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Effects of soil water repellency on infiltration rate and flow instability

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Abstract

Laboratory infiltration experiments were carried out to quantify the effects of soil water-repellency on infiltration rate and the wetting front instability. A two-dimensional transparent chamber (41.5 cm wide, 50 cm high and 2.8 cm thick) was constructed for infiltration experiments using three water-repellent Ouddorp sands (The Netherlands) and a wettable silicon sand. The results showed that if the water-ponding depth (h_0) at the soil surface was lower than the water-entry value (h_{we}) of repellent sands, infiltration would not start until the water drop penetration time (WDPT) is exceeded; and contrary to infiltration in wettable soils, the infiltration rate increased with time. However, infiltration could immediately start at any time when $h_0 > h_{we}$. The wetting front was unconditionally unstable for $h_0 < h_{we}$, resulting in fingered flow. However, the flow was conditionally stable for $h_0 > h_{we}$ if the soil was not layered in a fine-over-coarse or wettable-over-repellent configuration, and if soil air was not compressed during infiltration. The occurrence of stable and unstable flow in repellent soils was consistent with the prediction based on a linear instability analysis. The findings can be used to improve irrigation efficiencies in water repellent soils, e.g. using high-ponding irrigation methods. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil water repellency; Infiltration rate; Flow instability

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1. Introduction

Many soils of the world are water repellent. They are difficult to manage and pose negative effects on agricultural productivity and environmental sustainability (Debano, 1969; Letey, 1969; Bond, 1969; van't Woudt, 1969; Jamison, 1969; Holzhey, 1969; Letey et al., 1975; Ritsema et al., 1993). The effects of water repellency on infiltration are not yet fully understood. Field observations have indicated that the rates of water infiltration into repellent soils are very irregular. The fingered by-passing flow is more likely to occur in repellent soils rather than in wettable soils (Raats, 1973; Philip, 1975; Parlange and Hill, 1976; Glass et al., 1989; Wang et al., 1998b,c). Fingered preferential flow causes uneven distribution of water in the crop root zone, and accelerates the contaminant transport to ground water.

The purpose of this paper is to quantify the effects of soil water repellency on infiltration rate and flow instability. We apply the unstable flow theory to predict the onset of wetting front instability and the

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occurrence of fingering in the vadose zone of water-repellent soils. Two-dimensional chamber experiments were carried out to study the dynamics of infiltration and fingering in three Ouddorp repellent sands of The Netherlands. The results are compared with infiltration and fingering in a wettable sand of the same texture.

2. Theoretical analysis

Little is known from previous publications about the law of infiltration into repellent soils. Experimental studies have indicated that infiltration into repellent soils is complicated by the occurrence of fingering in porous media. Many field and laboratory studies have shown that fingering occurs in both wettable and repellent soils, not only in structureless sandy soils but also in structured loam and clay soils, and under both rainfall and irrigation conditions (Parlange and Hill, 1976; Starr et al., 1978, 1986; Clothier et al., 1981; Diment and Watson, 1985; Jury et al., 1986; Hillel and Baker, 1988; Glass et al., 1988, 1989; Butters et al., 1989; Kung, 1990; Ghodrati and Jury, 1990; Baker and Hillel, 1990; Roth et al., 1991; Ghodrati and Jury, 1992; Selker et al., 1992; Jury and Flühler, 1992; Ritsema et al., 1993; Flury et al., 1994; Liu et al., 1994; Nieber, 1996; Held and Illangasekare, 1995; Dekker and Ritsema, 1994, 1995). Many investigators suspect that factors leading to fingering may include vegetation, microtopography, irrigation method, soil water-repellency, soil layering, and soil macropores. However, theoretical analyses suggest that fingering can be induced by the onset of flow instability at the wetting front between two qualitatively different fluids. Fingering may take place in two-fluid flow even if there is no porous structure, e.g. in cracks or the Hele–Shaw cells (Saffman and Taylor, 1958). It is then possible that many of the aforementioned factors can induce wetting front instability in different ways.

The original linear instability analyses of Saffman and Taylor (1958) considering viscous and gravitational forces, and of Chuoke et al. (1959) and Wang et al. (1998c) later including capillary forces, resulted in theoretical criteria for the onset of instability at the wetting front. According to Wang et al. (1998c), the condition for the onset of instability at the interface of two immiscible fluids in a porous medium is

$$V + \frac{e(\rho_{\mathrm{w}} - \rho_{\mathrm{nw}})gk\cos\beta}{(\mu_{\mathrm{w}} - \mu_{\mathrm{nw}})} - \frac{e|\sigma^*|k\alpha^2}{(\mu_{\mathrm{w}} - \mu_{\mathrm{nw}})} > 0 \tag{1}$$

where V is the infiltration rate, the subscript w refers to the wetting fluid and nw the nonwetting fluid; e indicates the wettability of the driving fluid to the porous medium ($e = 1$ for the wetting fluid displacing the nonwetting fluid, and $e = -1$ for the reversed displacement); ρ is the density and μ the viscosity of the fluids, g the acceleration due to gravity, k the effective permeability of the porous medium, β the angle between the gravitational direction and the direction of the flow, σ^* the effective macroscopic interfacial tension, and α the magnitude of a disturbance to the wetting front.

During vertical infiltration ($\beta = 0$) of water into the vadose zone, the density and viscosity of air are negligible. Thus Eq. (1) can be reduced (Wang et al., 1998c) into

$$\frac{|h_{we}|^3}{c} < \frac{V}{K_{\mathrm{s}}} < 1 - \frac{|h_{\mathrm{we}}|^3}{c} \tag{2}$$

where K_{s} is the natural saturated conductivity, h_{we} the water-entry value of the porous medium, and c is a constant indicating the relative effects of the maximum wetting front perturbation and microscopic heterogeneity on flow instability. According to the experiments by Yao and Hendrickx (1996), $c \approx 175000$ if h_{we} is in cm of water height. Thus, it can be predicted that the downward infiltration wetting front is unstable in porous media with $|h_{\mathrm{we}}| < 42$ cm, otherwise the wetting front is stable.

Assuming a sharp wetting front for the initially stable infiltration flow, the infiltration rate V can be expressed as

$$V = K_{\mathrm{s}}\left(1 - \frac{h_{\mathrm{af}} + h_{\mathrm{we}} - h_0}{L}\right) \tag{3}$$

where h_0 is the water pressure head at the soil surface, h_{af} the gauge air pressure head below the wetting front, h_{we} the water-entry pressure of the porous medium, and L the depth of the wetting front. In most fingering-prone sandy soils $|h_{\mathrm{we}}| < 10$ cm, thus the capillary effect on wetting front instability is negligible. Substituting Eq. (3) into Eq. (2) while assuming $|h_{\mathrm{we}}|^3/c = 0$, one obtains two alternative

Table 1
Properties of the porous media used in this study

Porous medium type	γ_d, Dry bulk density (g/cm^3)	ϕ, Total porosity for $\rho_s = 2.65$ (cm^3/cm^3)	K_s, Saturated water conductivity (mm/min)	h_{we}, Water-entry value (cm)
Water wettable sand	1.52	0.43	15.4	−9
Water repellent sands[a]				
1st Horizon (humose topsoil)	1.41	0.47	7.99	12
2nd Horizon (transition layer)	1.54	0.42	8.01	7
3rd Horizon (bottom layer)	1.59	0.40	8.11	2

[a] Sands of Ouddorp, The Netherlands.

criteria for predicting the onset of wetting front instability:

$$V < K_s \tag{4}$$

and

$$F = h_0 - h_{wb} - h_{af} < 0 \tag{5}$$

Thus, any time when $V < K_s$, or the net matrix potential difference (F) across the wetted layer is less than zero (i.e. opposing the downward flow of water), the wetting front is unstable resulting in fingering. Otherwise, the flow should be stable manifesting a uniform and sharp wetting front. Eq. (4) is the criterion of Parlange and Hill (1976), whereas Eq. (5) is identical to the criteria suggested by Raats (1973) and Philip (1975). We refer to Eq. (4) as the velocity (V) criterion, and Eq. (5) as the pressure head (F) criterion in this paper.

According to Eq. (5), wetting front instability can be induced by the individual or combined effects of three factors: (a) a decrease in surface pressure head h_0, for instance during redistribution of water following infiltration ($h_0 < 0$); (b) an increase in water-entry value h_{we} due to, for instances, the presence of a fine-over-coarse layering in the direction of flow, the occurrence of macropores ($h_{we} \approx 0$), and infiltration into water repellent soils ($h_{we} > 0$); and (c) an increase in soil air pressure below the wetting front. Diment and Watson (1985) confirmed fingering as caused by factor (a). Hill and Parlange (1972), Glass et al. (1991), Baker and Hillel (1990), and Selker et al. (1992) focused on fingering in the fine-over-coarse layered soils. Fingering due to air entrapment was confirmed by White et al. (1976) with experiments in the Hele–Shaw cells and by Wang et al. (1998a,b) in a sandy soil. Numerous other experiments have indicated preferential flow due to soil macropores and a combination of the aforementioned factors.

In the repellent soils, fingered flow was observed by Ritsema et al. (1993) and Hendrickx et al. (1993). According to Eq. (5), assuming $h_{af} \equiv 0$, the unstable flow should occur when $h_0 < h_{we}$. In other words, the flow is unstable when the surface pressure head is lower than the water-entry value that is positive in repellent soils.

Field soils are heterogeneous and layered. The topsoil is often macroporous or sometimes water-repellent. The soil air can easily be entrapped during high-intensity rainfalls or ponded surface irrigation events. The soil surface is otherwise under non-ponding infiltration or drainage conditions resulting in negative water heads at the soil surface. All these natural conditions tend to induce unstable flow. Hence, fingering is more likely a common phenomenon rather than the exceptions in the field.

3. Experimental materials and methods

The purposes of the experiments are to measure the rate of infiltration in repellent soils; to identify conditions for the occurrence of fingered preferential flow in repellent soil; to verify the accuracy of Eqs. (4) and (5) with respect to the observed unstable flow patterns; and to compare the results with infiltration rates and occurrence of fingering in a wettable soil. The effects of soil water repellency and natural air compression on infiltration rate and occurrence of fingering were also investigated.

The Ouddorp water-repellent sands of The

Table 2
Matrix of laboratory experiments

Porous medium and air flow combination	A, Air-drained	B, Air-confined
1. Homogeneous sand	I	II
2. Homogeneous repellent sand (1st horizon)	III	IV
3. Homogeneous repellent sand (2nd horizon)	V	VI
4. Homogeneous repellent sand (3rd horizon)	VII	VIII
5. Three-layer water repellent sands ($h_0 < h_{we}$)	IX	X
6. Three-layer water repellent sands ($h_0 > h_{we}$)	XI	XII

Netherlands (Ritsema et al. 1993) and a water-wettable silicon sand (Wang et al., 1998a) were used in this study. The sands were initially oven-dried under 105°C for 24 h and then placed in the open air for at least 2 days before use. Hydraulic parameters of the two sands are listed in Table 1. The saturated hydraulic conductivity was measured using the constant-head method. The water-entry value (h_{we}) of the wettable sand was measured using the tension-pressure infiltrometer (TPI) method (Wang et al., 2000). The water-entry values of the repellent sands were measured using a water-ponding (WP) method (Wang et al., 1998b).

A Plexiglas slab chamber was constructed for 2D visualization of the dynamic infiltration flow in the repacked soils. The inside dimension of the chamber was 2.8 cm thick, 41.5 cm wide and 60 cm deep. The soil air phase was treated in two ways. When the soil air is allowed free to drain from ahead of the wetting front through an air exit at the bottom, the system condition is refereed to as an "air-draining" condition. In contrast, when the air is allowed to escape only from the soil surface, the system is refered to as an "air-confined" condition. The soil air pressure head (h_{af}) below the wetting front was measured using a water manometer. Control of soil surface water head (h_0) and measurement of the infiltration rate (V) were achieved by the use of a tension-pressure infiltrometer (Perroux and White, 1988). Water was uniformly applied to the soil surface through an inverted T tube (Wang et al., 1998b).

Six experiments for 12 different combinations of the two soils and two air-flow conditions were carried out (Table 2). The dry sand was packed into the 2D chamber using a funnel-extension-randomizer assembly and a drop impact method (Glass et al., 1989). When preparing the repellent soil with different horizons, care was taken to maintain a clear textural interface and good contact between the layers. The surface of the packed soil was carefully smoothed and levelled.

After a complete packing and set-up installation, the infiltration was then initiated by simply turning on the TPI. The development of wetting fronts behind the transparent Plexiglas plate, the falling water level in the TPI, and the gauge air pressure change in the water manometer, were recorded using video and photo cameras.

4. Results and analyses

The recorded changes with time t of the infiltration rate V, the water pressure head h_0 at the soil surface, the air pressure h_{af} ahead of the wetting front (in case $h_{af} > 0$), and the water pressure difference $F = h_0 - h_{we} - h_{af}$, are shown in Figs. 1–4. The advance of wetting fronts for the corresponding experiments are shown in Figs. 5–8.

4.1. Infiltration into a homogeneous wettable sand

Water infiltration into the homogeneous wettable sand, without air-entrapment, was stable as predicted since the rate of infiltration V was always higher than the saturated hydraulic conductivity K_s (Fig. 1a). The wetting front propagation was always stable manifesting a sharp wetting front (Fig. 5a). The stable flow condition was consistent with both the V and F criteria ($V > K_s$ and $F > 0$). The air-confined infiltration in the wettable sand resulted in unstable flow as shown in Figs. 1b and 5b. The gauge air pressure h_{af} abruptly rose at the start of infiltration. Then, air bubbles intermittently escaped from the soil surface, which led to fluctuations in h_{af} and F as shown in Fig. 1b. When the instability criterion $V < K_s$ was satisfied at about $t = 3$ min and the criterion $F < 0$ satisfied at $t = 1$ min,

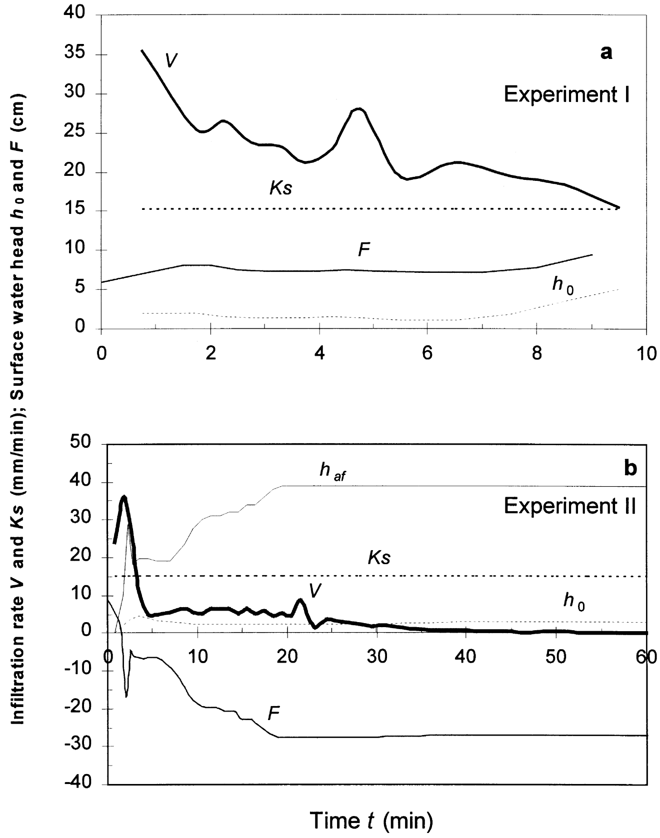

Fig. 1. Variation of infiltration rate, V, surface water head h_0, gage air pressure head, h_{af}, and pressure head difference $F = h_0 - h_{we} - h_{af}$, with respect to infiltration time t in a wettable silicon sand: (a) air-draining condition; and (b) air-confined condition. K_s indicates the soil's saturated hydraulic conductivity.

the wetting front became unstable at about $t = 2$ min. The flow became fingered after $t = 5$ min. Two fingers appeared in the limited chamber as shown in Fig. 5b.

4.2. Infiltration into homogeneous repellent sands

Dynamics of water infiltration into separately packed three horizons of Ouddorp sands are shown in Fig. 2. In all the three repellent horizons, the infiltration rate V was initially zero despite the ponding depths (h_0) at the soil surface. In the most repellent sand (top horizon), water started to infiltrate after a ponding time t exceeded 30 min (Fig. 2a) that is approximately the water drop penetration time of the repellent sands (Ritsema et al., 1993). Notice that the infiltration rate increased with time, which is contrary to the law of infiltration in the wettable sand (Fig. 1a). In the lesser repellent second and third horizons, the required water drop penetration time was about 5 and 2 min, respectively. The infiltration rates were very low. The instability criteria, $V < K_s$ and $F < 0$, were satisfied in the above three experiments, and the wetting fronts indeed became fingered. The fingered flow patterns in the second and third horizons are shown in Fig. 6a and b, respectively. The wetting front in the third horizon was initially stable corresponding to the satisfied stability criteria $V > K_s$ and $F > 0$ as shown in Fig. 2c. Our experiments in the air-confined conditions indicated that soil air was not compressed due to very slow infiltration rate in the repellent sands. The flow patterns were almost the same as under the air-draining condition.

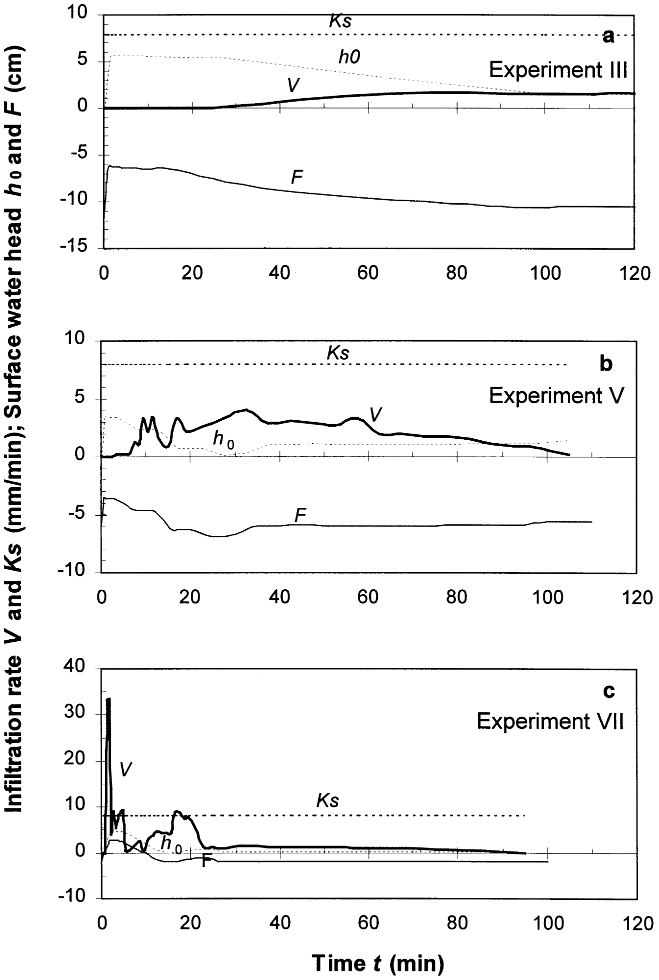

Fig. 2. Infiltration into the Ouddorp water-repellent sands: (a) the most repellent first horizon; (b) less repellent second horizon; and (c) least repellent third horizon (symbols are as defined for Fig. 1).

The experimental results indicate that infiltration into the repellent sands was very slow and fingered in contrary to high-rate and stable infiltration in the wettable sand. When soil air was entrapped and compressed, flow in both the wettable and repellent sands behaved similarly with low infiltration rate and fingered flow patterns.

4.3. Infiltration into layered repellent sands under low-ponding heads

The Ouddorp repellent sands were packed into the 2D chamber in a three-layer configuration. The most repellent sand (first horizon) was on the top 10 cm, the moderately repellent sand (second horizon) in the middle 20 cm, and the least repellent sand (third horizon) at the bottom 20 cm. For both the air-draining (experiment IX) and air-confined (experiment X) conditions under low-ponding depths varying from 2 to 3 cm, the repellent soil was extremely difficult to wet up. Water did not start infiltrating until 40 min after ponding as shown in Fig. 3. 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 (Fig. 7a) and three fingers in the

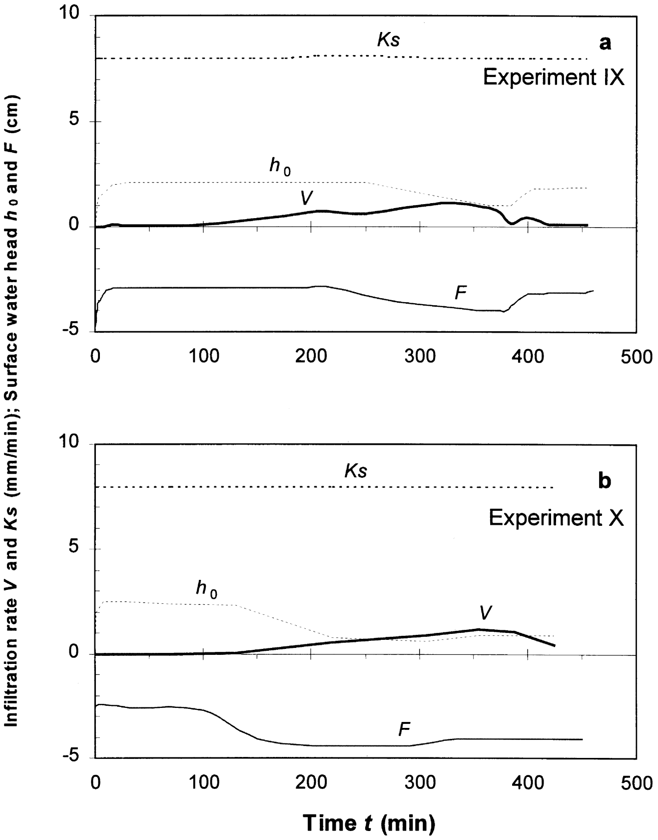

Fig. 3. Infiltration into layered Ouddorp water-repellent sands under low-ponding depths: (a) air-draining condition and (b) air-confined condition (symbols are as defined for Fig. 1).

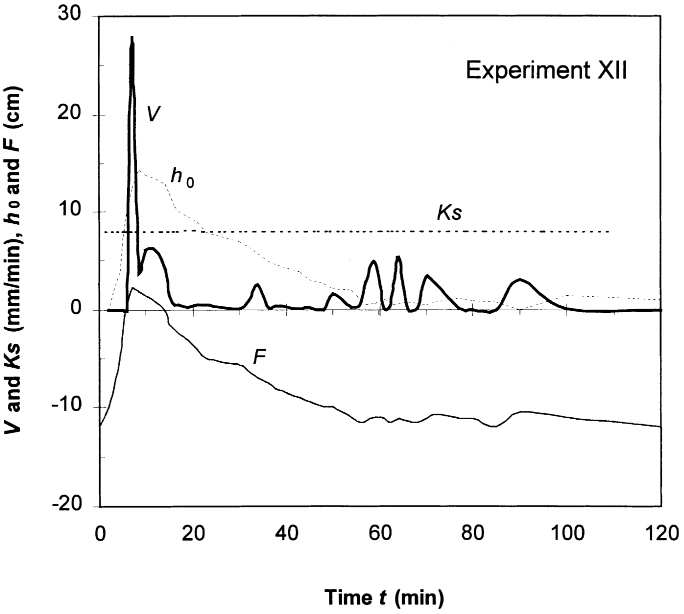

Fig. 4. Infiltration into layered Ouddorp water-repellent sands under high-ponding depths and the air-confined condition (symbols are as defined for Fig. 1).

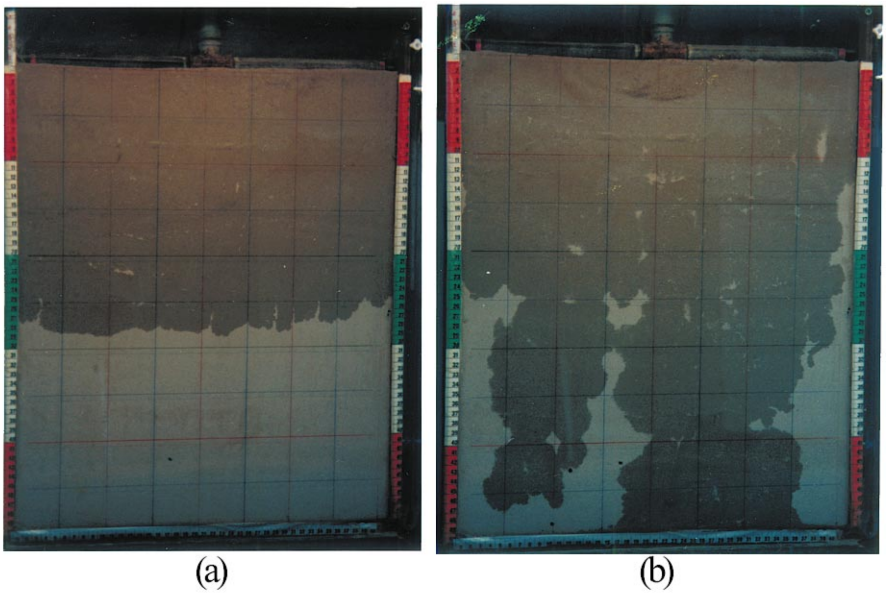

Fig. 5. Wetting front patterns during water infiltration into a wettable silicon sand: (a) stable flow with the air-draining condition (Fig. 1a, $t = 5$ min) and (b) unstable fingered flow with the air-confined condition (Fig. 1b, $t = 19$ min).

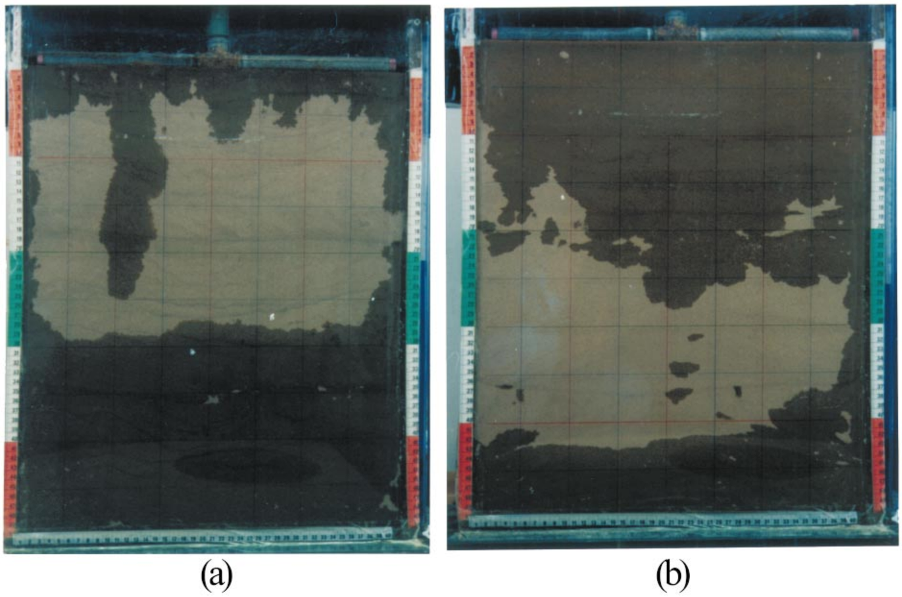

Fig. 6. Wetting front patterns during water infiltration into separate layers of Ouddorp water-repellent sands: (a) fingered flow in the second horizon repellent sand (Fig. 2b, $t = 50$ min) and (b) initially stable flow and subsequently fingered flow in the third horizon sand (Fig. 2c, $t = 20$ min).

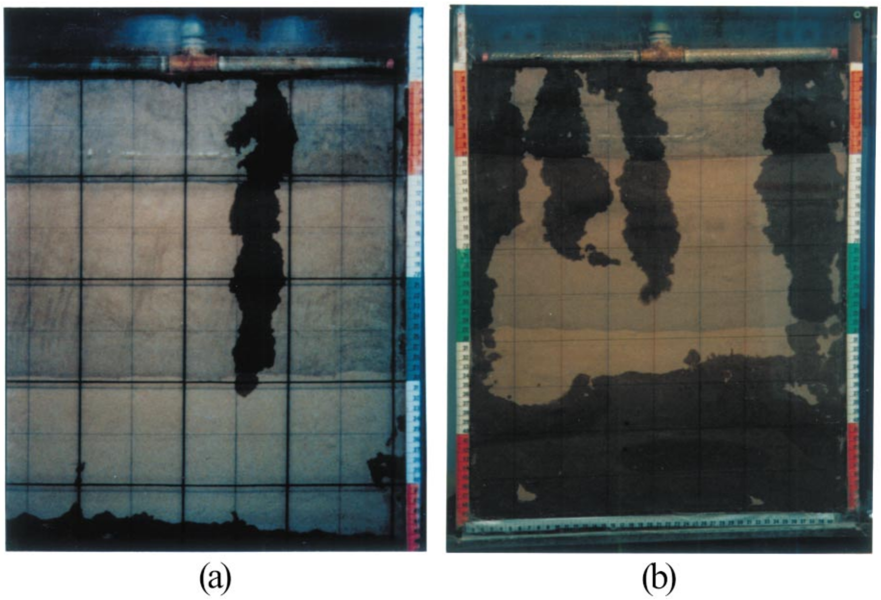

Fig. 7. Wetting front patterns during water infiltration into a three-layer configuration of Ouddorp water-repellent sands under the low-ponding condition: (a) fingered flow with the air-draining condition (Fig. 3a, $t = 190$ min) and (b) fingered flow with the air-confined condition (Fig. 3b, $t = 300$ min).

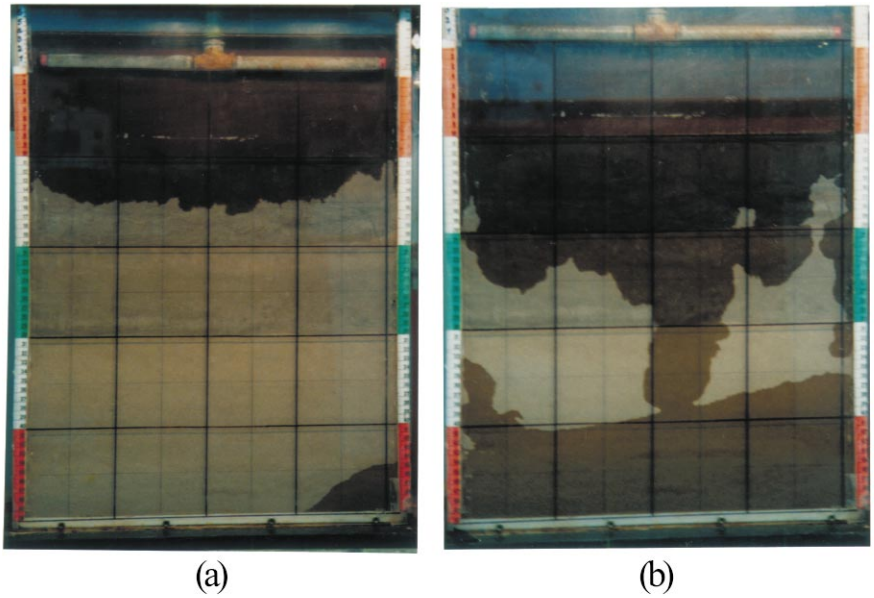

Fig. 8. Wetting front patterns during water infiltration into a three-layer configuration of Ouddorp water-repellent sands: (a) stable flow when the surface ponding depth $h_0 = 14$ cm, greater than $h_{we} = 12$ cm, the water-entry value of the repellent sand (Fig. 4, $t = 7$ min) and (b) fingered flow when $h_0 < h_{we}$ (Fig. 4, $t = 33$ min). The soil surface was 10 cm below the inverted T tube.

air-confined chamber (Fig. 7b). Due to the extremely low infiltration rate, soil air was not compressed before the edge flow reached the bottom. During the fast upward wetting, soil air in both chambers was slightly compressed. Air bubbles broke through a very thin layer of the wetted top layer and escaped into the open air.

4.4. Infiltration into layered repellent sands under high-ponding heads

For the above experiments the water-entry value ($h_{\mathrm{we}} = 12$ cm) of the top repellent sand was not exceeded, which resulted in a zero infiltration rate at the beginning of infiltration. In experiment XI and XII (Table 1), we applied a greater than 12 cm of ponding head at the soil surface to observe the effects of high ponding. The results of experiment XII are shown in Figs. 4 and 8. Infiltration started promptly at $t = 6$ min when the ponding depth h_0 exceeded 12 cm. The wetting front was stable for a short time between $t = 6$ and 9 min (Fig. 8a) when $h_0 > h_{\mathrm{we}}$, which is consistent with $V > K_{\mathrm{s}}$ and $F > 0$ for stable flow. As soon as h_0 was reduced below 12 cm at about $t = 10$ min, the wetting front became unstable and fingered as shown in Fig. 8b. In this case, the soil air entrapment between the waters at surface and bottom of the soil could have been compressed, which could have accelerated the occurrence of fingering. The unstable flow again corresponded well to the instability criteria $V < K_{\mathrm{s}}$ after $t = 9$ min and $F < 0$ after $t = 15$ min.

5. Discussions and conclusion

The initially dry repellent sands were difficult to wet. If the repellent sand was eventually wetted after a long time of wetting, the infiltration flow advanced through fingered paths, bypassing a large volume of soil in the top layer. In addition to this study conducted in the laboratory, there are many other studies that have also confirmed the occurrence of fingering in the field (e.g. Ritsema et al., 1993; Hendrickx et al., 1993; Dekker and Ritsema, 1994, 1995; Ritsema and Dekker, 1994, 1995). The size and speed of the fingered flow in repellent soils were successfully predicted by Wang et al. (1998b,c).

The infiltration rates in repellent sands were very slow. Fingering occurred if the surface ponding head h_0 was less than the soil water-entry value, h_{we}. However, the infiltration flow became stable if $h_0 > h_{\mathrm{we}}$. This principle was also found to be true for wettable sandy soils (Wang et al., 1998b). All of the observed unstable and stable flows were accurately predicted by the velocity criterion ($V < K_{\mathrm{S}}$) (Parlange and Hill, 1976) and the pressure criterion $F = h_0 - h_{\mathrm{we}} - h_{\mathrm{af}} < 0$ (Raats, 1973; Philip, 1975; Wang et al., 1998b). The findings here are significant for field water management in repellent soils. For example, the difficulties in wetting the repellent soils can be overcome by using the high-ponding surface irrigation methods (e.g. level-basin or deep furrow irrigation). The high-ponding methods will increase infiltration. However, since the surface water head will become negative after the cessation of infiltration, the pressure head criterion of $h_0 < h_{\mathrm{we}}$ can easily be satisfied, thus fingering will eventually occur during redistribution of infiltrated water.

Summarizing existing reports on the occurrence of unstable preferential flow, the individual or combined effects of air entrapment, soil layering, soil macropores, surface desaturation, and soil water repellency, are responsible for fingering in the field. With the unavoidable effect of surface desaturation (redistribution following infiltration), field infiltration and drainage cycles will more likely result in fingering. Further research is urgently needed to incorporate the unstable flow theory into simulation models, since unstable flow is an important mechanism for preferential contamination of groundwater systems.

References

Baker, R.S., Hillel, D., 1990. Laboratory tests of a theory of fingering during infiltration into layered soils. Soil Sci. Soc. Am. J. 54, 20–30.

Bond, R.D., 1969. The occurrence of water-repellent soils in Australia. In: Debano, L.F., Letey, J. (Eds.), Water Repellent Soils. Proceedings of the Symposium on Water Repellent Soils, Univ. Calif., Riverside.

Butters, G.L., Jury, W.A., Ernst, F.F., 1989. Field scale transport of bromide in an unsaturated soil: 1. Experimental methodology and results. Water Resour. Res. 25, 1575–1581.

Chuoke, R.L., van Meurs, P., van der Poel, C., 1959. The instability of slow, immiscible, viscous liquid–liquid displacements in permeable media. Trans. Am. Inst. Min. Metall. Pet. Eng. 216, 188–194.

Clothier, B.E., White, I., Hamilton, G.J., 1981. Constant-rate rainfall infiltration: field experiment. Soil Sci. Soc. Am. J. 45, 245–249.

DeBano, L.F., 1969. Water repellent soils: a worldwide concern in management of soil and vegetation. Agric. Sci. Rev. 7 (2), 11–18.

Dekker, L.W., Ritsema, C.J., 1994. How water moves in a water repellent sandy soil: 1. Potential and actual water repellency. Water Resour. Res. 30, 2507–2517.

Dekker, L.W., Ritsema, C.J., 1995. Fingerlike wetting patterns in two water-repellent loam soils. J. Environ. Qual. 24, 324–333.

Diment, G.A., Watson, K.K., 1985. Stability analysis of water movement in unsaturated porous materials, 3: Experimental studies. Water Resour. Res. 21, 979–984.

Flury, M., Flühler, H., Jury, W.A., Leuenberger, J., 1994. Susceptibility of soils to preferential flow of water: a field study. Water Resour. Res. 30, 1945–1954.

Ghodrati, M., Jury, W.A., 1990. A field study using dyes to characterize preferential flow of water. Soil Sci. Soc. Am. J. 54, 1558–1563.

Ghodrati, M., Jury, W.A., 1992. A field study of the effects of soil structure and irrigation method on preferential flow of pesticides in unsaturated soil. J. Contam. Hydrol. 11, 101–125.

Glass, R.J., Parlange, J.-Y, Steenhuis, T.S., 1991. Immiscible displacement in porous media: stability analysis of three-dimensional, axisymmetric disturbances with application to gravity driven wetting front instability. Water Resour. Res. 27, 1947–1956.

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

Glass, R.J., Steenhuis, T.S., Parlange, J.-Y., 1989. Wetting front instability, 2. Experimental determination of relationships between system parameters and two dimensional unstable flow field behavior in initially dry porous media. Water Resour. Res. 25, 1195–1207.

Held, R.J., Illangasekare, T.H., 1995. Fingering of dense nonaqueous phase liquids in porous media 1. Experimental investigation. Water Resour. Res. 31, 1213–1222.

Hendrickx, J.M.H., Dekker, L.W., Boersma, O.H., 1993. Unstable wetting fronts in water repellent field soils. J. Environ. Qual. 22, 109–118.

Hill, D.E., Parlange, J.-Y., 1972. Wetting front instability in layered soils. Soil Sci. Soc. Am. Proc. 36, 692–702.

Hillel, D., Baker, R.S., 1988. A descriptive theory of fingering during infiltration into layered soils. Soil Sci. 146, 51–56.

Holzhey, C.S, 1969. Water repellent soils in Southern California. In: DeBano, L.F., Letey, J. (Eds.), Water Repellent Soils. Proceedings of the Symposium on Water Repellent Soils, Univ. Calif., Riverside, pp. 31–41.

Jamison, V.C., 1969. Wetting resistance under citrus trees in Florida, In: DeBano, L.F., Letey, J. (Eds.), Water Repellent Soils. Proceedings of the Symposium on Water Repellent Soils, Univ. Calif., Riverside, pp. 9–15.

Jury, W.A., Flühler, H., 1992. Transport of chemicals through soil: mechanism, models, and field applications. Adv. Agron. 47, 141–201.

Jury, W.A., Elabd, H., Resketo, M., 1986. Field study of napropamide through unsaturated soil. Water Resour. Res. 5, 749–755.

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

Letey, J., 1969. Measurement of contact angle, water drop penetration time, and critical surface tension, In: DeBano, L.F., Letey, J. (Eds.), Water Repellent Soils, Proceedings of the Symposium on Water Repellent Soils, Univ. Calif., Riverside, pp. 43–47.

Letey, J., Osborn J.F., Valoras, N., 1975. Soil water repellency and the use of nonionic surfacants. Contribution No 154, Univ. Calif., Davis, 85 pp.

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

Nieber, J.L., 1996. Modeling finger development and persistence in initially dry porous media. Geoderma 70, 207–229.

Parlange, J.Y., Hill, D.E., 1976. Theoretical analysis of wetting front instability in soils. Soil Sci. 122, 236–239.

Perroux, K.M., White, I., 1988. Designs for disc permeameters. Soil Sci. Soc. Am. J. 52, 1205–1215.

Philip, J.R., 1975. Stability analysis of infiltration. Soil Sci. Soc. Am. Proc. 39, 1042–1049.

Raats, P.A.C., 1973. Unstable wetting fronts in uniform and non-uniform soils. Soil Sci. Soc. Am. Proc. 37, 681–685.

Ritsema, C.J., Dekker, L.W., 1994. How water moves in a water repellent sandy soil: 2. Dynamics of fingered flow. Water Resour. Res. 30, 2519–2531.

Ritsema, C.J., Dekker, L.W., 1995. Distribution flow: a general process in the top layer of water repellent soils. Water Resour. Res. 31, 1187–1200.

Ritsema, C.J., Dekker, L.W., Hendrickx, J.M.H., Hamminga, W., 1993. Preferential flow mechanism in a water repellent sandy soil. Water Resour. Res. 29, 2183–2193.

Roth, K., Jury, W.A., Fluhler, H., Attinger, W., 1991. Tranport of chloride through an unsaturated field soil. Water Resour. Res. 27, 2533–2541.

Saffman, P.G., Taylor, S.G., 1958. The penetration of fluid into a porous medium or Hele–Shaw cell containing a more viscous liquid. Proc. R. Soc. Ser. A 245, 312–329.

Selker, J.S., Steenhuis, T.S., Parlange, J.-Y., 1992. Wetting front instability in homogeneous sandy soils under continuous infiltration. Soil Sci. Soc. Am. J. 56, 1346–1350.

Starr, J.L., DeRoo, H.C., Frink, C.R., Parlange, J.-Y., 1978. Leaching characteristics of a layered field soil. Soil Sci. Soc. Am. J. 42, 386–391.

Starr, J.L., Parlange, J.-Y., Frink, C.R., 1986. Water and chloride movement through a layered field soil. Soil Sci. Soc. Am. J. 50, 1384–1390.

Van't Woudt, B.D, 1969. Resistance to wetting under tropical and subtropical conditions, In: DeBano, L.F., Letey, J. (Eds.), Water Repellent Soils. Proceedings of the Symposium on Water Repellent Soils. Univ. Calif., Riverside, p. 7.

Wang, Z., Feyen, J., van Genuchten, M.Th., Nielsen, N.R., 1998a. Air entrapment effects on infiltration rate and flow instability. Water Resour. Res. 34, 213–222.

Wang, Z., Feyen, J., Ritsema, C.J., 1998b. Susceptibility and predictability of conditions for preferential flow. Water Resour. Res. 34, 2169–2182.

Wang, Z., Feyen, J., Elrick, D.E., 1998c. Prediction of fingering in porous media. Water Resour. Res. 34, 2183–2190.

Wang, Z., Wu, L., Wu, Q.J., 2000. Water-entry value as an alternative indicator of soil water-repellency and wettability. J. Hydro. 231–232, 76–83.

White, I., Colombera, P.M., Philip, J.R., 1976. Experimental studies of wetting front instability induced by sudden changes of pressure gradient. Soil Sci. Soc. Am. Proc. 40, 824–829.

Yao, T.-M., Hendrickx, J.M.H., 1996. Stability of wetting fronts in dry homogeneous soils under low infiltration rates. Soil Sci. Soc. Am. J. 60, 20–28.