Development of capillary barriers during water infiltration in a geotextile-reinforced soil wall

F. H. M. Portelinha
Federal University of Sao Carlos, Sao Paulo, Brazil

J. G. Zornberg
The University of Texas at Austin, Texas, USA

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ABSTRACT: Nonwoven geotextiles have often been selected to provide internal drainage when reinforcing fine-grained soils. However, capillary effects have been typically neglected, although there are evidences that such barriers can develop in this system. In practical applications, backfill materials present low water contents and, consequently, negative pore water pressures (matric suction) often develop within the fill. This study includes an experimental investigation of the possible development of capillary barriers during infiltration in an unsaturated geotextile-reinforced soil model. A full-scale wall model was constructed in laboratory using a clayey sand soil. A wetting system was developed to simulate rainfall infiltration. The test setup allows simultaneous rainfall and loading. During infiltration, instrumentation was used to monitor water content and matric suction inside the reinforced fill. The testing program allowed observations of the capillary barrier development at interface soil-geotextile during infiltration process. In addition, the drainage function of reinforcements after the breakthrough was observed to occur when water pressure became negligible. Capillary barriers retarded the infiltration by 7 days per reinforced layer. Experimental profiles based on water contents measured inside the wall could be well defined and are represented for three values of water content: initial water content (compaction), field capacity water content (during infiltration) and saturation water content (capillary barrier formation). The configuration of capillary barriers development in reinforced systems requires that designers account for this phenomenon when using fine-grained backfill soils.

Keywords: Geotextiles, Infiltration, Capillary barriers, reinforced soil, drainage

1 INTRODUCTION

Although granular soils are recommended in design of geosynthetic reinforced soil structures in North America (FHWA, 1998, AASHTO, 2002) and Europe (BS 8006, 1995), this type of structure has also been constructed using local soils, frequently poorly draining soils. Use of these soils may lead to significant cost savings in areas where granular materials are not readily available (Zornberg and Mitchell, 1994, Stulgis, 2005, Pathak and Alfaro, 2010). As poorly draining soils are capable of developing pore water pressures, permeable geosynthetics (e.g. nonwoven geotextiles, geocomposites) can be used as a double function material: reinforcement and internal drainage (Ling and Tatsuoka, 1994; Zornberg and Mitchell, 1994, Kempton et al., 2000; Tan et al., 200;, Zornberg and Kang, 2005; Portelinha et al., 2013). However, in-plane drainage of the nonwoven geotextile can only occur after reaching high moisture content (or saturation) of the soil-reinforcement interface. In practical applications, backfill materials present low water contents and, consequently, also have negative pore water pressures (matric suction). Zornberg et al. (2010) reports capillary barriers develop in nonwoven geotextiles when the soil suction exceeds a certain value, at which the nonwoven geotextile permeability becomes lower than the permeability of soil. Iryo and Rowe (2005) shows by finite element simulation that nonwoven geotextiles act as a drainage material only when the threshold limit is reached and that their drainage performance improves when they are installed with an inclination.

Capillary barriers can be understood by the assessment of water flow and storage in porous geomaterials (e.g. granular soils, geosynthetics) under unsaturated conditions. As a material dries, its hydraulic conductivity drops significantly with decreasing saturation degree. The hydraulic conductivity of unsaturated materials with relatively large pores decreases more significantly than that of fine-grained soils. This characteristic leads to the counterintuitive situation in which the hydraulic conductivity of unsaturated gravel or geotextiles can be significantly smaller than that of fine-grained soils. 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).

This paper consists of an experimental examination of the infiltration into a geotextile-reinforced soil wall, focusing on the capillary barriers effects and internal drainage effectiveness. It involves monitoring of an instrumented full-scale geotextile-reinforced wall model constructed to evaluate the infiltration in the reinforced fill with specific focus on the interface hydraulic behavior.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

A Full-scale model was constructed using a lateritic soil. The grain size distribution is presented in Figure 1a. Physical properties of the soil are reported in Table 1. As the soil includes approximately 40% of fine particles, it would not meet the AASHTO (2002) specifications. As this study focus in an unsaturated behavior of soil-geotextile interface, the soil water retention curve is provided in Figure 1b.

Table 1. Physical properties of soil

Properties	Standard	Values
G_s	NBR6508	2.75
Liquid Limit	NBR6459	40%
Plasticity index	NBR 7180	19
Maximum dry unit weight	ASTM D1557	17.88 kN/m^3
Optimum water content	ASTM D1557	14.6%
Cohesion	ASTM D7181	15 kPa
Friction angle	ASTM D7181	32º
Hydraulic conductivity	NBR14545	4.9x10^{-7} m/s

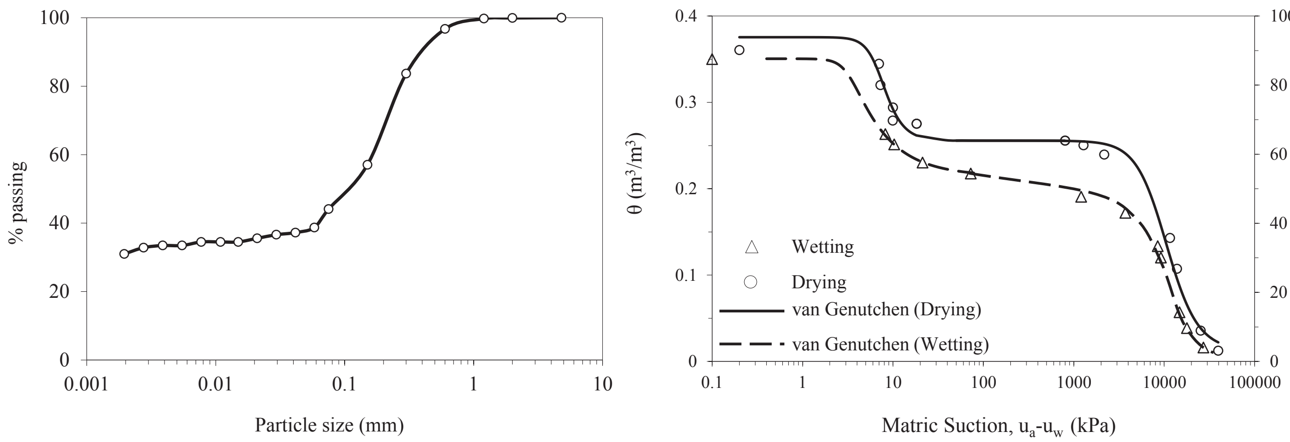

Figure 1. Properties of backfill soil: (a) Grain size distribution; (b) Soil water retention curve.

The reinforcement is a polyester needle-punched nonwoven geotextile with a mass per unit area of 293 g/m^2, thickness of 2.69 mm, tensile strength of 10 kN/m and strain at failure of 83% (ASTM D4595). Hydraulic properties of this geotextile include its permittivity of 1.96 s^{-1} (ASTM 4491), transmissivity of 6x10^{-6} m^2/s (ASTM 4716) and apparent opening size of 93 μm (AFNOR G38-17).

2.2 *Full scale models*

Full-scale walls were constructed in the Laboratory of Geosynthetics located within the Sao Carlos School of Engineering at the University of Sao Paulo, Brazil. A reinforced steel frame allows the reinforced soil wall structures to be constructed with 1.8 m height by 1.55 m width, with backfill soil extending to a distance of 1.8 m from the front edge of the metallic box. For this study, the soil was compacted to 98% of relative density and optimum water content in relation to standard Proctor (Table 1). In order to obtain the required relative density, compaction was performed manually in 5 cm high layers. Compaction control was achieved using the drive-cylinder method (ASTM D2937), spiked every compacted layer reaching 30 cm height. The backfill soil was placed over a rigid concrete foundation.

Geotextile reinforcements were placed at 30 cm vertical spacing with a declivity of 1% towards the face. Each layer of reinforcement had a total length of 1.60 m measured from the face. The wall was constructed with no facing batter and using the wrap-around technique. Protective shotcrete coating ranging from 5 to 8 cm in thickness was used. Drainage geocomposites were used as face drainage elements in the second and forth reinforced layers, extending to 30 cm from the face forward into the wall. Figure 2 presents the cross section view of the model. Figure 3a shows a photograph of the model during test.

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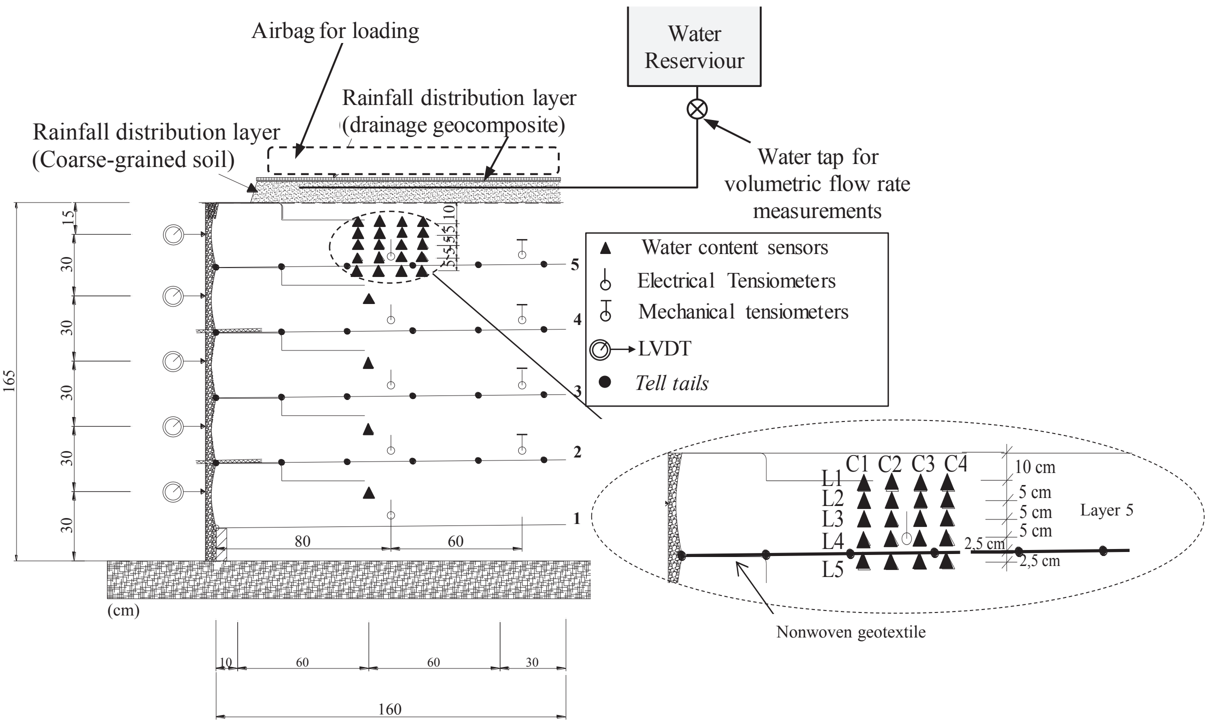

Figure 2. Cross section of the full-scale reinforced wall model, instrumentation layout and wetting system.

2.3 *Wetting system*

After construction of the wall, a wetting system was installed on the top of the wall surface, which was graded with an inclination of 2% toward the face. The wetting system includes a series of supplying pipes and a water distribution layer placed over the structure. The water distribution layer involves a 15 cm high sand layer and a drainage geocomposite installed over the sand layer. The configuration of the drainage geocomposite and the sand layer provided a uniform water distribution over the top surface. Water was supplied by a reservoir with a float switch enabling constant hydraulic head to induce a uniform rainfall intensity. The intensities of precipitation were controlled by defining of volumetric flow rate in the output water tap installed in the water reservoir, using a bucket and chronometer. Figures 2 and 3b provide details of the wetting system.

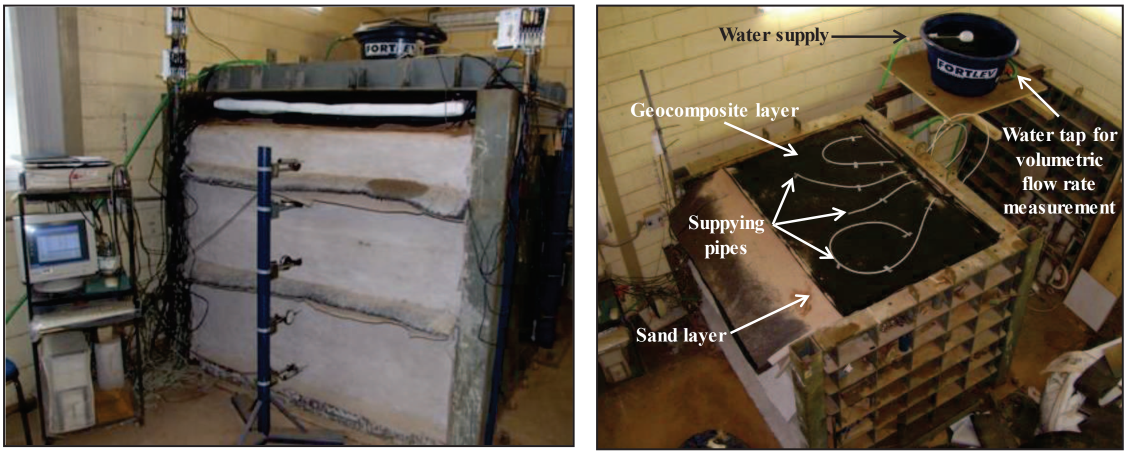

Figure 3. Full -scale reinforced wall model: (a) frontal view; (b) view of wetting system.

2.4 *Instrumentation*

Instrumentation was installed to monitor positive and negative (matric suction) pore water pressures, water content, internal horizontal displacements and horizontal face displacements. The instruments layout is presented in Fig. 6. As the focus of this paper is on the infiltration, the data on the mechanical response of the wall are not to be reported herein.

The advancement of water infiltration into the model was monitored using piezometers with a measurement range of -100 to 100 kPa placed in each reinforced layer 5 cm over the reinforcements. Frequency domain reflection sensors (FDR) were installed to measure the water content in each reinforced layer (located 15 cm over the reinforcement). Four columns and five lines of sensors were specifically concentrated on layer 5 (upper layer), in order to evaluate capillary barriers effects as shown in Fig 6b.

2.5 *Test procedure*

Data from the multiple instruments installed in the full-scale model were collected during wetting simultaneously. An infiltration rate of $1.8x10^{-7}$ m/s was applied over the full-scale prototype, while maintaining a uniform loading of 100 kPa during the entire test. Loading was applied using air bags on the top of the wall and a reaction structure. No pounding occurred on the top of the wall, because the imposed water flow was lower than the hydraulic conductivity of soil (approximately 2.5 times smaller than the saturated hydraulic conductivity of the soil).

3 RESULTS

The water content along each column is shown in Figure 4 for each of the five elevations where sensors had been placed. The positioning of various sensors is also illustrated in Figure 2. As illustrated by the water content data shown in Figure 4, three distinct phases of water flow can be identified after applying a constant infiltration rate in this test. Initially, the entire profile was relatively dry, with an as-compacted volumetric water content of 0.262, identified herein as the initial volumetric water content (θ_i). Although the supplied infiltration rate is constant, the wetting front moves through soil layer as a transient process. As the wetting front reaches the location of each of the sensors the water content is observed to increase up to a value of approximately 0.310, which corresponds to the field capacity volumetric water content (θ_{fc}). Once the wetting front reached the top of the geotextile (after 3000 to 6000 min), water did not immediately flow into the geotextile. Instead, a capillary barrier developed and water accumulated within the soil immediately above the geotextile until the matric suction decreases to a value at which capillary breakthrough occurred (after 10000 to 15000 min). During the water storage by capillary effect, the water content was approximately 0.340, which corresponds to the saturation value (θ_{sat}). The capillary barriers temporarily prevented infiltration into reinforced layer 4. Specifically, this mechanism retarded the infiltration by 7 days per reinforcement layer, until the threshold level was achieved and pore pressure exceeds the value at which geotextiles become more permeable than soil. After capillary breakthrough, water progress to the underlying layer and transient flow resulted in a moisture towards to the corresponding field capacity water content value.

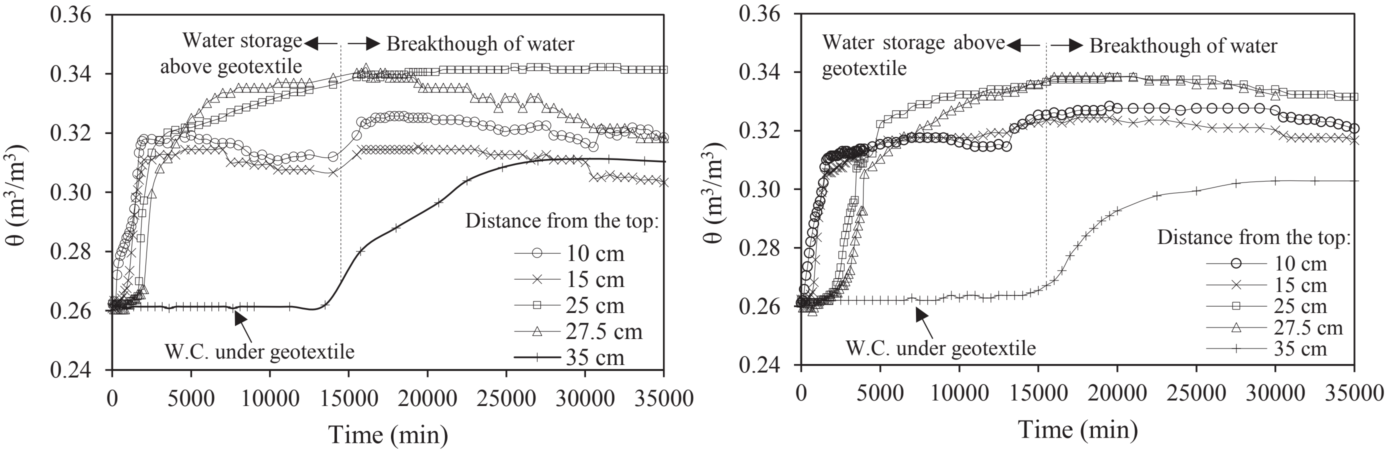

Figure 4. Time history of water content during infiltration: (a) in column location C1; (b) in column location C2.

Considering the three distinct water content values occurring during infiltration (θ_i, θ_{fc}, θ_{sat}), infiltration profiles were defined for different times of the test. Accordingly, infiltration front advancement could be examined, including the development of capillary barriers. Figure 5 illustrates infiltration profiles at three different times. Using the three distinct water content values allowed a reasonable definition of infiltrations front, even though the field capacity water content showed to be lower in long periods of test, since geotextile drainage reduced the infiltrated volume of water due to in-plane lateral flow.

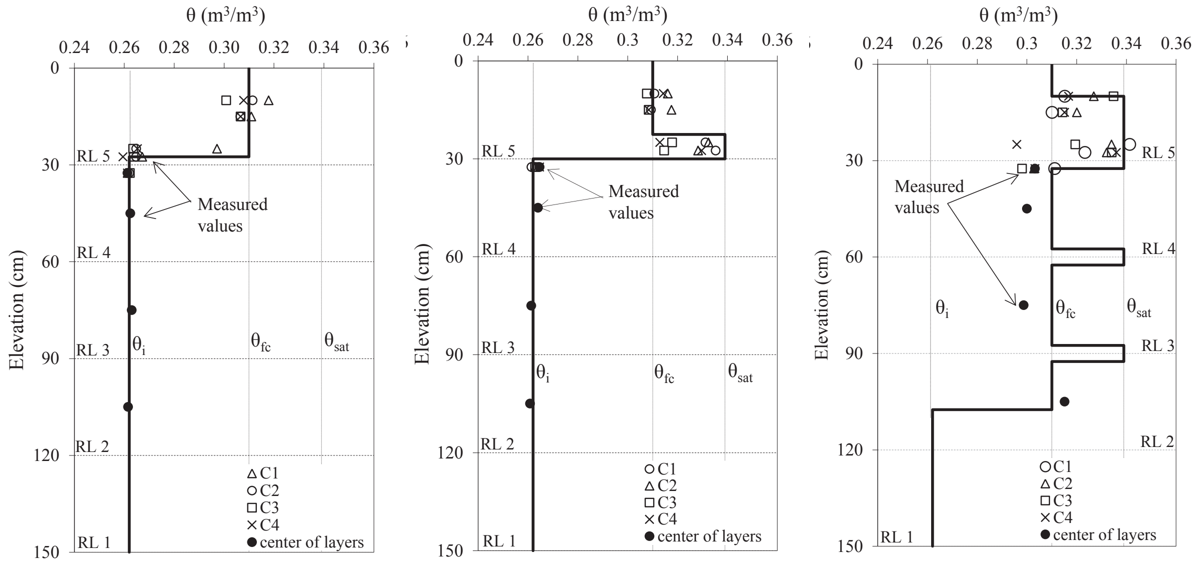

Figure 5. Infiltration profiles based on VWC after (a) 2000 min., (b) 10000 min. and (c) 30000 min. of irrigation.

Progress of the infiltration front into the reinforced soil wall prototype with time is shown in Figure 6a. This plot was defined using the infiltration profiles for different periods of test, as illustrated in Figure 5. The figure shows predicted infiltration without reinforcements and measured and predicted infiltration with reinforcements. Infiltration without reinforcement was predicted using the rate of the infiltration front based on readings from sensors located in the upper layer before reaching the geotextile. The same approach was used to predict the infiltration with geotextile reinforcements; however, with capillary barriers retarding infiltration. The figures show that the predicted infiltration with geotextile agreed with the experimental values. Additionally, infiltration into the full-scale model without reinforcements was expected to completely occur in 10 days; however, it occurred in 22 days. As regards the internal drainage, this hydraulic behavior was observed with the reduction of saturation degree toward the wall toe, mainly after infiltration front through the layer 5 (Figure 5c). Figure 6b shows a view of the transparent side of the wall during infiltration in which moisture stains of the face are evidenced exactly along reinforcement elevations.

Fig 6. (a) Predicted and measured infiltration advancement with time, (b) Transparent side of the wall.

Results have shown positive and negative effects of using geotextiles as reinforcement and internal drains, simultaneously. As positive effects, the internal drainage was clearly observed, even though not measured, which allows the use of fine-grained soil as backfill material of reinforced soil walls. As regards capillary barriers, to predict or design the restriction of water flow by capillary barriers for a specific region can assure that water do not progress to the reinforced zone. This solution keeps the unsaturated condition of the fine-grained backfill, resulting in a good performance of the structure. On the other hand, if the water flow advances to the reinforced zone and capillary barriers formation occurs, resulting in water storage, water pressure can increase and interface shear strength (soil-geotextile) can be reduced.

4 CONCLUSIONS

This paper presents the results of an experimental evaluation involving water infiltration into an instrumented full-scale model reinforced with nonwoven geotextiles. Experiments were conducted to examine the effect of the hydraulic responses of nonwoven geotextiles in a fine-grained backfill soil. Based on the analysis and instrumentation results, the following results can be drawn:

- Capillary barriers were found to develop, which ultimately retarded infiltration in the reinforcement soil mass, until enough water accumulated at the soil-geotextile interface to reach negligible matric suction during infiltration. Infiltration into the full-scale model without nonwoven geotextile reinforcements was expected to occur in 10 days to the wall toe; however, it occurs in 22 days. Therefore, the nonwoven geotextiles used as reinforcements were found to provide beneficial in-plane drainage, but only after enough moisture had accumulated to lead breakthrough.
- Infiltration monitored properly, using volumetric water content sensors, which allowed identifying three representative values of water content during infiltration: initial compaction water content; field capacity water content; and, saturation water content observed during development of capillary barriers.
- Reduction of saturation degree toward the wall toe and moisture stains in the concrete wall face provide evidences of the in-plane drainage occurring in the geotextiles after breakthrough.

As recommendation, capillary barrier in reinforced systems requires that designers account for this phenomenon when using fine-grained backfill soils since it has a significant influence on drainage capacity. This can be predicted based on water retention curve of both materials in the interface as recommended by Zornberg et al. (2010) and others research works.

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