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Capillary barriers can be an effective solution to minimise or delay infiltration of liquids in soils. These alternative barriers may be particularly appropriate and cost-effective in cover systems of waste disposal systems in arid and semi-arid regions. The mechanism of flow control in a capillary barrier involves the impedance of flow moving from a porous medium of small voids to another porous medium of larger voids, due to differences in the water storage between the two materials for the same suction at their interface. Granular soils have been used to induce a capillary barrier. However, the use of geotextiles as barriers can offer not only the relevant difference in water storage but also the repeatability and consistency of properties offered by manufactured materials, besides other advantages. The objective of this paper is to investigate the behaviour of capillary barriers using non-woven geotextiles under controlled laboratory conditions. Accordingly, fine-grained soil and geotextiles with different properties were used in the testing programme. Granular materials (sand and gravel) were also utilised to form granular capillary barriers for comparison purposes. Overall, the experimental results show that geotextiles can develop capillary barriers with similar storage capability as those provided by natural granular materials.

Notation

D_n soil particle diameter for which n (in percentage) of the mass of the soil particles has a diameter smaller than that value
d_f fibre diameter
F_{OS} filtration opening size
G_s soil particle density
K coefficient of permeability normal to the geotextile plane under saturated conditions
M_A geotextile mass per unit area
n specimen porosity
t_{GT} thickness under 2 kPa normal stress
w_L soil liquid limit
w_{opt} optimum moisture content
w_P soil plastic limit
y elevation: m
γ_d dry unit weight of the soil specimen
γ_{dmax} maximum dry unit weight (normal Proctor energy)
θ volumetric water content (dimensionless)
θ_{sat} soil specimen volumetric moisture content at saturation
ψ permittivity
ψ_{aev} air entry suction value
ψ_{wev} water entry suction value

Introduction

Geotextiles have been used in geotechnical engineering projects for over five decades, not only mainly in filtration and drainage applications, but also in projects involving their use as separators, protective layers and reinforcement. Their use as barriers against the flow of water, when acting as capillary barriers, can be considered a comparatively recent application in relation to other traditional applications. Capillary barriers are structures that impede the flow of water as a consequence of capillary forces developed at the interface between an unsaturated fine-grained soil layer and another porous material with relatively large-sized pores such as sands, gravels or non-woven geotextiles (Zornberg *et al*., 2010). Kisch (1959) was the first to observe the phenomenon of capillary barrier, which subsequently was also observed by other researchers in layered soil profiles in geotechnical applications (Barbour, 1990; Nicholson *et al*., 1989; Rasmusson and Eriksson, 1987; Shackelford *et al*., 1994; Woyshner and Yanful, 1995; Yanful, 1993; Zornberg *et al*., 2010).

The hydraulic conductivity of soils under saturated conditions may be significantly higher than that under unsaturated conditions. It is well known that coarse-grained soils under saturated conditions have a higher hydraulic conductivity than that of fine-grained soils. However, under unsaturated conditions, coarse-grained soils have high values of suction and a comparatively low unsaturated hydraulic conductivity. While counter-intuitive, the hydraulic conductivity of coarse-grained soils can be lower than that of fine-grained soils at higher suctions. Williams *et al*. (2011) reported on a high-visibility site where a capillary barrier was recently designed involving a fine-grained soil layer, under unsaturated conditions, overlying a coarse-grained soil layer. The increase in moisture content in the fine-grained soil causes a decrease in suction and an increase in its hydraulic conductivity. However, the hydraulic conductivity of the underlying granular layer may remain lower than that of the fine-grained soil over a comparatively wide range of suction. Thus, water will not yet flow into the granular layer and will instead build up at the interface between the fine- and coarse-grained soil layers. Eventually, as flow continues to decrease suction, the hydraulic conductivity of the coarse- and fine-grained soils will reach the same value. This suction value is termed the breakthrough suction and corresponds to the value at which the capillary barrier has been 'broken' and moisture has begun to flow into the underlying granular layer. Heibaum (2010) defines the fine-grained soil layer overlying the granular material as a capillary layer, whereas the granular material is defined as a capillary block.

Geotextiles can be attractive alternatives to developing a capillary barrier, particularly in regions where granular materials are scarce. According to McCartney *et al*. (2008), geotextiles can be effective capillary barriers since they have a pore structure that is similar to that of granular soils while also providing the additional benefits of separation, protection and drainage. Geotextile pores are larger than those in fine to medium sands, which have been considered for capillary barriers. When used in contact with a fine-grained soil, a geotextile can function as a barrier to water flow due to the capillary break effect. McCartney *et al*. (2008) state that the movement of water from the fine-grained soil layer to the geotextile is influenced by the type of polymer employed in the manufacturing of the geotextile. Polypropylene, which is a common polymer used to produce geotextiles, is hydrophobic, which causes further difficulty for water to enter the geotextile voids (Henry and Patton, 1998).

Morris and Stormont (1997, 1999) and Park and Fleming (2006) highlight the use of capillary barriers in final covers of landfills and in mining waste piles. The barrier will prevent or reduce the amount of rainwater that infiltrates into the waste, providing the benefit of reducing the volume of liquid reaching the bottom drainage system of a landfill or mining waste pile.

Evapotranspirative barriers, including those incorporating geotextiles, provide the advantage of reducing the potential for soil cracking, when compared to compacted clay barriers. Evapotranspirative covers are vegetated with native plants that survive on natural precipitation and have been shown to be stable over long periods of time (Zornberg *et al*., 2010). They are also easy to construct and require comparatively low maintenance. Morris and Stormont (1999) also point out the longevity and low cost of this type of cover system. This type of barrier can be constructed with a variety of soil types, reducing costs associated with the importation of specific soils over long distances. According to Zornberg and McCartney (2007), the water balance in the evaluation of these covers should take into account a wide range of components, including evaporation, transpiration by plants, precipitation, run-off, storage of moisture and lateral drainage and basal drainage. In this context, infiltration tests on soil columns are useful tools to understand better the conditions of water flow in capillary barriers. Column tests may simulate real cover systems by replicating the dimensions and types of soil layers and geotextiles used in real projects. The downward water flow causes changes in soil moisture content and suction that can be monitored using appropriate instrumentation. Kuhn and Zornberg (2006) and McCartney (2007) performed column tests on compacted fine-grained soil layers overlying capillary barriers, consisting of granular materials and geosynthetics, and observed the effectiveness of this type of barrier.

This paper presents the results of a study on the effectiveness of capillary barriers incorporating non-woven geotextiles by means of laboratory column tests. Tests involving the use of granular materials as capillary barriers were also carried out for comparison purposes. The following sections present the test methodology, results obtained and discussion of the results.

Equipment and materials

Column tests were carried out using an acrylic cell with 197 mm internal dia. and a total height of 300 mm. The soil used in the tests was compacted inside the cell, with a thickness of 170 mm, overlying the capillary barrier layer (geotextile, sand or gravel). Figure 1 shows a typical test set-up of one test utilising a geotextile.

Sensors used for measurement of volumetric moisture content and suction were installed at different elevations (15, 75 and 135 mm) along the cell height (Figure 1). Moisture content sensors ECH$_2$O EC-5, manufactured by Decagon Devices, were used to obtain volumetric moisture content. These sensors were 89 mm long, 18 mm wide and 7 mm thick. An MPS-1 sensor, also manufactured by Decagon Devices, was installed at a depth of 135 mm from the soil specimen top for the measurement of suction. A low-flow peristaltic pump was used to pump water from a reservoir to the top of the soil specimen. The use of a graduated cylinder with a capacity of 1000 ml as a water reservoir allowed the calculation of the volume of water that infiltrated through the system with time. A constant rate of water inflow of approximately 0·2 ml/min was utilised in the tests. A filter paper was used on the top face of the soil specimen to ensure a uniform infiltration of water in the soil specimen.

Hanging column tests were carried out on the geotextiles used in the experiments as part of the research programme to understand better the behaviour of geotextile capillary barriers. The

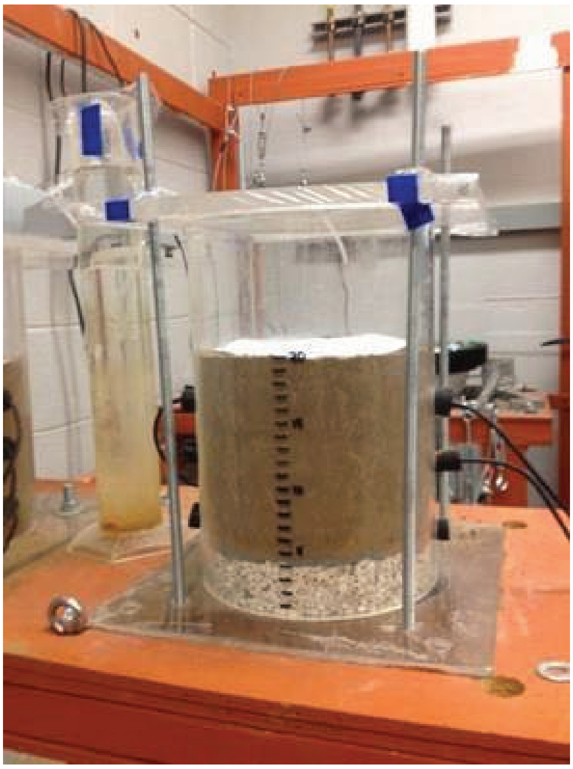

Figure 1. Capillary barrier test cell

equipment used for these tests was similar to that proposed by Stormont *et al*. (1997) to determine the water retention curve of a geotextile and is presented in Figure 2. The maximum suction that can be applied to the geotextile specimen caused by the difference between water levels in the reservoir and the base of the specimen is equal to 3·5 kPa. This suction was sufficient to drain the water completely in an initially saturated geotextile specimen. The diameter of the geotextile specimens was equal to 55 mm.

The soil used in the experiments was collected from the area of test plots for the cover system at the Rocky Mountain Arsenal (RMA),

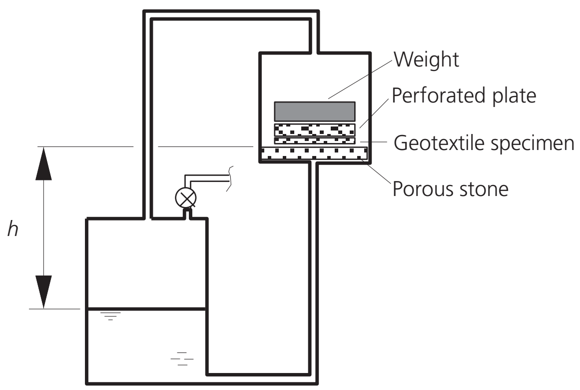

Figure 2. Hanging column test equipment

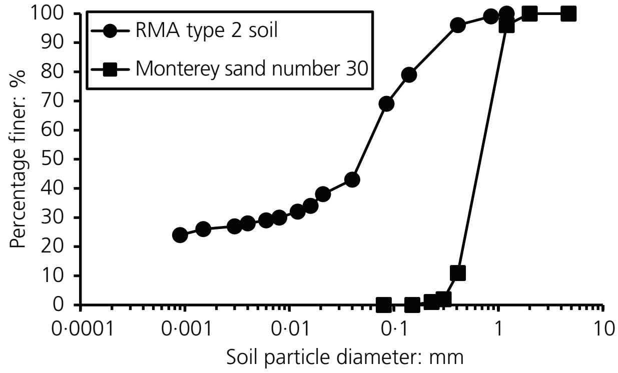

Figure 3. Grain size distribution curves of the soils used

near Denver, Colorado, USA. This soil is referred to as RMA type 2 soil. The soil is classified as a low-plasticity clay (CL by the Unified Soil Classification System). Figure 3 shows the grain size distribution curve of the soil tested, and Table 1 presents its relevant geotechnical properties. Additional information on RMA type 2 soil properties is reported by McCartney (2007). The soil specimens were compacted with a density corresponding to 80% of the maximum dry density (γ_{dmax} = 18·0 kN/m^3, optimum moisture content of 14·5%) obtained in compaction tests (standard Proctor compaction energy). The soil specimen was compacted in the cell by tamping 30 mm high lifts, with a target initial volumetric moisture content of 15%, which corresponds to a gravimetric moisture content of 10·2%. The final height of the soil specimen was 150 mm. Under saturated conditions, the volumetric moisture content of the soil equals 46% at the stated relative compaction of 80%. The water retention curve for RMA type 2 soil was obtained by hanging column and pressure plate tests (McCartney, 2007). The results from these tests indicate that the soil has a porosity of 49·2%, a water entry suction value of 1 kPa and a residual moisture content of approximately 5%. For the conditions of the test, the infiltration flux rate of the system was equal to 1·1 × 10^{-5} cm/s.

Table 1. Properties of the soils tested

Property	RMA soil type	Monterey sand number 30
D_{10}: mm	<0·0009	0·4
D_{50}: mm	0·05	0·68
D_{85}: mm	0·2	1·0
w_L: %	28·7	NA
w_P: %	17·2	NA
γ_{dmax}: kN/m^3	18·0	17·1
w_{opt}: %	14·5	NA
γ_d: kN/m^3	14·4	15·6
G_s	2·71	2·66
θ_{sat}	0·46	0·40
n: %	46	40

D_n , soil particle diameter for which n (in percentage) of the mass of the soil particles has a diameter smaller than that value; G_s, soil particle density; NA, not applicable or not available; n, specimen porosity; w_L, soil liquid limit; w_{opt}, optimum moisture content; w_P, soil plastic limit; γ_d, dry unit weight of the soil specimen; γ_{dmax}, maximum dry unit weight (normal Proctor energy); θ_{sat}, soil specimen volumetric moisture content at saturation

Non-woven geotextiles, sand and gravel were employed to produce capillary barriers as part of this testing programme. When a geotextile layer was used, it was installed on top of the gravel layer. The gravel has a D_{50} of 3 mm, where D_{50} is the particle diameter for which 50% of the remaining particles have diameters smaller than that value. The purpose of the gravel layer was to provide free drainage below the geotextile layer to guarantee that the capillary barrier effect would take place at the soil–geotextile interface. The sand capillary barrier was prepared with Monterey sand number 30, placed at a relative density of 55% and a unit weight of 15·6 kN/m^3. The grain size distribution of Monterey sand number 30 is shown in Figure 3, with Table 1 presenting its relevant geotechnical properties.

Three needle-punched, polyester, non-woven geotextiles (G1, G2 and G3) were used as capillary barriers in the experimental testing programme. Table 2 presents the main properties of the geotextiles used in this study. The mass per unit area of the geotextiles ranged from 200 to 400 g/m^2, while their opening size ranged from 0·16 to 0·23 mm. Hanging column tests were performed on the geotextiles in this testing programme to understand and quantify better their contribution to the capillary barrier effect. Figure 4 presents the results of water retention curves for the three geotextiles tested in terms of volumetric water content against suction during drying (filled symbols) and wetting stages (open symbols). The results in this figure are consistent with the sizes of the openings of the geotextiles. The larger the geotextile filtration opening size (Table 2), the lower the suction required to reduce its volumetric moisture content. Almost complete drainage of the water in the specimen voids was achieved for suctions greater than 2·3, 2·8 and 3·3 kPa for geotextiles G1, G2 and G3, respectively. Using the procedure presented by Bouazza *et al*. (2006), observed values of air entry suction (ψ_{aev}) are close to 1 kPa for geotextiles G1 and G2 and approximately 1·3 kPa for geotextile G3. Water entry suction values (ψ_{wev}) were of the order of 0·1 kPa for the three geotextiles tested, showing that water can enter the geotextile structure under very little suction, smaller than that of the RMA type 2 soil (ψ_{wev} = 1 kPa (McCartney, 2007)).

Additional information on material properties, equipment and testing methodology is provided by De Lima (2014).

Table 2. Properties of the geotextiles tested

Property	G1	G2	G3
M_A: g/m^2	200	300	400
t_{GT}: mm	2·3	2·6	3·7
n	0·93	0·93	0·92
d_f: mm	0·027	0·027	0·027
K: cm/s	0·4	0·4	0·4
ψ: s^{-1}	1·9	1·5	1·1
F_{OS}: mm	0·23	0·18	0·16

M_A, geotextile mass per unit area; t_{GT}, thickness under 2 kPa normal stress (ASTM D 5199 (ASTM, 2012)); n, porosity; d_f, fibre diameter; K, coefficient of permeability normal to the geotextile plane under saturated conditions (ASTM D 4491 (ASTM, 2017)); ψ, permittivity (ASTM D 4491); F_{OS}, filtration opening size (from hydrodynamic sieving (*AFNOR G38017* (CFGG, 1986))

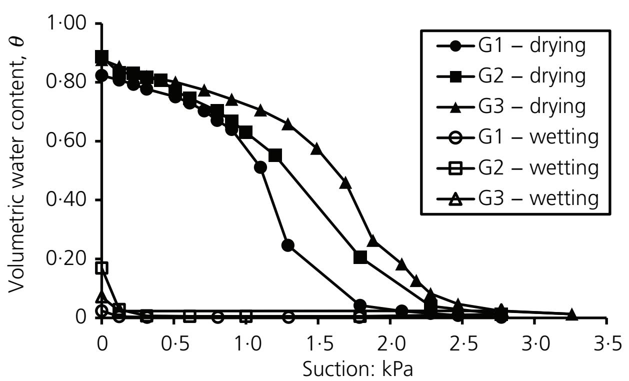

Figure 4. Water retention curves of three types of geotextiles for the wetting and drying cycles

Results

Tests with geotextile capillary barriers

Figure 5 presents the variation of volumetric water content with the volume of inflow water for the system where geotextile G1 (200 g/m^2) was used as a capillary barrier. The tests described in this section involve the geotextile layer resting on top of the gravel layer. The moisture content sensor at elevations of 135 and 75 mm above the geotextile surface registered that the wetting front reached that elevation after volumes of approximately 40 and 231 ml of inflow water, respectively. After the wetting front passed the top two sensors, the moisture content remains constant at approximately 0·27. If there were no capillary barrier in the column, it would be expected that after the moisture front passed the bottom sensor, the entire column would be at a constant volumetric moisture content of 0·27. However, once the wetting front reaches the last sensor (at an

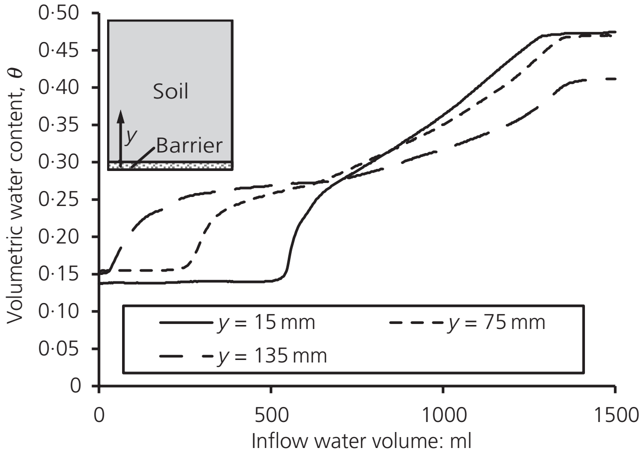

Figure 5. Volumetric water content against inflow water volume measured at three different depths (15, 75 and 135 mm). Test with geotextile G1

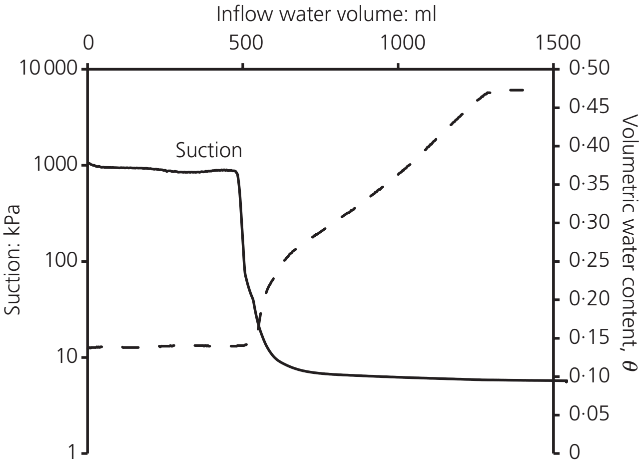

Figure 6. Suction and volumetric water content against inflow water volume. Test with geotextile G1, y = 15 mm

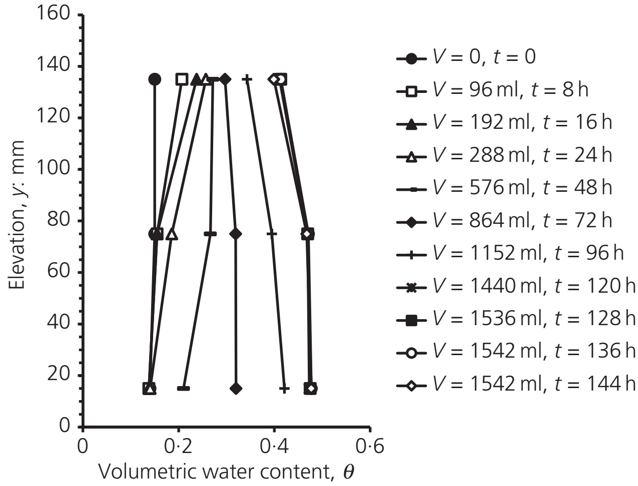

Figure 7. Volumetric water content profiles for different inflow water volumes. Test with geotextile G1

elevation of 15 mm above the geotextile) after 504 ml of flow, the moisture in all three sensors starts increasing to over 0·27. The moisture content in the column finally stops increasing and remains constant after around 1300 ml of flow. The value of θ at the end of the test was approximately equal to 0·47, the closest to the geotextile layer, indicating that the amount of water infiltration was sufficient to saturate the lower half of the soil specimen volume. Therefore, the capillary barrier formed by geotextile G1 was broken for a volume of inflow water of about 1300 ml.

Suction and volumetric moisture content against inflow water volume at an elevation of 15 mm above the geotextile layer are shown in Figure 6. This figure shows a sharp reduction of suction at a water volume of 480 ml, immediately before θ starts to increase. These small differences between water volumes associated with suction decrease and moisture content increase are a consequence of different sensitivities of the respective sensors.

The profiles of variation of θ along the height of the soil layer for different values of inflow water volume and times since the beginning of the test are shown in Figure 7. Larger values of θ at the lower half of the soil specimen were reached after 576 ml (t = 48 h) of inflow water volume.

Figure 8 presents the variation of θ with infiltrated water volume in the test with geotextile G3 (400 g/m^2), the thickest geotextile tested. The moisture content sensor at all elevations above the geotextile surface showed that the wetting front reached a constant value of approximately 0·27 before the formation of a capillary barrier, similar to the previous test. Once the wetting front reaches the bottom sensor (at an elevation of 15 mm above the geotextile) after 520 ml of flow, the moisture in all three sensors starts increasing again. The moisture content in the column finally stops increasing and remains constant after around 1500 ml of flow. Therefore, the capillary barrier formed by geotextile G3 was broken for a volume of inflow water of about 1500 ml. At the end of the test, a constant value of θ of 0·46 was reached at 15 and 75 mm above the geotextile layer. These values are similar to those obtained for the other geotextiles tested. In fact, the tests for G2 were almost identical to those of G3.

The variations of θ along the soil layer height for different inflow water volumes and times since the beginning of the test with geotextile G3 are shown in Figure 9. The results show little variation of the moisture content profile after 1656 ml (t = 120 h) of water infiltration, indicating that the capillary barrier has been broken. The plot also displays the accumulation of water at the lower half of the soil specimen due to the capillary barrier effect caused by the geotextile layer.

The variations of θ and suction with inflow water volume 15 mm above the geotextile layer are depicted in Figure 10 for the test

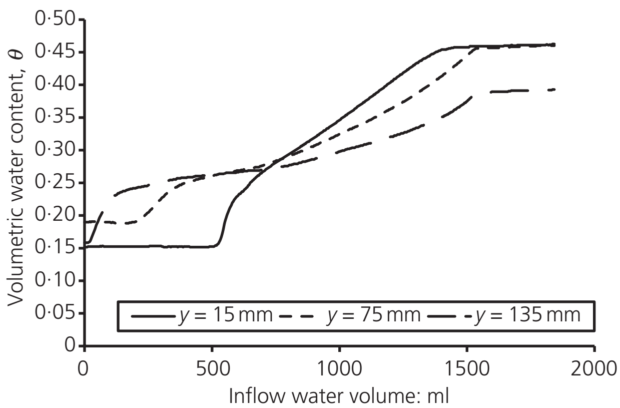

Figure 8. Volumetric water content against inflow water volume measured at three different depths (15, 75 and 135 mm). Test with geotextile G3

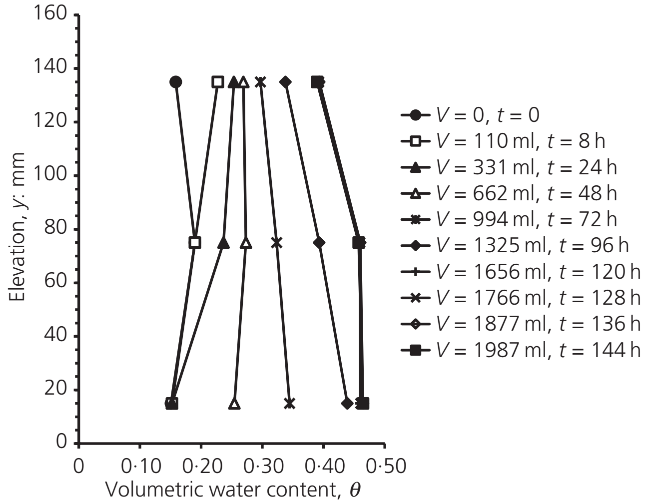

Figure 9. Volumetric water content profiles for different inflow water volumes. Test with geotextile G3

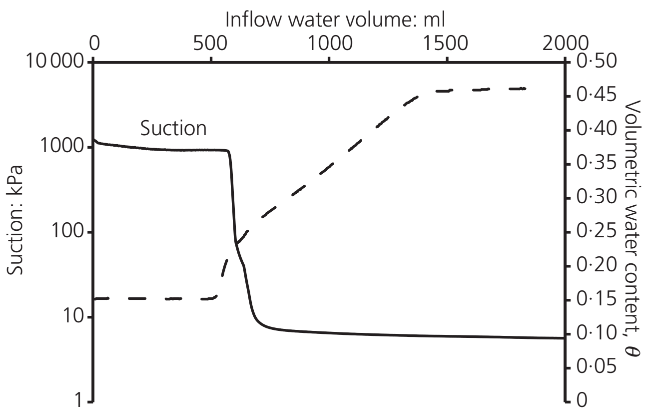

Figure 10. Suction and volumetric water content against inflow water volume. Test with geotextile G3, $y = 15$ mm

with geotextile G3. A marked drop in suction can be observed for a water volume of 575 ml, which is also associated with the increase in volumetric moisture content.

Granular capillary barriers

Tests with granular capillary barriers consisting of layers of sand or gravel were also carried out for comparison purposes. Figure 11 shows the variation of volumetric moisture content with inflow water volume at the sensor closest to the soil–barrier interface (15 mm above the interface) in tests with capillary barriers consisting of Monterey sand number 30 and gravel. In the test with the sand barrier, the moisture content started to increase at a water volume of 379 ml. On the other hand, in the test with the gravel barrier, the increase in moisture content started at a slightly greater water volume equal to 391 ml. The final value of moisture content was greater in the test with gravel than in the

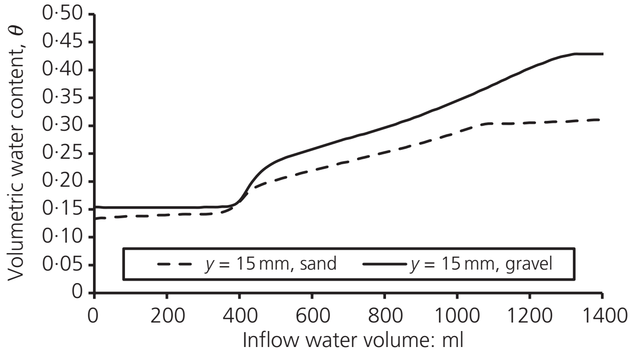

Figure 11. Volumetric moisture content against inflow water volume at $y = 15$ mm. Tests with sand and gravel capillary barriers

test with sand. Barrier breakthrough occurred first in the sand barrier for an infiltrated water volume of 1050 ml, in comparison with the value of 1321 ml in the test with the gravel barrier. The final moisture content in the sand column was 0·30, compared to a final moisture content of 0·43 in the gravel column. The lower final moisture content and quicker breakthrough indicate that the sand barrier is weaker than the gravel barrier. This is expected since sand is more fine-grained than gravel and will more closely match the grain size distribution of the overlying clay.

Comparison between capillary barrier systems

Figure 12 shows the variation of volumetric moisture content with infiltrated water volume for the sensor closest to the barrier layer in tests with and without geotextiles. The results show that the moisture content started to increase earlier in the test with the thinner geotextile G1, in comparison with what was observed in the tests with geotextiles G2 and G3. In the tests with geotextile barriers, breakthrough took place for inflow water volumes around 1300 and 1500 ml, depending on the geotextile considered. Therefore, the use of a geotextile barrier delayed the exit of water through the bottom of the soil system. The total volumes

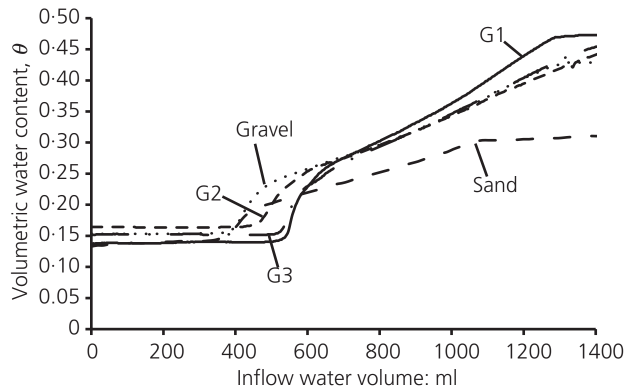

Figure 12. Volumetric water content against inflow water volume at $y = 15$ mm. Comparison between different capillary barriers

(1300–1500 ml) of inflow water in the tests with geotextile barriers when barrier breakthrough occurred were similar to the value for the test with the gravel barrier (1321 ml). The gravel and geotextile tests had moisture build-ups of 0·43–0·47, which are also very similar. Based on these results, it is clear that a geotextile can produce a capillary barrier similar to or even stronger than the barrier produced by gravel. On a similar note, all tests with geotextiles and gravel produced a stronger capillary barrier than a barrier formed only with sand. Since the water retention curves for all three geotextiles are fairly similar (Figure 4), this can explain why all the geotextiles produced a very similar capillary barrier.

Conclusions

This paper presents the results from an experimental testing programme involving granular and geotextile capillary barriers. The soil used in the tests was RMA type 2 soil, while gravel, sand and non-woven geotextiles were utilised to form capillary barriers. The main conclusions obtained in this research programme are summarised in the following paragraphs.

Regardless of the nature of the capillary barrier material (granular material or geotextile), the various capillary barriers tested in this programme were found to delay effectively the flow of water through the soil. Accordingly, geotextiles were found to be a potentially excellent choice for this type of barrier as they are characterised by good quality control as well as easy and quick installation in the field. These barriers can also be employed in situations where suitable natural materials are scarce or their use is restricted by environmental regulations.

The results of column tests on soil–barrier systems showed that the capillary barriers were capable of significantly increasing the amount of water storage in the soil. Barrier breakthrough took place for inflow water volumes between 1050 ml (sand test) and 1500 ml (test with geotextile barrier – 43% increase with respect to the value obtained for the sand barrier). Breakthrough water volumes in tests with geotextiles were similar or greater (14%) than the value obtained for the gravel barrier, depending on the geotextile considered. The barriers produced by the geotextiles were found to be similar or stronger than the barrier produced by only gravel. Both the gravel and geotextile barriers produced stronger barriers than the sand-only barrier. The thicker the geotextile, the greater the water volume necessary to cause barrier breakthrough. Hanging column tests on the geotextiles showed that the values of water entry suction of the products tested were considerably smaller than those of the soil tested. The similarity in the water retention curves also indicates that all of the geotextiles tested in this programme would produce a similarly strong capillary barrier for the conditions of the tests.

Further research is needed to obtain a better understanding of the performance of geotextile capillary barriers in order to develop appropriate design methodologies and accurate predictive models for this type of solution.

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