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Numerical parametric investigation of infiltration in one-dimensional sand–geotextile columns

Greg Siemens*, Richard J. Bathurst

GeoEngineering Centre at Queen's – RMC, Civil Engineering Department, 13 General Crerar, Sawyer Building, Royal Military College of Canada, Kingston, Ontario, Canada K7K 7B4

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ABSTRACT

Geotextiles are routinely used in separation and filtration applications. Design of these systems is currently based on saturated properties of the geotextiles and the surrounding soils. However, in the field, soil and geotextile can be in an unsaturated state for much of their design life during which they are essentially hydraulically non-conductive. Periodic wetting and drying cycles can result in rapid and large changes in hydraulic performance of soil–geotextile systems. The writers have reported the results from physical water infiltration tests on sand columns with and without a geotextile inclusion. The geotextile inclusions were installed in new and modified states to simulate the influence of clogging due to fines and to broaden the range of hydraulic properties of the geotextiles in the physical tests. This paper reports the results of numerical simulations that were undertaken to reproduce the physical tests and strategies adopted to adjust soil and geotextile properties from independent laboratory tests to improve the agreement between numerical and physical test results. For example the paper shows that the hydraulic conductivity function of the geotextile must be reduced by up to two orders of magnitude to give acceptable agreement. The lower hydraulic conductivity is believed to be due to soil intrusion that is not captured in conventional laboratory permeability tests. The calibrated numerical model is used to investigate the influence of geotextile and soil hydraulic conductivity and thickness as well as height of ponded water at the surface on wetting front advance below the geotextile and potential ponding of water above the geotextile due to a capillary break mechanism. A simple analytical model is also developed that predicts the maximum ponding height of water above the geotextile based on two-layer saturated media and 1-D steady state flow assumptions. The analytical model is used to generate a design chart to select geotextiles to minimize potential ponding of water above the geotextile. Ponding can lead to lateral flow of water along the geotextile in reinforced wall, slope, embankment and road base applications.

1. Introduction

Research and design of geotextiles for hydraulic applications such as filtration and separation have typically focused on saturated conditions. For example, design of geotextile filters uses the saturated hydraulic conductivity as well as the apparent opening size (AOS) or Filtration Opening Size (FOS) of the geotextile (Holtz et al., 1997; Koerner, 2005; Canadian Foundation Engineering Manual, 2006). However, a geotextile may be unsaturated for much of its lifetime since it de-saturates at very low suctions (typically equivalent to negative 1–2 cm of water). The hydraulic conductivity of geotextiles can change by orders of magnitude as the geotextile moisture content changes between residual and saturated conditions. The large changes in hydraulic conductivity of the geotextile during wetting and drying cycles may be expected to have important consequences to hydraulic performance. It is for this reason that the unsaturated–saturated hydraulic properties of geotextiles have been the subject of investigation by a number of researchers. A review of related earlier work can be found in the paper by Bathurst et al. (2009). Of particular relevance to the current study are contributions by Bouazza et al. (2006), Cartaud et al. (2005), Knight and Kotha (2001), Krisdani et al. (2006, 2008), Lafleur et al. (2000), Nahlawi et al. (2007) and Stormont et al. (1997) on the in-isolation unsaturated properties of geotextiles. Important related contributions describing the unsaturated–saturated response of soil–geotextile columns have been reported by Bathurst et al. (2007, 2009), Ho (2000), Krisdani et al. (2008) and Stormont and Morris (2000). An excellent summary of experimentally

* Corresponding author. GeoEngineering Centre at Queen's – RMC, Civil Engineering Department, 13 General Crerar, Sawyer Building, Room 2305, Royal Military College of Canada, Kingston, Ontario, Canada K7K 7B4. Tel.: +1 613 541 6000x6396; fax: +1 613 541 6218.

E-mail address: Greg.Siemens@rmc.ca (G. Siemens).

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determined water characteristic curve data and relative hydraulic conductivity curve data available at the time for nonwoven geotextiles is provided by Iryo and Rowe (2003). Examples of fitting curves using van Genuchten (1980) equations are also provided. Iryo and Rowe (2005a, b) and Garcia et al. (2007) have reported the results of numerical modelling of geotextile reinforced slopes and embankments subjected to surface water infiltration loading.

The main objective of the work described in the current paper was to carry out a numerical parametric analysis of the influence of geotextile hydraulic properties on the 1-D response of initially unsaturated sand–geotextile columns subjected to surface water infiltration. The numerical simulations are used to expand the database of experimental 1-D column test results reported by Ho (2000) and Bathurst et al. (2007, 2009). The first step in the numerical investigation was to verify that the numerical model could satisfactorily reproduce the hydraulic response of the physical tests. It is shown that to do this the hydraulic conductivity of the geotextiles deduced from conventional permittivity tests must be reduced by up to two orders of magnitude to account for the influence of soil particle intrusion. Some of the same physical tests have been used by Iryo and Rowe (2003, 2004) to calibrate a 1-D numerical model for infiltration loading. However, there are important differences between the current study and this earlier work that are explained later in the paper. The calibrated model in the current study is then used to investigate the influence of geotextile hydraulic conductivity, thickness and permittivity, soil hydraulic conductivity and thickness, and surface boundary condition on 1-D sand–geotextile systems subjected to surface water infiltration. An analytical model is derived to predict ponding above the geotextile by assuming steady state flow conditions. The numerical results lead to recommendations for selection of geotextiles to minimize potential ponding of water above the geotextile that could cause lateral flow of water along the geotextile in reinforced wall, slope, embankment and road base applications.

2. Physical tests

A brief review of the 1-D column test methodology and materials is presented for completeness. The test apparatus is illustrated in Fig. 1. The Plexiglas column was about 2 m in height with an inside diameter of 10 cm. A control test was carried out with sand only and four other tests were carried out with a different geotextile layer located at about mid-height. The columns were prepared by pluviating sand into the water column and then draining the column to residual water content of the sand. Next a constant head of water (10 cm) was applied to the top of the column until a hydrostatic pore-pressure distribution was measured in the tensiometers. Tensiometers and conductivity probes were located along the column to record pore-water pressures (including suctions) and the location of the wetting front as the experiment progressed. Details of the physical tests, instrumentation, measurement interpretation, and the properties of sand and geotextile materials can be found in the papers by Bathurst et al. (2007, 2009).

2.1. Sand

The sand used in the physical tests is poorly graded sand (SP) according to the United Soil Classification System. The as-placed porosity of the pluviated sand was 0.52 and the saturated hydraulic conductivity of the sand was reported to be 2.0×10^{-3} m/s. The water retention characteristics of the sand were measured using a Tempe cell. The drying and wetting data points are plotted in Fig. 2 along with the fitted Fredlund and Xing (1994) curve for the wetting soil–water characteristic curve (SWCC) expressed as

$$\theta(\Psi, a, n, m) = C(\Psi)\frac{\theta_s}{\left\{\ln\left[e + \left(\frac{\Psi}{a}\right)^n\right]\right\}^m} \tag{1a}$$

$$C(\Psi) = 1 - \frac{\ln\left(1 + \frac{\Psi}{\Psi_r}\right)}{\ln\left[1 + \left(\frac{1\,000\,000}{\Psi_r}\right)\right]} \tag{1b}$$

where θ = water content, Ψ = suction; $C(\Psi)$ = correction function, θ_s = saturated water content, and a, n, m, Ψ_r = fitting parameters. The data obtained from the Tempe cell show the air entry value to be 0.5 kPa, with a water entry value of 2–3 kPa and a residual water content of 8% (gravimetric). Little hysteresis was observed as the wetting and drying data points are very close.

The column preparation procedure also provided an independent measurement of the SWCC. Following pluviation of the sand particles in water, the bottom valve was opened and water drained from the column until the sand came into equilibration with the free water boundary (Fig. 1). Equilibrium was determined when water stopped flowing from the column and the tensiometer measurements became constant. Next, very small samples of sand were extracted through the sampling ports along the height of the column and these samples used for gravimetric water content (GWC) analysis. Consistent measurements of approximately 9–10% GWC were measured for the five infiltration tests. These are plotted with open circles in Fig. 2 assuming a hydrostatic pore-pressure profile above the free water boundary. These in-situ column measurements taken prior to infiltration loading are considered to be more accurate than values using the Tempe cell. The initial gravimetric water content measurements correspond to about 1.1 kPa suction using tensiometer measurements from the five infiltration tests. In this investigation the SWCC was judged to be best fitted to the column measurements at low moisture content and using the Tempe cell values at saturated states (samples were not taken from the flooded column). The Fredlund and Xing (1994) curve is plotted in Fig. 2 over the practical wetting range of interest (<2 kPa suction) using the fitting parameters in Table 3.

2.2. Geotextiles

Two typical commercially available geotextile materials were used in the column tests and their relevant properties are given in Table 2. One material was a woven geotextile manufactured from polypropylene slit film monofilament. The second geotextile was a nonwoven manufactured from continuous entangled polypropylene filament. To simulate potential clogging which can reduce hydraulic conductivity (Palmeira and Gardoni, 2000) the geotextiles were modified by the addition of a kaolin powder. Infiltration tests were carried out on sand columns with new and modified geotextile inclusions to assess the impact of clogging on infiltration behaviour and to broaden the range of hydraulic properties for the geotextile inclusions.

For numerical simulations, the geotextile properties of interest are the thickness, saturated hydraulic conductivity and geotextile–water characteristic curve (GWCC). Geotextiles will compress under vertical pressure. In the column tests, geotextile inclusions were placed at 120 cm below surface. From one-dimensional compression tests performed on the geotextile specimens, this depth corresponds to a thickness (t_g) of 1.8 mm and 3.8 mm for the woven and nonwoven geotextiles, respectively. In practice, geotextile thickness cannot normally be measured to an accuracy of ±0.1 mm. According to ASTM D5199 (2004) the measurement repeatability limit is ±14% for thickness of a geotextile under a 2 kPa load. This level of accuracy corresponds to ±0.25 mm and ±0.53 mm for the woven and nonwoven geotextiles, respectively. However,