Efficacy of Nonwoven Based Geosynthetic Drainage Product for Pore Pressure Reduction in Moderately Fine Soils or Tailings

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ABSTRACT

A common challenge in geotechnical engineering is to reduce pore pressures in fine-grained soils or tailings and geosynthetic drainage may be proposed for such applications. Depending on the relative unsaturated permeability of soil and geotextile, a capillary break may develop, resulting in higher water content in the soil along with increased pore pressure (or lower suction) and consequent decrease in factor of safety against slope failure. While high (saturated) geotextile permeability may be desirable under some conditions, formation of a capillary break inhibits drainage and compromises overall performance of the soil/geosynthetic system. In this study, the water characteristic curve (GWCC) was measured for a common geocomposite drainage product. An unsaturated permeameter was used to measure permeability under limited matric suction. The applicability of the Fredlund-Xing equation to estimate unsaturated permeability from the GWCC was confirmed. A series of transient and steady-state experiments were carried out in a lab-scale physical model with two different silt-sized soils to confirm that the unsaturated behaviour of the soil/geosynthetic composite system could be predicted by independent laboratory measurements of the two materials. Finally, numerical simulations were conducted of the performance of the drainage product in reducing pore-pressures in an unsaturated embankment subject to rainfall.

INTRODUCTION & BACKGROUND

The performance of a geosynthetic in any geotechnical engineering application depends on the resulting *soil-geosynthetic system*. In some cases, measurement of soil and geosynthetic properties separately is insufficient to enable the response of the composite system to be predicted. In the case of geosynthetic drainage, historical emphasis has been on saturated properties (i.e. standards for measurement of saturated permeability for in-plane or cross-plane directions). As is well established in geotechnical engineering, permeability (or hydraulic conductivity) soil is not a *value* (although the saturated conductivity k_{SAT} is), but rather a *function*, depending upon the degree of saturation, or more commonly expressed as a function of soil suction (Fredlund et al, 2012).

The soil-water characteristic curve (SWCC) is characterised by the following parameters(Fredlund et al, 2012):

i. saturated water content (= porosity);
ii. the air-entry value (AEV) for drying curves or the water-entry value (WEV) for wetting curves which is the suction at which air begins to enter the larger pores of a saturated soil or water enters the finest pores of a dry soil; and
iii. the residual water content and residual suction.

The performance under field conditions of a drainage geosynthetic placed within fine or moderately fine-grained soil or soil-like materials (i.e. mine tailings) will therefore depend on the unsaturated permeability of the two (or more) materials *and their interaction*. The capillary barrier effect occurs when a finer material overlies a coarser material, and the system is subject to downward vertical flow. The capillary barrier effect has been extensively studied in the context of soil covers for mining waste by Nicholson et al (1989), Barbour (1990), Akindunni et al (1991), O'Kane et al (1998) Bussière et al (2003) along with numerous others. Figure 1 shows the vertical distribution of pressure head and water content under steady state downward vertical flow through such a system (Barbour, 1990).

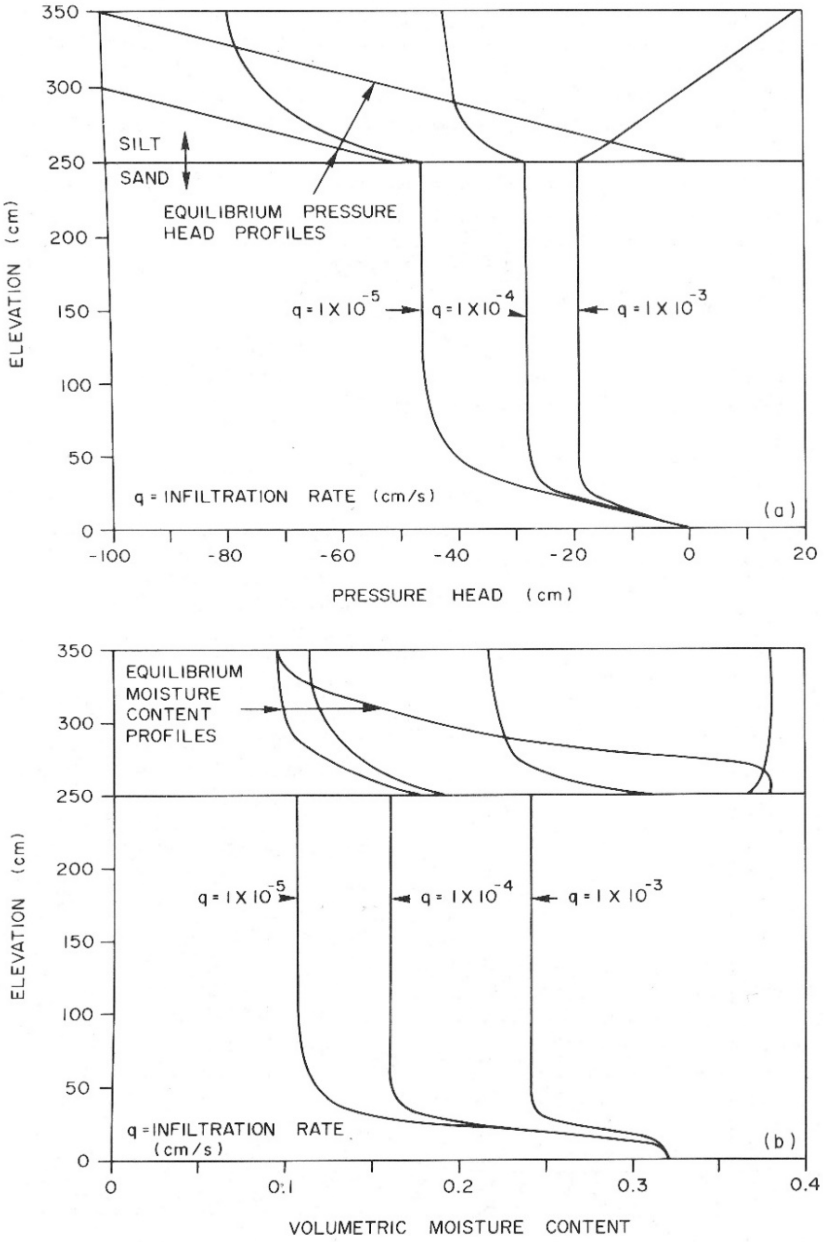


Fig. 1. Profiles of pressure head and volumetric moisture content vs. elevation for silt over sand under constant infiltration rate. *(from Barbour, 1990 used with author's permission)*

For geotextiles, work by Henry (1990 and 1995), Stormont and Morris (2000), and Henry and Holtz (2001) evaluated the use of geotextiles as moisture limiting barriers in unsaturated soils. Their work focused on the change in hydraulic behaviour of an unsaturated, layered soil system due to the inclusion of a nonwoven geotextile and concluded that a geotextile may be effective in mitigating upward moisture migration in unsaturated soils.

Numerous studies have been conducted to obtain the WCC of nonwoven geotextiles which are characterized by low AEV and desaturate at relatively low suctions compared to soils. Various testing methods have been used, and the literature shows general agreement between methods ranging from simple to complex. Stormont et al (1997) and Lafleur et al (2000) both performed hanging column tests on several nonwoven geotextiles along consecutive wetting and drying paths which demonstrated the difference between geotextile products, wet/dry hysteresis, and the impact of manufacturing surfactants. The WCC was unique for each geotextile product. Knight and Kotha (2001) measured the WCC of a nonwoven geotextile by controlling water outflow in a capillary pressure cell and compared the methodology to that of Stormont et al. (1997). The method allowed for control of the suction and thus volumetric water content of the specimen by precisely applying small increments of air pressure and suggest that that this method provides more detail in the curve in a fraction of the time of the hanging column method. Knight and Kotha (2001) repeated the test with one, three, and six geotextile samples stacked in the cell and found the WCC was unaffected.

In the Stormont et al (1997) study, when wetted a second time, the geotextile reached a reduced peak water content due to air entrapment from drying. Residual surfactants from manufacturing reduced the saturated water content of the geotextile. This is similar to the findings of Park & Fleming (2004) who showed the effect on the WCC of both the test method (hanging column and pressure plate) which suggested evaporation loss in a hanging test, even with the sample contained in a humid polyethylene tube and also confirmed the effect of pre-washing the sample to remove the lubricating oils used during needle-punching (Figure 3).

In addition to comparing geotextiles composed of polypropylene (PP) and polyester (PET), Stormont & Morris (2000) also considered the wetting behavior of the PET geotextile when modified with clay, silt and sand and found that it increased the WEV compared to the unmodified geotextile. Similarly, Bathurst et al. (2009) obtained a WRC for a nonwoven PP geotextile in a suction plate apparatus as part of a sand column infiltration study. Samples were tested in a new condition and a modified condition, which involved rubbing the sample with a wet kaolin paste. Excess kaolin was brushed off after drying. The tests were conducted along drying paths following by wetting paths and the authors noted the considerable difference between modified and new samples, with the saturated water content more closely resembling that of the kaolin.

McCartney and Znidarcic (2010) measured the WCC of a nonwoven geotextile using a permeameter with flexible walls. The approach is far more complex than those previously discussed, requiring a specially designed system and pump. The apparatus enabled application of higher confining pressure to their samples than is possible in a pressure plate cell. Previous students at the University of Saskatchewan (Park, 2005, Cunningham, 2018, Andree, 2021) have used a Tempe cell suction plate apparatus to measure drying WCCs of nonwoven geotextiles. The cell was modified to allow for confining pressure to be applied vertically through the cap as shown in Figure 2. Typical results are presented in Figure 4.

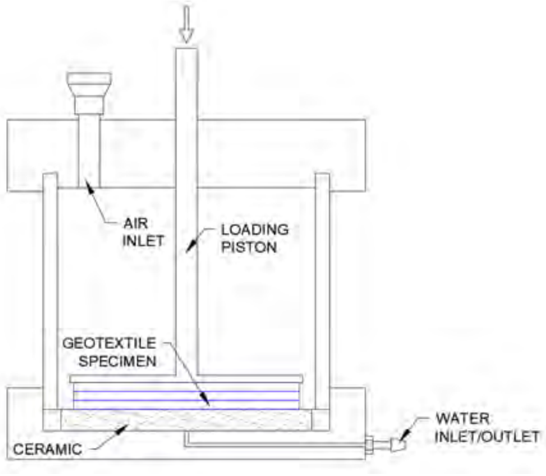


Figure. 2. Pressure cell apparatus used at Univ of Saskatchewan to measure WCC of nonwoven geotextile under varying normal stress.

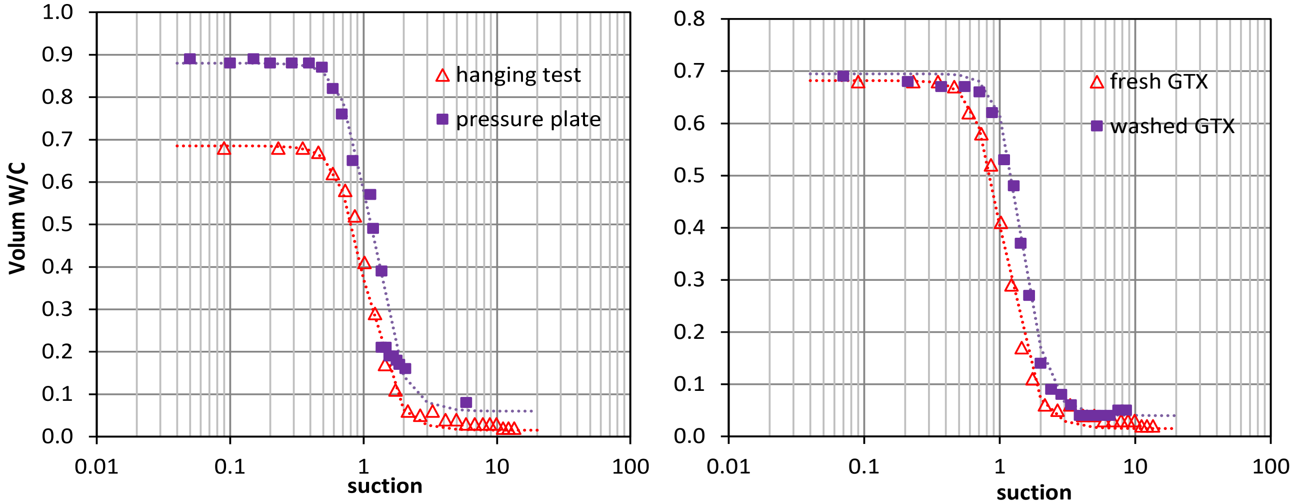


Figure 3. Wetting and drying WCC for nonwoven geotextile and effect of washing the fabric (left) and effect on WCC of test method (right) *From Park & Fleming, 2004.*

Determination of the unsaturated hydraulic conductivity of nonwoven geotextiles is a challenging undertaking at a single point of suction, let alone at a variety of suctions. For this reason the common practice is to use curve-fitting parameters based on the WCC to predict the hydraulic conductivity function of a material (e.g. van Genuchten 1980, Fredlund et al. 1994). On the other hand, Iryo and Rowe (2003) showed that the predicted K-functions based on WCC curve fitting parameters for geotextiles may not show good agreement with observed values, perhaps due to the different pore shapes for particle vs fibre based porous media.

This presents a challenge for application of geosynthetic drainage to finer grained soils or soil-like materials such as tailings as a capillary break will often develop (Park & Fleming, 2004). A number of additional studies have examined this, including Bathurst et al, (2009) who constructed a sand column, sand-new geotextile column, and sand-modified geotextile column where the geotextile was rubbed with a kaolin paste. Instead of applying water by infiltration, a 225 cm total head was applied at the top, and 20 cm at the bottom. The pore pressure at the wetting front was observed with tensiometers. In the sand-only column there was no evidence of a capillary break, however, a capillary break formed in both geotextile columns. For the new geotextile, pressure above the geotextile reached 0.5 kPa. In the modified geotextile column, the influence of kaolin clogging increased the pressure above the geotextile to near 5 kPa. The degree of ponding suggests that the WCCs are not conservative as they do not accurately capture the soil-geotextile interaction. However, the application of a total head boundary rather than an infiltration boundary could be the cause of this high pressure, as similar studies did not exhibit pressures above 0 kPa.

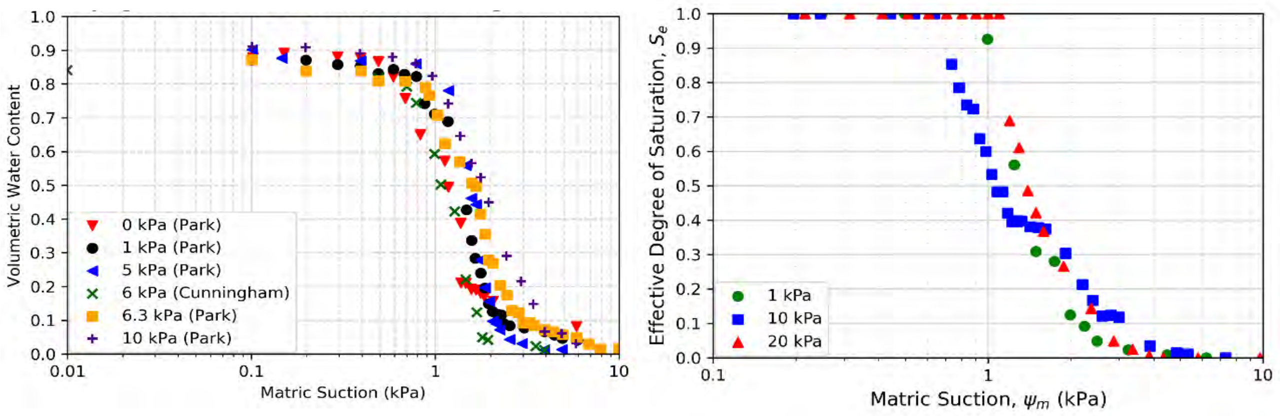


Figure 4. Previous work at UofS showing effect of normal stress on WCC of nonwoven geotextiles (left, *Park, 2005* & *Cunningham, 2018*; right *Andree & Fleming, 2021*).

Portelinha and Zornberg (2017) constructed a nonwoven PET geotextile-reinforced wall with a clayey sand backfill. Backfill was compacted and five reinforcement layers were placed sloping toward a geocomposite drain and shotcrete facing. A simulated rainfall was applied from the top of the wall. Frequency Domain Reflectometry (FDR) was used to monitor water content at the midpoint above each geotextile layer and tensiometers were placed immediately over each geotextile. A large FDR array was placed in the topmost layer to evaluate the development of a capillary barrier. Once the rainfall was applied, no ponding was observed. As the infiltration front advanced, the volumetric water content reached an equilibrium of 0.31 compared to the initial 0.26. As the front reached the top geotextile layer, FDR sensors in the upper layer approached a saturated water content of 0.36, indicating that a capillary barrier was formed. This resulted in a 4 day delay for infiltration to reach each subsequent layer until suction reduced to breakthrough. In total, it took 30 days to reach the bottom of the wall. Piezometers at the geotextile-soil interface showed that pressure reached 0 kPa but did not rise above. Moisture sensors in the bottom four layers did not detect saturated water content at any point. The geotextiles were ineffective as drains until breakthrough of each capillary break occurred. In total, 25% of the water volume was diverted through the geotextiles. Wetting stains on the shotcrete facing indicated that most drainage occurred in the upper layers.

All of the above studies have clearly shown that under most conditions, the hydraulic properties of nonwoven geotextiles are similar to those of sands or fine gravels. This is not particularly surprising. While nonwoven geotextiles are not *coarse-grained*, the experimentally obtained WCCs do imply that they are *coarse-pored* and have a similar average pore size to sands and gravels (Zornberg et al. 2010).

MATERIALS & METHODS

The current study was intended to evaluate the performance of a drainage geocomposite DrainTube© which incorporates small perforated corrugated mini-pipes placed in pockets between two layers of the 2 or-3 geotextile layers that are needle-punched together. First, the SWCC was measured for the various layers of nonwoven geotextile under various normal loads (Figure 4r). Subsequently, an in-plane unsaturated permeameter was designed and built so as to enable a range of normal (cross-plane) stress to be applied to a sample while in-plane flow is measured under a range of hydraulic gradients (Figure 5). This apparatus was loosely based on previous work (Stormont et al. 1998, Stormont & Morris, 2000) in which unsaturated in-plane geotextile transmissivity was directly measured.

Andree and Fleming (2021) described the apparatus and presented results for k(ψ) up to about 2 kPa of suction at which this particular nonwoven geotextile was at about 20% effective saturation. Significantly, it was found (Andree et al, 2022) that using the formulation of Fredlund et al (1994) to predict the k(ψ) unsaturated permeability function a better fit was found than had been possible using the formulation of van Genuchten (1980). This addresses a concern that had been raised by Iryo & Rowe (2003) that given that the methods to estimate k(ψ) from the WCC are based on experiments with soil (a particulate porous media), these same fitting parameters might not be adequate for fibre-based porous media such as nonwoven geotextiles. SWCC fitting parameters for all materials are included in Table 1.

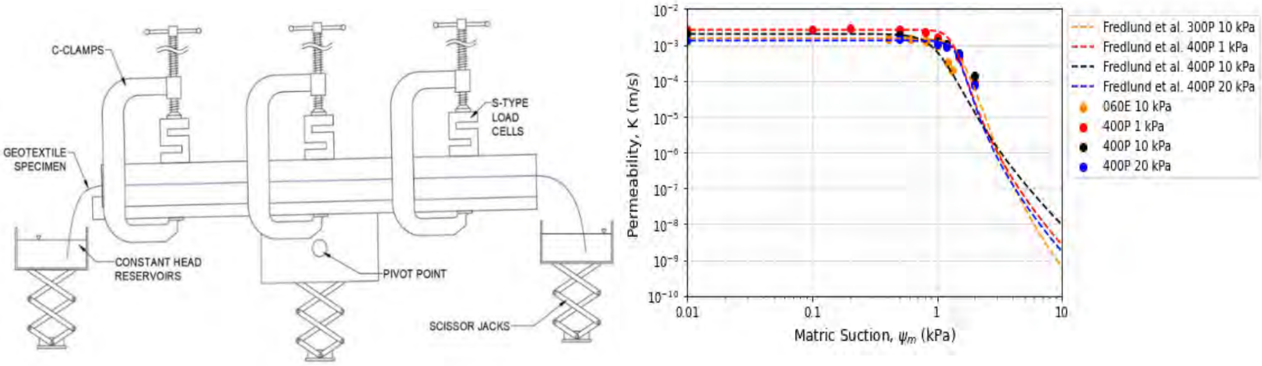


Figure 5. Unsaturated permeameter for nonwoven geotextiles under normal stress.

Table 1. Fitting parameters for all materials used in this study.

Material (Vertical Load)	van Genuchten		Fredlund and Xing (1994)		
	a_{vg}	n_{vg}	a_{fx}	n_{fx}	m_{fx}
Geotextile 1 (1 kPa)	1.28	5.71	1.19	7.79	1.46
Geotextile 1 (10 kPa)	0.98	3.22	0.86	4.45	1.21
Geotextile 1 (20 kPa)	1.39	6.36	1.27	8.56	1.40
Geotextile 2 (10 kPa)	1.42	5.31	1.43	5.23	2.15
Aluminum Oxide Grit	9.96	8.98	8.28	14.81	0.64
Sand	10.90	11.72	9.14	24.61	0.40

A lab-scale physical model was then constructed which incorporated a layer of the drainage geocomposite. Under various infiltration rates the capture rate of the geocomposite was measured at varying position and height above the water table. Electronic tensiometers (METER Terros 31) were placed at various elevations above and below the geocomposite as shown in Figure 6. The mini-pipes in the drainage geocomposite were connected directly to small laboratory valves installed in the sidewall. Pinholes were also drilled through the sidewall to allow collection and quantification of the water flowing in the nonwoven between the mini-pipes.

The apparatus was filled with two different moderately fine-grained soil materials. One was a commercially available aluminum oxide (alox) grit that is commonly used for sandblasting. The second material was a rock crusher dust that was sieved to a particle size of 75-150 microns with some fines present. Both soils are classified by USCS as silty sands and have similar grain size distribution (GSD) and WCC as shown in Figure 7.

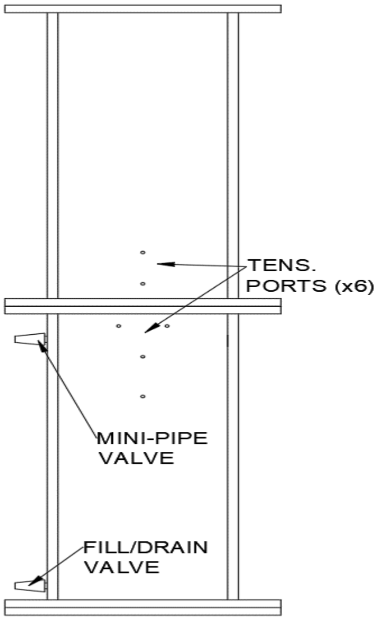


Figure 6. Lab-scale physical model

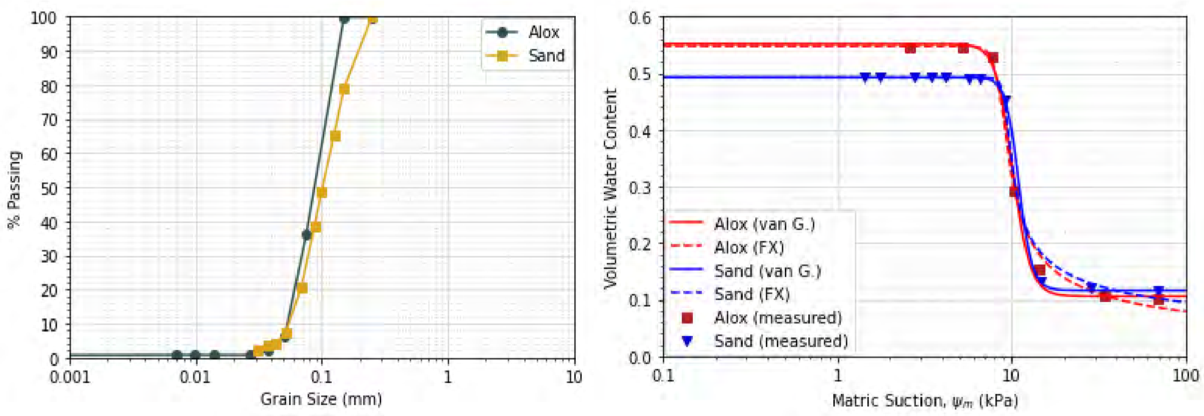


Figure 7. Grain size distribution and SWCC for the two soils used in the lab scale model.

RESULTS & ANALYSES

The capture efficiency was found to be dependent chiefly on the infiltration rate and depth to the water table. As shown in Figure 8, the capture efficiency was higher when the water table is shallower. Interestingly, capture occurred with a water table at 220 mm below the geosynthetic in the sand but did not occur at similar conditions when applied over the alox grit.

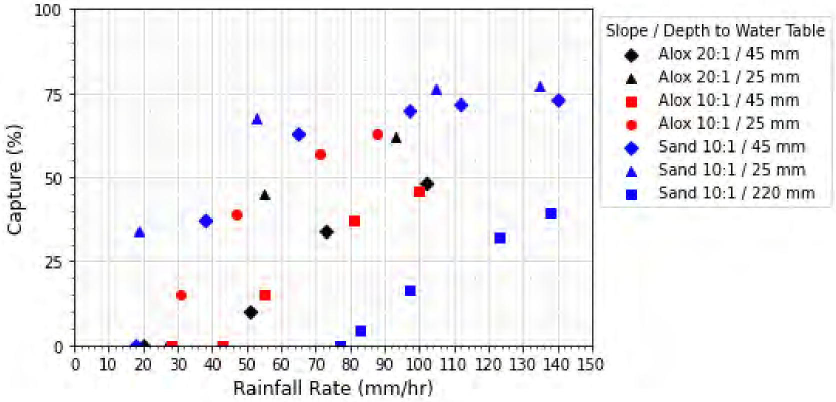


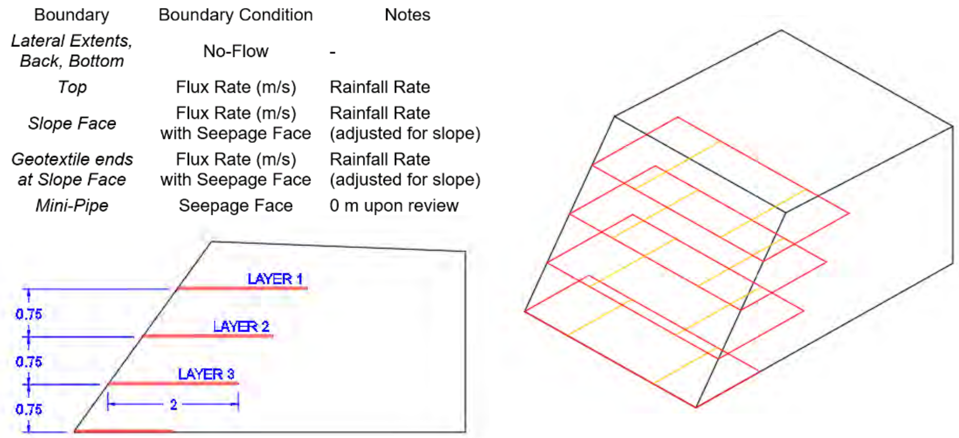
Figure 8. Capture efficiency in the lab-scale physical model

These results were then satisfactorily reproduced with a 3D saturated-unsaturated finite element simulation using GeoStudio SEEP3D using the same dimensions as the physical infiltration apparatus. A unique steady-state analysis was created for each rainfall rate and water table level that was experimentally tested. The geotextile was represented as a 3 mm thick prism with a 1 mm mesh. The soil near the geotextile was meshed similarly fine and became larger with distance from the geotextile. The mini-pipe was represented as a “seepage face” boundary condition, which requires the program to review the nodes along the boundary to check for positive pressures. If pressures are above 0 kPa, the node is set to a zero-pressure boundary condition. The downstream end of the geotextile was also represented by this condition.

Calibration was achieved simply by adjusting the saturated permeability of the geotextile, alox grit, and sand. The WCC’s were also slightly “softened” by changing the fitting parameters to smooth the sharp transition between saturated, desaturation, and residual states which enhances the solver’s ability to converge while not significantly altering the characteristics of the material

The lab-scale physical model demonstrated that the material properties and interaction in a composite soil-geosynthetic system may be characterised using laboratory-determined properties for the materials determined independently. In order to evaluate the anticipated performance of the drainage geocomposite under service conditions, transient 3D saturated-unsaturated seepage models were constructed in SEEP3D based on the 3 m tall embankment model by Iryo and Rowe (2005b). Analyses considered durations of several days to achieve a steady-state pressure condition. The model geometry and boundary conditions are shown in Figure 9.

The results shown in Figure 10 clearly show the development of a capillary barrier effect at the geosynthetic-soil interfaces with greater severity at the upper elevations, exceeding the base case pressure. The geosynthetic-only case provided little reduction in pressure head over the base case over the full profile, while the inclusion of mini-pipes provided relief of pore pressure, particularly between elevations 0 m and 0.75 m. It is also evident that a tighter spacing of mini-pipes provides a greater reduction in pressure head, particularly at the embankment toe.



Boundary	Boundary Condition	Notes
Lateral Extents, Back, Bottom	No-Flow	-
Top	Flux Rate (m/s)	Rainfall Rate
Slope Face	Flux Rate (m/s) with Seepage Face	Rainfall Rate (adjusted for slope)
Geotextile ends at Slope Face	Flux Rate (m/s) with Seepage Face	Rainfall Rate (adjusted for slope)
Mini-Pipe	Seepage Face	0 m upon review

Figure 9. Numerical model setup for the 3 m embankment

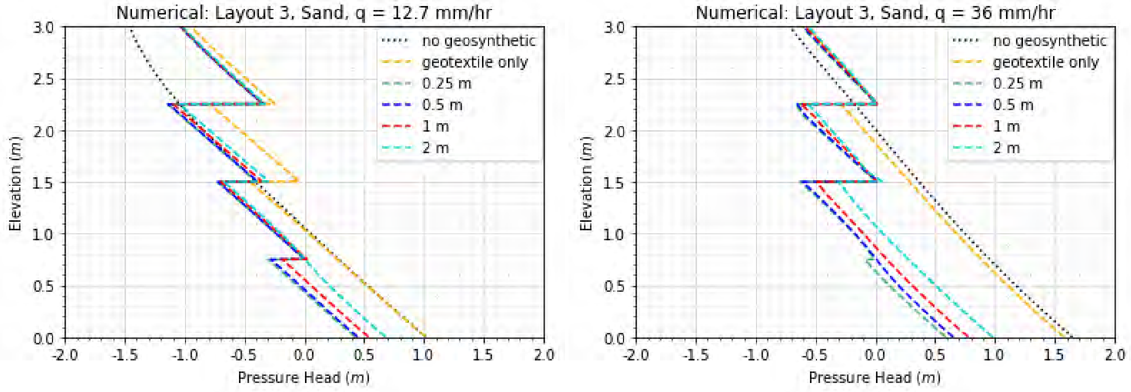


Figure 10. Numerical model results for the 3 m embankment

CONCLUSION

The work summarised in this paper has clearly demonstrated that the principles of unsaturated soil mechanics apply to fibre-based porous media just as they do to particulate porous media. The fitting parameters of Fredlund et al (1994) may be used to estimate $k(\psi)$ with a good degree of fit to carefully-obtained experimental data (the fitting parameters of van Genuchten (1980) do not provide the same degree of fit and have no advantage in the authors' opinion).

Physical modelling showed that laboratory-determined WCC's (and consequently $k(\psi)$ functions) obtained independently for the soil and geosynthetic materials can be used as inputs in saturated-unsaturated numerical seepage models to describe the performance of the soil-geosynthetic composite system (at least for these specific materials tested).

For the 3m embankment composed of silty sand, placement of a drainage geocomposite may introduce the capillary barrier effect.

In the case where nonwoven geotextile alone is used, numerical simulations suggested that pore pressures (or matric suction) would be unchanged in the lower 1.5 m of the structure and that suction would be decreased (i.e. higher water content) in the upper 1.5 metres, thus decreasing stability. Addition of the mini-pipes improved performance relative to the nonwoven alone, increasing suction in the lower 2.25 m – most of the embankment. – and thus increasing stability.

In general it may be concluded that for moderately fine materials, placement of geosynthetic drainage can be beneficial, but the designer must be careful to avoid certain combinations of material properties, geometry and hydraulic loading under which the capillary barrier effect can increase pore pressure and reduce stability.

In order to ensure success, the geotechnical engineer is well-advised to carry out proper laboratory characterisation of the unsaturated properties of the soils as well candidate geosynthetic materials. Properly conducted, numerical simulations of saturated-unsaturated flow can be used to evaluate variations in geometry, layer spacing etc to evaluate the response of the system and select design parameters for improved stability.

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