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Effect of Wet-Dry Cycles on Capillary Break Formation in Geosynthetic Drainage Layers

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Abstract. This study investigates the impact of wet-dry cycles on the formation of a capillary break between an unsaturated, compacted soil profile and a geosynthetic drainage layer. Moisture content and suction data during infiltration and evaporation from a vegetated landfill test cover in the field and large-scale columns in the laboratory are used to interpret the formation of a capillary break. The landfill cover is a monolithic, low plasticity clay layer over a geosynthetic drainage layer. It was monitored for six years to assess the movement of water through the system under actual atmospheric boundary conditions. Two laboratory column tests were used to interpret the behavior noted in the field. A longer column was used to observe the moisture profiles in the soil during controlled infiltration and evaporation events. Similar moisture profiles observed in the laboratory and field suggest formation of a capillary break. A shorter column was used to investigate the influence of wet-dry cycles on the formation of a capillary break. The capillary break was observed to occur at the same suction value upon repeated wet-dry cycles.

INTRODUCTION

Geosynthetic drainage layers consisting of a geonet sandwiched between two nonwoven geotextiles are often used to provide drainage of water from soil profiles. Important geotechnical applications involving geosynthetic drainage layers include leachate collection and leak detection systems in landfills, lysimeters for performance evaluation of alternative landfill cover systems, sub-base separation systems in roadways, and drainage systems for mechanically stabilized earth walls. When saturated, the permittivity and transmissivity of geosynthetic drainage layers are typically higher than the soil being drained, and do not have a significant impact on the flow of water through the system. The behavior of a saturated system can be characterized using only the hydraulic conductivity values of the soil and geosynthetic drainage layer. When the system is unsaturated (*i.e.*, at suctions greater than 1 kPa), geosynthetic layers are practically non-conductive to water even though most fine-grained soils can still transport water. Depending on the soil, the geosynthetic drainage layer may have a significant impact on the flow of water through an unsaturated system. In this case, there are two hydraulic properties that can be used to interpret the interaction between unsaturated soils and geosynthetics, the water retention curve (WRC) and the hydraulic conductivity function (K-function). Due to their uniform and relatively large pore size, nonwoven geotextiles will retain an amount of water equal to their porosity until reaching a certain suction value, at which they drain to residual water retention (Stormont *et al.* 1997). At residual water retention, the hydraulic conductivity of a porous media is negligible. This behavior implies that movement of water through an unsaturated soil into a nonwoven geotextile is influenced by the capillary break effect (McCartney *et al.* 2005). A capillary break is evidenced as an increase in moisture storage of the soil in excess of the volume that would be stored during flow under a unit hydraulic gradient. This effect prevents water from flowing from the soil into the geosynthetic drainage layer until the suction at the interface is reduced to the point at which the geotextile becomes conductive to water. When this critical suction is reached, referred to as the water entry or breakthrough suction, the hydraulic conductivity values of the two materials are similar and drainage will occur across the interface.

This study investigates the hydraulic interaction between unsaturated, low plasticity, compacted clay and a geosynthetic drainage layer. Specifically, results from a vegetated landfill test cover in the field and from large-scale soil columns in the laboratory are used to interpret the formation of a capillary break during cycles of wetting and drying. Results from the field study are used to interpret the movement of water through a clay-geosynthetic system under actual atmospheric boundary conditions, while results from the laboratory study are used to observe the formation of a capillary break during controlled infiltration and evaporation events.

MATERIALS

Geosynthetic Drainage Layer. The geosynthetic drainage layer used in the laboratory component of this study is a 12.5 mm-thick GSE Fabrinet® geocomposite, composed of a 200-mil geonet sandwiched between two 6 oz/yd^2 polypropylene nonwoven geotextiles (GSE 2004). The geosynthetic drainage layer used in the field component of this study also included 6 oz/yd^2 polypropylene nonwoven geotextiles, but is not commercially available. The hydraulic interaction between the soil and geosynthetic drainage layer is associated with the porosity of the nonwoven geotextile, which can be calculated as follows (Koerner 2005):

$$\eta = 1 - \frac{\mu}{t\rho_f} \tag{1}$$

The nonwoven geotextile component has a thickness t of 2.56 mm, a mass per unit area μ of 20 kg/m^2, and a fiber density ρ_f of 910 kg/m^3. The porosity of the nonwoven geotextiles was calculated to be 0.99. The porosity is used to calculate the degree of saturation from the gravimetric water content of the geotextile.

Compacted Clay. The low plasticity clay (CL) used in this study has a specific gravity of 2.708, an average plasticity index of 12%, and an average liquid limit of 27%. The same soil used in the field study was used in the laboratory tests. The specified range of relative compaction in the field was 70 to 80% of the maximum standard proctor dry density (1902 kg/m^3). In the laboratory and field, the clay was compacted at the optimum water content of approximately 11.5%. The compaction energy was controlled using a lightweight roller in the field, and using a Bellofram piston compactor in the laboratory.

Hydraulic Properties. The hanging column and pressure plate methods (Wang and Benson 2004) were used to define drying-path WRCs for the nonwoven geotextile component of the geosynthetic drainage layer and for specimens of the clay at relative compactions of 70% and 80%. The WRC results shown in Figure 1(a) indicate that the nonwoven geotextile drains from saturation to residual conditions at a suction of approximately 0.2 kPa, while the clay drains more gradually. The porosity of the clay soil is 0.49 for the specimen with RC = 70% and 0.44 for the specimen with RC = 80%. The density has only a slight impact on the SWRC. The he hydraulic conductivity of saturated soil and geosynthetic drainage layer specimens was assessed using a flexible-wall permeameter. The specimens were back-pressure saturated with tap water as the permeating fluid. An effective stress of 7 kPa was used, along with an average hydraulic gradient of 2.0. The K-functions shown in Figure 1(b) for the different materials were predicted from the WRC using the van Genuchten-Mualem model (1980). The hydraulic conductivity of the geotextile is higher than the clay when saturated, but is lower for suction greater than 2 kPa.

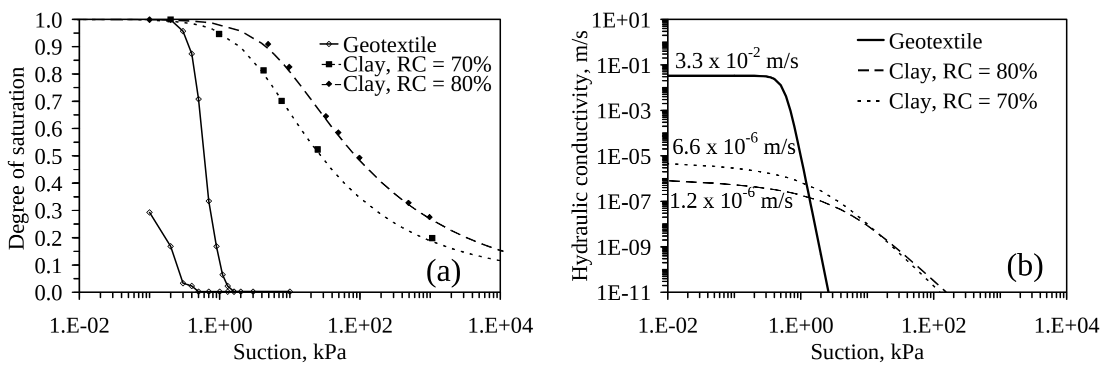


Figure 1: Hydraulic properties of compacted clay and nonwoven geotextile; (a) Water retention curves; (b) K-functions predicted from WCRs

FIELD STUDY

The landfill test cover is located at the Rocky Mountain Arsenal, near Denver, Colorado. It consists of a 1.27-m-thick monolithic layer of low plasticity clay atop a geosynthetic drainage layer. The system is underlain by a 60-mil geomembrane placed on a 3% grade in order to collect the water that passes through the system (referred to as percolation). The combination of a geosynthetic drainage layer and geomembrane is referred to as a lysimeter. The test cover was built in the summer of 1997 and was monitored until 2003. The soil was vegetated with Cheatgrass, a local plant with a rooting length less than the thickness of the cover. A schematic of the cover is shown in Figure 2. The cover was instrumented with a weather station to measure precipitation. The cover also has a vertical nest of 6 horizontally-oriented water content reflectometer (WCR) probes, which infer the volumetric moisture content. The depth of each probe is shown in Figure 2. More information on WCR probes can be found in McCartney and Zornberg (2006).

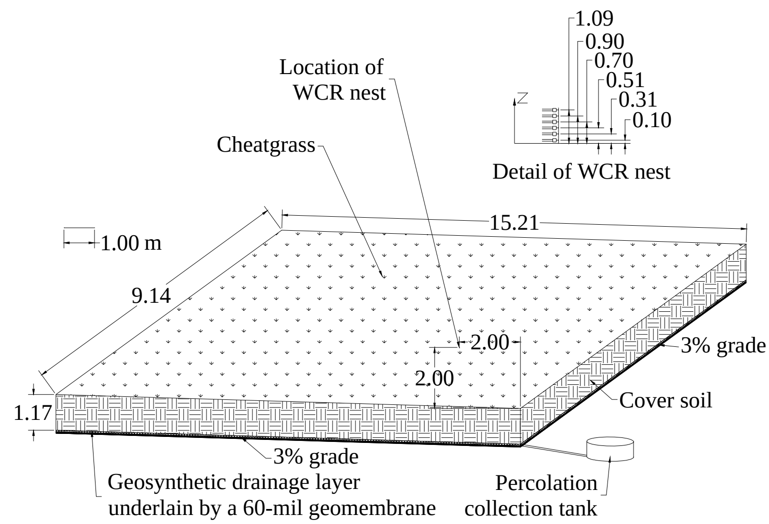
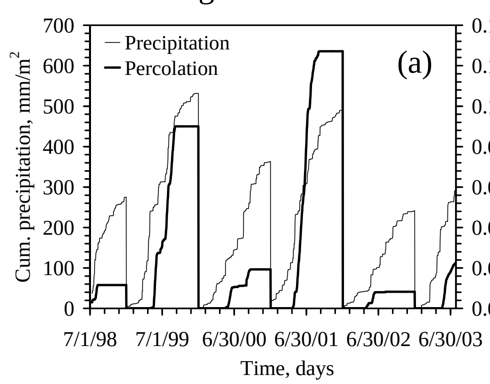


Figure 2: Schematic of the landfill test cover

The precipitation and percolation for the test cover are shown in Figure 3(a). The percolation collected from the lysimeter is concurrent with periods of high precipitation (spring and early summer months). The annual percolation was less than 0.02% of the annual precipitation. The moisture content time series shown in Figure 3(b) indicate that the base of the cover was the highest at the times that percolation was observed. However, the moisture content at the base of the cover often reached higher moisture content values than the rest of the cover.



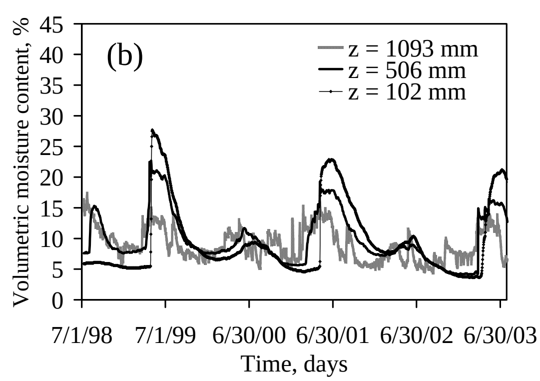


Figure 3: (a) Precipitation and percolation; (b) Moisture content time series

The moisture content profiles shown in Figure 4(a) illustrate the migration of a wetting front through the cover. The wetting front progresses at a moisture content of 20%, but after reaching the base the moisture content increases to approximately 28%. This is referred to as ponding, and is evidence of a capillary break effect. Percolation was observed after ponding occurred. Of particular interest to this study is the fact that the cover "recovered" after ponding occurred. Specifically, the soil dried over the course of six months due to evaporation and plant transpiration, as shown in Figure 4(b). The ponding and recovery trends were observed to occur on two subsequent occasions during the six year monitoring period, as indicated in Figure 3(b). This behavior has important implications on the behavior of landfill covers that rely on a capillary break to prevent moisture migration into a waste mass.

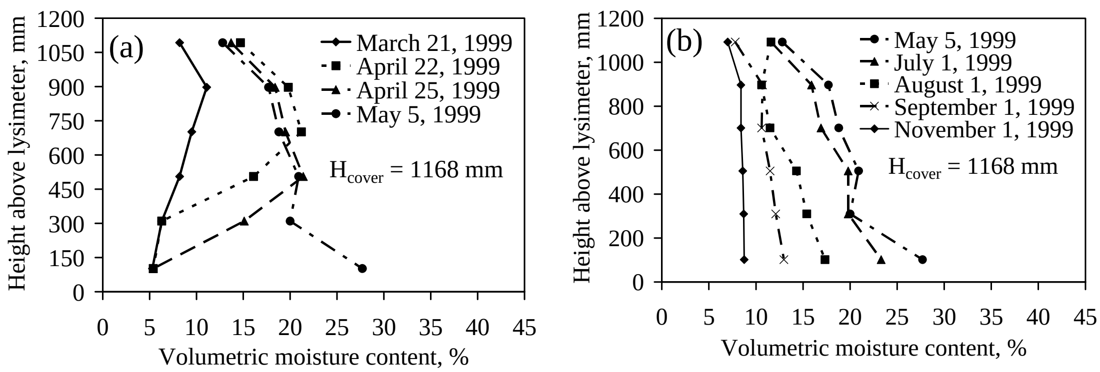


Figure 4: Moisture content profiles: (a) Wet season; (c) Dry season

LABORATORY TESTING PROGRAM

Soil Profiles. To investigate the behavior noted in the field program in a controlled setting, two soil-geosynthetic profiles were constructed in 203-mm diameter cylindrical columns. The columns are clear PVC tubes mounted with an “o”-ring seal onto a perforated acrylic disc, supported by a wooden platform. Tensioned wires are used to confine the permeameter to the acrylic disc. Outflow is measured using a tipping bucket rain gauge mounted below the acrylic disc. Profile A is a 1350-mm-thick clay layer placed at a relative compaction of 70% above a geosynthetic drainage layer. This profile is used to replicate the moisture and suction profiles observed in the field during controlled infiltration and evaporation events. Profile B is a 125-mm-thick clay layer placed at a relative compaction of 80% above a geosynthetic drainage layer. This profile is used to investigate the influence of wet-dry cycles on the formation of a capillary break. A schematic of the two profiles is shown in Figure 5.

Test Procedures. The geometry, soil conditions, and wet-dry cycles are summarized in Table 1. During infiltration, water is supplied to a reservoir on the surface of the soil profile via a peristaltic pump, and the water is distributed from the reservoir to the soil surface using a system of cotton fiber wicks. The walls of the cylinder were greased to minimize side-wall leakage. The flow rates were selected to be less than the saturated hydraulic conductivity of the clay to ensure unsaturated conditions. Air entrapment during infiltration is expected, but this is still representative of conditions in surface soils. Each infiltration stage involved applying the flow rate, measuring the volumetric moisture content and suction changes with time as the wetting front progresses through the soil. Infiltration was complete when the outflow discharge velocity was the same as the inflow discharge velocity. During evaporation, an infrared lamp and a fan were used to induce drying from the soil surface, as shown in Figure 5(b). A piece of fiberglass insulation with a hole having the same diameter as the column was placed on top of the column to limit heating of the sides of the column. Each evaporation stage involved measurement of the surface temperature and relative humidity along with the moisture content and suction changes with depth during drying. Thermocouples were also used to measure the temperature in profile.

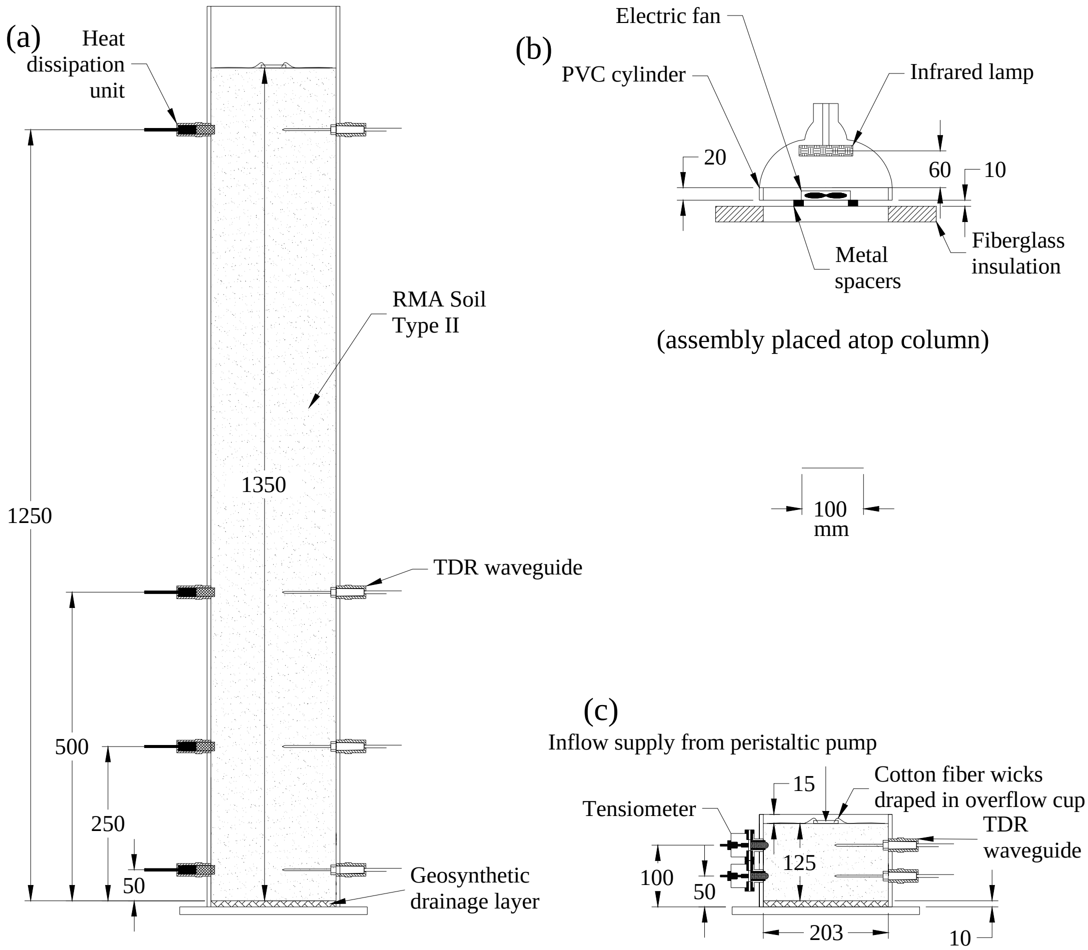


Figure 4: Column testing apparatus: (a) Profile A; (b) Evaporation setup; (c) Profile B

Table 1: Details of the laboratory column testing program

Column name	Length (mm)	Relative compaction %	Compaction water content (%)	*n*	$K_{s,system}$ (m/s)	Phase name	Phase description	Duration (hs)	Infiltration rate (m/s)	Evaporation surface suction (kPa)
A	1350	70	11.5	0.49	6.20E-06	A1(i-1)	Infiltration	2423	3.4E-09	N/A
						A1(i-2)	Infiltration	683	6.5E-08	N/A
						A1(e)	Evaporation	2179	N/A	3.0E+05
						A2(i)	Infiltration	819	3.4E-08	N/A
						A2(e)	Evaporation	857	N/A	3.0E+05
B	125	80	11.5	0.44	1.20E-06	B1(i)	Infiltration	135	8.0E-09	N/A
						B1(e)	Evaporation	101	N/A	3.0E+05
						B2(i)	Infiltration	93	8.0E-09	N/A
						B2(e)	Evaporation	174	N/A	3.0E+05
						B3(i)	Infiltration	596	8.0E-09	N/A

Note: N/A is not applicable

$$\text{Boundary Suction} = -\frac{\rho_w RT}{M_w}\ln\left(\frac{R_h}{100\%}\right)$$

where ρ_w = water density, R = universal gas constant, T = temperature in K, Mw = molecular mass of water vapor, and R_h = relative humidity in percent

Monitoring System. Volumetric moisture content was inferred during infiltration using time domain reflectometry (TDR). The TRASE© system developed by SoilMoisture, Inc. (1996) was used in this study. Suction was measured using flushing tensiometers and heat dissipation units (HDUs) embedded in the walls of the columns. Ridley and Burland (1995) describe the use of tensiometers, while Flint et al. (1999) describe the use of HDUs. Tensiometers are particularly useful for measurement of suction near saturation (less than 100 kPa), while HDUs are useful for measurement of high suctions (greater than 100 kPa). The soil was placed into the columns in 25 mm lifts using the Bellofram compactor. The TDR waveguides were placed in the middle of a lift. The tensiometers and HDU were screwed into the walls of the column after compaction.

RESULTS

The inflow and outflow data in Profile A during the different phases, shown in Figure 5(a), highlight the testing time involved in this study. The progress of the wetting front shown in Figure 8(b) indicates that the initial wetting front reached the base of the profile in 1400 hs, but capillary breakthrough did not occur until 1874 hs.

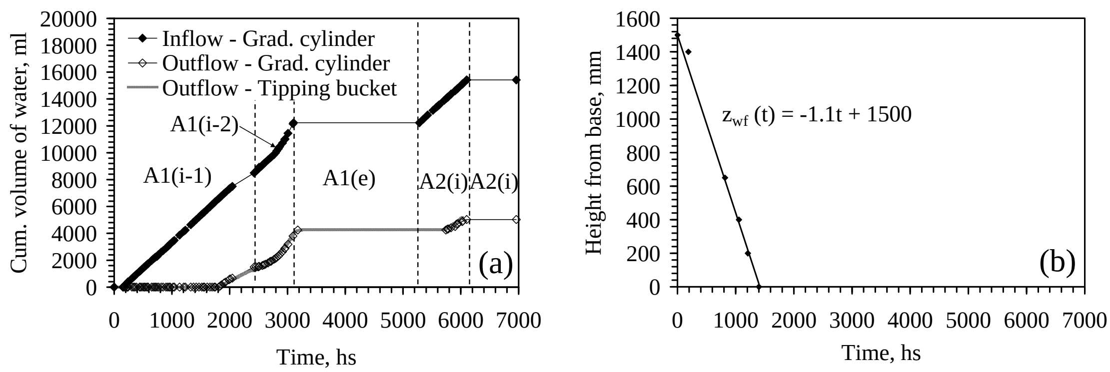


Figure 6: Profile A: (a) Cumulative inflow and outflow; (b) Initial wetting front

The four suction time series for Profile A, shown in Figure 7(a), indicate that the HDUs are relatively responsive to changes in suction during the initial infiltration phase and during evaporation, they were not sensitive to changes in suction below 20 kPa. Accordingly, they did not prove useful for investigation of the capillary break effect. The four moisture content time series shown in Figure7(b) indicate that a wetting front passed through the cover at a moisture content of 24%, but increased in moisture content after reaching the base of the profile. The moisture profiles shown in Figure 7(c) indicate that ponding occurred in the profile, similar to the field study results in shown in Figure 4(a). Different from the field study results, the moisture content at the base was close to saturation before breakthrough occurred. During the first evaporation phase (3100 hs), the moisture content nearest to the surface of the profile decreased. The suction at this depth also increased to 40 kPa. A decrease in moisture content was noted at the other TDR locations, but this was more likely due to gravity drainage. Gravimetric water content measurements indicate that the drying front progressed 700 mm into the cover during Phase A1(e). The data in Figure 3(b) indicate that the base of the cover (1093 mm) decreased slightly in moisture content after two months, likely due to percolation after capillary breakthrough, but required approximately six months of drying and transpiration to dry from 28% to 10%

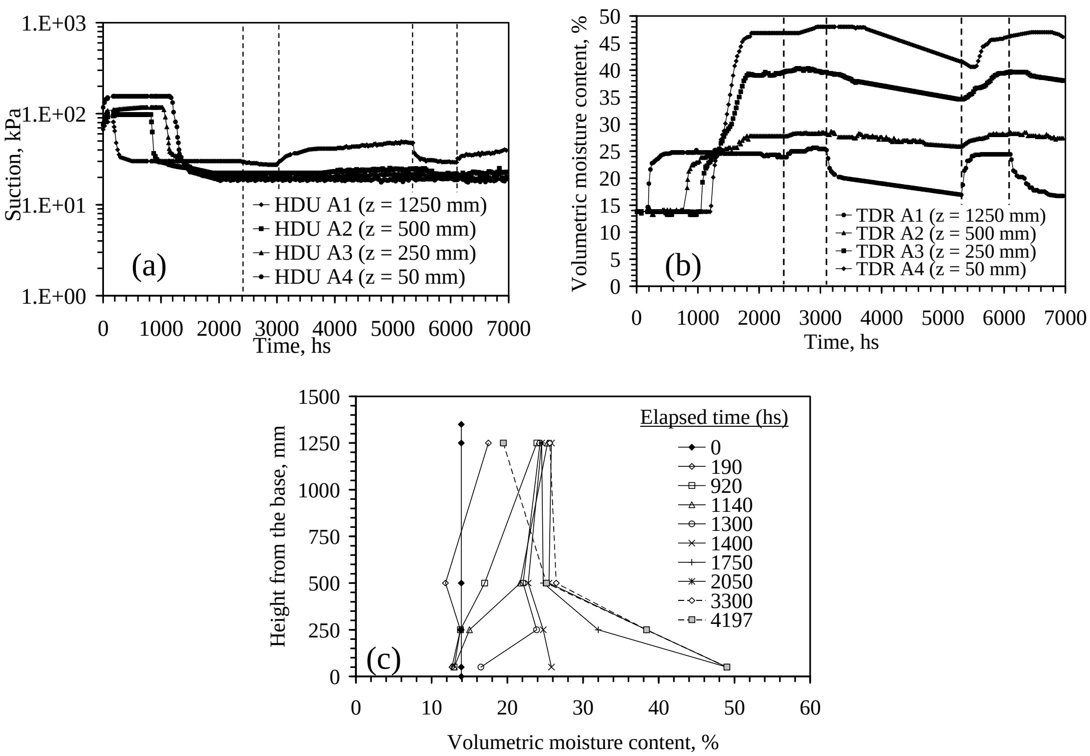


Figure 7: Profile A: (a) Suction; (b) Moisture content; (c) Moisture content profiles

The inflow and outflow during the different phases for Profile B are shown in Figure 8(a), and the resulting changes in temperature and relative humidity at different locations in the column are shown in Figure 8(b). The infrared lamp led to an increase in surface temperature from 23 to 44 °C and a decrease in surface relative humidity from 96 to 13%. The temperature in the soil also increased significantly during early stages of evaporation, but reached a steady-state profile after 40 hs. This translates to a steady-state total suction at the surface of approximately $3x10^5$ kPa.

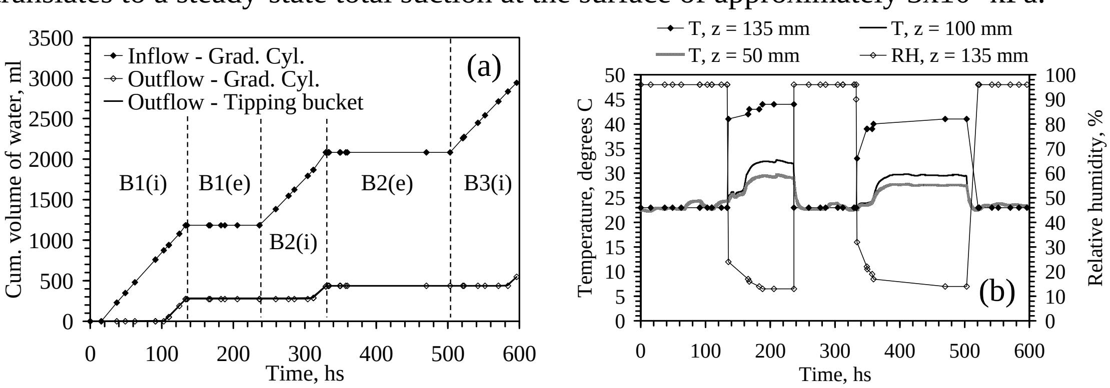
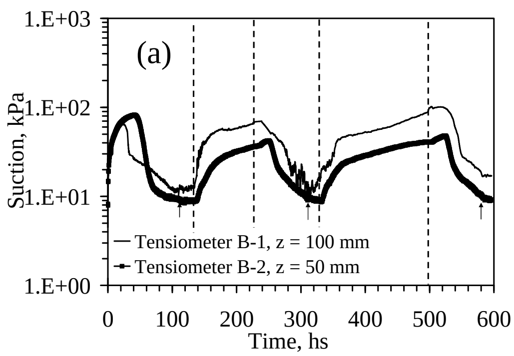


Figure 8: (a) Cumulative inflow and outflow; (b) Temperature and relative humidity

The boundary has a significant effect on the suction and moisture content in Profile B due to its short length. However, it is very useful to investigate the behavior of the interface. The suction time series for Profile B shown in Figure 9(a) indicates that tensiometers were more suitable for measurement of suction near capillary breakthrough. The tensiometer at a height of 100 mm was affected by vibrations from the fan at low suctions. The tensiometers required about 40 hours to come into equilibrium with the initial suction in the soil at the beginning of testing. Despite different durations of the three wet-dry cycles conducted for this profile, breakthrough occurred at approximately the same suction. Unlike the moisture content time series for Profile A, the upper portion of the profile did not remain at a moisture content of the wetting front, but quickly increased due to ponding about the geosynthetic drainage layer. The first bend after infiltration was started corresponds to passage of the wetting front. The moisture content at this bend was consistently about 24%. A second, consistent bend in the moisture content after infiltration was observed slightly before capillary breakthrough. The moisture content and suction time series indicate that the profile never fully dried, as the upper sensor location was always drier than the lower sensor location (except initially). A capillary break may have also occurred in the profile if long-term drainage was allowed after the initial infiltration phase (*i.e.*, no evaporation). However, as the main indicator of a capillary break is the moisture content profile, a capillary break may not have been apparent.



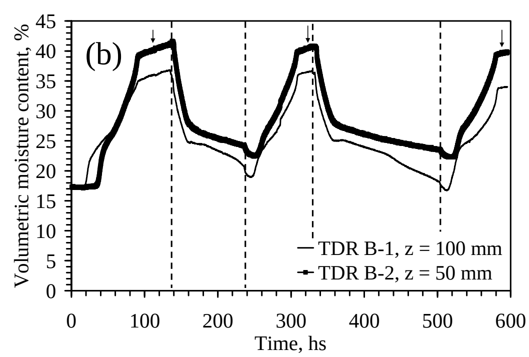


Figure 9: Profile B: (a) Suction; (b) Moisture content (Arrows denote breakthrough)

DISCUSSION

The results of Profiles A and B are summarized in Table 2. It is interesting to note similarities between the two profiles: the moisture content and suction at the wetting front are similar (24% and 25 to 30 kPa), and the breakthrough moisture content is at a similar degree of saturation (94%). The breakthrough degree of saturation of 94% and breakthrough suction of 3.6 kPa are consistent with the transition of the geotextile WCR from residual conditions to saturated conditions [Figure 1(a)]. The speeds of the wetting and drying fronts are also similar in the field and laboratory profiles, despite differences in density and infiltration rates.

Table 2: Summary of column test results

Column name	Wet-dry cycle	Depth of evaporation front	Speed of wetting front	Suction at wetting front	Moisture content at wetting front	Time until steady state infiltration	Breakthrough suction	Breakthrough moisture content	Speed of evaporation front
		(mm)	(m/s)	(kPa)	(%)	(hs)	(kPa)	(%)	(m/s)
A	A1	500	2.7E-07	30.1	24.7	1874	?	46.2	?
	A2	700	1.0E-06	29.6	24.4	453	?	45.6	?
B	B1	125	9.6E-07	21.1	24.3	105	3.64	40.2	3.5E-06
	B2	125	1.5E-06	25.0	24.1	75	3.74	40.5	3.1E-06
	B3	125	1.8E-06	25.8	24.2	83	3.64	39.6	N/A

The transient WRCs for Profile B, shown in Figures 10(a) and 10(b), were obtained from the TDR and tensiometer data. The wetting and drying paths follow the WRC for clay with a relative compaction of 80% [see Figure 1(a)]. It is common to obtain the drying WRC in practice, so these results indicate that it may not be a bad approximation to estimate the breakthrough suction from the drying WRC.

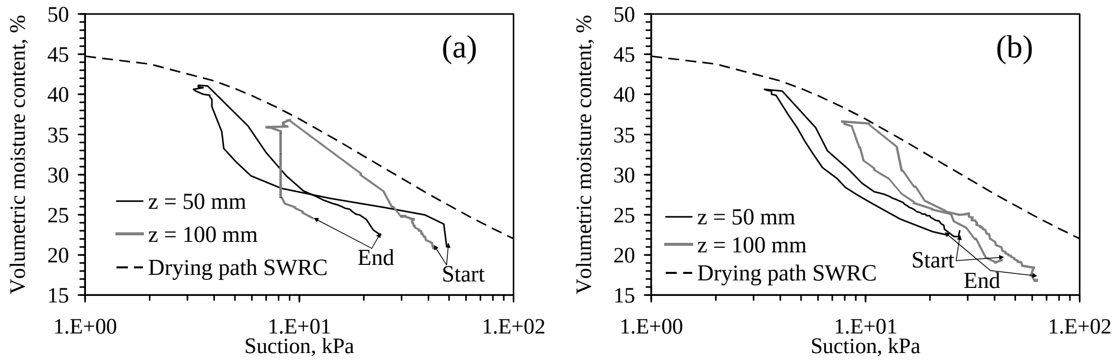


Figure 10: Transient WRC for Profile B: (a) Cycle 1; (b) Cycle 2

The results of this study indicate that the capillary break effect will occur at the same suction and moisture content after repeated wet-dry cycles. This finding implies that cover systems using geosynthetic drainage layers, like the test cover described herein, can effectively cause a capillary break effect, which may provide additional moisture storage during significant storms.

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