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# Geosynthetic drainage layers in contact with unsaturated soils

## Drainage des geosynthetiques dans le contact avec les sols non saturés

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ABSTRACT
The use of geosynthetic drainage layers in contact with unsaturated soils is being investigated at the University of Texas at Austin. A series of large-scale soil-geosynthetic profiles were constructed using a silt soil in contact with a sand drainage material as well as with a drainage geocomposite (a geonet sandwiched between geotextiles). In contrast to the performance of saturated drainage layers, unsaturated drainage layers were found to impede downward flow of moisture consistent with the formation of a capillary break at the drainage layer-silt interface. Accumulation of moisture associated with an increase in moisture storage in the silt soil was observed, which progressed with depth until breakthrough of flow occurred into the drainage layer. Despite having significantly lower thickness than the sand capillary break, the geocomposite capillary break exhibited similar performance.

RÉSUMÉ
L'usage de couches de drainage de geosynthetiques dans le contact avec les sols non saturés est examiné à l'Université de Texas à Austin. Un feuilleton de profils de sol-geosynthetic à grande échelle a été construit utilisant un sol de terre blanche de silty dans le contact avec un matériel de drainage de sable conventionnel de même qu'avec un geocomposite de drainage (consistant en un geonet sandwiched entre geotextiles). Par opposition à l'exécution de couches de drainage saturées, les couches de drainage ont été trouvées pour empêcher le flux descendant d'humidité, mener à une augmentation dans l'emmagasinage d'humidité dans le sol de terre blanche de limon, jusqu'à ce qu'un niveau d'humidité critique a été atteint causant la percée de flux dans la couche de drainage. Ceci est conforme à la formation d'une coupure capillaire à l'interface entre le geosynthetic et le sable. Malgré avoir de abaisse l'épaisseur que le coupure capillaire de sable, le coupure capillaire de geocomposite a exposé l'exécution similaire.

## 1 INTRODUCTION

Geosynthetic drainage layers are being increasingly used as alternatives to conventional sand or gravel drains in landfills, roadway subgrades, mechanically stabilized walls, and dams. Geosynthetic drainage layers typically consist of a combination of geosynthetics combined with the objectives of providing the functions of a filter, a high fluid conductivity drain, and a separation or protection layer. The primarily used geosynthetic drainage layer configuration consists of a geonet for drainage sandwiched between nonwoven geotextile filters. The in-plane flow through geotextiles and geonets can be reasonably well defined if the soil overlying the geosynthetic drainage layer is saturated. However, the overlying soil is often under unsaturated conditions and, in this case, a capillary break may develop within the soil layer. This can lead to build up of moisture at the interface between the soil and the geosynthetic material. Understanding of this mechanism is relevant in aspects such as quantification of the impinging flow used in the design of drainage layers, performance evaluation of systems used for quantifying percolation through alternative landfill covers, and interpretation of the information gathered in leak detection systems.

Nonwoven geotextiles and drainage geocomposites with different configurations are being evaluated at The University of Texas at Austin in infiltration tests using large geosynthetic-soil profiles. The profiles are instrumented to continuously measure in-plane drainage and soil water content with depth. This paper will focus on an experimental testing program being implemented to assess the unsaturated fluid flow interaction between soil and underlying geosynthetics, boundary condition control, and soil moisture storage capacity. The overall objective of this study is to assess the performance of geosynthetics in contact with unsaturated soils, when used as drainage layers, separation layers, protection layers, or hydraulic barriers.

## 2 MATERIALS

The geocomposite drainage layer used in this study is the GSE Fabrinet® geonet, and consists of a geonet sandwiched between two nonwoven geotextiles (GSE, 2004). The nonwoven geotextiles have a thickness ($t$) of 0.127 cm, an apparent opening size (AOS) of 0.212 mm, a mass per unit area ($\mu$) of 0.02 g/cm$^2$, and a fiber density ($\rho_f$) of 0.91 g/cm$^3$. This information can be used to calculate the geotextile porosity ($\eta$) (Stormont et al. 1997):

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

The porosity of the geotextile was found to be 0.827. The saturated permittivity of the geotextile is 1.5 sec$^{-1}$, which corresponds to a cross-plane saturated hydraulic conductivity of 0.1905 cm/s.

Three soils were used in the testing program. A silt was used as a relatively low conductivity material. For all tests, the silt was statically compacted to 70% density relative to the maximum dry unit weight from standard proctor tests (1.96 g/cm$^3$). Monterey sand #30 was used for comparison with geosynthetic drainage layers as it is a high conductivity material representative of conventional drainage layers. In all tests, the sand was placed at a void ratio of relative density of 50% ($e_{max}$ = 0.78, $e_{min}$ = 0.56). A coarse gravel with very high hydraulic conductivity was used as a foundation layer.

The grain size distribution for the silt and sand are shown in Figure 1, along with the apparent opening size of the nonwoven geotextile component of the geocomposite. This figure indicates that the silty loam has a wide range of particle sizes and should retain significant water even when unsaturated. The sand is poorly graded, with a large proportion of coarse particles, indicating that it will drain rapidly. According to Carroll's criterion (AOS < $2.5d_{85}$), the geotextile is an acceptable filter for both the silt and the sand (Koerner, 1998).

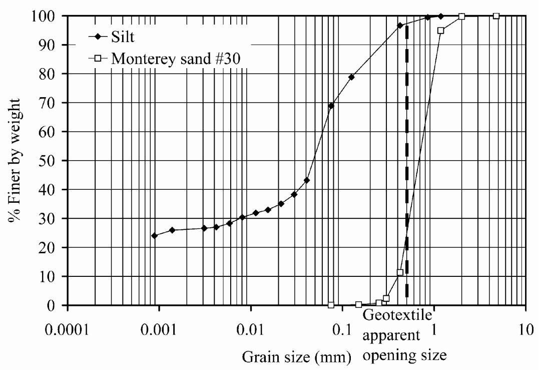


Figure 1: Comparison between the silt and Monterey sand #30 grain size distributions and the geotextile apparent opening size

The water characteristic curve (WCC) is the relationship between the volumetric water content (or degree of saturation), and the capillary pressure (or suction) for a porous material. This relationship is not unique and changes depending on whether the material is wetting or drying. The hanging column and pressure plate methods (Klute, 1986) were used to define drying-path WCCs for specimens of silt, sand, and the geotextile component of the geocomposite. During WCC testing, the specimens were confined within a metal ring under a seating normal stress of 0.25 kPa. Although this study involves infiltration into dry soil following the wetting-path WCC, the drying-path WCC defined in this study can still be used to highlight important hydraulic differences between the materials. Figure 2(a) shows the results from hanging column testing (used for suctions less than -15 cm) and from pressure plate testing (used for higher suctions), along with the best-fit WCCs defined using the van Genuchten model (van Genuchten 1980). The theoretical hydraulic conductivity functions (K-functions) for the three materials were defined using the van Genuchten-Mualem model (van Genuchten 1980). The hydraulic conductivity functions shown in Figure 2(b) were defined using the WCC parameters and the saturated hydraulic conductivity ($K_s$) values obtained from flexible wall permeameter tests. The results in Figure 2(b) indicate that as suction increases, the conductivities of the three materials decrease at different rates. Table 1 shows the van Genuchten parameters ($\theta_r$, $\theta_s$, $\alpha$, $n$) and the saturated hydraulic conductivity values ($K_s$) for the three materials.

Table 1: van Genuchten Model Parameters

| Material | $\theta_r$ | $\theta_s$ | $\alpha$ ($cm^{-1}$) | $n$ | $K_s$ (cm/s) |
|---|---|---|---|---|---|
| Silt (RC = 72.8%) | 0.025 | 0.47 | 0.033 | 1.335 | 4.70E-04 |
| Monterey sand #30 (RD = 50%) | 0.013 | 0.40 | 0.100 | 3.000 | 1.00E-01 |
| Nonwoven geotextile | 0.020 | 0.83 | 0.160 | 7.000 | 1.91E-01 |
| Gravel layer | 0.030 | 0.90 | 0.016 | 1.250 | 1.00E+02 |

The K-functions in Figure 2(b) indicate that a capillary break is likely at the interface between the silt and the nonwoven geotextile, as well as between the silt and the nonwoven geotextile. As suction at an interface between two materials is continuous,

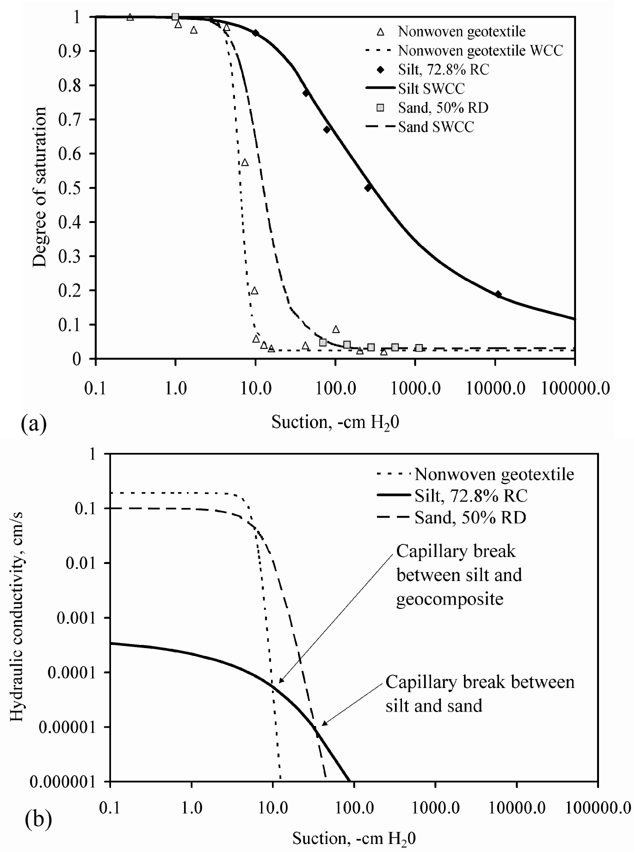


Figure 2: Soil and geocomposite hydraulic characteristics: (a) Water characteristic curve; (b) Hydraulic conductivity functions (K-functions)

Figure 2(b) indicates that the three materials tested may have different conductivities for a given value of suction, except when their curves intersect. Specifically, in vertical, downward flow through an initially dry (high suction) horizontally layered system, a capillary break will occur when the underlying layer has significantly lower conductivity than the overlying layer. Water will not flow into the lower 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 silt and the sand or the geotextile component of the geosynthetic drainage layer. Figure 2(a) indicates that as suctions increases from -10 to -100 cm, the geocomposite and sand become highly unsaturated, while the silt still has a high degree of saturation. Likewise, Figure 2(b) indicates that the hydraulic conductivities of the geotextile and sand quickly decrease with increasing suction, while that of the silt decreases slowly, intersecting the other curves at low suctions.

Evidence of a capillary break is a cease in movement of the wetting front (the vertical depth to which water has infiltrated), and storage of moisture in the overlying material in excess of the amount that would be drained by gravity. When a critical suction is reached, the conductivity of the two materials reaches the same value, and water breaks through the interface. This critical suction is referred to as the water entry suction. The goals of the experimental testing program are to measure the progress of the wetting front, measure the water content with time to infer the water entry suction, and identify the amount of water stored above the capillary break in excess of the value that would have been drained by gravity.

## 3 EXPERIMENTAL TESTING PROGRAM

### 3.1 *Soil Profiles*

In order to quantify the unsaturated interaction between conventional and geosynthetic drainage layers with low hydraulic conductivity soils, several geosynthetic-soil profiles were constructed using different soil and geosynthetic materials horizontally layered in cylindrical tubes with a relatively large diameter (20.32 cm). Figure 3 shows a schematic of two profiles that have been tested as part of this study.

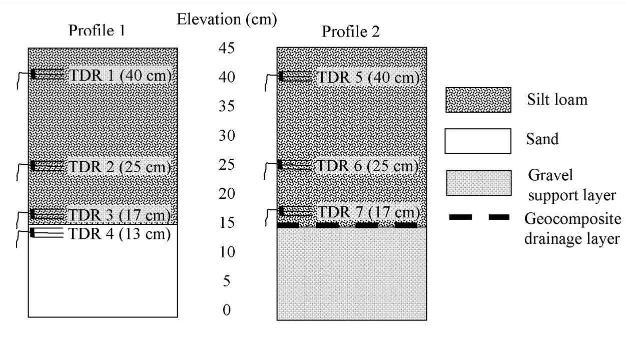


Figure 3: Schematic of soil profiles

Profile 1 includes a conventional drainage layer, consisting of silt placed over a sand layer. 15 cm of sand was pluviated to reach the target relative density of 50%. 30 cm of silt was placed in 5 cm lifts over the sand layer using static compaction to the target dry unit weight of 70% of the maximum dry unit weight based on the standard proctor and a gravimetric moisture content of 8%. Profile 2 includes a geosynthetic drainage layer, consisting of silt placed above a geocomposite, resting on a gravel foundation layer. 30 cm of silt was placed in 5 cm lifts using the same procedures as Profile 1.

### 3.2 *Monitoring System*

Volumetric moisture content values were continuously measured throughout the vertical soil profiles using time domain reflectometry technology (TDR). Figure 3 shows the location of the TDR probes in both profiles. In Profile 1, four TDR probes were used. Probes were placed 2 cm above and below the interface between the silt and the sand to measure the behavior at the interface. In Profile 2, three probes were used, including a probe located 2 cm above the geocomposite.

### 3.3 *Test Procedures*

A peristaltic pump was used to apply a relatively constant flow rate of 0.4 $cm^3/s$ to the top surface of the silt. This corresponds to a Darcian velocity of $2.06 \times 10^{-5}$ cm/s. The flow rate was selected to be less than the saturated hydraulic conductivity of the silt to ensure unsaturated conditions. The test procedure involved applying the flow rate, measuring the volumetric moisture content changes with time as the wetting front progresses through the soil, and stopping flow after steady state outflow was reached. The profiles were covered with foil in order to minimize evaporation, but an air gap between the cover and the silt surface was left to allow air escape. Air entrapment during infiltration is expected, but this is still representative of conditions in surface soils. Flow is assumed to occur in one dimension, although air entrapment and heterogeneities may cause temporary preferential flow during infiltration. Outflow was collected and measured in graduated cylinders.

## 4 RESULTS

Figure 4 shows the change in water content at four depths in Profile 1. This figure indicates that the sand is initially very dry, at a volumetric moisture content of approximately 5% (degree of saturation of 0.125). At this moisture content, the sand has low conductivity. The silt soil is initially at a volumetric moisture content of approximately 12% (degree of saturation of 0.25) throughout the profile thickness. The volumetric moisture content measured by TDR 1 (near the soil surface) increases to approximately 25% as the moisture front advances through the silt. Similarly, the volumetric moisture content measured by TDR 2 increases to 25% after a period of about 5000 minutes. The volumetric moisture content measured by TDR 3 increases to 25%, similar to TDRs 1 and 2. However, TDR 3 shows a continued increase in moisture content to approximately 38%. Also, around 7000 minutes TDR 2 begins to increase in a similar fashion as TDR 3. This behavior suggests that the wetting front reached the sand interface, but accumulation of moisture above the interface occurred instead of flowing directly into the sand layer. After the silt reached a volumetric moisture content of 35% at the interface, the volumetric moisture content in the sand layer measured by TDR 4 increased rapidly to 26% (degree of saturation of 0.65). The timing of the increase in volumetric moisture content in the sand layer was consistent with the commencement of outflow from the profile, which occurred after 9000 min.

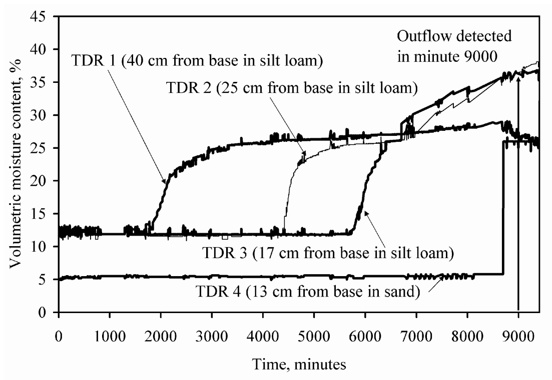


Figure 4: Volumetric moisture content with depth in Profile 1

The performance of Profile 1 is consistent with the development of a capillary break, and indicates that the silt layer has a volumetric moisture content of approximately 35% (degree of saturation of 0.74) at breakthrough. The silt WCC in Figure 2(a) indicates that this water content corresponds to a water entry suction of approximately -80 cm. This suction is consistent with the intersection of the K-functions for the silt in sand shown in Figure 2(b).

Figure 5 shows the change in water content at three depths in the silt in Profile 2. Although the same behavior as Profile 1 is noted, the wetting front progresses faster through Profile 2. This is because of a clog was that noted in the water supply tube from the peristaltic pump to Profile 1 after the first 300 minutes of testing. However, comparison between the two profiles is still possible. The volumetric moisture content in the silt in Profile 2 is 12% at the beginning of testing. The volumetric moisture content recorded by TDR 5 (near the soil surface) increases to approximately 25% after 2000 minutes. The volumetric moisture content measured by TDR 6 also increases to approximately 25% after 3500 minutes. Unlike the other two TDRs, the volumetric moisture content measured by TDR 7 (nearest the geocomposite) shows a continued increase in moisture content to approximately 39%. After TDR 7 shows an increase in volumetric moisture content, the volumetric moisture content recorded by TDRs 5 and 6 also increase from 25% to 39%. This behavior suggests that a capillary break and storage of water over the geosynthetic interface also occurs in Profile 2.

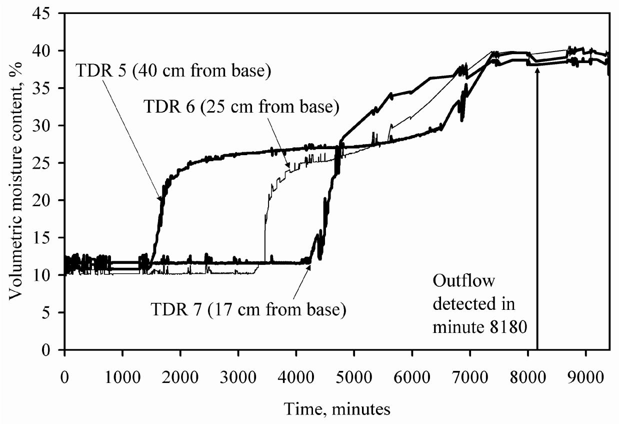


Figure 5: Volumetric moisture content with depth in Profile 2

Outflow from Profile 2 was detected after 8180 min, indicating that the breakthrough of the capillary break occurred at a volumetric moisture content of approximately 39% (degree of saturation of 0.83). The silt WCC in Figure 2(a) indicates that this corresponds to a water entry suction of -20 cm. This is consistent with the intersection of the K-functions for the silt and the geotextile in Figure 2(b).

The results in Figures 4 and 5 indicate that similar behavior can be expected from both conventional granular drains and geosynthetic drainage layers overlain by unsaturated soil. The moisture front advance was indicated by an increase in volumetric moisture content within the profile to approximately 25%, which is the value corresponding to the impinging flow rate. However, as the wetting front reached the interface, the unsaturated drainage material created a barrier to flow, and water accumulated above the interface indicated by an increase in volumetric moisture content to approximately 35 to 39%. Further, the soil above the interface began to store water to a height of at least 25 cm, indicated by an increase in volumetric moisture content measured by upper TDRs from 25% to approximately 35 to 39%, above the interface. Although suction was not monitored, the shape of the WCC for the silt indicates that the suction can change significantly with small changes in moisture content near saturation. Accordingly, even though moisture was relatively constant above the interface about 1000 minutes before breakthrough in both profiles, the suction was likely still decreasing.

Figures 6(a) and 6(b) show the moisture profiles with depth in Profiles 1 and 2, respectively. These figures indicate five different phases of infiltration: an initially dry profile (100 minutes), progression of a wetting front (1000 to 5000 minutes), development of the capillary break and accumulation of moisture (5000 to 8000 minutes), and breakthrough (after 8000 minutes). Figure 6(c) shows the moisture storage in the silt soil over time for both profiles, 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 moisture storage reference values are shown in Figure 6(c) the storage corresponding to a moisture content of 25% (the moisture content in equilibrium with the impinging flow rate), and the moisture storage corresponding to saturated conditions. The shape of the moisture storage curves for both profiles indicates that the silt stores moisture in excess of the value expected from freely-draining soil.

Analysis of the outflow indicates that the behavior of a geosynthetic drainage layer is governed by either the geosynthetic or by the overlying soil, depending if the soil in contact with the drainage layer is saturated or unsaturated. When a soil profile is unsaturated, the unsaturated hydraulic conductivity of the geocomposite drainage layer controls the flow because it acts as a barrier. After breakthrough, the saturated hydraulic conductivity of the silt controls the flow through the profile as the capillary break will not redevelop unless the impinging flow ceases.

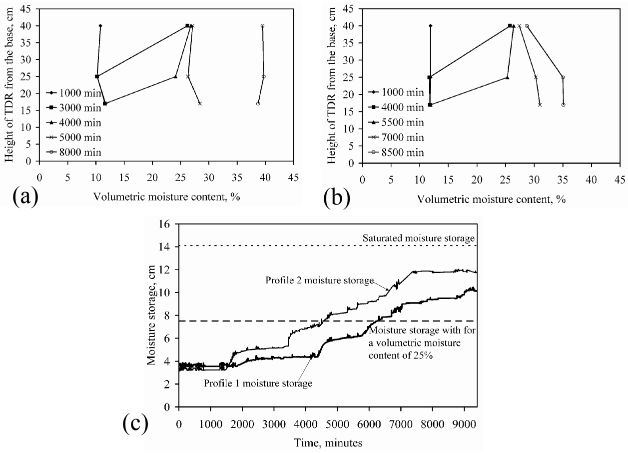


Figure 6: (a) Moisture profiles in Profile 1 (silt-sand); (b) Moisture profiles in Profile 2 (silt-geocomposite); (c) Water storage in Profiles 1 and 2 at flow equilibrium and at saturation

## 5 DISCUSSION AND CONCLUSIONS

The phenomenon of a capillary break occurring between an unsaturated soil and an underlying geosynthetic drainage layer has potential implications on the design of landfill leak detection systems, performance evaluation of alternative landfill cover systems, roadway designs using geosynthetic materials as subbase separators, and in mechanically stabilized earth walls constructed from low conductivity backfill. In landfill leak detection systems, the secondary liner will be under unsaturated conditions. The development of a capillary break will thus not indicate leakage immediately because leachate will be temporarily stored within the secondary liner. In alternative landfill cover systems, lysimeters are typically used to quantify basal percolation of water through the cover. A capillary break at the geosynthetic interface will cause water accumulation, resulting in a distortion in the suction profile within the cover. In roadway design, moisture may accumulate in the soils placed above geosynthetic separation layers causing swelling. In mechanically stabilized earth walls in low conductivity backfills, geosynthetics used to drain infiltration or dissipate pore pressures may cause moisture accumulation resulting in wall instability.

Specific conclusions from this study, based on results from infiltration tests on geosynthetic and sand drainage layers, are:

- Geosynthetic drainage layers in contact with unsaturated soils behave similarly to conventional sand drainage layers, and develop a capillary break, resulting in a barrier to flow and accumulation of water above the drainage interface.
- The capillary break water entry suction was found to be approximately -20 cm of water for the geosynthetic drainage layer, -80 cm of water for the conventional sand layer. This is consistent with material hydraulic characterization.
- The unsaturated geosynthetic drainage layer led to an increase in moisture storage through the depth of the soil profile that is well above that expected for freely-draining soils.

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