Unstable Water Flow in a Layered Soil: II. Effects of an Unstable Water-Repellent Layer

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ABSTRACT

Water repellent soils are found throughout the world and can exhibit significantly different water flow characteristics as compared to a wettable soil. The purpose of the study was to determine the significance of the stability of the water repellency on the development of unstable water flow below a water repellent layer. Unstable water-repellent soil refers to a soil whose degree of repellency changes with time after contact with water. Experiments were conducted in a specially built rectangular chamber where wetting front patterns could be observed through a Plexiglas sheet. The experiments were done on water repellent sand layers that were treated to create water drop penetration time (WDPT) values of 1, 10, and 150 min. The WDPT of the layer and the ratio ($h_o + L$)/h_p were important in the development of fingers, where h_o is the depth of ponded water at the soil surface, L is the depth of the water repellent layer and h_p is the water entry pressure head of the water repellent layer. For low WDPT (1 min) no fingers formed. As the WDPT increased, the tendency for finger formation also increased. The medium WDPT (10 min) layer caused finger formation, however, the fingers broadened and converged after continued flow and an almost uniform wetting front eventually developed. The combination of a high WDPT (150 min) and ($h_o + L$)/h_p <1 produced the most dramatic and persistent fingering. The finger development across the layer and the flux through the layer was found to be a function of time. Water repellency at the soil surface has the greatest impact on infiltration because water depth may not be sufficient to overcome the water entry pressure and runoff would decrease the time of exposure to water to overcome unstable water repellency.

Water repellency greatly affects water flow into and through soils. Unstable or *finger* flow has been observed to occur in water repellent soil systems (Hendrickx et al., 1993; Bauters et al., 1998; Wang et al., 1998; Carrillo et al., 2000, this issue) Carrillo et al. (2000, this issue) determined in a laboratory study that the formation of finger water flow was related to the ratio $(h_o + L)/h_p$, where h_o is the depth of ponded water, L is the depth to the water repellent layer ($L = 0$ for the soil surface being water repellent), and h_p is the water entry pressure. Water did not penetrate the stable water-repellent material if the ratio was <1, finger flow occurred when the ratio was in the range of 1.0 to 1.5, and uniform flow occurred when the ratio was >1.5.

The WDPT is a common procedure for measuring water repellency. If the initial soil water contact angle is <90 degrees, a water drop placed on the soil will spontaneously enter the soil. A water drop will not penetrate the soil if the contact angle is >90 degrees; and if the repellency is stable, the water will remain on the soil surface indefinitely. However, typically the water drop penetrates the soil after some time of contact suggesting that the repellency is not completely stable. The time the water remains on the surface reflects the effects of a combination of initial degree of water repellency and the stability of the repellency.

Carrillo et al. (2000) treated sand with octadecylamine to create a stable water-repellent system with a WDPT of infinite time. This approach eliminated the confounding time effects associated with unstable water-repellent systems and allowed the basic mechanism associated with finger formation to be identified. However, since most natural soils exhibit a finite value of WDPT (unstable water repellency) additional research was conducted on sand treated in a manner to create unstable water repellency. This paper reports the results of this research.

MATERIALS AND METHODS

The same procedures as described in Carrillo et al. (2000) were used in this study and they will only be summarized here. Coachella sand (mixed, thermic Typic Xeropsamment) obtained from the University of California Coachella Valley Research Station was sieved and the 0.05- to 2.0-mm size fraction was used in the experiments. The sand was washed to remove fine particulates.

Treating the sand with solvent extracts of peat moss using ethanol or benzyl alcohol produced unstable water-repellent material. The extracts were made by mixing 200 g of peat with 1.5 L of either solvent. The peat–solvent mixtures were shaken for 24 h and then filtered through a number 3 Whatman filter. One thousand grams of sand were mixed with 250 and 500 mL of the filtered ethanol extract, and with 250 mL of the filtered benzyl alcohol extract. The ethanol extract-treated sands were dried under the hood for 24 h and the benzyl alcohol treatments were dried in a 100°C oven for 72 h. The WDPT was measured by placing 10 g of the sand in an agar plate and leveling the sand. Then three drops of water were placed on the surface and the time for each drop to infiltrate was recorded. The average measured value was used as the WDPT of the sand. The water entry pressure, h_p, was measured using the technique of Carrillo et al. (1999). Briefly the method consisted of measuring the height of the water which could be retained on the surface before instantaneous infiltration. The initial contact angle, θ_{in}, was measured by using the following relationship (Carrillo et al., 1999).

$$\cos\theta_{in} = [(\gamma_{ND}/\gamma_w)^{1/2} - 1] \quad [1]$$

where θ_{in} refers to the initial contact angle between the water and the solid prior to interactions that change the contact angle with time after contact with water, γ_{ND} is the surface tension of the liquid that would have a contact angle with the solid equal to 90°, and γ_w is the surface tension of water.

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Abbreviations: γ_{ND}, 90° surface tension; WDPT, water drop penetration time.

The 90° surface tension (γ_{ND}) measurement was made by first mixing a series of aqueous ethanol solutions to create a range of surface tensions. A plot of percent ethanol vs. surface tension was produced by measuring the surface tension of each mixture using a surface tensiomat. Drops of each mixture were place on the top of each sand treatment and the time of infiltration noted. The surface tension of the mixture that had a five second infiltration time was taken as γ_{ND}, as specified by Watson and Letey (1970).

The chamber used to observe water flow through the sand was 52 cm wide, 2 cm deep and 61 cm tall and built from 0.64-cm (1/4 in.) Plexiglas so that the water flow could be observed. The bottom of the chamber was constructed from fine wire screen mounted on a rigid perforated plate. This bottom allowed air to escape as well as providing mechanical support. Uniform packing was achieved by using a *soil randomizer* (Glass et al., 1989). A 1-cm water-repellent layer was added at specific depths using the soil randomizer. The final top layer was added and packed and any excess sand removed with the vacuum to achieve the desired level.

The chamber was leveled. Water was applied rapidly and uniformly by placing water in a specially built tray whose width was equal to that of the chamber. The lip of the tray was placed over the front part of the chamber and the water was rapidly poured into the chamber. A constant head was maintained by applying water to the top of the chamber with a pressurized water application system.

Water movement through the sand was recorded using a Panasonic video camera. The video images were digitized using a Jandel Imaging Analysis System and analyzed for finger width and velocity. The time for water to penetrate the water repellent layer after it reached the layer, t_p, was determined for each case. The flow rate into the chamber was measured by a flow meter connected in line to the pressurized water application system. The flow rate data were collected by connecting the output signal of the flow meter to a Datalogger data acquisition system and downloaded to a personal computer for storage.

The following variables were investigated for their effects on finger formation: (i) WDPT's of 1.0 (low), 10 (medium), and 150 min (high); (ii) hydrophobic layer depth, L, of 0 and 3 cm; and (iii) depth of ponded water, h_o, values between 2.5 and 5 cm water.

RESULTS AND DISCUSSION

A summary of the experiments and the values for h_o, L, h_p, t_p, θ_{in}, and WDPT for each experiment are presented in Table 1. Note that an increase in the WDPT is associated with an increase in h_p and θ_{in}. The initial repellency is characterized by θ_{in} and the WDPT is a measure of the stability of the repellency. The WDPT and the ratio $(h_o + L)/h_p$ had a profound influence on t_p and on the degree of finger formation.

Table 1. Summary of experiments (Expt): h_o is ponded water depth, L is depth to water repellent layer, h_p is the water entry pressure, θ_{in} is the initial soil–water contact angle, WDPT is the water drop penetration time, and t_p is the time for water to penetrate the water repellent layer.

Expt. no.	h_o	L	h_p	θ_{in} degrees	WDPT	t_p	$(h_o + L)/h_p$	Figure
	——	cm	——		min	s		
1	1	0	2.5	96	1	0	0.4	
2	2	3	2.5	96	1	0	2.0	
3	2.5	0	4.0	100	10	35	0.62	2a
4	5.0	0	4.0	100	10	5	1.25	
5	2.0	3	4.0	100	10	8	1.25	1a
6	3.0	3	4.0	100	10	3	1.5	
7	2.5	0	4.8	102	150	352	0.52	2b
8	5.0	0	4.8	102	150	48	1.04	3a
9	2.0	3	4.8	102	150	40	1.04	3b
10	3.0	3	4.8	102	150	6	1.25	1b

Figures 1, 2, and 3 show fingers forming and water flowing with time. A comparison between water repellent layers that had a WDPT of 10 and 150 min with a $(h_o + L)/h_p$ value of 1.25 is illustrated in Fig. 1. Although the soils had quite large WDPT values, the water pressure head was sufficient to cause the water to penetrate the repellent layer in <10 s for both materials (Table 1). In both cases the water initially penetrated the water repellent layer in discrete locations creating fingers. However, the wetting front became more uniform with time and depth for the medium WDPT treatment. Finger formation was persistent with time and depth for the high WDPT treatment.

Water did not penetrate a stable water repellent layer

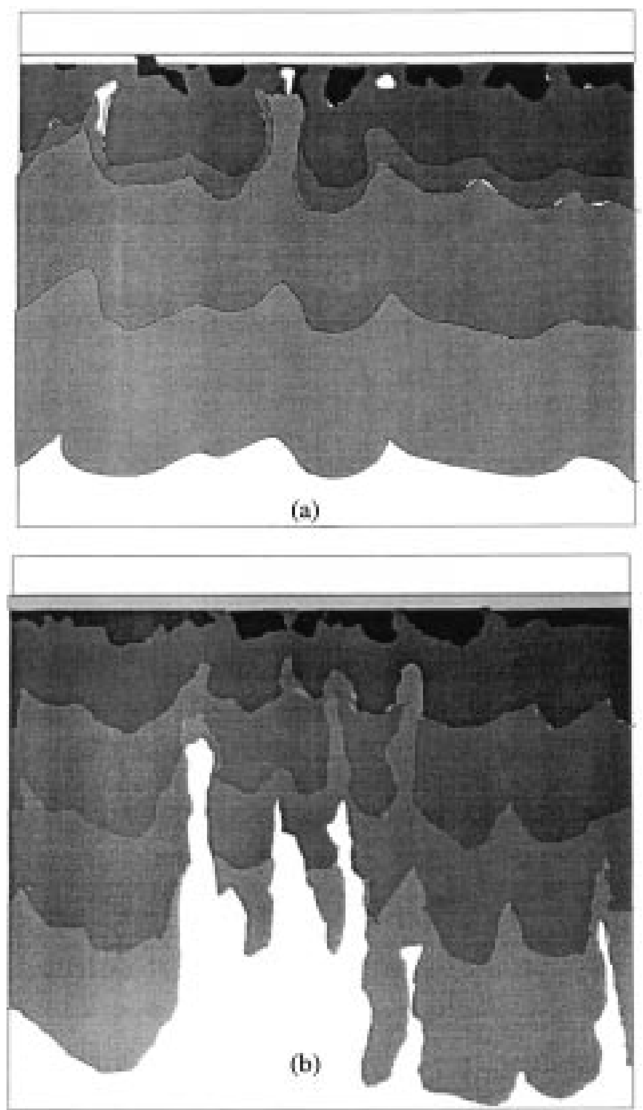

Fig. 1. Wetting patterns below the water repellent layer at different times for $(h_o + L)/h_p$ equal to 1.25 and water drop penetration time (WDPT) equal to 10 min (a) and WDPT equal to 150 min (b). Lighter shades indicate later times.

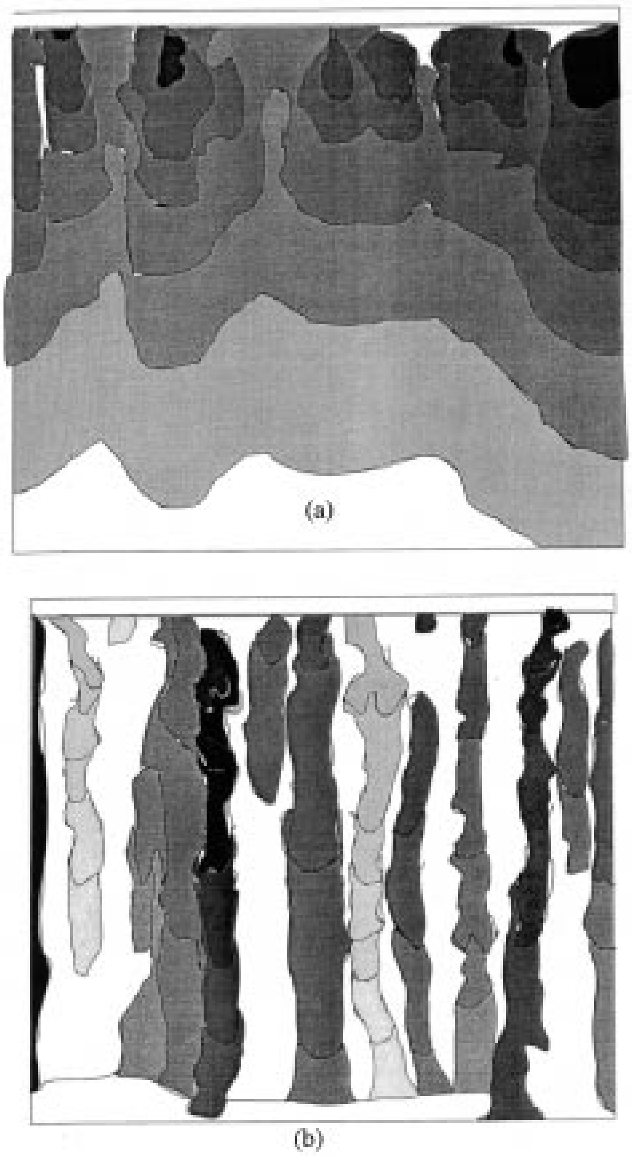

Fig. 2. Wetting patterns below the water repellent layer at different times for $(h_o + L)/h_p$ equal to 0.625 and water drop penetration time (WDPT) equal to 10 min (a) and $(h_o + L)/h_p$ equal to 0.52 and WDPT equal to 150 min (b). Lighter shades indicate later times.

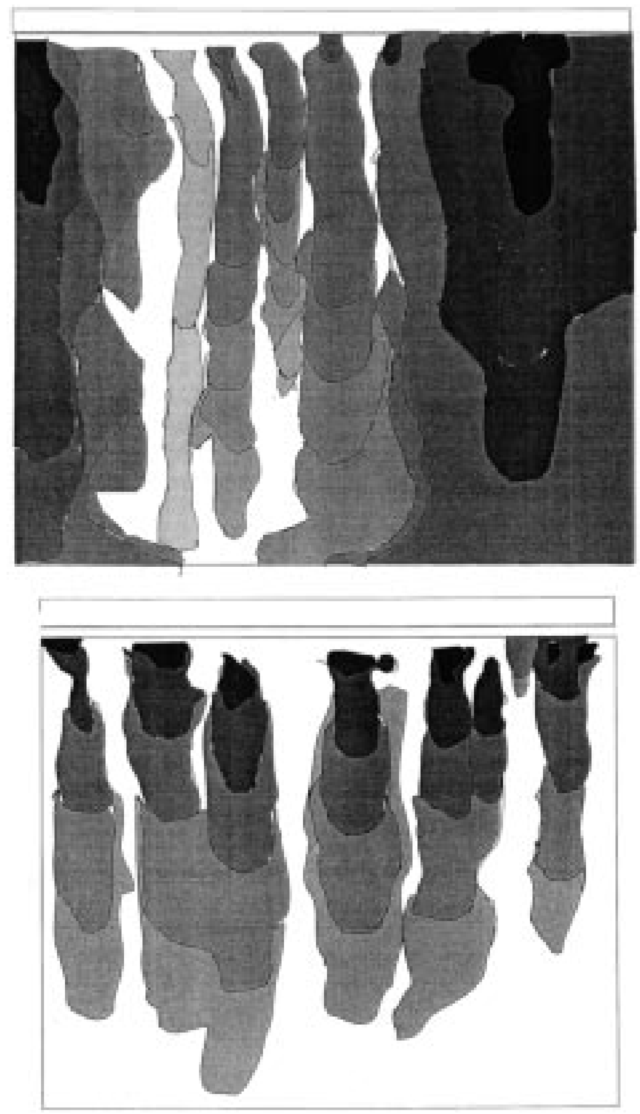

Fig. 3. Wetting patterns below the water repellent layer at different times for $(h_o + L)/h_p$ equal to 1.04 and water drop penetration time (WDPT) equal to 150 min (a) $L = 0$ cm and (b) $L = 3$ cm. Lighter shades indicate later times.

when $(h_o + L)/h_p$ was <1 (Carrillo et al., 2000, this issue). However, water did ultimately penetrate an unstable water repellent layer when $(h_o + L)/h_p$ was as low as 0.52 (Table 1). Water penetration was delayed by 35 s in the medium WDPT treatment when $(h_o + L)/h_p$ was as low as 0.62 and delayed by 352 s in the high WDPT treatment when $(h_o + L)/h_p$ equaled 0.52. Decreasing values of $(h_o + L)/h_p$ resulted in increasing amount of time for the water to penetrate the water repellent layer.

The soil profile wetting patterns are illustrated in Fig. 2 for the two water repellent materials when $(h_o + L)/h_p$ was equal to 0.62 for the medium WDPT treatment and $(h_o + L)/h_p$ was equal to 0.52 for the high WDPT treatment. In both cases water penetrated the repellent layer at discrete points at different times. However, with time the fingers broadened and merged with each other for the medium WDPT treatment and wetting front became almost uniform. In contrast the fingers formed on the high WDPT treatment remained small and each finger moved straight down through the underlying wettable material. Fingers developed at different times at different locations.

Figure 3 illustrates the wetting pattern for the high WDPT treatment and $(h_o + L)/h_p$ equal to 1.04. Figure 3a is for h_o equal to 5 and L equal to 0 cm whereas Fig. 3b is for h_o equal to 2 and L equals to 3 cm. Approximately one-half the cross section of the profile was wet uniformity and the other half had distinct fingers when the water repellent layer was on the surface (Fig. 3a). The entire cross-section of the profile demonstrated distinct finger formation when the repellent layer was buried (Fig. 3b).

A comparison of Fig. 1b, 2b, and 3b reveals that increasing the value of $(h_o + L)/h_p$ caused increasing thick-

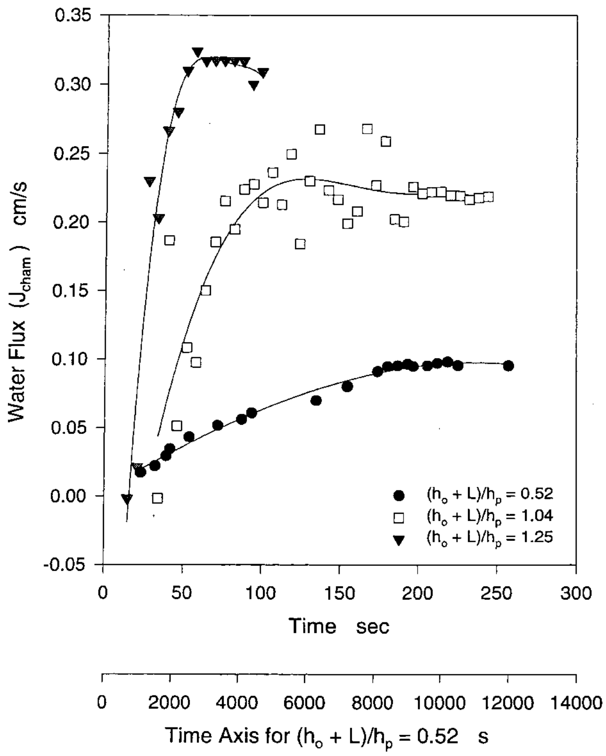

Fig. 4. Water flux in the chamber, J_{cham}, for water drop penetration time (WDPT) = 150 min. (Note the different time axis for the $(h_o + L)/h_p = 0.52$ data.)

ness of the fingers for the high WDPT treatment. Increasing the value of $(h_o + L)/h_p$ had relatively little effect on the resultant flow pattern in the medium WDPT treatment (Fig. 1a and 1b).

There are some general conclusions that can be made from these experiments. (i) The stability of the particle coating (reflected by the WDPT values) had an influence on the development of fingered flow, (ii) fingers formed at different times, in contrast to a stable water-repellent layer where all the fingers tended to form at the same time, (iii) when $(h_o + L)$ was less than h_p water initially penetrated at discrete spots, as time progressed a larger fraction of area was wetted, but some zones never were wetted, and (iv) lateral flow below the water repellent layer diminished the fingering effect with depth and time for the medium WDPT treatment.

The water fluxes in the chamber as a function of time for experiments with the buried high WDPT treatment layer are illustrated in Fig. 4. Note that the flux increased with time and then plateaued. The rate of the flux increase and the steady state flux value both increased at $(h_o + L)/h_p$ increased consistent with the wetting patterns illustrated in Fig. 1, 2, and 3. As more and wider fingers formed in the sublayer, the flux through the chamber increased. (Note the different time axis for the data representing $(h_o + L)/h_p$ equal to 0.52.)

The experiments reported in this paper indicate that an unstable water-repellent layer can cause fingers to develop in a wettable layer beneath it. The WDPT of the layer as well as the ratio of $(h_o + L)/h_p$ of the water repellent sand were important in the development of fingers. In low WDPT (1 min) soil, no fingers were formed. As the WDPT increased the tendency for finger formation also increased. The WDPT values were dependent on h_p values. Treatment of the sand to induce increased WDPT values also induced increased h_p values. However, the effects of h_p can be scaled by the ratio of $(h_o + L)/h_p$ to more clearly identify the effects of WDPT. The combination of a WDPT on the order of hours and a ratio $(h_o + L)/h_p < 1$ produced the most dramatic and persistent fingering. The finger development across the layer was found to be a function of time. The flux through the layer was also found to increase with time for constant boundary condition. This caused the finger width and velocity to increase as the fingers moved down the chamber.

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