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Geosynthetic Capillary Barriers

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ABSTRACT: An overview of the interaction between soils and geosynthetics under unsaturated conditions is provided in this paper. In particular, this paper presents information useful to assess the development of a capillary barrier at the interface between soil and geosynthetics. Specific applications are presented to illustrate new opportunities and applications that may result from a better understanding of the unsaturated hydraulic properties of geosynthetics. Experimental data is provided illustrating that geosynthetic capillary barriers are superior to soil-only capillary barriers. Based on this observation, it is emphasized that no capillary barrier should be designed without consideration of the enhanced performance offered by the inclusion of nonwoven geotextiles under the fine-grained soil component of the cover.

1. INTRODUCTION

A capillary barrier develops when an unsaturated fine-grained soil layer is underlain by another unsaturated porous material with relatively large-sized pores, such as a coarse-grained soil layer (e.g. sand, gravel), or a porous geosynthetic (e.g. a nonwoven geotextile). This phenomenon was initially observed in geotechnical and geoenvironmental applications involving earthen materials (Rasmusson and Eriksson 1987; Nicholson *et al.* 1989; Barbour 1990; Shackelford *et al.* 1994; Yanful 1993; Woyshner and Yanful 1995). The capillary break effect that develops in systems involving geosynthetics [*e.g.,* geosynthetic drainage layers (GDLs)] has been evaluated only more recently. The main impact of the capillary break effect on an unsaturated soil-GDL system is that a measurable amount of water will not flow from the soil into the underlying GDL until reaching a critical condition (Stormont 1995; Bouazza *et al.* 2006a). Because of this, the capillary break effect has been observed to increase the water storage capacity of soils beyond the level that would normally drain under gravity (Stormont and Morris 1998; Khire *et al.* 2000).

Key to the understanding of capillary barriers is the assessment of water flow and storage in porous geomaterials (e.g. soils, geosynthetics) under unsaturated conditions. As a geomaterial desaturates, its hydraulic conductivity does not remain constant but, instead, drops significantly with decreasing degrees of saturation. The hydraulic conductivity of unsaturated geomaterials with relatively large pores (e.g. gravel, geotextiles) decreases faster than that of fine-grained soils. This characteristic leads to the counterintuitive situation in which the hydraulic conductivity of unsaturated gravel or geotextiles can be significantly smaller than that of fine-grained soils (e.g. orders of magnitude smaller than the saturated hydraulic conductivity of the bentonite component of GCLs).

Understanding of the concepts of water flow in unsaturated soils has gained added relevance in landfill design due to the increased number of alternative covers that have been recently designed and constructed for waste containment and mine tailing facilities. Specifically, capillary barriers have been recently used in lieu of geomembrane liners in multiple projects located in arid and semi-arid sites (e.g. in the Western United States, Western Australia, South Africa). It turns out that geosynthetics not only can be used in capillary barrier systems but, as will be demonstrated in this paper, they provide superior performance to soil-only capillary barriers. Geosynthetic capillary barriers have been recently permitted, designed, and constructed in high-visibility, hazardous waste facilities in the United States.

2. HYDRAULIC PROPERTIES OF UNSATURATED GEOTEXTILES

Among the various types of geosynthetics, geotextiles have been used in geotechnical engineering applications to fulfill the widest range of functions (Koerner 2005, Zornberg and Christopher 2007). This includes separation between different soil layers, protection of geomembranes or other geosynthetics from puncture, drainage from surrounding soil, and reinforcement of poorly draining backfills. Geotextiles are able to meet these requirements despite their small thickness (e.g. 2.5 mm) partly due to their high porosity (typically about 0.9), which is greater than that of most soils. Geotextiles have a uniform pore size compared to most soils (Palmeira and Gardoni 2002, Aydilek *et al.* 2007). In addition, important hydraulic properties of unsaturated geotextiles include their water retention curve and their hydraulic conductivity function.

A thorough overview of the state of the practice on the interaction between unsaturated soils and geosynthetics was presented during the First African Conference on Geosynthetics (Zornberg et al. 2009, 2010). This paper provides a summarized and updated version of the current state of the knowledge on geosynthetic capillary barriers.

2.1 Water Retention Curve

The water storage of soil and geosynthetics is typically quantified using the relationship between volumetric water content and suction, referred to as the Water Retention Curve (WRC). Figure 1 shows the WRCs for different geotechnical materials. The coarser materials (sand and geotextile) show a highly nonlinear response, with a significant decrease in water content (or degree of saturation) within a comparatively narrow range of suction. The fine-grained soil shows instead a more gradual decrease in water content with increasing suction. The nonlinearity observed in these relationships is partly caused by the range of pore size distributions in these materials. During initial drying of a fully saturated geomaterial, the negative pressure in the water increases, but water does not flow from the geomaterial until the value of suction corresponding to the air entry value is reached. When this suction value is reached, air enters the specimen and the water content decreases. After reaching the air entry value, the water content drops from saturation to a value that remains approximately constant with increasing suction. This low water content value is often referred to as the residual water content. The residual condition occurs because the water becomes occluded (or disconnected) within the soil pores, with no available pathways for water to flow.

The WRC for a given material is not only sensitive to the pore size distribution, but also to the soil mineralogy (for the case of soils), polymeric material (for the case of geosynthetics), density, and pore structure (Hillel 1988, Bouazza *et al.* 2006a, 2006b). The WRC can show significantly different wetting and drying paths, a phenomenon referred to as hysteresis (Topp and Miller 1966, Kool and Parker 1987, Bouazza *et al.* 2006a). During drying, the largest pores drain first, followed by the smaller pores. During wetting, the smaller pores fill first, but the presence of large pores may prevent some of the small pores from filling. Also, wetting of a dry geomaterial often leads to entrapment of air in the larger pores, preventing saturation of the media unless positive pressure is applied to the water. Air entrapment causes the wetting path to be relatively flat for high suction, with a steep increase in volumetric water content at lower suctions. Several techniques have been developed to determine experimentally the WRC of soils (Wang and Benson 2004, Klute *et al.* 1986). These techniques have been recently adapted to obtain experimentally the WRC of geotextiles. Two main groups of techniques that have been used to define the WRC include physical techniques and thermodynamic techniques.

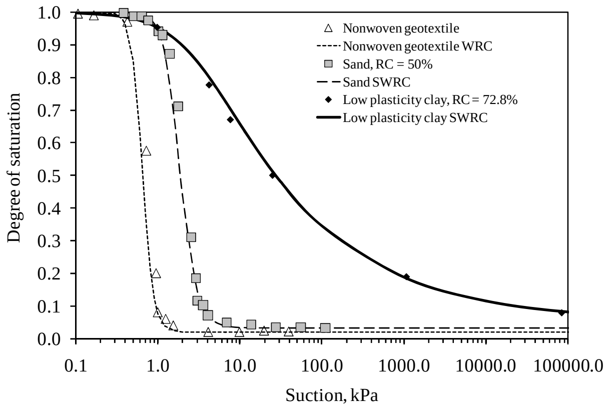


Figure 1. Typical WRCs for different geotechnical materials (after McCartney *et al.* 2005)

The first group of techniques ("physical" techniques) involves an initially water-saturated geomaterial from which water is slowly expelled by imposing suction to a specimen boundary. Flow continues until reaching a condition at which the water content and suction are in equilibrium. The most commonly used physical technique for geotextiles is the hanging column test. A schematic of a typical hanging column used for soils is shown in Figure 2(a). This test involves a ceramic plate that is connected to a manometer tube. A negative pressure is imposed on the ceramic plate by holding the water level in the manometer tube beneath the plate. Stormont *et al.* (1997) applied the experimental technique available for soils to measure the water retention functions of geotextiles. The testing apparatus is similar to the hanging column apparatus used for testing the water retention functions of soils as presented by Klute (1986). The apparatus consists of a Buchner filter funnel fitted with a porous plate, a bottle acting as a water reservoir, and tubing used to connect the bottom of the funnel to the bottom of the bottle as well as the top of the funnel to the top of the bottle. The original test schematic as presented by Stormont *et al.* (1997) is shown below in Figure 2(b). The geotextile specimen is placed on the porous ceramic plate under a seating load to facilitate contact between the two porous materials. The porous plate is initially saturated and connected to the reservoir. The funnel is moved to different elevations above the air-water interface in the reservoir to impose a target suction value to the geotextile specimen. The specimen is removed from the testing apparatus after equilibrating at a desired suction (typically 24-hours) and weighed to determine the water content at the target suction. The measured values of suction and water content are then used to define one point of the WRC. Other variations of the hanging column test have been reported by McCartney *et al.* (2005) and by Bouazza *et al.* (2006a, 2006b). Variations include flushing of the geotextile samples with CO_2 and extended equilibration times.

Another common physical technique is the axis translation or pressure plate test. Figure 3(a) shows the typical setup used for soil testing, which involves placing a soil specimen on a ceramic plate that conducts only water and applying air pressure to the specimen. The air pressure leads to a hydraulic gradient in matric suction in the specimen, causing the pore water to flow through the ceramic plate. At equilibrium, the air pressure corresponds to the capillary pressure since the water pressure is kept equal to zero. The outflow volume is then measured using a constant head Mariotte bottle. This approach is repeated for successively higher pressures that gradually dry the specimen. The pressure may be subsequently decreased to measure the wetting behavior. At the end of testing the gravimetric water content is measured destructively, and the water content at each pressure increment can be back-calculated from the outflow measurements. Additional details regarding the testing procedure can be found in the ASTM standard for WRC determination (ASTM D6836 2002). Knight and Kotha (2001) modified the technique used for soils to measure the water retention function of nonwoven geotextile specimens. Nahlawi *et al.* (2007a) and Bathurst *et al.* (2009) modified further the capillary pressure cell to accommodate large diameter samples and to very accurately control the air pressure through a pneumatic pressure controller. Before testing, the geotextile and the porous ceramic disc were flushed with CO_2 to facilitate the solution of air bubbles in the wetting phase. The test apparatus is shown schematically in Figure 3(b).

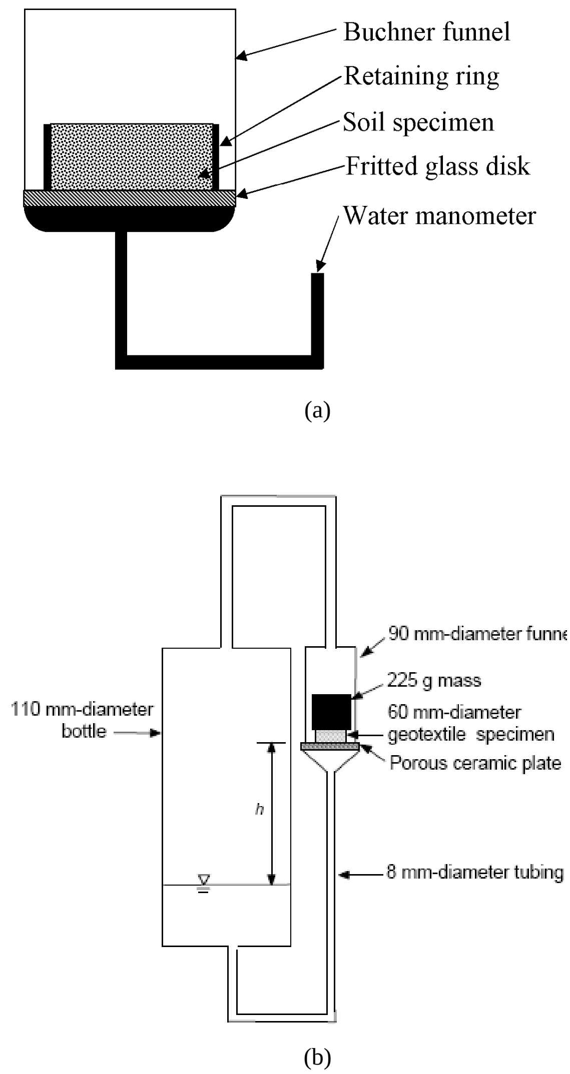
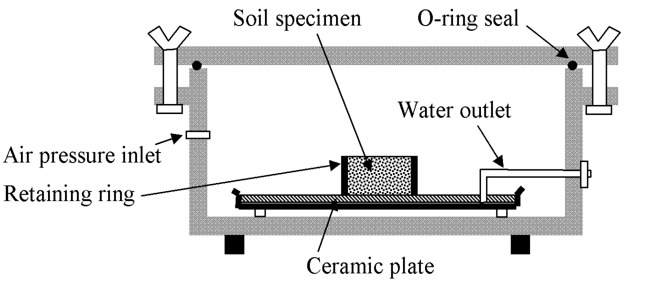


Figure 2. Hanging column test: (a) Conventional test used for soil specimens; (b) Modified test used for geotextile specimens (Stormont *et al.* 1997)

The second group of techniques ("thermodynamic" techniques) involves allowing water to evaporate from a specimen in a closed chamber under controlled relative humidity. The relative humidity is controlled by allowing water to evaporate from a saturated salt solution placed within the chamber, as shown in Figure 4. Another commonly used thermodynamic technique is the chilled mirror hygrometer (Wang and Benson 2001). This device infers the total soil suction (matric and osmotic) by measuring the vapor pressure in the soil, which is related to the temperature at which water condenses on a mirror. When condensation occurs, a change in the optical properties of the mirror is detected. In general, physical techniques are used for relatively low suctions (*e.g.* under 1500 kPa) while thermodynamic techniques are used for higher suctions. Thermodynamic techniques have not been used for the case of geosynthetics probably because the water content of geotextiles at high suction values is so low that its measurement has not been needed for practical applications.



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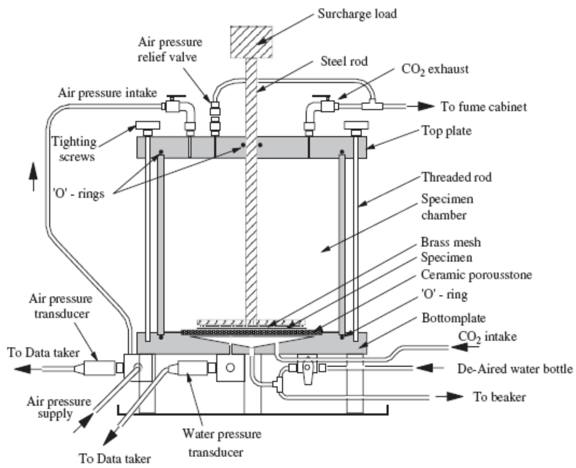


(b)

Figure 3. Pressure plate test: (a) Conventional test used for soil specimens; (b) Modified test used for geotextile specimens (Nahlawi *et al.* 2007a)

A technique not used for characterization of the WRC of soils, but that has proven useful for characterization of geotextiles is the capillary raise test. Specifically, Henry and Holtz (1997) monitored water capillary rise by submerging one end of a strip of geotextile in water and measuring the height to which the water rises. The height of capillary rise provides a good estimate of the water entry suction of the material in the in-plane direction (Stormont and Ramos, 2004, Nahlawi *et al.* 2008). A modification of this technique was presented by Lafleur *et al.* (2000), who measured the in-plane water retention function by submerging the end of a 500 mm long geotextile specimen strip in water and allowing it to equilibrate during 72-hours. The volumetric water content was measured at different positions above the water surface by cutting the specimen into 20 or 50 mm-long segments and weighing the samples before and after oven drying. Variations of this testing approach are discussed by Stormont and Ramos (2004), Krisdani *et al.* (2006), and Nahlawi *et al.* (2008). The test setup as presented by Lafleur *et al.* (2000) is shown in Figure 5. In-plane drying tests have also been conducted using initially saturated geotextile strips that are allowed to drain vertically under gravity, thus allowing the development of the in-plane WRC of geotextile in both wetting and drying paths (Nahlawi 2009).

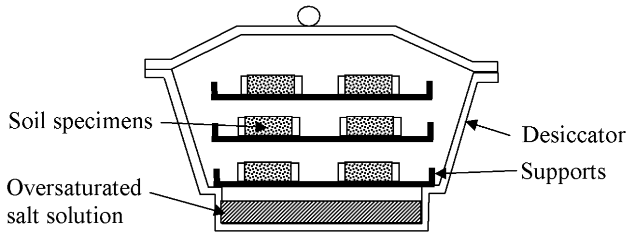


Figure 4. Conventional methods to determine the soil WRC using saturated salt solutions

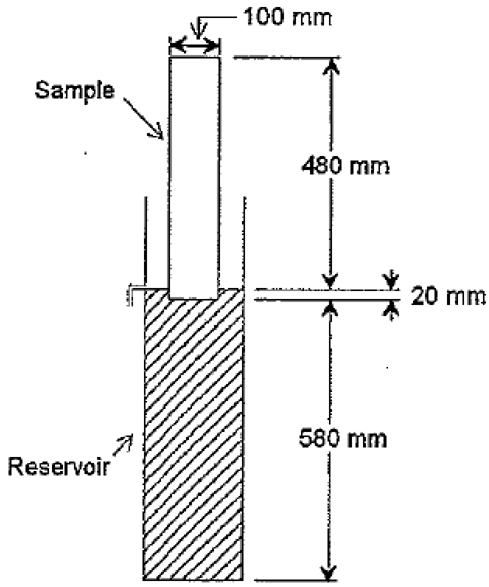


Figure 5. Test apparatus used to measure the in-plane water retention function of unsaturated geotextile specimens. (Lafleur *et al.*, 2000)

Conventional techniques to define the WRC of geomaterials often require significant time to obtain limited data. For example, determination of the WRC for a high-plasticity clay specimen may take several months. Also, conventional testing methods require the use of several specimens and destructive measurement of water content. Problems specific to WRC determination involve diffusion of air across porous ceramics, lack of control of volume change during drying and wetting (*e.g.* Cabral *et al.* 2004), and inability to impose a stress state representative of field conditions. Centrifugation has been used to alleviate shortcomings of conventional characterization of the WRC. Centrifugation increases the body forces on a porous media, accelerating fluid flow because time increases quadratically with g-level. Centrifuges were first used in the early 1930's to define the WRC by soil scientists and petroleum engineers (Gardner 1937, Hassler and Bruner 1945). Centrifuge technology has been recently used at The University of Texas at Austin for expeditious characterization of the unsaturated hydraulic properties of soils, and can provide insight into the unsaturated behavior of geosynthetics (McCartney and Zornberg 2010a, Zornberg and McCartney 2010).

The WRC of geomaterials is typically quantified by fitting experimental data to power law, hyperbolic, or polynomial functions (Brooks and Corey 1964, van Genuchten 1980, Fredlund and Xing 1994). Although the Brooks and Corey (1964) model is able to represent a sharp air entry suction, the van Genuchten (1980) model has been most commonly used in numerical analyses because it is differentiable for the full suction range. Preliminary estimates of the WRC have been obtained using databases that rely on the granulometric distribution of soils (Fredlund and Xing 1994). The functions used to fit experimental data from WRC have also been proven to be useful for the case of geotextiles (Bouazza *et al.* 2006a, Nahlawi *et al.* 2007a).

2.2 Hydraulic Conductivity Function of Unsaturated Geomaterials

The relationship between hydraulic conductivity and suction, also referred to as the *K*-function, provides a measure of the increased impedance to water flow with decreasing water content. The saturated hydraulic conductivity K_s corresponds to the minimum impedance to water flow through geomaterials. Figure 6 shows the *K*-functions of different geomaterials. Near saturation, the coarser materials (sand and geotextile) have a comparatively higher hydraulic conductivity than the fine-grained materials (silt and clay). However, as the water content decreases, the coarser materials end up being less conductive than the fine-grained soil. That is, since the fine-grained materials can retain more water in the pores as suction increases, they have more pathways available for water flow and are thus more conductive than coarser materials. The good performance in arid climates of evapotranspirative covers relative to compacted clay covers has been attributed to the lower unsaturated hydraulic conductivity of the selected cover soils.

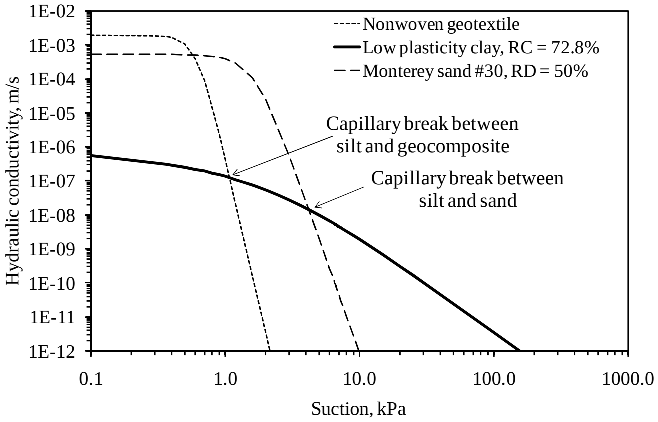


Figure 6. Typical *K*-functions for different geotechnical materials (after McCartney *et al.* 2005)

Conventional methods used to define the *K*-function may be costly, time consuming, and prone to error due to experimental issues involved in the control of water flow through unsaturated geomaterials. Accordingly, *K*-functions (*e.g.* such as those in Figure 6) are often predicted based on the information obtained using theoretical derivations based on the measured WRC. Other predictive relationships for the *K*-function are given by Burdine (1953), Brooks and Corey (1964) and Fredlund and Xing (1994) among others. Nahlawi et al. (2007a) noted that the *K*-functions were better estimated by the van Genuchten WRC equation because it is continuous.

In spite of the experimental difficulties, a few techniques have been proposed for direct determination of the *K*-function of soils in the laboratory (Benson and Gribb 1997). Techniques that have been used to measure the *K*-function of soil specimens typically involve flow of water through a specimen confined within a permeameter. The hydraulic conductivity can be measured by either applying flow across the specimen, and measuring the corresponding hydraulic gradient, or by applying a hydraulic gradient and measuring the corresponding flow rate. Flow is applied to unsaturated soil specimens using surface infiltration imposed with flow pumps, lowering or raising of a water table to cause imbibition or drainage of water from a dry or saturated soil specimen, or by applying pressure to high-air entry porous discs that only transmit water (not air). Figure 7 shows a typical permeameter setup used to measure the hydraulic conductivity using infiltration or evaporation (Meerdink *et al.* 1996, McCartney *et al.* 2007).

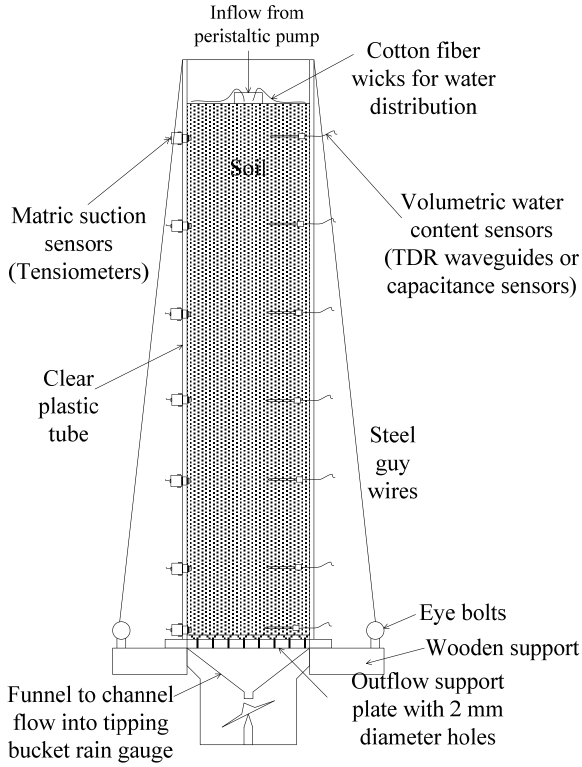
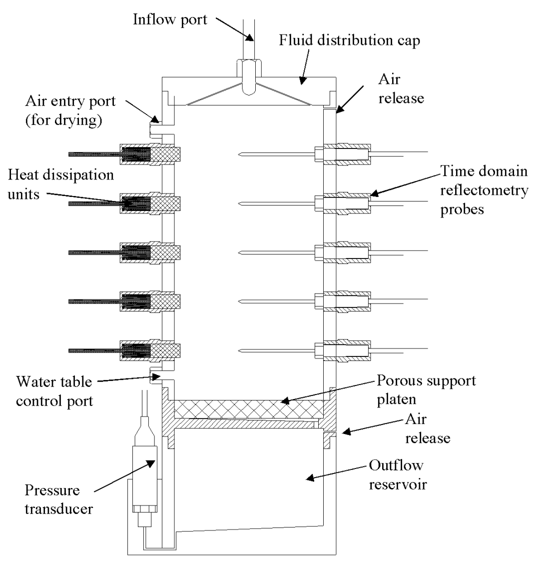


Figure 7. Column permeameter for unsaturated flow testing: (McCartney and Zornberg 2010)

Permeameters have differed in specimen confinement and size, control of boundary conditions, and availability of instrumentation. The *K*-function can be estimated using steady or transient flow processes. During steady water infiltration, a unit hydraulic gradient (*e.g.* i = 1) is typically observed in the soil profile sufficiently far from a water table boundary. Accordingly, suction does not change with depth and water flow is driven only by gravity. In this case, the hydraulic conductivity equals the imposed steady-state discharge velocity. Additional points of the *K*-function can be obtained by changing the imposed flow. During transient flow processes, the suction and water content profiles are measured as a function of depth and time, and the *K*-function can be estimated using outflow measurements (Gardner 1956) or the instantaneous profile method (Watson 1966, Meerdink *et al.* 1996). While techniques based on transient processes yield more information about the *K*-function, steady state techniques typically provide more reliable information (McCartney *et al.* 2007).

To alleviate the difficulties associated with direct determination of the *K*-function of unsaturated soils, centrifuge testing has been used to define the *K*-function of soil used in projects involving the design of alternative covers (Nimmo *et al.* 1987, Conca and Wright 1994, Zornberg *et al.* 2003). For steady state conditions, the Darcy's law under increased gravitational field and an imposed discharge velocity can be directly used to determine the *K*-function. Early centrifuge studies (Nimmo *et al.* 1987, Conca and Wright 1994) did not allow the direct monitoring in-flight of the relevant variables (suction, water, discharge velocity) during testing. If the suction gradient is assumed to be negligible, the hydraulic conductivity becomes inversely proportional to the square of the angular velocity. To alleviate shortcomings of early studies, an improved centrifuge device was recently developed (Zornberg and McCartney 2010). This device incorporates the use of a low-flow hydraulic permeameter and a high-g centrifuge capable of continuously, non-destructively, and non-intrusively measuring suction, water content, and fluid flow rate in a single specimen during centrifugation. Accordingly, the new centrifuge allows an expedited determination of both the WRC and *K*-function from a single soil specimen in a single test. Figure 8(a) shows the centrifuge permeameter and its instrumentation layout and Figure 8(b) shows a view of the new centrifuge. A special low-flow fluid union is used to supply fluid from the stationary environment to the rotating specimen within the centrifuge. An important feature to point out is that the centrifuge permeameter shown in Figure 8(a) is essentially a column test such as that shown in Figure 7. The centrifuge is a suitable tool to provide expeditious evaluation of the soil-geosynthetic interaction arising from a capillary break induced by geotextiles.



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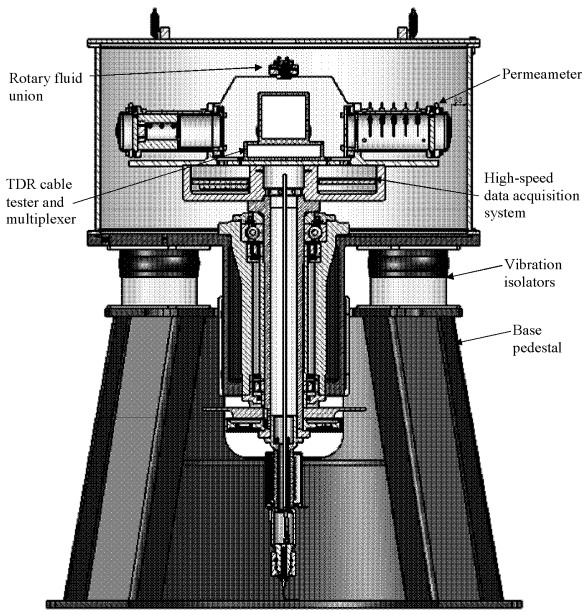
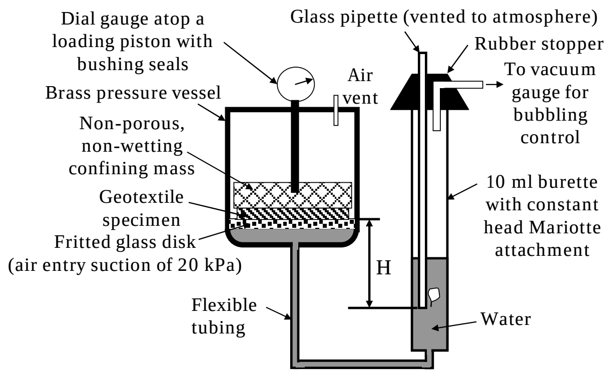


(b)

Figure 8. Permeameter for Unsaturated Soils: (a) Permeameter; (b) Centrifuge layout including a permeameter

K-function of nonwoven geotextiles has been measured in only a few studies. McCartney et al. (2008) adapted a hanging column test to measure outflow [Figure 9(a)], and used it to calculate the K-function of unsaturated geotextiles. Specifically, a Mariotte burette was used to maintain a constant suction value on the geotextile specimen, while still permitting outflow to be measured with the burette. This study used an approach proposed by Gardner (1956) to calculate the hydraulic conductivity from the outflow data obtained during different increments of suction applied with the hanging column. The measured K-function was consistent with the K-function predicted using the WRC. The hydraulic conductivity of geotextiles has also been estimated using instant profiling methods (*e.g.* Morris 2000, Stormont and Morris 2000). Figure 9(b) shows a view of the instantaneous profile setup. Very fine wire probes were used for time domain reflectometry (TDR) measurements to minimize their impact on water movement through the geotextile. However, these tests required long time and interpretation of transient flow using the instant profiling method and variability in the shape of the K-function is often obtained. Stacked geotextile and capillary rise tests have also been used to determine the hydraulic conductivity of unsaturated geotextiles (Knight and Kotha 2001, Nahlawi et al. 2008). In principle, it is possible to concurrently determine the *K*-function from test used to measure the WRC, but difficulties arise due to variability in results, head losses through the high-air-entry porous stones, and the lack of instrumentation in the stacked geotextile and capillary rise tests.



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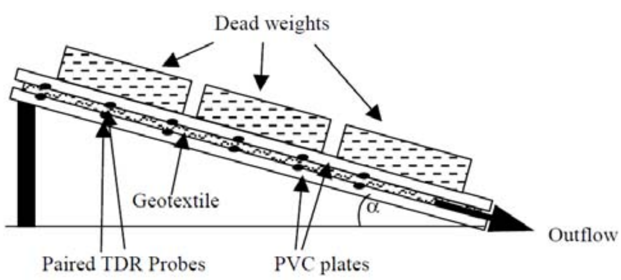


(b)

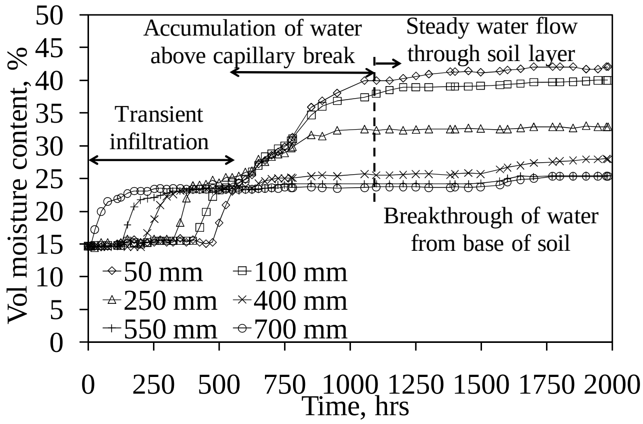
Figure 9. Equipment to measure the hydraulic conductivity of unsaturated geotextiles: (a) Hanging column with outflow measurement; (b) Inclined instantaneous profile test (Morris 2000)

3. COLUMN STUDIES

Column studies have been conducted with the objective of reproducing the behavior of geosynthetic capillary barriers under controlled laboratory conditions. These studies have been used to evaluate water flow across layered geomaterials under unsaturated conditions (Stormont and Anderson 1999) or to determine the hydraulic conductivity of unsaturated soil layers (Moore 1939, McCartney *et al.* 2007). Several column tests have been reported in which constant infiltration rates were applied to a clay layer underlain by a nonwoven geotextile (McCartney *et al.* 2005, Stormont *et al.* 2008, McCartney and Zornberg 2010b). Other tests have been conducted by inducing a constant head by ponding water atop the soil surface (Bathurst *et al.* 2007, 2009). For a constant head inflow condition, a saturated wetting front passes through the soil, while for a constant flow rate condition (with a flow rate less than the saturated hydraulic conductivity), an unsaturated wetting front passes through the soil column. The infiltration condition involving evaluation of an advancing unsaturated wetting front is of particular relevance for the review presented in this paper, as it corresponds to conditions representative of alternative cover systems.

The changes in water content with time in a column study conducted at the University of Texas at Austin to evaluate the development of a capillary barrier effect is shown in Figure 10. Water was supplied to the top surface of soil at a constant inflow rate, and its transient infiltration through the soil column was monitored both visually and using embedded water content sensors. Specifically, the water content was inferred using time domain reflectometry (TDR) waveguides placed at different elevations on a 750-mm-long column of low plasticity clay underlain by a geocomposite. As illustrated by the water content data shown in Figure 10(a), three distinct phases of water flow can be identified for a constant infiltration rate of 4×10^{-8} m/s (approximately 100 times smaller than the saturated hydraulic conductivity of the soil). Initially, the entire profile was relatively dry, with an as-compacted volumetric water content of 15%. Although the infiltration rate supplied at the top of the profile is constant, the wetting front moves through soil layer as a transient process. As the wetting front reaches the location of each of the TDR waveguide, the water content is observed to increase up to a value of approximately 24%. Once the wetting front reaches the base of the soil layer (550 hrs), water did not immediately flow into the geotextile. Instead, because of the capillary break, water accumulated within the soil immediately above the geotextile until the matric suction was reduced to a value at which capillary breakthrough could occur. Specifically, outflow was only collected from the base of the column once the soil reached a water content of approximately 40% (degree of saturation of 90%). The breakthrough suction is consistent with the suction value expected based on the WRCs for these materials (see discussion in Section 4.2). Once outflow was collected after breakthrough, steady downward flow of water was established through the soil-geotextile system.

Figure 10(b) shows the water content profiles with height at different times. The results in this figure better illustrate the impact of the geosynthetic capillary break on the water storage within the soil layer during infiltration at a constant flow rate. The water content towards the top of the profile (= 25%) corresponds to the condition in the soil layer in which there is no impact of the bottom boundary condition (i.e. a profile without the influence of a capillary barrier). This particular value of water content corresponds to the infiltration rate used in this study, assuming that infiltration occurs under a unit hydraulic gradient. During infiltration under a unit hydraulic gradient, the suction does not change with height, so the total head difference with height equals the elevation head change with height. If the suction is constant with height, this implies that the water content should also be constant with height. A constant water content value with height is only noted in the top of the column for all times and for early stages of infiltration before the wetting front reached the level of the geosynthetic (i.e. before 550 hours). The water content at the base of the soil layer continued to increase after the wetting front had reached the level of the geosynthetic, beyond the water content corresponding to infiltration under a unit hydraulic gradient. Specifically, as shown in the figure, water content increases to a value of approximately 40% due to the development of a capillary break. As also shown in Figure 10(b), approximately 0.3 m of soil experienced an increase in water storage due to the capillary break above that corresponding to infiltration under a unit hydraulic gradient. Additional column tests having greater lengths and different geosynthetic characteristics reported by McCartney and Zornberg (2010b) indicate that the geosynthetic capillary barrier can lead to an increase in soil water storage up to a height of 0.5 m above the geosynthetic.



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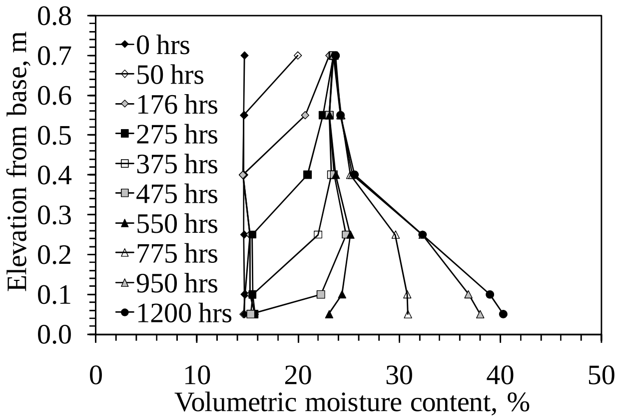


(b)

Figure 10. Results from column infiltration tests: (a) TDR water content time series for different heights from the base of a soil layer undergoing infiltration from the surface at a constant rate; (b) Water content profiles with depth for different times

A discussion of the increase in water storage in a soil layer due to a capillary barrier must acknowledge the effect of the infiltration rate applied to the soil surface. The data in Figure 11 shows the progression in water storage in the soil with time during infiltration, calculated by integrating the water content profiles in Figure 10(b) from 0 to 300 mm. The water storage in this figure was normalized in relation to the water storage at saturation (*i.e.* the maximum water storage). Also shown in this figure are the water storage values expected in the soil layer for different infiltration rates. The water storage was also higher than that corresponding to the "unit-gradient" infiltration into a soil profile with no lower boundary effects, in which case the water content depends only on the magnitude of the infiltration rate. Further, the water storage of the soil layer at capillary breakthrough is significantly higher than the field capacity water storage. The field capacity water storage is an empirically derived quantity, which generally reflects the volume of water that can be stored in a soil against the downward pull of gravity.

Theoretical investigations have described the reasons why water storage in the soil layer under steady state infiltration and without the influence of a capillary barrier is directly related to the magnitude of the infiltration rate (Choo and Yanful 2000, Dell'Avanzi *et al.* 2004). McCartney *et al.* (2005) found that the use of a constant inflow rate smaller than K_s led to a 40% increase in water storage near the geosynthetic capillary in relation to storage that occurs without a capillary barrier. On the other hand, if the inflow rate equals K_s, no increase in water storage should be expected beyond that occurring in the soil during infiltration. This is because infiltration is occurring under saturated conditions, so the water storage in the soil during infiltration equals the maximum water storage in the soil. This response was confirmed by Bathurst *et al.* (2007), who performed infiltration tests on soil-geotextile profiles in which infiltration was imposed by ponding water on the soil surface, and found that capillary breakthrough occurred when the wetting front (with a suction value of approximately 0.0 kPa) reached the geosynthetic interface. Bathurst *et al.* (2009) and Siemens and Bathurst (2010) provided further information and numerical analysis from this testing program, including transient suction and water content profiles with time. These results confirm that the geotextile only led to a short delay in the progress of the saturated wetting front through the soil layer. This finding implies that an increase in volumetric water content is not expected due to the capillary break effect for infiltration conducted under ponding conditions. While the results of this study are relevant for many practical applications, it should be noted that the occurrence of sustained ponding is not a representative condition for the design of alternative cover systems, which have been typically used in arid and semi-arid conditions.

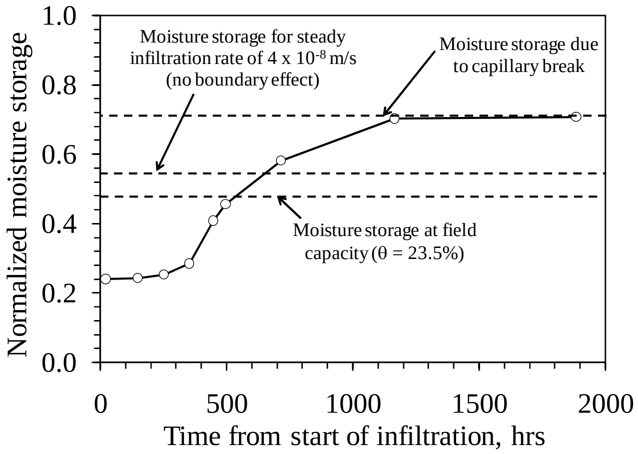


Figure 11. Increase in normalized water storage in the 300 mm of soil overlying the capillary break with time from the start of infiltration

Additional column studies have corroborated the previously discussed response of capillary barriers involving geosynthetics. Stormont and Morris (2000) carried out infiltration column tests using a silty sand layer placed over a layer of coarse sand or silty sand. A control test and a test with a nonwoven polypropylene geotextile layer at the interface between soil layers were reported. Suction was measured using tensiometers placed directly above and below the interface location. They reported the development of a capillary break when the geotextile was placed between the silty sand and the underlying coarse sand. Krisdani *et al.* (2006) reported the results on a column fitted with tensiometers and TDRs to examine the saturated-unsaturated response of a geocomposite under infiltration simulating rainfall conditions. Both physical and numerical tests showed that the geosynthetic inclusion caused a break in the pore water pressure head profile through the height of the fine sand column at the elevation of the inclusion during and after infiltration loading. Nahlawi *et al.* (2007b) carried out infiltration tests in a dry sand-geotextile column under constant head with the objective of determining the transient pore-water pressure response and the advancement of the wetting front. The column was instrumented with air pressure transducers, waters probes, pore pressure and tensiometers. The test results showed the development of preferential flow (fingering) in the dry sand with the accumulation of water above the geotextile before the breakthrough.

Column studies have also been performed to quantify the impact of different variables on the behavior of capillary barrier systems. McCartney and Zornberg (2007) performed a series of infiltration column tests on 125-mm long soil columns, and found that soil density may impact the geosynthetic capillary barrier behavior. In particular, this study found that loosely compacted clays reach breakthrough at smaller suctions than highly compacted clays. However, the speed of the water front is significantly higher in loosely compacted soils, leading to a condition in which comparatively short precipitation events quickly lead to full saturation of the cover layer. McCartney and Zornberg (2010b) investigated the transient movement of water in unsaturated soil layers underlain by a geocomposite drainage layer (GDL) during application of cycles of infiltration and evaporation to the soil surface. A 1350 mm-high soil column was used to evaluate the impact of the GDL on the vertical distribution of volumetric water content in the soil above the geosynthetic drainage layer during transient infiltration. Results from this test indicate that the capillary break effect influences the volumetric water content profile in the soil column up to a height of 500 mm above the GDL. Specifically, an increase in volumetric water content of up to 20% was observed above that expected for the case of infiltration under a unit hydraulic gradient. Due to the long duration of this test (2,000 hrs), a shorter soil column with a height of 150 mm was also used to investigate the values of matric suction and volumetric water content near the soil-GDL interface during cycles of infiltration and evaporation. The measured suction and volumetric water content at breakthrough were consistent after each breakthrough event. The volumetric water content in the soil after each breakthrough event were found to be close to that corresponding to the matric suction where the drying-path WRC of the nonwoven geotextile rapidly transitions from residual to saturated conditions. Further, and consistent with results reported by Stormont *et al.* (2008), the capillary break was re-established after the matric suction at the soil-geosynthetic interface increased over the breakthrough suction value. This is important because it indicates that geosynthetic capillary barriers constructed in the field are expected to have a long-term sustainable performance even if they experience capillary breakthrough.

4. PRACTICAL APPLICATIONS INVOLVING CAPILLARY BARRIERS

A number of geotechnical and geoenvironmental applications can benefit from capillary barriers induced by nonwoven geotextiles. Along these same lines, there are also several situations in which poor performance of an earth structure involving nonwoven geotextiles may be encountered if the capillary break effect is ignored. A brief overview of these general geotechnical applications is presented in Section 3.1. The impact of geosynthetic capillary barriers in the specific case of alternative cover systems is discussed in Section 3.2.

4.1 Impact of Geosynthetic Capillary Barrier in Geotechnical Applications

4.1.1 Impact on Slope Stability

The capillary break effect may have detrimental implications on the performance of slopes or walls if a nonwoven geotextile is expected to drain water an unsaturated fill in a similar way as if the fill were fully saturated. Richardson (1997) reported the failure of a slope with a geosynthetic underdrain. Specifically, while design calculations had used the dry unit weight of the soil in the stability analysis, the soil above the geosynthetic underdrain became nearly saturated due to the development of a capillary barrier. Consequently, the actual unit weight was indeed approaching that of a saturated fill. This resulted in a decrease in the factor of safety by the factor corresponding to the ratio of these two unit weight values [i.e. $1/(1 + w)$, where w is the gravimetric water content].

The impact on slope stability induced by infiltration through soil-geosynthetic systems needs to account for the results of column studies. For example, results from the column study reported by Bathurst et al. (2009) indicate that for soil-geotextile systems subjected to cross-plane infiltration, the current design practice of requiring that the saturated hydraulic conductivity of the geotextile be at least equal to that of the overlying soil may need to be revised. Specifically, a higher ratio between the saturated hydraulic conductivity of the geotextile and that of the soil may be needed in order to provide an additional margin of safety and minimize water ponding over the geotextile layer.

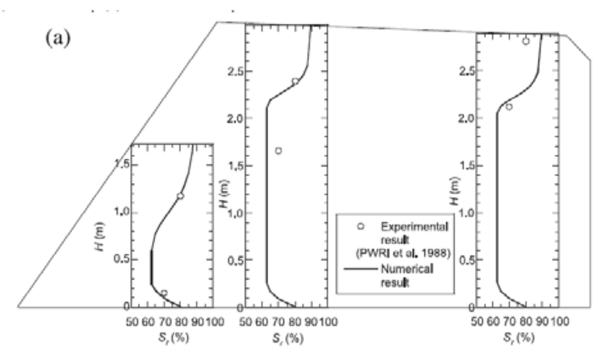
Iryo and Rowe (2005) performed a series of transient finite element analyses of water infiltration into soil–geocomposite layers considering a variety of soil types, slope inclinations and infiltration rates. The influence of these variables on the effectiveness of geocomposites as a drainage material and as a capillary barrier indicated a higher flow into the geocomposite for decreasing slope angle and increasing infiltration rate. In other words, this study found that the impact of the geosynthetic capillary barrier is more pronounced for smaller infiltration rates and steeper slopes. This is consistent with previously reported observations that the rate of infiltration affects the water storage of the soil above a geosynthetic capillary barrier. Modelling results confirmed the observation of Richardson (1997) that the soil immediately above the geocomposite becomes nearly saturated before the geocomposite starts draining water, and it remains under high water conditions over long periods of time after the infiltration event.

The theory of water flow in unsaturated geomaterials generally considers for simplicity that the pore air pressure equals zero. However, in landfill cover systems atop actively biodegrading waste, the pore air (or gas) pressure is positive. For example, Thiel (1999) reported that slope stability can be seriously impacted by the gas pressure beneath a geomembrane liner. However, it should be noted that this condition may also be expected if geotextiles, rather than geomembranes, are used in the cover system and a capillary break develops at the geotextile interface. Since wet geomaterials have a much lower permeability for gas flow (Bouazza 2004), accumulation of water over the geotextile would act as a barrier to gas flow, as in the case of a geomembrane. This effect should be considered in the design of gas collection systems, even for the case of covers that do not include geomembranes.

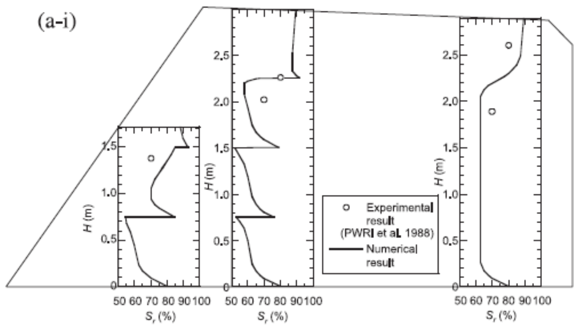
4.1.2 Impact on Reinforced Soil Structures

Proper drainage within the backfill is one of the most important design issues to be considered in the design of reinforced soil structures. This is especially the case in earth retention systems involving poorly draining backfills due to their higher susceptibility to develop positive pore water pressures (Zornberg and Mitchell 1994, Mitchell and Zornberg 1995). Geosynthetic drains have been proposed for use within these backfill soils to reduce the drainage paths. However, it should be recognized that these drains will only conduct water after the soil becomes nearly saturated. As in the previously discussed case of slope underdrainsthe soil unit weight to be considered in the design should correspond to nearly saturated conditions due to the capillary break effect.

Iryo and Rowe (2005b) used finite elements to simulate the hydraulic and mechanical response of geosynthetic-reinforced embankments. Specifically, numerical simulations were conducted to examine the effect of geotextile arrangement and infiltration conditions as well to assess the effectiveness of nonwoven geotextiles as drainage material. Using pore water pressures obtained from the finite element analysis, water flow analyses indicated that nonwoven geotextiles may retard the water flow in situations where the pore pressure is negative, whereas they act as a drainage material in situations where the pore pressure is positive. Some of the reported results are shown in Figure 12, which show that nonwoven geotextiles contributed more significantly as drains within the fill than as reinforcement inclusion. Garcia *et al.* (2007) reported experimental results that are useful to assess the observations made by Iryo and Rowe (2005b) using numerical simulations. In this study, model embankments were built using two layers of permeable geosynthetics, and their performance was assessed under infiltration and evaporation conditions. Their results indicate that geosynthetics embedded within the soil approached saturation only when the pore water pressure within the surrounding soil approached zero. Local failure was observed during infiltration due to water accumulated above the geosynthetics. Failure occurred because of pore water pressure increases within the soil immediately above the geosynthetic layers. Garcia *et al.* (2007) observed that geotextiles placed in the form of strips minimized the capillary barrier effect and facilitated water drainage.



(a)



(b)

Figure 12. Comparison between water profiles in a retaining wall: (a) without reinforcements; (b) with geotextile reinforcements (Iryo and Rowe 2005b)

4.1.3 Impact on Pavements

Two major issues that affect pavement performance are frost heave and capillary rise. Frost heave can lead to significant differential movements in the subgrade and base course layers of pavements, which can contribute to pavement surface cracking and deterioration. Capillary rise from fluctuating water tables can lead to a change in the stiffness of pavement soils. Specifically, compacted base course soils have high stiffness and shear strength because of the high matric suction induced under comparatively low water content values. As compacted fills are frequently used in flexible pavements and foundations for structures (walls, footings), decrease in suction induced by water flow into the fill may compromise performance of the system. Nonwoven geotextiles could be used within the flexible pavement as a hydraulic barrier to capillary flow (from a water table or drainage ditch), as shown in Figure 13. Configurations such as these can be used to prevent water flow that could lead to reduction in stiffness, frost heave, or swelling of expansive clay subgrades.

Henry (1996) proposed the use of geotextiles as barriers to frost heave in pavement structures. Laboratory tests showed that properly selected geotextiles reduce frost heave in soils by functioning as capillary barriers. Christopher *et al.* (2000) described the results from a field experiment in Maine in which geocomposites were placed at different depths within the subgrade to reduce frost-susceptibility in pavements. Henry and Holtz (2001) investigated the potential for geosynthetic capillary barriers to reduce frost heave in soils. In this study, soil-geosynthetic systems were subjected to freezing temperatures, and the frost heave and final water content profiles of specimens were measured. Isolated geotextile layers placed did not experience a reduction in frost heave beyond control specimens. However, geocomposites, comprised of a drainage net sandwiched between two needle-punched polypropylene geotextiles, were found to reduce frost heave. The presence of the air gap within the drainage net was found to minimize the upward movement of water into the overlying soil layer observed when using isolated geotextiles.

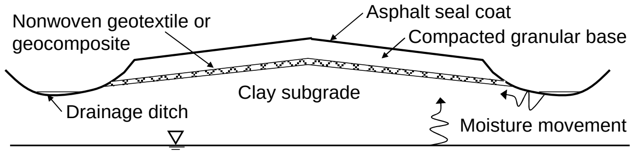


Figure 13. Nonwoven geotextile used as a hydraulic barrier in a flexible pavement

Clough and French (1982) performed an early study on the use of geotextiles in pavement systems to mitigate water fluctuations in base courses induced by capillary rise from underlying soils. They found that upward flow was blocked by placing a geotextile a few centimeters above the water table and above the level at which the water content approaches saturation. McCartney *et al.* (2008) evaluated the use of nonwoven geotextiles and geocomposite drainage layers as water barriers in geotechnical applications where capillary flow is expected. This study used a similar approach to that of Henry and Holtz (2001) to observe the impact of capillary rise on layered soil-geosynthetic systems and soil-only control systems. Capillary rise was observed to occur rapidly in a control model, while capillary rise occurred more slowly when a nonwoven geotextile was placed between two soil layers (Figure 14). This was attributed to the low hydraulic conductivity of the geotextile under unsaturated conditions. Consistent with observations by Henry and Holtz (2001), capillary rise was prevented when using a geocomposite between two soil layers due to the air gap in the geonet. Filter paper measurements indicated that negative water pressure was transmitted from the soil through the nonwoven geotextile, but not across the geocomposite.

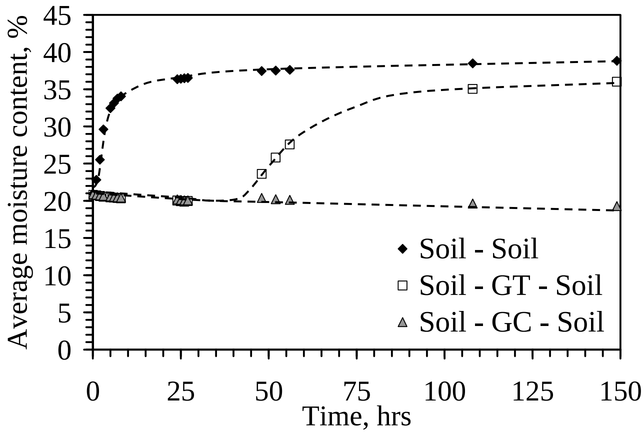


Figure 14. Water content changes due to capillary rise in different soil-geosynthetic systems (McCartney et al. 2008)

In addition to causing a capillary break, geosynthetics have been used in pavements to drain water from unsaturated soils by wicking action (Zerfass 1986). In this case, the polymer type must be carefully selected to ensure that the geosynthetic is wettable. Stormont *et al.* (2007) used geocomposites with fiberglass geotextiles to induce a wicking action that would drain water from unsaturated, compacted base course layers in a pavement system. Fiberglass has a higher affinity to water than other geosynthetic polymers (Stormont and Ramos 2004, Henry and Patton 1998). The geocomposite capillary barrier drain removes water from soil while pore pressures remain negative, leading to higher stiffness in the system. The geocomposite system comprises a capillary barrier layer (a geonet) sandwiched between transport layers (certain geotextiles). This study involved an experimental component in which water was infiltrated on the top of a pavement base course, and drainage from the geocomposite and the soil layers was collected. The geocomposite was successful in draining sufficient water under suction to prevent development of positive pore water pressures in the base course and to limit water movement into the underlying subgrade soil.

4.1.4 Impact on Landfill Leak Detection Systems

Rowe and Iryo (2005) noted that a geosynthetic capillary barrier may lead to unexpected behavior in the leak-detection or secondary leachate collection system below a landfill composite liner. Finite element simulations were used to conduct a parametric study that included assessment of the impact of the initial conditions in the underlying foundation soils and of the distance from the leakage point to the drainage point on the time for leakage to be detected. They found that the time for leakage depends on the initial degree of saturation of the material. Good comparison was obtained between predicted leakage using numerical simulations and field monitoring results. It was concluded that the time at which leakage occurs from primary landfill liner systems may be seriously overestimated.

4.2 Impact of Geosynthetic Capillary Barriers on the Design of Alternative Covers

4.2.1 Overview of Evapotranspirative Cover Systems

The design of cover systems involving capillary barriers relies heavily on the quantification of atmospheric processes and water flow though unsaturated geomaterials (soil or geosynthetics). In the United States, the design of final cover systems for new municipal and hazardous waste containment systems is prescribed by the U.S. Resource Recovery and Conservation Act (RCRA) Subtitles D and C, respectively. Federal- and state-mandated cover systems for municipal and hazardous waste landfills have endorsed the use of resistive barriers. Resistive cover systems involve a liner (*e.g.* a compacted clay layer) constructed with a low saturated hydraulic conductivity soil (typically 10^{-9} m/s or less) to reduce basal percolation. Figure 15(a) shows the water balance components in a resistive system, in which basal percolation control is achieved by maximizing overland runoff. In order to enhance cover performance and lower construction costs, RCRA regulations allow the use of alternative cover systems if comparative analyses and/or field demonstrations can satisfactorily show their equivalence with prescriptive systems. Evapotranspirative covers are alternative systems that have been recently implemented in several high-profile sites in various parts of the world. Evapotranspirative covers are vegetated with native plants that survive on the natural precipitation and have been shown to be stable over long periods of time. Figure 15(b) illustrates the water balance components in an evapotranspirative cover system. Evapotranspiration and water storage are components that influence significantly the performance of this system. Internal lateral drainage may also be a relevant component in some cover types (capillary barriers on steep slopes). The novelty of this approach is the mechanism by which basal percolation control is achieved: an evapotranspirative cover acts not as a barrier, but as a sponge or a reservoir that stores water during precipitation events, and then releases it back to the atmosphere as evapotranspiration or lateral drainage. Silts and clays of low plasticity are the soils most commonly used in evapotranspirative covers, as they can store water while minimizing the potential for cracking upon desiccation.

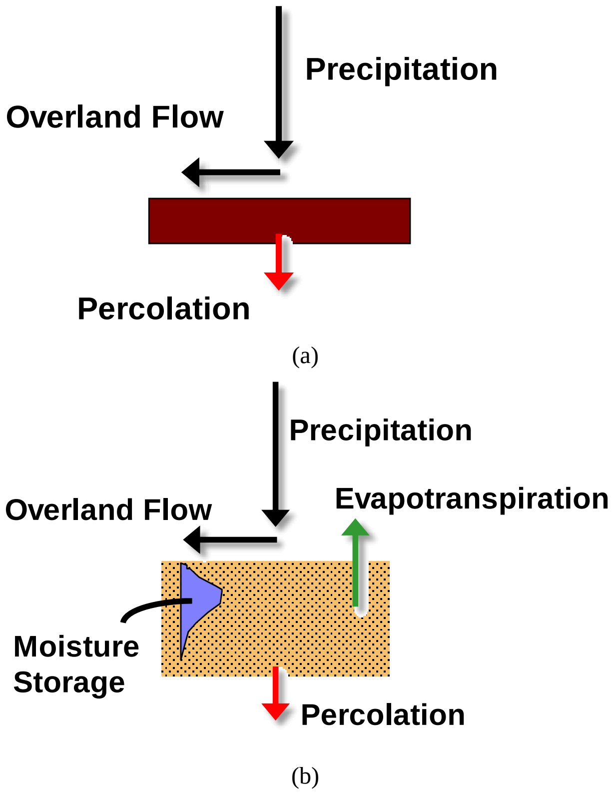


Figure 15. Components of the water balance in cover systems: (a) Resistive barrier; (b) Evapotranspirative cover

Additional advantages of evapotranspirative covers over clay barrier systems include low potential for desiccation cracking, easy construction, and low maintenance. Also, evapotranspirative covers can be constructed with a reasonably broad range of soils, contributing to cost savings associated with the use of site-specific soils instead of imported material. The performance of evapotranspirative cover systems has been documented by field experimental assessments (Anderson *et al.* 1993, Dwyer 1998), and procedures have been developed for quantitative evaluation of the variables governing their performance (Khire *et al.* 2000, Zornberg *et al.* 2003).

The increased use of alternative cover systems in recent years has led to concerns within the geosynthetics industry, as implementation of these covers can potentially result in decreased use of geosynthetics in landfill cover projects. In particular, the Geosynthetic Research Institute has issued a White Paper on “the questionable strategy of soil-only landfill covers” (GRI 2003). The White Paper was prepared in response to the reported findings of a large scale field study, funded by the U. S. Department of Energy at Sandia National Laboratories, which compared the performance of composite (CCL-geomembrane) covers along with capillary barriers, anisotropic and monolithic covers (Dwyer 1998, Dwyer 2001). The heart of the controversy lied in the fact that holes were purposely made in the geomembranes of the composite cover system. Independent of the results of that particular study, an understanding of the capillary break induced by nonwoven geotextiles may place a different perspective on the overall role of geosynthetics in alternative covers. As will be discussed in this paper, this is because: (1) much of the field instrumentation data documenting the good performance of evapotranspirative covers has been based on lysimeters, which significantly underestimate the basal flow due to the development of a capillary and (2) available research has recently shown that the use of nonwoven geotextiles in a capillary barrier system provides superior performance when compared to the use of traditional coarse-grained soils.

This paper includes an evaluation of the current state-of-the-knowledge of the hydraulic properties of geosynthetics under unsaturated conditions that are relevant for geosynthetic capillary barrier design. These properties include the water retention curve and the hydraulic conductivity function. In addition, the mechanisms involved in the development of capillary barriers are evaluated to explain the storage of water that develops at the interface between materials with contrasting hydraulic conductivity (e.g. a fine-grained soil and a nonwoven geotextile). Finally, specific applications and case histories are discussed to illustrate new opportunities that may result from a better understanding of the unsaturated hydraulic properties of geosynthetics.

Two important aspects related to geosynthetic capillary barriers affect significantly the assessment of alternative covers involving evapotranspirative systems. One of these aspects is the fact that lysimeters, the monitoring instruments that have been used for demonstration of the acceptable performance of these covers, have been providing erroneously low (unconservative) percolation values due to the development of an often overlooked capillary barrier. The second aspect is regarding the superior performance of geosynthetic capillary barriers in relation to soil-only capillary barriers. These two aspects are discussed next.

4.2.2 Impact of Geosynthetic Capillary Barriers on Lysimetry

A discussion on lysimetry is necessary within the context of this paper, as this is a monitoring device that, at least in the US and more recently in Australia, has provided the basis to most of the equivalence demonstrations that led to the acceptance of alternative cover systems. US Regulations for municipal and hazardous waste landfills allow the use of alternative covers as long as it is demonstrated that the alternative "achieves an equivalent reduction in infiltration" as the prescriptive cover. However, this equivalency demonstration has recently become a source of controversy, and at the centre of this controversy is the capillary barrier effect induced by nonwoven geotextiles. Accordingly, understanding of the capillary barrier phenomenon may have profound implications on current landfill design practice. This is because lysimetry is the currently accepted field monitoring method for equivalence demonstration of an alternative cover. Specifically, the demonstration often involves the construction of a suite of proposed alternative covers and subsequent monitoring through lysimetry the basal percolation under representative weather conditions.

In a nutshell, a lysimeter is a device placed under a soil layer that collects water that has percolated through a soil layer. Lysimeters were first used in agronomy, although engineers began using them to prove equivalency of alternative earthen final covers. While there are different types of lysimeters (e.g. pan lysimeters, suction lysimeters), pan lysimeters have been the most commonly used type to measure percolation through alternative covers. The pan lysimeter consists of a geocomposite drainage layer that is overlain by the proposed cover and is underlain by a relatively impermeable layer, usually a geomembrane (Gee and Hillel 1988). The expectation has been that percolating flow, moving downwards through the proposed monolithic cover would be collected by the lysimeter. The collected flow would then be directed into a collection tank where the volume of collected water would be quantified. The schematic view of a pan lysimeter is shown in Figure 16 (Benson et al. 2001). As seen in the figure, the lysimeter is placed at a minimum inclination so that the water collected in the geocomposite drain can be carried by gravity to the percolation pipe and into the collection basin. In this particular example, the lysimeter includes a low linear density polyethylene (LLDPE) geomembrane as the impervious layer both under the geocomposite drainage layer and in the sidewalls located at the perimeter of the lysimeter. Sidewalls are used to prevent lateral diversion of water. Lysimeters became popular because they provide a direct measurement of the variable of interest (i.e. basal percolation through the proposed cover). Also, lysimeters can be constructed with a size that is large enough to account for spatial variability of the soil layer. Despite these potential advantages, there are several major drawbacks that may have been overlooked in the current state of the practice.

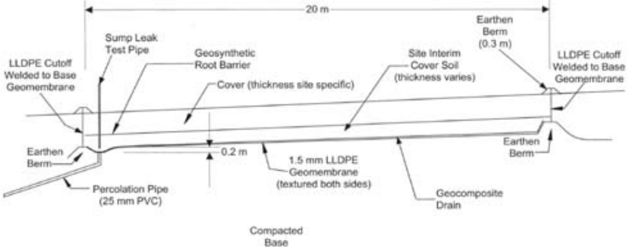


Figure 16. Schematic view of a typical pan lysimeter used for eval of the performance of alternative cover systems (Benson et al. 2001)

Lysimeters have been proven adequate for the comparatively high flow rates induced in irrigation for agronomy studies. They were then used for evaluation of alternative cover systems because they were thought to be an adequate approach for direct measurement of basal percolation through a soil profile (Gee and Hillel 1988). In 1998, the EPA-funded Alternative Cover Assessment Program (ACAP) initiated research into the effectiveness of certain alternative covers. The goal of ACAP was to produce field data from field-scale tests of alternative and prescriptive covers. Over nineteen sites, ranging from municipal solid waste landfills to hazardous waste landfills, were instrumented using lysimetry. In some cases, sensors were also used for measurement of water content and suction. ACAP focused on ET covers and includes a variety of covers with varying dimensions. Many of the sites involved monolithic covers, although some projects involved capillary barrier covers of varying depths. For the monitoring of percolation, ACAP requires that each site contain at least one test section (10 m x 20 m) that consists of a large scale, pan type lysimeter. It appears that little attention has been given in this program to how the lysimeters themselves may affect the flow of water in the covers. However, recent infiltration studies have brought to light concerns regarding the adequacy of relying heavily on lysimetry for evaluation and acceptance of alternative covers. As observed in column studies, a capillary barrier develops at the interface between the cover soil and the underlying geocomposite drainage layer. In addition to laboratory infiltration studies, data collected from lysimeters and water profiles installed at the high-visibility Rocky Mountain Arsenal site (Zornberg and McCartney 2003) reveals that the water content at the field lysimeters followed the same pattern as that shown in Figure 10. Specifically, water had accumulated at the base of the cover (i.e. top of the lysimeter) due to the development of a capillary barrier on the very instrument meant to monitor percolation. In other words, measurement was compromised of the actual percolation that would have occurred through the base of the cover soil had the lysimeter not been installed (i.e. field conditions representative of a monolithic cover system). Consequently, the development of a capillary barrier has led to an underestimation of the actual basal percolation through the cover. Accordingly, an alternative cover that has been proven to be acceptable (i.e. demonstrated equivalency) using only lysimeter measurements may indeed have an unacceptably high percolation in the field, where the beneficial effect of the capillary break will not develop.

By their nature, lysimeters are intrusive measurement devices since the flow pattern within a soil layer located over a lysimeter will differ from that within the same soil layer without a lysimeter. Because of the development of a capillary barrier, the authors recommend that use of lysimetry be used with caution in test plots involving proposed monolithic covers as these covers will not have an engineered capillary barrier. Also, the use of lysimetry should be carefully evaluated even in test plots for covers including capillary barrier as the nature of the capillary barrier that will develop over the lysimeter should be proven to be equivalent to the one that is expected to develop in the constructed cover. Indeed, as will be shown in the next section of this paper, geosynthetic capillary barriers have been shown to provide higher water storage than soil-only capillary barriers. Construction of duplicate test covers, both with water content sensors but only one of them with an underlying lysimeter may prove useful for proper evaluation of the proposed alternative covers. In summary, while the use of geosynthetic capillary barriers is beneficial as it leads to increased water storage in alternative covers, the use of lysimetry in current practice may have led to alternative covers that are unconservatively designed.

4.2.3 Impact of Geosynthetic Capillary Barriers on Water Storage

As indicated by the results of column tests such as those shown in Figure 10, the development of a capillary barrier enhances the performance of an alternative cover system (e.g. a monolithic cover) since the water storage within the finer-grained material is increased in relation to that associated with free drainage. The increased storage capacity in the overlying material makes additional precipitation water available for subsequent release to the atmosphere as evapotranspiration rather than for continued downward infiltration into the waste.

However, even in projects involving the construction of a capillary barrier, the amount of water storage for a given fine-grained soil will depend on the properties of the selected capillary barrier material. More specifically, as illustrated by Figure 1, the amount of water storage will depend on the WRC and *K*-function of the of the capillary barrier material. A study was conducted by McCartney *et al.* (2005) to compare the performance of geosynthetic capillary barriers with that of soil-only capillary barriers. Figure 17 shows a schematic view of two profiles that were constructed for this study. Column 1 includes fine-grained low plasticity clay placed over a sand layer acting as capillary barrier. Specifically, a 300 mm layer of clay was placed in 50 mm lifts over the sand layer using static compaction to the target dry unit weight of 75% of the maximum dry unit weight (based on the standard Proctor compaction effort) and a gravimetric water content of 8% (volumetric water content of 12%). Column 2 includes the same fine-grained soil, but placed over a geocomposite drainage layer that rests on a gravel foundation layer. Volumetric water content values were continuously measured throughout the vertical soil profiles using TDRs. Figure 17 shows the location of the TDR probes in both columns. In Column 1, four TDR probes were used, including two probes located immediately above and below the interface between the clay and sand layers to monitor the interface behaviour. In Column 2, three probes were used, including a probe located immediately above the geocomposite. A peristaltic pump was used to supply a relatively constant flow rate of 0.4 cm^3/s to the top surface of the clay. This water supply corresponds to a Darcian velocity of 2.06×10^{-7} m/s. The flow rate was selected to be less than the saturated hydraulic conductivity of the clay to maintain unsaturated soil conditions. As reported by McCartney *et al.* (2005) the low plasticity clay had a relatively low saturated hydraulic conductivity of 1.2×10^{-6} m/s, while the sand had a saturated hydraulic conductivity of 5.3×10^{-4} m/s. The geocomposite drainage layer used in this study involved a geonet sandwiched between two nonwoven geotextiles with a cross-plane hydraulic conductivity of 1.9×10^{-3} m/s.

Although this study involves infiltration into dry soil (i.e. following the wetting-path of the soil WRC), the drying-path WRC was deemed appropriate to highlight important hydraulic differences between the two different materials used as capillary barrier. Figure 1 showed the water retention data of the three geomaterials used in this study along with the best-fit WRCs defined using the van Genuchten (1980) model. Also, the results previously shown in Figure 6 correspond to the *K*-functions of the three geomaterials used in this study. They were defined using the WRC parameters and the saturated hydraulic conductivity (K_s) values obtained from flexible wall permeameter tests for both the clay and the sand. The geotextile saturated hydraulic conductivity was based on the permittivity measurement as reported by the geocomposite manufacturer. As previously discussed, the results in Figure 6 indicate that as suction increases, the hydraulic conductivity values of the three materials decrease at different rates.

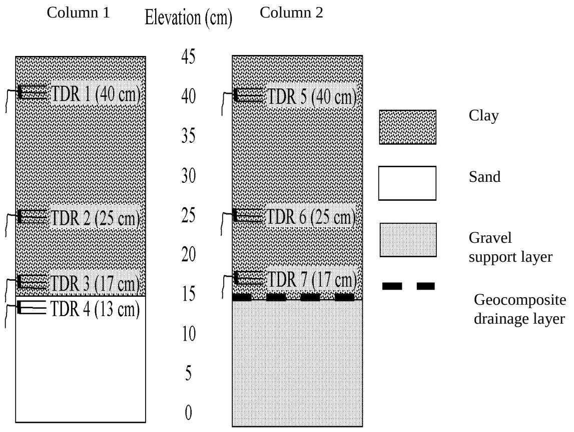


Figure 17. Schematic view of infiltration columns (McCartney *et al.* 2005)

The *K*-functions in Figure 6 indicate that a capillary break is likely at the interface between the clay and the nonwoven geotextile, as well as between the clay and the sand. While suction across the interface of two geomaterials in contact is the same, Figure 6 highlights that the three tested materials may have different hydraulic conductivities for a given value of suction, except when their curves intersect. Specifically, as a result of downward flow through the initially dry (high suction) clay layer water will not flow into the underlying layer until the suction decreases to the value at which the conductivity of both layers is the same. This is the case for the interface between the clay and the sand and between the clay and the geotextile component of the geosynthetic drainage layer. It should be noted in Figure 6 that the hydraulic conductivity of both the geotextile and the sand decrease sharply with increasing suction, although such drop occurs at lower suction values in the case of the geotextile than in the case of the sand.

Figure 18 shows the changes in water content with time at four different elevations in Column 1. This figure indicates that the sand is initially very dry (volumetric water content of approximately 5%), which corresponds to a negligible hydraulic conductivity. The initial volumetric water content of the clay soil is approximately 12% throughout the entire thickness of the profile. The volumetric water content measured by TDR 1 (near the soil surface) increases to approximately 25% as the water front advances through the clay. Similarly, the volumetric water content measured by TDR 2 increases to 25% after a period of about 5,000 minutes. The volumetric water content measured by TDR 3 also increases to 25%, but due to the proximity to the capillary barrier it shows a continued increase in water content to approximately 36%. Subsequently, after approximately 7,000 minutes TDR 2 shows increasing water consistent with TDR 3 readings. This behaviour indicates that the wetting front reached the sand interface, but water accumulated above the interface rather than flowing directly into the sand layer. After the clay reached a volumetric water content of 36% near the interface, breakthrough is noted by a sudden increase in the volumetric water content (26%) recorded by TDR 4 located within the sand layer. The increase in volumetric water content within the sand layer occurred around the same time when outflow was collected at the base of the profile (after approximately 9,000 min). The performance of Column 1 is consistent with the development of a capillary break, and indicates that the clay layer has a volumetric water content of approximately 36% at breakthrough. The WRC of the clay (Figure 1) indicates that this volumetric water content corresponds to a suction of approximately 5 kPa. In turn, this suction value is consistent with the suction value at which the *K*-functions of the clay and sand intersect (Figure 6).

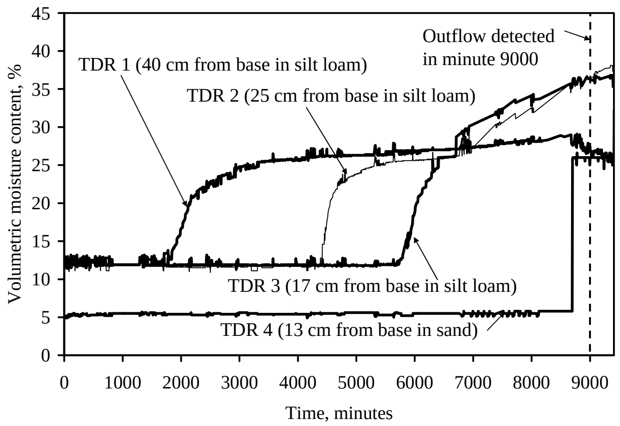


Figure 18. Volumetric water content with depth in Column 1 (McCartney *et al.* 2005)

Figure 19 shows the changes in water content with time at three different elevations in Column 2. Also in this case, the initial volumetric water content of the clay soil is approximately 12%. Consistent with the response shown by Column 1, the volumetric water content recorded in Column 2 by TDR 5 (near the soil surface) increases to approximately 25% as the water front advances through the clay. Similarly, the volumetric water content measured by TDR 2 increases to 25% after a period of about 3500 minutes. Finally, the volumetric water content measured by TDR 7 (near the geocomposite) also increases, but its continued increase is to a water content that is higher than reached near the interface of Column 1 (around 40%). Also unlike the response shown in Column 1, not only TDR 6 but also TDR 5 (near the soil surface) shows an increase in water content from 25% to 40%. Consequently, essentially the entire Column 2 was affected by the capillary break induced by the geocomposite, indicating that use of a geocomposite (rather than sand) as capillary barrier led to increased water storage within the clay layer. Outflow from Column 2 was detected after 8180 min. As shown by the clay WRC (Figure 1), a water content of approximately 40% corresponds to a suction value of about 3 kPa. This suction value is slightly lower than that obtained at breakthrough in Column 1, and consistent with the intersection of the *K*-functions for the clay and the geotextile (Figure 6).

Figure 20 shows the water storage within the clay soil as a function of time for both columns, calculated by integrating the water content profile with depth. This figure shows that the water storage increases as the infiltration front advances through the soil. Two values of water storage are shown as reference in the figure: the storage corresponding to a water content of 25% (the water content associated with free draining of the imposed impinging flow rate), and the water storage corresponding to saturated conditions. The shape of the water storage curves for both profiles indicates that the clay stores water well in excess of the value expected from a freely-draining condition. Also, as clearly shown by the water measurements in this study, the geosynthetic capillary barrier outperformed the sand capillary barrier. Similar results were obtained in an infiltration study reported by Krisdani *et al.* (2006).

In summary, geotextile capillary barriers provide higher water storage than that provided of granular soils. In addition, they also offer separation and filtration benefits that are necessary for a good long-term performance of capillary barriers involving granular soils. Based on these findings, it is recommended that all granular capillary barriers consider the inclusion of a nonwoven geotextiles at the base of the soil component of the cover.

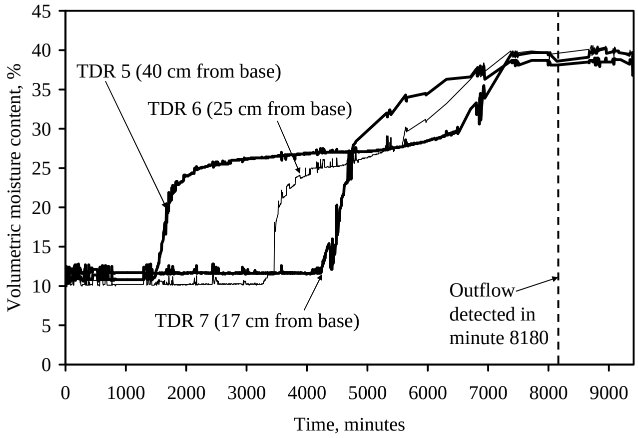


Figure 19. Volumetric water content with depth in Column 2 (McCartney *et al.* 2005)

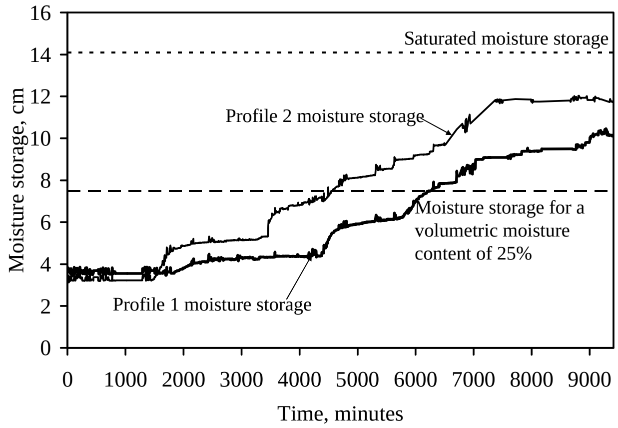


Figure 20. Water storage in Columns 1 and 2 during infiltration and at saturation (McCartney *et al.* 2005)

5. CONCLUSIONS

This paper provides theoretical background, laboratory data and full-scale measurements useful to understand the interaction between soils and geosynthetics under unsaturated conditions. An evaluation is provided of the current state-of-the-knowledge regarding the hydraulic properties of porous geosynthetics under unsaturated conditions relevant for geosynthetic capillary barrier design. Specific applications are presented to illustrate new opportunities and applications that result from a better understanding of the unsaturated hydraulic properties of geosynthetics. The following conclusions can be drawn from this evaluation:

- The hydraulic conductivity of unsaturated geomaterials with relatively large pores (e.g. gravel, geotextiles) decreases faster than that of fine-grained soils. This phenomenon leads to the counterintuitive situation in which the hydraulic conductivity of unsaturated geotextiles can be significantly smaller than that of fine-grained soils.
- Several techniques have been developed to determine experimentally the WRC of geotextiles, which are generally based on techniques originally developed for soils. These include hanging column tests, pressure plate tests, and capillary rise tests.
- As in the case of soils, the *K*-function is still rarely obtained experimentally. Instead, the *K*-function of geotextiles has been generally defined using theoretical formulations based on the use of WRC parameters and the measured saturated hydraulic conductivity.
- Recent column studies have clearly shown the development of a capillary break at the interface between soils and an underlying nonwoven geotextile. Information from the WRC and *K*-function of the components of a capillary barrier can be used to predict the breakthrough suction and water storage expected in the fine-grained component.
- The development of geosynthetic capillary barriers may benefit a number of geotechnical and environmental applications. On the other hand, poor performance of earth structures involving nonwoven geotextiles may result from ignoring the capillary break effect. Geotechnical projects in which the development of capillary break is relevant include slopes with underdrains, reinforced soil structures, pavements, landfill leak detection systems, and agricultural systems.
- The development of a capillary break in lysimeters used to monitor the performance of alternative covers has been often overlooked in current practice. This has led to erroneously low (unconservative) records of percolation in equivalence demonstrations.
- Results from infiltration studies demonstrate that geosynthetic capillary barriers in alternative covers typically outperform the soil-only capillary barriers.

The results from geotextile hydraulic characterization, column studies, and case histories, as presented in this paper clearly document that capillary barriers develop at the interface between geotextiles and unsaturated soils. Consequently, proper design of capillary barrier covers should always consider the use of a nonwoven geotextile at the interface between fine-grained soils and the underlying coarse-grained capillary barrier material.

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