



## Geosynthetic Capillary Barriers: Principles and Applications

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### ABSTRACT

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. 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 moisture that develops at the interface between materials with contrasting hydraulic conductivity (e.g. a fine-grained soil and a nonwoven geotextile). Finally, specific applications are presented to illustrate new opportunities and applications that 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 at the base of the soil component of the cover.

### 1. INTRODUCTION

Capillary barriers are becoming an established technology to control water flow in unsaturated soils. 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). 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 phenomenon 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 used in GCLs).

Understanding of unsaturated flow concepts has recently gained added relevance in landfill design due to the increased number of alternative covers that have been 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 also be used in capillary barrier systems but also, as will be demonstrated in this paper, that 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. While the focus of this paper is on the use of geosynthetic capillary barriers for landfill and mine tailing covers, it should be recognized that an understanding of flow of water in unsaturated geosynthetics can also be useful in design for optimization of drainage layers, pavement systems, reinforced soils with poorly draining backfills, and agricultural applications, all of which involve unsaturated soils.

The design of landfill or mine tailing cover systems involving capillary barriers relies heavily on the quantification of atmospheric processes and water flow through 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 US 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 1(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 1(b) shows the water balance components in an evapotranspirative cover system. Evapotranspiration and moisture 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 moisture 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.

Additional advantages of evapotranspirative covers over typical clay barrier systems include lower potential for desiccation cracking, easier construction, and lower maintenance. Also, evapotranspirative covers that function effectively can be constructed with a reasonably broad range of soils, which can lead to significant cost savings as site-specific soils can be used instead of importing materials. 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).

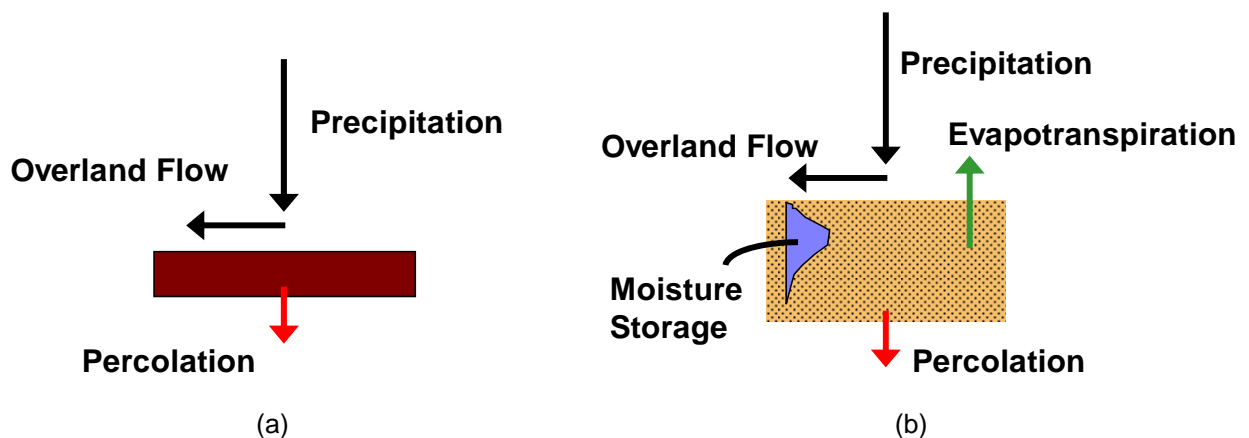


Figure 1: Components of the Water Balance in Cover Systems: (a) Resistive Barrier; (b) Evapotranspirative Cover

The increased use of alternative cover systems in practice in recent years led to concerns within the geosynthetics industry, as the implementation of these covers has the potential to cause a decreased use of geosynthetics as barrier components in their design. In particular, the Geosynthetic Research Institute issued a White Paper on “the questionable strategy of soil-only landfill covers” (GRI, 2003). The White Paper was in response to a large scale field study funded by the U. S. Department of Energy at Sandia National Laboratories (Dwyer 1998, 2001), which compared the performance of composite (GCL-geomembrane) covers along with capillary barriers, anisotropic and monolithic covers. 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 has been based on lysimeters, which significantly underestimate the basal flow due to the development of a capillary break (see Section 6.1.1), and (2) available research has recently shown that the use of nonwoven geotextiles

in a capillary barrier system provides superior performance than the use of traditional coarse-grained soils (see Section 6.1.2).

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 moisture 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 and applications that result from a better understanding of the unsaturated hydraulic properties of geosynthetics.

## 2. WATER FLOW THROUGH UNSATURATED GEOMATERIALS

The principles of water flow through unsaturated geomaterials are more complex than those for water through saturated media. This is partly because the most important variable that governs the rate of water flow through geomaterials (i.e. the hydraulic conductivity) is not constant when the water storage in the geomaterial changes. Instead, the hydraulic conductivity under unsaturated conditions varies with the level of suction (or moisture content) within the geomaterial. Consequently, relative amounts of water and air in the geomaterial highly influence the geomaterial hydraulic behaviour. Unlike the case of many other geotechnical applications, the moisture content is typically quantified on a volumetric basis for the case of unsaturated flow problems. The volumetric moisture content  $\theta$ , is defined as the ratio between the volume of water and the total control volume. The porosity  $n$ , which is the ratio between the volume of voids and the total control volume, corresponds to the volumetric moisture content at saturation (i.e.,  $n = \theta_s$ ). The degree of saturation  $S$ , commonly used to normalize the moisture content of a geomaterial is the ratio between the volumetric moisture content and the porosity.

In the case of unsaturated soils, water is held within the pores against the pull of gravity by a combination of adsorptive and capillary pressures (Olson and Langfelder 1965). Adsorptive pressures are present in soils due to electrical fields and short-range attractive forces (van Der Waals forces) that tend to draw water toward the soil particles. These pressures may be significant in highly plastic clays, where the net negative charges on the surface of clay particles interact with water dipoles and cations in the pore water. In the case of granular soils and geosynthetics, only capillary pressures are relevant. The adsorptive and capillary pressures are considered together as a single variable, referred to as the matric suction  $\psi$ , which has units of pressure (kPa). The matric suction in a geomaterial is quantified as the difference between the pore air pressure and the pore water pressure. Water is a wetting fluid for most soil minerals and geosynthetic polymers, implying that the air-water menisci between individual soil particles or geosynthetic fibres are convex, tensioned membranes (Henry and Patton 1998). Accordingly, the air pressure is greater than the water pressure, so the water pressure has a negative magnitude when air is under atmospheric pressure. The capillary rise in a pipette provides an analogy useful to assess the influence of pore sizes on the matric suction. In this case, the matric suction  $\psi$  is given by the expression:

$$\psi = P_a - P_w = h_c \rho_w g = \frac{2\sigma_{aw} \cos \gamma}{R} \quad [1]$$

where  $P_a$  is the pore air pressure,  $P_w$  is the pore water pressure,  $h_c$  is the height of capillary rise in a pipette of radius  $R$ ,  $\rho_w$  is the density of water,  $g$  is the acceleration of gravity,  $\sigma_{aw}$  is the surface tension between water and air, and  $\gamma$  is the wetting contact angle (typically  $10^\circ$  for quartz minerals). Equation 1 assumes that air is under atmospheric pressure ( $P_a = 0$ ) and indicates that the suction is inversely proportional to the pore radius  $R$  (note that all other variables are constants). Accordingly, for the same volumetric moisture content, a fine-grained soil (with comparatively small pore radii) will have a higher suction than a coarse-grained soil or a nonwoven geotextile (with comparatively large pore radii). The relationship between moisture content and suction is thus related to the pore size distribution of the

geomaterial. In engineering practice, the relationship between moisture content and suction is referred to as the Water Retention Curve  $\theta(\psi)$  (WRC).

Flow of water through geomaterials is driven by a gradient in the hydraulic energy, which can be quantified by the fluid potential (energy per unit mass of water). The fluid potential is given by an expanded form of Bernoulli's equation:

$$\Phi = gz + \frac{1}{2} \left( \frac{v}{n} \right)^2 + \frac{(-\psi)}{\rho_w} + \frac{P_o}{\rho_w} \quad [2]$$

where  $\Phi$  is the fluid potential (i.e. energy per unit mass of fluid),  $z$  is the vertical distance from the datum,  $v$  is the water discharge velocity,  $n$  is the porosity, and  $P_o$  is the osmotic suction. In Equation 2, the four terms on the right hand side correspond to the potential energy, the kinetic energy, the energy due to the water suction ( $\psi = -P_a$  if  $P_a = 0$ ), and the energy due to the osmotic suction. The water seepage velocity ( $v/n$ ) is comparatively small, so the kinetic energy component is negligible. The osmotic suction is typically considered constant, and consequently does not lead to a contribution to the hydraulic potential gradient. The energy due to water suction is often the governing term. As in the case of water-saturated geomaterials, Darcy's law for unsaturated geomaterials indicates that flow is driven by the gradient in total hydraulic potential. However, the available pathways for water flow in an unsaturated geomaterial decrease as the moisture content decreases (or as suction increases). This is quantified by the hydraulic conductivity function  $K(\psi)$  (the  $K$ -function), which accounts for the decrease in conductivity with increasing suction (or decreasing moisture content). The  $K$ -function is discussed in Section 3.2. The water discharge velocity through a geomaterial in the vertical direction  $z$  can be estimated using Darcy's law and Equation 2, as follows:

$$v = \frac{Q}{A} = -\frac{K(\psi)}{g} \frac{\partial \Phi}{\partial z} = -K(\psi) \frac{\partial}{\partial z} \left( 1 - \frac{1}{\rho_w g} \frac{\partial \psi}{\partial z} \right) \quad [3]$$

where  $Q$  is the volumetric flow rate, and  $A$  is the area of geomaterial perpendicular to the flow direction. The continuity principle in this control volume can be expressed by:

$$\frac{\partial \theta(\psi)}{\partial t} = -\frac{\partial v}{\partial z} \quad [4]$$

In Equation 4, the left-hand side represents the change in moisture storage in the control volume with time, and the right hand side represents the change in flow rate with distance across the control volume. Substitution of Equation 3 into Equation 4 leads to the governing equation for 1-D flow through unsaturated porous materials, referred to as Richards' equation:

$$\frac{\partial \theta(\psi)}{\partial \psi} \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z} \left[ K(\psi) \left( 1 - \frac{1}{\rho_w g} \frac{\partial \psi}{\partial z} \right) \right] \quad [5]$$

Richards' equation is a coupled, nonlinear parabolic equation, which can be solved using finite differences or finite elements. Inspection of Richards' equation illustrates that suction plays a significant role in unsaturated flow. Numerical solutions to Richards' equation can be challenging because the constitutive functions  $\theta(\psi)$  and  $K(\psi)$  are highly nonlinear and may have undefined or zero derivatives. More importantly, the constitutive functions  $\theta(\psi)$  and  $K(\psi)$  need to be obtained experimentally. In the case of geosynthetics, recent research efforts have been undertaken to obtain experimentally  $\theta(\psi)$  (the WRC - See Section 3.1) and  $K(\psi)$  (the  $K$ -function - See Section 3.2).

As will be discussed, the hydraulic conductivity of nonwoven geotextiles under unsaturated conditions is typically lower than that of most soils, working then as hydraulic barriers. The reason why nonwoven

geotextiles are effective as hydraulic barriers for unsaturated soils is the same that makes them effective for separation, protection and drainage: their greater pore size than that of most soils. The specific phenomenon that resists the passage of water from an unsaturated soil into a nonwoven geotextile is referred to as the capillary break effect (Stormont and Anderson 1999). The capillary break effect is encountered in everyday life with baby bottles, as milk will not pour freely from the small hole of an inverted bottle into the relatively large opening of air on the other side of the nipple. Even though the water pressure on the milk-side of the nipple equals the hydrostatic pressure of milk in the bottle, an additional suction must be applied on the air side of the nipple to induce flow. The capillary break effect is observed at the interface between fine-grained materials having relatively small pores and coarse-grained materials having relatively large pores, shown schematically in Figure 2. The air-water meniscus at the interface between the small and large pores must overcome the shift in radius from  $r_1$  to  $r_2$  to force air from the large pore. Inspection of Equation 1 indicates that the small soil pores of radius  $r_1$  result in comparatively large suction, and water can only move to the larger geotextile pores when a significantly smaller suction (corresponding to the larger radius  $r_2$  of the geotextile) develops in the system. In other words, the energy in the pore water has to be sufficient to permit it to break into the large pore. Macroscopically, the capillary break effect prevents a measurable amount of water from flowing from the soil into the nonwoven geotextile until reaching a critical suction close to zero (saturation). At this point, water is capable of “breaking” into the large pore from the small pore.

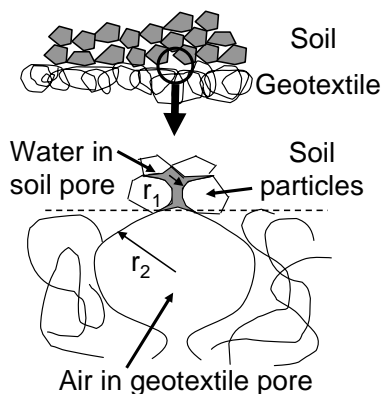


Figure 2. Schematic of capillary break effect at soil-geotextile interface

Early field evidence of the impact of the capillary break, arising from the contrast in hydraulic conductivity between soil and geotextiles under unsaturated conditions, were reported by Clough and French (1989) and Richardson (1997). Clough and French (1989) realized that nonwoven geotextiles used as under drains in unbound pavements led to an increase in water content of the overlying soils. Similarly, Richardson (1997) observed that nonwoven geotextiles used in a slope drainage layer did not drain water readily from overlying unsaturated soils until the soil was nearly saturated. The failure of the soil-geosynthetic system was attributed to this phenomenon, as the designer had not considered the increased unit weight of the nearly saturated soil on the slope. It wasn't until the time of Richardson's observations that the first studies on the hydraulic characterization of geotextiles under unsaturated conditions were performed. A discussion on the characterization of hydraulic properties of unsaturated geotextiles is presented in the next section.

### 3. UNSATURATED HYDRAULIC PROPERTIES OF GEOTEXTILES

Among the various types of geosynthetics, geotextiles have been used in geotechnical engineering applications to fulfil 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 exceeding 0.9), which is greater than that of most soils used in engineering applications. Geotextiles have a uniform pore size compared to most soils (Palmeira and Gardoni 2002, Aydilek *et al.* 2007). In addition, as discussed in this section, important characteristics of geotextiles that



are relevant to unsaturated flow include their soil water retention curve and their hydraulic conductivity function.

### 3.1 Water Retention Curve

The moisture storage of soil and geosynthetics is typically quantified using the relationship between volumetric moisture content and suction, referred to as the Water Retention Curve (WRC). Figure 3 shows the WRCs for different geotechnical materials. The coarser materials (sand and geotextile) show a highly nonlinear response, with a significant decrease in moisture content (or degree of saturation) in a comparatively narrow range of suction. The fine-grained soil shows instead a more gradual decrease in moisture 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 moisture content decreases. After reaching the air entry value, the moisture content drops from saturation to a value that remains approximately constant with increasing suction. This low moisture content value is often referred to as the residual moisture content. The residual condition occurs because the water becomes occluded (or disconnected) within the soil pores, with no available pathways for water flow to occur.

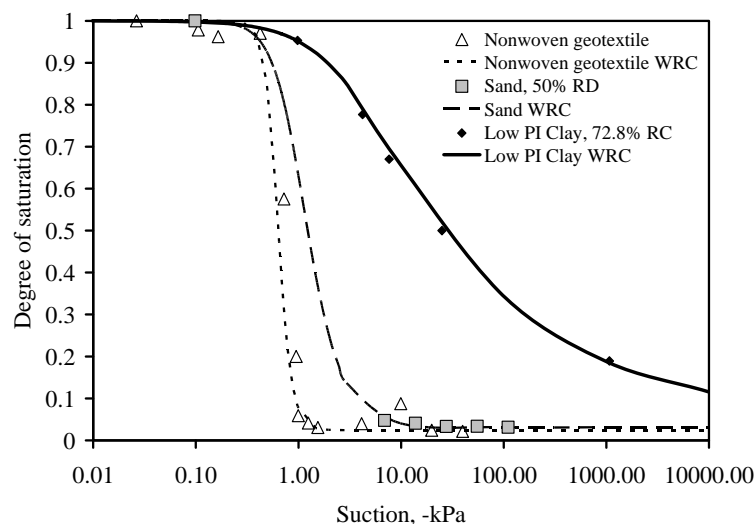


Figure 3: Typical SWRCs for different geotechnical materials (McCartney *et al.* 2005)

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, which prevents 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 moisture content at lower suctions. Figure 4 shows the WRC of three geotextiles, illustrating the significant hysteresis in their response to wetting and drying (Bouazza *et al.* 2006a). In addition, recent experimental results highlighted also the impact on hysteresis of the direction of flow measurement (Nahlawi, 2009). In particular, it was found that the volumetric water content of geotextiles along the cross-plane direction differed from that obtained along the in-plane direction for the same suction head. Also, nonwoven geotextiles were found to exhibit differences in air entry values when tested cross-plane and in-plane as a result of the geotextile anisotropy in terms of pore size.

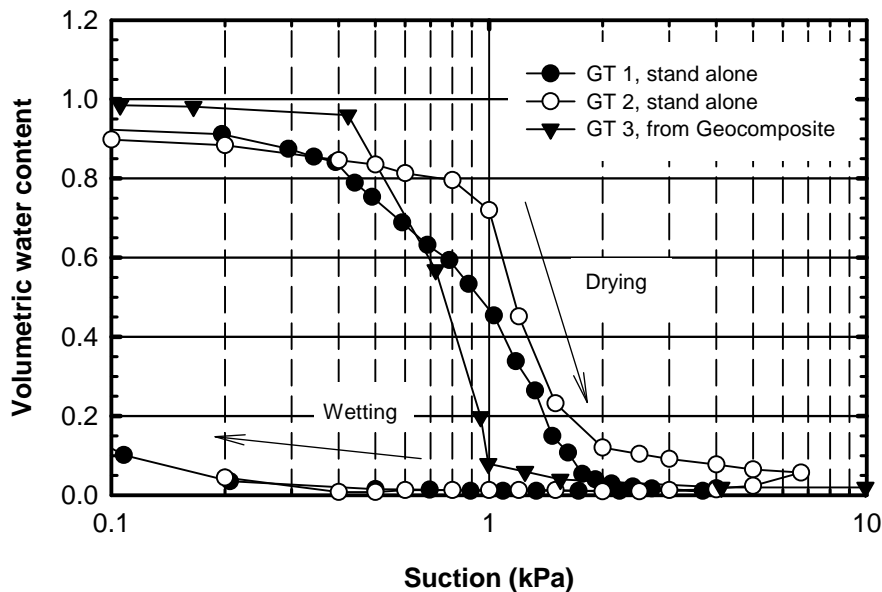


Figure 4: Typical geotextile Water Retention Curves (WRCs) (Bouazza *et al.* 2006)

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.

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 moisture content and suction are in equilibrium. The most commonly used physical technique is the axis translation technique. A common test that is based on this technique is the hanging column test, which is shown in Figure 5(a) for the case of soils. 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, tubing connects 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 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, which is filled with tap water. The funnel is moved to different elevations above the air-water interface in the reservoir to impose a suction  $h$  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 moisture content at that 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  $\text{CO}_2$  and extended equilibration times. The original test schematic as presented by Stormont *et al.* (1997) is shown below in Figure 5(b).

Another common physical technique is the pressure plate test. Figure 6(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 forces the pore water 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 behaviour. At the end of testing the gravimetric moisture content is measured destructively, and the moisture 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 control very accurately the air pressure through a computer controlled pneumatic pressure controller. Before testing, the geotextile and the porous ceramic disc were flushed with CO<sub>2</sub> to facilitate the solution of air bubbles in the wetting phase. The test apparatus and testing assembly are shown schematically in Figure 6(b). Among the various techniques used to define the WRC of geotextiles, the capillary pressure cell is the only one that allows some control on the stress state of geotextile specimens.

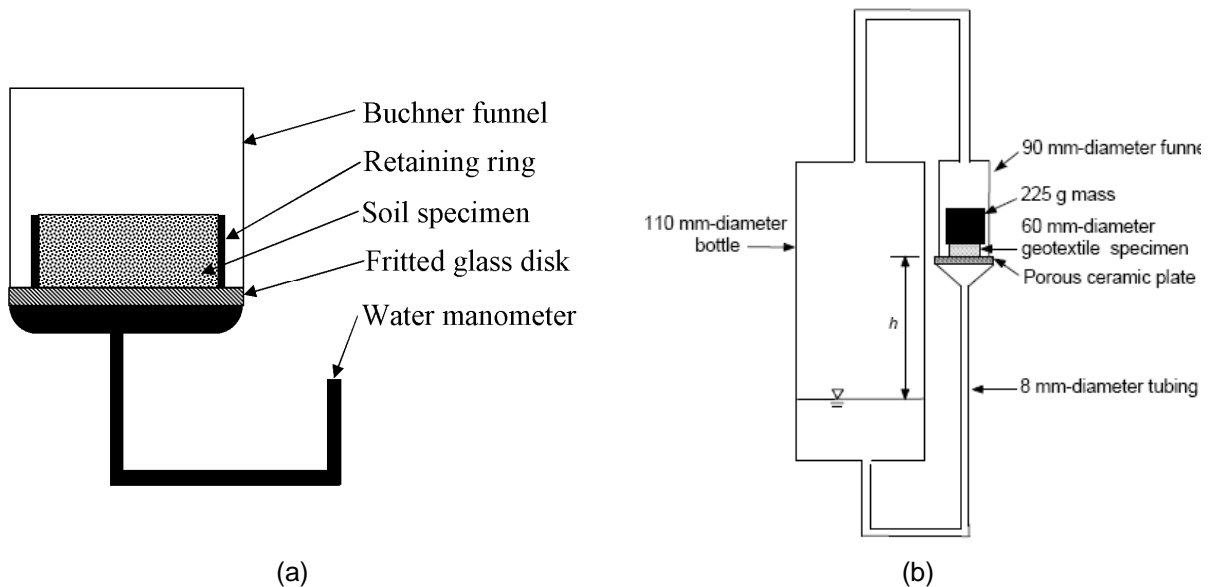


Figure 5: Hanging column test: (a) Conventional test used for soil specimens; (b) Modified test used for geotextile specimens (Stormont *et al.* 1997)

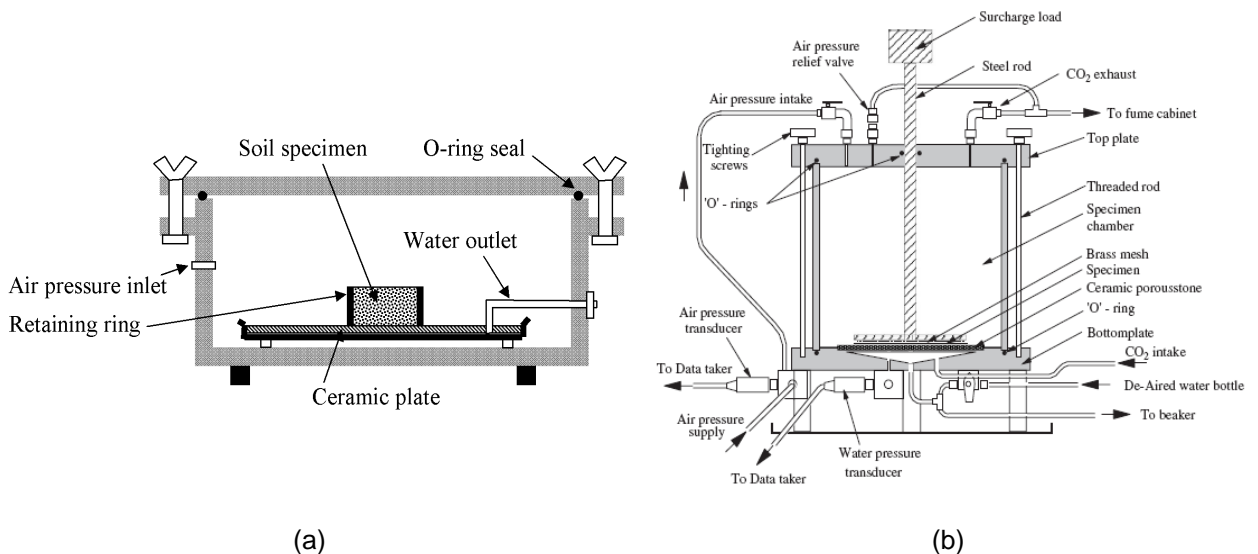


Figure 6: Pressure plate test: (a) Conventional test used for soil specimens; (b) Modified test used for geotextile specimens (Nahlawi *et al.* 2007a)



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 7. 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 moisture 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 moisture content of geotextiles at high suction values is so low that it may be assumed to be negligible without further measurements.

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 is 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 approach as presented by Lafleur *et al.* (2000) is shown in Figure 8. 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).

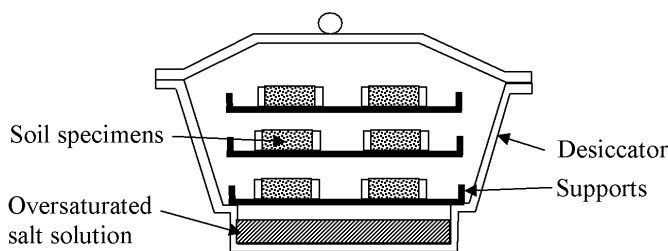


Figure 7: Conventional methods to determine the soil WRC using saturated salt solutions

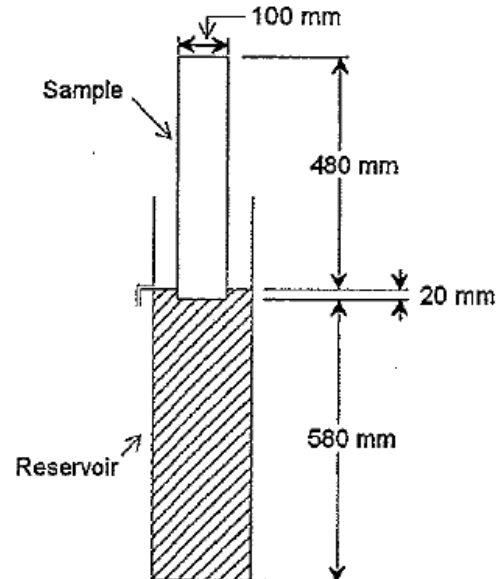


Figure 8: Test apparatus used to measure the in-plane water retention function of unsaturated geotextile specimens. (Lafleur *et al.*, 2000)

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 moisture 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 behaviour of geosynthetics (McCartney and Zornberg 2005).

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 range of suctions. The van Genuchten model is given by:

$$\theta = \theta_r + (\theta_s - \theta_r) \left[ 1 + (\alpha \psi)^N \right]^{-\left(1 - \frac{1}{N}\right)} \quad [6]$$

Where  $\theta_r$  is the residual moisture content,  $\theta_s$  is the saturated moisture content (porosity), and  $\alpha$  (units of  $\text{kPa}^{-1}$ ) and  $N$  (dimensionless) are fitting parameters. 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).

### 3.2 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 moisture flow with decreasing moisture content. The saturated hydraulic conductivity  $K_s$  provides a measure of the minimum impedance to moisture flow through geomaterials. Figure 9 shows  $K$ -functions for different geomaterials. Near saturation, the coarser materials (sand and geotextile) have a comparatively high hydraulic conductivity, while the fine-grained materials (silt and clay) have a lower hydraulic conductivity. However, as the soil dries, the coarse 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 still have available pathways 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.

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 9**) are often predicted based on the information obtained using theoretical derivations based on the measured WRC. Specifically, the  $K$ -function obtained using the parameters from the van Genuchten-Mualem model (1980) is:

$$K(\theta) = K_s \sqrt{\frac{\theta - \theta_r}{\theta_s - \theta_r}} \left[ 1 - \left( 1 - \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1-N} \right)^{\frac{1}{1-N}} \right]^2 \quad [7]$$

$K(\psi_m)$  can be defined by substituting Equation 6 for  $\theta$  into Equation 7. 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 equations due to the continuity of the conductivity function.

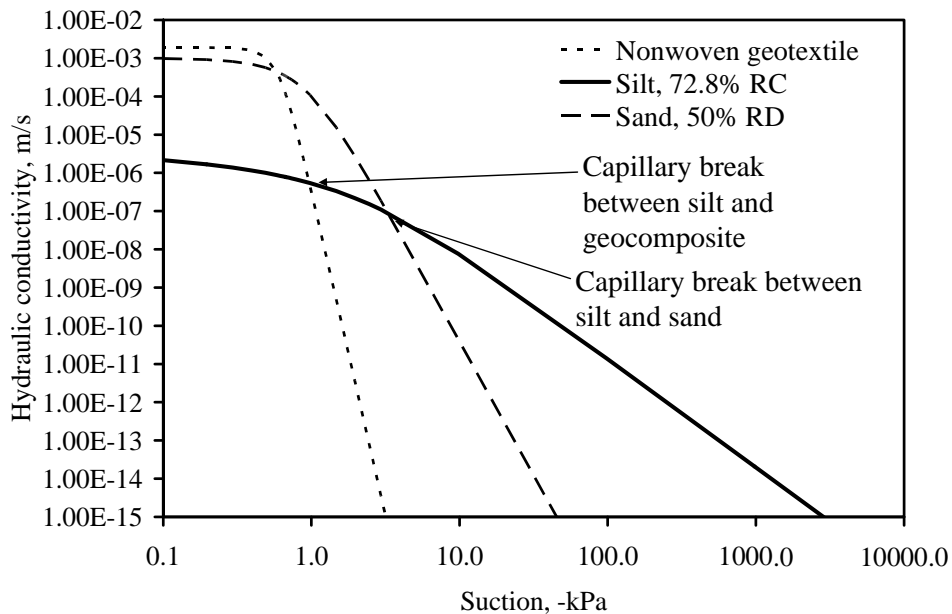


Figure 9: Typical  $K$ -functions for different geotechnical materials (McCartney *et al.* 2005)

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 Gibb 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 10(a) shows a typical permeameter setup used to measure the hydraulic conductivity using infiltration or evaporation (Meerdink *et al.* 1996, McCartney *et al.* 2007), while Figure 10(b) shows a typical permeameter use to measure hydraulic conductivity using cross-plane water flow in a flexible wall permeameter (Znidarcic *et al.* 1991; Lu and Likos 2005). 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 moisture 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 are obtained by changing the imposed flow. During transient flow processes, the suction and moisture 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, as follows:

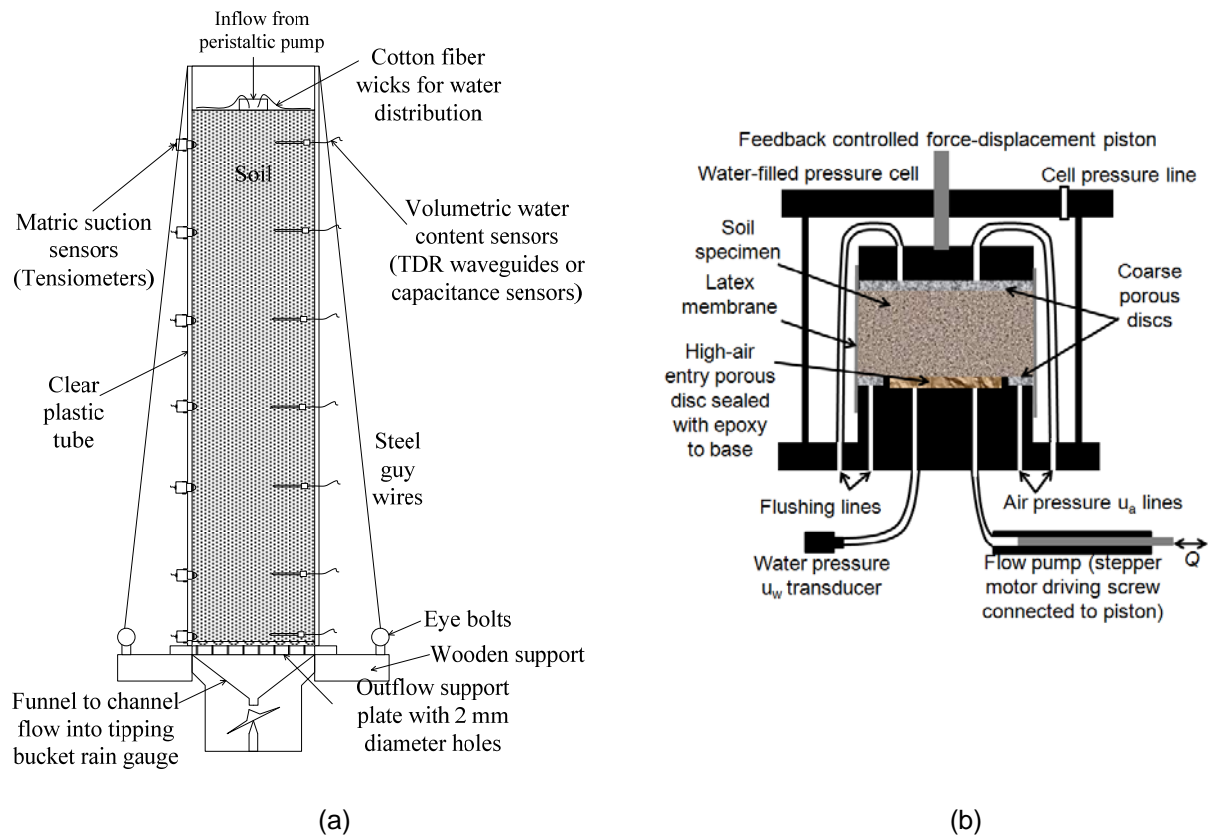


Figure 10: Permeameters for unsaturated flow testing: (a) Column permeameter (McCartney and Zornberg 2009); (b) Flexible-wall permeameter (Znidarcic *et al.* 1991)

$$K(\psi) = \frac{-v}{\left[ \frac{1}{\rho_w g} \frac{d\psi}{dz} - \frac{\omega^2 r}{g} \right]} \quad [8]$$

where  $v$  is the imposed discharge velocity and  $\omega$  is the angular velocity and  $r$  is the centrifuge radius. Points on the  $K$ -function curve are defined using Equation 8 after reaching steady state flow conditions. Early centrifuge studies (Nimmo *et al.* 1987, Conca and Wright 1994) did not allow the direct monitoring in-flight of the relevant variables (suction, moisture, discharge velocity) during testing. If the suction gradient in Equation 8 is assumed to be negligible, the hydraulic conductivity becomes inversely proportional to  $\omega^2$ . To alleviate shortcomings of early studies, an improved centrifuge device was recently developed (McCartney and Zornberg 2005). 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, moisture 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 11(a) shows the centrifuge permeameter and its instrumentation layout and Figure 11(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 11(a) is essentially a column test such as that shown in Figure 10(a). The centrifuge is a suitable tool to provide expeditious evaluation of the soil-geosynthetic interaction arising from a capillary break induced by geotextiles.

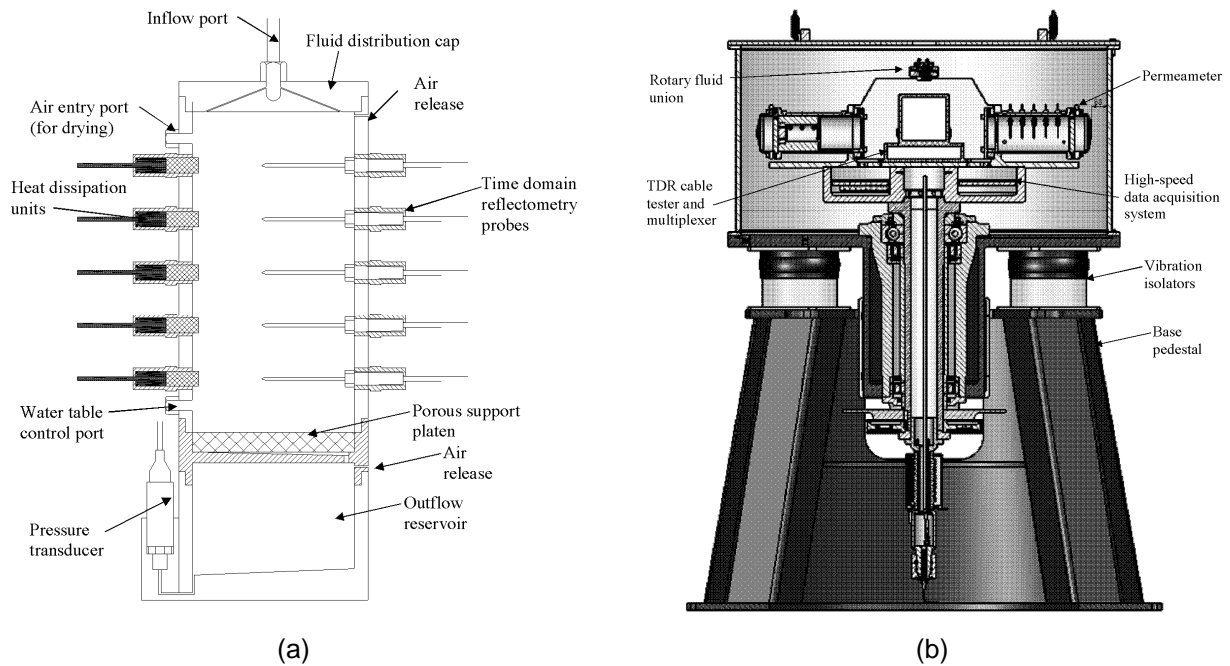


Figure 11: Permeameter for Unsaturated Soils: (a) Permeameter; (b) Centrifuge layout including a permeameter

Compared to soils, the  $K$ -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 12(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 12(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 principal, it is possible to concurrently determine the  $K$ -function from test used to measure the WRC, but difficulties arise due variability in results, the head loss through the high-air-entry porous stone in the hanging column and capillary pressure cell tests, and the lack of instrumentation in the stacked geotextile and capillary rise tests.

#### 4. ALTERNATIVE COVER SYSTEMS

Various types of alternative covers have been recently implemented in arid and semi-arid climates. As shown in Figure 1(b), both evapotranspiration and moisture storage are relevant water balance components that can benefit the performance of alternative covers. The focus of this paper is on capillary barriers; although the various types of alternative covers are discussed next as they are closely related, and can all involve geosynthetic components.



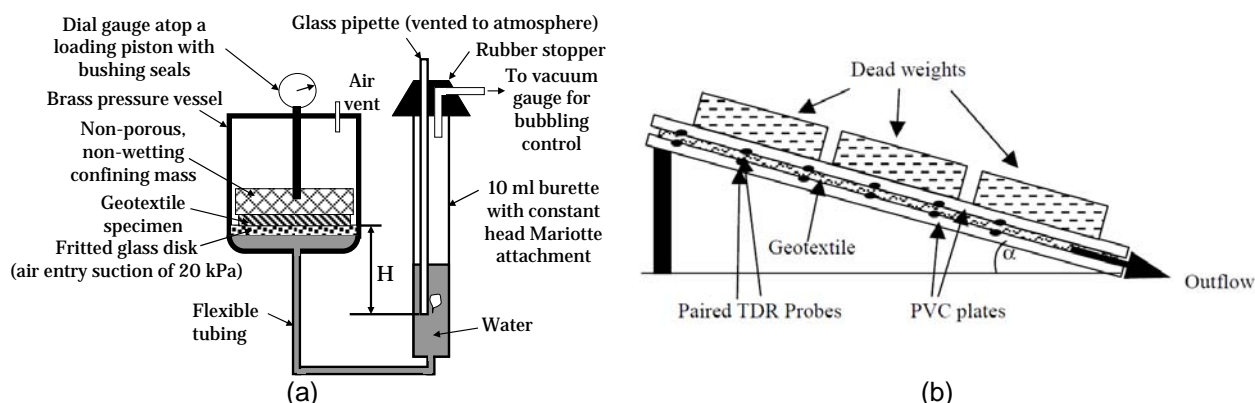


Figure 12: Equipment to measure the hydraulic conductivity of unsaturated geotextiles: (a) Hanging column with outflow measurement; (b) Inclined instantaneous profile test (Morris 2000)

#### 4.1 Monolithic Covers

Monolithic covers are evapotranspirative covers that consist of a single soil layer placed directly over the waste (Zornberg *et al.* 2003). Figure 13(a) shows a schematic view of a monolithic soil cover. The soil layer acts both as a substrate for vegetation and a hydraulic barrier. A foundation layer consisting of the same soil type is typically used to provide a level surface above the waste. Early research focused on investigation of the long-term behaviour of natural soil layers in arid regions, assuming that the behaviour is analogous to that of an engineered monolithic cover (Waugh 1994). These studies found that moisture content fluctuations in natural analogues in recent geologic history are typically confined to the upper metres of soil, indicating that monolithic covers may be an acceptable long-term solution to waste disposal.

The major aspects in monolithic cover design are the proper characterization of the hydraulic properties ( $K$ -function and WRC) of the soils as well as the determination of the appropriate thickness of the engineered soil cover. Figure 13(b) shows schematic moisture profiles, illustrating typical seasonal fluctuations in a properly performing monolithic cover. The moisture profiles illustrate wetting during infiltration events and subsequent drying due to evapotranspiration. Although some moisture fluctuations are expected to reach the base of the cover in extreme events, most of the moisture fluctuations are expected to be confined within the upper portion of the cover. Monolithic cover design requires selection of the cover thickness and soil moisture storage necessary to keep the basal percolation below a minimum allowable (design) value, given the expected weather conditions for a site.

The soil moisture storage of a cover storage depends on the shape of the soil WRC. The greater the moisture retained in a soil for the suction values expected in the field, the greater the moisture storage. A parameter that has been used to quantify the moisture storage is the field capacity, which is defined as the threshold moisture content value above which the soil no longer retains water by capillarity under the effects of gravity (Zornberg *et al.* 1999). When water is added to a soil that is at field capacity, drainage occurs. The field capacity may be obtained from infiltration tests, although a generally accepted value for silt and low plasticity clay soils is the moisture content corresponding to a suction of 33 kPa (Nachabe 1998, Meyer and Gee 1999). The storage capacity of a monolithic cover can be preliminarily estimated by multiplying the volumetric moisture content at field capacity (obtained using the WRC) by the cover thickness.

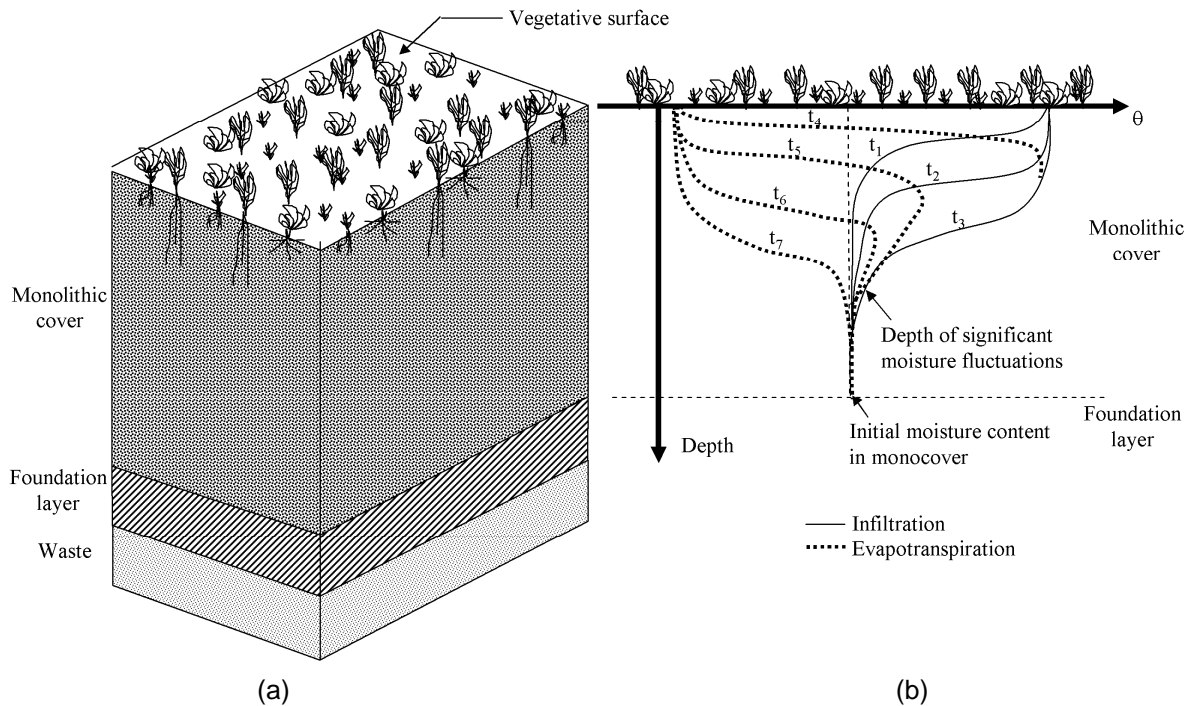


Figure 13: Monolithic cover: (a) Soil profile; (b) Typical seasonal moisture content fluctuations (Zornberg and McCartney 2007)

#### 4.2 Capillary Barrier Covers

Capillary barriers are evapotranspirative covers composed of a layered system that involves a fine-grained soil (silt, clay) placed over a coarse-grained geomaterial (sand, gravel, nonwoven geotextile). Capillary barriers use the contrast in hydraulic properties between the fine- and coarse-grained soils to enhance the ability of the fine-grained material to store moisture (Shackelford *et al.* 1994, Stormont and Anderson 1999, Khire *et al.* 1995, 2000). The upper portion of this cover can be considered as a monolithic cover (Section 4.1) that benefits from added storage induced by a capillary break. The capillary break minimizes the amount of water that can flow across the interface from the fine-grained component of the cover into the coarse geomaterial until the overlying soil is nearly saturated. The pressure (or energy) in the water within the fine-grained soil must increase (i.e. the suction must decrease) to the point that it is sufficient to overcome the surface tension forces holding the water within the small pores. The pressure (or energy) in the water also has to be sufficient to force the air out of the pores of the coarse-grained soil (or the geotextile). The energy in the pore water in an unsaturated soil can be quantified by the matric suction (see Equation 1), equal to the difference between the pore air and water pressures. Figures 14(a) and 14(b) show WRCs and  $K$ -functions for a sand or nonwoven geotextile (coarse-grained component), and a low plasticity clay (fine-grained component).

The capillary break concept relies on the continuity of suction, even at the interface between two different materials. Accordingly, the shapes of the WRCs for the soil and geotextile indicate that the degree of saturation in the two materials may be different for the same suction. For example, Figure 14(a) shows that when a system is at an initially suction of 10 kPa, the clay has a degree of saturation of 0.7 (relatively wet) while the underlying coarse material is at residual moisture content of 0.03 (very dry). Figure 14(b) indicates that at this suction of 10 kPa the clay has a hydraulic conductivity of approximately  $1 \times 10^{-9}$  m/s while the sand has considerably higher impedance to flow (essentially impervious). Consequently, if moisture infiltrates into the fine-grained material after a precipitation event and reaches the interface with the coarse-grained material it can only progress into the coarse-grained material at a very slow rate. That is, water will accumulate at the interface until the suction at the interface reaches a value at which the hydraulic conductivity of the coarse grained material is no longer below that of the

fine-grained material [4.0 kPa in Figure 14(b)]. This suction value is referred to as the breakthrough suction. A breakthrough suction of 4.0 kPa is significantly below the suction corresponding to field capacity (typically considered at 33 kPa for clay), which indicates that the degree of saturation in the clay will be relatively high (95%) when breakthrough occurs. For suction values less than that corresponding to field capacity, water would have drained downwards by gravity had the capillary break not been present. When the breakthrough suction is reached, leakage is observed into the coarse-grained layer at a rate approaching that corresponding to the saturated hydraulic conductivity of the barrier layer.

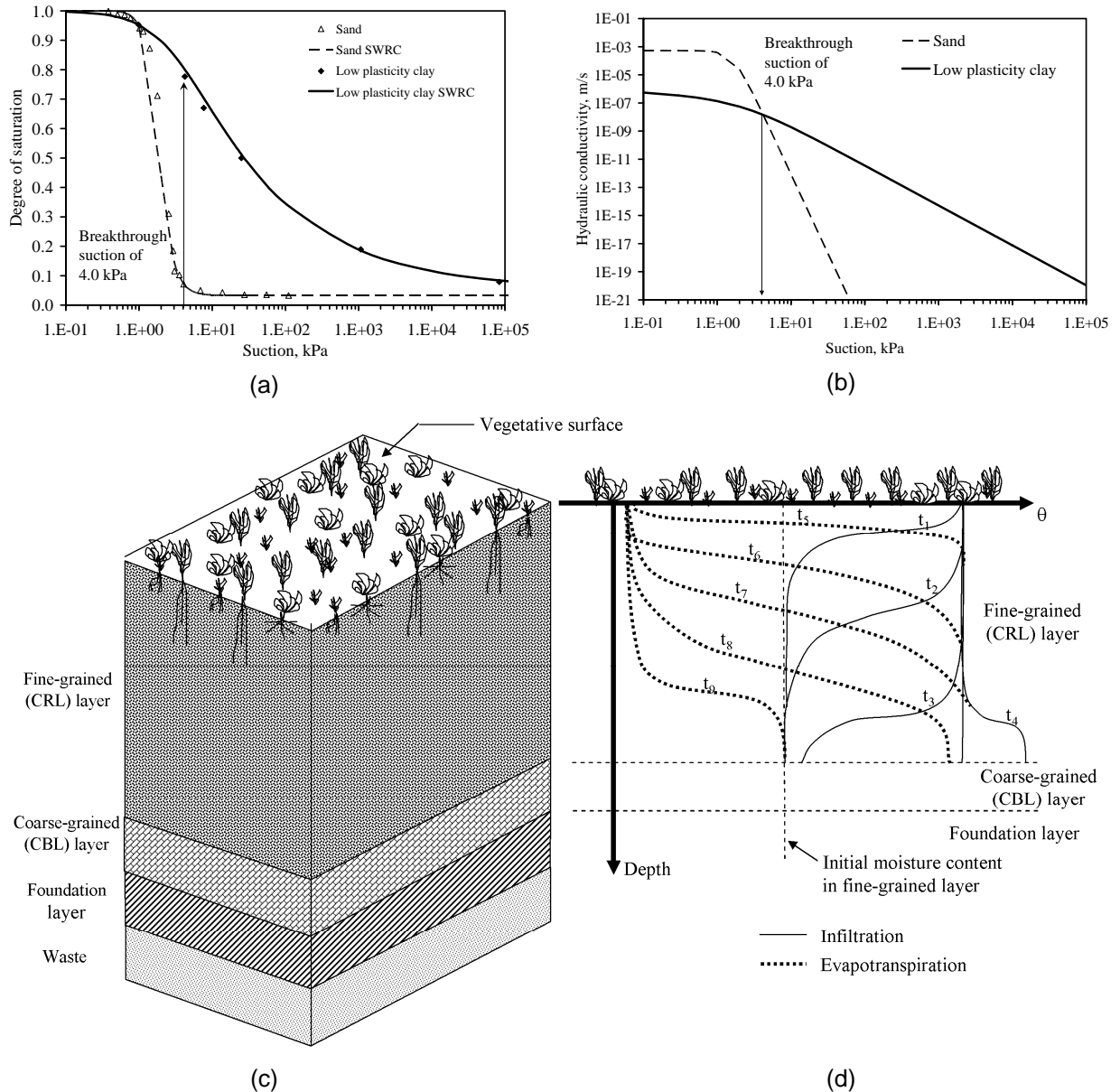


Figure 14: Capillary barrier details: (a) Conceptual SWRC illustration of the capillary break effect; (b) Conceptual K-function illustration of the capillary break effect; (c) Capillary break soil profile; (d) Typical seasonal moisture content fluctuations (Zornberg and McCartney 2007)

Figure 14(c) shows a schematic view of a capillary barrier. Similar to the monolithic cover, the soil layer acts both as a substrate for vegetation and a hydraulic barrier (or capillary retention layer, CRL). However, a coarse-grained material (capillary break layer, CBL) is placed over the foundation material to create a capillary break at the interface between the CRL and the CBL. Figure 14(d) shows schematic moisture profiles illustrating the expected seasonal fluctuations in a properly performing capillary break

cover. Unlike the monolithic cover, the moisture front can reach the bottom of the CRL layer without resulting in basal percolation, provided that the moisture at the interface does not exceed the breakthrough value. An important benefit of capillary breaks is that the moisture storage within the fine-grained soil can exceed its freely draining state (field capacity). Consequently, more water can be stored in a capillary break cover than in a monolithic cover of equivalent thickness. Alternatively, a thinner fine-grained soil layer can be used in a capillary break cover to obtain the same moisture storage as in a monolithic cover. Inclined covers may experience lateral diversion, which leads to greater moisture contents in the lower portion of a slope, resulting in a greater likelihood for breakthrough. Conservatism should be used in capillary barrier design, as these barriers have typically been reported to experience breakthrough during spring snowmelt when plant evapotranspiration is at a minimum (Khire *et al.* 1999). In addition, preferential flow through larger pores may lead to significant variability in the breakthrough suction (Kampf and Holfelder 1999).

#### 4.3 Anisotropic Barrier Covers

Anisotropic barriers are similar to capillary barriers, but their design accounts for the internal lateral drainage through one or more drainage layers resulting from the inclination of the cover (Stormont 1995, Bussiere *et al.* 2000, Parent and Cabral 2005). Figure 15(a) shows a schematic view of an anisotropic barrier. Anisotropic layers typically involve a soil vegetation substrate overlying a coarse-grained drainage layer, which are in turn underlain by a primary barrier layer a second coarse-grained layer to provide a capillary break. The coarse-grained drainage layer functions both as a capillary break to the vegetation substrate and as a drainage layer for breakthrough water. The water collected by the drainage layer, along with moisture migrating laterally within the vegetation substrate is typically diverted to a ditch before a significant amount of water can infiltrate into the primary barrier. Figure 15(b) shows moisture profiles illustrating the expected trends along the length of an anisotropic barrier during a wet season. The capillary break at the drainage layer increases the moisture storage capacity of the vegetative substrate. Infiltration of water into the barrier layer generally occurs towards the toe of the slope due to water accumulation from infiltration and lateral drainage. Design of anisotropic covers is more complex than that of monolithic or capillary break covers due to the need to quantify the required hydraulic properties for the layered profile as well as the volume of laterally diverted water. Field comparisons between the performance of test-scale capillary break, anisotropic, and monolithic covers performed by Dwyer (1998) indicate that the anisotropic cover performed well compared to the other covers for the same weather conditions over a 5 year monitoring program. However, its construction was the most difficult of the three covers.

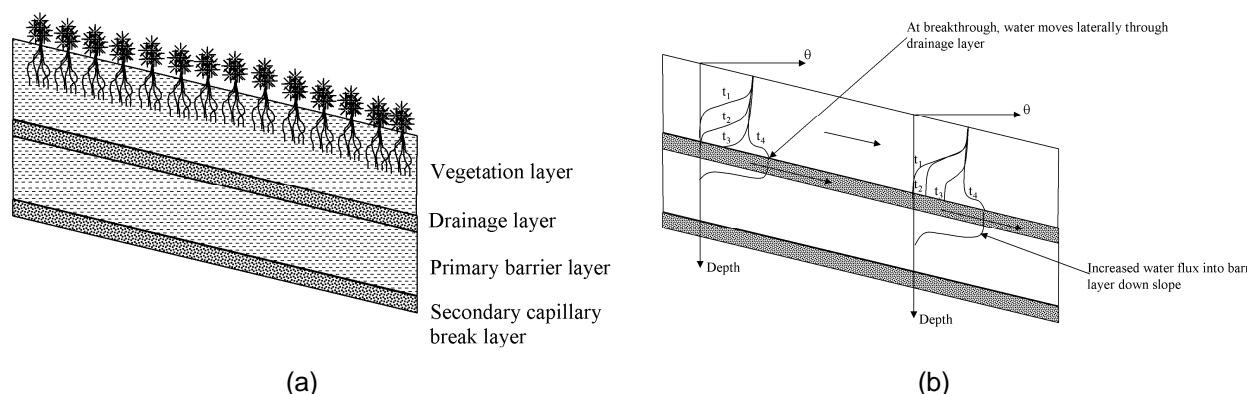


Figure 15: Anisotropic barrier: (a) Soil profile; (b) Typical moisture content fluctuations during infiltration (Zornberg and McCartney 2007)

## 5. 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 in unsaturated conditions (Stormont and Anderson 1999) or to

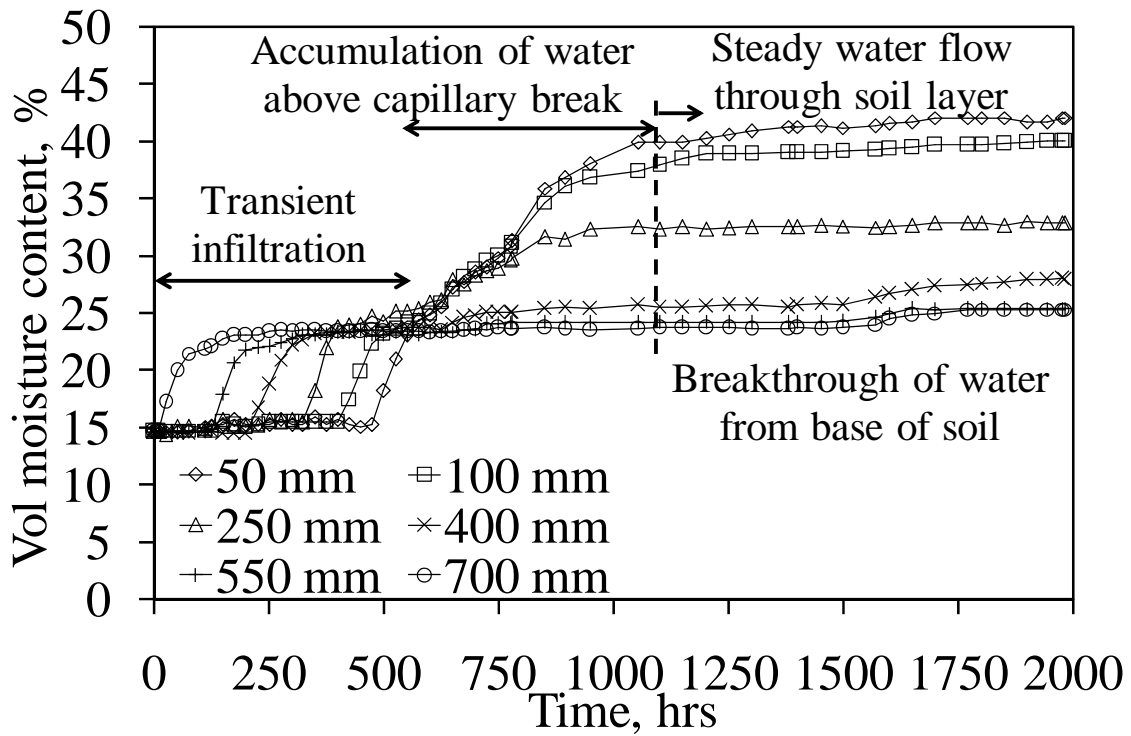


determine the hydraulic conductivity of unsaturated soil layers (Moore 1939, McCartney *et al.* 2007). A number of column tests have been reported in which constant infiltration rates were applied to a clay layer underlain by a nonwoven geotextile (McCartney *et al.* 2005, Stormont *et al.* 2008, McCartney and Zornberg 2009). 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 with a moisture content proportional to the flow rate passes through the soil. 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.

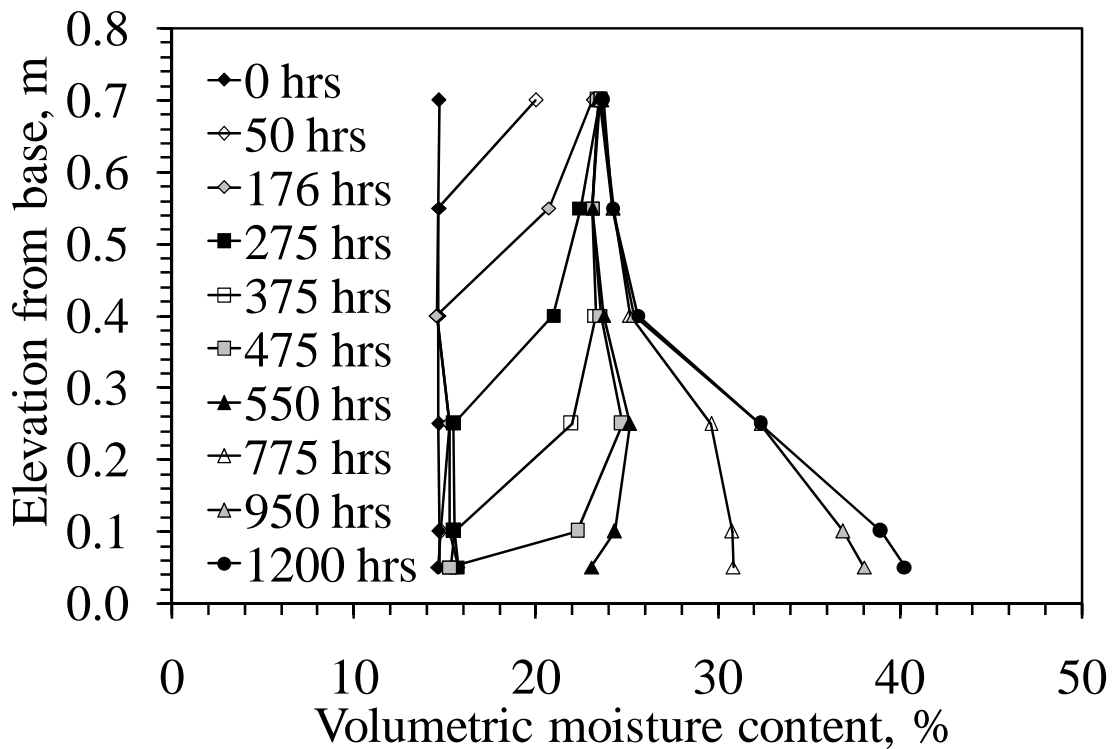
The changes in moisture content with time in a column study conducted at the University of Texas at Austin to evaluate the development of a capillary barrier effect is shown in Figure 16. Water was supplied to the top surface of soil at a constant inflow rate, and its transient infiltration through the soil column was monitored both visually and using embedded moisture content sensors. Specifically, the moisture 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 moisture content data shown in Figure 16(a), three distinct phases of moisture flow can be identified for a constant infiltration rate of  $4 \times 10^{-8} \text{ m}^3/\text{s}/\text{m}^2$  (approximately 100 times smaller than the saturated hydraulic conductivity of the soil). Initially, the entire profile was relatively dry, with an as-compacted volumetric moisture 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 moisture 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 moisture 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 16(b) shows the moisture content profiles with height at different times. The results in this figure better illustrate the impact of the geosynthetic capillary break on the moisture storage within the soil layer during infiltration at a constant flow rate. The moisture content towards the top of the profile ( $\theta = 25\%$ ) 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 moisture 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 moisture content should also be constant with height. A constant moisture 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 moisture content at the base of the soil layer continued to increase after the wetting front had reached the level of the geosynthetic, beyond the moisture content corresponding to infiltration under a unit hydraulic gradient. Specifically, as shown in the figure, moisture content increases to a value of approximately 40% due to the development of a capillary break. As also shown in Figure 16(b), approximately 0.3 m of soil experienced an increase in moisture 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 (2009) indicate that the geosynthetic capillary barrier can lead to an increase in soil moisture storage up to a height of 0.5 m above the geosynthetic.





(a)



(b)

Figure 16: Results from column infiltration tests: (a) TDR moisture content time series for different heights from the base of a soil layer undergoing infiltration from the surface at a constant rate; (b) Moisture content profiles with depth for different times

A discussion of the increase in moisture 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 17 shows the progression in moisture storage in the soil with time during infiltration, calculated by integrating the moisture content profiles in Figure 16(b) from 0 to 300 mm. The moisture storage in this figure was normalized in relation to the moisture storage at saturation (*i.e.*, the maximum moisture storage). Also shown in this figure are the moisture storage values expected in the soil layer for different infiltration rates. The moisture 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 moisture content depends only on the magnitude of the infiltration rate. Further, the moisture storage of the soil layer at capillary breakthrough is significantly higher than the field capacity moisture storage. The field capacity moisture storage is an empirically derived quantity, which generally reflects the volume of moisture that can be stored in a soil against the downward pull of gravity.

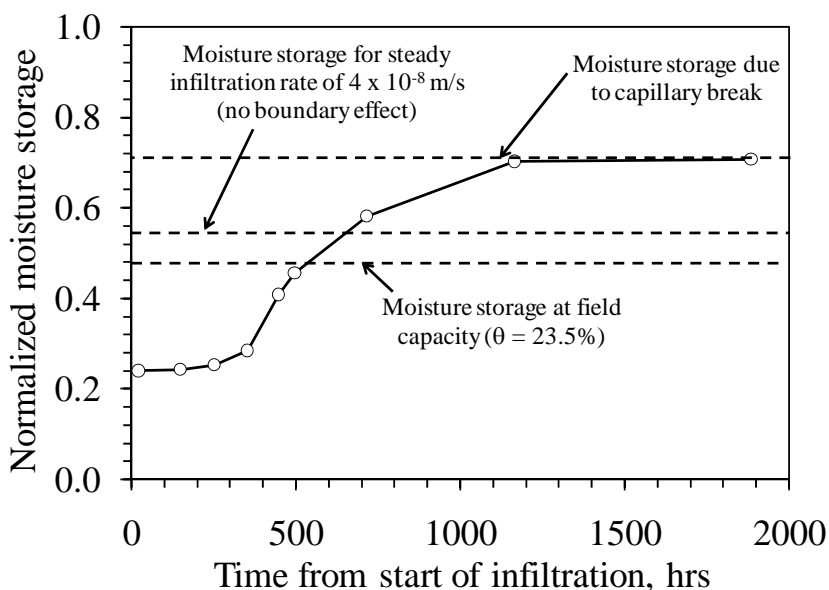


Figure 17: Increase in normalized moisture storage in the 300 mm of soil overlying the capillary break with time from the start of infiltration

Theoretical investigations have described the reasons why moisture 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 moisture 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 moisture storage should be expected beyond that occurring in the soil during infiltration. This is because infiltration is occurring under saturated conditions, so the moisture storage in the soil during infiltration equals the maximum moisture 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) provided further information 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 will not be observed in any soil due to the capillary break effect for infiltration 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 conditions is not a representative condition for the design of alternative cover systems, which have been constructed in arid and semi-arid conditions.

There have been several other column studies that corroborate the observed behaviour noted in this section. Stormont and Morris (2000) carried out infiltration column tests using a 10 cm-diameter tube with a 20-cm high layer of silty sand placed over a 5-cm deep 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. The objective of the tests was to investigate these materials as capillary breaks under downward infiltration flows. 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 1-m high column fitted with tensiometers and TDRs to examine the saturated-unsaturated response of a geocomposite under infiltration simulating rainfall conditions. Both the 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 1.6 m dry sand-geotextile column test under constant head with the objective of determining the transient pore-water pressure response and the corresponding advancement of the wetting front along the column. The column was instrumented with air pressure transducers, moisture 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.

Several other column studies have been performed to quantify the impact of different variables on the behaviour 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 have a significant impact on geosynthetic capillary barrier behaviour. In particular, this study found that loosely compacted clays have capillary breakthrough at smaller suctions than highly compacted clays. However, the speed of the moisture front may increase significantly, leading to the potentially unacceptable condition in which a comparatively short rainy event may lead to full saturation of the cover. McCartney and Zornberg (2009) 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 breakthrough suction and volumetric water content measured in this column 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 transitions from residual to saturated conditions. Further, and consistent with results reported by Stormont *et al.* (2008), the capillary break was re-establish after the matric suction at the soil-geosynthetic interface increases over the breakthrough suction value. This is important because it indicates that field geosynthetic capillary barriers are expected to have a long-term sustainable performance even if they experience capillary breakthrough.

## 6. PRACTICAL APPLICATIONS INVOLVING CAPILLARY BARRIERS

While the focus of this paper was mainly on geosynthetic capillary barriers for alternative cover design, many other geotechnical and environmental applications could take into account the advantages of inducing a capillary barrier induced by nonwoven geotextiles. Along these same lines, there are many situations in which poor performance of an earth structure involving nonwoven geotextiles may be encountered should the capillary break effect be ignored. A brief overview of these applications is presented in Section 6.1. The impact of geosynthetic capillary barriers in the specific case of alternative cover systems is discussed in Section 6.2.

## 6.1 Impact of Geosynthetic Capillary Barrier in Geotechnical Applications

### 6.1.1 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 from unsaturated fill in a similar way as if the fill were saturated. Richardson (1997) observed the failure of a slope with a geosynthetic underdrain, and found that the failure could be explained by the use in the design of the dry unit weight of the soil in the stability analysis. However, the soil above the geosynthetic underdrain became nearly saturated due to the development of a capillary barrier, so the actual unit weight was closer to the saturated unit weight. 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 need to account for the results of column studies reported in Section 5. For example, results from the column study reported by Bathurst et al. (2009) indicate that for soil-geotextile systems subjected to cross-plane infiltration, current design practice that the saturated hydraulic conductivity of the geotextile be at least equal to 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 ponding of water over geotextiles.

As part of an effort to better understand this phenomenon, 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 indicates that more drainage is observed from the geocomposite when the slope angle is decreased and the infiltration rate is increased. 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 the observations in Section 5 that the rate of infiltration affects the moisture 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 in these conditions for a relatively long period of time after the infiltration event.

The theory of water flow in unsaturated geomaterials presented in Section 2 considered for simplicity that the pore air pressure equals zero. However, in landfill cover systems atop waste that is actively biodegrading, 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 impact can also occur if geotextiles, rather than geomembranes, are used in the cover system and a capillary break develops in the geotextile component. Since wet geomaterials have a much lower permeability for gas flow (Bouazza 2004), accumulation of water 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 the gas collection system even for covers that do not involve geomembranes.

### 6.1.2 Impact on Reinforced Soil Structures

Proper drainage within the backfill is one of the most important design issues that must be considered to have good behaviour of reinforced soil structures. This is especially the case in earth retention systems with poorly draining backfill (Zornberg and Mitchell 1994, Mitchell and Zornberg 1995) due to the lower hydraulic conductivity of these soils. Although geosynthetic drains have been proposed for use in these soils to reduce the drainage paths, these drains may not conduct water from the soil until the soil is nearly saturated. As in the previously discussed case of slope underdrains, the development of a capillary barrier implies that the soil unit weight to be considered in the design should account for the nearly saturated conditions.

Iryo and Rowe (2006) used finite elements to simulate the hydraulic and stability behaviour of reinforced embankments. Numerical simulations were conducted to examine the effect of geotextile arrangement and infiltration conditions as well to provide insight into 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. As illustrated in Figure 18, this study also noted that the contribution as drains of nonwoven geotextiles within reinforced fills is more significant than their reinforcement function.

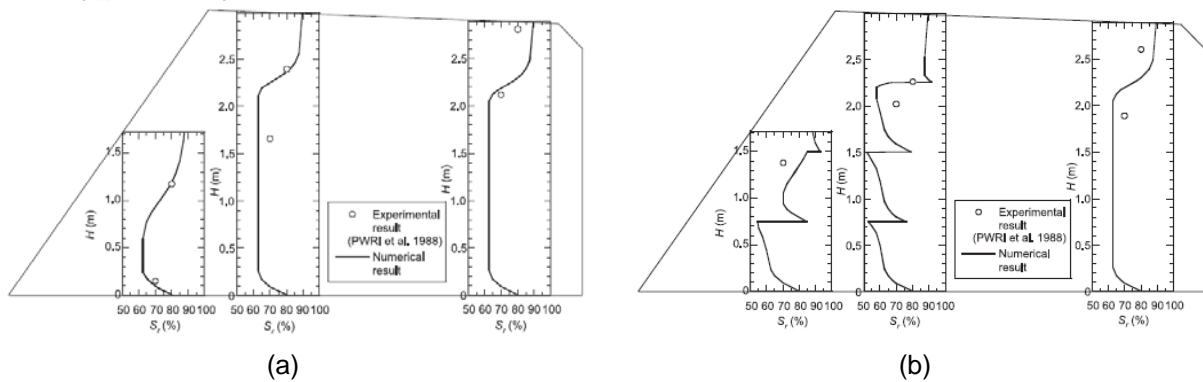


Figure 18: Comparison between moisture profiles in a retaining wall: (a) without reinforcements; (b) with geotextile reinforcements (Iryo and Rowe 2006)

Garcia *et al.* (2007) obtained experimental results to support the observations made by Iryo and Rowe (2006) using numerical simulations. In this study, model embankments were built using two layers of permeable geosynthetics, and their performance was assessed during infiltration and evaporation boundary conditions. Their results indicate that geosynthetics embedded within the soil approached saturation only when the pore water pressure of the surrounding soil was close to zero or positive. Local failure was observed during infiltration due to water accumulated above the geosynthetics. Failure occurred because the pore water pressure increased within the soil immediately above the geosynthetic layers. Garcia *et al.* (2007) observed that strips of geotextile prevented the capillary barrier effect and allowed the free drainage of water through an embankment.

### 6.1.3 Impact on Pavement Design

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 dynamic soil properties of pavement soils. Specifically, compacted base course soils have high stiffness and shear strength partially because of matric suction induced for comparatively low moisture content values. Flow of water into the fill will cause a decrease in suction. As compacted fills are frequently used in flexible pavements and foundations for structures (walls, footings), a decrease in suction may compromise performance of the system. A nonwoven geotextile could be used in a flexible pavement system as a hydraulic barrier to capillary flow (from a water table or drainage ditch), as shown in Figure 19. Configurations such as these can be used to prevent moisture flow that could lead to frost heave or a reduction in stiffness. Also in this case, the geotextile also serves as a separation layer and lateral drain.

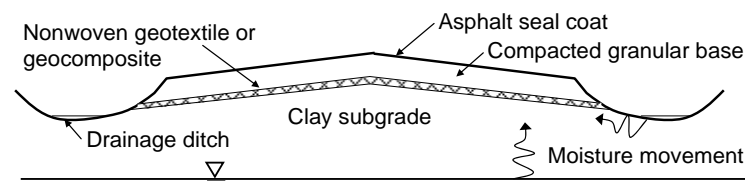


Figure 19. Nonwoven geotextile used as a hydraulic barrier in a flexible pavement

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 in 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 within soil prepared to simulate field conditions 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 prevent the continued upward movement of water into the overlying soil layer observed when using isolated geotextiles.

Clough and French (1982) performed an early study on the use of geotextiles in pavement systems to mitigate moisture fluctuations in base courses induced by capillary rise from underlying soils. They found that upward flow was blocked by placing a geotextile a few centimetres above the water table and above the level at which the moisture content approaches saturation. McCartney *et al.* (2008) evaluated the use of nonwoven geotextiles and geocomposite drainage layers as moisture 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 20). 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 presence of an 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.

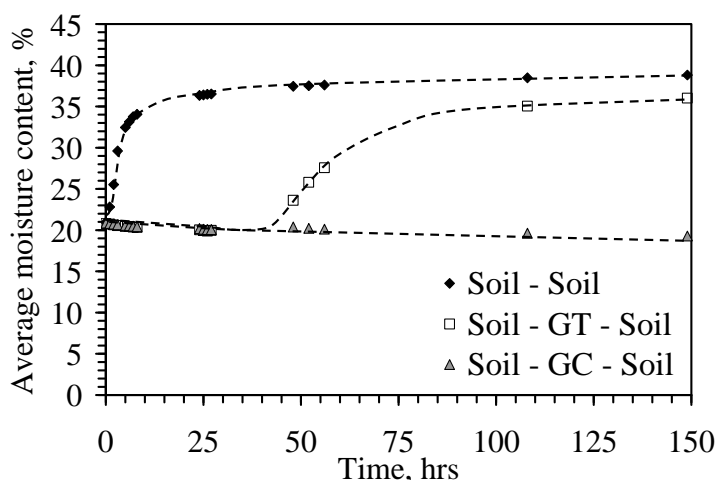


Figure 20: Water content changes due to capillary rise in different soil-geosynthetic systems

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 provide wicking action to 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 (GCBD) removes water from soil while pore pressures remain negative, leading to higher stiffness in the system. Further, because the water is removed through lateral transmission, the chances that continued infiltration from the soil surface will lead to capillary breakthrough decrease. The GCBD 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 GCBD and the soil layers was collected. The GCBD was successful

in draining sufficient water under suction to prevent positive pore water pressures from developing in the base course and to limit water movement into the underlying subgrade soil.

#### 6.1.4 Impact on Landfill Leak Detection Systems

Rowe and Iryo (2005) noted that a geosynthetic capillary barrier may lead to an unexpected behaviour in the leak-detection or secondary leachate collection system below a landfill composite liner. The effects of the initial conditions in the underlying foundation soils, the distance from the leakage point to the drainage point, and several other factors on the time for leakage to be detected were evaluated using finite element simulations. They found that the time for leakage depends on the initial degree of saturation of the material. Good comparison was observed 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.

#### 6.1.5 Impact on Agriculture and Turf Underdrain Applications

McCartney and Allen (2008) evaluated the use of geosynthetic capillary barriers to increase moisture storage within the plant rooting zone in order to increase the effectiveness of irrigation. Column tests were performed using low plasticity soil obtained from a test farm to evaluate the impact of the thickness of the soil layer atop a geosynthetic layer on plant growth. The geosynthetic capillary barrier was observed to cause an increase in soil moisture storage to an elevation of nearly 0.5 meters above the geosynthetic. Also, the response of a vegetated soil column containing a geosynthetic capillary break was compared to another column without a capillary break. The irrigation volumes, surface radiation (from growing lamps), and moisture storage were tracked from the time of planting over a three month time period. The results indicated that plants grew healthier in the columns with a geosynthetic capillary break. The results from this study can be extended to the design of turf systems for sports fields. This is because turf health may be improved if the water content in the soil is increased, although excessive moisture may also be detrimental to the performance of the sports field. Selection of the depth of the geosynthetic layer is a key design element to achieve adequate performance of turf underdrain systems.

### 6.2 Impact of Geosynthetic Capillary Barriers on the Design of Alternative Covers

Two important aspects related to the impact of geosynthetic capillary barriers affect significantly the perceived good performance 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. It should be recognized that proper design of capillary barrier covers should always incorporate a nonwoven geotextile at the interface between fine-grained soils and the underlying coarse-grained capillary barrier material. These two important issues are discussed next.

#### 6.2.1 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 demonstration of equivalency 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, which may sound as an academic discussion to many, 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 of the basal percolation using the proposed soils 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 geotechnical engineers began using them to prove equivalency of alternative earthen final covers such as the monolithic covers previously described in Section 4.1 with conventional regulatory-prescribed cover systems. While there are different types of lysimeters (e.g. pan lysimeters, suction lysimeters), pan lysimeters have been the most common lysimeter used in measuring 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 collected water would be measured. The schematic view of a pan lysimeter is shown in Figure 21 (Benson 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 moisture. Lysimeters became popular because they provide a direct measurement of the variable of interest (i.e. basal percolation through the proposed cover) thought to be the most direct and accurate way to measure percolation through the soil. Indeed, a perceived advantage of lysimeters is that they can be constructed with a size that is large enough to account for spatial variability of the soil layer. Despite the potential advantages, there are several major drawbacks that may have been overlooked in the current state of the practice.

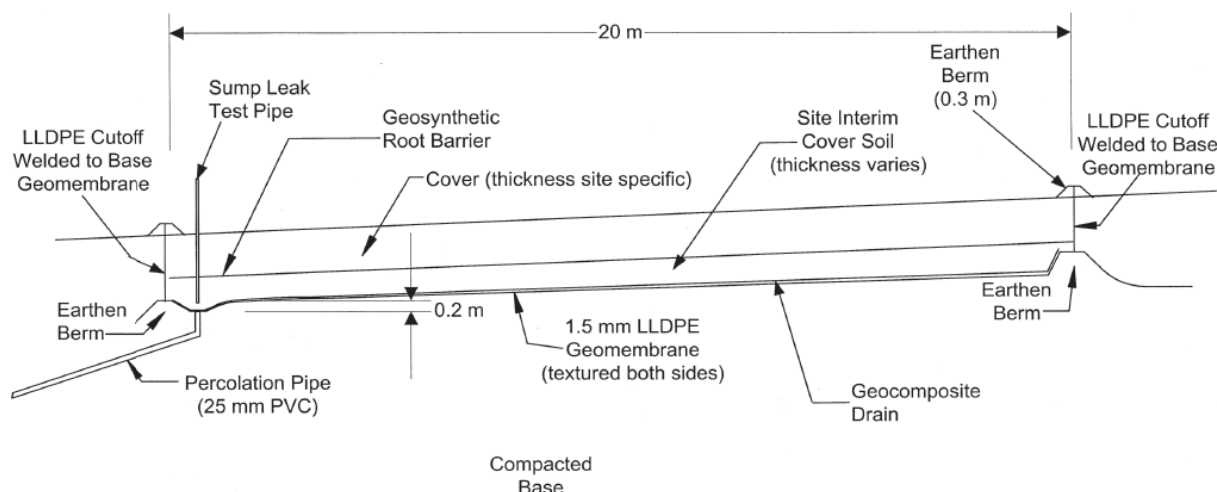


Figure 21: Schematic view of a typical pan lysimeter used for evaluation of the performance of altern cover systems (Benson 2001)

Lysimeters were initially used in agronomy to determine irrigation needs for crops, and 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 moisture content and suction. ACAP focused on ET covers and constructed a variety of covers with varying dimensions to gain a better understanding of their effects. 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 the ACAP program to how the lysimeters themselves may possibly affect the flow of moisture in the

covers. However, recent infiltration studies such as those discussed in Section 5 of this paper have brought to light concerns regarding the adequacy of relying heavily on lysimetry for evaluation and acceptance of alternative covers. As discussed in Section 5, a problem associated with lysimeters is the development of a capillary barrier at the interface between the cover soil and the underlying geocomposite drainage layer. In addition to laboratory infiltration studies, a recent report on data collected from lysimeters and moisture profiles installed at the high-visibility Rocky Mountain Arsenal site (Zornberg and McCartney 2003) reveals that moisture content data collected at the field lysimeters follows the same pattern as that shown in Figure 16. 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, accumulation of water above the lysimeter prevents proper measurement 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. This means that an alternative cover that has been proven to be acceptable (i.e. demonstrated equivalency) using lysimeter measurements, may indeed have an unacceptably high percolation after field construction without the beneficial effect of the capillary break effect.

By their nature, lysimeters are intrusive measurement devices since the flow pattern within a soil layer located over a lysimeter will be different than 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 avoided 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 involving proposed capillary barrier covers, 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 demonstrated in Section 6.1.3, geosynthetic capillary barriers have been shown to provide higher moisture storage than soil-only capillary barriers. Construction of duplicate test covers, both with moisture 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 since the geosynthetic capillary barrier that develops lysimeters does not necessarily develop in the constructed alternative cover.

## 6.2.2 Impact of Geosynthetic Capillary Barriers on Moisture Storage

As indicated by the results of column tests such as those shown in Figure 16, the development of a capillary barrier enhances the performance of an alternative cover system (e.g. a monolithic cover) since the moisture 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 system, the amount of moisture storage for a given fine-grained soil will depend on the properties of the selected capillary barrier material. More specifically, as illustrated by Figure 3, the amount of moisture 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 22 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) and a gravimetric moisture content of 8% (volumetric moisture content of 12%). Column 2 the same fine-grained soil, but placed over a geocomposite drainage layer that rests on a gravel foundation layer. Volumetric moisture content values were continuously measured throughout the vertical soil profiles using time domain reflectometry (TDR). Figure 22 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  $0.4 \text{ cm}^3/\text{s}$  to the top surface of the clay. This water supply corresponds to a Darcian velocity of  $2.06 \times 10^{-7} \text{ m/s}$ . The flow rate was selected to be less than the saturated hydraulic conductivity of the clay to maintain unsaturated soil conditions.

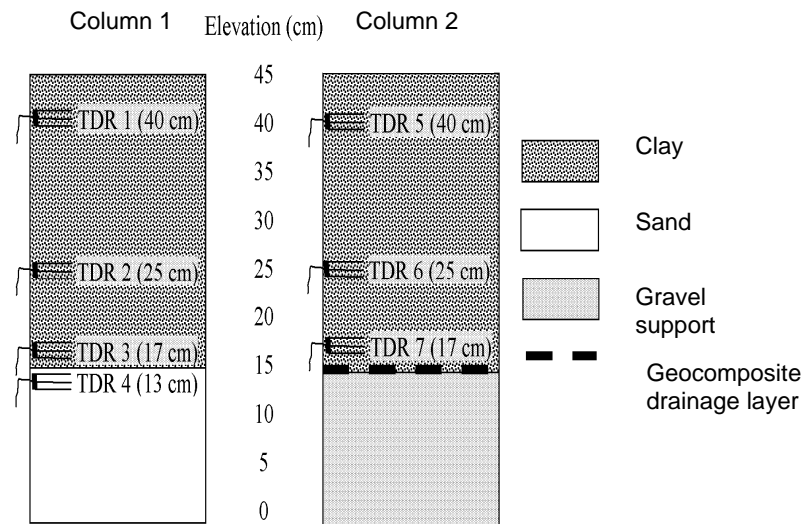


Figure 22. Schematic view of infiltration columns (McCartney *et al.* 2005)

As reported by McCartney *et al.* (2005) the low plasticity clay showed a relatively low saturated hydraulic conductivity of  $1.2 \times 10^{-6} \text{ m/s}$ , while the sand showed a saturated hydraulic conductivity of  $5.3 \times 10^{-4} \text{ m/s}$ . The geocomposite drainage layer used in this study involved a geonet sandwiched between two nonwoven geotextiles with a cross-plane hydraulic conductivity of  $1.9 \times 10^{-3} \text{ m/s}$ .

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 3 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 discussed in Section 3.1. Also, the results previously shown in Figure 9 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 9 indicate that as suction increases, the hydraulic conductivity values of the three materials decrease at different rates.

The  $K$ -functions in Figure 9 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 in the two geomaterials in contact is the same, Figure 9 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 9 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. As will be discussed subsequently, this difference leads to a higher moisture storage induced by the geotextile in relation to that induced by the granular soil.



Figure 23 shows the changes in moisture content with time at four different elevations in Column 1. This figure indicates that the sand is initially very dry (volumetric moisture content of approximately 5%), which corresponds to a negligible hydraulic conductivity. The initial volumetric moisture content of the clay soil is approximately 12% throughout the entire thickness of the profile. The volumetric moisture content measured by TDR 1 (near the soil surface) increases to approximately 25% as the moisture front advances through the clay. Similarly, the volumetric moisture content measured by TDR 2 increases to 25% after a period of about 5,000 minutes. The volumetric moisture content measured by TDR 3 also increases to 25%, but due to the proximity to the capillary barrier it shows a continued increase in moisture content to approximately 36%. Subsequently, after approximately 7,000 minutes TDR 2 shows increasing moisture consistent with TDR 3 readings. This behaviour indicates that the wetting front reached the sand interface, but moisture accumulated above the interface rather than flowing directly into the sand layer. After the clay reached a volumetric moisture content of 36% near the interface, breakthrough is noted by a sudden increase in the volumetric moisture content (26%) recorded by TDR 4 located within the sand layer. The increase in volumetric moisture 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 moisture content of approximately 36% at breakthrough. The WRC of the clay (Figure 3) 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 9).

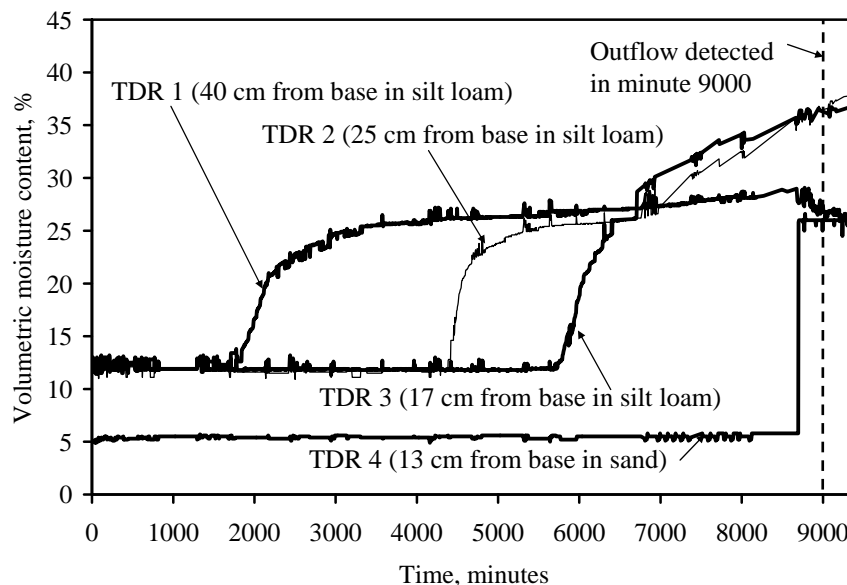


Figure 23: Volumetric moisture content with depth in Column 1 (McCartney *et al.* 2005)

Figure 24 shows the changes in moisture content with time at three different elevations in Column 2. Also in this case, the initial volumetric moisture content of the clay soil is approximately 12%. Consistent with the response shown by Column 1, the volumetric moisture content recorded in Column 2 by TDR 5 (near the soil surface) increases to approximately 25% as the moisture front advances through the clay. Similarly, the volumetric moisture content measured by TDR 2 increases to 25% after a period of about 3,500 minutes. Finally, the volumetric moisture content measured by TDR 7 (near the geocomposite) also increases, but its continued increase is to a moisture 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 moisture 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 moisture storage within the clay layer. Outflow from Column 2 was detected after 8,180 min. As shown by the clay WRC (Figure 3), a moisture 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 9).

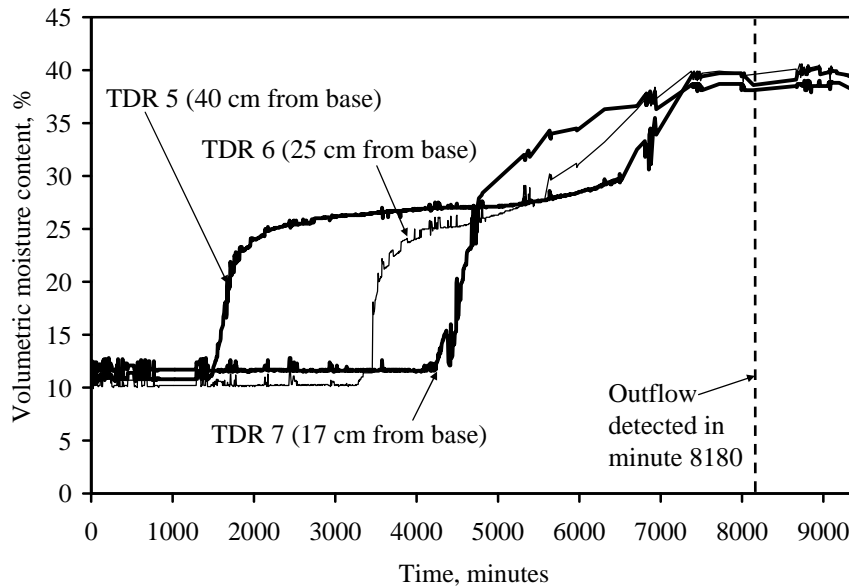


Figure 24: Volumetric moisture content with depth in Column 2 (McCartney *et al.* 2005)

Figure 25 shows the moisture storage within the clay soil as a function of time for both Columns, calculated by integrating the moisture content profile with depth. This figure shows that the moisture storage increases as the infiltration front advances through the soil. Two values of moisture storage are shown as reference in the figure: the storage corresponding to a moisture content of 25% (the moisture content associated with free draining of the imposed impinging flow rate), and the moisture storage corresponding to saturated conditions. The shape of the moisture storage curves for both profiles indicates that the clay stores moisture well in excess of the value expected from a freely-draining condition. Also, as clearly shown by the moisture 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). Also, this finding is consistent with the fact that the WRC the geotextile reported in this study and, in general, of geotextiles reported in the literature (Section 3.1) show a drop in moisture content at suction values that are lower than those typically observed in granular materials.

In summary, not only geotextile capillary barriers provide higher moisture storage than that provided of granular soils, but it offers 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 barrier consider the inclusion of a nonwoven geotextiles at the base of the soil component of the cover.

### 6.2.3 The Rocky Mountain Arsenal Case History

The Rocky Mountain Arsenal is a Superfund site located near Denver, Colorado (USA), which corresponds to one of the most highly contaminated hazardous waste sites in the US. One of the remediation components at the site involved the design and construction of alternative covers. This project is a good example of the previously discussed issues because the use of lysimeters as part of the design phase brought to light the concerns associated with the use of lysimeters for equivalence demonstration.

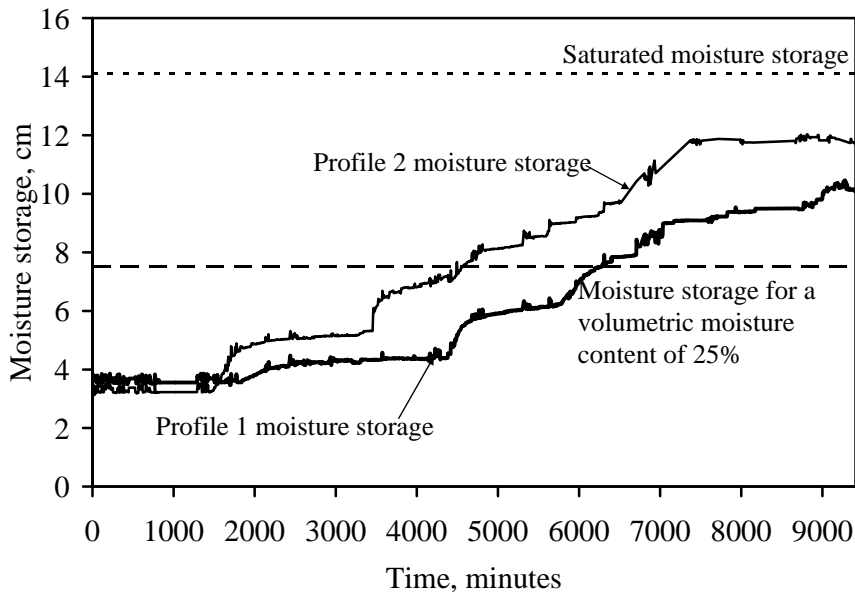


Figure 25: Water storage in Columns 1 and 2 during flow and at saturation (McCartney *et al.* 2005)

The project involved almost 200 acres of RCRA-Equivalent evapotranspirative covers. The climate in Denver is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1,394 mm (as quantified for the 1948 to 1998 period). The wettest months of the year (April to October) are also the months with the highest pan evaporation, which is appropriate for an evapotranspirative cover. The Record of Decision (ROD) for this hazardous waste site required a compliance demonstration to show equivalence of the alternative design with a prescriptive cover before construction of the final evapotranspirative covers. The design and compliance of the covers at the RMA site is governed by a quantitative percolation criterion. A threshold of 1.3 mm/year was selected at this site, which was based on eight years of leachate data collected from two landfill covers built to RCRA Subtitle C standards in Hamburg, Germany, according to analyses described by Melchior (1997). This type of criterion was selected for its simplicity, as it sets a benchmark to be used in post-closure monitoring to demonstrate compliance, and is representative of the basal percolation for resistive covers.

The compliance demonstration at the Rocky Mountain Arsenal involved a field demonstration, which was complemented with comparative numerical analyses (Kiel *et al.*, 2002). Four evapotranspirative test covers were constructed on a rolling plain at the site in the summer of 1998. A plan view of the four test covers, referred to as test covers A, B, C, and D, is shown in Figure 26(a). The covers were constructed using site-specific clays of low plasticity (CL), compacted atop large pan lysimeters (9.1 m by 15.2 m) placed on a 3% grade to allow gravity drainage to a collection tank. Figure 26(b) shows a schematic view of the monitoring layout used in the test covers. The instrumentation program involved monitoring of the basal percolation, precipitation, soil volumetric moisture content, and overland runoff in the four test covers. Basal percolation was collected in gravity lysimeters, which involved a geocomposite underlain by geomembrane. Rain and snow were monitored using an all-season rain gauge. Surface water was collected in polyethylene geomembrane swales constructed around the cover perimeters. Water content reflectometer (WCR) probes were used to measure volumetric moisture content profiles. Specifically, the covers were instrumented with nests of eight WCR probes. This included six WCR probes placed in a vertical profile and spaced evenly with depth. In addition, redundant WCR probes were placed at the same depth as the top and the bottom probes, approximately 1 foot aside from the vertical profile of WCR probes. Cover D was instrumented using three vertical nests of WCR probes. Figure 26(c) shows an elevation view of the covers, indicating the depth of each cover. The covers are separated from each other by 2.4 m-wide buffer zones, and the entire area is vegetated with local grasses and shrubs.

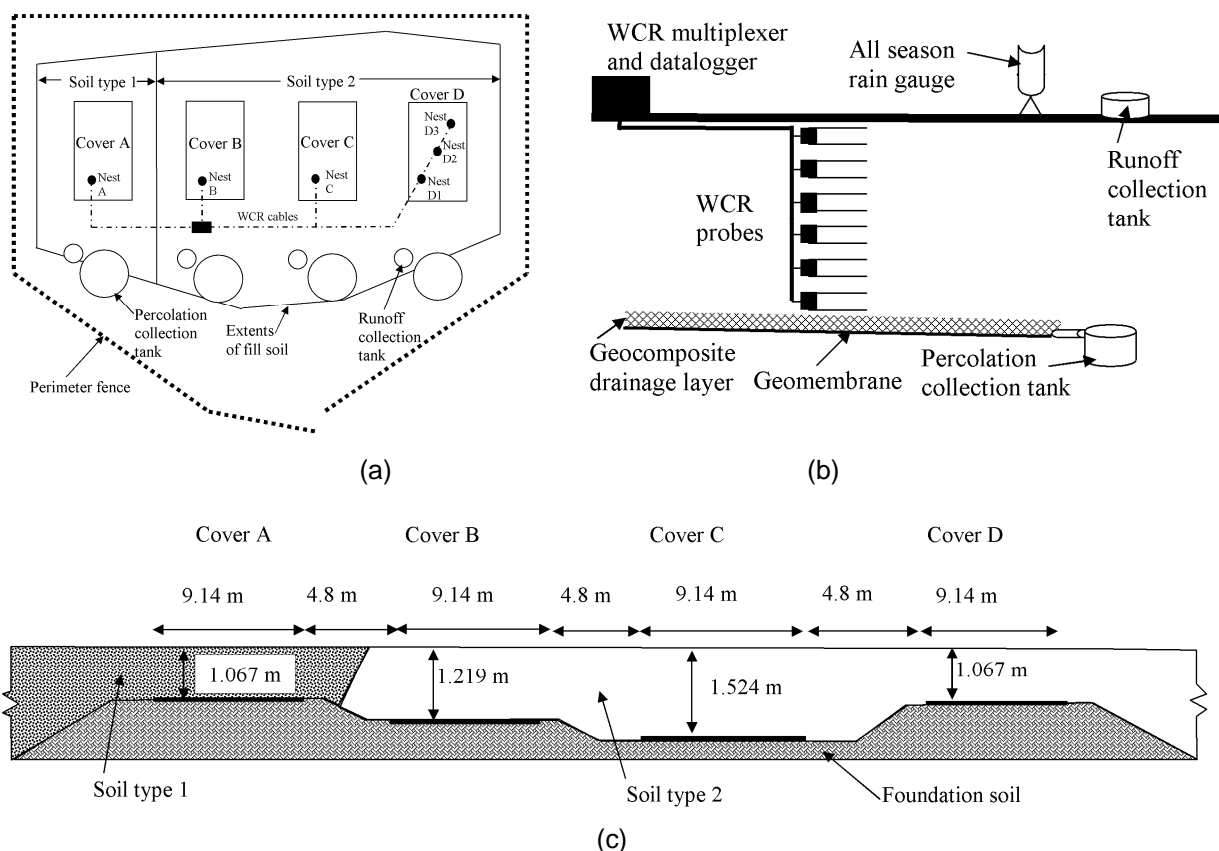


Figure 26: Layout for the monitoring program at the Rocky Mountain Arsenal: (a) Plan view; (b) Schematic view of instrumentation; (c) Elevation view

While the test plots were well instrumented, the equivalent demonstration process initially focused almost exclusively on the lysimeter measurements, since the goal was to verify that the moisture flux through site-specific soils under local weather conditions remains below the threshold of 1.3 mm/year (Kiel *et al.* 2002). According to the lysimeter measurements, all test plots at the Rocky Mountain Arsenal satisfied the quantitative percolation criterion over the period 1998-2003 of operation. That is, all four lysimeters recorded a yearly basal percolation rate below the despite having complemented the natural precipitation with irrigation. Although Cover D showed surface depressions, possibly due to installation of moisture probes or burrowing animals, the collected basal percolation over this cover was still below the percolation threshold.

However, subsequent evaluation of the moisture content records revealed that the lysimeters had affected the natural flow of moisture due to the creation of a capillary barrier (Zornberg and McCartney 2002). The moisture profiles (similar to those shown by the column study in Figure 16) led to under prediction of percolation for the alternative covers. Even though this effect was not identified until after the alternative covers had been approved, with no provision of an engineered capillary barrier, the cover design was amended to include a capillary barrier. In this way, the constructed cover system would have the same components of the tests plots used in the demonstration program; including the capillary break induced by the lysimeters.

The final cover design for the first group of alternative covers being constructed at the Rocky Mountain Arsenal is shown in Figure 27. As shown in the figure, the final cover design includes a geosynthetic capillary barrier. Specifically, the cover profile includes a 1.067 m-thick barrier layer, similar to that used in covers A and D. An additional 0.152 m-thick layer of topsoil is used for vegetation development. The specifications for the final cover soil are based on those for Soil Type 1 used in Test Cover A. The final design includes a nonwoven geotextile over a chokestone layer (coarse gravel) to form a capillary break

at the bottom interface of the barrier soil. The geotextile also helps minimizing the migration of soil particles into the chokestone layer. The chokestone is underlain by a biotic barrier consisting of crushed concrete from a demolition site. A biotic barrier was incorporated to prevent plants and burrowing animals from reaching the waste. The final cover is being instrumented with gravity lysimeters placed within the final cover to measure basal percolation, but also with WCR probes to measure moisture profiles within the barrier soil.

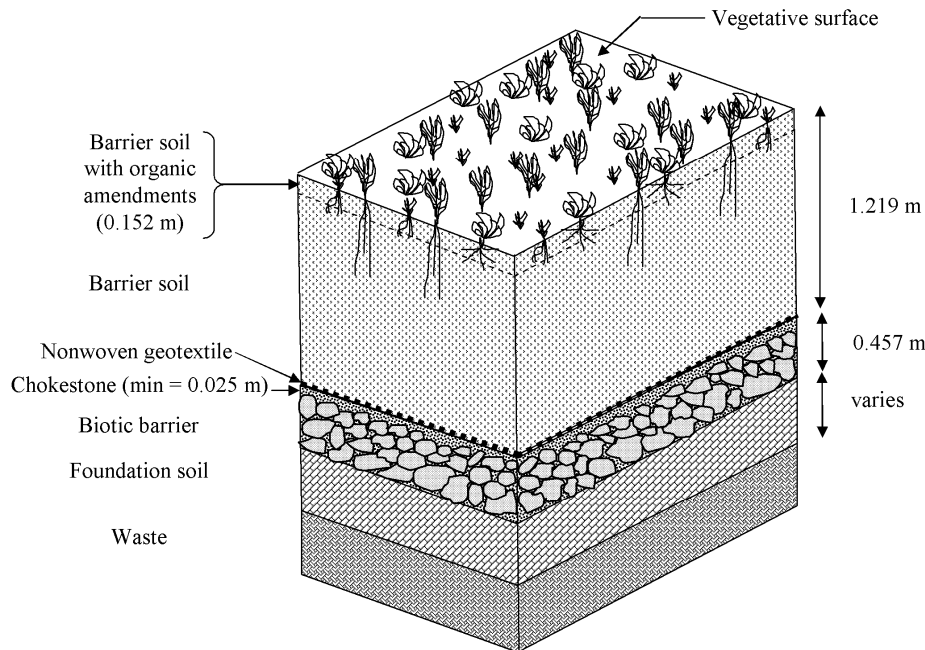


Figure 27: Final cover design at the Rocky Mountain Arsenal in Denver, Colorado, USA

## 7. 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.

Based on the information presented in this paper, engineered (polymeric) capillary barriers are within reach of the geosynthetics industry. The following conclusions can be drawn:

- 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 gravel or 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.
- The design and construction of alternative cover systems (e.g. monolithic covers, capillary barrier covers, anisotropic barrier covers) has grown significantly in arid and semi-arid regions. They account for evapotranspiration and moisture storage, two components of the water balance that are not formally considered in the design of resistive covers.



- 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 moisture 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. Cases in which the development of capillary break is relevant include the design of slopes, reinforced soil structures, pavements, landfill leak detection systems, and agricultural applications.
- The development of a capillary barrier in lysimeters has been often overlooked in current practice. This has led to erroneously low (unconservative) records of percolation in the equivalence demonstration of alternative covers.
- Experimental data is provided illustrating that geosynthetic capillary barriers are superior to soil-only capillary barriers.
- Results from infiltration studies have demonstrated that geosynthetic capillary barriers in alternative covers typically outperform the soil-only capillary barriers.
- Based on the results presented in this paper, 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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