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Susceptibility and predictability of conditions for preferential flow

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Abstract. Preferential flow in the field might be caused by various factors and is difficult to observe in situ. This experimental study was designed to identify the combined effects of air entrapment, surface desaturation (suction head), soil layering, and water repellency (hydrophobicity) of the porous media on unstable preferential flow (or fingering) in the vadose zone. The predictability of unstable flow was studied on the basis of two existing criteria for gravity fingering: (1) a velocity criterion proposed by *Hill and Parlange* [1972] and (2) a pressure head criterion by *Raats* [1973] and *Philip* [1975]. Two-dimensional transparent chambers (60 cm high, 41.5 cm wide, and 2.8 cm thick and 90 cm deep, 74.5 cm wide, and 1.8 cm thick) were used to visualize water infiltration into a water-wettable sand, a water-wettable loam, differently layered sand and loam, and a water-repellent sand. The results suggested that infiltration into the homogeneous sand and a sand-over-loam system, without the effects of air entrapment and surface desaturation, was unconditionally stable. Infiltration in the loam was also stable as observed in the limited chambers. The flow was unconditionally unstable in a fine-over-coarse stratified sublayer and conditionally unstable in the homogeneous sand under the effects of air entrapment and surface desaturation. In multiple-layered systems, infiltration flow was semiunstable; fingers developed in the sand layer and were stabilized in the loam. In the repellent sand the wetting front was unstable under low ponding conditions; however, it was stabilized when the ponding depth exceeded the water-bubbling (entry) value of the hydrophobic medium. Both the velocity and pressure head criteria predicted fingering in the sand (layers) with the effects of gravity. However, the criteria failed to predict stable flow in the loam, indicating that the capillary (stabilizing) effects on the flow need to be included in theoretical developments. Finally, the observed width and speed of the fingers and the system flux were found to be always higher under air-draining fingering conditions than with fingering under air-confined conditions.

1. Introduction

Preferential (bypass) flow can be of two types: macropore flow and unstable flow. In the case of macropore flow, surface-connected continuous channels left behind by soil animals and decayed roots, or cracks in the soil, provide pathways through which a liquid can rapidly reach large depths [see *Germann*, 1988]. This type of flow is outside the scope of this study. In the case of unstable flow treated in this paper, the macroscopic wetting front in the soil matrix may become unstable under certain conditions. The initially planar or sharp wetting front then breaks up into preferential wetting columns, called fingers.

The problem of immiscible fingering (or unstable preferential flow) in porous media affects the efficiency of oil recovery from a reservoir. The same problem has been found to affect water and solute transport in the vadose zone. Increasing numbers of experimental studies have shown that the unstable wetting fronts might result in fingered flow of water and nonaqueous phase liquids (NAPLs) toward the groundwater [*Hill and Parlange*, 1972; *Kueper and Frind*, 1988]. Preferential flow also causes uneven distribution and the loss of water and fertilizers in the crop root-zone [*Clothier et al.*, 1981]. It has been confirmed that fingering occurs in both homogeneous and heterogeneous media, not only in sandy soils [*Peck*, 1965; *Glass et al.*, 1988, 1990; *Selker et al.*, 1992; *Ritsema et al.*, 1993] but also in loam and clay soils [*Flury et al.*, 1994], and under both rainfall and irrigation conditions. The exact fluid and medium conditions under which preferential flow occurs in the field need to be understood. Theoretical and experimental investigations are actively being conducted in the hydrologic and environmental research communities.

Experimental observations by many researchers indicate that factors leading to fingering may include vegetation, microtopography, water repellency of the media, soil layering, and macropores. However, theoretical considerations suggest that fingering is induced by the onset of instability at the wetting front during miscible or immiscible displacement between two qualitatively different fluids. Fingering may take place in two-fluid flow even if there is no porous structure [*Saffman and Taylor*, 1958]. It is possible that many of the aforementioned factors induce instabilities at the wetting front in different ways. The original linear stability analyses of *Saffman and Taylor* [1958] considering viscous and gravitational forces, and of *Chuoke et al.* [1959] including capillary forces, resulted in

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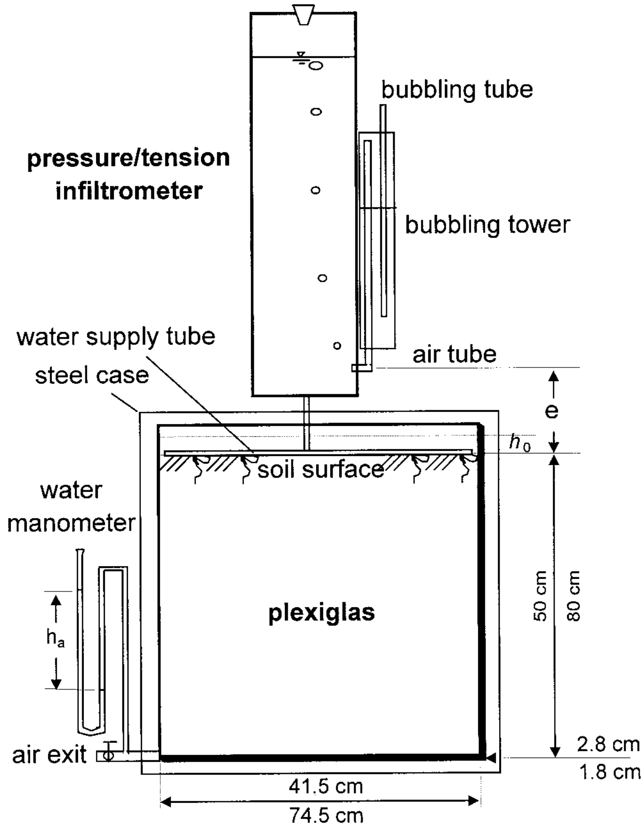


Figure 1. A two-dimensional experimental setup. The dimensions of the chambers are shown by numbers above (small chamber) or below (large chamber) the arrowhead lines.

theoretical criteria for the onset of instability at the wetting front. According to *Chuoke et al.* [1959], the condition for the onset of instability at a downward interface is

$$V + \frac{(\rho_w - \rho_{nw})gk \cos\beta}{(\mu_w - \mu_{nw})} + \frac{k\sigma^*\alpha^2}{(\mu_w - \mu_{nw})} > 0 \quad (1)$$

where V is the Darcy velocity of the displacement, the subscript w refers to the wetting fluid and nw refers to the nonwetting fluid, ρ is the density and μ is the viscosity of the fluids, g the acceleration due to gravity, k is the effective permeability of the porous medium, β is the angle between the gravitational direction and the direction of the flow; σ^* is the effective interfacial tension (positive if the wetting fluid is driving the nonwetting fluid and vice versa), and α is the magnitude (or wave number) of a disturbance to the wetting front.

During vertical infiltration ($\beta = 0$) of water into the vadose zone the density and viscosity of air (773 and 55 times lower than that of water, respectively) can be neglected. When the capillary force was neglected, (1) was reduced [*Hill and Parlange*, 1972] to

$$V < \frac{\rho_w gk}{\mu_w} \approx K_s \quad (2)$$

where K_s is the natural saturated conductivity of the porous medium to water. Thus, any time when the downward infiltration velocity is $<K_s$, the wetting front is unstable, resulting in fingering. Otherwise, the flow is stable, showing a planar or sharp wetting front. We call (2) the velocity criterion or V criterion for wetting front instability in the air-water system. Assuming a sharp wetting front (piston flow) for the initially stable infiltration flow, the Darcy velocity V can be expressed as

$$V = K_s\left(1 - \frac{h_{af} - h_{wb} - h_0}{L}\right) \quad (3)$$

where h_0 is the water pressure at the soil surface, h_{af} is the gage air pressure immediately below the wetting front, h_{wb} is the capillary water-bubbling (entry) pressure of the porous medium, and L is the depth of the wetting front. Substituting (3) into (2), one obtains an alternative criterion for the onset of instability at the wetting front:

$$F = h_0 + h_{wb} - h_{af} < 0 \quad (4)$$

Thus, any time when the net pressure difference F across the wetted layer is <zero (i.e., opposing the downward flow of water), the wetting front is unstable. This supplementary criterion is identical to those obtained by *Raats* [1973] on the basis of a frontal acceleration hypothesis and *Philip* [1975] on the basis of a dynamic linear stability analysis. The sharp wetting front (delta-function) assumption, although approximate, should be appropriate for predicting the gravity fingering which occurs mainly in coarse media. We call (4) the pressure head criterion, or F criterion, in this paper. Both V and F criteria for predicting the onset of instability at the wetting front were supposed to be valid for vertical downward displacement of air by water in any porous medium.

Application of (2) requires the estimation of the saturated conductivity K_s and the infiltration rate V in the system, which may be complicated in the field, whereas the application of (4) requires the estimation of the water pressure at the soil surface h_0, water entry suction h_{wb} of the medium and the gage air pressure h_{af} below the wetting front, which can be easily done in situ [*Fallow and Elrick*, 1996; *Wang et al.*, 1998]. According

Table 1. Properties of the Packed Porous Media Used in This Study

Medium Type	γ_d, Dry Bulk Density, g/cm^3	ϕ, Total Porosity for ρ_s = 2.65, cm^3/cm^3	K_s, Saturated Water Conductivity, mm/min	h_{wb}, Water-Bubbling (Entry) Value, cm
Water-wettable sand	1.52	0.43	15.4	9
Water-wettable loam	1.287	0.51	0.257	14
Water-repellent sands*				
First horizon (humose topsoil)	1.41	0.47	7.99	−12
Second horizon (transition layer)	1.54	0.42	8.01	−7
Third horizon (bottom layer)	1.59	0.40	8.11	−2

*Sands of Ouddorp, Netherlands.

Table 2. Matrix of Laboratory Experiments

Sequence	Media Combinations*	A Air-Draining	B Air-Confined
1	Homogeneous sand	I-a	II-a
	Same material in large chamber	I-b	II-b
2	Homogeneous loam	III	IV
3	Negative water pressure on loam surface	V	VI
4	Negative water pressure on sand surface	VII	XIII
5	Two layers of loam (10 cm) over sand (40 cm)	IX-a	X-a
	Two layers of loam (20 cm) over sand (60 cm) in large chamber	IX-b	X-b
6	Two layers of sand (30 cm) over loam (20 cm)	XI	XII
7	Four layers of loam (5, 10 cm) over sand (15, 20 cm)	XIII	XIV
8	Four layers of sand (15 cm) over loam (10 cm)	XV	XVI
9	Three layers of repellent sands (low ponding, $h_0 < -h_{wb}$)	XVII	XVIII
10	Three layers of repellent sands (high ponding, $h_0 > -h_{wb}$)	XIX	XX

*All experiments done in small chamber unless otherwise noted.

to (4), instability of the wetting front could be induced by the following factors or situations: (1) a decrease in h_0 or redistribution of infiltrated water following infiltration (h_0 becomes negative), (2) a decrease in h_{wb} due to, for instance, the occurrence of macropores or the presence of a fine-textured layer overlaying a coarse-textured layer, (3) infiltration into hydrophobic media that have negative values of h_{wb}, and (4) an increase in soil air pressure below the wetting front. *Diment*

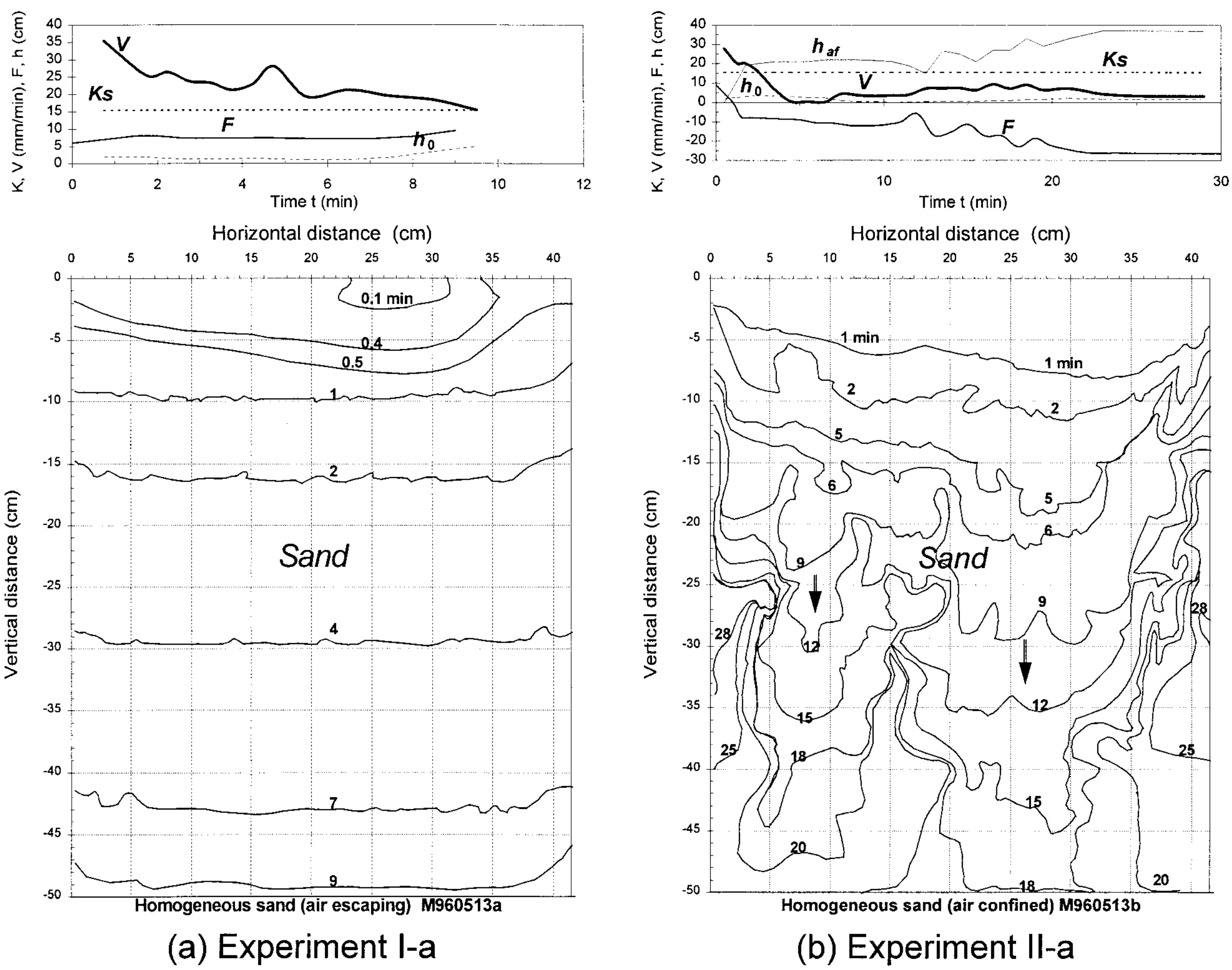


Figure 2. Variation of infiltration rate V, surface water head h_0, air pressure h_{af} below the wetting front, pressure difference $F = h_0 + h_{wb} - h_{af}$, and the wetting front advancement with time in a homogeneous water-wettable sand (small chamber): (a) stable flow for the air-draining condition and (b) fingered flow for the air-confined condition. The downward arrows show positions of the developed fingers, the upward arrows show the rise of water table, and the subtitles show the medium (airflow) conditions and the date of the experiment (e.g., M960513 = May 13, 1996).

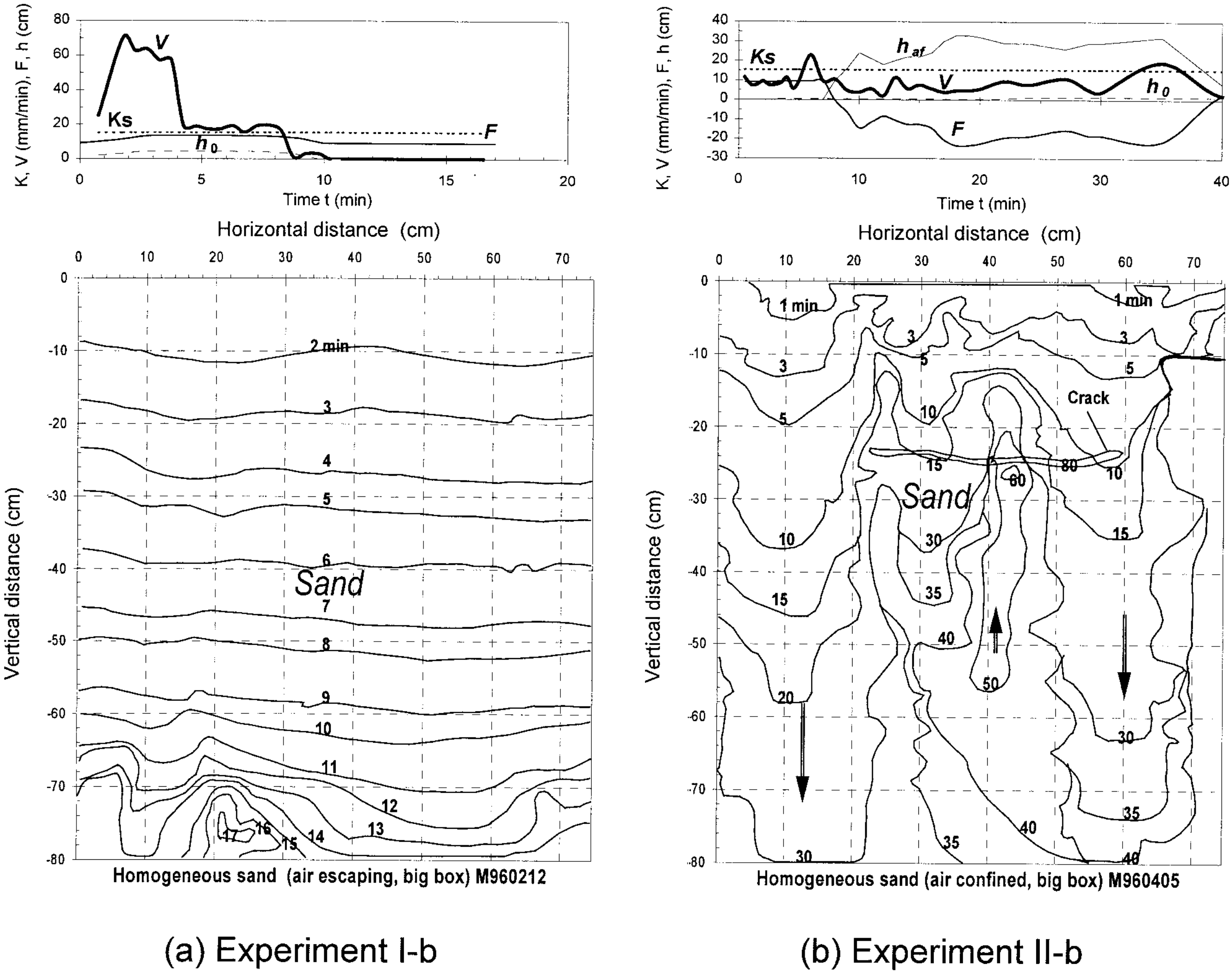


Figure 3. Infiltration into a homogeneous water-wettable sand (large chamber): (a) stable flow for the air-draining condition and (b) fingered flow for the air-confined condition (symbols are as defined for Figure 2).

and Watson [1985] confirmed fingering as caused by factor 1. *Hill and Parlange* [1972], *Parlange and Hill* [1976], *Glass et al.*, [1991], *Baker and Hillel* [1990], and *Selker et al.* [1992] focused on factor 2, whereas factor 3 was confirmed by *Ritsema et al.* [1993] and *Hendrickx et al.* [1993]. Situation 4 was confirmed by *White et al.* [1976, 1977] with experiments in the Hele-Shaw cells and by *Wang et al.* [1998] in a sandy soil.

For the ideal condition of ponded infiltration into a homogeneous, unsaturated, water-wettable porous medium without air entrapment, the flow is predictably stable since $V > K_s$. Unfortunately, field soils are mostly heterogeneous; the soil can be water repellent, and the soil air could become entrapped. During high-intensity rainfall or surface irrigation events, the soil air is compressed between the saturated soil surface and the groundwater table (or the low air permeable layers). The soil surface is otherwise under nonponding conditions during light rainfall or sprinkle irrigation events, resulting in negative water pressure at the surface. In natural water-repellent soils, water becomes a nonwetting fluid, which adds to the complexity of the infiltration flow processes. Previous experimental studies on unstable infiltration were all concentrated on individual factors outlined for onset of fingering. However, several factors often coexist and interact with each other in the field. Experimental studies considering the combined factors, rather than individual ones, will provide more realistic information for field investigations.

The objectives of this study are to (1) identify the occurrence of unstable flow under combined porous medium and fluid conditions, (2) verify the predictability of the observed unstable flow by (2) and (4), and (3) predict conditions under which stable or unstable flow will occur in the field. Therefore a set of 20 controlled two-dimensional infiltration experiments were conducted to investigate the combined effects of (1) natural air compression ahead of the wetting front by the infiltrating water, (2) desaturation (suction condition) at the soil surface, (3) layering of a sand and a loam, and (4) water repellency of the media.

2. Experimental Materials and Methods

With controlled laboratory experiments the effects (and the sensitivity) of various parameters on flow instability and finger development can be studied. Visualization of the dynamic changes of flow is important for validating the instability criteria outlined. It has long been realized that the displacement of immiscible fluids in saturated/unsaturated porous media requires an analysis in three dimensions. However, a three-dimensional (3-D) investigation complicates the flow visualization and data collection. Therefore the two-dimensional visu-

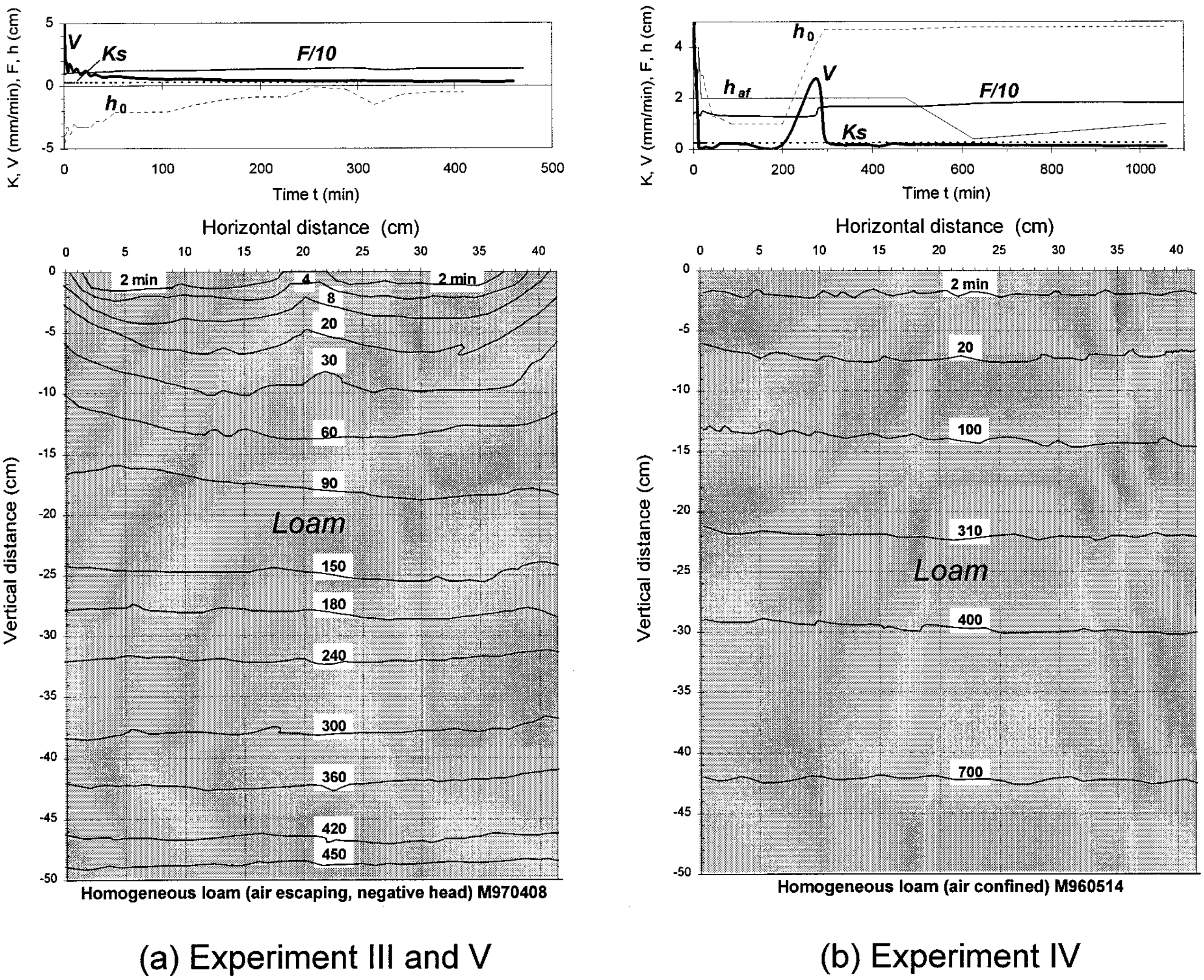


Figure 4. Infiltration into a homogeneous water-wettable loam (small chamber): (a) stable flow for the air-draining condition and (b) stable flow for the air-confined condition (symbols are as defined for Figure 2).

alization method has been used. According to *Glass et al.* [1991], two-dimensional fingers have diameters of $\pi/4.8$ times that of the equivalent three-dimensional fingers.

Two Plexiglas slab chambers were constructed to hold soil samples of different sizes. The small portable chamber had an inside space 2.8 cm thick, 41.5 cm wide, and 60 cm deep, and the large chamber had an inside space 1.8 cm thick, 74.5 cm wide, and 90 cm deep (Figure 1). The dimensions of the 2-D chambers were large enough to allow development of a full finger. Rubber materials were used to seal any air openings between the steel case and the Plexiglas plates so that the soil air phase could be controlled. When the soil air is allowed to drain freely from ahead of the wetting front through an air exit at the bottom, the system condition is referred to here as an "air-draining" or "air-escaping" condition. In contrast, when the air is allowed to escape only from the soil surface, the system condition is referred to as an "air-confined" condition. Initial experiments [*Wang et al.*, 1998] showed that the gage air pressure in the dry media was uniformly distributed ahead of the wetting front. Thus the soil air pressure head h_{af} was measured only at the bottom of the chamber, using a water manometer. The control of water pressure head h_0 at the soil surface and the measurement of the infiltration rate V were achieved by use of a tension infiltrometer [*Perroux and White*, 1988]. Water was uniformly applied to the soil surface through an inverted T tube (Figure 1).

Three types of oven-dried soils, a water-wettable sand, a water-wettable loam, and a water-repellent sand were used for this study. Hydraulic parameters of the three soils are listed in Table 1. The wettable sand was described by *Wang et al.* [1998]; the water-repellent Ouddorp sands were described by *Ritsema et al.* [1993], who recognized three layers with decreasing degree of water repellency. The wettable loam was a well-structured soil taken from an agricultural field in Leuven, Belgium. The saturated water conductivity of each repacked soil was measured using the constant-head (permeameter) method. The capillary water-bubbling value h_{wb} of the wettable soil was measured using the tension infiltrometer method [*Fallow and Elrick*, 1996], whereas the capillary water-bubbling (entry) value of the repellent sand was measured using a water-ponding method. By increasing the ponding depth at the repellent soil surface, one will notice a critical depth at which water suddenly starts to infiltrate into the hydrophobic medium. This critical depth of ponding is equal to the negative of the capillary water-bubbling value h_{wb}, the magnitude of which indicates the degree of water repellency.

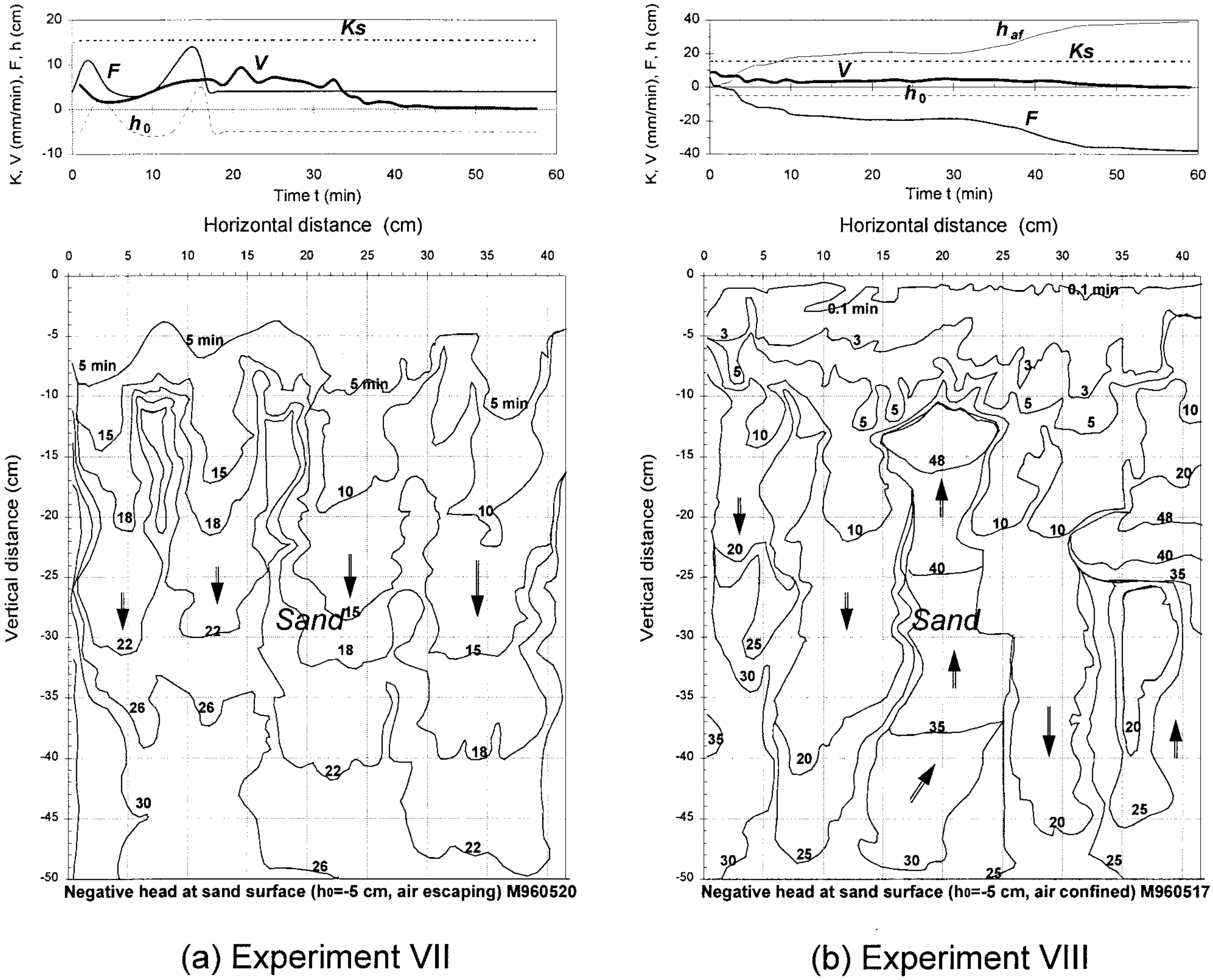


Figure 5. Nonponding (negative pressure) infiltration into sand (small chamber): (a) fingered flow for the air-draining condition and (b) fingered flow for the air-confined condition (symbols are as defined for Figure 2).

Twenty experiments for 10 different combinations of the three soils and two airflow conditions were carried out (Table 2). The dry soil(s) was packed into the 2-D chambers using a funnel-extension-randomizer assembly and a drop impact method [*Glass et al.*, 1989d]. When preparing samples with different layers, care was taken to maintain a clear textural interface and good contact between the layers. The surface of the repacked soil was carefully smoothed and leveled.

After a complete installation, the infiltration was initiated by simply turning on the tension infiltrometer. The negative water pressure head h_0 on the soil surface was set by pushing down the bubbling tube to a depth equal to $|h_0| + e$ cm below the water level in the bubbling tower (Figure 1), where e is the vertical distance between the air tube and the soil surface. Infiltration tests under air-draining conditions were first conducted with surface water heads h_0 varying between -10 and 10 cm. Each experiment was then repeated under the air-confined condition (Table 2). The development of wetting fronts behind the transparent Plexiglas plate, the falling water level as shown in the tension infiltrometer, and the gage air pressure as indicated in the water manometer were recorded using a video camera (SONY model CCD-TR808E). The images of wetting front advancement were then digitized into computer plot-files via hardware and software packages of ARC/INFO 3.4 and AutoCAD11.

3. Results and Analyses

The recorded changes with time of the infiltration rate V, the natural saturated water conductivity K_s, the water pressure difference F across the wetted layer, the water pressure head h_0 at the soil surface, and the air pressure h_{af} ahead of the wetting front (in the case where $h_{af} > 0$) are shown in the top section of Figures 2–11. The advancements of the wetting front for the corresponding experiments are shown in the bottom section of Figures 2–11.

3.1. Displacement Instability With Air Compression in Homogeneous Media

Wetting front movement in the homogeneous sand (small 2-D chamber) was stable, as predicted when soil air was free to escape from the system (Figure 2a). Despite an initial nonuniform water application at the soil surface the wetting front quickly became sharp and moved uniformly downward after 1 min of infiltration. The stable flow condition is consistent with the predictions by the V and F criteria ($V > K_s$ and $F > 0$;

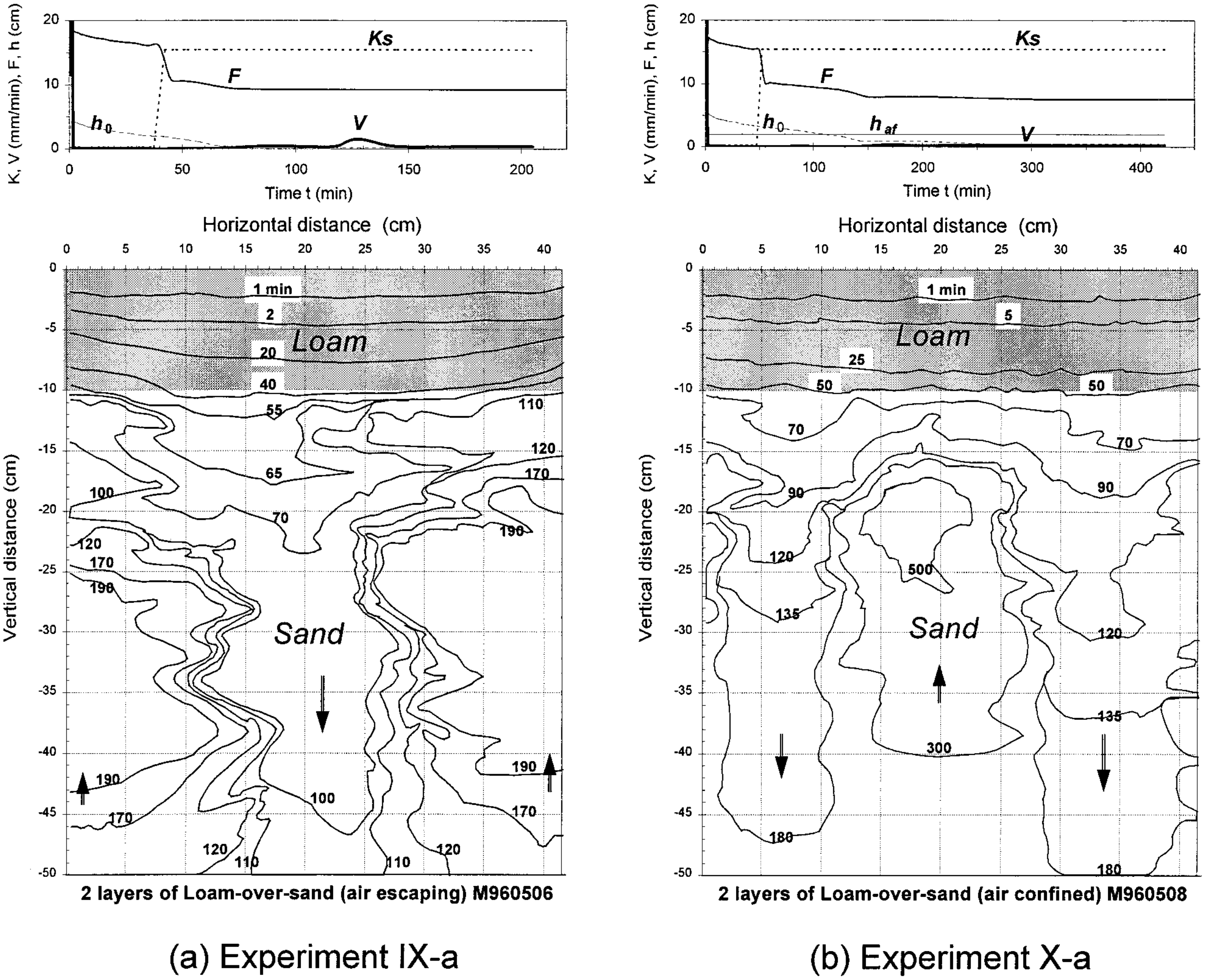


Figure 6. Infiltration into a layered fine-over-coarse system (small chamber): (a) fingering in the coarse sublayer for the air-draining condition and (b) more fingers in the coarse sublayer for the air-confined condition (symbols are as defined for Figure 2).

see the top section of Figure 2a). The results for the air-confined condition are shown in Figure 2b. Air ahead of the wetting front was compressed naturally by the infiltrating water. The gage air pressure h_{af} abruptly rose as soon as water completely covered the soil surface. Air bubbles intermittently escaped from the soil surface, which led to fluctuations in h_{af} and F as shown in the top section of Figure 2b. The infiltration rate V was reduced to zero for a short period from $t = 4$ to 7 min. When the instability criterion $V < K_s$ was satisfied at about $t = 3$ min and the criterion $F < 0$ was satisfied at $t = 1$ min, the wetting front became unstable at about $t = 2$ min. The flow became fingered after $t = 5$ min. There appeared two fingers as shown by the downward arrows.

Experimental results using the same sand in the large chamber are shown in Figure 3. The infiltration flow patterns appearing in the small chamber were qualitatively reproduced in the large chamber: the flow was stable for the air-draining condition (Figure 3a) and unstable for the air-confined condition (Figure 3b). Notice in Figure 3a that when water on the soil surface disappeared, causing surface desaturation after $t = 9$ min, the wetting front appeared unstable, which is consistent with the condition of $V < K_s$ (The surface desaturation must have caused h_0 to be negative; however, we could not measure the h_0 value. Thus the condition of $F > 0$ after $t = 9$ min was false.) In the large but thinner chamber (1.8 cm thick) the compressed air created a large crack (as shown in Figure 3b). The crack in the repeated large chamber experiment grew wider than 10 cm and practically cut the flow from infiltrating downward. Since cracks are not expected to appear in the field in sandy soils, the experimental results from the very thin 2-D columns should be interpreted with care. In our small 2-D column of 2.8 cm thick, no such cracks were detected; hence, most of our conclusions will be based on the small chamber experiments.

In the homogeneous loam the infiltration flow was stable for the air-draining chamber (Figure 4a), consistent with the prediction of V and F criteria. The wetting front in the air-confined chamber (Figure 4b) seemed also to be stable, which was inconsistent with the condition of $V < K_s$. We suspect that a finger in the loam could be wider than half the width of the chamber, so that we were not able to measure the full width of the finger. A recent equation of *Wang et al.* [this issue, equation (19)] predicted that the finger width d in this air-confined experiment should be about $d = 0.25\ \pi h_{wb}/(1 - V/K_s) =$

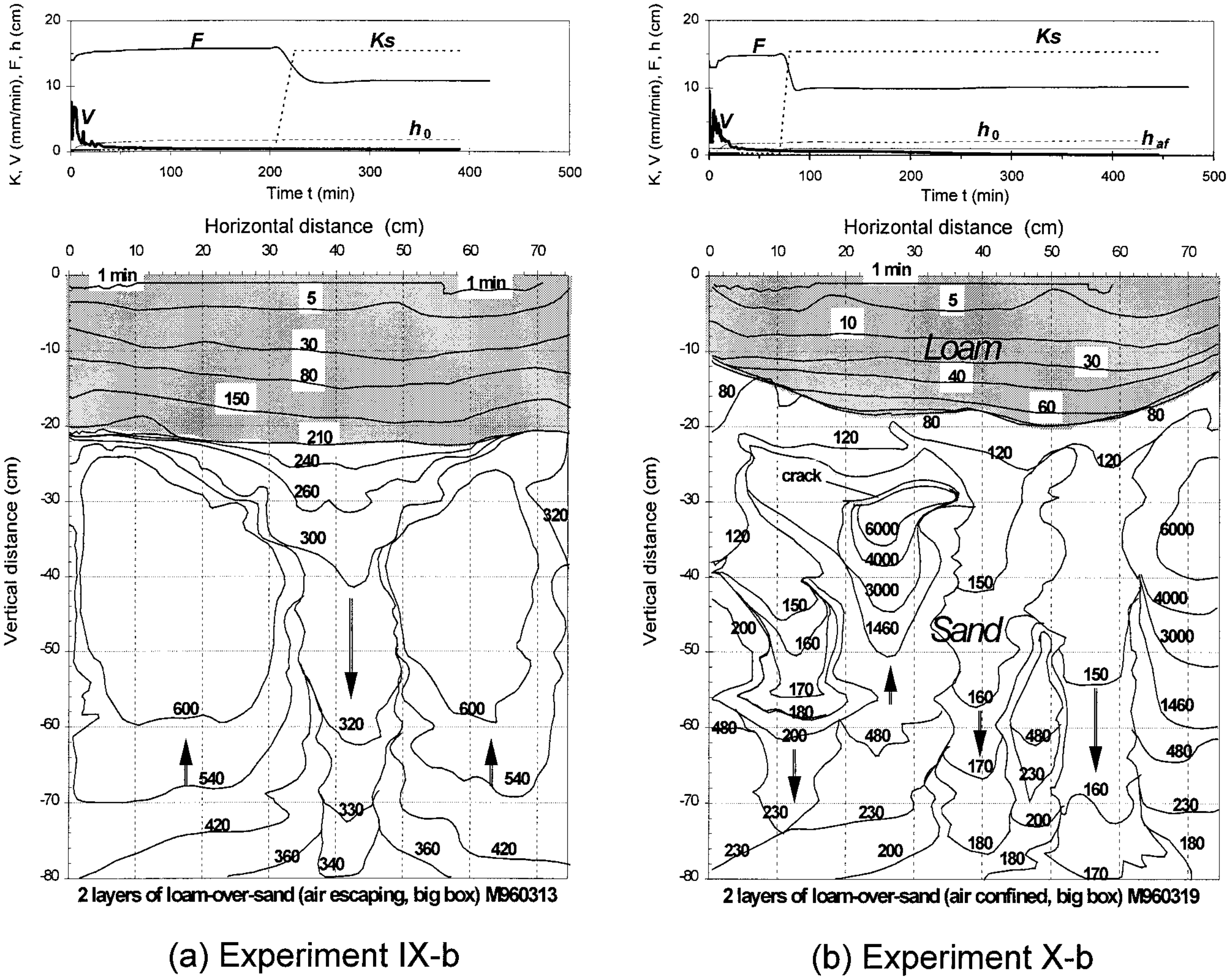


Figure 7. Infiltration into a layered fine-over-coarse system (large chamber): (a) fingering in the sublayer for the air-draining condition and (b) more fingers in the sublayer for the air-confined condition (symbols are as defined for Figure 2).

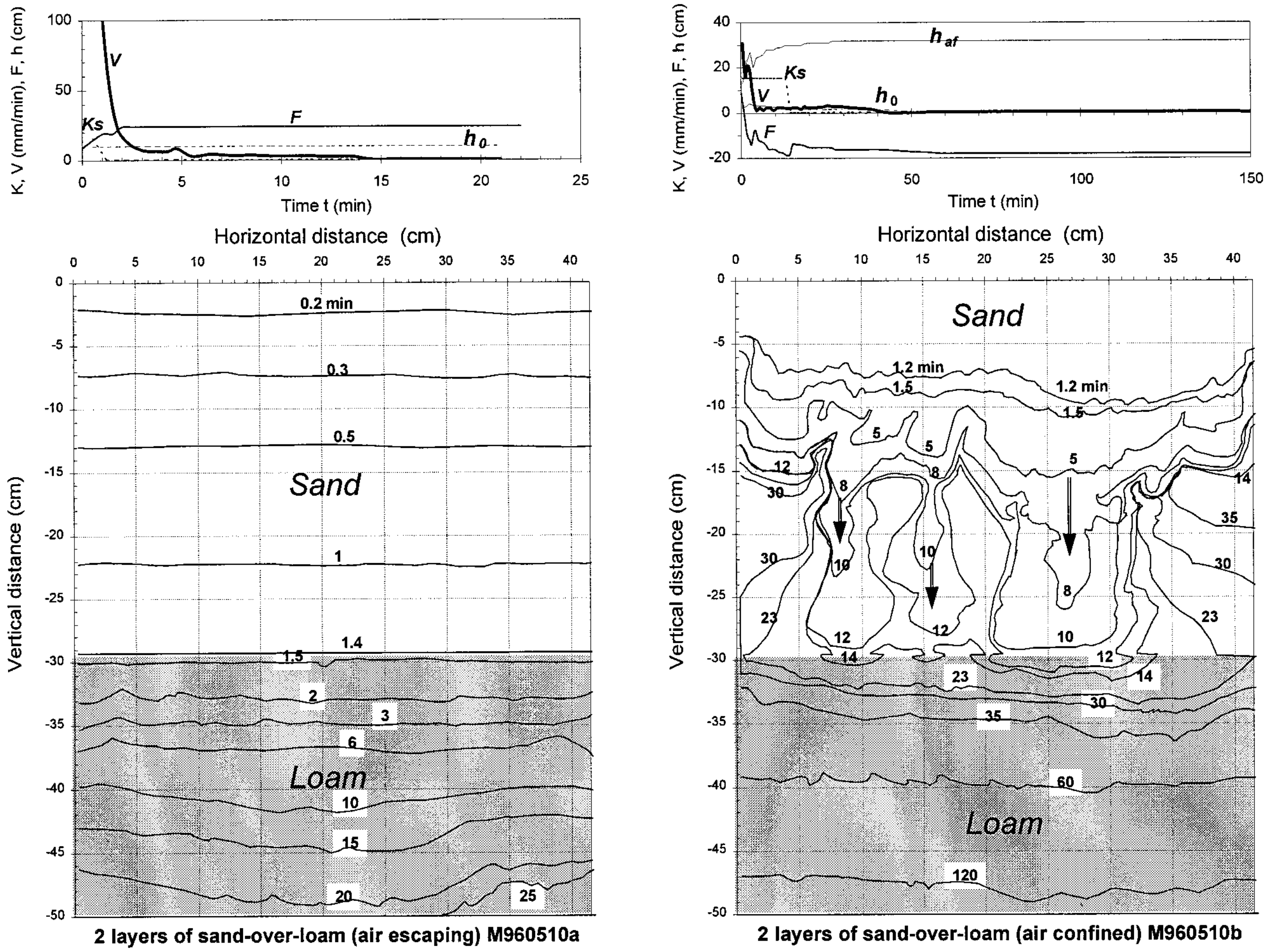
$0.25 \cdot \pi \cdot 14/(1 - 0.8) \approx 55$ cm, which is even wider than the full width of the chamber. It is clear that such a finger can only be observed in a much larger chamber: its width must be at least $2d = 110$ cm, and its height must be great enough for full development of the finger. Thus future experiments are still needed to confirm fingering in fine soils. The F criterion ($F > 0$), based on piston flow assumption, then failed to predict the "unstable" flow in loam.

In Figure 4b a sudden increase in h_0 led to abrupt increase in V at about $t = 200$ min. The value of V decreased at $t = 250$ min because of a temporary increase in soil air pressure h_{af}. We found that the rate of water infiltration into the loam was so low that air could not be significantly compressed ahead of the wetting front (h_{af} rose to only 4 cm of water). The confined soil air did not escape from the surface. Apparently, the total volume of the confined air was encapsulated in the soil pores or dissolved in the infiltrated water. *Adrian and Franzini* [1966] observed that for uniform media having particle sizes smaller than 0.3 mm the air could not escape upward into the atmosphere through the wetted top layer. *Christiansen* [1944] explained that the entrapped air was gradually dissolved by water in the transmission zone, although he made no attempts to observe air compression ahead of the wetting front. Further studies are needed to investigate the mechanisms for air encapsulation in the fine materials and air dissolution into water.

3.2. Displacement Instability With Negative Pressure Source

During redistribution of infiltrated water (or surface desaturation) following a rainfall or irrigation and during the natural nonponding infiltrations, water pressure at the soil surface is negative. *Diment and Watson* [1985], *Tamai et al.* [1987], *Selker et al.* [1992], *Nicholl et al.* [1994], and *Babel et al.* [1995] confirmed fingering during redistribution of infiltrated water in sandy soils or glass beads without air compression ahead of the wetting front.

Application of a negative pressure ($h_0 = -5$ cm) at the sand surface produced fingers for both the air-draining (Figure 5a) and the air-confined (Figure 5b) conditions. The wetting front was immediately unstable upon the nonponding infiltration, consistent with the velocity instability criterion $V < K_s$. The sand at the surface in experiment VII (Figure 5a) was probably looser than the sublayers, exhibiting a higher than -5



(a) Experiment XI

(b) Experiment XII

Figure 8. Infiltration into a layered coarse-over-fine system (small chamber): (a) stable wetting for the air-draining condition and (b) fingering in the sandy top layer and stable flow in the loamy sublayer for the air-confined condition (symbols are as defined for Figure 2).

cm of soil water entry value. Thus the source water under $h_0 = -5$ cm could not infiltrate into the sand. Hence we temporarily increased the surface pressure h_0 to initiate the infiltration. For the air-draining condition (Figure 5a), fingers were uniformly spaced in the column. However, for the air-confined condition (Figure 5b), there were less and irregularly distributed fingers. Wider areas of the soil matrix were bypassed during finger development for the air-confined condition. After the fingers reached the bottom of the chamber the "groundwater table" rose. It took a long time to wet the bypassed areas.

Notice that under the negative pressure source for the air-draining condition (Figure 5a), the F criterion failed to predict fingering in the sand; the V criterion failed to predict stable flow in the loam for the air-confined condition (Figure 4b). This may be related to pronounced capillary action in both cases. The infiltration under a suction head without air compression (Figure 5a) and the flow in a loam (Figure 4b) tend to be capillary rather than gravity driven. Hence the instability criteria, (2) and (4), for the gravity fingering are not applicable if capillary forces tend to dominate the flow. A case of capillary-driven fingering in a sandy soil was recently reported by *Yao and Hendrickx* [1996]. It was confirmed in other experimental studies [e.g., *Hill and Parlange*, 1972; *Parlange and Hill*, 1976; *Starr et al.*, 1986; *Diment and Watson*, 1985; *Glass et al.*, 1988] that infiltration into fine wettable materials, without air compression, was unconditionally stable.

3.3. Displacement Instability in Layered Media

The occurrence of fingering in layered fine-over-coarse systems has been most extensively studied in the past [*Hill and Parlange*, 1972; *Parlange and Hill*, 1976; *Starr et al.*, 1986; *Diment and Watson*, 1985; *Glass et al.*, 1988, 1989a, b, c, 1990, 1991; *Hillel and Baker*, 1988; *Baker and Hillel*, 1990; *Selker et al.*, 1992; *Lu et al.*, 1994; *Chang et al.*, 1994]. However, the effect of air entrapment on the flow was carefully avoided or ignored. In a field experiment designed to study leaching characteristics of a sandy loam-over-coarse sand layered soil with a water table at a depth of 1.8 m, *Starr et al.* [1978] reported that the gage air pressure ahead of the wetting front rose to 40 cm of water. They also concluded that air compression ahead of the wetting front enhanced fingering in the fine-over-coarse system. When air pressure was suddenly released into the atmosphere through an access tube, the basic infiltration rate increased by nearly twofold.

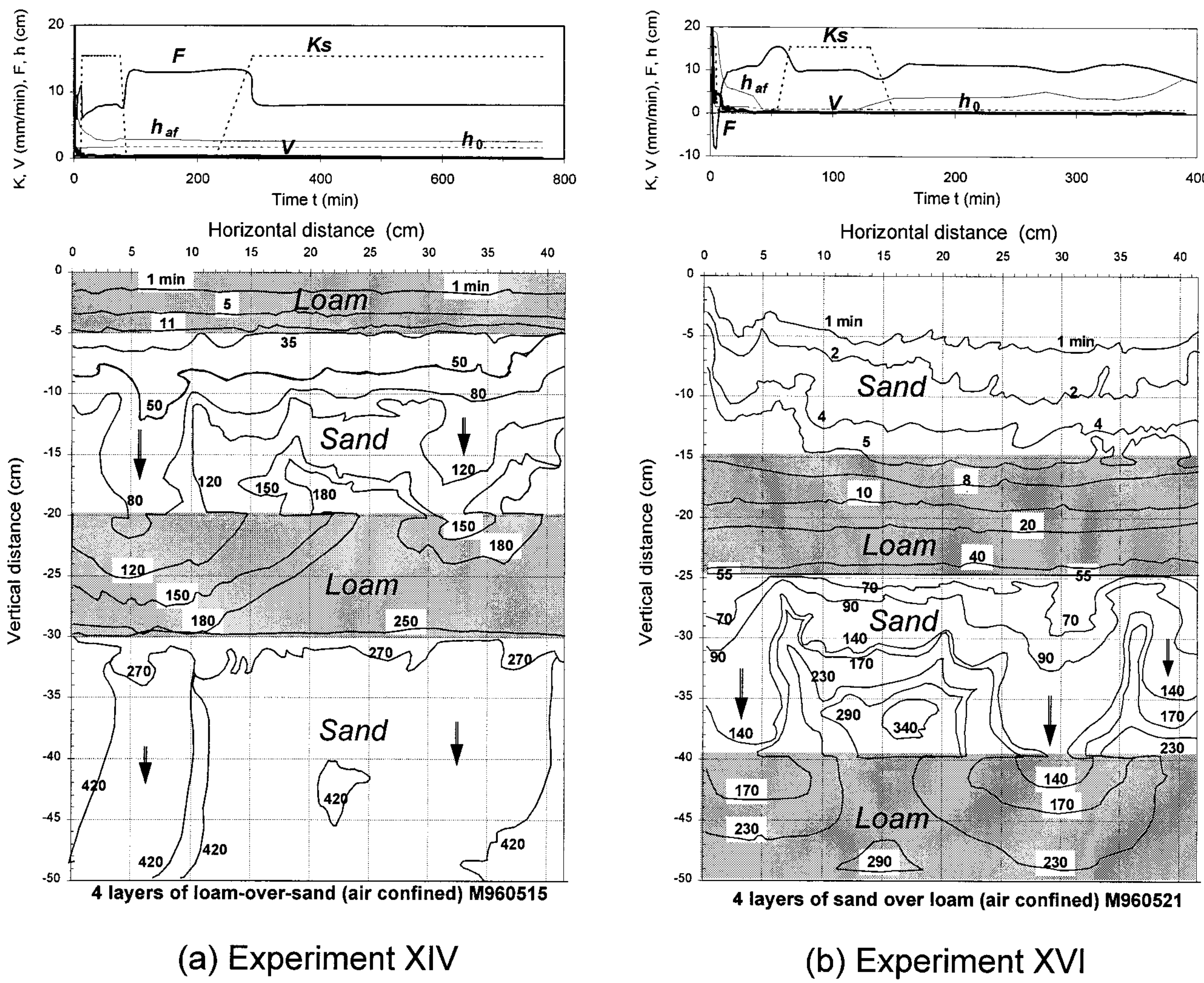


Figure 9. Infiltration into multilayer systems (small chamber): (a) multiple layers with the loam on top for the air-confined condition and (b) multiple layers with sand on top for the air-confined condition (symbols are as defined for Figure 2).

Our experimental results for the combined effects of air entrapment and the layered loam-over-sand system on flow instability are shown in Figure 6. The infiltration flow could be judged as "unstable" in the top layer, consistent with prediction of $V < K_s$. As outlined in section 3.2, the finger width in the top loamy layer could be wider than the width of the chamber. The flow became fingered immediately below the interface. The F criterion ($F > 0$) failed to predict fingering in both layers because of the assumption of piston flow. The same flow patterns were reproduced in our large chamber experiments with results as shown in Figures 7a and 7b. Apparently, there were more fingers in the air-confined columns (Figures 6b and 7b) than in the air-draining columns (Figures 6a and 7a). The width of the fingers, as measured near the finger tip, varied between 8 and 15 cm in both the large chamber and the small chamber. The time needed to completely wet the entire soil matrix in the air-confined chamber (Figures 6b and 7b) was 2–10 times that for the air-draining chambers (Figures 6a and 7a). It was also observed that the wetting front in the loam retarded (or paused) at the interface. The phenomenon is consistent with the capillary theory, which was explained by *Hillel and Baker* [1988]. Water began to infiltrate into the lower sand layer only after the entire matrix of the top layer was sufficiently saturated and the capillary pressure (suction) in the loam was reduced to the water entry value of the sublayer (sand).

The combined effects of a coarse-over-fine system and air entrapment on infiltration are shown in Figure 8. With the sand on top of the loam without air entrapment (Figure 8a), the wetting front was sharp and stable in both the sand and loam layers, consistent with predictions of both the V and F criteria (where $V > K_s$ and $F > 0$). In the air-confined chamber (Figure 8b), infiltration was initially stable before $t = 1.5$ min, consistent with stable conditions of $V > K_s$ and $F > 0$. As air pressure developed ahead of the wetting front in both the sand and loam layers, fingers occurred in the sand, reflected by the unstable conditions of $V < K_s$ and $F < 0$. The finger tips expanded immediately in the loam, leading to a stable wetting front in the fine layer. Notice that both the V and the F criteria failed to predict the stable flow in the loam, because of capillary dominance.

Results of water infiltration into the multilayer systems for the air-confined condition are shown in Figure 9. When a fine layer (loam) was on top of the system (Figure 9a), soil air could

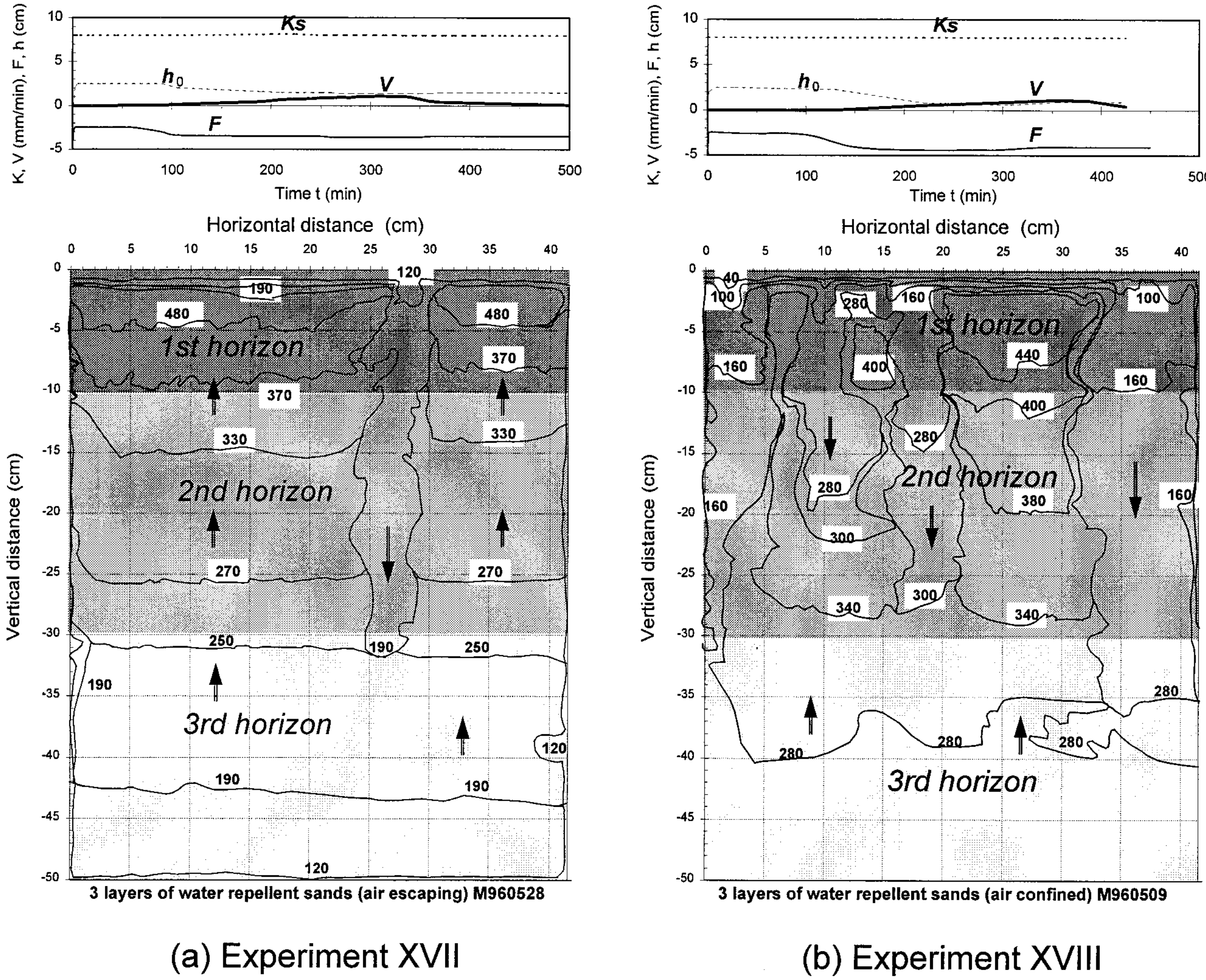


Figure 10. Infiltration into a three-layer water repellent sand under low ponding depth (small chamber): (a) fingered flow for the air-draining condition and (b) fingered flow for the air-confined condition (symbols are as defined for Figure 2).

not be considerably compressed, resulting in a stable wetting front in this zone. The flow is fingered in the sand layer, stabilized in the second loam layer, and fingered again in the bottom sand layer. Inversely, when a sand layer was on top of the system (Figure 9b), air pressure h_{af} increased sharply, causing unstable flow in this region. The flow was stabilized in the underlying loam, fingered in the second sand layer, and stabilized again in the bottom loam layer. The fingers were formed in the sand layers when $V < K_s$. However, the F criterion failed to predict fingering in multiple layers.

3.4. Displacement Instability in Hydrophobic Media

Natural accumulation of organic materials and pesticides in soils lead to soil water repellency (hydrophobicity). Fingering was observed in water-repellent soils by *Ritsema et al.* [1993], *Hendrickx et al.* [1993], *Dekker and Ritsema* [1994, 1995], and *Ritsema and Dekker*, [1994, 1995]. The Ouddorp water-repellent sandy soil horizons [*Ritsema et al.*, 1993] were packed into the small chamber in a three-layer system (Figure 10), with the most water-repellent horizon on top (10 cm thick), the second horizon in the middle (20 cm), and the third horizon at the bottom (20 cm). For both the air-draining (Figure 10a) and air-confined (Figure 10b) conditions under low ponding depths (varying from 2 to 3 cm), the repellent soil was extremely difficult to be wetted. Water started to infiltrate only after 40 minutes of ponding. A considerable amount of edge flow occurred along the side walls of the chamber, causing the water table to rise from the bottom. A single finger appeared in the air-draining chamber (Figure 10a), and three fingers appeared in the air-confined chamber (Figure 10b). The fingers grew slowly and did not extend into the third horizon. Because of the extremely low rate of water infiltration, soil air was not compressed before edge flow reached the bottom. During the fast upward wetting, soil air in both chambers was compressed. Air bubbles broke through a very thin layer of the wetted top layer and escaped into the open air. A waxed chamber was used to prevent edge flow for experiment XIX under the air-draining condition. The results (Figure 11a) showed that there was a smaller amount of edge flow compared to the previous experiments with the repellent sand. A long finger developed into the third horizon, causing the water table to rise.

For the above three experiments the water entry value of the repellent soil was not exceeded, which resulted in a zero rate infiltration at the beginning of ponding. Notice that the capil-

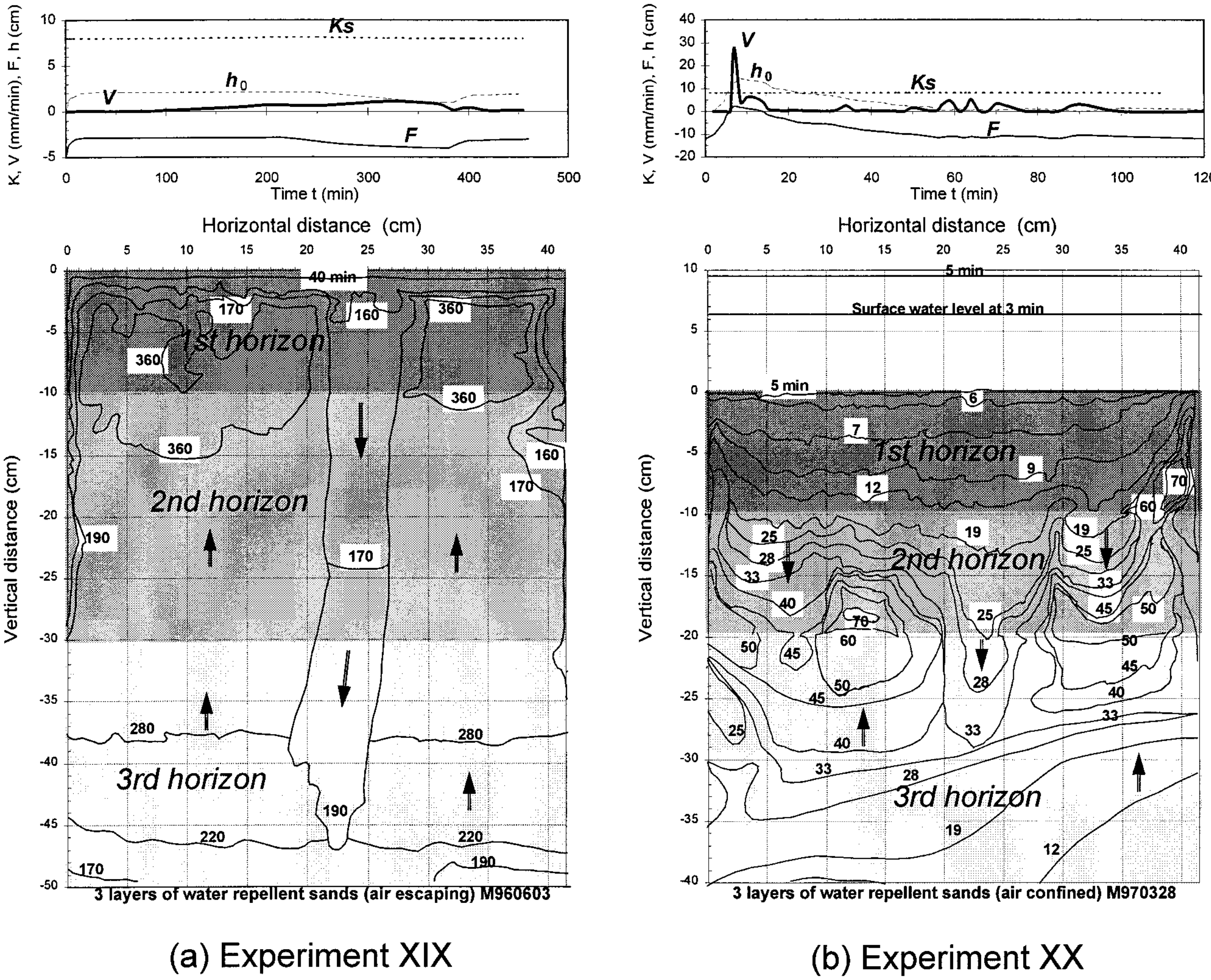


Figure 11. Infiltration into a three-layer water repellent sand (waxed small chamber): (a) fingered flow for the air-draining condition under low ponding depth (h_0) and (b) initial stable flow under high ponding followed by fingering due to air compression below the wetting front (symbols are as defined for Figure 2).

lary water-bubbling (entry) value of the repellent humose topsoil (Table 1) was $h_{wb} = -12$ cm, which is equivalent to 12 cm of ponded water on the soil surface. Therefore we applied a surface head in experiment XX of more than 12 cm. The results are shown in Figure 11b. The infiltration started promptly at $t = 6$ min when the ponding depth h_0 exceeded the threshold entry value h_{wb} of 12 cm. The wetting front was stable for a short time between $t = 6$ and 9 min when $h_0 > h_{wb}$, consistent with $V > K_s$ and $F > 0$ for stable flow. Air compression ahead of the wetting front (due to the fast infiltration) caused $V < K_s$ after $t = 9$ min and $F < 0$ after $t = 15$ min. The wetting front became critically unstable at $t = 12$ min and fingered after $t = 19$ min, corresponding closely with predictions of both the V and F criteria.

To summarize, water infiltration into initially dry hydrophobic media is slow and normally fingered under low ponding conditions. The flow is stabilized only when the ponding depth exceeds the water entry value of the water-repellent medium.

3.5. Finger Size and Fingered Flow Rate

The general results regarding flow instability and the size and speed of the fingers for all the experiments are listed in Table 3. About one third (7 out of 20) of the tested conditions resulted in stable flow. The wetting front was always stable in the fine material (loam) packed in the chambers of limited sizes. The flow in the sands is stable only when air is not entrapped below the wetting front and the soil surface is under a water pressure that is higher than the water-bubbling value of the porous medium. Unstable flow appeared to be closely related to air entrapment, soil layering, negative pressure source, and water repellency of the sand materials. Apparently, there appeared more fingers (as indicated by n) for the air-confined condition than for the air-draining condition. The finger width W was 7–15 cm (10 cm on average) in the water-wettable sand and 7–10 cm in the water-repellent sand. For the air-confined condition the fingered fractional area occupied approximately half of the soil cross section ($F \approx 0.5$). The frontal propagation velocity v of all the fingers varied between $v = 0.15$ and 2.5 cm/min, with the slowest finger occurring in the water-repellent sand and the fastest in the water-wettable sand. The system flux V of the fingered flow varied the same way as that of v. Since $F < 1$, the flux through the fingers, $q = V/F$, is thus $1/F$ times greater than V. We observed that for

Table 3. Stable and Unstable Flow in the Two-Dimensional Columns

		Air-Draining		Air-Confined	
Sequence	Media Combinations	Finger Width (area), $n \times W$ (F)	Front Velocity (System Flux), v(V)	Finger Width (area), $n \times W$ (F)	Front Velocity (System Flux), v(V)
1	Homogeneous sand	stable	4.5 (1.3$K_{S,S}$)	2 × 10 (0.48)	2.5 (0.52$K_{S,S}$)
	Same material in the large chamber	stable	6.5 (1.1$K_{S,S}$)	2 × 15 (0.4)	2.4 (0.55$K_{S,S}$)
2	Homogeneous loam	stable	0.12 (1.3$K_{S,L}$)	stable	0.06 (0.8$K_{S,L}$)
3	Negative pressure on loam surface	stable	0.1 (1.2$K_{S,L}$)	stable	0.05 (0.6$K_{S,L}$)
4	Negative pressure on sand surface	4 × 8 (0.78)	2 (0.45$K_{S,S}$)	3 × 7 (0.5)	1.7 (0.25$K_{S,S}$)
5	Two layers of loam over sand	1 × 10 (0.25)	0.8 ($K_{S,L}$)	2 × 10 (0.5)	0.3 ($K_{S,L}$)
	Same materials in the large chamber*	1 × 10 (0.13)	0.6 (1.3$K_{S,L}$)	3 × 10 (0.4)	0.6 (1.1$K_{S,L}$)
6	Two layers of sand over loam	stable	0.8 (1.6$K_{S,L}$)	3 × 7 (0.5)	2 (0.1$K_{S,S}$)
7	Four layers of loam over sand	2 × 7 (0.33)	0.3 ($K_{S,L}$)	3 × 7 (0.5)	0.25 ($K_{S,L}$)
8	Four layers of sand over loam	2 × 7 (0.33)	0.25 ($K_{S,L}$)	3 × 7 (0.5)	0.2 ($K_{S,L}$)
9	Water-repellent sands ($h_0 > -h_{wb}$)	1 × 7 (0.12)	0.5 (0.05$K_{S,R}$)	3 × 10 (0.5)	0.15 (0.05$K_{S,R}$)
10	Water-repellent sands ($h_0 > -h_{wb}$)	stable	2 (1.1$K_{S,R}$)	3 × 10 (0.72)	1.5 (0.15$K_{S,R}$)

Symbol n represents the number of fingers, W (cm) is the average width of the fingers, F is the fraction of the fingered area to the total cross-sectional area of the chamber, v (cm/min) is the propagation velocity of the wetting front (or finger tip), and V (mm/min) is the system flux. $K_{S,S}$, $K_{S,L}$, and $K_{S,R}$ are the natural saturated water conductivity of the sand, the loam, and the repellent sand, respectively (see Table 1).

*The large chamber made of 1 cm thick Plexiglas (74.5 cm wide, 80 cm high, and 1.8 cm interval) expanded as the loam was compacted. The loam layer here had a lower bulk density than described in Table 1.

the fine-over-course systems (porous medium combination numbers 5, 7, and 8), V was exactly equal to the saturated conductivity ($K_{S,L}$) of the top layer (loam), indicating that the infiltration rate in the sub layer was controlled by the conductivity of the top layer. Our experimental results confirmed the first two hypotheses of *Hillel and Baker* [1988] and *Baker and Hillel* [1990] for preferential flow in fine-over-coarse systems: (1) The wetting front pauses at the textural interface until the top layer is sufficiently saturated, whereafter water starts to infiltrate into the sublayer only when suction in the top layer falls to the water-entry suction h_{wb} of the sublayer, and (2) fingering is initiated when there is an insufficient flux supply from the top layer (i.e., when flux V_t in the top layer is smaller than the natural saturated conductivity $K_{S,S}$ of the sublayer at water-entry suction). However, our results were not in line with *Hillel and Baker*'s [1988] third hypothesis that the wetted fraction F should be equal to the ratio of conductivity of the finer top layer and that of the coarser sublayer at the water-entry suction. Data of the system flux ratio, $R_s = V/K_S$, and the finger flux ratio, $R_f = (V/F)/K_s$, from Table 3 can be used to validate predictions for finger diameter and velocity [*Chuoke et al*., 1959; *Parlange and Hill*, 1976; *Glass et al*., 1989c, d; *Wang et al*., this issue], which will be shown in a separate work of *Wang et al*. [this issue]. Finally, the data in Table 3 indicate that the finger propagation speed v and the system flux V are considerably lower under an air-confined condition than under an air-draining situation. If, for a porous medium, fingers occurred in both the air-draining and the air-confined condition (see, for instance, Figures 5a–5b, 6a–6b and 10a–b), finger velocity and system flux were always higher for the air-draining situation.

4. Conclusions

The combined effects of air entrapment, soil layering, surface desaturation, and water repellency of the porous media on the stability of infiltration wetting fronts were studied experimentally. The results showed that infiltration into a sand and loam under a higher than water-entry pressure without air entrapment was stable. Infiltration into the water-wettable and water-repellent sandy and loamy soils was mostly unstable because of mixed conditions of (1) air compression ahead of the wetting front, (2) nonponding infiltration, and/or (3) soil stratification. Infiltration in the multiple-layered system can be described as semistable or semiunstable. The flow is unstable in the coarse layer but is stabilized in the fine layer. Therefore the degree of system instability depends on the relative thickness of the coarse layer. Models of water flow and solute transport in the vadose zone should incorporate the effects of such fingered flow phenomena.

Most of the stable and the unstable flow phenomena were accurately predicted by the velocity criterion ($V < K_S$) [*Hill and Parlange*, 1972] and the pressure criterion ($F = h_0 + h_{wb} - h_{af} < 0$) [*Raats*, 1973; *Philip*, 1975]. However, the F criterion failed to predict fingering in the water-wettable sand for the air-draining condition under a negative pressure source (Figure 5a) and for the layered fine-over-coarse systems. The failed cases were most probably caused by pronounced dominance of capillary over gravity forces. Low infiltration rates in fine or water-repellent media prevented compression of air below the wetting front. Soil air under these conditions was slowly encapsulated in the wetted layer and dissolved into the water. Further studies of the encapsulation and dissolution mechanisms of air in water-filled medium fine pores are needed. Fingered flow under air-draining conditions always had a higher velocity and system flux compared with fingering under air-confined conditions.

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