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Film and Pulse Flow in Artificial Macropores

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It is generally recognized that macropore flow may occur in unsaturated soil and that this should be taken into account when modelling flow of water and solutes in soil. The objective of the present study was to examine the water pressure potential conditions at which macropore flow may occur and to elucidate the nature of macropore flow. A laboratory setup consisting of a sand column 20 cm in diameter and 20 cm high with outlet into a 50 cm long glass tube was used. The outlet characteristics of the glass tube was either free to the atmosphere or the glass tube terminated in gravel. The tube diameters used were 3, 4 , and 6 mm while the water application rates used were 1.2, 2.2, 12, and 18.5 mm h $^{-1}$. Experiments covering 26 combinations of tube diameter, water application rate and outlet characteristics were conducted. Water entered the macropores at a water pressure potential in the overlying sand more or less equivalent to the water entry pressure potential of the macropore according to capillary theory. The nature of flow in the macropore was for the tubes of 3 mm and 4 mm in diameter predominantly pulse flow while film flow was more likely to occur in the tube of 6 mm in diameter. During pulse flow events a pressure potential gradient was consistently created in the sand column, the pressure potential decreasing to -20 cm to -30 cm corresponding approximately to the air entry pressure potential of the sand. The pulse flow events occurred repeatedly during the infiltration as long as water application was continued. When film flow occurred after a pulse flow event, the film flow continued at a water pressure potential less than -20 cm in the sand close to the opening of the artificial macropore.

Introduction

It is generally recognized that macropores in soil can act as fast transport ways for water and solutes.This has been revealed through numerous field experiments and in studies using undisturbed soil columns (Ehlers 1975; Germann 1981; Edwards 1989, 1993; Quisenberry 1994; Flury *et al.* 1994;Shipitalo1996; Singh and Kanwar 1991; Petersen *et al.* 1997a, Petersen *et al.* 1997b; Petersen *et al.* 2001). Macropores in soil have been defined as large pores without appreciable capillary properties (Beven 1982). They can be created by physical-chemical as well as by biological processes. Macropores generated by earthworms are common in many soil types and the density of earthworm burrows may be as high as several hundreds per square metre soil (Petersen *et al.* 1997b).

In the temperate humid zone, the earthworm species *Lumbricus terrestris* is often abundant, digging vertically oriented channels, 1 – 10 mm in diameter extending down to 3 m beneath the soil surface depending on soil and environmental conditions (Lee, 1985). Thus, under conditions in which soil water enters the macropores, earthworm burrows may be important channels for transport of water and solutes in soil.

Ehlers (1975) focused on the infiltration rate into non-tilled soil where macropores from earthworm burrows extended to the soil surface. The infiltration rate due to earthworm burrows in the non-tilled soil was found to be six times higher than the infiltration rate into the tilled soil.

Edwards *et al.* (1988) made a characterization of macropores that affect infiltration rate and he found an average of more than 10,000 pores per square metre larger than 0.4 mm in diameter in the upper 30 cm of the soil profile in a non- tilled soil. A total of 160 pores were even larger than 5 mm in diameter and they were created mainly by *Lumbricus terrestris*. Macropore flow may also occur in tilled soil in which the macropores may not extend to the soil surface. Thus dye tracing field experiments (Petersen *et al.* 1997b) strongly indicated that macropore flow was initiated in the soil at a soil depth corresponding to approximately the plough depth. Neither the hydraulic conditions at which the macropore flow was initiated nor the nature of flow in the macropores were discovered in these experiments.

For water to enter macropores, it is generally recognized that according to capillary theory the soil water pressure potential has to exceed the water entry value of the macropore. In tilled soils, a plow pan in the form of a compacted soil layer with low hydraulic conductivity often occurs just beneath the plough depth. Thus, Petersen *et al.* (1997b) concluded that the initiation of macropore flow was likely to be the result of accumulation of infiltrating water eventually creating conditions close to saturation immediately above the plough pan where many macropores terminate.

A detailed examination of the nature of flow in undisturbed soil is difficult because of the complex nature of the structure of the soil. The soil pore system is geometrically complex and composed of a variety of pore sizes including macropores with different geometry, tortuosity and coatings (Beven 1982). Li and Ghodrati (1994, 1995) conducted studies on flow in macropores of root channels and earthworm burrows by introducing plants and earthworms into packed soil columns. Stehouwer *et al.* (1993) showed that the lining of burrows of *Lumbricus terrestris* was enriched in organic carbon relative to the soil matrix and that the lining had higher sorption capacity for atrazine than the soil matrix. According to Lee (1985) the burrows of *Lumbicus terrestris* are lined with mucus rich secretions which is likely to make the burrow surface only partly hydrophilic.

The detailed mechanisms of macropore flow have not been studied very extensively. In such studies Logsdon (1995) and Li and Ghodrati (1997) used constructed macropores in packed soil columns while Godrati *et al.* (1999) used a split macropore column technique. Philips *et al.* (1989) used a simulated macropore of glass tube connected to a porous glass plate and they found that water could enter the glass tube at a water pressure potential of -10 cm in the porous plate as long as a water film was present in the glass tube.

However, in addition to film flow water may flow very fast through macropores as a pulse flow as the macropores may become saturated. This may enhance not only transport of solutes but also particle facilitated transport of chemicals. Thus, the objective of the present study was to examine the water pressure potential conditions at which macropore flow may occur and to elucidate the nature of macropore flow. For the sake of having a well defined macropore system, the study was conducted using a sand column with an artificial macropore system.

Materials and Methods

A schematic drawing of the sand – artificial macropore system is shown in Fig.1. In this system water was applied to the top of a sand column and infiltrated into a homogenous sand matrix. At a depth of 20 cm, water flow was blocked by the presence of an artificial impermeable plough pan in terms of a bottom plate. Thus the applied water could escape from the system only through the 50 cm long artificial macropore with its opening at the interface between sand and the bottom plate. The pressure potential of water at the sand – plough pan interface was monitored continuously by tensiometers connected to sensitive pressure transducers. The artificial macropore terminated either in the free atmosphere or in a porous medium of coarse sand.

The soil material used for the experiments was acid washed sand having a particle density of 2.66 Mg m^{-3} and particle diameters in the range of 0.1- 0.3 mm. The sand was packed in the column to an average bulk density of 1.53 Mg m^{-3} giving a porosity of 0.42 m^3 m^{-3} . Saturated conductivity was determined to be 2×10^{-4} m s^{-1}. The water retention characteristics of the sand were established by using a filter plate connected to a burette. The air entry value of the filter plate was 80 cm. A sample of

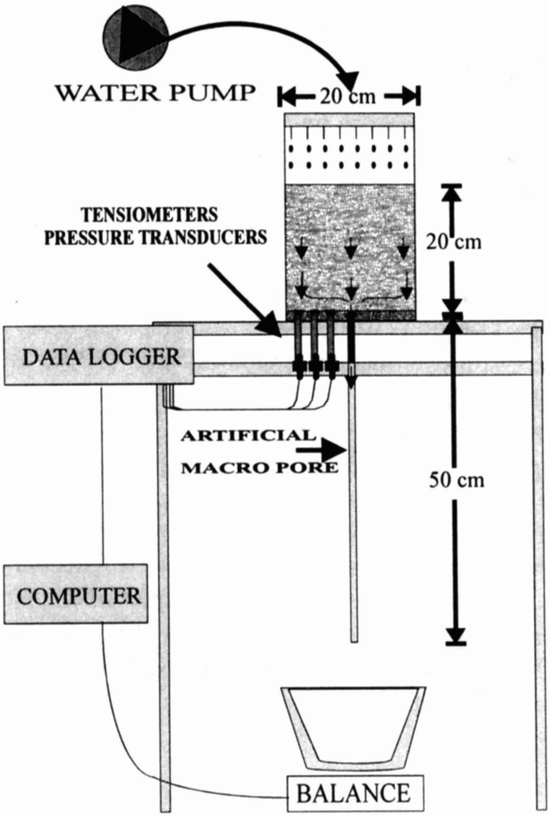

Fig. 1. Schematic drawing of experimental setup.

the sand, 1 cm high with a bulk density of 1.53 Mg m^{-3}, initially water saturated was drained stepwise to a pressure potential of about -60 cm and then stepwise rewetted to saturation. A total of 7 such drainage-rewetting runs were performed in addition to two drainage runs. The results are presented in Fig.2.

The bottom plate of the soil column setup consisted of a 1 cm thick plexiglass plate with a hole in the middle 10 mm in diameter. A glass tube was fitted watertight into this hole, so that the top of the glass tube was in line with the top of the bottom plate. The system was designed so that the glass tube could be easily changed. In the present study, glass tubes of 3, 4 and 6 mm in inside diameter were used. The tubes made of Duran glass were washed in alcohol and flushed with distilled water before use. Estimates of the contact angle (28 -32°) for water in the tubes indicated that the tubes were partly hydrophilic. By using glass tubes the flow in the tubes could be directly observed visually.

To prevent the sand from escaping the column through the glass tube, a metal net of stainless steel was placed over the hole in the plexiglass bottom. The net had a

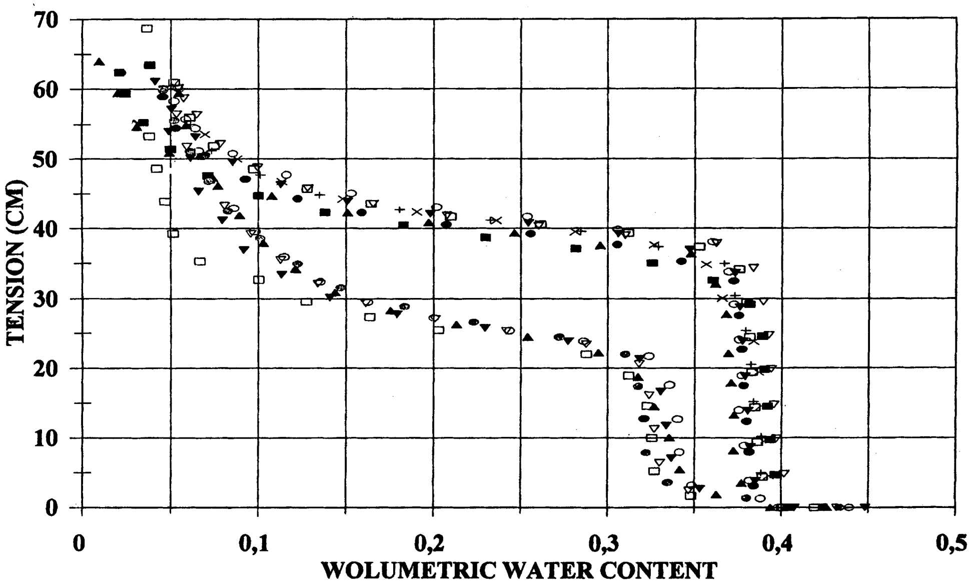

Fig. 2. Water retention characteristics of the sand. Symbols indicate different drainage-rewetting runs.

spacing of 250 μm implying a water entry pressure potential of the net of about -6 cm. As this was higher than the water entry pressure potential of the sand used in the experiment, the metal net presumably did not influence the flow of the water. Distilled water was applied to the sand surface through a sprinkling device consisting of 26 hypodermic needles. The sprinkling device automatically rotated during the experiments to ensure a uniform application of the water to the soil surface. Furthermore, a filter paper was placed on top of the sand column to avoid disruption of the sand surface from the impact of the water drops.

The water application rate was controlled by a laboratory pump (FMI Lab pump model QG 400). Water application rates of 1.2, 2.0, 12.0, and 18.5 mm h^{-1} were used. The amount of water entering and leaving the system was monitored continuously during the experiments by weighing the application reservoir and the water collected from the outlet, respectively.

The pressure potential of water was measured by using differential type pressure transducers (Micro Switch 26PC PK 8875 2) connected to tensiometers. The tensiometers were discs of sintered glass 1 cm in diameter and 3 mm thick, with an air entry value of 180 cm. These tensiometers were mounted in the bottom plate of the column 2.5, 5.0, and 7.5 cm from the centre of the plate. The measurement range of the transducers was -70 cm to 70 cm. The transducers were calibrated while placed in the laboratory setup. The transducers did not show any hysteresis effect, but they were sensitive to temperature fluctuations. Thus, the experiments were performed in a room with constant temperature. All the measurements were made continuously and recorded automatically by computer logging. Each experiment was started with dry tubes. When a pulse flow occurred it drained water out of the sand column. In some experiments application of water was continued after a pulse flow event. When a film flow occurred, the flow became steady-state and the experiment was terminated.

Table 1 – Experimental set up and main results of all experiments. Flow type: P: Puls Flow; F: Film Flow.

Exp No.	Macro pore diam. (mm)	Outlet	Flow rate (mm/h)	Flow type in macropore	Pressure at bottom at macropore flow start (cm)	Lowest pressure (cm)
1	3	free	1.15	P,P,P	-0.5,-0.5,-0.5	-26,-26,-26
2	3	free	2.24	F	-0.5	-4
3	3	free	12.11	P,P,P,F	-0.7,-0,6,-1.0,1.5	-26,-26,-26,1.5
4	3	free	18.41	P,P,P,P,F	-1.0,-1.0,1.7,1.6	-26,-27,-27,-4
5	3	gravel	1.31	P,P,F	-0.6,-1.0,0.3	-28,-28,-3
6	3	gravel	2.29	F	0.4	-1
7	3	gravel	11.51	P,P,P,P,F	-0.6,-0.6,-0.9,-1.0,1.2	-27,-28,-28,-28,1
8	3	gravel	18.46	F/P,P/F	2.5,1.5	-28,-20
9	4	free	1.26	P,P,P	y,-0.2, -0.1	y, -25,-25
10	4	free	1.83	P	-0.5	-25
11	4	free	2.15	P,P	-0.2,0.3	-25,-23
12	4	free	11.70	P,P,P	-0.4,0.3,0.8	-24,-24,-24
13	4	free	18.52	P,P,P(x),P/F	0.2,0.1,-0.6,-0.1	-23,-23,-23,-23
14	4	gravel	1.21	P	0.3	-23
15	4	gravel	2.09	P,P,P	0.5,0.0,-0.3	-25,-25,-23
16	4	gravel	12.07	P,P,P/F	0.0,0.4,-0.3	-24,-23,-24
17	4	gravel	18.55	P(x),P(x),P(x)	0.1,-0.3,0.3	-23,-23,-23
18	6	free	1.20	P/F	0.0	-4
19	6	free	1.25	P	0.2	-31
20	6	free	2.07	P,P/F	0.1,0.2	-32,-10
21	6	free	11.40	P/F	0.0	-4
22	6	free	18.52	F	-0.2	-4
23	6	gravel	1.14	P/F	0.0	-5
24	6	gravel	1.95	P,P/F	0.2,0.3	-31,-4
25	6	gravel	12.05	F	-0.6	-3
26	6	gravel	18.51	P/F	-0.5	-28

x: Pulse flow occurs but water outflow continues after pulse flow has ceased.
y: Measurement missing.

Results and Discussion

A total of 26 different experiments were performed including 8 experiments using a glass tube of 3 mm in diameter, 9 experiments using a glass tube of 4 mm, and 9 experiments using a glass tube of 6 mm in diameter. The experimental setups and results of the experiments are summarized in Table 1. The different outlet conditions (free outlet and outlet in gravel) were included in order to investigate whether different outlet conditions would result in differences in the macropore flow patterns and the conditions at which macropore flow occurs. However, the results obtained did not show any influence of the outlet conditions applied. Fig. 3 shows typical examples of the behavior of the pressure potential, 2.5 cm from the tube and accumulated outflow during the experiments, for different tube diameters and outlet characteristics at a water application rate of 12 mm h^{-1}. The experiments were started with dry tubes and a low soil water pressure potential in the sand matrix. During the water infiltration the pressure potential increased at the bottom of the sand column because of water accumulation.

When the pressure potential was more or less equivalent to the water entry pressure potential of the macropore according to capillary theory, the water began to enter the tube and either a pulse flow or a film flow occurred in the tube. No consistent difference was noted regarding the way the water pressure builds up at the bottom of the sand column prior to pulse flow and film flow events, respectively, although in some cases the pressure apparently builds up faster prior to a film flow case. In several experiments, pulse flow events occurred repeatedly during the infiltration when water application was continued.

The experiments showed that both film flow and pulse flow occurred in the three different macropores used. When film flow occurred the flow became steady-state. For the flow rates used, the film flow could be maintained with the applied amount of water. For experiments in which film flow occurred in one event only, experiment number 8 event 1, the flow became unstable and resulted in pulse flow. When a pulse flow was initiated, the sand matrix rapidly drained, and a gradient in the pressure potential developed at the bottom of the sand column. For each pulse event, the lowest value of the pressure potential was always recorded 2.5 cm from the macropore and the highest value was recorded at the 7.5 cm distance from the macropore. Thus, the pulse flow created a rapid flow of water close to the macropore and a potential gradient extending some distance into the sand matrix. Typical examples of the behavior of the pressure potential at the bottom of the sand column during flow events are shown in Fig 4.

The lowest recorded pressure potential when water entered the macropore was -1.0 cm at 7.5 cm distance from the macropore. This was observed in experiment 4 (Table 2) prior to pulse flow event 1 and 2. At the same time the pressure potential at 2.5 cm distance from the macropore was – 0.9 cm. The highest recorded pressure potential when macropore flow was initiated was 1.9 cm measured 7.5 cm from the

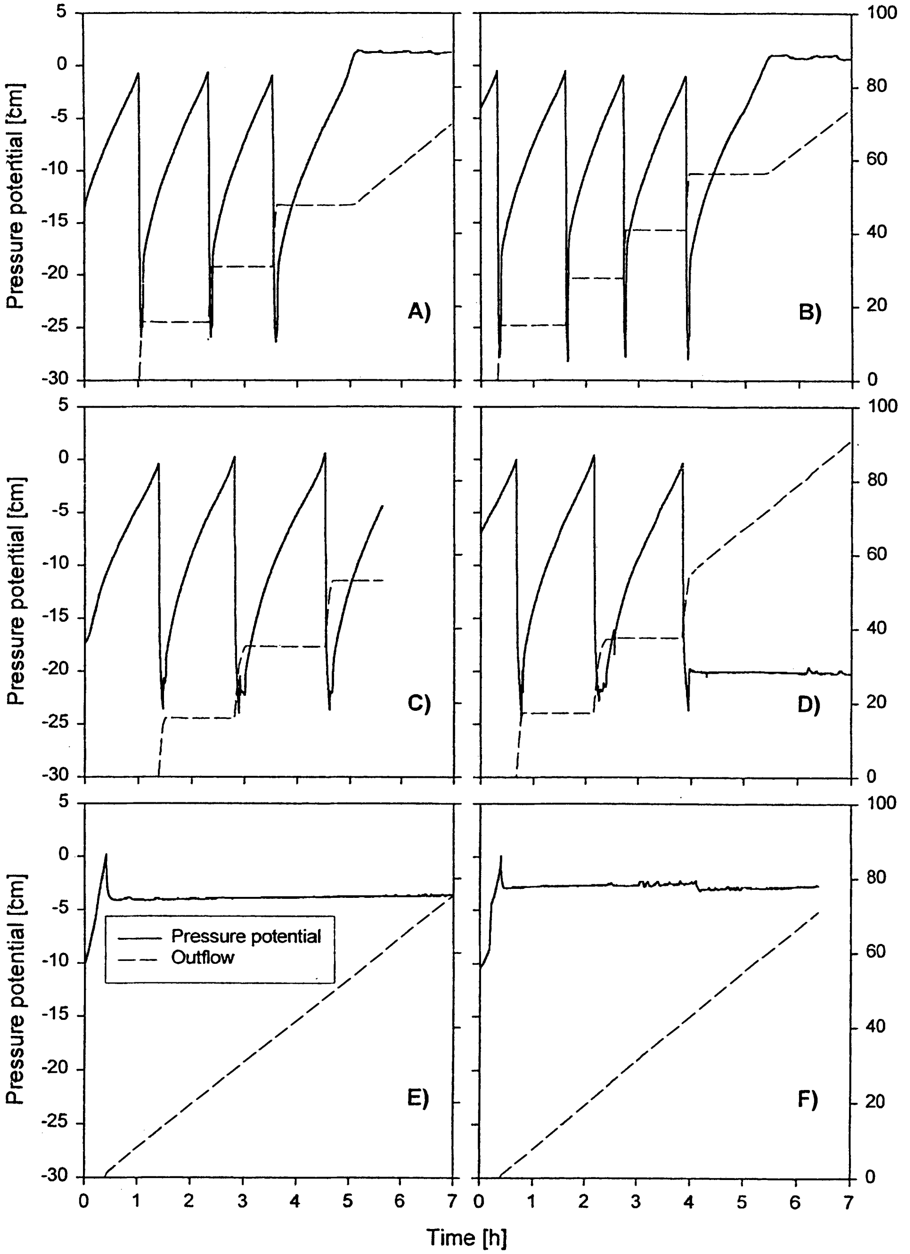

Fig. 3. Pressure potential close to the macropore and cumulative outflow plotted against time for 12 mm h^{-1} water application rate at different diameter of the artificial macropore, and outlet characteristics. A: 3 mm with free outlet; B: 3 mm with outlet into gravel; C: 4 mm with free outlet; D: 4 mm with outlet into gravel; E: 6 mm with free outlet; F: 6 mm with outlet into gravel.

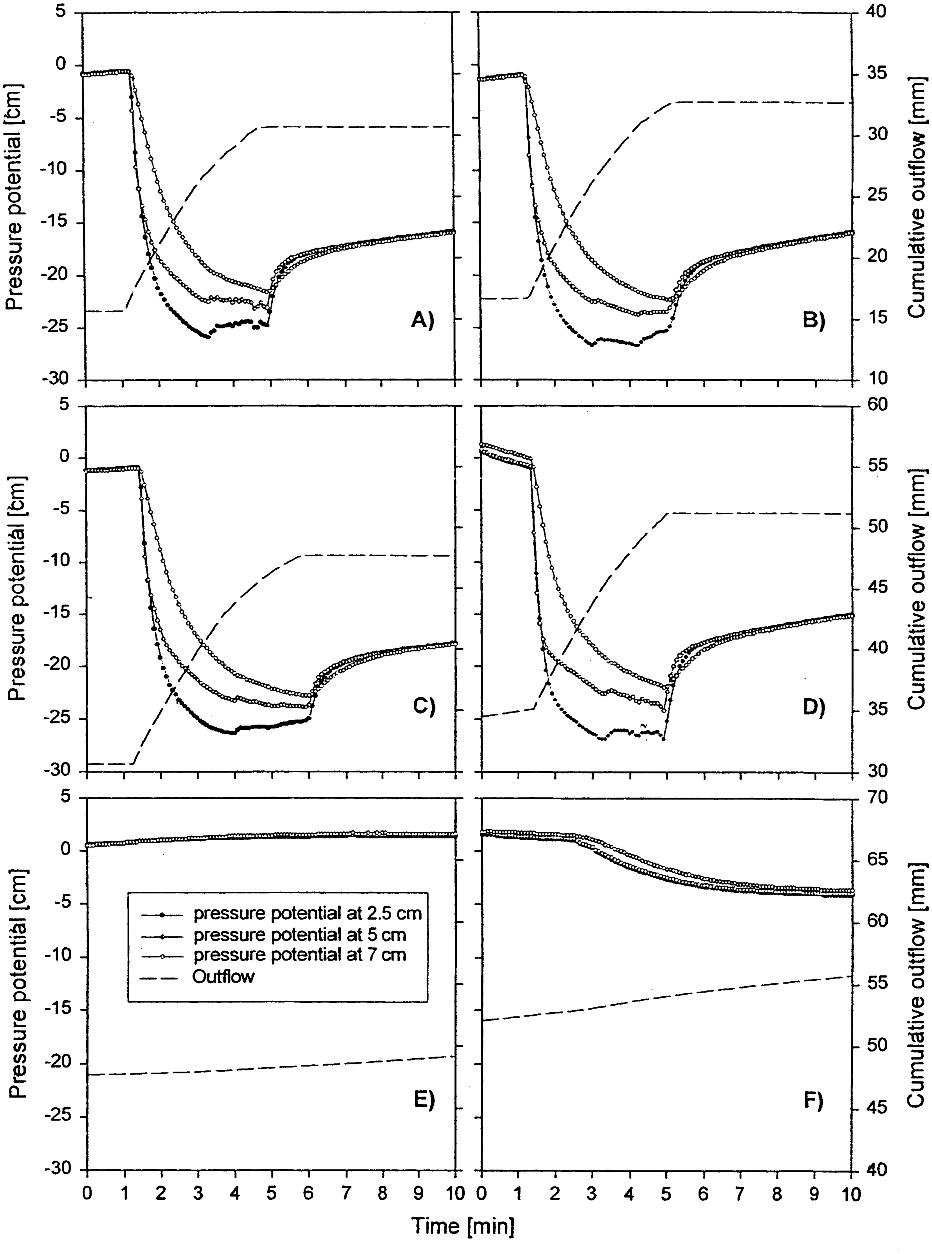

Fig. 4. The course of outflow and the development of pressure potential gradients during different flow events at 12 mm h^{-1} water application rate at different diameter of the artificial macro pore, and outlet characteristics. A: 3 mm with free outlet, pulse flow event 2; B: 3 mm with outlet into gravel, pulse flow event 2; C: 4 mm with free outlet, pulse flow event 3; D: 4 mm with outlet into gravel, pulse flow event 3; E: 6 mm with free outlet; F: 6 mm with outlet into gravel.

macropore and 1.5 cm measured 2.5 cm from the macropore. This was observed also in experiment 4 prior to pulse flow event 3 and 4. These results confirm that for water to enter macropores and initiating macropore flow, the soil water pressure potential has to exceed the water entry value of the macropore.

Pulse flow occurred most frequently for the small tubes of 3 mm and 4 mm. When a pulse flow occurred the water pressure potential in the soil matrix decreased rapidly. The suction in the full running macropore was able to drain the sand matrix. According to potential theory a macropore of 50 cm length should be able to drain the sand matrix to a pressure potential of -50 cm at the entry point of the macropore. However, during the pulse flow events the water pressure potential at the bottom of the sand column decreased only to -20 cm to -30 cm which is in the region between the air entry and the water entry pressure potential of the sand, Fig. 2. Hence, in this case it seems to be the water retention properties of the sand rather than the length of the macropore which governs at which pressure potential the macropore flow event terminates.

The average duration of pulse flow events was 7 minutes (range 3-15 minutes). The average amount of water released from the soil matrix during pulse flow events was 465 cm^3 (range 373-546), and 512 cm^3 (range 461-608) for 3 mm and 4 mm tubes, respectively. The average time between pulse flow events was 829 minutes (range 677-911), 489 minutes (range 475-512), 81 minutes (range 66-102), and 59 (range 54-68) for flow rate 1.2 mm h^{-1}, 2.2 mm h^{-1}, 12.0 mm h^{-1}, and 18.5 mm h^{-1}, respectively. The steady-state film flow events that occurred could be recognized by a constant pressure potential at the bottom of the sand column and a constant outflow rate from the macropore corresponding to the water application rate, Figs. 3 and 4. However, the resulting pressure potential at the bottom of the sand column was quite different for the different film flow events. The most frequent pressure potential during film flow was -4 cm which occurred in 7 film flow events. The highest recorded pressure potential during film flow was 1.5 cm which happened in experiment 3. The lowest recorded pressure potential during film flow was -23 cm in experiment 26. This value is considerably less than the value (- 10 cm) obtained by Phillips *et al.* (1989) who used a porous plate-glass tube presumably without water storage capacity, while in our study the porous media had a certain water storage capacity. Thus, the results obtained in the present study indicate that soil water may continue to flow into macropores in soil under unsaturated conditions providing a hydraulic contact exists between the soil matrix and the macropores.

Summary

The objective of the present study was to examine the pressure potential conditions at which macropore flow may occur and to elucidate the nature of macropore flow. A laboratory setup consisting of a sand column with an outlet into a glass tube was used. The tube diameters used were 3, 4 , and 6 mm while the water application rates used were 1.2, 2.2, 12, and 18.5 mm h $^{-1}$. The outlet characteristics of the glass tube were either free to the atmosphere or the glass tube terminated in gravel. Experiments covering 26 combinations of tube diameters, water application rates and outlet characteristics were conducted.

Water entered the artificial macropores at a pressure potential of water in the overlying sand more or less equivalent to the water entry pressure potential of the macropore according to capillary theory. The nature of flow in the macropore was for the tubes of 3 mm and 4 mm in diameter predominantly pulse flow, while film flow were more likely to occur in the tube of 6 mm in diameter. During pulse flow events a pressure potential gradient was consistently created in the sand column, the pressure potential decreasing to -20 cm to -30 cm which is in the region between the air entry and the water entry pressure potential of the sand. The pulse flow events occurred repeatedly during the infiltration as water application was continued. When film flow occurred after a pulse flow event, film flow continued at a water pressure potential less than -20 cm in the sand close to the opening of the macropore.

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