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A Numerical Investigation of Drainage Characteristics of Nonwoven Geotextile in Unsaturated Fine-grained Soil

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Received: 9 February 2025 / Accepted: 19 August 2025 / Published online: 8 September 2025
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Abstract

This study presents a comprehensive numerical investigation into the drainage behavior of nonwoven geotextiles embedded within unsaturated fine-grained soils. The simulations were calibrated using laboratory data to ensure consistency and reliability. Transient seepage analyses were performed to evaluate the dual functionality of geotextiles-as capillary barriers and drainage layers-under varying infiltration conditions. The study examined geotextile performance in both lateral and vertical drainage configurations, considering the presence or absence of vertical drains, and evaluated behavior under varying initial soil moisture contents and successive wetting-drying cycles. Results demonstrate that geotextiles act as effective capillary barriers, delaying water migration until a breakthrough suction is reached. The time to breakthrough was found to depend strongly on the geotextile's hydraulic properties and the initial moisture content of the surrounding soil. The study also showed that geotextiles maintain lower suction values in the subsurface, even after prolonged drying periods. A parametric analysis involving seven geotextile types revealed that air-entry suction is a critical factor governing lateral drainage performance. Geotextiles with higher air-entry or water-entry suction values facilitated quicker breakthroughs and more efficient drainage. Overall, this research provides valuable insight into the hydraulic mechanisms governing geotextile behavior in unsaturated conditions and underscores the importance of incorporating unsaturated soil-geotextile interactions into drainage system design.

Keywords Nonwoven geotextile · Capillary barrier · Infiltration · Unsaturated soil · Breakthrough suction · Drainage function · Marginal soil

Introduction

Geotextiles have been used in many geotechnical and geoenvironmental applications to provide multiple functions to the system such as reinforcement, separation, filtration, and drainage. There are three main types of geotextiles-woven, nonwoven, and wicking-classified based on their manufacturing processes. Nonwoven geotextiles are highly permeable and serve as effective drainage media. They

are commonly used in pavements, earth-retaining structures, and embankments constructed with poorly draining soils [1–6]. Despite their drainage benefits, the use of fine-grained soils as fill material is often discouraged by design guidelines due to poor performance under rainfall infiltration [7, 8]. Both internal and external water ingress can compromise the performance of geosynthetic-soil systems. However, using locally available marginal soils-typically with low hydraulic conductivity-offers a cost-effective and sustainable solution for infrastructure development [9–12]. Several laboratories and field studies have investigated the drainage performance of nonwoven geotextiles in the presence of fine-grained soils. These studies demonstrate that nonwoven geotextiles can improve stability by draining infiltrated water from the system. For example, Bhattacharjee and Viswanadham [13]) conducted seepage analyses on silty sand slopes reinforced with hybrid geosynthetic layers. Their results showed that the nonwoven geotextiles effectively lowered the phreatic surface by dissipating

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excess pore water pressure during rainfall. In the field, soils are often compacted at moisture contents below optimum, resulting in unsaturated conditions [14, 15]. Under these conditions, particularly in fine-grained soils, the nonwoven geotextile can act as a capillary barrier, limiting its effectiveness as a drainage layer. This behavior has been reported in several studies [14, 16–25]. When the overlying fine-grained soil is unsaturated, water cannot readily flow into the nonwoven geotextile due to the sharp contrast in hydraulic conductivity between the two materials. Flow initiation occurs only after the soil suction exceeds the breakthrough suction of the geotextile-at which point the hydraulic conductivities of the soil and geotextile become equal [21]. Portelinha and Zornberg [6] conducted a full-scale seepage test on geotextile-reinforced soil walls under controlled rainfall. Their results confirmed the formation of a capillary break at the soil-geotextile interface, which delayed the advancement of the wetting front. Several studies have highlighted the effectiveness of wicking geotextiles in mitigating capillary barrier effects, particularly in the lateral direction [26, 27]. These materials enhance drainage by promoting lateral water movement, unlike conventional geotextiles that rely on cross-plane flow. While most previous studies have concentrated on the continuous infiltration behavior of geotextile-reinforced systems [22, 27, 28], only a limited number have examined the effects of alternating infiltration and drying phases, including the recovery of suction within the system [29, 30]. Investigating these cyclic conditions is particularly important given the growing impact of climate change on the performance of geotechnical structures. Infrastructures constructed with poorly draining backfill soils are especially vulnerable to environmental stressors such as wetting-drying cycles, groundwater table fluctuations events, and extended periods of rainfall. These factors can significantly alter pore water pressure distributions within the reinforced backfill, potentially compromising the stability and long-term performance of such systems.

Despite extensive research, several experimentally observed behaviors still require further investigation to fully understand wetting front advancement and pore-water pressure development within the soil-geotextile system. Obtaining comprehensive system-wide information using embedded sensors remains challenging, as the sensor's influence area is often limited relative to the scale of the system. Full-scale field or laboratory infiltration tests using marginal soils are also difficult to conduct due to their time-intensive nature and complex methodologies. In such cases, a well-calibrated numerical model can offer valuable insights into system behavior prior to performing physical tests. This study aims to examine the complex drainage behavior of nonwoven geotextiles and improve understanding of water flow in unsaturated soil systems. A numerical

model simulating unsaturated water flow was first developed and validated against laboratory results. Subsequently, in-plane drainage characteristics of various geotextiles were analyzed under different boundary conditions to evaluate their performance under unsaturated conditions.

Numerical Analysis of Transient Seepage Flow in Unsaturated Soil Media

Calibration of Numerical Model

Transient seepage through the unsaturated soil-geotextile system was simulated numerically using the SEEP/W module of the finite element program GeoStudio. SEEP/W solves the nonlinear two-dimensional flow of water in the unsaturated soil using Richards [31] equation. Bouazza et al. [18, 19] performed infiltration test in a soil column consisting of clay layer underlain by sand. In the numerical simulation, the initial volumetric water contents for sand and clay were assumed to be 5% and 12%, respectively, as determined from laboratory investigations [18, 19]. The soil column consisted of a 30 cm thick clay layer overlying a 15 cm thick sand layer (Fig. 1a). The diameter of the cylindrical soil column was 20 cm. A constant rate of water was supplied on the top of the soil column. Water movement through the soil profile was monitored by measuring the change in volumetric water content over the time [18, 19]. In the current study, a numerical model of the soil column was developed which is presented in Fig. 1b. Four-node quadrilateral elements were used and discretized the soil domain. The boundary conditions were characteristically chosen to simulate the one-dimensional flow of water through the soil column. An impermeable boundary was placed at the lateral edge of the soil column to prevent any transverse water flow. An impermeable boundary was placed at the base of the soil column to allow seepage water to accumulate (Fig. 1b). A constant rate of unit flux of 2.059×10^{-7} m/hr was applied at the topmost free boundary of the soil column to simulate rainwater infiltration. During infiltration, surface runoff was triggered when positive pore water pressure developed at the top boundary. To simulate this condition, boundary condition was dynamically updated from a constant unit flux to a zero pore-pressure condition. This adjustment prevented water ponding on the surface of the numerical model. Overall, this approach effectively simulated a practical one-dimensional soil column for rainwater infiltration testing.

This study uses the Van Genuchten [32] model (Eqs. 1–3) to define the unsaturated hydraulic properties of both the geotextile and the soil. The adopted model-fitting parameters are listed in Table 1. The corresponding water retention and hydraulic conductivity curves are presented in Fig. 2.

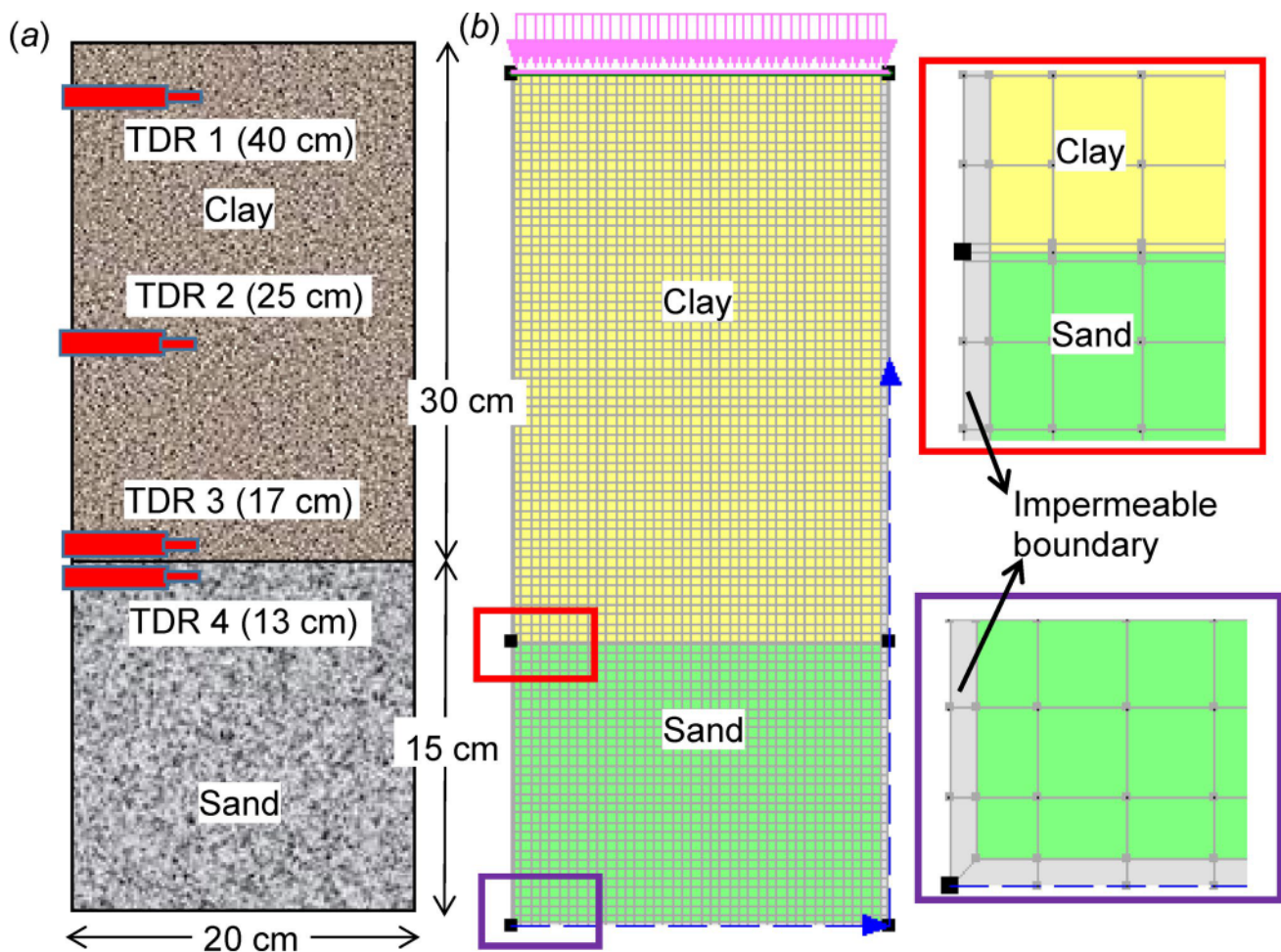


Fig. 1 (a) Schematic representation of the cylindrical soil column used in the laboratory experiment, showing the locations of time domain reflectometry (TDR) moisture sensors. (modified from Bouazza et al.,

2006, 2013); and (b) one-dimensional finite element model of the soil column used for numerical simulation, illustrating boundary conditions, soil layering, and geometric dimensions.

Table 1 Hydraulic parameters of soil and geotextile for cylindrical soil column test

Material	α (1/kPa)	n	Saturated water content θ_s	Residual water content θ_r	Saturated hydraulic conductivity (m/hr)	References
Clay	0.21	1.5	0.46	0.05	4.32×10^{-3}	Bouazza et al. [18]
Sand	0.56	4.8	0.38	0.3	1.908	Bouazza et al. [18]
Geotextile	1.569	7	0.99	0.02	6.84	Bouazza et al. [18]
Gravel	33.33	2.5	0.33	0.03	46.8	Stormont and Anderson [38]

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\psi)^n]^m} \quad (1)$$

$$k_w = k_s \frac{[1 - (\alpha\psi)^{n-1}][1 + (\alpha\psi)^n]^{-m}}{[1 + (\alpha\psi)^n]^{m/2}} \quad (2)$$

$$n = \frac{1}{1 - m} \quad (3)$$

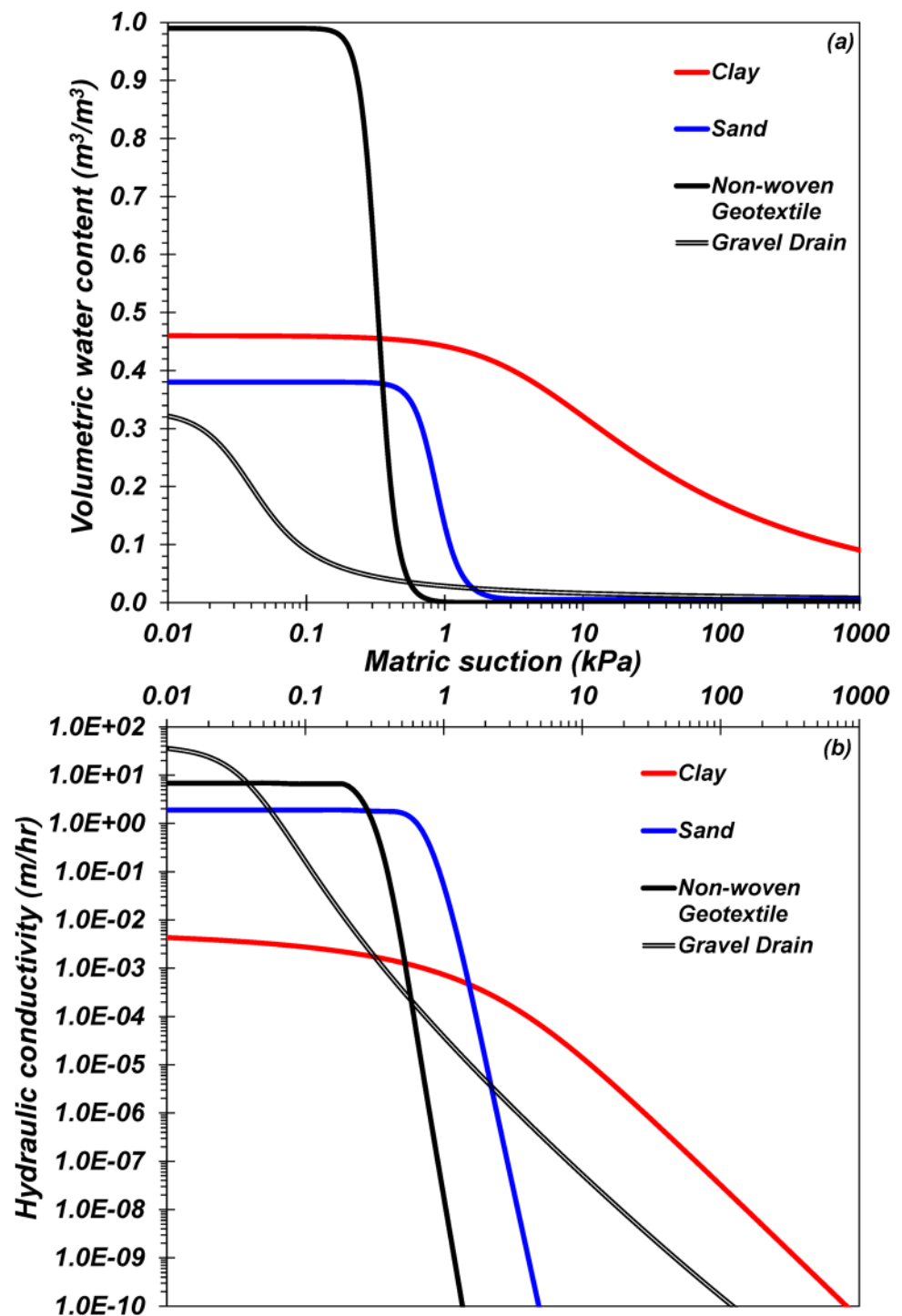
water content, ψ is the suction, k_w is the hydraulic conductivity at a particular suction value, k_s is the saturated hydraulic conductivity, α , n and m are the model fitting parameters. The initial unsaturated condition of the soil was defined by its moisture content, which influences the transient flow of water through the soil medium.

Methodology

Richard's equation was used to model the transient flow of water through unsaturated soil. It is expressed as:

where, θ_w represents the volumetric water content, θ_r indicates the residual water content, θ_s denotes the saturated

Fig. 2 Hydraulic characteristics of the soil and nonwoven geotextile used in the cylindrical soil column test, showing (a) water retention curves and (b) corresponding unsaturated hydraulic conductivity curves used in the numerical simulation for the infiltration study



$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = \frac{\partial \theta_w}{\partial t} = m_w \gamma_w \frac{\partial h}{\partial t} \quad (4)$$

where, k_x and k_y denote the unsaturated hydraulic conductivities at a given suction, h represents the total head, θ_w is the volumetric moisture content and, m_w indicates the slope of the storage curve. SEEP/W is a finite element program that numerically solves transient seepage problems based on

Darcy's Law. The corresponding finite element form of the transient seepage equation is expressed as

$$[k] \{H\} + [M] \{H\}, t = \{Q\} \quad (5)$$

where, $[k]$ is the unsaturated conductivity matrix at a given suction, $\{H\}$ represents the total head vector at the nodes, $\{Q\}$ is the flux vector at the corresponding nodes, and $[M]$

denotes element mass matrix. In transient seepage analysis, the total head at each node is computed at every time step by numerically solving the governing equations. This solution is based on the previously estimated total head values and incorporates the unit flux conditions defined at the boundary nodes.

Calibration Results

The pore water pressure distribution throughout the soil column is shown in Fig. 3a. One-dimensional water flow through the soil column is assured as there is no flow along the side and bottom boundary of the model, indicated by zero flux at the edges as represented in Fig. 3a. Following the transient seepage analysis, the volumetric water content was monitored at four specific nodes within the soil column (A, B, C, and D) throughout the simulation period. These nodes were selected to match the location of pore-pressure measurement sensors used in the experiment by Bouazza et al. [18]. The observed change in volumetric water content at these locations, as reported in Bouazza et al. [18, 19] are presented in Fig. 3b. The corresponding variation of water content at these four nodes obtained from the numerical simulation is shown in Fig. 4a. A comparison of Figs. 3b and 4a indicate that the numerical results closely resemble

the laboratory experiment result. At Node A, the volumetric water content gradually increased over time from its initial value of 12%. A similar trend in volumetric water content was observed at the other nodes. The time taken for the infiltrated water to reach at each node closely matched the results from laboratory experiment. Table 2 presents a comparison between the experimental observations and numerical simulation results used for model calibration and validation. The time required for water to reach the moisture sensors (TDR 1 to TDR 4) shows good agreement between the experimental and numerical results, with slight differences attributed to idealized boundary conditions and assumptions of material homogeneity in the simulation. The volumetric water content in the clay at the time of breakthrough in the underlying sand layer matched exactly between the simulation and experiment ($\theta_w = 0.36$; Fig. 4a), supporting the accuracy of the model. The simulated matric suction in the clay during breakthrough was 1.48 kPa, (Fig. 4b and c) compared to an estimated experimental value of approximately 5 kPa [19]. Notably, the theoretical matric suction at breakthrough, estimated from the hydraulic conductivity curve, also corresponds closely to the simulated value of 1.48 kPa. This consistency further confirms that the numerical model captures the hydraulic response of the systems. However, the experimental data showed slightly

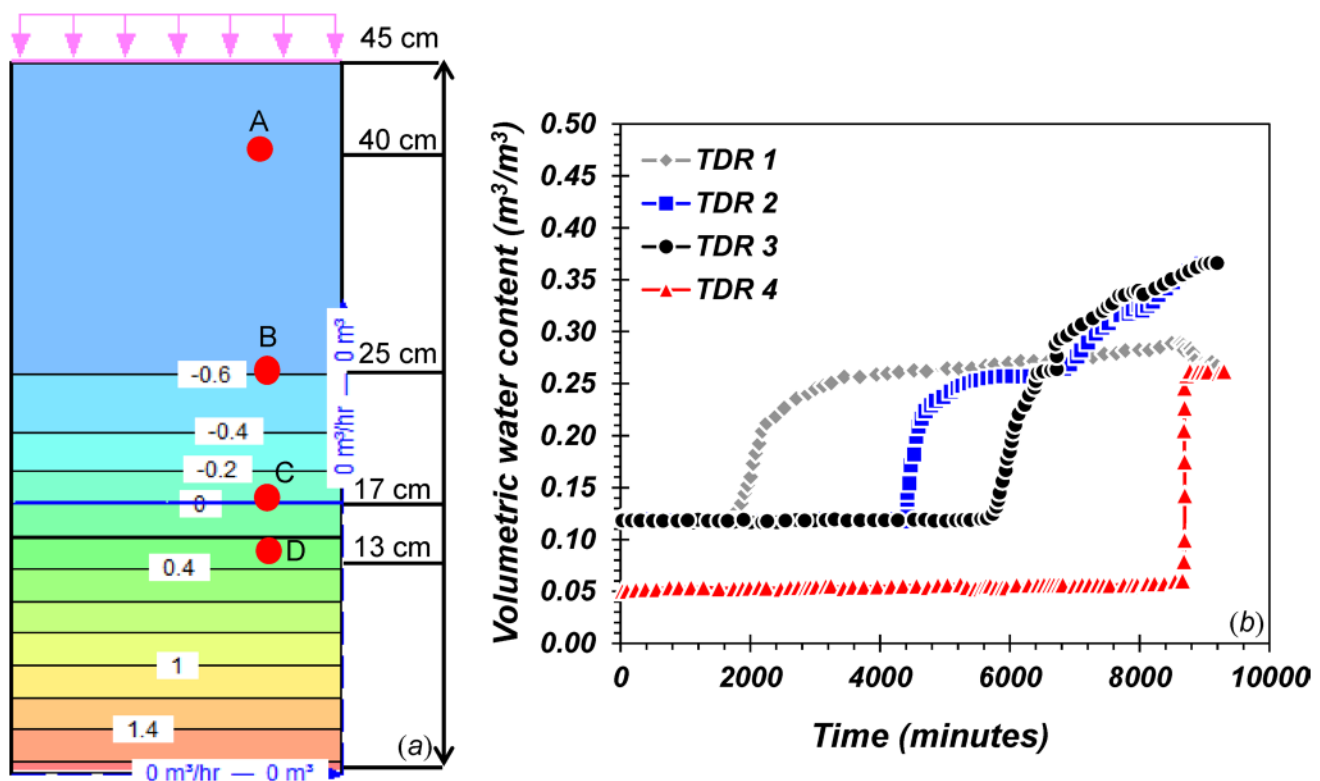


Fig. 3 Simulation and experimental results for the cylindrical soil column test, showing (a) pore water pressure profiles (in kPa) obtained from numerical simulations and (b) volumetric water content profiles

with depth from experimental measurements (modified after Bouazza et al., 2006, 2013)

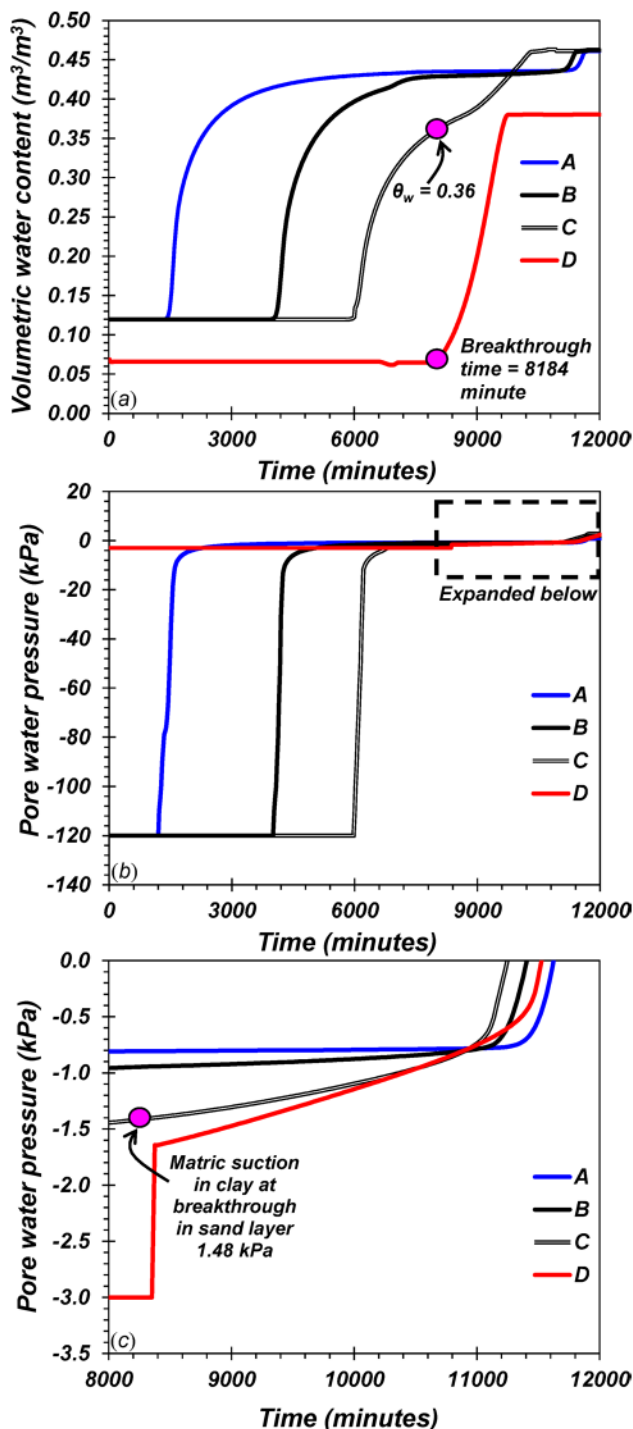


Fig. 4 Numerical simulation results of infiltration in the soil column, showing: (a) volumetric water content, (b) pore water pressure distribution over time, and (c) expanded view of the pore water pressure distribution

lower volumetric water content at various nodes compared to numerical simulation. This discrepancy is attributed to air entrapment in the soil pores of the physical model, as noted by Iryo and Rowe [33], a factor not accounted for in the finite element simulations. During rainwater infiltration,

Table 2 Comparison of numerical simulation and experimental results

Parameters	Location	Experimental observations	Numerical simulation
Time for water to reach nodes (minutes)	TDR 1 (A)	1898	1512
	TDR 2 (B)	4523	4152
	TDR 3 (C)	5734	5976
	TDR 4 (D)	8544	8184
Volumetric water content in clay at breakthrough in sand layer	TDR 3 (C)	0.36	0.36
Matric suction in clay at breakthrough in sand layer (kPa)	TDR 3 (C)	5 (estimated)	1.48

the suction of the soil gradually decreased from its initial value, indicating progressive saturation of the soil column (Fig. 4b). Despite the potential influence of air entrapment, numerical simulation effectively captured unsaturated water flow behavior, demonstrating model's suitability for investigating transient seepage in unsaturated soil. Following successful calibration, the same numerical framework was implemented to simulate drainage characteristics of the geotextile as described below.

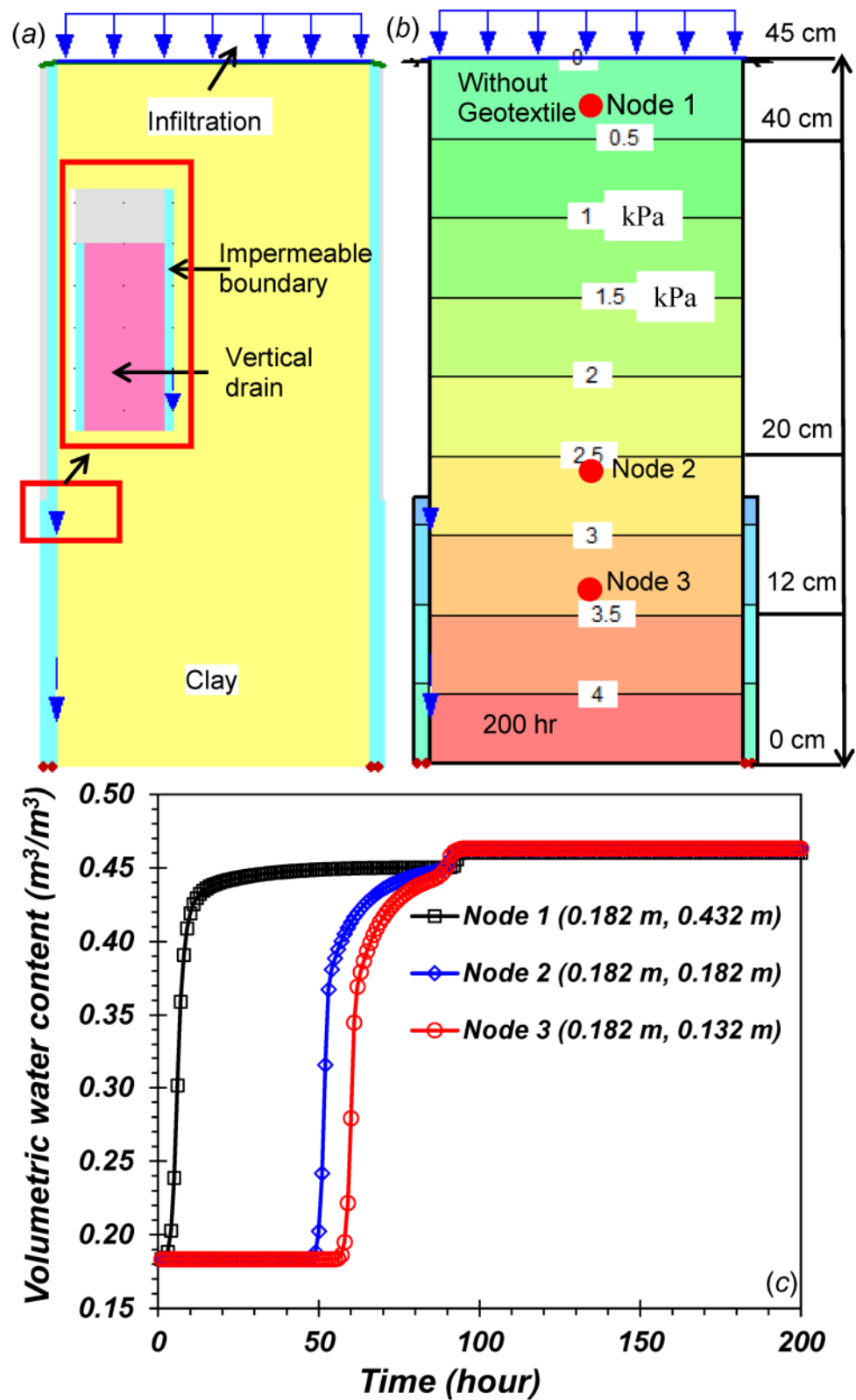
Drainage Behavior of Geotextile in a One-Dimensional Soil Column Under Different Soil and Boundary Conditions

In this section, a stepwise procedure was implemented to investigate the response of geotextile as a drainage material under both saturated and unsaturated conditions. Five distinct seepage cases were analyzed using a clay soil column to evaluate different hydraulic scenarios. The primary objective was to eloquently delineate the drainage behavior of the geotextile, thereby enhancing the understanding of its drainage mechanism.

Water Flows in a One-Dimensional Soil Column Without Geotextile

A numerical model of the clay soil column was developed to monitor the water infiltration. The boundary conditions and hydraulic properties were kept consistent with the previous analysis. In this case, the sand layer was replaced with an identical overlying clay layer as shown in Fig. 5a. The initial moisture content of the clay was assumed 18%. A constant infiltration rate (unit flux 2.059×10^{-7} m/hr) was applied at the top boundary of the soil column. After 200 h of infiltration, the resulting pore water pressure distribution within

Fig. 5 Numerical models of the soil column infiltration tests: (a) model without non-woven Geotextile, (b) simulation results showing pore water pressure distribution, and (c) variation of volumetric water content over time at selected nodes



the soil column is shown in Fig. 5b. Pore pressure contours from the transient seepage analysis closely resembles those expected under fully submerged condition. Since the entire soil column reached fully saturation by the end of 200 h infiltration period, the variation of pore water pressure along the height corresponds to the hydrostatic pore water pressure distribution under submergence condition. The variation of moisture content at three selected nodes (Node 1, 2, and 3 in Fig. 5b) was examined and presented in Fig. 5c. The results demonstrate a gradual increase in saturation as the wettingfront advanced through the soil column during infiltration.

Water Flows in the Soil Column with Geotextile Inclusion

In this section, a 3 mm thick geotextile was embedded within the clay at an elevation of 15 cm, as illustrated in Fig. 6a. The geotextile was not inserted inside the vertical drain to prevent any lateral flow through it. Only the flow in the cross-plane direction (i.e. vertical flow towards the base of the soil model) was investigated. A discontinuity in the impermeable boundary between the drain and the geotextile is visible in Fig. 6a. The water retention characteristics curve of the geotextile is presented in Fig. 2. Notably, geotextile exhibits a water entry suction of approximately 1 kPa, which is significantly lower than that of the clay soil. When the suction in the unsaturated soil exceeds the water entry suction of the geotextile, the geotextile remains impermeable, as its hydraulic conductivity is significantly lower than that of the clay at the corresponding matric suction. The boundary condition and hydraulic properties of the soil were kept identical to those used in the previous analysis. After performing transient seepage analysis, the water front migration in the clay column was monitored in the presence of geotextile. The pore water pressure distribution inside the soil column at 200 h is shown in Fig. 6b. The results indicate that the geotextile functions as barrier, preventing water migration into the underlying soil layer. Consequently, the soil above the geotextile reaches saturation, while the soil beneath the geotextile remains unsaturated. The change in the moisture content of the soil at different time instances is shown in Fig. 6c. It can be observed that Node 1 and Node 2 reached saturation, while there was no significant change of water content at Node 3, indicating the barrier effect of geotextile. As shown in Fig. 5c, in the absence of a geotextile layer, water content at Node 3 increased over time. In contrast, with the geotextile in place (Fig. 6a), Node 3 exhibited negligible change in water content (Fig. 6c). This comparison confirms that the geotextile effectively impedes water migration into the unsaturated soil layer below and facilitates moisture accumulation above it. A similar observations

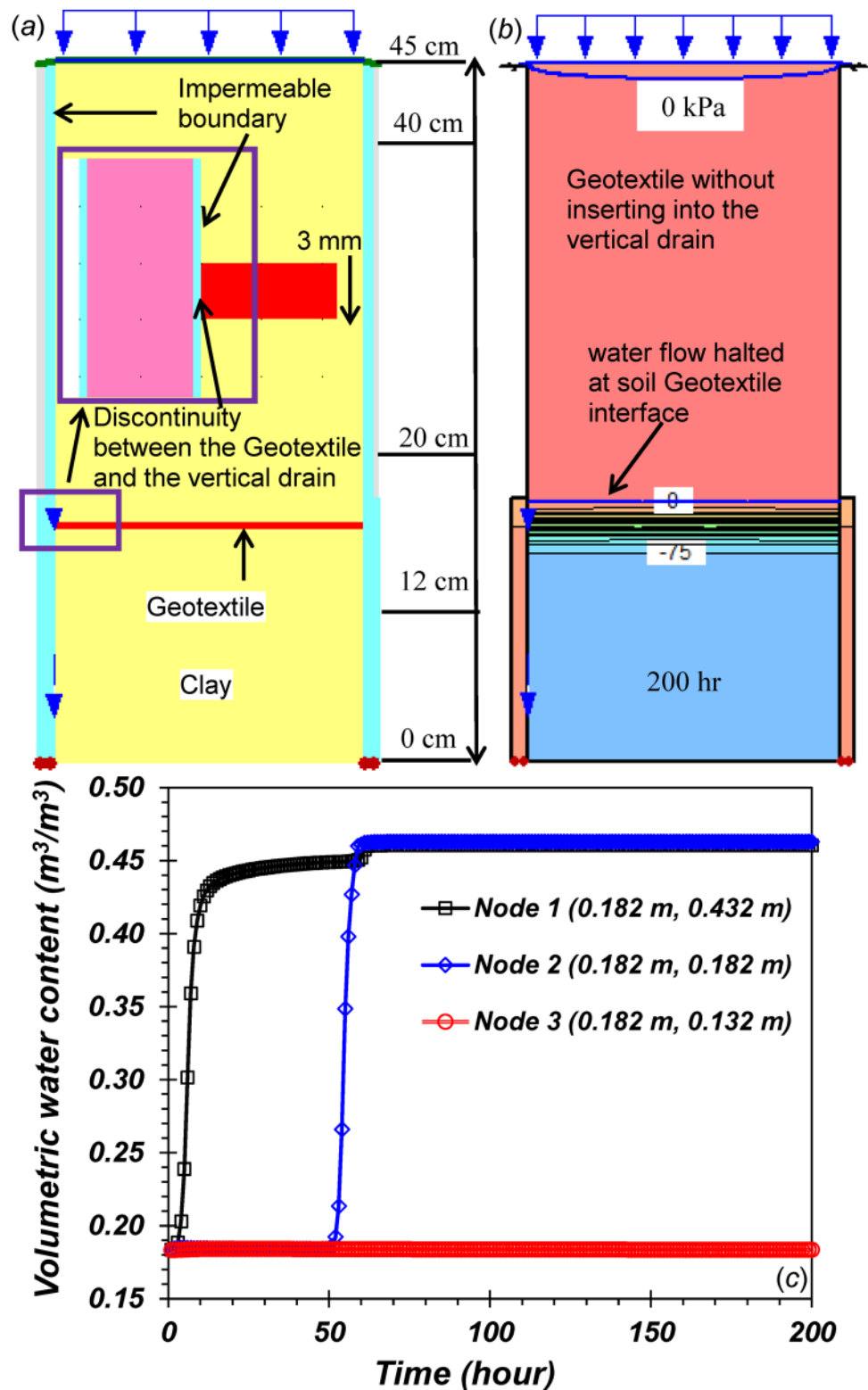
have been reported in laboratory studies one-dimensional water flow in the presence of geotextiles [19–21, 33–36].

Drainage Response of the Geotextile Layer in the Presence of a Vertical Gravel Drain

In the previous section, the geotextile's barrier mechanism was demonstrated under one-dimensional vertical flow conditions in an unsaturated soil medium. However, the lateral flow or the in-plane drainage characteristics of geotextile during rainwater infiltration was not explored in detail. Aristizabal et al. [37] reported a laboratory investigation of horizontal drainage function of geotextile in a soil column. To study this aspect numerically, the earlier numerical model was modified to evaluate the horizontal drainage characteristics of a nonwoven geotextile under rainwater infiltration. A vertical drain composed of Pea gravel was incorporated in the numerical model to simulate a facing drain system commonly used in geotechnical infrastructure. The soil water characteristics curve for the drainage layer (Fig. 2) was adopted from Stormont and Anderson [38]. The end of the geotextile was inserted into the vertical drain as shown in Fig. 7a. A toe drain was also introduced at the end point of the vertical drain to provide an escape route for the accumulated water. The boundary conditions and material properties used in this model were kept identical to those in the previous simulation.

Following the transient seepage analysis, the pore water pressure distribution in the soil column was determined and shown in Fig. 7b. The variation in moisture content at three node points over time is shown in the Fig. 7c. During the infiltration, there is an insignificant change in initial moisture content at Node 3, indicating limited water migration to that depth. On the other hand, the moisture content at Node 1 and Node 2 gradually increased with the elapsed time. The moisture content at these nodes (1 and 2) decreased when the geotextile began functioning as horizontal drainage by facilitating the accumulated water to flow into the vertical drain. Three points K (0.16 m, 0.156 m), L (0.16 m, 0.163 m), and M (0.16 m, 0.147 m) were chosen along the soil-geotextile interface to monitor the variation in pore water pressure over time (Fig. 7d). Point K is located above the geotextile within the overlying soil, Point L lies directly on the geotextile surface, and Point M is positioned below the geotextile within the underlying soil layer. Points K, L, and M are located so close proximity, such that they appear as a single dot in the model visualization. Therefore, their individual locations are not distinguishable in the figure; instead, their X and Y coordinates are reported here for clarity. The results indicate that the geotextile initially functioned as a barrier, causing water to accumulate above it and leading to an increase in pore water pressure

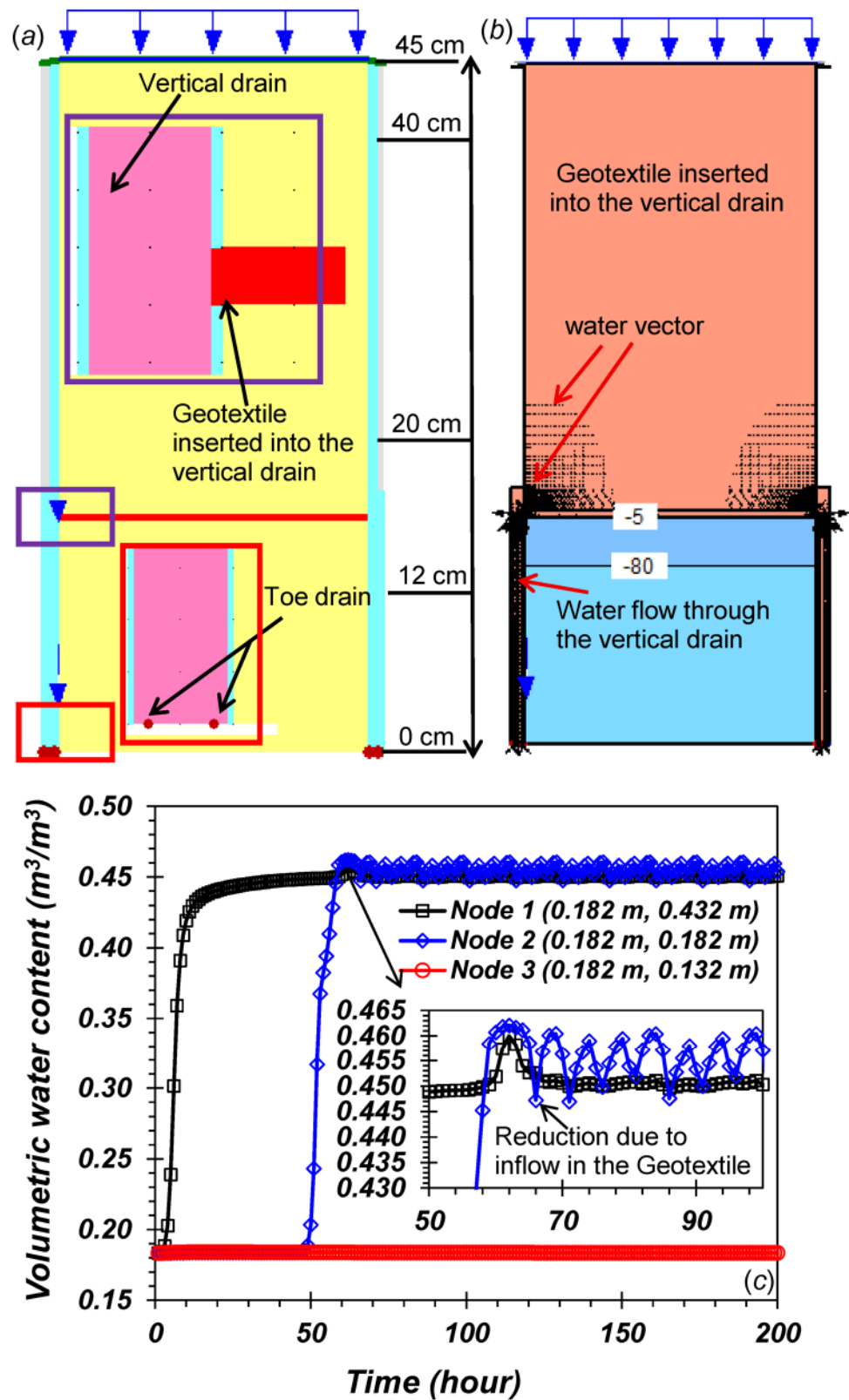
Fig. 6 Numerical models of the soil column infiltration tests: (a) model with non-woven Geotextile, (b) simulation results showing pore water pressure distribution, and (c) variation of volumetric water content over time at selected nodes



in the overlying soil. Once the suction in the soil above the geotextile reached the breakthrough value, the geotextile began to function as a drainage layer, allowing water to flow in the vertical drain and resulting in dissipation of pore water pressure above the geotextile (Fig. 8a). It is

important to note that the draining through the geotextile is a transient phenomenon. After water drained through the geotextile, the pore water pressure above the geotextile dropped below 0 kPa, rendering the geotextile temporarily impermeable to further water flow. This cyclic process

Fig. 7 Numerical models of the soil column infiltration tests: (a) model with non-woven Geotextile layer inserted into the vertical gravel drain, (b) simulation results showing pore water pressure distribution, and (c) variation of volumetric water content over time at selected nodes



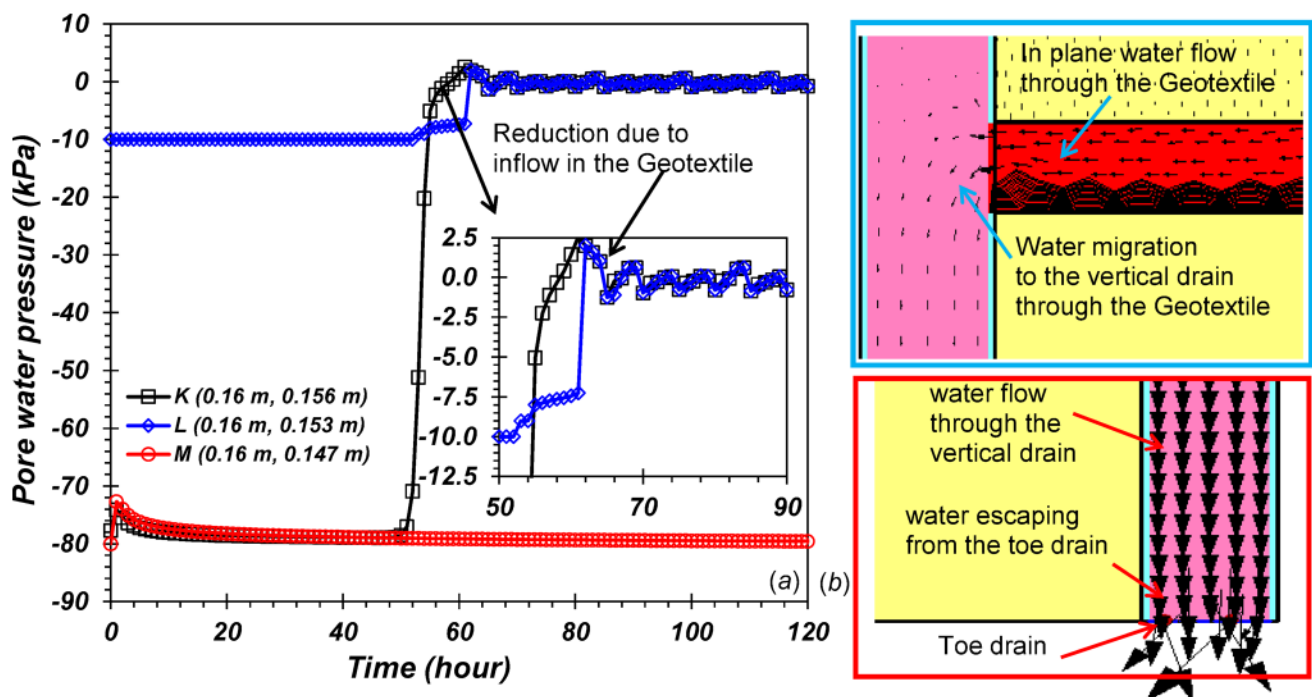


Fig. 8 Numerical simulation results of the soil column infiltration tests showing: (a) variation of pore water pressure at the soil-geotextile interface for the case where a geotextile layer is inserted into the verti-

cal gravel drain, and (b) water flow vectors through the soil column illustrating the in-plane drainage function of the geotextile

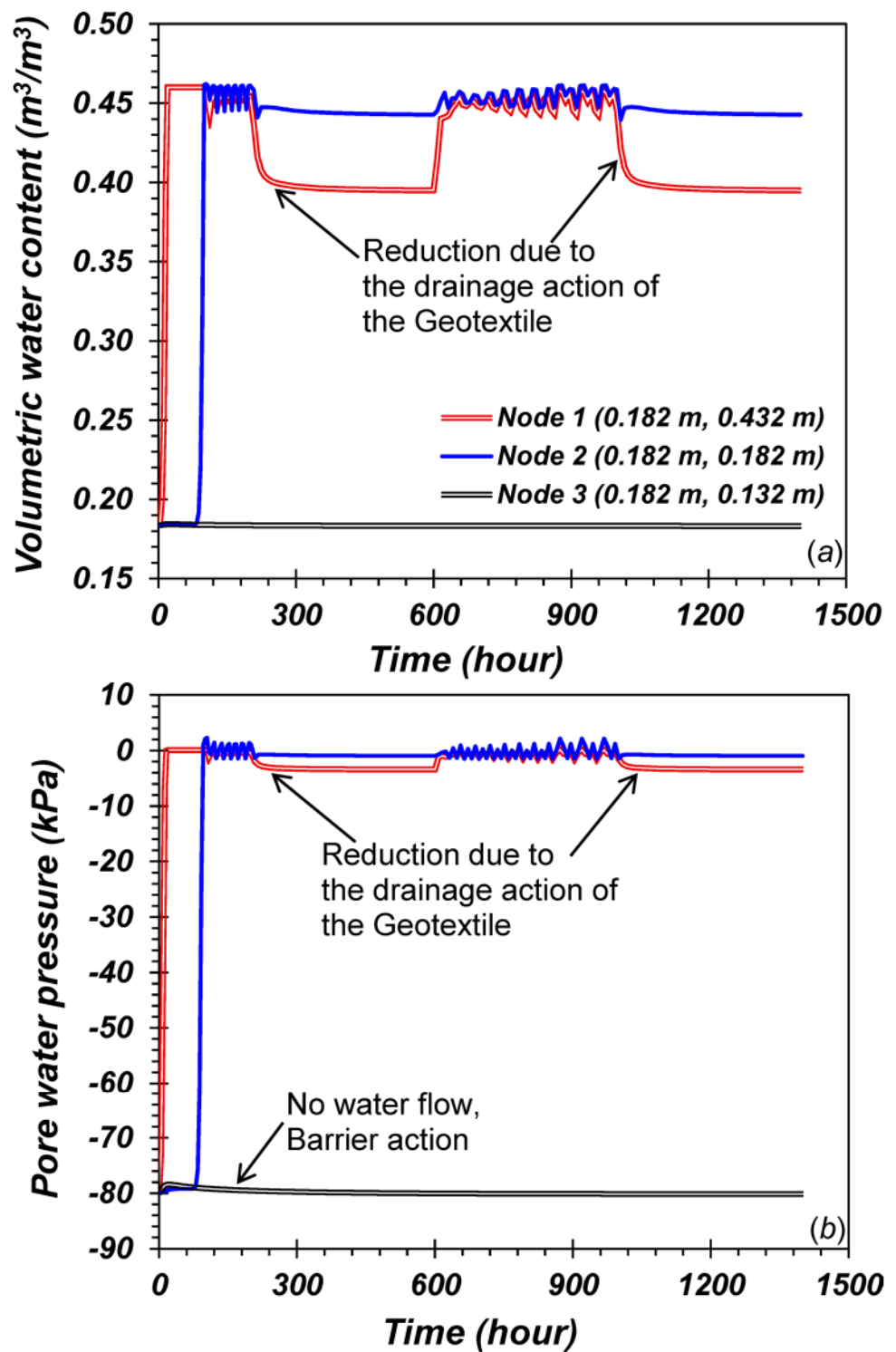
moisture accumulation above the geotextile, attainment of breakthrough suction, drainage through the geotextile, and subsequent pressure drop-repeated over time, as illustrated in Fig. 8a. This behavior is further examined in the following section by considering successive stages of infiltration, including wetting and drying cycles. The migration of the water within the soil column is illustrated by the water flow vectors shown in Fig. 8b. The geotextile clearly functioned as a drainage layer, directing water into the vertical drain. During this process, water preferentially flowed towards the more permeable vertical drain rather than migrating into the underlying low permeable clay soil. The accumulated water within the geotextile subsequently escaped out the system through the toe drain, as indicated by the water flow vectors in Fig. 8b. Similar horizontal drainage behavior of geotextiles within unsaturated soil column has been reported in various laboratory studies by Azevedo and Zornberg [35]; Aristizabal et al. [37].

Drainage Response of the Geotextile Layer during Successive Stages of Infiltration

The horizontal drainage characteristics of the geotextile were further examined under two successive infiltration stages (wetting and drying cycles) to better understand the underlying hydraulic mechanism occurring through the geotextile. In the first stage, continuous infiltration was applied

for 200 h, followed by a 400-hour drying period with zero-infiltration. The second stage involved another 400 h of infiltration, again followed by a 400-hour drying period. During the entire duration, the flow characteristics of the soil were monitored. The variations in moisture content and the pore pressure distribution at the three selected nodes (Node 1, 2 and 3) are shown in Fig. 9. Following the cessation of infiltration at 200 h, both the moisture content and pore water pressure at Nodes 1 and 2 began to decrease, while Node 3 showed no significant change. This observation is attributed to the drainage of water through the geotextile toward the more permeable vertical drain, from which subsequently exited via the toe drain. The dissipation of accumulated water occurred rapidly after infiltration stopped, resulting in porewater pressure falling 0 kPa. After this initial dissipation, only a marginal reduction in the volumetric water content and pore water pressure was observed during the remainder of zero-infiltration stage, as shown in Fig. 9b. This behavior is attributed to the generation of negative pore water pressure within the soil medium. The numerical study highlighted that the geotextile effectively functioned as a drainage layer only when the soil suction approached 0 kPa approximately equal to the air entry value. Beyond this threshold, under more negative suction conditions, the geotextile was ineffective in expelling water from the unsaturated soil. Notably, the soil suction within the soil column did not return back to its initial value of 80 kPa, even after

Fig. 9 Drainage characteristics of the geotextile at different infiltration periods, showing: (a) volumetric water content, and (b) pore water pressure variation at three time-history points



extended drying periods. The aforementioned outcome is attributed to the capillary barrier effect of the geotextile, which inhibited evaporation and moisture loss.

Effect of Initial Soil Moisture Content and Geotextile Unsaturated Characteristics on Drainage Performance

A parametric study was performed to examine the effect of the initial moisture content on the drainage performance of the geotextile. In the previous analysis, the entire soil column was assumed to have a uniform initial moisture content of 18%. In the current study, the initial moisture content of the clay layer beneath the geotextile was increased to 22%, while the soil above the geotextile retained the original moisture content of 18%. This configuration aimed to simulate the effect of a rising of groundwater table during the rainy season, which can increase the moisture content of the lower soil layers through capillary rise. The objective was to evaluate the geotextile's drainage response under such conditions. A transient seepage analysis was conducted for this scenario, and the variation in water content at the three monitored nodes is shown in the Fig. 10a. The results indicate breakthrough occurred into the underlying clay layer due to the elevated initial water content beneath the geotextile. The increased water content led to higher hydraulic conductivity in the clay, thereby facilitating easier water migration from the geotextile into the underlying soil. Although geotextiles generally exhibit higher hydraulic conductivity compared to clay soil in the saturated condition, the relative difference decreases as the system becomes unsaturated. Under conditions of positive pore water pressure, the geotextile remained highly permeable and acted as a horizontal drainage path, directing the accumulated water

toward the vertical drain. This horizontal flow behavior is illustrated by the water movement vectors in Fig. 10b. The numerical simulation revealed that the geotextile began to function as effective drainage medium only after the suction at soil-geotextile interface reached the breakthrough value. When the suction in the surrounding soil remained below this threshold, geotextile was unable to facilitate drainage. These findings demonstrate that the hydraulic characteristics of the geotextile were effectively simulated in numerical analysis. This approach provides valuable insights into the drainage function of geotextiles in soil systems containing unsaturated marginal soils and can inform the design of drainage solutions in similar geotechnical applications.

Furthermore, it is essential to examine the influence of different types of geotextiles on the hydraulic behavior of the soil-geotextile system. The present study examines six distinct categories of geotextiles. Table 3 presents the parameters pertaining to soil water characteristics, whereas Fig. 11 depicts the hydraulic properties of the six geotextiles. The initial volumetric water content of the soil was set to be 18%. Figure 12 illustrates the variations in volumetric water content observed during successive infiltration stages for each of the six geotextile types. The geotextile layer functioned as a barrier in all instances, thought to varying extents. The occurrence of barrier breakthrough was not seen for GT-2, GT-5 and GT-6, as their breakthrough suction value was found to be relatively low (Fig. 11b). In contrast, the water movement was impeded to some degree by GT-1, GT-3, and GT-4 prior to the emergence of the barrier breakthrough mechanism. The differing drainage responses observed in Fig. 12 can be explained by the variation in unsaturated hydraulic properties of the geotextiles, as detailed in Table 3. In particular, the unsaturated hydraulic conductivity at different suction levels governs whether

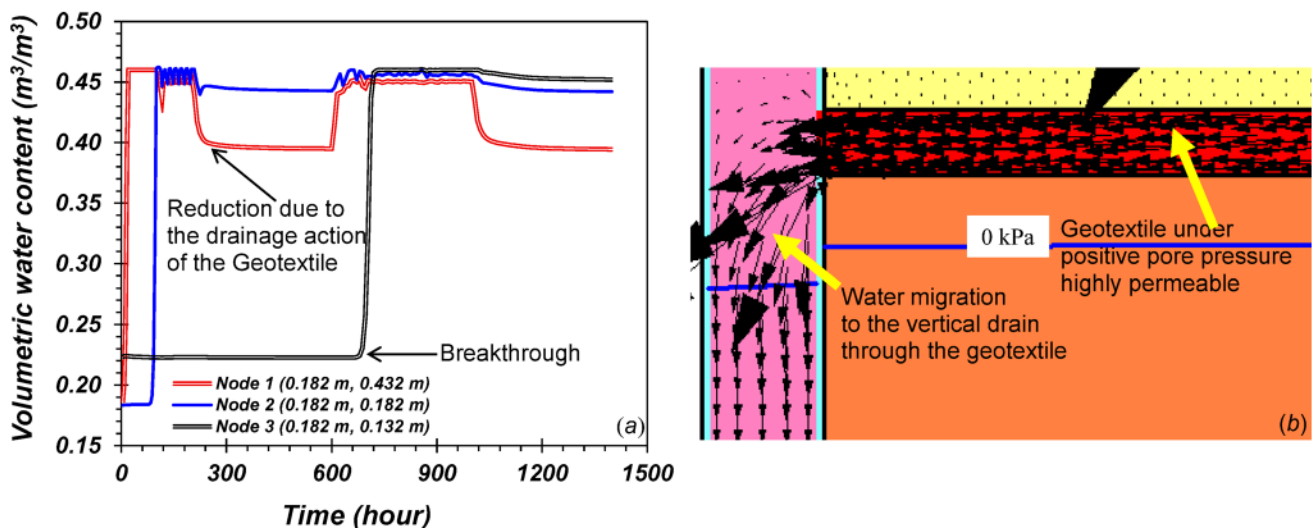
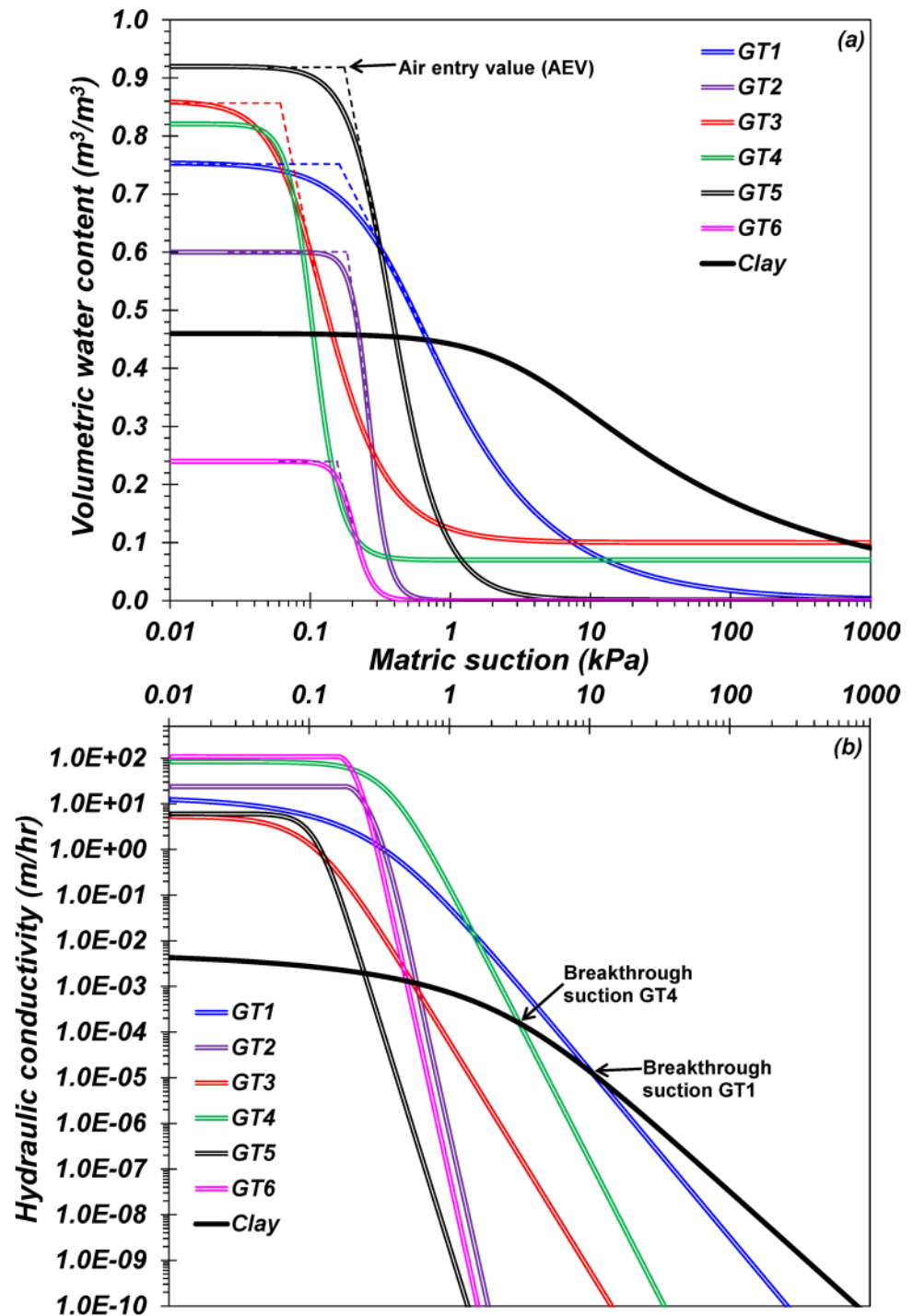


Fig. 10 Barrier breakthrough of the geotextile layer due to an increase in the initial moisture content of the underlying soil layer, showing: (a) onset of barrier breakthrough, and (b) water flow vectors through the geotextile under saturated conditions after breakthrough

Table 3 Hydraulic parameters geotextiles for sensitivity analysis

Geotextile	α (1/kPa)	n	Saturated water content θ_s	Residual water content θ_r	Saturated hydraulic conductivity (m/h)	References
GT-1	2.577	1.68	0.754	0	12.384	Stormont and Morris [34]
GT-2	3.891	6.9	0.6	0	23.76	Stormont and Morris [34]
GT-3	11.10	2.5	0.86	0.1	5.22	Iryo and Rowe [16]
GT-4	8.46	4.95	0.821	0.07	82.8	Zornberg et al. [22]
GT-5	3.0	3.0	0.92	0	6.012	Iryo and Rowe [17]
GT-6	5.0	7	0.24	0	108	Thuvo et al. [14]

Fig. 11 Hydraulic properties of different geotextiles (GT) used in the present study: (a) water retention curves, and (b) hydraulic conductivity curves

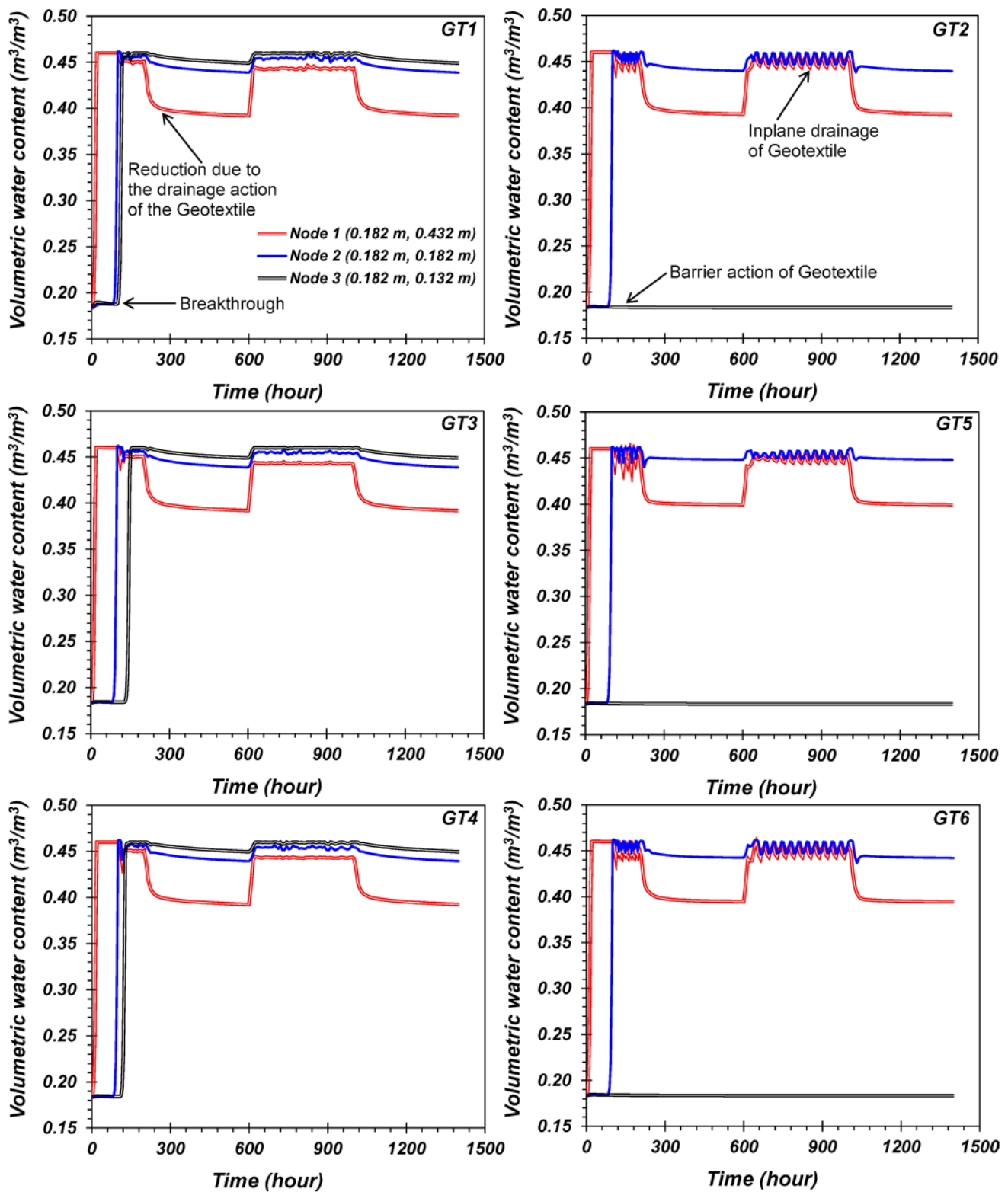


Fig. 12 Effect of different geotextiles on the volumetric water content of the model soil columns

geotextile acts as a barrier or allows drainage. Geotextiles GT2, GT5, and GT6 exhibit relatively lower hydraulic conductivity at larger suction values (Fig. 11b), which promotes the accumulation of water above the geotextile and results in a temporary barrier effect. Conversely, GT1, GT3, and GT4 show higher hydraulic conductivity under similar suction conditions, and relatively higher breakthrough suction value, allowing water to migrate through the geotextile without significant retention or buildup. This distinction highlights the role of unsaturated conductivity behavior in controlling the transition between barrier-like and freely draining performance in geotextile-reinforced systems. When the suction at the soil-geotextile interface exceeds the breakthrough suction, and the hydraulic conductivity of the geotextile is lower than the soil hydraulic conductivity at the interface, the geotextile acts as a capillary barrier, restricting water flow. Conversely, when the suction at the interface is equal to or less than the breakthrough suction and the hydraulic conductivity of the geotextile exceeds the soil hydraulic conductivity, the geotextile functions as a permeable medium, facilitating drainage. This characteristic has been found beneficial in promoting subsurface drainage of road embankments, soil wall, and slopes, and highlights the need to consider climatic conditions when evaluating drainage performance of geotextile in unsaturated soil (Albino et al. [39]). Based on the numerical results, it can be concluded that the effectiveness of geotextile drainage is strongly influenced by its air-entry suction and the breakthrough suction value. This observation aligns with current research focused on wicking geotextiles, which exhibit higher air-entry suction in the lateral (in-plane) direction than in the cross-plane direction resulting greater breakthrough suction. Such properties enable them to function effectively as horizontal drainage media under unsaturated conditions [26, 27]. However, due to the scope and brevity of this study, numerical simulation involving wicking geotextiles are not discussed here.

Discussion

Overall, the numerical results highlight the dual behavior of geotextiles in unsaturated soils, functioning initially as capillary barriers and subsequently as drainage layers once breakthrough suction is attained. This transition is governed by the interplay between soil suction, water entry value of the geotextile, and the moisture conditions surrounding the interface. Water accumulation above the geotextile during infiltration delays downward migration until the local suction overcomes the breakthrough suction threshold—consistent with the capillary barrier concept described by previous researchers [14, 16–22, 34, 35]. Our simulations

also demonstrate that the presence of higher initial moisture content in the underlying soil accelerates breakthrough by reducing the suction gradient, a trend that aligns with laboratory findings by Bouazza et al. [19], who observed enhanced drainage under near-saturated conditions. Moreover, the lateral drainage response of the geotextile under positive pore pressure conditions captures the behavior of geotextiles studied by Aristizábal et al. [37], particularly in terms of preferential flow toward more permeable zones such as vertical drains. The results from the present study underscore the transient nature of geotextile drainage behavior during successive wetting and drying cycles. This observation aligns with the findings of Nunes et al. [29], who conducted numerical investigation of geocomposite-reinforced soil (GRS) walls constructed with marginal soils under varying climatic conditions. Their study revealed that soil suction within the reinforced zone fluctuates over time—on a daily basis near the surface and on a monthly basis in deeper layers—highlighting the dynamic hydrological response of geocomposite systems. Notably, Nunes et al. [29] observed the formation of capillary breaks at unsaturated soil-geocomposite interfaces, especially under arid conditions. These capillary barriers were beneficial in restricting the downward movement of the wetting front, similar to the capillary barrier effect observed in the current study. Moreover, their findings indicated that the lateral drainage function of geocomposite becomes ineffective under unsaturated conditions and is only activated once the backfill soil approaches saturation. This behavior is consistent with this study, where geotextile drainage effectiveness significantly increased only when the soil suction approached the breakthrough suction. These comparisons affirm that the modeled behavior of nonwoven geotextiles under transient unsaturated flow conditions is in agreement with experimental evidence and extends current understanding by quantifying the temporal dynamics of suction redistribution, drainage onset, and water retention beneath the geotextile.

It is important to note that the air-entry suction value of geotextiles, a critical parameter influencing drainage performance in unsaturated conditions, is not typically provided in commercial product specifications. Most manufacturers report only the saturated hydraulic conductivity of the material. However, recent research by Kawamura et al. [40] provides a practical approach for estimating unsaturated hydraulic properties, including the air-entry suction, using available saturated permeability data. In their study, a series of water retention tests were conducted on five nonwoven geotextiles with varying materials and manufacturing methods. The resulting water retention curves, which were S-shaped and similar to those of soils, were effectively modeled using the van Genuchten [32] equation. Their findings

demonstrate that the water retention behavior and unsaturated hydraulic conductivity of nonwoven geotextiles can be reasonably estimated from the saturated hydraulic conductivity values. This approach offers a practical and accessible method for geotechnical designers to characterize the unsaturated behavior of geotextiles when direct laboratory measurements are unavailable.

Conclusions

This study employs numerical simulation techniques to analyze the infiltration characteristics of unsaturated soil. The simulation was calibrated using results from laboratory experiments to ensure accuracy and reliability. The research investigates the dual functionality of geotextiles as both a barrier and a drainage layer within unsaturated soil medium, using transient seepage analysis. The drainage characteristics of geotextile were examined in both lateral and vertical directions, considering the presence and absence of vertical drainage path. Additionally, the study evaluates the lateral drainage performance of geotextiles, under varying initial moisture conditions in the underlying soil and during successive infiltration phases, including wetting and drying cycles. To further explore the role of material properties, seven different types of geotextiles were simulated. This parametric investigation highlights the critical influence of air entry suction on the effectiveness of geotextiles as horizontal drainage media in unsaturated conditions. Based on the analysis, the following key findings are presented:

- The infiltration simulation results for the unsaturated soil column demonstrate that the geotextile effectively functions as a capillary barrier. This barrier prevents the downward movement of the saturated wetting front, restricting water from reaching the underlying unsaturated soil until a breakthrough suction is achieved. As a result, water accumulates in the soil above the geotextile layer, with the capillary barrier effect persisting until the suction at the soil-geotextile interface reaches the breakthrough threshold.
- The study reveals that the time required for capillary barrier breakthrough is significantly influenced by the initial moisture content of the surrounding soil and the hydraulic properties of the geotextile. An increase in the initial water content of the adjacent soil reduces the suction gradient across the geotextile, thereby shortening the breakthrough time.
- Successive stages of infiltration including wetting and drying cycles, show that after the initial dissipation of accumulated water, there is an insignificant reduction in the volumetric water content and pore water pressure

during the zero-infiltration (drying) stage. This behavior is attributed to the generation of negative pore water pressure in the soil medium which limits further drainage.

- The soil suction within the geotextile-reinforced soil column did not return to its initial value of 80 kPa, even after successive drying cycles. This outcome is attributed to the capillary effect of the geotextile, which inhibited water evaporation from the system. As a result, the suction profiles obtained over time consistently showed values below 10 kPa.
- Seven distinct types of geotextiles were evaluated through numerical simulations to assess the influence of the air-entry suction on the lateral drainage performance in unsaturated soils. The results indicate that the geotextile's drainage efficiency is strongly governed by its air-entry and breakthrough suction value. A higher air-entry suction value significantly reduces the time required to achieve capillary breakthrough, thereby enhancing the geotextile's effectiveness as a horizontal drainage medium.
- The geotextile functioned as a lateral drainage layer, facilitating the movement of water toward the vertical drain. During this process, water followed the path of least resistance, preferentially flowing into the more permeable vertical drain rather than infiltrating the underlying low permeable clay soil. This mechanism helped maintain higher suction levels in the subsurface soil over an extended period.

While this study provides important insights into the drainage performance of geotextiles in unsaturated soils, it does not account for potential long-term clogging of the geotextile layer due to particle intrusion. Clogging can significantly reduce the hydraulic conductivity of geotextiles over time, thereby diminishing their drainage efficiency. Additionally, the current numerical model does not incorporate coupled heat and moisture transport, which limits the ability to accurately simulate evaporation and its influence on suction recovery during drying cycles. Future studies should integrate clogging behavior and evaporation dynamics to more realistically assess geotextile performance under field-relevant, long-term unsaturated conditions.

Author Contributions AJ: numerical analyses, interpretation of results, and writing-original draft. AD: writing-review and editing.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability All the data presented in this study appears in the figures of the manuscript.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest associated with this research.

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