Unstable Water Flow in a Layered Soil: I. Effects of a Stable Water-Repellent Layer

M. L. K. Carrillo, J. Letey,* and S. R. Yates

ABSTRACT

The development of preferential water flow in a soil profile can cause accelerated movement of pollutants to the groundwater thus reducing groundwater quality. This study investigated the effects of a stable water-repellent soil layer on the development of unstable water flow in a homogenous profile. Stable water-repellent soil is defined as one whose degree of water repellency does not change with time after contact with water. The effects of water entry pressure (h_p), water-repellent layer depth (L) and depth of ponded water at the soil surface (h_o) on the development of unstable flow were investigated using homogenous coarse sand packed into a specially built rectangular chamber. The hydraulic conductivity of the water repellent soil was also measured as a function of h_p and h_o in a separate experiment using the constant head method. The hydraulic conductivity and the water content of the water repellent soil increased as h_o/h_p increased. No water penetrated the water repellent layer for values of $(h_o + L)/h_p < 1$, unstable flow developed for values between 1 and 1.5 and a stable front developed for values > 1.5. The conclusion is that stable flow occurred when the water flux through the water repellent layer exceeded the saturated hydraulic conductivity of the underlying wettable layer. The water flux through the water repellent layer was a function of the hydraulic conductivity of the water repellent layer which increased as h_o/h_p increased.

ACCURATE PREDICTION OF WATER AND CHEMICAL TRANSPORT through the vadose zone requires an understanding of all the fundamental mechanisms which impact the transport. This subject is important when chemicals are applied or discharged to land because groundwater quality can be affected. Chemical transport is linked to water movement through the soil matrix. Traditionally, water and chemicals were considered to move uniformly through the soil matrix and movement could be described using a convection–dispersion framework. However, movement of a fraction of the applied chemicals towards the groundwater has been observed to be more rapid than predicted by the convection–dispersion model. The term *preferential flow* has been used to describe this phenomena and it has been shown to be the rule rather than the exception in a wide variety of soils (Flury et al., 1994).

Preferential flow is a term that can have different connotations. Ambiguity arises because of different dimensional scales of consideration ranging from pore size dimension to several centimeters. Different processes can induce preferential flow depending on soil structure and inlet boundary conditions. Preferential flow can originate from cracks and macropores in the soil profile (Beven and Germann, 1982), textural discontinuities (Kung, 1990), or from unstable wetting fronts (Raats, 1973; Philip, 1975).

The instability of a dynamic wetting front is defined as the unconstrained growth of randomly occurring small perturbations to the wetting front. Unstable wetting fronts can be caused by an increase in hydraulic conductivity with depth, such as in a fine layer overlying a coarse layer (Hill and Parlange, 1972; Glass et al., 1989; Glass et al., 1990; Baker and Hillel, 1990). Others have shown that unstable flow can occur in homogenous profiles (White et al., 1976). In all of these systems, infiltration was assumed to follow the Green–Ampt model.

Philip (1975), using linear stability analysis, concluded that the fundamental criterion for instability is that the water pressure gradient immediately behind the wetting front opposes the flow for a soil that obeys the Green–Ampt infiltration model. Thus, the criterion for stability reduces to whether this gradient is positive or negative. Raats (1973) noted that the stability of a wetting front depended on the rate of change of the wetting front velocity with depth to the wetting front. Instability is maintained when the velocity increases with depth and tends to disappear when the velocity decreases with depth.

Hillel and Baker (1988) proposed that instabilities arise whenever the hydraulic conductivity of the underlying layer at the water-entry suction $K(y_e)$, is greater than the flow rate, Q, through the top layer. This idea is similar to Saffman and Taylor (1958) model in which they state that if Q is less than K_{sat} of the underlying layer, unstable flow will develop.

There is field evidence that a water repellent layer can induce preferential flow through a soil profile (Hendrickx et al., 1988, 1993; Ritsema et al., 1993; DeBano, 1971; Burcar et al., 1994). Field studies revealed that solutes traveled faster to the groundwater in water repellent soils than in wettable soils (Hendrickx et al., 1993; Ritsema et al., 1993). These authors concluded that unstable flow was the main cause for the accelerated movement of solutes to the groundwater in the water repellent systems.

This paper investigates wetting front instability formation caused by a stable water repellent layer located at the surface or within the soil profile. A stable water-repellent layer is defined as one where the degree of repellency does not change after contact with water. A water drop placed on the soil never penetrates the soil. Hendrickx et al. (1993), Bauters et al. (1998) and Wang et al. (1998) also investigated preferential flow in water repellent materials. This subject has received relatively little research attention even though it has been impli-

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Abbreviations: WDPT, water drop penetration time.

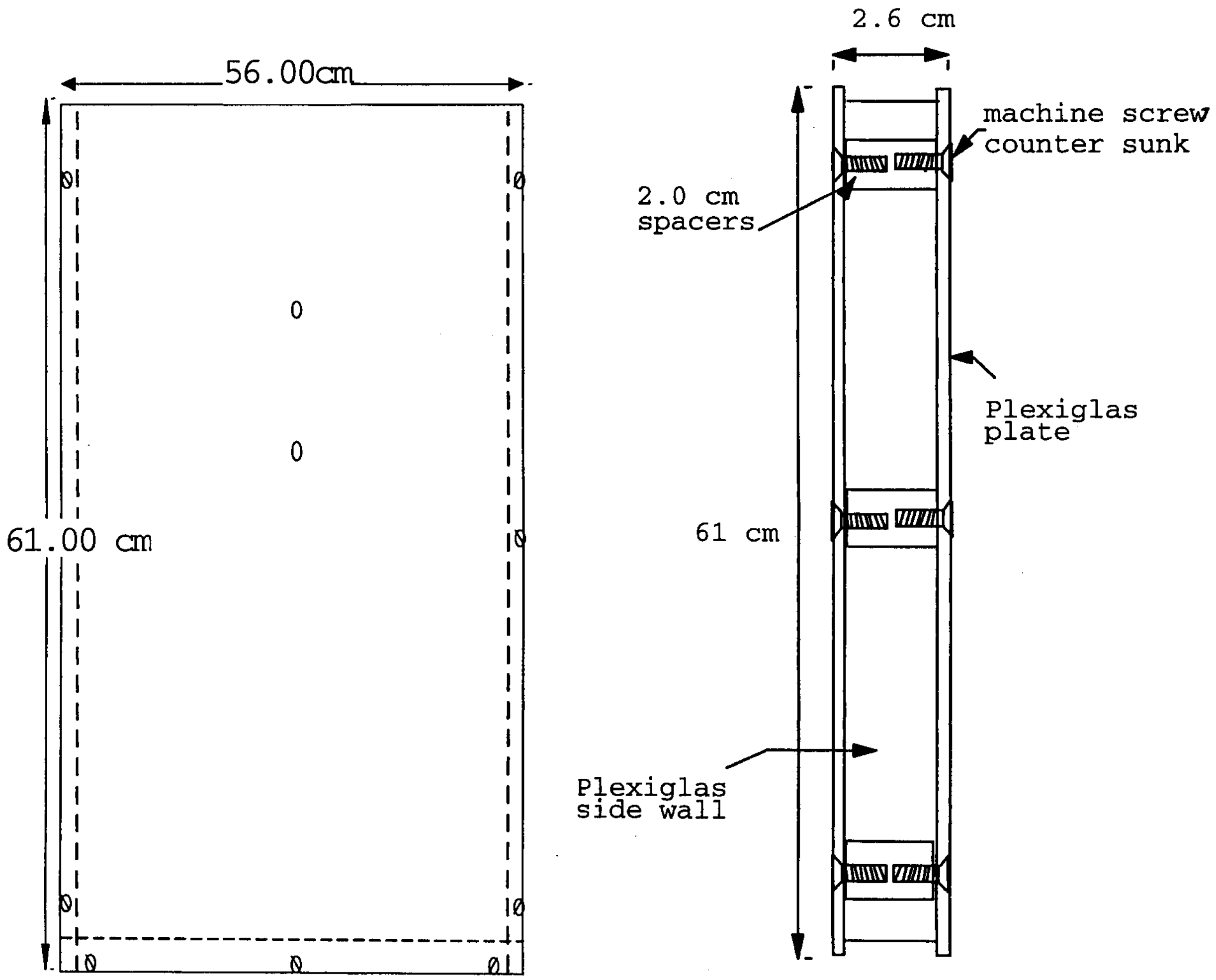

Fig. 1. Infiltration chamber front and side view.

cated as the leading cause of preferential flow in dry surface soils high in organic matter (Jury and Roth, 1990) and in structureless sandy soils (Ritsema et al., 1993).

The objectives of the research were to quantify the effects of water entry pressure of a water repellent soil, depth of water repellent layer and water flow boundary conditions on the development of unstable flow. This research will lead to a better understanding of the consequences of land disposal of organic water, or other practices which may induce water repellency, on water and chemical transport through soil.

MATERIALS AND METHODS

Infiltration Chamber

Figure 1 shows the front and end view of the chamber used to observe water flow through a slab of repacked soil material. The front and back plates were constructed of 0.64 cm (1/4 in.) Plexiglas. Grooves were cut into both plates to a depth of 0.3 cm approximately 2 cm from the right and left sides of the plate and used to secure the end walls. The end walls were constructed of 0.3 cm (1/8 in.) Plexiglas and were 2.5-cm wide. A 0.3-cm-deep groove cut into the bottom of both plates was used to secure the placement of the chamber bottom. The chamber bottom was constructed of 60 mesh stainless steel screen mounted on a 0.16-cm thick perforated metal plate to allow air to escape from the chamber and provide mechanical support.

The chamber was assembled by first mounting 2-cm thick by 2-cm long by 1-cm wide plastic spacers onto the back plate using 1.27-cm (1/2 in.) machine screws. The plate was then laid flat and the end walls snapped into the grooves. Rope caulk was placed at the intersection of the back plate and the end walls to prevent water from bypassing the soil. The grooves in the front plate were filled with rope caulk and the front plate placed on top of the back assembly. The front and back plates were fastened together using 1.27-cm (1/2 in.) machine screws. The front and back of the chamber were supported by a steel frame made from 2.54-cm by 0.3-cm angle iron. Bowing of the Plexiglas plates was minimized by placing metal cross-members along the front and back of the chamber. The chamber was maintained upright and level by a holding frame constructed from wood and aluminum brackets. The inside chamber walls were sprayed with a Teflon dry film lubricant before each packing to prevent water from preferentially flowing down the container wall.

Sand Preparation

Coachella sand (mixed, thermic Typic Xeropsamment) from the top 10 cm of the soil profile was obtained from the University of California Coachella Valley Research Station. The sand was sieved and the material between 2 and 0.05 mm was used for the experiments. The sand was rinsed with tap water until the rinse water was clear. Then the sand was washed with a detergent solution and rinsed 20 times with tap water and then 20 times with distilled water. The sand was dried at 70°C and stored until used.

Water Repellent Sand Preparation

The water entry pressure, h_p, is defined as the pressure necessary to force water into a water repellent porous media. Treatments were applied which resulted in h_p values of 4.0 and 8.1 cm H_2O. Sand treatment consisted of mixing 2.5 kg of clean, dry sand with 2.0 L of distilled water containing either 6.5 g (for $h_p = 4.0$) or 12 g (for $h_p = 8.1$) of octadecylamine in a large V-mixer. After 24 h of mixing the mixture was placed in an 70°C oven for 48 h. Any excess octadecylamine was removed by rinsing the treated sand twice with distilled water and then drying the sand in the oven for 24 h. This treatment produced a stable water repellency that did not change with time after contact with water. Water drops placed on the surface did not penetrate the sand, but if left long enough they evaporated. The water entry pressure 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 it infiltrated.

Packing Procedure

Various researchers (Glass et al., 1988; Hill and Parlange, 1972; White et al., 1976) showed that heterogeneities from segregation of sand particle size during packing of chambers produce misleading results. In addition to uniformity, the sand must also be packed sufficiently dense to prevent further consolidation when wetted. To achieve this packing, an extension called a *soil randomizer* (Glass et al., 1989) was built. The soil randomizer had the same dimensions as the chamber except that it contained two coarse wire mesh grates at 10 and 20 cm from the bottom of the extension. These grates randomized the sand as it fell through the extension into the chamber. Once the soil randomizer was in place, the sand was poured evenly into the extension. As the sand passed through the wire screens and fell into the chamber it rose evenly in the chamber thus avoiding microlayering. Once the chamber was filled, a rubber hammer was used to pack the sand by tapping the side walls. Using this technique an average bulk density of 1.4 g cm^{-3} was obtained with a standard deviation of 0.04 for the entire chamber.

Once the chamber was filled, a vacuum was used to remove sand to the depth where the water repellent layer was to be placed. A 1-cm water-repellent layer was added 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.

Infiltration Procedure

The chamber was leveled and the lip of a tray extending the full width of the chamber was placed over the front part of the chamber. The tray containing the water was tipped and water was applied rapidly and uniformly into the chamber. A constant water head was maintained by applying water to the top of the chamber with a pressurized water application system. The overall experimental system is illustrated in Fig. 2. 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, velocity and percent area wetted by fingers. The water flow rate into the chamber was measured by an inline flow meter connected to the pressurized water application system. The flow rate data were collected by connecting the output signal of the flow meter to a data logger acquisition system and downloading to a personal computer for storage.

The variables investigated for their effects on the development of unstable flow were: (i) h_p values of 4.0 and 8.1 cm water, (ii) water repellent layer depth, L, of 0, 5, and 15 cm, and (iii) depth of ponded water, h_o, between 1.5 and 10 cm.

In a separate experiment, the steady-state water flux, J_w, through a 5-cm water-repellent sand column was measured as a function of ponded water depth, h_o. The water repellent sand was packed into a 10 cm diam. plastic tube to a bulk density of 1.41 g cm^{-3}. A wire screen at the bottom of the tube retained the sand. Prior to each experiment, the inside of the column was treated with Teflon dry film lubricant to prevent water from preferentially flowing down the column wall. Water was added and maintained at a specific height and the steady-state water flux measured. After each experiment the sand was removed, weighed, dried at 105°C for 24 h and reweighed to calculate the volumetric water content, θ_v. The hydraulic conductivity was calculated using the water flux and hydraulic head gradient measurements. This procedure was repeated with different depths of ponded water.

RESULTS AND DISCUSSION

No water flowed into the water repellent layer under any combination of variables unless h_o plus L was

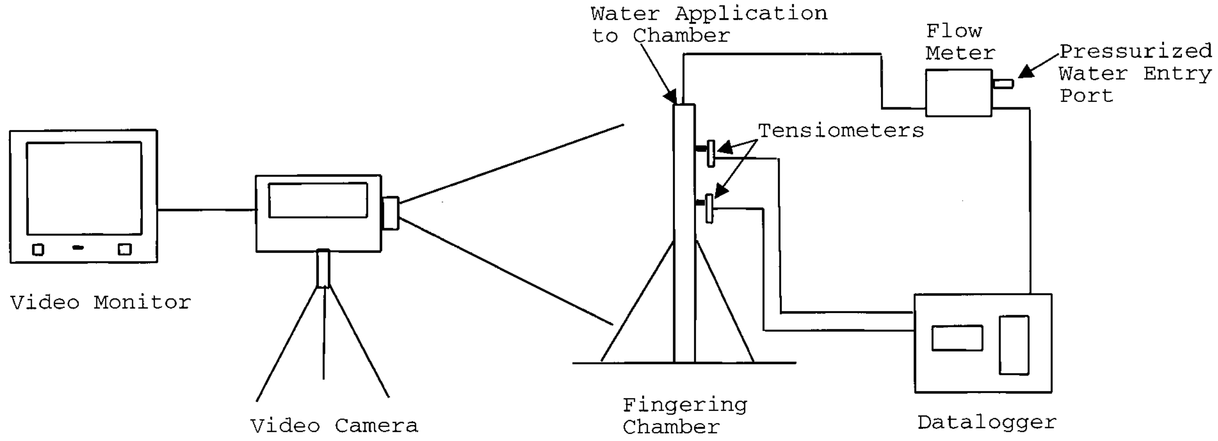

Fig. 2. Experimental set-up of chamber study showing video equipment, chamber and data collection system.

greater than h_p. Figure 3 shows the effects of h_o, L, and h_p on finger development. Figure 3a through 3d represents h_p equal to 8.1 cm H_2O at a depth of 5 cm with successively increasing values of h_o. Figure 3e is for an L of 15 cm and h_o equal to 5 cm. Note that as h_o or L increased the degree of fingering decreased. Compare Fig. 3b and 3f for the effect of h_p on finger formation for equal h_o and L values. As h_p increased the tendency for fingering also increased.

The relationship between the ratio $(h_o + L)/h_p$ and the percent area wetted in the chamber is illustrated in Fig. 4. For $(h_o + L)/h_p < 1$, no water penetrated the water repellent layer. For values between 1 and 1.5, finger formation occurred and for values exceeding 1.5 there was stable flow.

At the end of each experiment the chamber was taken apart and the water repellent layer examined. As $(h_o + L)$ increased the fraction of the wetted water-repellent layer increased. For Fig. 3a, the water repellent layer was dry except where water was observed to have penetrated the repellent layer. For Fig. 3b through 3f the layer had progressively increasing wetness.

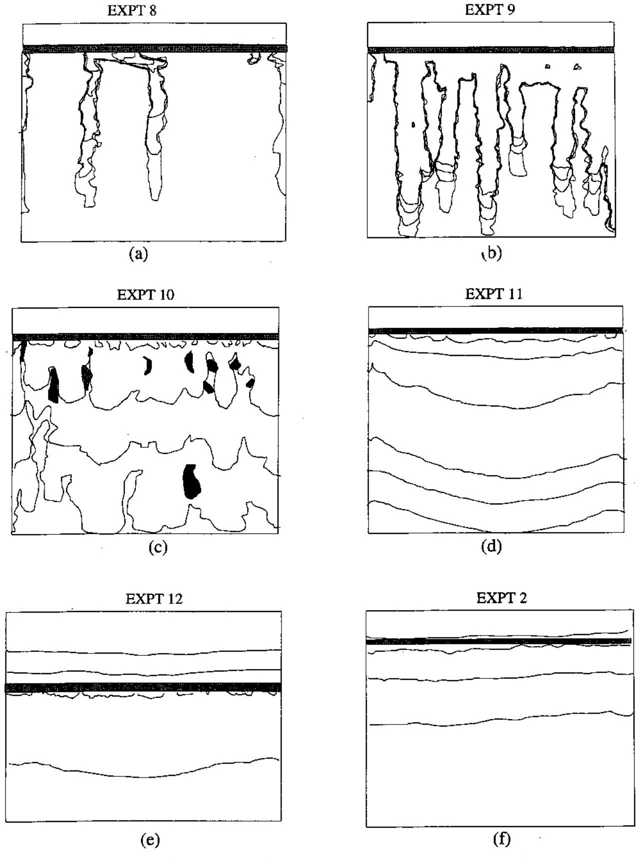

Fig. 3. Effects of h_o, L, and h_p on finger formation. (a) $h_o = 3.5$, $L = 5$, $h_p = 8.1$; (b) $h_o = 5$, $L = 5$, $h_p = 8.1$; (c) $h_o = 7$, $L = 5$, $h_p = 8.1$; (d) $h_o = 10$, $L = 5$, $h_p = 8.1$; (e) $h_o = 5$, $L = 15$, $h_p = 8.1$; (f) $h_o = 5$, $L = 5$, $h_p = 4.0$.

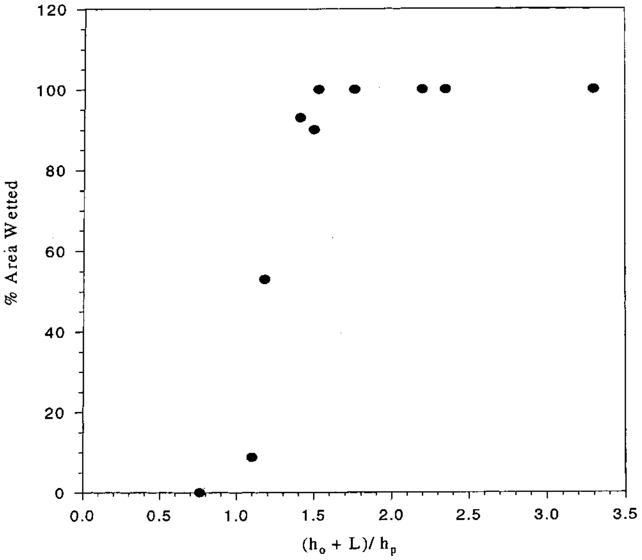

Fig. 4. Effects of increasing the ratio $(h_o + L)/h_p$ on the fraction of area wetted in wettable sublayer.

Figure 5 is a plot of the chamber water flux (J_{cham}) vs. $(h_o + L)/h_p$ and the flux measured in the separate column (J_w) vs. h_o/h_p. The flow rate in each system was about the same where the $(h_o + L)/h_p$ of the chamber and the h_o/h_p in the column were equivalent. Furthermore, as these ratios increased so did the flux. So by either increasing h_o or $h_o + L$ (for the chamber) the flow rate increased. The thickness of the water repellent layer had no apparent effect on the flux since the chamber flow was through a 1-cm layer and the column was through a 5-cm layer. The maximum J_{cham} value that could be measured by the instrumentation was 0.32 cm s^{-1}. All $(h_o + L)/h_p$ values >2 resulted in a $J_{cham} > 0.32$ cm s^{-1}.

Figure 6 is a plot of the hydraulic conductivity, K, measured from the column studies as a function of h_o/h_p. In a normal wettable soil, K is independent of h_o; but this was not observed for the water repellent sand (Fig. 6). This result is consistent with the capillary equation ($h = 2\gamma\cos(\theta)/rgr$) which states a larger head should fill smaller pores in the water repellent system. Another

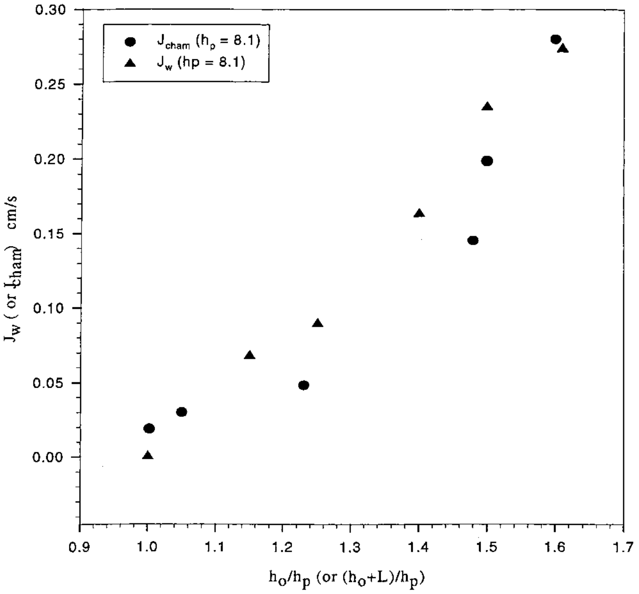

Fig. 5. Column (J_w) and chamber (J_{cham}) flux as a function of the ratio h_o/h_p or $(h_o + L)/h_p$.

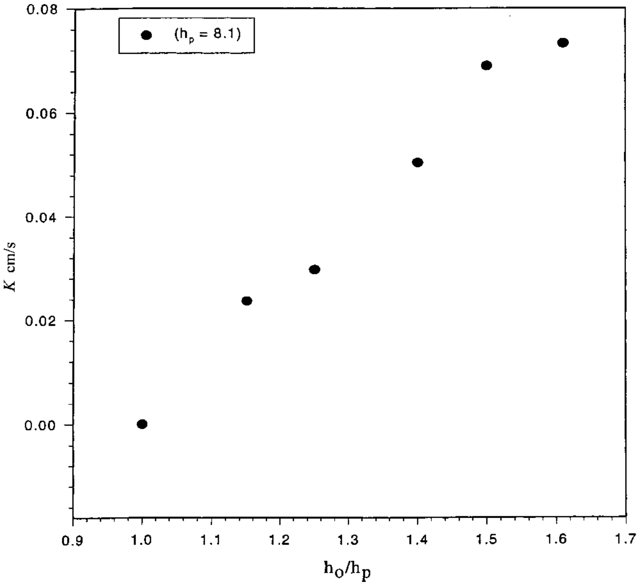

Fig. 6. Hydraulic conductivity as a function of h_o/h_p.

possibility is that only a small fraction of the sand layer was wetted and the fraction increased with increasing values of h_o. Data presented in Fig. 7 show the percent average volumetric water content (θ_v) varied from about 0.12 to 0.22. The increase in K with increasing θ_v is consistent with basic water flow principles. Note that even at the highest h_o/h_p values the sand was not saturated. The measured value of K_{sat} for the untreated sand was 0.24 cm s^{-1}.

The basic concepts of flux through a water repellent layer as affected by the total head may explain the finger formation. Glass et al. (1989), studying gravity-driven instabilities, showed that instability occurred if the flux through the system was less than K_{sat}. Note that 100% of the underlying wettable soil area was wetted when $(h_o + L)/h_p$ exceeded 1.5 (Fig. 4). The J_{cham} was slightly less than K_{sat} (0.24 cm s^{-1}) when $(h_o + L)/h_p$ exceeded 1.5 (Fig. 5) but exceeded K_{sat} for $(h_o + L)/h_p$ values equal to 1.6 or greater. Thus the finger formation may have been induced by the low hydraulic conductivity of the water repellent layer at low water heads.

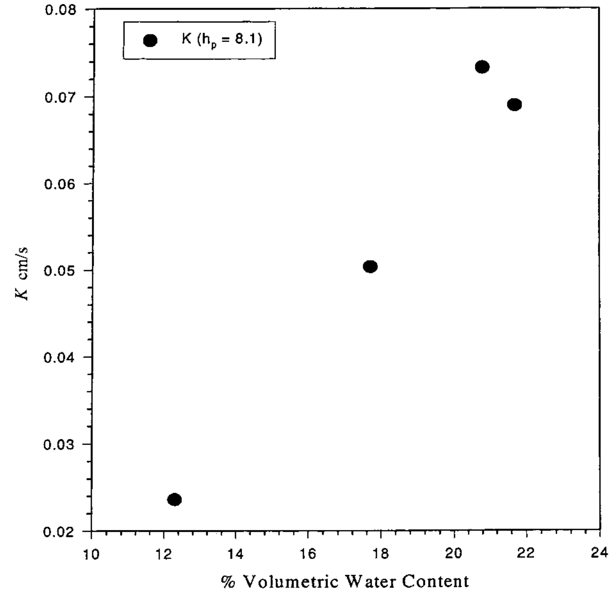

Fig. 7. Hydraulic conductivity as a function of the volumetric water content.

Once the fingers were formed in the sublayer they tended to have a constant velocity and width and the velocity tended to increase with increased finger width (data not shown). This observation is consistent with Glass et al. (1989) who found that velocity increased as the finger width increased. In contrast, Hill and Parlange (1972) found the fingers to have a constant velocity (close to the saturated pore velocity) and width. Glass et al. attributed the differences to heterogeneity in the bottom layer of Hill and Parlange experiments.

Our results are consistent with those reported by Bauters et al. (1998) and Wang et al. (1998) who also conducted experiments on sieved soil samples in slab chambers where water flow could be observed through a clear chamber wall. Whereas, we investigated the effects of water repellent layers on water flow, the other two studies filled the entire chamber with water repellent material. Wang et al. (1998) used a naturally occurring water-repellent soil which would wet after a time of exposure to water. Bauters et al. (1998) created a stable water-repellent sand by chemical treatment and mixed the treated and untreated sand in various ratios to get different degrees of repellency as characterized by the water drop penetration time (WDPT).

The water head at the surface was controlled by Wang et al. (1998). If the water head did not exceed the water entry pressure head, several minutes of ponding were required before infiltration started. Finger flow patterns developed under these conditions. When the water head exceeded the water entry pressure, infiltration started instantly and a stable, nearly horizontal wetting front was established. However, after a short time of stable flow, finger formation occurred. This may have been the result of a decreased water head at the wetting front.

Water was applied to the surface at a constant rate using a peristaltic pump by Bauters et al. (1998). Ponding occurred before infiltration started on the water repellent material. The depth of ponding required to initiate infiltration increased as the degree of repellency as measured by WDPT increased. Fingers were formed in the water repellent material when infiltration occurred.

Hendrickx et al. (1993) conducted a field study by comparing soil wetting patterns on two adjacent plots: one with a water repellent top layer, and one treated with clay to remove water repellency in the top 30-cm layer. Dye placed on the soil surface to identify wet and dry zones revealed a mosaic surface wetting of the water repellent soil and a uniform surface wetting of the wettable soil. Although water repellency existed in the treated plot below the 30-cm depth, it did not cause nonuniform soil wetting. This field observation is consistent with our finding that stable flow will occur if the depth to the water repellent layer was sufficiently deep.

The referenced studies indicate that preferential flow, on a scale of a few centimeters, can occur in water repellent soil because of unstable wetting fronts. However, dry areas in the range of square meters adjacent to wet soil zones are observed in the field. Examples of these observations include Jamison (1945), Bond (1964), Ritsma and Dekker (1996), and Dekker and Ritsema (1997). The nonuniform wetting on a larger scale observed in the field may be associated with a nonuniform degree of water repellency, nonuniform depth of the water repellent layer, uneven topography where water ponding to different depths could occur, or a combination of all three. The spatial distribution of these features could be subtle, and yet, have profound effects on soil profile wetting. This is because when water penetrates any zone of a water repellent soil, infiltration rate increases with time (Letey et al., 1962) and draws water from adjacent zones, keeping them dry.

This paper reported the results from a very stable water-repellent system (infinite WDPT) which was useful to eliminate the confounding temporal effects associated with water repellency which changes with time after contact with water. The latter condition is more prevalent in the field and the results of a study on an unstable water-repellent system is reported in another paper (Carrillo et al., 2000, this issue).

CONCLUSIONS

Gravity driven instabilities can be induced by a water repellent layer. The important parameter for the development of unstable flow in these systems was the ratio $(h_o + L)/h_p$. The hydraulic conductivity of the water repellent soil increased as this ratio increased. Also the degree of wetness increased as the ratio increased. Once the flux through the layer was approximately equal to or greater than the K_{sat} of the untreated soil, fingers did not form in the sublayer.

Wetting front instabilities can invalidate theories of vertical infiltration and groundwater recharge. Instabilities allow streams of water to carry pollutants rapidly to the groundwater by avoiding some of the soil matrix. Few prior experiments have shown how unstable flow develops except in fine over coarse systems. This research shows that unstable flow can occur in systems other than fine over coarse and should help in the development of understanding how water moves through water repellent soils.

REFERENCES

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

Bauters, T.W.J, D.A. DiCarlo, Tammo, S. Steenhuis, and J.-Y. Parlange. 1998. Preferential flow in water-repellent sands. Soil Sci. Soc. Am. J. 62:1185–1190.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311–1325.

Burcar, S., W.W. Miller, S.W. Tyler, and D.W. Johnson. 1994. Seasonal preferential flow in two Sierra Nevada soils under forested and meadow cover. Soil Sci. Soc. Am. J. 58:1555–1561.

Bond, R.D. 1964. The influence of the microflora on the physical properties of soils. II. Field studies on water repellent sands. Austr. J. Soil Res. 2:123.

Carrillo, M.L.K., J. Letey, and S.R. Yates. 1999. Measurement of initial soil–water contact angle of water repellent soils. Soil Sci. Soc. Am. J. 63:433–436.

Carrillo, M.L.K., J. Letey, and S.R. Yates. 2000. Unstable flow in layered soil: II. The effects of an unstable water-repellent layer. Soil Sci. Soc. Am. J. 64:456–459 (this issue).

DeBano, L.F. 1971. The effect of water repellent substances on water movement in soil during infiltration. Soil Sci. Soc. Am. Proc. 35: 340–343.

Dekker, L.W., and C.J. Ritsema. 1997. Effect of maize canopy and water repellency on moisture patterns in a Dutch plaggen soil. Plant Soil 195:339–350.

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

Glass, R.J., T.S. Steenhuis, and J.Y. Parlange 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.

Glass, R.J., S. Cann, J. King, N. Baily, J.Y. Parlange, and T.S. Steenhuis. 1990. Wetting front instability in unsaturated porous media: A three-dimensional study in initially dry sand. Trans. Porous Media 5:247–268.

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

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

Hendrickx, J.M.H., L.W. Dekker, E.J. van Zuilen, and O.H. Boersma. 1988. Water and solute movement through a water repellent sand soil with grasscover. Int. Conf. and Workshop on Validation of Flow and Transport Models for the Unsaturated Zone, Ruidoso, NM. 23–26 May 1988.

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

Hill, D.E., and J.Y. Parlange. 1972. Wetting front instability in layered soils. Soil Sci. Soc. Am. Proc. 36:697–702.

Jamison, V.C. 1945. The penetration of irrigation and rain water into sandy soils of central Florida. Soil Sci. Soc. Am. Proc. 10:25.

Jury, W., and K. Roth. 1990. Evaluating the role of preferential flow on solute transport through unsaturated field soils. p. 23–30. *In* K. Roth et al. (ed.) Field-scale water and solute flux in soils. Birkhaeuser Publ. Basel, Switzerland.

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

Letey, J., N. Welch, R.E. Pelenshek, and J. Osborn. 1962. Effect of wetting agents on irrigation of water-repellent soils. Calif. Agric. 16(12):12–13.

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 nonuniform soils. Soil Sci. Soc. Am. Proc. 37:681–685.

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

Ritsma, C.J., and L.W. Dekker. 1996. Water repellency and its role in forming preferred flow paths in soils. Austr. J. Soil Res. 34:475–487.

Saffman, P.G., and G.I. Taylor. 1958. The penetration of a liquid into a porous medium or hele-shaw cell containing a more viscous fluid. R. Soc. London Proc. A245:312–329.

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

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