WETTING FRONT INSTABILITY AS A RAPID AND FAR-REACHING HYDROLOGIC PROCESS IN THE VADOSE ZONE

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ABSTRACT

Wetting front instability in the vadose zone causes the formation of fingers which transversely transport both water and solute in the plastic surface. The development of the unstable flow field in laboratory experiments is described for an initially dry, two-layer sand system, in which the upper layer has a finer texture than the bottom layer. The effect of repeated infiltration events and of initial moisture content at field capacity are presented. Fingers were formed in the dry upper media and failed to sustain location even after several infiltration events. Only saturation and subsequent drainage alters the finger structure within the sandy layer. Eastern Long Island, New York, USA, field infiltration experiments using the combination of two dyes showed that water moved through finger-like structures.

INTRODUCTION

Understanding pollutant transport mechanisms through the unsaturated zone is of primary importance in predicting and avoiding groundwater contamination. Spatial variability of solute transport in the field has been found to cause predictions based on one-dimensional flow models to be misleading. Recent research primarily has been concerned with the description of horizontal variability of soil properties (e.g., Nielsen et al. 1975; Vieira et al., 1984; Wagner et al., 1984) and with various forms of bypass flow due to cracks and other macropores (e.g., Beven and Germann, 1982; Toppkister, 1983; Smetsen and Cullis George, 1984; Richard and Steenhuis, 1988) as the major cause of nonuniform solute transport. However, in addition to flow variability caused by soil structure and property variation in the horizontal, current field and laboratory evidence (Hill and Parlange, 1972; Starr et al., 1972, 1986; Glass and Steenhuis, 1984; Dinant and Watson, 1985; Glass et al., 1987) has shown flow variability where horizontal heterogeneity was minimal and according to the traditional reorientation of unsaturated flow, one-dimensional flow should occur. For soils in which the hydraulic conductivity increases with
depth but does not necessarily vary from point to point in the horizontal, the phenomenon of wetting front instability, often called "sweeping," in which water and fines move in eddies or structures to ground water at speeds of the order of the saturated percolation velocity. The conditions for fingering due to a sudden increase in conductivity with depth are present along much of the eastern seaboard of the United States, on Long Island, in river valleys of post-glacial regions and elsewhere. Toxic waste sites consisting of a very impermeable or leaky impermeable liner overlying pervious media are another important example where fingering might occur.

As cited in a recent review paper (Hill, 1987), to date there have been five theoretical analyses of the wetting fronts instability problem, those by Wallis (1975a, 1975b) and Hill (1976a, 1976b) and Diment and Watson (1985) and Diment and Wase (1985). In addition to the situation where the conductivity of the top layer is less than the bottom layer in the theoretical analysis of Rave (1979) and Philip (1977) each have further postulated instability for a number of other situations including infiltration of nonpenetrating rain or an increase in the initial moisture content with depth, non uniform hydraulic conductivity which increases with depth but does not exceed early layer, and movement into low wetting soil.

Actual wetting front instabilities have been noted in a number of experiments (e.g., Tashuchi, 1967; Miller and Gardner, 1980; Tnek, 1980; Smith, 1987): previous work there have been four reported experiments conducted in the laboratory specifically designed to demonstrate wetting front instability: Hill and Parlane (1975) for layered soils, White et al. (1975) for air pressure increase in front of the wetting front, Diment and Watson (1985) for both layered soils and redistribution following infiltration under different uniform initial moisture contents and Tama et al. (1985) for redistribution following infiltration are all coarse sized. In addition there have been three field studies specifically designed to document the existence of the phenomena in the field (Searle et al., 1976, 1986, Diment et al., 1986). Many other field studies where fingers were not considered in the experimental design have yielded results inconsistent with standard conceptualizations of water and solute movement (Smith, 1987; Grubbs et al., 1983). Their results, however, might be accounted for by the process of wetting front instability.

Understanding of the phenomenon is not complete and its importance for field situations, that is, under what circumstances and in what soils it occur, cannot be adequately assessed. It is clear that systematic quantitative laboratory-experimental formation and field experimentation together with theoretical analysis is needed to our understanding of wetting front instability is to be advanced and the question of its importance resolved. The purpose of current research into this aspect should be to fill this need. Our approach is focused on experimentation designed to answer two essential questions. First, under what circumstances does wetting front instability occur and second, once the flow starts has become unstable how can its behavior be described in terms of the relevant system parameters. The major thrust of our research has been in the

layered soil system because its presence is ubiquitous in agricultural soils and of particular relevance to agriculture on Long Island where we have conducted field research (Searle et al., 1986). The results of our work, however, are of a more general nature and shed light on the general phenomenon of wetting front instability.

In Glass et al. (1986a) a theoretical framework for wetting front instability experimentation is developed through classical dimensional analysis. Relationships between system parameters and unstable flow field behavior are derived. Miller scaling (Miller and Miller, 1960) of these relationships allows their generalization to similar porous media with different mean grain sizes and shows the effects of conservations and fluid properties. Preliminary results presented in Glass and Steehhan (1986) support the scaling theory and found that the smaller mean grain sizes the wider the fingers and slower the finger. The effect of unstable flow field behavior of the flow rate through an initially dry face over coarse textured layered sand system is explored in Glass et al. (1986a). Relationships derived previously through dimensional analysis between finger width, velocity, flow through individual fingers, and properties of the bottom layer are evaluated.

In this paper, we present the results of two experimental studies that begin to bridge the laboratory and the field. We emphasize qualitative description as, to our knowledge, most aspects of the flow behavior in the experiments have not been preserved in detail before and yield insight into the behavior of wetting front instability in the field. In the first study, conducted in the laboratory, we explore the effect of initial moisture content and an influencer of wetting front instability in a two-layered sand system with a fine layer overlying a coarse layer. We describe in detail the measurement of the infiltrating water and document the persistence of fingers over a sequence of infiltration cycles. The second study was conducted in the field. We present the results of these two infiltration experiments conducted on Long Island, NY, USA, where the flow field was delineated through use of two devices with different adsorption coefficients as a way of looking for fingers in the field.

LABORATORY EXPERIMENTATION

Since it is true that field soils are uniformly dry, it is important to understand the effect of initial moisture content and its distribution on wetting front instability. The effect of initial moisture content on the width of fingers was seen in the photos of Steehhan (1986) showing a narrow finger moving down through dry sand to widen several fold when it enters a wetted region at the bottom of the experimental chamber. Initial moisture content also may affect the stability of the one-dimensional wetting front. Diment et al. (1982) and Diment and Watson (1985) suggest increasing uniform initial moisture content a have a stabilizing effect. However, Searle et al. (1986) found fingering to occur in field soils with high initial moisture content.
A two-dimensional flow field was created in a slab chamber 1 cm deep, 30 cm wide and 100 cm high. Horizontal gaps in the chamber were 0.1 cm deep. Slender silken ribbons, fractions, denoted by 125; square numbers that define the top and bottom of the fractions, constitute the porous media used in the experiments. The 12-20 fractions were used for the bottom layer and the 40:60, 60:40, and 100:160 fractions formed more regressive top layers. The sands were cleaned with soap and rinsed several times and dried before and between use to assure purity. The chamber was filled through a funnel/extension/attomixer assembly and then packed using a deep impact method. Layers were separated by a thin piece of cotton cloth to keep fine particles from filtering down into the bottom layer and to assure that layers could be easily separated after the experiment. The cotton cloth was not found to influence the flow field behavior. Further details of the experimental apparatus and cleaning, filling, and packing procedures were discussed in Glaes et al. (1988b).

Dissolved water with a constant, low non-saturating dye concentration (0.0035% solution of UNDA Red No 30) was passed to 1.0 cm and maintained throughout the duration of each experiment. Flow field data were recorded with time-lapse photography on movie film. Data was obtained from the film by projecting it onto a screen and then tracing the wetting front position with time on acetate sheets. The velocity field at various times was visualized by injecting pulses of blue dye (1%) solution of UNDA Blue No 2 into the water supply. The flow out the bottom of the chamber was measured through a "drift section" which divided the outflow across the bottom of the chamber into 10 increments or sampling points each having a width of 0.1 cm. Each of the 10 sampling positions were isolated with a pin from each other by a thin metal barrier higher than the capillary fringe for the bottom layer used so that the lateral movement of water in the saturated zone at the bottom of the chamber was restricted. The drift section enabled the monitoring of the flow rate through individual fingers and its interface was monitored.

The initial moisture distribution was varied systematically by using three consecutive infiltration experiments in each of three two-layer combinations (see Table 1). In the first experiment series, a lower case "a" followed by the experiment number, the sand was initially dry. This experiment was conducted for twenty-four hours and then the chamber was tilted to collect evaporated moisture and allowed to drain for twenty-four hours. The moisture content field at the end of the drainage cycle formed the initial moisture field for the second experiment. The second experiment, denoted by a lower case "b" followed by the experiment number, was then conducted for twenty-four hours. In preparation for the third experiment, the bottom layer was saturated several times and afterwards sealed and drained for twenty-four hours. An almost uniform moisture content field (0.5%) in the bottom layer resulted and formed the initial condition for the third experiment also conducted for twenty-four hours and further denoted by a lower case "c" following the experiment number.

In this way the first ("a") and third ("c") experiments represented the initial moisture content conditions (i.e., uniform often used in numerical and numerical studies of infiltration flows. The second ("b") experiment measured more realistically a field situation where initial moisture content varies from point to point.

Presentation of laboratory results

The infiltration experiments yield a clear qualitative description of the unstable flow field instituted by the increase in pore size across a textural interface, its development in time and the effect of the initial moisture. The qualitative aspects are identical for experiments 1, 2, and 4. This experiment 3 will be used as an example here. Figure 1 shows drawings of the wetting front position after various times since the onset of infiltration in experiment 1.

For infiltration in initially dry two-layer sand systems ("a" experiments), flow in the lower top layer is characterized by the initially flat wetting front and vertical streamlines. The flow at the interface between the two layers shows that water passes into the bottom layer at discrete, fairly regularly placed locations or "point sources." Small fingers form under these sources and then grow upward within the next 10 cm to form wider fingers. These fingers then pass into the fully developed finger zone which is characterized by fairly constant finger velocity, width and spacing. Occasionally in this zone, a merger of fingers will occur to produce a faster moving, wider finger.

Three stages in the development of the flow field in the initially dry experiments may be delineated: (a) an initial "rapid" period, (b) a transitional "slow" period and (c) a final period of almost no change. The initial "rapid" period is characterized by rapid change in wetting front position with time. This period is shown in Fig. 1 for experiment 1. In time the descending fingers arrive at the water table or, in the case of the laboratory experiments, when they arrive at the bottom of the chamber.

The transitional "slow" period is characterized by very slow changes in wetting front position as wetting fronts diffuse laterally into the dry areas.
between fingers creating a less saturated "fringe" area around the more saturated original finger "core" areas. This period is shown in Fig 2 for experiment a. When a blue dye pulse is added, the core areas become blue while the fringe areas remain red, demonstrating that most of the flow in the system continues to occur downward in the core areas. Occasionally during this period, a finger forms that is unable to advance and a small off-finger or "dendrite" may form and move slowly downward to the water table. This period ends when the lateral wetting fronts have diffused through all the porous media and some moisture is present at all locations.

The final period is characterized by no perceptible change in the flux direction or magnitude within the flow field. Most are content differences are visible between the core areas and the fringe areas and the addition of blue dye verifies that most of the flow in the system continues to occur downward through the core areas. This period has been documented to last for at least 10 days of continuous infiltration (Ghoss, 1985) and may well last indefinitely.

In the "b" experiment, performed with an homogeneous initial moisture content, the next stage of the "a" experiment, fingers form in the same locations as in the "a" experiment. Movement in the former fringe areas is enhanced over the "a" experiment but the size and configuration of the core areas match almost exactly with those of the previous initially dry experiment thus demonstrating the persistence of finger path. Basically, the heterogeneous initial moisture content field formed by a previous unstable wetting cycle allows a rapid transition into the third and final flow period, seen in the "a" experiment, by retaining movement in the fringe areas. As evidenced by dye tracer pulses, the majority of the flow continues to be conducted by the core areas with no change in flow field during the duration of the 24 hr infiltration cycle.

In the final "c" experiment, the initial moisture content in the bottom layer is at approximately 65%. The wetting front becomes wavy as it moves into the bottom coarse layer and the amplitude of the wave increases as the wetting front proceeds downward. Thus, the wetting front is indeed unstable, but since the wavelength of the disturbance is on the order of the width of the chamber, separate fingers cannot form. The dramatic finger structure found in the dry and heterogeneous initial moisture content distribution experiments is not observed. However, after the wetting front has reached the bottom of the chamber, blue dye pulses show an exaggeration of the initial wave form of the wetting front thus indicating faster movement of moisture in the "core" areas.
It shows a further reduction in the standard deviation of the flux distribution to a constant 1.45 throughout the final 24-hour infiltration cycle. Thus, the influence of high, uniform initial moisture content is to make the flow field on the scale of the chamber more uniform than the "a" or "b" experiment. However, the fact that the standard deviation is not lower than 1.45 suggests the result of dye pulses that the flow is still not entirely uniform.

Summary of laboratory results

From the two-layer experiments, five major points can be remarked. First, the test material provides a very strong permeability, disrupting the uniform flow at a number of discrete point sources. Second, under dry initial conditions, fingers that form have a dramatic moisture content structure - very wet inside the finger and very dry outside the finger. Third, over time, slow sideways diffusion of moisture from finger core areas takes place resulting in a steady flow field with finger core areas persisting and continuing to conduct most of the flow. Fourth, on subsequent infiltration cycles, flow remains concentrated in the same core areas as the initial delineated fingers, thus emphasizing the importance of slight variation of initial moisture content between past fringe and core areas in the heterogeneous system structure and the persistence of fingers. Fifth, when the initial moisture content is artificially uniform and high, fingers widen and can coalesce giving the appearance of an almost uniform flow field but with horizontal variation in flux still apparent.

FIELD EXPERIMENTATION

Traditional field techniques are not able to either detect fingers or adequately monitor solute transport through soils when they occur. The fingering process in the subsurface has been shown to have an effect on the infiltration as measured at the soil surface (Parlange and Hill, 1972). If tensiometers and neutron probes are installed in order to measure water flow or if soil core samples are taken to monitor subsurface transport, the measurements would not necessarily indicate that fingering is occurring and are inconsistent between measurements would often be explained by faulty technique, experimental error, or by heterogeneity in porous media properties. To verify that fingering is occurring, the fingers themselves can be revealed through the use of dyes as was first shown by Starr et al. (1979). We employ similar methodology, but add the use of two dyes to document the existence of fingers structures in eastern Long Island.
outwash plain with soils typical of the region. Soil at the site is a Hyperel (NYSS Soil Survey) with a high to moderate available moisture, good internal drainage, poor natural fertility, moderate permeability in the surface layer and high permeability in the substratum. Some characteristics of this soil are given in Table 2, taken from Steenhuis et al. (1979). It can be seen from the table that hydraulic conductivity increases dramatically with depth and thus fulfills the criteria for the occurrence of infiltration flow instability given by theory. This soil is not only representative of the soils on Long Island but also many gravelly to sandy soils along the Atlantic coast from Maine to Florida as well.

Previous to our work, several studies conducted at the site indicated extremely heterogeneous flow possibly due to fingering. A traditional infiltration study at the field site using a tensiometer at depths of 15, 30, 60, 90, and 120 cm below the surface and one neutron probe access hole was accomplished by Leopoldo Valenzuela (1980). This methodology was not designed for the detection of fingering; however, the comparison of the neutron probe data to the tensiometer data indicates the advance of the wetting front near the neutron probe to be much faster than near the tensiometer. Steenhuis et al. (1984) studied natural recharge at the site using two circular plots 3 m in diameter instrumented with tensiometers to replicate at depths of 30, 60, 90, and 120 cm and in duplicate at 152, 180, and 213 cm distributed in a single ring pattern with 2.5 cm deep neutron probe access hole in the center of the plot. Data collected showed large variation between measurements at the same depth but located at different places in the plot. This variability of water movement is in itself horizontally heterogeneous soil instigated research to determine the variability of unsaturated soil physical properties at the site. Over 100 soil samples, taken at two depths (10 cm above the pine pan and 10 cm below the pine pan), were analyzed in the laboratory for their hydraulic properties (Cruise, 1983). It was determined that little horizontal variability can be found at the site at either 40 cm or the 15 cm depths. With these previous studies in mind a dye tracer study was planned in order to track the path of water movement through the soil profile during infiltration.

Field experimental method

One-pored infiltration experiment was conducted in three different field use areas at the site. The specific locations of the field infiltration experiments are shown in Fig. 4, a map of the Long Island Horticultural Research Farm. Location 1 had been in quiescence for three years until the

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Table 2

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Moisture content (%)</th>
<th>Tensiometer data</th>
<th>Neutron probe data</th>
</tr>
</thead>
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<tr>
<td>0-15</td>
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<td>2.73 x 10^-2</td>
<td>2.73 x 10^-2</td>
</tr>
<tr>
<td>15-30</td>
<td>0.05</td>
<td>3.00</td>
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</tr>
<tr>
<td>30-60</td>
<td>0.10</td>
<td>4.20</td>
<td>4.20</td>
</tr>
<tr>
<td>60-90</td>
<td>0.15</td>
<td>5.17</td>
<td>5.17</td>
</tr>
</tbody>
</table>

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Fig. 4 Map of the property of Cornell University's Long Island Horticultural Research Farm showing the location of the three field infiltration experiments.
spring before our experiment when they were removed, the field was disked and fallow until the time of the infiltrometry experiment. Location 2 had been cultivated the year previously and was currently in potatoes. Location 3 had been in grass for at least 4 years.

An infiltrometry ring 1 meter in diameter was pounded into the topsoil to a depth of 60 cm. Some grasses were applied to the surface before installation to ensure a good seal and inhibit preferential movement of water around the sides of the infiltrometry ring. The top 2 cm of the soil inside the ring at locations 1 and 2 were homogenized and leveled with a trowel after ring installation. At location 3 the soil was left intact. The soil in 3 cm of the edge of the infiltrometry ring was then slightly compacted to ensure agreement against water movement down the sides of the ring.

With reference to the laboratory study above, in order to visualize fingers in a situation much like that of the "b" experiment the use of two dyes with different absorbances would allow the delimitation of fingers with their core and fringe areas. Two dyes were chosen as tracers which could be clearly seen in the soil and which had much different absorbances in the soil. UNDA green #2 food coloring was found to move along with the water front in a laboratory test and so to be a good indication of the front of the infiltrating water body. Rhodamine WT was found to absorb much more strongly than the green food coloring and so was chosen as the tracer to indicate high flow regions that is, where rhodamine WT is found to penetrate deepest in the soil profile. 13 cm of flow was occurring. Infiltrometry was started by applying 5 cm of red colored water (rhodamine WT 1 mg/L 0.25%) solution was then added through a constant head device to maintain the ponding depth at 5 cm until a total of 43 cm had infiltrated.

As soon as ponding disappeared, the soil was carefully excavated to give horizontal flat surface approximately every 20 cm and photographs of the flat surface were made to show the location of dyed soil.

Results of field experiments

Previous work at the site had indicated that the subsoil at the site was horizontally layered and it was assumed to vary only slightly between the three locations as they were all within 5% of one another. However, the geology of location 1 was extremely different below the 130 cm level due to the presence of vertically distributed discontinuous and non horizontal clay laminae. We describe below the dye pattern for each location in detail.

Flow through the top soil (to 30 cm) at location 1 was very nonuniform due to the combination of macropores along depressional runoff paths and competition between rows from tractor tires. At 5 cm depth, average 10% of the horizontal plane was dyed while the remaining 90% was the color of the original soil. The dyed areas were spread more or less evenly through the horizontal plane (small 1 cm diameter "spokes") and also in a 15 cm wide strip between rows. At the top of the subsoil at 30 cm the blocky pattern disappeared and the dyed regions contained very few undyed "spokes" within green dyed regions. The strip of undyed soil beneath the tire runs perpetuated itself into the subsoil so as be seen in scale drainage right from color slicks of horizontal cross sections at 50, 70, 90, 115, and 140 cm depths shown in Fig. 5. The dye pattern indicates infiltration to be occurring in the subsoil mainly through columnar, finger like structures. One of these structures located beneath a large grassy mat in the top soil reached a depth of 100 cm before green dye could no longer be detected by eye. Below this "top" the sand was noticeably wetter indicating a deeper penetration of water than shown by the dye. This seemed to reason since some water within the profile moves ahead of the advancing dyed water and also the green dye does absorb slightly to the soil.

Movement in the topsoil at location 2 was not very influenced by macro pores or uniform compaction as indicated by an evenly sized red/green color throughout the topsoil. Drawings of the dye patterns within the subsoil at the 60, 109 and 160 cm levels are given in Fig. 6. While a number of flow regions can be seen at the 60 cm level, two major regions of flow designated by red and green regions had developed. These two regions reached 105 and 185 cm respectively before green dye could no longer be distinguished. The sand was noticeably wetter beneath these two regions again indicating an even deeper penetration of the infiltrating water.

At location 3, flow through the topsoil took place mainly through evenly distributed flow macro pores associated with the sand. At the top of the subsoil the soil was green everywhere with many red specks distributed evenly across the wetted region. Drawings of the dye patterns within the subsoil at the 60, 125, 170 and 180 cm levels are given in Fig. 7. At a depth of 60 cm the red specks had coalesced to form several small soil columns regions which disappeared by 70 cm. At 140 cm a fairly horizontal clay layer was evidenced by the infiltrating water. The clay layer had several holes or holes through it and water moved through them. Below, an anoxic mixture of coarse sand and clay layers was found extending down to 160 cm. The green dye indicated water to move through the sand layers in narrow finger like structures. When the next clay layer was encountered the finger would widen above and move along the sloping layer until a hole through it was found. At the 150 cm level, 8 discontinuous green spots were conducting the flow. By 190 cm all but two of these green regions had disappeared. The largest of these areas encountered a gradually sloping clay layer which followed into the side of the excavation hole at least 1 meter below where the front was reached by the tracer.

Summary of field results

The use of the more highly adsorbed red and almost non adsorbed green dyes allows the delineation of core areas where most of the flow was taking place and based areas where water was lost (green). The dominance of vertical versus horizontal water movement in the coarse sandy subsoil is
Fig. 5. Field subsection experiment, location 1. Drawings of the pattern at horizontal cross sections at depths of (a) 0.5 mm, (b) 1 mm, (c) 1.5 mm, and (d) 2 mm. Circle shows the position of the surface of the 1 mm-diameter calibration ring. Lighter areas indicate green/dry regions while darker areas indicate red-dried regions.

Fig. 6. Field subsection experiment, location 2. Drawings of the pattern at horizontal cross sections at depths of (e) 0.5 mm, (f) 1 mm, and (g) 2 mm. Circle shows the position of the surface of the 1 mm-diameter calibration ring. Lighter areas indicate green/dry regions while darker areas indicate red-dried regions.

Fig. 7. Field subsection experiment, location 3. Drawings of the pattern at horizontal cross sections at depths of (h) 0.5 mm, (i) 1 mm, and (j) 2 mm. Circle shows the position of the surface of the 1 mm-diameter calibration ring. Lighter areas indicate green/dry regions while darker areas indicate red-dried regions.

Fig. 8. Field subsection experiment, location 4. Drawings of the pattern at horizontal cross sections at depths of (k) 0.5 mm, (l) 1 mm, and (m) 2 mm. Circle shows the position of the surface of the 1 mm-diameter calibration ring. Lighter areas indicate green/dry regions while darker areas indicate red-dried regions.

demonstrated in each experiment by the flow. Most flow occurred directly beneath the red-dried surface. The split in the flow field caused by the tractor tire run at location 1 also emphasizes the importance of the heterogeneous supply surface at the top of the sand as a determinant of where most or very little of the flow will occur; that is, given a supply surface where the flow is mainly concentrated in certain regions, finger core areas will grow beneath these regions.
In conclusion, the wavelike and meandering flow was observed only if the initial moisture content was uniform; a condition not often found in nature.

The most striking result of the laboratory study is the effect of a heterogeneous distribution of moisture content on the flow pattern. The results of the field experiments support this conclusion. However, the presence of lateral heterogeneities in the soil material affects the initial conditions of the flow field, and the flow pattern resulting from these heterogeneities may vary significantly from one experiment to another. These results emphasize the need for more detailed studies of the initial conditions in field experiments, as well as the importance of considering the heterogeneity of the soil material in the design and interpretation of field experiments.

The laboratory study demonstrates that fingers-like structures will form with some degree of predictability if the initial conditions are uniform. This conclusion is based on the results of laboratory experiments and field experiments. The presence of lateral heterogeneities in the soil material affects the initial conditions of the flow field, and the resulting flow pattern may vary significantly from one experiment to another. These results emphasize the need for more detailed studies of the initial conditions in field experiments, as well as the importance of considering the heterogeneity of the soil material in the design and interpretation of field experiments.

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pollutant is transported in the subsurface will also influence fate prediction since the breakdown of toxicants is usually performed by microbial activity which decreases rapidly with depth. Thus, the fingering process can not only hasten the arrival of toxicants, but also increase the loading due to shorter retention times in the root zone.

It is important that the implications of fingering be incorporated into current toxic monitoring and fate prediction procedures for areas where the phenomenon exists. For this purpose we are currently conducting both laboratory and field studies to determine the effect of fingering on solute transport. Since water flow in the capillary fringe region is still vertical and, as we have shown in the laboratory experiments presented in this paper, fingers will widen and coalesce under high uniform moisture content, the use of suction lysimeters placed in the capillary fringe region above the water table shows promise as a field soluble monitoring technique.

**CONCLUSION**

In a fine to coarse layered sand system, instability of the infiltration flow often causes the formation of fingers in the bottom layer. Fingers, once formed, persist from one infiltration cycle to the next. These conditions for the majority of the flow can only be destroyed by artificially uniformizing the moisture content within the bottom layer by saturation and drainage. In the field, finger structures were demonstrated through the use of two days of an unstructured coarse sand and about three by a fine topsoil. Not only were finger structures associated with the textural change but also regions of concentrated flow in the surface layer. Macropores in the topsoil supplied water uniformly to the unstructured and macropore-free soil causing the formation of fingers below. Other flow concentrating structures within the soil profile such as clay lenses and rocks play a similar role. The combination of instability, macropores and heterogeneity in the properties of the porous media leads to a much more complex water flow field than with any of them acting alone and poses a severe challenge for the modeling and monitoring of toxic under vadose zone.

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**REFERENCES**


