Fingering in Unsaturated Zone Flow: A Qualitative Review with Laboratory Experiments on Heterogeneous Systems

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Abstract

Unstable unsaturated zone flow (fingering) is a potentially important process in recharge, pollution, and surface water/ground water body interactions. Extending previous workers' studies on homogeneous systems, sand tank experiments have been carried out on heterogeneous systems. The experiments on initially dry silica sands suggest that (1) stratification will tend to enhance rather than dissipate fingering; (2) in discontinuously layered systems, funneling influences the location of fingers; (3) in multilayered systems, lateral flow on top of fine-grained layers promotes greater flux (and more fingers) in the down-dip direction; (4) in systems where a top fine-grained layer has a variable thickness, finger frequency and, hence, amount of flow will be greatest where the fine-grained layer is thinnest; (5) surface depressions in an upper fine-grained layer will concentrate flow, with fingers forming below such areas; and (6) in systems where an upper fine-grained layer has macropores, the latter will concentrate water flow and fingers will form directly below these zones. The experiments also confirmed that fingers can persist in the same locations from one recharge event to another, and that in initially moist sands, fingers are widened. It is clear that a complex interplay between fingering and funneling processes can occur and that finger behavior is sensitive to heterogeneity.

Introduction

Flow in the unsaturated zone may be quite complex, especially in situations where the soil structure is highly heterogeneous. Instead of infiltrating slowly and uniformly, as most traditional models assume, water may travel rapidly through preferential pathways. The latter may be in the form of macropores (e.g., cracks, burrows, root holes, soil pipes). Such pathways may be regarded as obvious, and a substantial amount of literature is available on the transport of water in such soils (Beven and Germann 1982; Germann and Beven 1985; Davidson 1985; Bronswijk 1988). Research, especially over the last decade, has identified the importance of another class of preferential flowpaths. These pathways occur in macroporeless soils and may be caused by an instability at the wetting front (fingering) (Glass et al. 1988, 1989a; Baker and Hillel 1990; Selker et al. 1992a) or changes in the permeability structure of a soil (funneling) (Kung 1990a, 1990b). These pathways are transient in nature and highly dependent on the porous medium properties (grain size and structure), the infiltration flux, and the initial and boundary conditions. Evidence abounds in the literature that suggests nonuniform transport and rapid transfer of water from the surface to aquifers in macroporeless soils. The evidence includes rapid changes in water levels and chemistry in aquifers after a rainfall event (Steenhuis et al. 1996); recharge even when evapotranspiration is high (Beekman et al. 1996); marked lateral heterogeneity in moisture content in the unsaturated zone (Starr et al. 1978, 1986; Glass et al. 1988; van Ommen et al. 1988; Allison et al. 1994); and marked discrepancies between simulation model results and actual field measurements (Jury and Flühler 1992).

Research in the fingered flow process has been active in the last 30 years. Notable publications include theoretical analysis of the mechanism (Raats 1973; Philip 1975; Parlange and Hill 1976; Diment et al. 1982; Glass et al. 1989a; Selker et al. 1992a; Liu et al. 1994a; Hendrickx and Yao 1996; Wang et al. 1998a); modeling using numerical solution (Diment and Watson 1983; Tamai et al. 1987; van Dam et al. 1990; Nieber 1996; Durner and Flühler 1996); and experiments in laboratory chambers (Diment and Watson 1985; Tamai et al. 1987; Glass et al. 1988, 1989a; Baker and Hillel 1990; Selker et al. 1992b; Liu et al. 1994b; Wang et al. 1998b). Most of these experiments were conducted in homogeneous, initially dry sands. A few experiments have also been conducted to examine the effect of heterogeneity on the flow system (Hill and Parlange 1972; Diment and Watson 1985; Glass and Nicholl 1996). Recently, some laboratory experiments have been conducted to examine fingered flow of nonaqueous phase liquids in sands (Glass and Nicholl 1996; Butts and Jensen 1996). A few field experiments have also been reported (van Ommen et al. 1988, 1989; Glass et al. 1988; van Dam et al. 1990; Ritsema et al. 1996; Glass and Nicholl 1996).

Despite all this work, the understanding of field-scale fingering is still limited. This is partially because real world soils contain a plethora of complicating factors that can fundamentally affect and perhaps entirely suppress the fingering process (Glass and Nicholl 1996). The complicating factors include uniform and nonuniform initial moisture content, media heterogeneity, macropores, and fractures. An understanding of how these factors affect the fingered flow process is essential if one has to determine the field conditions where fingering can be expected and the nature of the fingering process when it occurs.

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The purpose of this paper is to provide a qualitative overview of the phenomenon of fingering as seen in the laboratory. Use is made of existing work; however, most existing studies have concentrated on homogeneous systems, so a further set of experiments on heterogeneous systems have been carried out. The following heterogeneities were simulated: layered, layered discontinuous, dipping multilayer systems, layers of variable thickness, undulating surfaces and variable moisture content. Flow in these systems is described.

Experimental Procedure

Experiment Series 1

In order to investigate finger characteristics in relation to grain size and flux, experiments were carried out in a system where a less permeable fine-grained top layer overlay a coarse-grained more permeable sublayer. These experiments were conducted in laboratory tanks constructed from transparent plastic plates with internal dimensions of 50 cm × 50 cm × 2 cm (Figure 1). Rectangular Plexiglas spacers separated the front and back plate at the edges of the tank. The base of the tank had a brass plate with several holes of 2 mm diameter. A mesh material covered these holes. The bottom of the chamber was divided into five separate units using 3 mm plates glued in between the front and back of the tank. The front and the sides of the chamber had several small diameter holes to ensure that air escaped freely. These holes were small enough to prevent sand from falling through.

Two grain-size ranges were used for the top layer: 70 to 105 μm and 90 to 125 μm. For the bottom layer, three grain-size ranges (μm) were used in experiments: 500 to 850, 850 to 1000, and 1000 to 2000. The sands were packed in the tank by pouring evenly from a beaker and tamped manually. In all experiments, a mesh material was placed between the fine and coarse sand. In certain cases, a mesh material was also placed on top of the fine sand to minimize the effect of the impact of water as it was poured down, thereby preventing scouring of the sand. A horizontal copper pipe drilled with several small diameter holes provided uniform flow of water to the top surface of the sand during infiltration runs. Potassium permanganate was used as a tracer. The wetting front was monitored from one side of the tank and photographs were taken every few seconds. The outflow was measured from five cylinders placed at the bottom of the chamber.

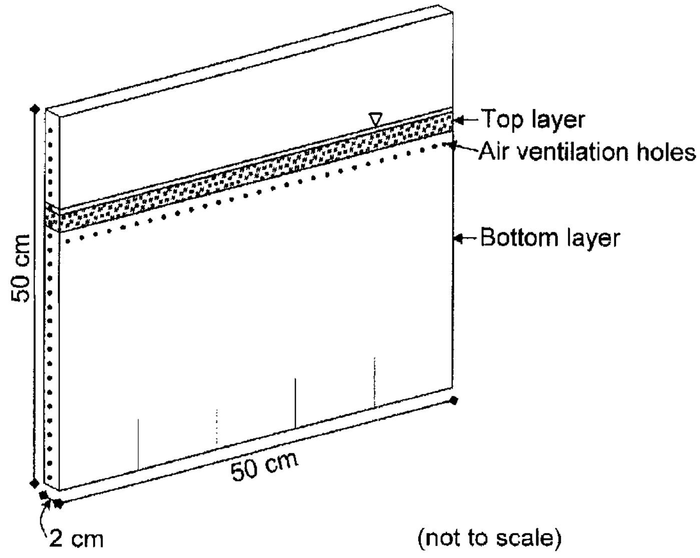

Figure 1. Experimental chamber.

Experiment Series 2–8

These experiments were conducted to examine the effect of various layered configurations, surface structures, and irregularities on fingered flow. The experiments were conducted in laboratory tanks with inside dimensions of 40 cm × 40 cm × 2 cm. The front of the tank consisted of a transparent plate while laminated wood was used for the back. Wood spacers were used for the sides and the bottom of the tank. Several 2 cm holes drilled within the bottom wood spacer allowed air to escape and drainage of water during infiltration experiments. A fine mesh covered these holes to prevent sand from falling through.

The packing and experimental procedure followed is similar to the one previously described. In this case, however, the flow rate was not monitored and observations were terminated once the fingers reached the bottom of the tank. Each experiment was repeated twice.

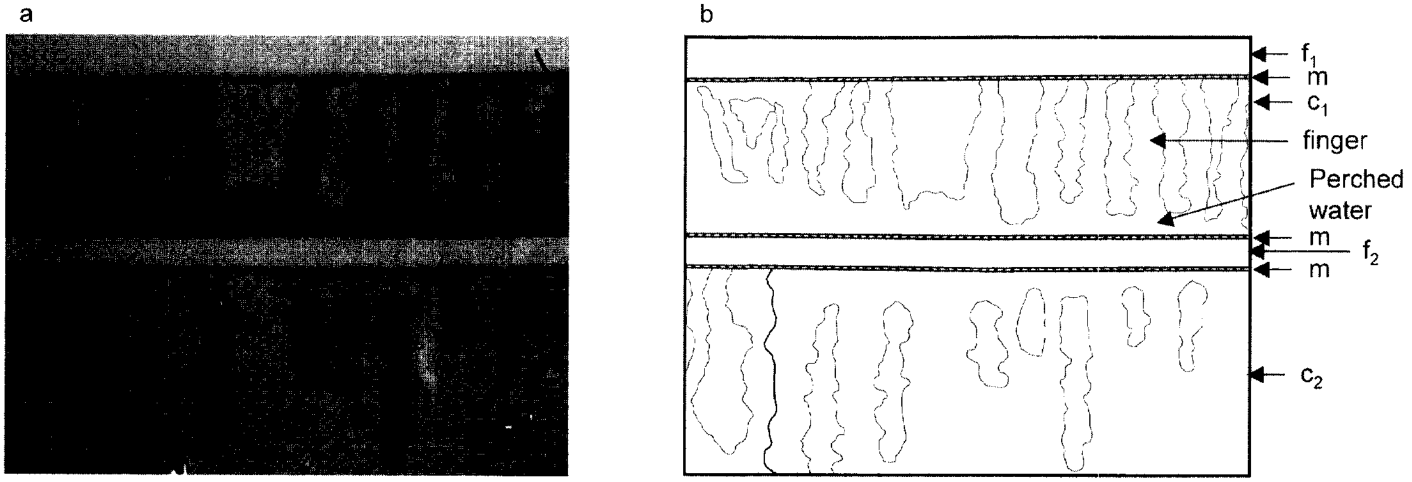

Figure 2. Fingered flow through a multilayered system: (a) photograph taken three minutes after start of infiltration experiment; (b) line drawing of photograph, where m represents mesh material, f_1 is top fine-grained layer, f_2 is bottom fine-grained layer, c_1 is top coarse-grained layer, and c_2 is bottom coarse-grained layer; grain size for f_1 and f_2 is 90 to 125 μm, and for c_1 and c_2 is 500 to 850 μm.

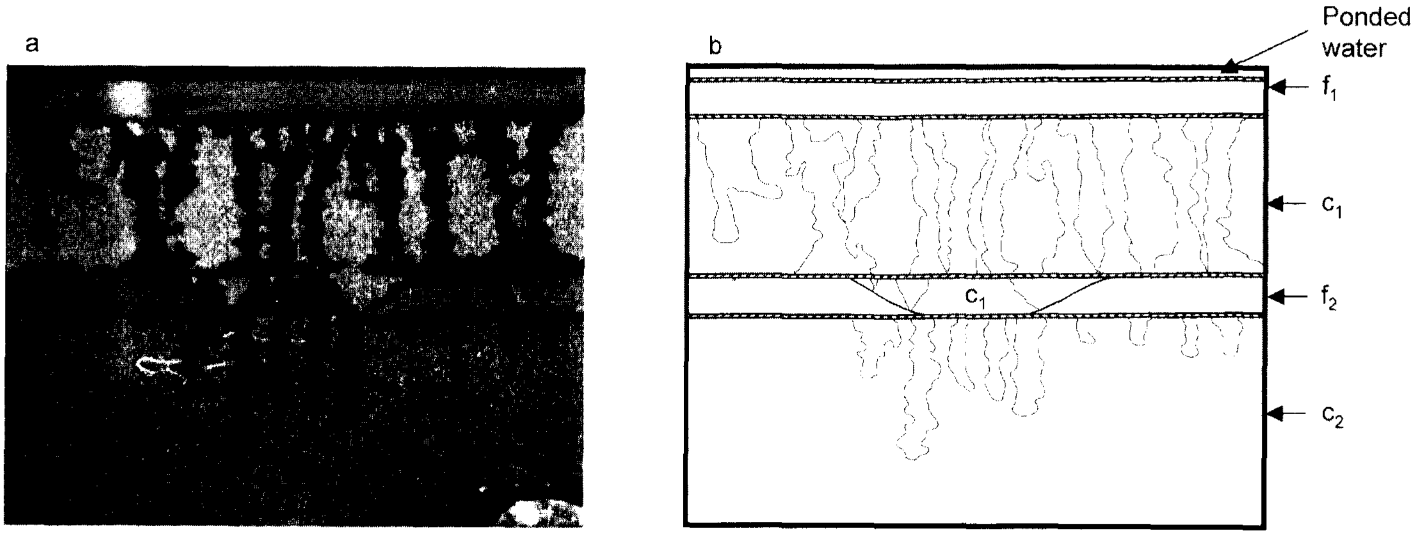

Figure 3. Flow through a discontinuous layered system: (a) photograph taken two minutes after start of infiltration experiment; (b) line drawing of photograph; grain size for f_1 and f_2 is 90 to 125 μm, and for c_1 and c_2 is 500 to 850 μm.

Table 1

(a) Finger Width in Relation to Grain Size

Bottom Layer Grain Size (μm)	Number of Experiments	Flow Rate (cm³/s)*	Maximum Finger Width (cm)
500–850	6	2–2.9	2.6–3.0
850–1000	5	1.4–3.2	1.5–1.9
1000–2000	4	1.1–3.1	1.1–1.2

*Value of flow rate within range indicated.

(b) The Effect of Flux on Finger Characteristics

Flow Rate (cm³/s)	Number of Fingers	Velocity of Fingers (cm/s)
5.0	22	0.37
2.9	17	0.32
1.4	15	0.26
1.3	14	0.26
1.0	14	0.25

Grain size of bottom layer was 500 to 850 μm for each trial.

Results and Discussion

Experiment Series 1: Flow from a Fine-Grained to a Coarse-Grained Layer

In all the experiments, water moved downward, with a nearly horizontal wetting front in the top fine-grained layer. Uniform wetting fronts have also been observed in experiments conducted by other workers (Hill and Parlange 1972; Baker and Hillel 1990). When the wetting front reached the textural interface, the downward movement of the wetting front was seen to slow down. A pause ranging between two to four seconds was observed in most experiments. According to Hillel and Baker (1988), during the pause, suction gradients at the interface will continue to diminish until the water-entry pressure of the bottom layer is achieved. Once the water-entry pressure is achieved, the wetting front crosses the interface into the coarse-grained sublayer. The water that was stored at the interface during the pause is "dewatered," causing moisture content and pressure there to decrease. This stage is followed by the development of protrusions, which rapidly grow into fully fledged finger structures. In the experiments conducted herein, the fingers were seen to move with a fairly constant velocity, width, and spacing. Similar behavior was reported by Glass et al. (1988). The edges of the fingers were not straight but irregular, which appears to have been caused by the packing procedure.

The results indicate that the maximum finger diameter that can develop decreases with increasing grain size. For any given flow rate, coarse-grained sands will tend to develop thinner, fewer, and comparatively more widely spaced fingers than finer-grained sands (Table 1a). For any given sand, increasing the flux has the effect of reducing the finger spacing, thereby increasing the finger density. An increase in flux would also lead to faster finger travel (Table 1b). Similar results were reported by Glass et al. (1989b) and Baker and Hillel (1990).

Experiment Series 2: Flow Through a Multilayered System

Flow in a multilayered system was simulated in these experiments (Figure 2). When the wetting front arrived at the first textural interface, an instability developed and water moved downward in preferential flowpaths (fingers). At the fine-grained middle layer, finger transport in the vertical direction was significantly reduced as the fine-grained horizon gradually became saturated. Subsequently, as indicated in Figure 2, a perched water body developed on top. At the interface with the coarse bottom sand, another instability developed and water started to flow as fingers again.

Stephens (1994) suggested that "under deep water table conditions, it is also possible that fingers gradually blend together with increasing depth due to moisture diffusion. This would be more likely in stratified soils which would cause fingers to spread laterally. At sites in arid climates with a deep water table where surface ponding is brief, the mechanism causing unstable flow may dissipate before finger infiltration reaches the aquifer." The present results indicate that stratification, rather than causing the mechanism of fingering to dissipate, will actually enhance the process.

Experiment Series 3: Flow Through a Discontinuous Layered System

Series 3 experiments were the same as for Series 2, except in

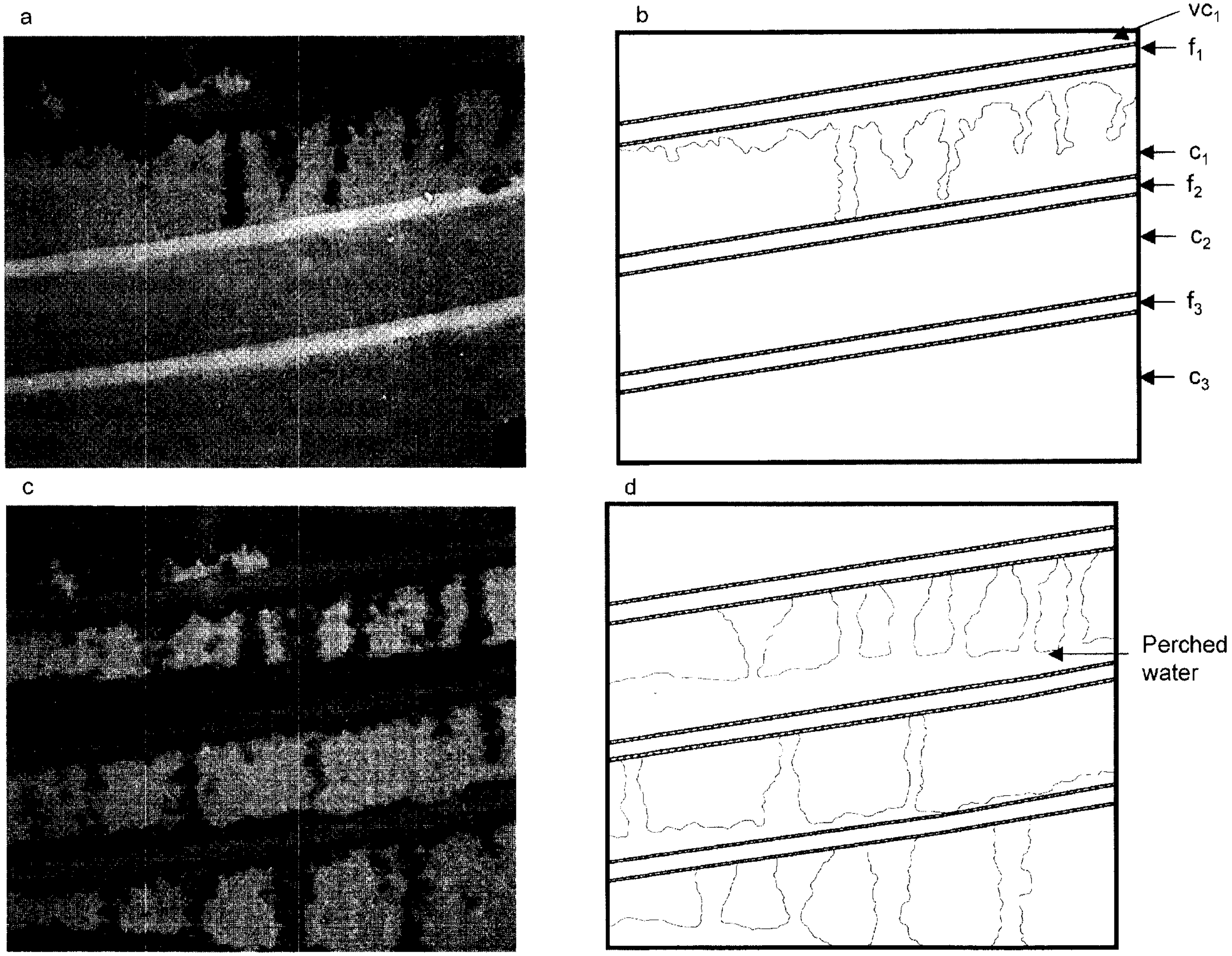

Figure 4. Flow through a dipping multilayered system: (a) photograph taken 30 seconds after start of infiltration experiment; (b) line drawing of photograph; grain size for the very coarse-grained layer (vc_1) is 1000 to 2000 μm; for f_1, f_2, and f_3 is 90 to 125 μm; and for c_1, c_2, and c_3 is 850 to 1000 μm; (c) photograph taken two and a half minutes after start of infiltration experiment; (d) line drawing of photograph.

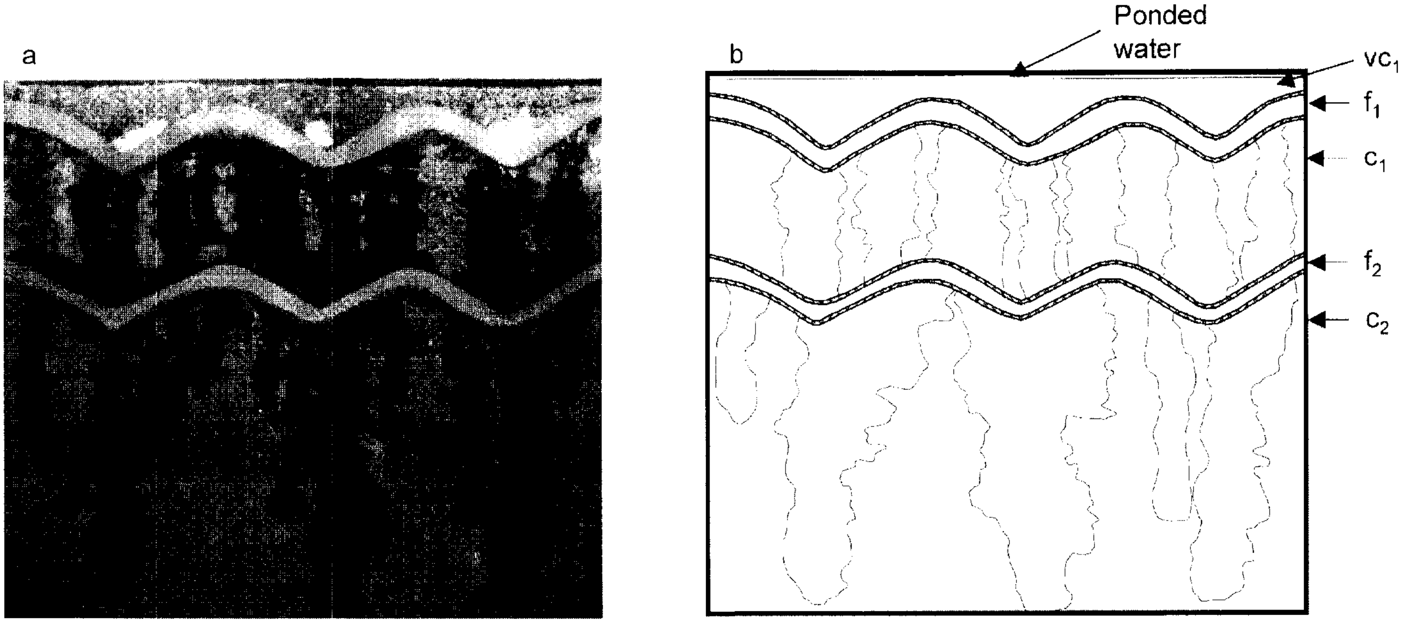

Figure 5. Flow through a system with undulating layers: (a) photograph taken two minutes after start of infiltration experiment; (b) line drawing of photograph; grain size for vc_1 is 1000 to 2000 μm, for f_1 and f_2 is 90 to 125 μm, and for c_1 and c_2 is 850 to 1000 μm.

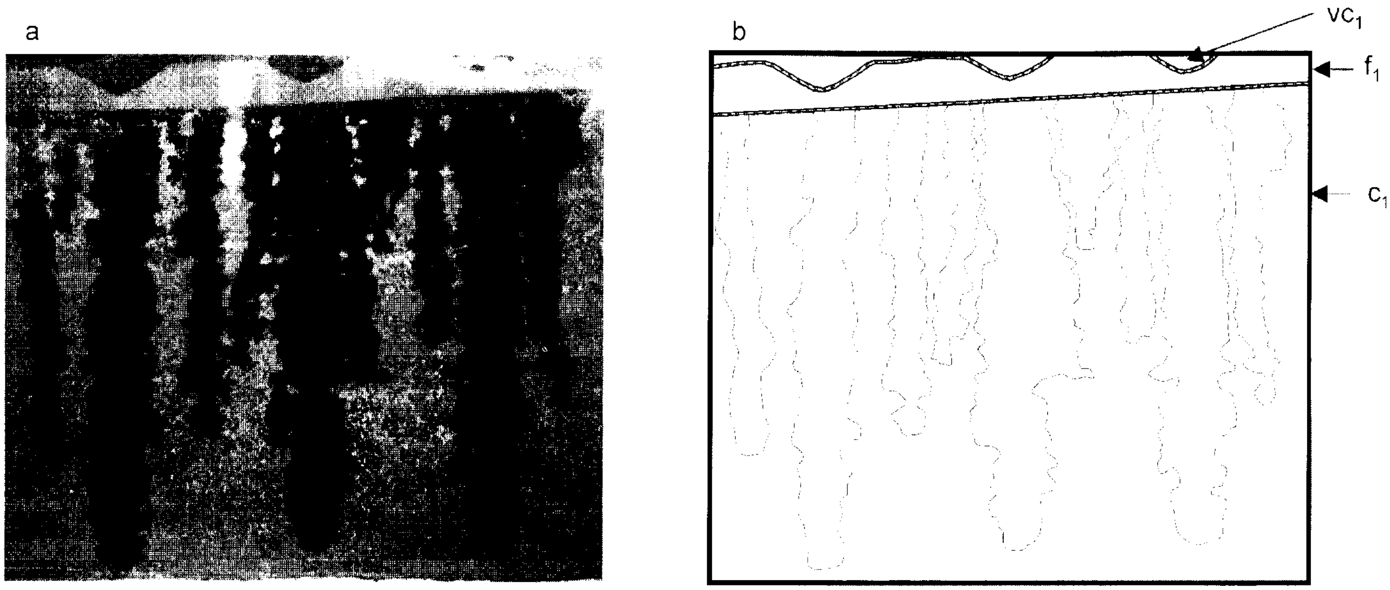

Figure 6. Flow through a system with depressions in the top fine-grained layer: (a) photograph taken two and a half minutes after start of infiltration experiment; (b) line drawing of photograph; grain size for vc$_1$ is 1000 to 2000 μm, for f$_1$ is 90 to 125 μm, and for c$_1$ is 500 to 850 μm.

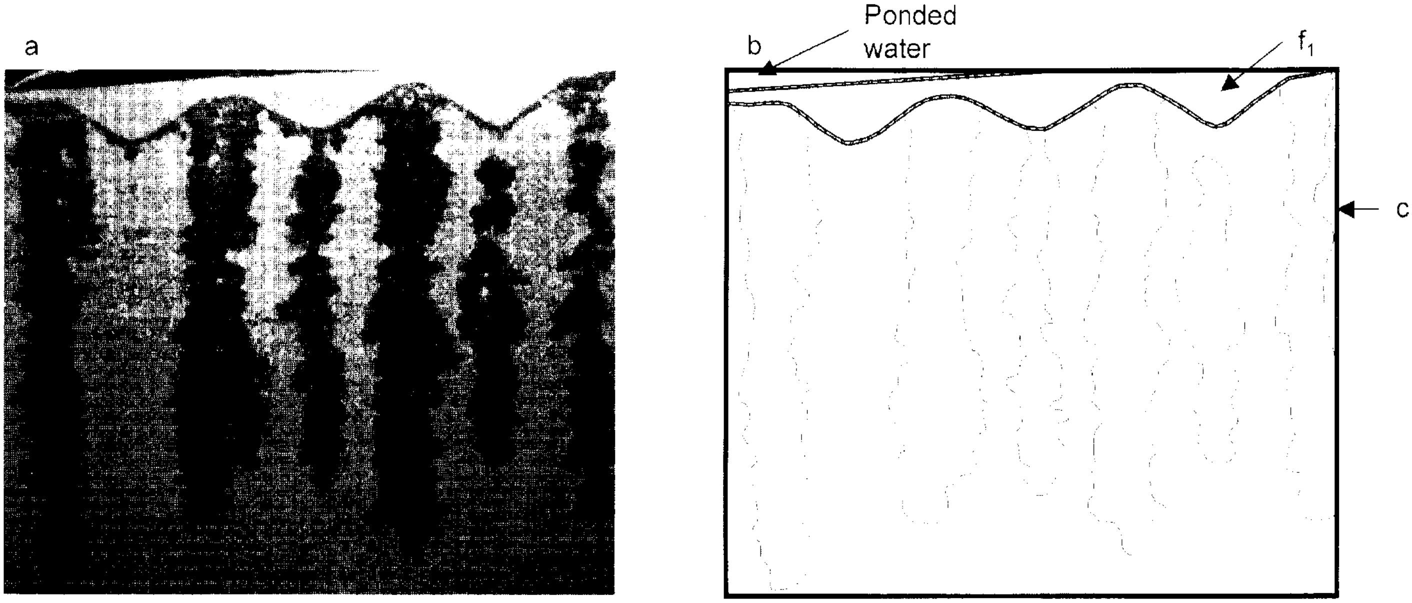

Figure 7. Flow through a system with an undulating interface between the fine-grained and coarse-grained layer: (a) photograph taken two minutes after start of infiltration experiment; (b) line drawing of photograph; grain size for vc$_1$ is 1000 to 2000 μm, for f$_1$ is 90 to 125 μm, and for c$_1$ is 500 to 850 μm.

having a discontinuous fine-grained middle layer (Figure 3). As the fine-grained middle layer approached saturation, lateral perched flow resulted in the formation of dominant fingers at the edge of the fine-grained layer. The fingers that formed in the discontinuous zone reached the tank base fastest. As indicated previously, a mesh was used to separate the top and bottom sections. The effect of the mesh is similar to a grain size discontinuity.

Experiment Series 4: Flow Through a Dipping Multilayered System

Dipping layers have the effect of increasing the residence time of water in the top layer in the down-dip direction and promoting flow down-dip. As Figure 4a shows, fingers developed below the upper fine-grained layer at the up-dip end, simply because of the small distance from the sediment surface. Subsequent lateral flow in and above the fine-grained layer resulted in the thickness of the perched zone increasing down-dip: this increases the flow rate so that most flow occurred in the down-dip section of the tank (Figure 4c). In effect, both funneling and fingering were occurring. Clearly, the extent of flow down-dip would not be so developed if the fine-grained layer were to continue down-dip beyond the edge of the tank.

The presence of perched water in these experiments is instructive. The perched water may rise to such a height that presence of fingers may be obliterated. This would be most likely in situations where the distance between an upper and lower fine-grained layer is small.

Experiment Series 5: Flow Through a System with Undulating Layers

In this series, the fine-grained sand was laid in two undulating layers. Coarse-grained sand was placed on top of the uppermost layer to prevent scouring and erosion during infiltration. Figure 5 shows that water travels faster along fingers associated with the depressions. The finger density seen in these experiments is much higher than that observed in previous experiments. The reason for this appears to be associated with the fact that a very thin fine-grained layer was adopted in these experiments. A thin layer has the effect of causing high hydraulic gradients and hence high flows through the top layer. The coarse-grained sublayer copes with such high flows by having a very small finger spacing, as was demonstrated in Series 1 experiments. A reduction in the number of fingers is observed as the second fine-grained layer is passed. The finger spacing also seems to increase slightly.

Experiment Series 6: Flow Through Layers of Variable Thickness

In the first set of experiments, the upper fine-grained layer was laid with varying thickness, with coarse-grained sand covering to prevent scouring when adding the water (Figure 6). It was found that the depressions in the fine-grained material concentrated flow and broad fingers formed in the coarse sand immediately below. In some cases, these fingers were formed by the merging of smaller fingers.

In the second set of experiments, the fine-grained sand was laid over an undulating surface of coarse-grained sand (Figure 7). In this case, the largest fingers formed below the highest points in the undulating surface. As in the first series of experiments, the broad fingers that formed traveled much faster than those that formed in adjacent areas. This behavior was also seen in Experiment Series 1, whereby increasing the flux led to faster finger travel. It would also appear, as for experiments of Series 5, that the thinner the fine-grained layer, the more fingers that form, presumably because a greater hydraulic gradient exists. These experiments also confirm the results of Series 1 experiments, which showed that increasing the flux would lead to reduction in the finger spacing, thereby increasing the finger density.

Experiment Series 7: Recommencement of Flow After a Period of No Flow

Once the Series 2 experiments were completed, the apparatus was left to stand for two weeks before Series 7 experiments were conducted. It was found that, as in Glass et al. (1989c), fingers reformed in exactly the same place as previously. This can be explained by the fact that during rewetting, water will first penetrate the coarse-grained layer at locations where the moisture content is relatively high (finger zones). The moisture content and, hence, the unsaturated hydraulic conductivity will increase rapidly at such zones. Flow is therefore likely to be dominated by these areas.

Experiment Series 8: Other Experiments

The first set of experiments was similar to Series 1 experiments, with highly permeable notches created within the fine-grained layer. It was found that broad fingers formed at the contact between the notches and the coarse-grained layers. These fingers dominated the flow in the coarse-grained layer.

Experiments were also conducted with low initial moisture content. The experimental procedure followed is similar to that reported by Diment and Watson (1985). The sand was prepared by adding water to the dry sand at a ratio of 10 mL/kg of dry sand. The moist sand was then placed in plastic bags for 12 hours to allow the water to become more uniformly distributed. The sand was then packed in the tank by tamping. Unlike in experiments with initially dry sands, no fingers were observed at the interface between the fine-grained and coarse-grained layer. Instead, the wetting front showed a wavy nature as it migrated downward. This behavior was also reported by Glass et al. (1988, 1989d), who observed that the wetting front became wavy as it moved into the coarse sublayer and the amplitude of the waves increased as the wetting front proceeded downward. These authors were able to show that water moved faster in areas associated with the bulges in the wavy wetting front.

Discussion and Conclusions

As reported by several workers in the soil science literature, fingering is likely to occur in many layered sand systems. From laboratory experiments, it has been shown that the maximum finger diameter that can develop decreases with increasing grain size. For any given flow rate, coarse-grained sands will tend to develop thinner, fewer, and comparatively more widely spaced fingers than fine-grained sands. For any given sand, increasing the flux has the effect of reducing the finger spacing and thereby increasing the finger density. An increase in flux also leads to faster finger travel.

In this paper, experiments are reported that expanded on previously published experiments on homogeneous porous media, to include a variety of heterogeneities. These experiments have shown that:

1. Stratification will not get rid of fingering; on the contrary, it will enhance the process.
2. In a discontinuous layered system, both fingering and funneling will occur.
3. In a dipping multilayered system, lateral flow on top of the fine-grained layers will increase the flux in the down-dip direction. The latter will dominate flow in the system because water will be received from both the lateral and vertical directions.
4. In systems where the top fine-grained layer has a variable thickness, finger density and amount of flow will be greatest at zones where the fine layer is thinner.
5. Surface depressions will concentrate water flow, and fingers forming below such areas will dominate the flow in the system.
6. Once formed, fingers can persist in the same locations for a long time. Fingers may be viewed as semi-permanent preferential flow structures that may transport water rapidly both in time and in space.
7. In systems where the upper fine-grained layer has macropores, the latter will concentrate water flow and fingers will form directly below these zones.
8. In moist sands, fingers will be broader and less distinct.

Generally, the experiments have shown that the overall effect of heterogeneities is to make fingers less regular, with the percentage of flow increasing through certain fingers in relation to others. It would appear that a certain combination of heterogeneities might work together to either enhance or suppress the formation of finger structures. Fingering will be enhanced in initially dry, layered, coarse-grained systems, especially where structures or features that focus flow are present. Factors that can suppress the fingered flow process include antecedent moisture content, small permeability contrast between an upper fine-grained layer and a lower coarse-grained layer, and presence of perched water bodies.

Several studies have already demonstrated that fingering does occur in field systems (van Ommen et al. 1988, 1989; Glass et al. 1988; Ritsema et al. 1996; Glass and Nicholl 1996). However, no general quantitative representations of fingering are as yet widely available, and although empirical equations and numerical solutions have been proposed, the presence of heterogeneities would seem to make their validity less certain. This is especially so in field systems where nonuniform conditions in soil structure and moisture content are the rule rather than the exception.

In situations where fingering is significant, current approaches based on an assumption of uniform flow are likely to give erroneous results. Hydrogeological applications that may be affected include recharge estimation, interpretation of hydrochemical data, and the monitoring, transport, and fate of contaminants in the unsaturated zone.

Fingering has important implications for monitoring of flow and contaminants within the unsaturated zone and some means of determining flow patterns is necessary. Kung and Donohue (1991) used ground penetrating radar (GPR) to locate soil layers with textural discontinuities that could trigger funnel flow. Based on GPR images, they were able to sample the solute concentration more accurately where finger and funnel flow were the dominant pathways of solute transport. Other possibilities include resistivity tomography or samplers of larger horizontal catchment volumes.

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References

Allison, G.B., G.W. Gee, and S.W. Tyler. 1994. Vadose zone techniques for estimating groundwater recharge in arid and semi-arid regions. *Soil Science Society of America Journal* 58, 6–14.

Baker, R.S., and D. Hillel. 1990. Laboratory tests of a theory of fingering during infiltration into layered soils. *Soil Science Society of America Journal* 54, 20–30.

Beekman, H.E., A. Gieske, and E.T. Selaolo. 1996. Groundwater recharge studies in Botswana (1987–1997): A critical review. Paper presented at DWAF/WRC Workshop on Recharge, October 16–17, Warmbaths, South Africa.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. *Water Resources Research* 18, no. 5: 1311–1325.

Bronswijk, J.J.B. 1988. Modeling of water balance, cracking and subsidence of clay soils. *Journal of Hydrology* 97, 199–212.

Butts, M.B., and K.H. Jensen. 1996. Effective parameters for multiphase flow in layered soils. *Journal of Hydrology* 183, 101–116.

Davidson, M.R.A. 1985. A numerical study of saturated-unsaturated infiltration in cracked soil. *Water Resources Research* 21, no. 5: 709–714.

Diment, G.A., K.K. Watson, and P.J. Blennerhassett.1982. Stability analysis of water movement in unsaturated porous materials: 1. Theoretical considerations. *Water Resources Research* 18, no. 4: 1248–1254.

Diment, G.A., and K.K. Watson.1983. Stability analysis of water movement in unsaturated porous materials: 2. Numerical studies. *Water Resources Research* 19, no. 4: 1002–1010.

Diment, G.A., and K.K. Watson.1985. Stability analysis of water movement in unsaturated porous materials: Experimental studies. *Water Resources Research* 21, no. 7: 979–984.

Durner, W., and H. Flühler. 1996. Multi-domain models for pore-size dependent transport of solutes in soils. *Geoderma* 70, no. 2–4: 281–297.

Germann, P.F., and K. Beven. 1985. Kinematic wave approximation to infiltration into soils with sorbing macropores. *Water Resources Research* 21, no. 7: 990–996.

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1988. Wetting front instability as a rapid and far-reaching hydrologic process in the vadose zone. *Journal of Contaminant Hydrology* 3, 207–226.

Glass, R.J., J.-Y. Parlange, and T.S. Steenhuis. 1989a. Wetting front instability: 1. Theoretical discussion and dimensional analysis. *Water Resources Research* 25, no. 6: 1187–1194.

Glass, R.J., J.-Y. Parlange, and T.S. Steenhuis. 1989b. Wetting front instability: 2. Experimental determination of relationships between system parameters and two-dimensional unstable flow field behavior in initially dry porous media. *Water Resources Research* 25, no. 6: 1195–1207.

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1989c. Mechanism of finger persistence in homogeneous, unsaturated porous media: Theory and verification. *Soil Science* 148, no. 1: 60–69.

Glass, R.J., G.H. Oosting, and T.S. Steenhuis. 1989d. Preferential solute transport in layered homogeneous sands as a consequence of wetting front instability. *Journal of Hydrology* 110, 87–105.

Glass, R.J., and M.J. Nicholl. 1996. Physics of gravity fingering of immiscible fluids within porous media: An overview of current understanding and selected complicating factors. *Geoderma* 70, no. 2–4: 133–163.

Hendrickx, J.M.H., and T.-M Yao. 1996. Prediction of wetting front instability in dry field soils using soil and precipitation data. *Geoderma* 70, no. 2–4: 265–280.

Hill, E.D., and J.-Y. Parlange. 1972. Wetting front instability in layered soils. *Soil Science Society of America Proceedings* 36, no. 5: 697–702.

Hillel, D., and R.S. Baker. 1988. A descriptive theory of fingering during infiltration into layered soils. *Soil Science* 146, no. 1: 51–56.

Jury, W.A., and H. Flühler. 1992. Transport of chemicals through soil: Mechanisms, models and applications. *Advances in Agronomy* 47, 141–201.

Kung, K.-J.S. 1990a. Preferential flow in sandy vadose zone: 1. Field observation. *Geoderma* 46, 51–58.

Kung, K.-J.S. 1990b. Preferential flow in sandy vadose zone: 2. Mechanisms and implications. *Geoderma* 46, 59–71.

Kung, K.-J.S., and S.V. Donohue. 1991. Improved solute sampling protocol in a sandy vadose zone using ground-penetrating radar. *Soil Science Society of America Journal* 55, 1543–1545.

Liu, Y., T.S. Steenhuis, and J.-Y. Parlange. 1994a. Closed-form solution for finger width in sandy soils at different water contents. *Water Resources Research* 30, no. 4: 949–952.

Liu, Y., T.S. Steenhuis, and J.-Y. Parlange. 1994b. Formation and persistence of fingered flow fields in coarse-grained soils under different moisture contents. *Journal of Hydrology* 159, 187–195.

Nieber, J.L. 1996. Modeling finger development and persistence in initially dry porous media. *Geoderma* 70, no. 2–4: 207–229.

Parlange, J.-Y., and D.E. Hill. 1976. Theoretical analysis of wetting front instability in soils. *Soil Science* 122, no. 4: 236–239.

Philip, J.R. 1975. Stability analysis of infiltration. *Soil Science Society of America Proceedings* 39, no. 6: 1042–1049.

Raats, P.A.C. 1973. Unstable wetting fronts in uniform and nonuniform soils. *Soil Science Society of America Proceedings* 37, 681–685.

Ritsema, C.J., T.S. Steenhuis, J.-Y. Parlange, and L.W. Dekker. 1996. Predicted and observed finger diameters in field soils. *Geoderma* 70, no. 2–4: 185–196.

Selker, J.S., T.S. Steenhuis, and J.-Y. Parlange. 1992a. Fingered flow in two dimensions: 2. Predicting finger moisture profile. *Water Resources Research* 28, no. 9, 2523–2528.

Selker, J.S., T.S. Steenhuis, and J.-Y. Parlange. 1992b. Wetting front instability in homogeneous sandy soils under continuous infiltration. *Soil Science Society of America Journal* 56, 1346–1350.

Starr, J.L., H.C. Deroo, C.R. Frink, and J.-Y. Parlange. 1978. Leaching characteristics of a layered field soil. *Soil Science Society of America Journal* 42, 376–391.

Starr, J.L., J.-Y. Parlange, and C.R. Frink. 1986. Water and chloride movement through a layered field soil. *Soil Science Society of America Journal* 50, 1384–1390.

Steenhuis, T.S., C.J. Ritsema, and L.W. Dekker. 1996. Introduction. *Geoderma* 70, no. 2–4: 83–85.

Stephens, D.B. 1994. A perspective on diffuse natural recharge mechanism in areas of low precipitation. *Soil Science Society of America Journal* 58, 40–48.

Tamai, N., T. Asaeda, and C.G. Jeevaraj. 1987. Fingering in two dimensional, homogeneous, unsaturated porous media. *Soil Science* 144, no. 2: 107–112.

van Dam, J.C., J.M.H. Hendrickx, H.C. van Ommen, M.H. Bannink, M.TH. van Genuchten, and L.W. Dekker, 1990. Water and solute movement in a coarse-textured water repellent field soil. *Journal of Hydrology* 120, 359–379.

van Ommen, H.C., L.W. Dekker, R. Dijksma, J. Hulshof, and W.H. van der Molen. 1988. A new technique for evaluating the presence of preferential flow paths in non-structured soils. *Soil Science Society of America Journal* 52, 1192–1193.

van Ommen, H.C., R. Dijksma, J.M.H. Hendrickx, L.W. Dekker, J. Hulshof, and M. van der Heuvel. 1989. Experimental assessment of preferential flow paths in a field soil. *Journal of Hydrology* 105, 253–262.

Wang, Z., J. Feyen, and C.J. Ritsema. 1998a. Susceptibility and predictability of conditions for preferential flow. *Water Resources Research* 34, no. 9: 2169–2182.

Wang, Z., J. Feyen, and D.E. Elrick. 1998b. Prediction of fingering in porous media. *Water Resources Research* 34, no. 9: 2183–2190.