0.36	0.04	0.36	0.05
Prewetted	0.22	0.03	0.18	0.05	0.17	0.05	0.17	0.05

the wet sand. In the dry sand, the velocity of each finger tip was slower in the first cycle than in the subsequent cycles (where the water moved through the paths established during cycle 1), while the opposite was true for the prewetted section. The cross-sectional area of the finger in the prewetted sand is larger than in the dry sand.

3.1. Finger formation in initially dry and wet sand

Fig. 1 shows a snapshot of the water distribution, in the first cycle, when water was applied to the air-dried sand, while the moving finger tip was about 2.5 cm above the dry/wet interface. Its vertical water content distribution is similar to that hypothesized by Raats (1973) and Glass et al. (1989), and obtained theoretically by Selker et al. (1992c). Two distinct zones within the vertically elongated core area can be distinguished. At the tip, there is a zone of about 12 cm with a water content near saturation ($0.36 \text{ cm}^3 \text{ cm}^{-3}$), followed by a drier zone, where the water content of the finger core decreased to $0.12 \text{ cm}^3 \text{ cm}^{-3}$. Surrounding the core area of 2 cm, is a narrow fringe, approximately 0.5 cm thick, where the water content changes rapidly (Fig. 2).

In the subsequent infiltration events (cycles 2 and 3), the water followed the finger path established during cycle 1 in the initially dry sand. Again, a higher water content was observed at the tip in the initially dry area, but the water content was only about $0.22 \text{ cm}^3 \text{ cm}^{-3}$ although the velocity was higher, as required by continuity (see Table 1).

As soon as the finger tip touched the prewetted area, the widening of the finger near the tip just above the interface stopped. Even under steady-state conditions, the water

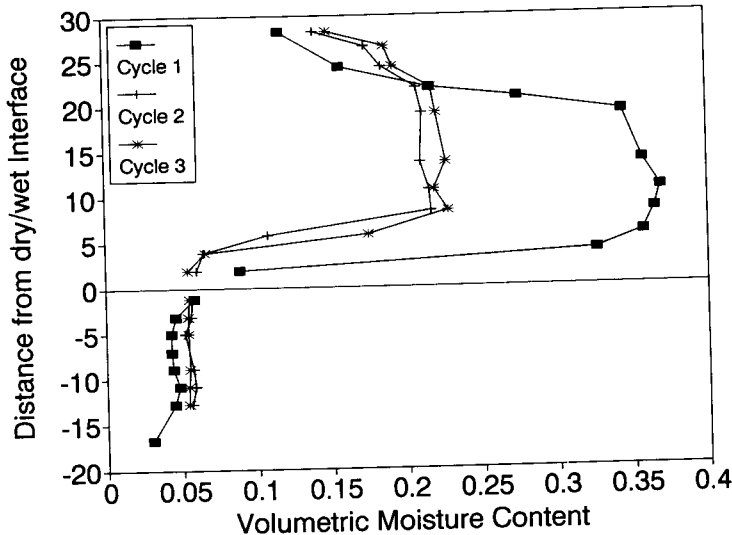


Fig. 1. The average moisture content of a finger core for cycles 1, 2 and 3. The finger tip is 2.5 cm above the dry/wet interface.

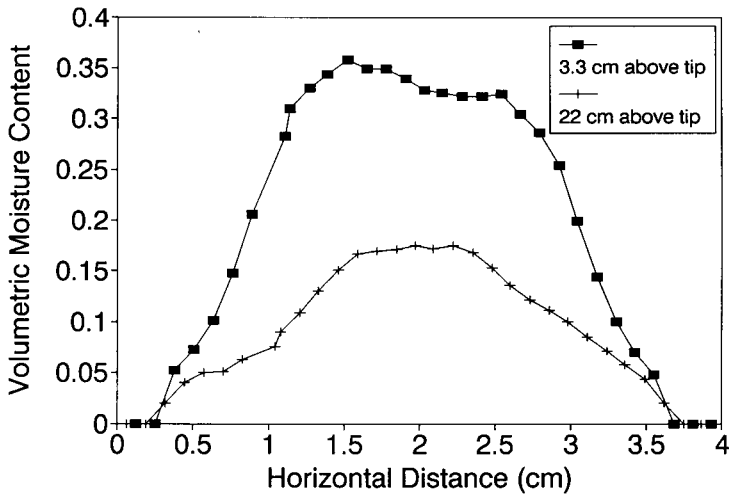


Fig. 2. The moisture content across a finger core at 3.3 cm and 22 cm above the finger tip in cycle 1. The finger tip is 2.5 cm above the dry/wet interface (same as Fig. 1).

flowed from the 2.5 cm wide finger in the top through a narrower saturated cross-section at the interface to a much wider cross-section below the interface. This is illustrated schematically in Fig. 3. The saturated area near the interface can be observed in Fig. 4 in which the water content distribution of the core is depicted when the finger tip is 12 cm below the interface. In Fig. 4, the water content of the core in the prewetted sand is about $0.2 \text{ cm}^3 \text{ cm}^{-3}$ and more or less constant with depth.

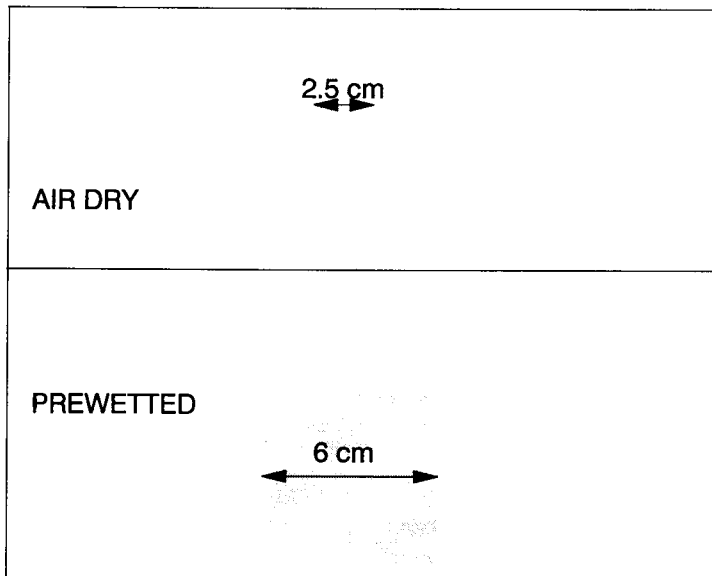


Fig. 3. The schematic drawing of a finger in both dry and wet areas.

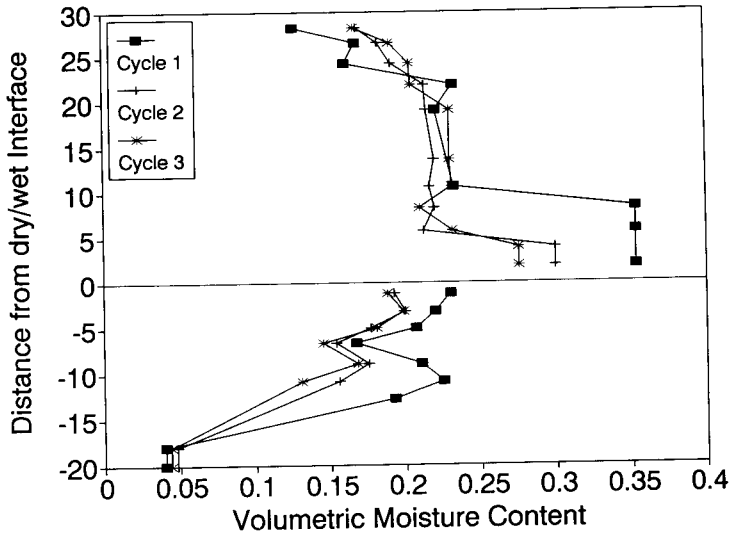


Fig. 4. The average moisture content of a finger core for cycles 1, 2 and 3. The finger tip is 12 cm below the dry/wet interface.

Thus, the saturated zone at the finger tip, which is characteristic for dry sand, did not occur in the prewetted soil. Comparison of the water content in the finger cores between infiltration cycles shows that the water content along the finger in the prewetted sand remained approximately the same.

3.2. Scanning curves

The tip (and the fringes) of the finger are on a wetting curve, while the remaining core of the finger is on a drying branch. This permits determination of the drying curves for the sand used by recording, simultaneously, the water content and the matric potential in the finger core throughout each infiltration event (including the draining phase). The wetting curves could not be measured directly in the chamber because moisture content changed over too short a distance (1–2 mm) and are determined by other means.

The drying curves for the initially dry and prewetted sand for three infiltration cycles are shown in Fig. 5. The drying curve for cycle 1 in the dry sand is the wettest. The next cycles (2 and 3) are drier than cycle 1, with cycle 3 (which follows cycle 2 shortly after drainage stops) being drier than cycle 2. In the prewetted sand, all cycles are drier than the initially dry sand, with cycles 2 and 3 being identical.

The solid line in Fig. 5 connecting all the starting points of the drying curves is the scanning wetting curve and is the same for all fingers infiltrating in previously wetted sand. The main wetting boundary for dry sand (Fig. 6) does not follow the scanning wetting curve and was determined in a segmented column by letting water rise upward in dry sand.

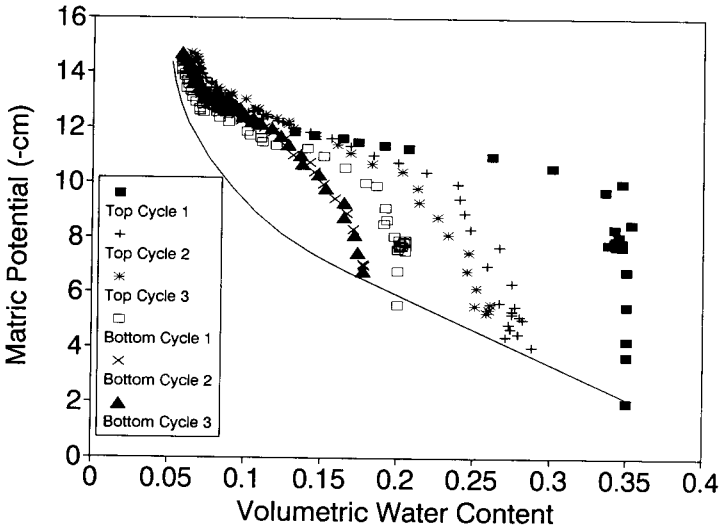


Fig. 5. The drying hysteresis curves for finger cores in the initially dry and wet sand for the three infiltration cycles. All drying curves start from the same wetting curve (solid line).

3.3. Stability and persistence

3.3.1. Initially dry sand

When the finger first penetrates into the dry sand, the tip is on the main wetting boundary, going from $\theta = 0$ to $0.35 \text{ cm}^3 \text{ cm}^{-3}$ almost discontinuously with the matric potential hardly increasing from about -3 to -2 cm (Fig. 6). For potentials below -3 cm , both sorptivity and conductivity are zero at the fringe. Since all drying curves

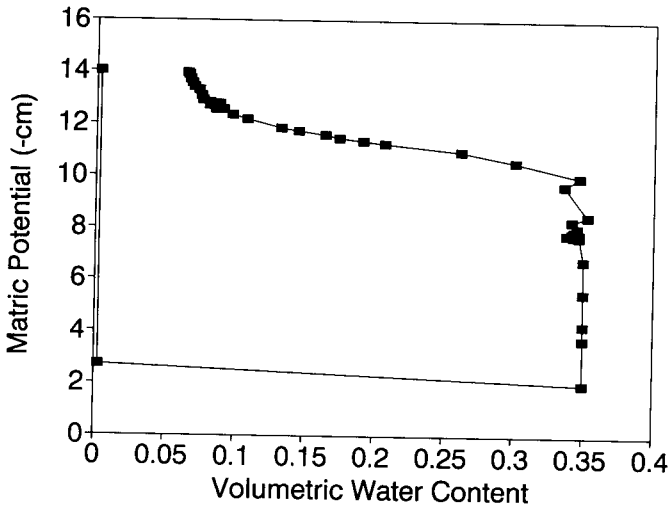


Fig. 6. Main wetting and drying boundary for a finger penetrating in initially dry sand.

for cycles 2 and 3 generated by the infiltrating water are at a pressure lower than -3 cm, it is impossible for the fingers to widen into the dry sand beyond the finger path established in cycle 1. Unlike the finger fringe, the finger core is on the drying branch where the moisture content is such that the conductivity can accommodate the flux imposed.

Actually, only liquid water transport across the finger boundary is zero, as lateral transport in the vapour phase by diffusion will still take place. This is a very slow process. However, if the present experiment had been run for a long time, as in the experiment of Glass et al. (1989), the matric potential in the initially dry sand would eventually have reached a small but non-zero value. The shorter duration of the present experiment resulted in a frozen equilibrium in the upper half of the chamber, with water present only in the original finger.

The form of the drying scanning loop is dependent on the history of wetting and drying. In the second cycle, the track of the first finger contains some moisture ($0.05 \text{ cm}^3 \text{ cm}^{-3}$) and the soil-water conductivity, which is a function of water content, is non-zero. Thus, water enters more readily than in the first cycle. Consequently, the potential in the finger tip is less than in cycle 1. In cycle 3, the residual water content in the finger is slightly higher ($0.08 \text{ cm}^3 \text{ cm}^{-3}$) and water moves in even more readily. Accordingly, the moisture content behind the finger tip is slightly lower in cycle 3 than in cycle 2. Thus, by varying the initial water content in the finger track, different drying curves are obtained, as shown in Fig. 5; the higher the initial water content, the drier the drying scanning curve is.

3.3.2. Prewetted sand

When the finger penetrates the prewetted sand, a consistent picture emerges. Unlike in the dry sand, the finger fringes in the prewetted sand are on a wetting curve for which the conductivity and sorptivity are finite (Fig. 5). This results in a much stronger lateral diffusion than in the dry sand. Thus, the finger path is much wider in the prewetted than in the dry sand. For the same initial water content ($0.05 \text{ cm}^3 \text{ cm}^{-3}$) having a larger cross-section, a much smaller water content behind the finger tip is required to carry the prescribed flux. Thus, the drying curves in the prewetted sand start drier than those for the originally dry sand. Because the initial water contents in cycles 2 and 3 are slightly higher than that for cycle 1, the fingers in cycles 2 and 3 are slightly drier than in cycle 1.

4. Conclusions

Fingered flow experiments were carried out in a slab chamber. Moisture content and matric potential were measured simultaneously in the fingers, resulting in a set of drying and wetting curves within the fingers that confirmed all aspects of the conceptual model first presented by Glass et al. (1989). This conceptual model remains valid for both uniformly initially dry and wetted sand. This study shows that, in particular, the initial water content within the finger and around it is crucially

important in understanding the width of the finger and which particular scanning curve is followed by the finger.

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