Surface water infiltration in a 1-dimensional soil-geotextile column

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ABSTRACT

This paper provides insight into laboratory experiments conducted to examine the one-dimensional unsaturated hydraulic behaviour of a layered soil-geotextile system under conditions of surface water infiltration. The main objective of the infiltration testing was to determine the transient pore-water pressure response and the corresponding advancement of the wetting front in a one-dimensional sand column containing a geotextile layer. Typical preliminary infiltration testing results are presented for a polyester needle-punched nonwoven geotextile embedded in a layer of sand. Testing was conducted for new geotextile specimens prepared under air-dry soil and gravity-drained soil conditions to simulate the possible range of geotextile conditions in the field. Based on the experimental results, the hydraulic behaviour of a one-dimensional soil-geotextile profile system during periods of infiltration is discussed.

1 INTRODUCTION

Nonwoven geotextiles are known to have a range of hydraulic behaviour and thus have a significant influence on the movement of moisture in unsaturated field conditions. They are more commonly incorporated in many applications (road pavements, landfill covers and liners, retaining walls, and embankments) as a replacement to coarse grained soils in engineering systems that require high saturated fluid conductivities. The thickness and the pore structures of nonwoven geotextiles indicate that they may behave as a typical porous medium, yet some materials tend to be non-wetting because of their hydrophobic characteristic. Generally, nonwoven geotextiles have relatively large pore sizes compared to most soils, and as a result their hydraulic behaviour may be expected to be similar to a coarse grained soil.

Iryo and Rowe (2004) emphasized the significance of studying the hydraulic behaviour of geotextiles within soil when subject to infiltration. The significance of infiltration rises from the fact that nonwoven geotextiles can perform functions such as, filtration of water between two porous media, drainage layer or moisture barrier depending on the soil condition around them. Published data on infiltration testing using one-dimensional soil-geotextile column layer include works from Baker and Hillel (1990), Ho (2000), Yang et al. (2004), Iryo and Rowe (2003, 2004). Ho (2000) carried out infiltration experiments to study the behaviour of 1-D soil-geotextile column under gravity-drained sandy soil after saturation condition. Ho's (2000) study showed that the development of pore water pressures in the 1-D soil-geotextile column profile upon the advance of the wetting front is different from that of a similar 1-D sand column profile without a geotextile layer.

This paper reports a study on two soil-geotextile profiles subjected to vertical infiltration of water. The tests featured two initial conditions, namely dry soil and gravity-drained soil after initial saturation. Typical experimental results are presented and the differences in wetting front characteristics are compared in light of these results.

2 MATERIALS

The geosynthetic material used in the present study is a nonwoven needle punched polyester geotextile supplied by a local manufacturer. The geotextile featured fibre density (ρ_f) of 1300 kg/m^3 and specific gravity of 1.3, and is characterised by an apparent opening size of 0.18 mm and a cross plane saturated hydraulic conductivity of 4 x 10^{-3} m/s, as specified by the manufacturer. The calculated average mass per unit area (M_A) was 0.29 kg/m^2 and the porosity was 0.90. The sand (# 8/16) was a screened material processed by a commercial sand producer (UNIMIN Melbourne).

Grain size distribution indicates that the sand had no clay fraction. The coarse sand was poorly graded (USCS: SP) with 100% of its particles size between 1 and 3 mm. The constant head permeability test method was used to measure the saturated hydraulic conductivity of the sand soil (in loose condition) and was estimated to be 4.5 x 10^{-2} m/s at a dry density of 1410 kg/m^3. The apparent opening size of the geotextile (AOS = 0.18 mm) indicates that it is a typical filter for sand (Koerner 1998).

3 TEST SET UP AND SOIL PLACEMENT

Infiltration experiments were conducted in a clear Perspex cylinder of 138.7 mm in diameter and 1,600 mm in height. The column assembly comprises four-part cylindrical sections, with each section having a 400 mm height, and a water reservoir (250 mm in height) placed above the column. Threaded screws, lock nuts, and O-rings seals hold the four separate parts of the column and the water reservoir, thus developing a tight seal. The main features of the column are the ability to accommodate a 1.6 m soil layer height to simulate field conditions and the ability to place three geotextile specimens at the column sections interfaces. The 1-D soil-geotextile column schematic drawing is presented in Figure 1.

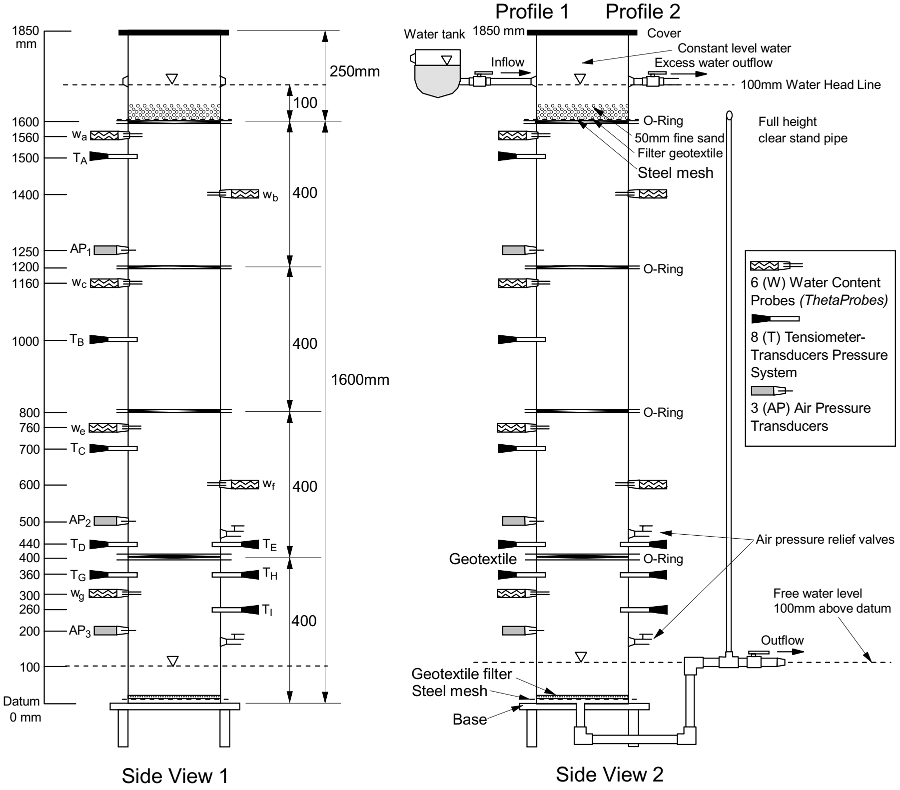


Figure 1: Schematic of the 1-D soil-geotextile column test apparatus

A set of volumetric water content probes, pore water pressure sensors, and air pressure sensors, were used in this test apparatus. Volumetric water content was measured throughout the entire soil profile height using six soil moisture probes, ThetaProbes ML-2. The ThetaProbes were calibrated in the laboratory for the sand soil and the volumetric water content readings for all the probes ranged between 1.38 % and 1.47 % for the air-dried sand, and between 46.22 % and 47.78 % for the saturated sand. The tensiometer-transducer system included eight tensiometer probes in which each probe consisted of a 100 kPa high-flow ceramic porous stone (6 mm diameter and 28 mm in length) and is attached to the tensiometer body *via* a plastic body tube assembly. The tensiometer is attached *via* the plastic tube to a pressure transducer that had a differential pressure range between –100 kPa and +100 kPa. Tensiometers can measure moisture tension (suction) and the pressure transducer can measure the transient pore-water pressure response within the soil-geotextile layer. Three air pressure transducers, having a range of 0 kPa to 35 kPa, were used to measure air pressure during the infiltration experiments under unsaturated conditions. The air pressure sensors were calibrated with a portable pressure calibrator DPI 603 with pressures up to 35 kPa. All the column sensors were placed in the soil profile during column construction and the location of all the sensors are shown in Figure 1.

An air-dried geotextile specimen was cut to a diameter of 180 mm from a new geotextile sheet as received from the manufacturer. The measured average thickness and air-dried weight of the geotextile was 2.3 x 10^{-3} m and 6 grams, respectively. The soil water characteristic curve of the sand was measured on the drying path by a Tempe pressure cell and the air entry value of the sand was found to be about 2.5 kPa. The geotextile specimen was placed on top of a 400 mm layer of sand and then was overlayed by 1200 mm layer of sand. The geotextile was extended to the flanges\ of the column and held in-place by O-rings seal. In the air-dry soil tests, the sand was placed in 100 mm thick lifts. Each lift was vibrated using an air powered vibrator in order to achieve the required dry density. The sand was densified to a dry density of 1550 kg/m^3 and a porosity of 0.41. In the gravity-drained tests, the column was filled with water and then loose sand was pluviated through the water from a height of 250 mm through a diffuser mesh (opening size = 2.8 mm) into the top of column. After the column was set up, the perimeter of the geotextile was sealed with silicon sealant to prevent water seepage around its perimeter. Both procedures were carried out starting from the lower 400 mm section of the column and then continued upward for the remaining sections of the column. The fully-saturated column was then allowed to drain by opening the drainage valve located at the bottom of the column. The sand was densified by the pluviation method to a dry density of 1500 kg/m^3 and a porosity of 0.44. The sand was retained at the bottom of the column by a fine screen mesh and a filter polyester geotextile. Since the sand is poorly graded, with large fraction of coarse particles, it is expected to drain rapidly. Hence, a thin layer of 50 mm fine soil sand (# 30/60) was used as a cover soil on top of the column because it has lower hydraulic conductivity in order to control the flow of infiltration water into the column. The coarse sand soil had an average flow rate of 3.9 x 10^{-6} m^3/s whereas the fine sand soil had an average flow rate of 1.37 x 10^{-6} m^3/s. A screen mesh and a filter geotextile were placed below the 50 mm fine soil layer.

4 INFILTRATION EXPERIMENTS

This paper presents two infiltration tests A and B that were carried out in the soil-geotextile column. Details of tests A and B are presented in Table 1. Test A was conducted with air-dry soil condition, and Test B was conducted with gravity-drained soil. Both tests were repeated under the same test conditions to confirm the repeatability of the tests procedure. To quantify the progress of the wetting front and the measured suctions and positive pore water pressures developing during the infiltration tests, the soil-geotextile column was divided into two Profiles (1 and 2) according to the distribution of the sensors on each side of the column. As shown in Figure 1, Profile 1 includes four ThetaProbes (a, c, e, and g), five tensiometer-transducer sensors (A, B, C, D, and G), and three air pressure sensors (1, 2, and 3). Profile 2 includes two ThetaProbes (b and f), and three tensiometer-transducer sensors (E, H and I). Data from all sensors were continuously logged to a smart data logger and then recorded and monitored on a PC using windows software for sensor/PC operation. During testing, the tensiometers' water filled tubing were frequently inspected for air bubbles and de-aired when necessary.

Table 1: Results from infiltration tests for soil-geotextile column

Infiltration Test	Duration of Infiltration (min)	Breakthrough Time (min)	Breakthrough Head (m)	Flux Rate (m/s)	Initial Soil condition
A	109	11.9	0.25	4.5 x 10^{-2}	Air-dry
B	102	22.7	0.16-0.22	4.05 x 10^{-2}	Gravity-drained

Constant upper and lower boundary conditions were formed at the top and bottom of the soil column. The upper boundary was formed by suppling water to the top of the soil column from a water tank by maintaining a constant head of water (100 mm) (Figure 1). Constant flow of water was applied until a breakthrough through the geotextile specimen occurred. The lower boundary was formed by maintaining a water table (100 mm) (elevation depth z = 0) above the soil column datum. The infiltration tests were conducted at room temperature (20 ± 2°C).

5 EXPERIMENTAL RESULTS

5.1 Infiltration test with air-dried soil (Test A)

Infiltration test A began 2 days after the column was constructed. Infiltration test A was conducted with an applied flow rate of 1.37 x 10^{-6} m^3/s and for a period of 109 minutes. With the propagation of the wetting front downward, the pore-water pressure head profile did not descend in a uniform pattern along the column and did not reach the soil-geotextile interface uniformly in Profiles 1 and 2. Fingering was observed instantaneously after the test started. In Profile 2, transducer "H" located 40 mm below the geotextile started to measure positive pore pressure at 11.90 minutes (0.24 kPa) indicating a breakthrough of water flow through the geotextile specimen. Yet, the breakthrough did not occur in Profile 1 at this time. Air pressure measurements were less than 1 kPa above the geotextile specimen, and 0 kPa below the geotextile specimen throughout the entire test period. This indicates that with the advance of the water front downward, very low air pressures occurred above the soil-geotextile interface, whereas air pressures were negligible below the interface. Figure 2 shows the change in pore water pressure with time for all the tensiometer-transducers sensors (for Profiles 1 and 2).

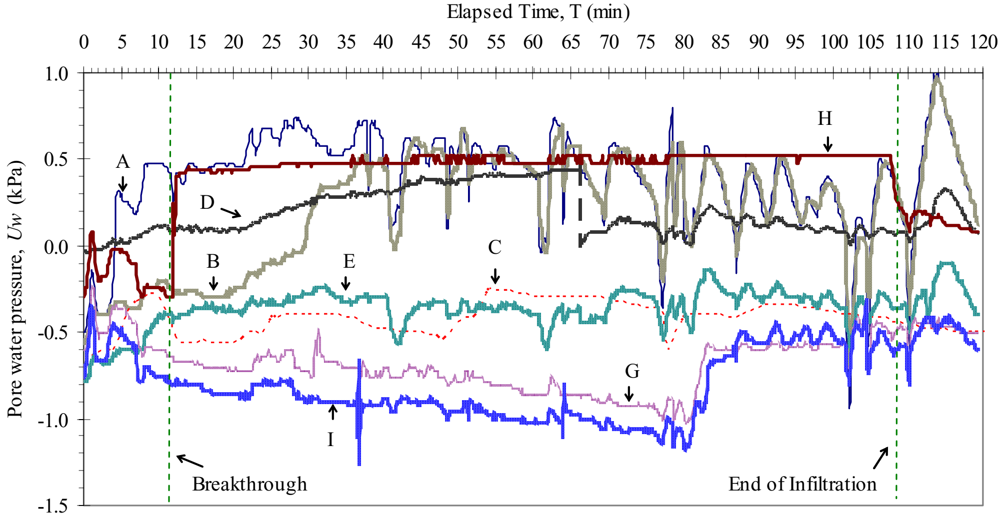


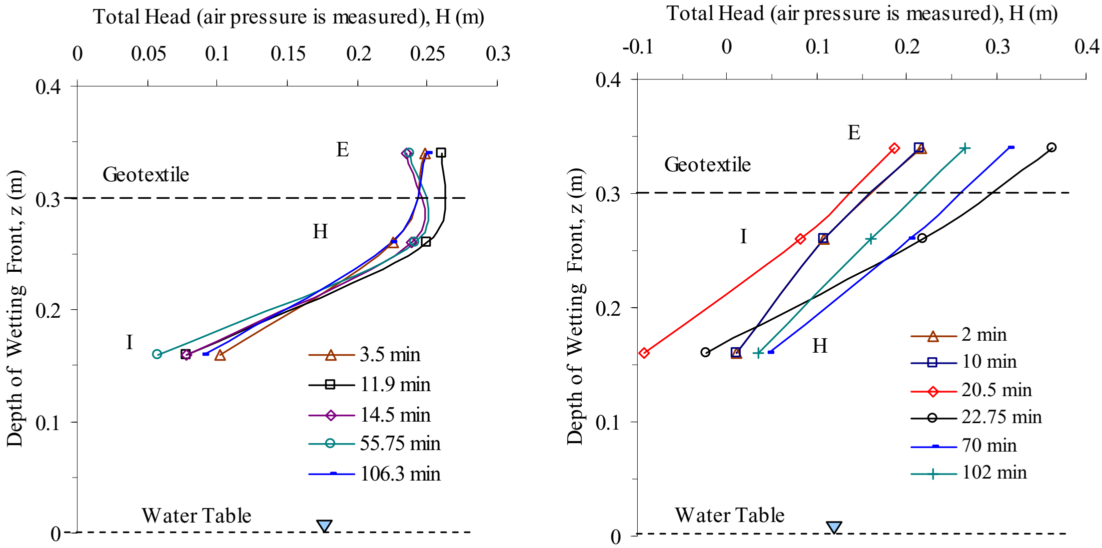
Figure 2: Pore water pressure versus elapsed time for all tensiometer-transducers

5.2 Infiltration test with initially gravity-drained soil (Test B)

Infiltration test B began 1 day after the column was filled, saturated and then gravity-drained. Infiltration test B was conducted with an applied flow rate of 1.37 x 10^{-6} m^3/s and for a period of 102 minutes. From the start of the test, the wetting front advanced downward with the pore-water pressure head profile descending in a uniform pattern throughout the column. The stable water flow in the soil profile in the absence of preferential flow of water (fingering process) indicates that the soil column was at hydrostatic equilibrium from the start of the test. Fingering is considered to occur when there is ponding of surface water above dry coarse sand, and the common conditions for flow instabilities are the vertical flow from a fine soil layer to a coarse layer (Baker and Hillel 1990). The air pressure sensors measured air pressures less than 1 kPa throughout the infiltration test. The breakthrough through the geotextile occurred at 22.7 minutes from the start of the test at the time the wetting front reached the soil-geotextile interface. Both tensiometers "G" and "I" captured the breakthrough at the same time with sensor "I" measuring 0.98 kPa (Profile 1) and sensor "I" measuring 0.4 kPa (Profile 2). At the same time, ThetaProbe "g" measured an increase in volumetric water content of 5.99 % (13.66 % saturation). The testing results showed that the wetting front advanced with stability through the column above and below the geotextile specimen.

6 Discussion

During infiltration testing, the soil column profile followed a wetting path. Breakthrough through the geotextile occurred at the breakthrough head when the geotextile became conductive. Infiltration tests A and B showed a breakthrough head of 0.16-0.25 m for the geotextile regardless of the initial soil water profile condition. The infiltration test results revealed that the gradient for both tests A and B is due to gravity since the total head gradient is close to 1. Therefore, the applied flux is equal to the hydraulic conductivity of the soil layer, for the corresponding water content. This indicates that the water flow was gravitational flow. Figure 3 shows total heads versus depth of wetting front for test A (Figure 3a) and test B (Figure 3b).



(a) (b)

Figure 3: Total head versus depth of wetting front: (a) Test A, Profile 2; (b) Test B, Profile 2

Observations from test A showed development of fingering which was consistent with coarse sand having large grain size overlayed by a finer soil layer and having different hydraulic conductivies. Fingering was observed from the top of the column until the soil-geotextile interface. Figure 3 shows that the total heads at several time intervals are not similar in tests A and B. Figure 3a indicates that the change in the head gradient in test A is due to instabilities in the wetting front. There was no head gradient across the geotextile and the flow was gravitational below the geotextile specimen after the breakthrough. Water downward movement through the coarse sand soil was observed to occur in rapidly draining fingers and not through the entire cross-sectional area of the soil layer. This has been confirmed by Baker and Hillel (1990) and Stormont and Anderson (1999) as a typical condition of soil profile with finer soil overlaying coarser soil. A downward flow in the top layer will tend to form preferential flow paths (fingers) in the sub-layer, when the hydraulic conductivity of a coarse sublayer soil is greater than the flow rate through a finer top soil layer (Baker and Hillel 1990). Stormont et al. (1997) suggested that oils and lubricants (hydrophobic materials) used in geotextile manufacturing can affect their wetting behaviour. Hence, the hydrophobicity of the nonwoven geotextile may have acted as an additional factor for water build up above the geotextile before the breakthrough head was attained. In infiltration test B fingering did not occur which indicates that the coarse soil column and the fine soil cover maintained similar hydraulic conductivities. The soil column was observed as a uniform column and the wetting fronts were stable above and below the soil-geotextile interface in both Profiles 1 and 2. Infiltration test A resulted in a higher flux rate ($q = 4.5 \quad x\ 10^{-2}$ m/s) than infiltration test B ($q = 4.05\ x\ 10^{-2}$ m/s). This shows that with lower flux rates, the wetting front become more stable (Yao and Hendrickx 1996). Figure 3b shows the consistency in pressure heads at several time intervals and indicate a stable head gradient (equals to 1) for the entire infiltration period.

7 CONCLUSIONS

A 1-D soil-geotextile column apparatus was developed for the investigation of water infiltration in a soil-geotextile layered profile. Typical results of two infiltration experiments carried out with air-dry soil and gravity-drained soil after saturation, respectively, are presented in this paper. The experimental data present a new perspective on the direct effect of the initial soil water content, and media type on the stability of the wetting fronts. This was verified by the measurements of the total head gradient of both tests. When the infiltration test was conducted with a dry soil, the wetting fronts became unstable and preferential flow (fingering) occurred. In addition, the hydrophobicity of the geotextile specimen may have led to water ponding above the geotextile before breakthrough. Whereas when the infiltration test was conducted with gravity-drained soil, preferential flow of water (fingering) did not develop in the soil profile. Test results showed that the wetting fronts advanced uniformly and the total head gradient was stable throughout the column height. The findings reported in the present paper implie that the unstable channelling of water fingers in a dry soil filter profile and the geotextile hydrophobicity can affect the stability of earthen structure combining soils and geotextiles.

ACKNOWLEDGMENT

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