1-D saturated-unsaturated behaviour of sand-geotextile columns

Le comportement saturé/non-saturé 1-D de colonnes sable-géotextile

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ABSTRACT

The paper describes a series of laboratory tests that were carried out to quantify the saturated-unsaturated hydraulic properties of woven and nonwoven geotextiles in virgin condition and contaminated with kaolin fines. The test program included 1-D column tests of a single geotextile layer in sand subjected to surface water infiltration loading. The column tests showed detectable changes in rate of wetting front advancement in the vicinity of the geotextile layer consistent with a capillary break mechanism. Transient ponding of water above the geotextile was observed to vary with the initial unsaturated hydraulic conductivity of the geotextile. A numerical code was developed to simulate the 1-D column tests and numerical results are shown to be in good agreement with physical test results. The work reported here leads to the recommendation that the ratio of geotextile to sand saturated hydraulic conductivity may have to be greater than one to prevent lateral flow of water above a geotextile in sand fills used in wall, embankment and road applications.

RÉSUMÉ

L'article décrit une série d'essais en laboratoire réalisés pour quantifier les propriétés hydrauliques saturées/non-saturées de géotextiles tissés et non-tissés à l'état vierge et contaminés de fines de kaolin. Le programme expérimental incluait des essais 1-D en colonne sur une couche unique de géotextile dans un sable sujet à une infiltration d'eau de la surface. Les essais en colonne ont montré des changements détectables du taux d'avancement du front d'humectation au voisinage de la couche de géotextile, en accord avec un mécanisme de coupure de capillarité. On a observé que l'accumulation d'eau transitoire au dessus du géotextile variait avec la conductivité hydraulique non-saturée initiale du géotextile. Un modèle numérique a été développé pour simuler les essais en colonne 1-D et les résultats sont révélé être en bon accord avec les résultats d'essais physiques. Le travail rapporté ici mène à la recommandation que le rapport de la conductivité hydraulique du géotextile sur celle du sable doit possiblement être supérieur à l'unité pour éviter l'écoulement latéral de l'eau au dessus d'un géotextile incorporé dans des remblais de sable utilisés pour les murs, les pentes et les applications routières.

Keywords : geotextiles, saturated-unsaturated flow, infiltration, 1-D column testing, numerical modeling

1 INTRODUCTION

The vast majority of research on the hydraulic properties of geotextiles has focused on their behaviour under fully saturated conditions. Less is known of their properties under unsaturated-saturated conditions. This is despite the observation that under in-situ (operational) conditions they often cycle between saturated and unsaturated conditions. Examples include geotextiles placed in road foundations, retaining walls and in earth embankments. The transient saturation levels that can occur in these systems are often the result of surface water infiltration and drying.

The main objectives of the paper are to review recent work by the writers to characterize the hydraulic properties of geotextiles under in-isolation laboratory conditions and in-situ conditions, and to report some numerical simulation results. The paper briefly reviews the results of suction plate tests on specimens of virgin and contaminated geotextiles to deduce model parameters for two well-known water characteristic curve formulations. The same materials were examined under simulated surface water infiltration events using a 1-D sand-geotextile column apparatus. New work shows how results of the physical tests have been used to verify a numerical code to simulate the hydraulic response of soil-geotextile layers under 1-D wetting and drying. Finally, a practical recommendation for the selection of geotextiles based on the ratio of saturated permeability of the geotextile and sand is made.

A detailed description of the physical testing reported here can be found in the papers by Bathurst et al. (2007, 2009). These papers also provide a review of related work by other researchers on this general topic. The description of numerical simulations presented here is taken from a paper in preparation at the time of writing.

2 MATERIALS

2.1 *Saturated hydraulic properties of test materials*

A woven and nonwoven geotextile with unmodified mass per unit area of 540 g/m^2 and 470 g/m^2, respectively, were used in this experimental program. The geotextiles were investigated in virgin and modified conditions. The hydraulic properties of the geotextiles were modified by contaminating them with kaolin powder. The reference saturated permeability K_{sat} and permittivity, Ψ, of the geotextiles in the cross-plane direction were determined from testing carried out using the ASTM D 4491 method of test. The estimated K_{sat} values for new woven and new nonwoven geotextile specimens were 240 and 520 cm/hr, respectively. The permittivity of the new woven geotextile was 0.36 s^{-1}; for the new nonwoven geotextile it was 0.38 s^{-1}. Wet kaolin powder was added to the surface of the specimens and any excess material removed. The resulting K_{sat} and permittivity values were lower. K_{sat} was computed as 230 and 170 cm/hr for the modified woven and nonwoven geotextile, and the permittivity as 0.35 s^{-1} and 0.13 s^{-1} for the modified woven and nonwoven geotextile, respectively. The K_{sat} values fall within the range of values for virgin geotextiles reported by Koerner (2005). Hence, the results of all tests were assumed to apply to a wider range of uncontaminated

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geotextiles. The sand used in the test program was a poorly graded material with D_{60} = 0.60 mm and saturated hydraulic conductivity of 740 cm/hr (ASTM D 2434).

2.2 *SWCC and GWCC properties*

The soil-water characteristic curves (SWCCs) for the sand were determined using a standard Tempe cell and carried out in accordance with the ASTM D 6386 method of test. The geotextile-water characteristic curves (GWCCs) were determined using a suction plate apparatus (Figure 1) with a normal load corresponding to a 1.2-m depth of soil (the depth of the geotextile layers in the 1-D column tests). The drying and wetting SWCCs for the sand are presented in Figure 2 together with fitted van Genuchten (1980) and Fredlund and Xing (1994) approximations. Drying was carried out first from a saturated state. The two fitted curves are very steep and show little hysteresis (relative to less porous media) which is consistent with data reported in the literature for other sand materials. The measured GWCCs for one of the geotextiles (woven) in new and modified conditions are shown in Figure 3 along with fitted models. Both woven and nonwoven geotextiles showed rapid drying at low suction with relatively little hysteresis (less than 1 kPa difference between air-entry and water-entry values) observed between the drying and wetting curves (Bathurst et al. 2009). The differences in air-entry and water-entry suction heads between the new and modified specimens showed that while the contamination level of the woven geotextile was lower than that for the nonwoven geotextile, the influence of fines content on the GWCCs was greater (i.e. relatively greater differences in air-entry and water-entry suction heads).

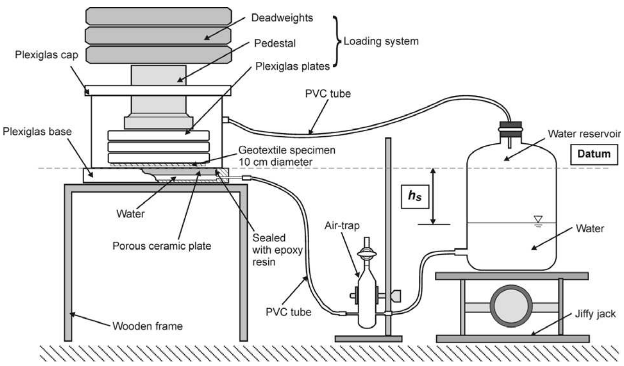


Figure 1. Test apparatus for determination of geotextile-water characteristic curves.

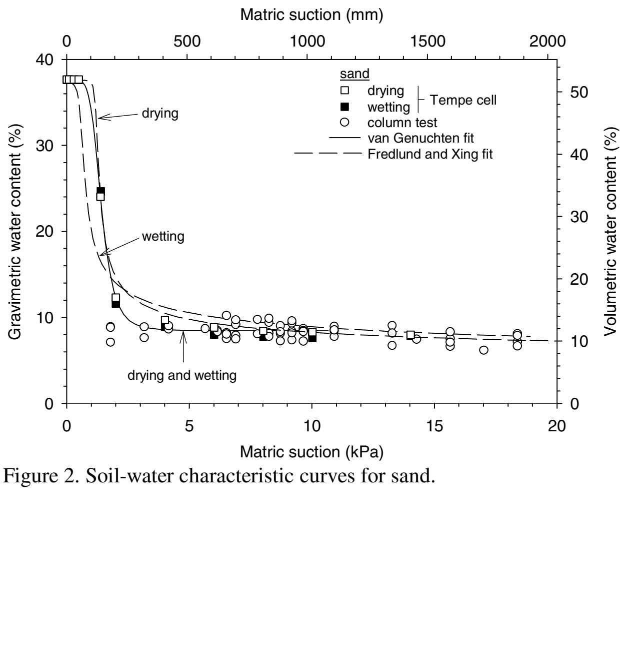
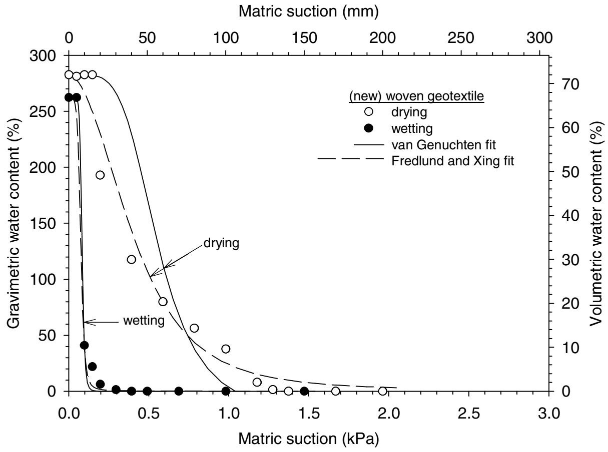
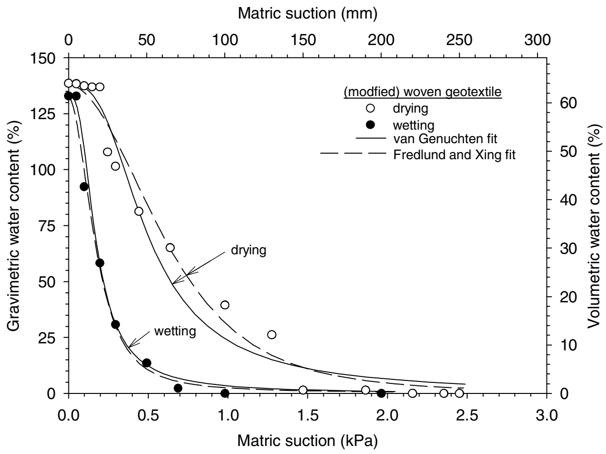


Figure 2. Soil-water characteristic curves for sand.



a) new condition



b) modified condition

Figure 3. Geotextile-water characteristic curves for new and modified woven geotextiles.

3 ONE-DIMENSIONAL COLUMN APPARATUS

A 215-cm high by 10-cm inside diameter instrumented Plexiglas column was used to carry out 1-D drying and wetting tests on the sand material alone and configurations with a geotextile placed at 1.2 m depth (Figure 4). Infiltration loading (wetting) was carried out by applying a constant head of water at the surface after the column had been allowed to drain from a fully saturated condition. The wetting front advance was detected using an array of conductivity probes mounted through the column walls (Figure 5). Transient pore water pressures (negative and positive) were recorded by tensiometers similarly mounted through the side of the apparatus (Figure 6). Manometer ports were attached to the side of the column to allow expulsion of air and to record positive pore water generation after the column was fully saturated. The moisture content profile of the soil column was determined by extracting small samples of the sand through sampling ports in trial columns at the end of the initial flooding and draining cycle.

4 NUMERICAL SIMULATION

The infiltration tests were simulated using the program SVFlux (SoilVision Systems Ltd). Simulation results were selected at locations matching instrument points in Figure 4. Fredlund and Xing (1994) fits to the GWCC curves determined from laboratory pressure plate tests (e.g. Figure 3) were used in the simulations for the hydraulic properties of the geotextiles. The Fredlund and Xing approximation to the measured SWCC curve in Figure 2 was adjusted slightly to match the observed moisture content profile and measured suction values at the start of the infiltration tests. In order to match observed ponding levels in the soil-geotextile columns the K_{sat} value for the geotextiles was decreased by an order of magnitude. This adjustment may be expected since sand particles will penetrate the surface of the geotextile and constrict the geotextile openings. This effect cannot be captured by in-isolation permeability tests that were carried out to determine K_{sat} values.

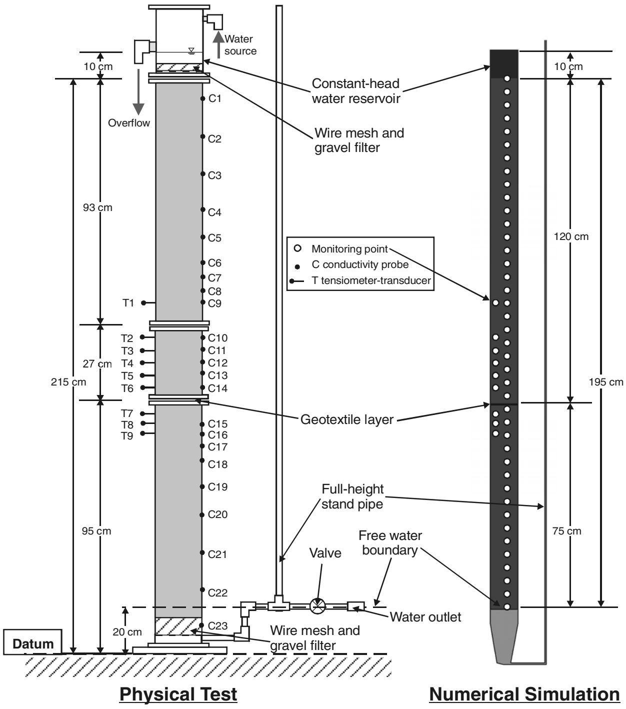


Figure 4. Schematic of 1-D test column and numerical simulation.

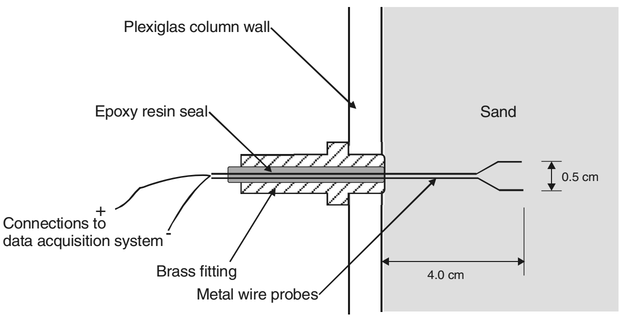


Figure 5. Schematic of conductivity probe and column installation.

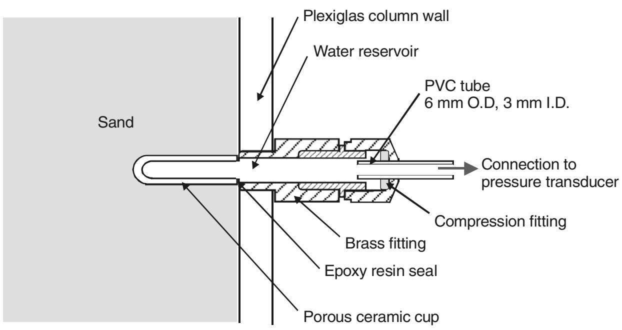


Figure 6. Cross-section view of tensiometer installation.

5 RESULTS

Selected physical and numerical results are presented together in this section. Figure 7 shows the pore water pressure response of selected tensiometers located above and below the geotextile in the test with the modified woven. The traces for the physical test show that there is evidence of ponding of water above the geotextile before the wetting front reaches the bottom of the column and begins to fill up (after about 290 seconds). The physical test results are smooth while the numerical response curves have abrupt changes at the time the wetting front reaches the geotextile and the bottom of the column. Nevertheless, there is a reasonably good match with respect to the magnitude of ponding pressure above the geotextile.

Bathurst et al. (2009) showed that the magnitude of the ponding was lowest for the new nonwoven geotextile with the highest saturated permeability and greatest for the modified nonwoven geotextile with the lowest saturated permeability.

Figure 8 shows the measured wetting front-time history deduced from conductivity probe and tensiometer readings for the test with a modified nonwoven geotextile. There is a pronounced change in rate of advance after the wetting front passes through the geotextile. This response is captured by the numerical simulation of the same test. Detectable differences in the rate of water front advancement below the geotextile were measured in the sand-geotextile column tests and the control column with sand only. As shown in Figure 7, the geotextile acted as a capillary break until a threshold ponding level was achieved. The sand-geotextile columns recorded greater head loss across the geotextile inclusion with decreasing hydraulic permeability using the (unconfined) saturated permeability as an index value.

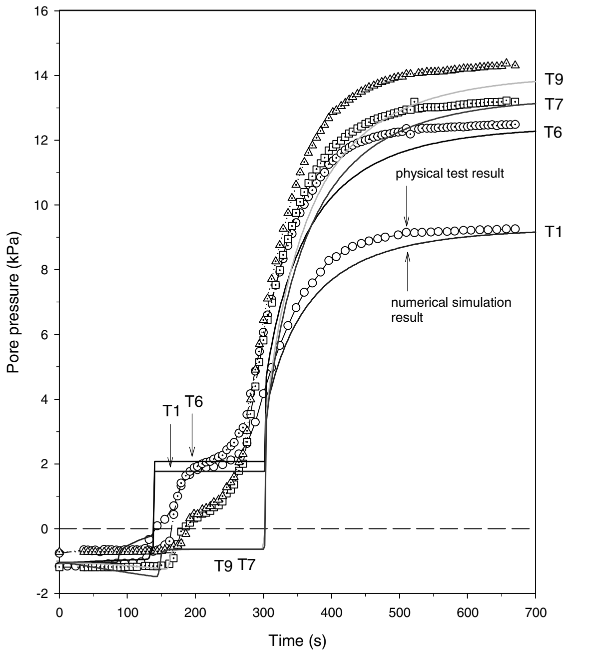


Figure 7. Pore water pressure response for selected tensiometers in column test with modified woven geotextile.

6 CONCLUSIONS AND IMPLICATIONS TO DESIGN

A practical observation from the program of testing reported here is that the ponding head required to generate flow across the geotextile in a sand-geotextile system is very much higher than would be expected from in-isolation suction plate testing. Hence, using the GWCCs from suction plate testing in numerical models will be non-conservative for design (i.e. less safe). The explanation for this discrepancy is that there are interactions between the confining sand and the geotextile which are not captured in the suction plate test even when the plate tests are carried out under matching vertical confining pressure. It is believed that the sand particles constrict the openings in the geotextile which effectively reduces both saturated and unsaturated conductivity values. It is for this reason that the saturated hydraulic permeability from in-isolation testing of the geotextiles was decreased by an order of magnitude to give better agreement between physical and numerical test results.

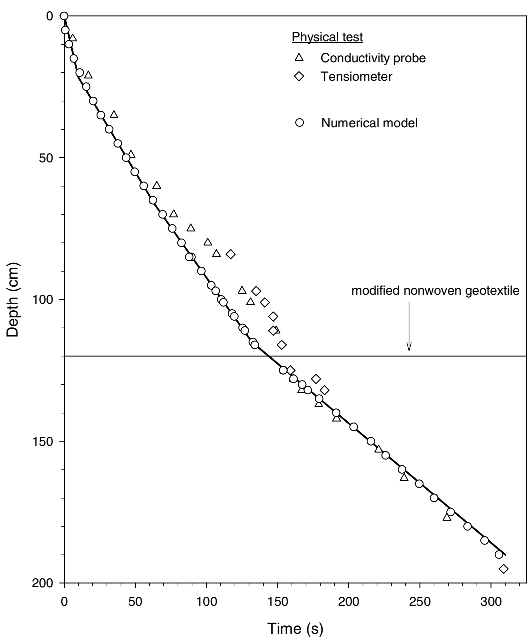


Figure 8. Wetting front advance in 1-D column test with modified nonwoven geotextile.

Conventional filter design practice is to select a geotextile that has a saturated hydraulic conductivity value (over the life of the geotextile) greater than or equal to that of the adjacent soil (i.e. K_{sat}(geotextile) $\geq$ K_{sat}(soil)). This ratio may be increased to a factor of 10 to provide an additional margin of safety against a reduced K_{sat} value for the geotextile due to clogging or for critical applications. The influence of saturated hydraulic ratio on ponding head is shown in Figure 9. Extrapolation of the log-log approximation to a conductivity ratio of one leads to an estimated ponding head of 4 cm and a ratio of 10 would result in negligible ponding (i.e. < 0.1 cm). However, in a field application such as a wall, slope or embankment, a 4-cm head may be sufficient to redirect infiltrated water along the surface of the geotextile inclusion to exit at the face of the structure and thus extend the duration of the capillary break mechanism. Hence, ponding of water over geotextiles in sand may only be preventable by adopting the stricter criterion K_{sat}(geotextile) $\geq$ 10 K_{sat}(soil) assuming that the hydraulic properties of the modified geotextiles in this study are equivalent to other (uncontaminated) geotextile materials.

Finally, the results reported here provide a valuable set of data to fit soil-water and geotextile-water characteristic curve model parameters. Appropriately adjusted parameters can then be used to calibrate or verify numerical models used to simulate the unsaturated-saturated response of geotextile-soil systems in earth structures subject to infiltration loading. This work is currently underway by the writers.

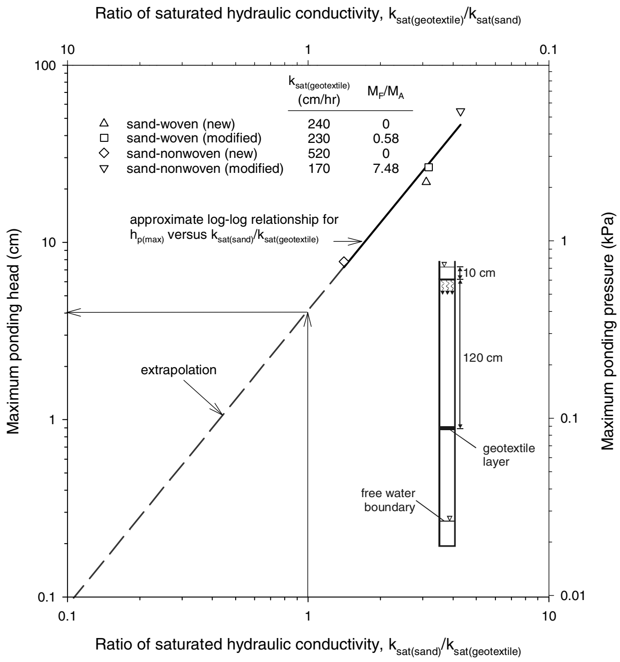


Figure 9. Maximum ponding depth (and pressure) during column infiltration test versus ratio of saturated hydraulic conductivity of geotextile and sand. Note: M_A = mass per unit area of geotextile; M_F = mass per unit area of kaolin fines.

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