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A Physical Model for Sloping Capillary Barriers

ABSTRACT: A physical capillary barrier model has been developed to study the mechanism and the effectiveness of a capillary barrier for slope stabilization purposes. A sloping two-layer capillary barrier model consisting of a relatively fine soil layer over a relatively coarse soil layer was constructed inside a specially designed apparatus. Simulated rainfalls of different intensities and durations representative of tropical climatic conditions were applied through a rainfall simulator. Various instruments consisting of tensiometers for pore-water pressure measurement, time domain reflectometry (TDR) for water content measurement, magnetic flow meter and electronic weight balances for water balance measurements were used in the experiment. The results obtained from various types of instrumentation were in good agreement. The experimental results show that the performance of the capillary barrier under the influence of a high precipitation rate is primarily governed by the storage capacity of the relatively fine soil of the capillary barrier.

KEYWORDS: capillary barrier, physical model, unsaturated water flow, pore-water pressure, volumetric water content, water balance, soil-water characteristic curve, matric suction.

A capillary barrier is a cover system commonly consisting of a relatively fine soil layer placed over a relatively coarse soil layer. Capillary barriers are generally unsaturated and function in response to changes in negative pore-water pressures. Capillary barriers have been studied and used widely in geo-environmental engineering as a soil cover for landfill and mines wastes to reduce water infiltration and to protect waste materials in arid to semi-arid climatic conditions (Ross 1990; Stormont 1996, 1997; Morris and Stormont 1998, 1999; Khire et al. 1997, 1999, 2000). Soil covers, capillary barriers, are constructed horizontally or at relatively flat slopes, and the infiltrated water is generally removed from the system through evaporation and evapotranspiration.

The infiltrated water can also be removed as lateral diversion when the capillary barrier is sloped. Water flows along the relatively fine layer under unsaturated conditions. The system is effective if the amount of infiltrated water is less than the combined effect of evaporation, transpiration, and lateral diversion, avoiding the occurrence of breakthrough (i.e., percolation into the underlying layer) (Stormont 1996).

Capillary barriers have potential for use as a slope stabilization technique by limiting infiltration into soil slopes during rainfall. However, the application of capillary barriers

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for slope stabilization against rainfall-induced landslides has never been fully investigated and hence is the focus of this study. When the soil in a slope is in an unsaturated condition, the infiltration of rainwater into the slope can cause an increase in the pore-water pressures. An increase in pore-water pressure decreases the shear strength of the soil, making the slope more susceptible to failure (Brand 1981). Construction of a capillary barrier as a slope cover can potentially reduce the infiltration of water into a slope during rainfall and maintain the slope in a "safe" condition.

When capillary barriers are used for slope stabilization purposes, the geometry must follow the surface of the slope and the slope can be rather steep. In addition, the capillary barrier could be subjected to a tropical climate with high rainfall intensities. In the current study, the flow within capillary barriers is studied on a relatively steep slope under high rainfall intensities.

In this paper, a laboratory model of a sloping capillary barrier is described, and experimental results are presented. The measurement results from various types of instrumentation are presented and discussed.

Description of the Sloping Capillary Barrier Model

The experimental study was conducted using an apparatus that was specially designed for this study. The general arrangement of the apparatus, along with a photo, are presented in Figs. 1 and 2, respectively.

The main components of the apparatus are: an infiltration box, a rainfall simulator, a water circulation system, and numerous measuring devices. The infiltration box is supported by a steel table, which also functions as an enclosure for a water sump tank (which provides the water used in the water circulation system) and a water pump. The capillary barrier model was constructed inside an infiltration box and was subjected to simulated rainfalls with varying intensities and durations. The rainfalls were applied through a rainfall simulator located on top of the infiltration box. Various types of instrumentation were installed along the infiltration box to monitor changes in pore-water pressure and water content in the capillary barrier model.

Prior to the design of the apparatus, numerical simulations were conducted to obtain the optimum dimensions, the most appropriate location for the instrumentations, and the appropriate soils for the capillary barrier model. These simulations were divided into two stages. The first stage of the study was related to obtaining optimum dimensions for the capillary barrier model. The laboratory model should have a sufficient length to minimize boundary effects to water flow within the capillary barrier model. The second stage of the study was to investigate the range of soil properties that were most suitable for the laboratory capillary barrier model studies in order to obtain meaningful experimental data (i.e., pore-water pressure, volumetric water content, runoff, lateral diversion, and breakthrough). Various soils with different soil-water characteristic curves (SWCC) and permeability functions were studied. Based on the results of the numerical study, a range of appropriate hydraulic properties for the materials was selected for use in the laboratory capillary barrier model. A detailed explanation of the numerical simulations associated with the design of the laboratory capillary barrier model is given in Tami et al. (2002).

Infiltration Box

The infiltration box has dimensions of 2.45 m in length, 2 m in height, and 0.4 m in width. The frame of the infiltration box was made of stainless steel, and the sidewalls were made of acrylic sheets of 15-mm thickness. The acrylic sheets were used for the box sidewalls in order to enable visual observation of the wetting front in the capillary barrier model.

At the base of the infiltration box, a soil-discharge outlet was provided as a way to remove the soil after one series of tests was completed. When impervious boundary conditions were used at the bottom of the capillary model, a polyvinyl chloride (PVC) plate was used as an impervious boundary. The entire structure was conservatively designed and constructed with deflection limit considerations in order to avoid leakages. Thus, watertightness was a high priority in the design.

A number of holes were drilled along both sidewalls for installing the connectors of the instruments. An instrument was installed on one sidewall of the infiltration box. Since the slope of a capillary barrier was considered as one of the controlling parameters, capillary barrier models would be studied at two different slope angles. One of the sidewalls of the infiltration box was prepared for a capillary barrier system with a 20° slope angle, and the other one was prepared for a capillary barrier system with a 30° slope angle. Two different arrangements of the instrumentation were designed in order to obtain accurate locations of every monitoring device for all series of experiments. These two differing arrangements were prepared in order to obtain accurate locations for every monitoring device for all series of experiments. Some additional holes along the sidewalls at the two ends of the infiltration box were drilled for drainage and run off, or lateral drainage, or breakthrough collection purposes.

Rainfall Simulator

A rainfall simulator, used to create a simulated rainfall, was placed on the top of the infiltration box. It was designed to produce rainfall intensities typical of tropical climate conditions. In order to obtain a uniform rainfall for the entire range of intensities, two types of rainfall simulators were designed. The first one was mainly for high rainfall intensities (i.e., higher than 60 mm/h), while the other was for rainfall intensities lower than 60 mm/h.

The first type of rainfall simulator used (i.e., Type A), consisted of a sprayer arm, sprayer units, and a drip screen. The rainfall was generated using five sprayer units constructed from 12.5-mm-diameter PVC pipes. The water was spread laterally from the sprayers through 1-mm-diameter holes distributed on 10-mm spacings. In order to create a uniform rainfall, a 6-mm-thick drip screen was used. The drip screen was placed 50 mm below the sprayer units. Similarly, water was distributed using 1-mm-diameter holes, spread at 15-mm spacings. The rainfall intensity was controlled using flow regulators. The arrangement of the sprayer units and drip screen above the infiltration box is shown in Fig. 3.

In contrast to the first type of rainfall simulator, a second type of rainfall simulator (i.e., Type B) was developed to produce a water mist. The water was spread out from two sides of the infiltration box and was blown using compressed air. Different air pressures were used for different rainfall intensities to obtain an acceptable uniformity for the simulated rainfall. The rainfall intensity was controlled using the nozzles' openings. Twenty-four nozzles with different opening sizes were fabricated to produce various rainfall intensities, ranging from 0.5 to 59.5 mm/h. Details of the spraying system for rainfall simulator Type B are shown in Fig. 4.

The applied rainfall intensities were measured using a magnetic flowmeter[5], and for water balance measurements three electronic weight balances[6] were used to measure the amount of runoff, lateral diversion, and breakthrough. The flowmeter was equipped with a signal converter[7], and the weight balances came with digital indicators[8] that allowed readings to be taken manually or automatically with the data acquisition system.

Water Circulation System

The water flow direction from the water circulation system is presented as a dashed line in Fig. 1. The distilled water used to create the simulated rainfall was supplied from a 350-L sump tank located beneath the infiltration box. Using a constant-rate pump, water was pumped to the sprayer units. A submersible centrifuge pump[9] with a flow capacity of 10 L/min and a 6-m head loss was considered to be adequate to supply the water to the sprayer unit. Since the amount of water supply needed to create the desired range of rainfall intensity is less than the capacity of the pump, overflow drainage back to the sump tank was provided in the water circulation system.

After the measurement of water discharge from the drainage outlets (using three electronic weight balances) on the infiltration box (i.e., runoff, lateral diversion, or breakthrough), the discharge was directed back to the sump tank. In order to remove the suspended particles from the circulated water, the sump tank was divided into four sections. The particles were sedimented in the first section and consecutively in the other sections as water flowed towards the last section of the sump tank.

Measuring Devices & Data Acquisition System

A number of instruments, consisting of tensiometers[10] and time domain reflectometry[11] (TDR) wave-guides were installed along the sidewall of the infiltration box. The tensiometers (small tip type with a flexible coaxial tubing) were used to measure the pore-water pressure changes inside the capillary barrier model, while the TDR wave-guides were used to measure changes in the volumetric water content.

A schematic drawing of the small tip tensiometer is shown in Fig. 5. The tensiometer consists of four main components, namely, a high-air entry ceramic tip, shaft, pressure transducer, and a jet-fill cup (reservoir). The high-air entry ceramic tip of the tensiometer

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[5] Magflo® MAG 1100, manufactured by Danfoss Instrumentation, USA.

[6] Load cell model PS-12K, manufactured by UWE, Taiwan.

[7] MAG 5000, manufactured by Danfoss Instrumentation, USA.

[8] Model KL-D1000, manufactured by Kobota, Japan.

[9] Model VIGILA 100(M), manufactured by ESPN, Spain.

[10] Model 2100F, manufactured by Soilmoisture Equipment Cooperation, Santa Barbara, CA.

[11] Trase BE 6050X2 with 4-MB memory card 6058C10 and buriable waveguides 6005L2, Soilmoisture Equipment Cooperation, Santa Barbara, CA.

has an air-entry value of 100 kPa. The pressure transducer[12] with a capability to measure negative and positive pressures (i.e., –100 to 75 kPa) was attached to each of the tensiometers for automatic recording. It was observed that the tensiometer-pressure transducer system used in this study could give almost instantaneous response (i.e., less than 1 min) to the changes in pore-water pressure in the fine sand. A connector was installed on each hole to provide watertight access for the coaxial tube of tensiometers installed along the walls of the infiltration box. The tensiometer connector was made of brass and consisted of two parts: one part was threaded into the box wall (called socket) and the other part was used to lock the coaxial tube and to provide the water tightness. Two O-rings were used for each tensiometer connector. The detail drawings and dimensions of the tensiometer connector, along with a photo, are presented in Fig. 6.

The TDR system consists of a step-pulse generator (i.e., Trase BE), coaxial cable, and wave-guides. Three-rod standard wave-guides (6005L2) were used. The outside dimension of the wave-guides was 50.8 mm, and the dimension of the rod was 3 mm in diameter and 200 mm in length. The three-rod probe was selected because it is most commonly used in practice. Similar connectors to those used for the tensiometers were also used for the TDR wave-guide connectors. Some changes in dimension were made to account for the difference in the diameter of the coaxial cable of the wave-guide and the diameter of the tensiometer tube. Figure 7 shows the photo of the TDR wave-guide and its connector.

A total of 25 tensiometers and 15 TDR wave-guides were installed along five sections with five tensiometers and three TDR wave-guides located in each section. The arrangement of the tensiometers and the TDR wave-guides along the capillary barrier models is shown in Fig. 8.

All the instruments were monitored continuously using four data loggers[13] connected to a computer. The interval of monitoring was 1 min, and the measured data were stored directly in the computer hard disk.

Soil Properties

Capillary barriers can be constructed in a simple form, consisting of a two-layer system of relatively fine and relatively coarse soil layers, to a multiple-layer design incorporating synthetic materials (e.g., geomembranes) (Stormont, 1996). However, it is important to first study the physical processes associated with storage of water (i.e., drying or wetting paths of soil-water characteristic curves used), the transmission of water, and the release of water to the atmosphere for a two-layer soil system. The same mechanism should also be applicable to other materials that could be used as the surface cover.

A two-layer system of the laboratory capillary barrier model was used in this study. Three different soils were used to construct three different combinations of the capillary barrier model, namely, silty sand over fine sand, silty sand over gravelly sand, and fine sand over gravelly sand. The fine sand had a coefficient of uniformity, C_u, of 2.1 and a coefficient of curvature, C_c, of 0.89. The gravelly sand was uniform in distribution and

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[12] Kristal K-line current pressure transducer, Type RAN25A2BV02 12, manufactured by Kisler®, Switzerland.

[13] DataShutlle^{TM} model DS-16-8-GP, manufactured by Iotech Inc., Cleveland, OH.

had a grain size of 4 to 20 mm with 50.1 % passing sieve No. 4 (ASTM). Both the gravelly sand and fine sand were categorized as poorly graded sand (SP according to USCS). The silty sand was a local residual soil and had a well-graded distribution of particle sizes (C_u = 1120 and C_c = 1.58) and was categorized as SM soils (USCS). The saturated coefficients of permeability, k_s, for the silty sand (at a dry density of 1.47 Mg/m^3), fine sand (at a dry density of 1.56 Mg/m^3), and gravelly sand (at a dry density of 1.62 Mg/m^3) were 2.2×10^{-6}, 2.7×10^{-4} and 7.6×10^{-2} m/s, respectively. The drying path of the soil-water characteristic curve was determined using the pressure plate test (ASTM D 2325–68), while the wetting path was measured using a soil column test (Fredlund and Rahardjo 1993; Lambe 1951).

The soil-water characteristic curves were fitted using the Fredlund and Xing (1994) equation, and the permeability functions were calculated using a statistical permeability function model (Childs and Collis George 1950), which uses the relationship between water content and matric suction.

Figure 9 presents the grain-size distribution plot of materials for the capillary barrier model, while the soil-water characteristic curves are given in Fig. 10 (i.e., W and D indicate wetting and drying paths, respectively).

Setting up of the Experiment

The setup of the instrumentation and the measuring devices plays a crucial role in obtaining good quality data. The subsequent sections describe the setting up of the experiment.

Calibration of Measuring Devices

An accurate monitoring system is important to ensure the success of the experimental study. All instruments used in the study were calibrated before being installed. Calibrations of the measuring devices were performed using the same connection arrangement with the data acquisition system as later used in the experiments.

Simulated rainfall from the rainfall simulator Type B was calibrated using ten measuring glasses distributed inside the infiltration box. Various intensities were applied for 1-h simulation, and the amount of rainfall from each measuring glass was measured. In order to obtain the most uniform distribution, an air pressure was applied to create a uniform water mist for various rainfall intensities. The applied air pressures varied from 200 to 350 kPa for rainfall intensities of 10 to 40 mm/h, respectively. The uniformity in the simulated rainfall was assessed using the Christiansen Uniformity Coefficient[*] described by Hall et al. (1989). The measured uniformity coefficient varied from 60.9 to 76.2 with a mean of 69.5 for rainfall intensities ranging from 10 to 40 mm/h.

The consistency of water balance measurements from the magnetic flowmeter and the electronic weight balance was also checked. The input flow measured by the flowmeter was compared with the output flow measured by the weight balance.

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[*] Christiansen Uniformity Coefficient $= 100 \text{ x} \left(1 - \frac{\sum |X_i - \overline{X}|}{\sum X_i}\right)$

$\overline{X}$ is the arithmetic mean of n equally weighted observations of depth X_i

Placement of Soil Inside the Infiltration Box

The materials for the capillary model were placed layer-by-layer with an approximate thickness of 20 to 30 mm parallel to the slope surface in order to maintain the homogeneity of the model. Each sub-layer was compacted after placement using a vibrator plate of 200 by 200 mm.

The compaction energy from the vibrator plate compactor was calibrated to achieve the desired density. Two plates with different sizes (i.e., 150 by 150 and 200 by 200 mm) were used to compact the soil in the infiltration box. These two sizes were selected to provide different energies for compaction.

In order to control the density of the soil, the weight of soil to be placed was initially measured. All soils had equal water content and were oven-dried for 24 h prior to placement in the infiltration box. Subsequently, the soils were compacted with a similar energy input, and the following densities (1.47, 1.56, and 1.62 Mg/m^3 for the silty sand, fine sand, and gravelly sand, respectively) were achieved.

Installation of the Measuring Devices

Small tip tensiometers and TDR wave-guides were installed during the placement of the soils, as these sensors must be in good contact with the soil and must be buried in the infiltration box.

Applying Boundary Conditions

The initial boundary conditions were established after placement and compaction of the soil. The laboratory capillary barrier model had four types of boundary conditions; namely, impermeable boundaries (along the bottom and on both sides of the model); an infiltration boundary along the surface of the model to simulate infiltration; and discharge boundaries at the toe end of the slope to simulate the outflow water from the capillary barrier model. The infiltration (or flux) boundary was generated using a simulated rainfall, and its intensities and durations were controlled using a magnetic flow meter. The discharge boundaries for runoff or lateral diversion collections were implemented using drainage outlets on the wall of the infiltration box. The amount of water flow was measured continuously using a water container placed on the electronic weight balance. Evaporation was assumed negligible during the test since the capillary barrier model was constructed in an enclosed box where the ambient environment had a high relative humidity (i.e., 90 %).

Testing Program

A series of experiments was conducted to study the operating mechanism and behavior (e.g., pore-water pressure changes, water content changes, and water balance) of a two-layer system of capillary barrier model under different initial conditions and different precipitation rates. The series involved a capillary barrier model with a fine sand and a gravelly sand layer, each 200 mm in thickness and placed at a 30^0 slope angle.

The experimental series consisted of five stages with different precipitation rates. Prior to the experiment, the model was left exposed to ambient conditions for more than

100 h after the previous series of experiments had ended. This was done to minimize the effect from previous tests in the series. Subsequently, a precipitation rate of 1.80 mm/h was applied for more than 50 h to obtain initial steady-state conditions where there were no changes in pore-water pressure and volumetric water content observed in the capillary barrier model. Therefore, the start of the experiment can be considered to be essentially a steady-state condition.

For each stage, a 24-h simulation was conducted, starting with wetting (i.e., application of simulated rainfall under a given intensity and duration) and subsequently followed by drying where rainfall was not applied. Two subsequent stages (except for Stage I) were considered to have similar initial conditions since the observed pore-water pressure and volumetric water content at the beginning of each stage were the same. It was observed that the magnitudes of pore-water pressure and volumetric water content along the capillary barrier model returned to the initial values 19 h after the simulated rainfall ended. During Stages I to IV, the simulated rainfall was applied for 5 h with intensities of 8.05, 8.07, 19.21, and 8.02 mm/h, respectively. During the fifth stage, the intensity of the simulated rainfall was 7.93 mm/h, and the simulation was conducted for 12 h. Table 1 presents the stages and the controlling parameters of the experiments. These stages are also shown at the top of Figs. 12 and 13 (W and D indicate wetting and drying, respectively).

In the first and the second stages, the behavior of the capillary barrier under the same intensity and duration of the rainfall, but with different initial conditions, was studied. In the second and the third stages, the behavior of the capillary barrier model under different rainfall intensities but the same duration of the rainfall and the same initial conditions was evaluated. Breakthrough was expected to occur during Stage III since the rainfall intensities applied were considered to be high. From the simulations conducted during Stages II and IV (i.e., where initial conditions and rainfall intensities were similar), the effect of breakthrough on the behavior of the capillary barrier model was studied. Stage II was conducted before breakthrough, and Stage IV was conducted after breakthrough. The total amount of simulated rainfall applied in Stages III and V were similar; however, the intensity and the duration were different. The different behavior of the capillary barrier under these two different conditions can be observed. The behavior of the capillary barrier model under different durations of the simulated rainfall but the same initial conditions and rainfall intensities can be evaluated from Stage IV and Stage V. In addition, the behavior of the capillary barrier model during the restoration process (i.e., releasing water with no rainfall applied) under different amounts of storage can be observed by comparing Stage III and Stage IV. The summary of the testing program and the controlling parameters associated with moisture flux are shown in Table 2.

Results and Discussion

The observations and conclusions in this paper are based on: time histories of fluxes, pressure head, and volumetric water content; water balance; storage changes and the scanning curves and bounding curves of the soil-water characteristic curves.

Time Histories of Moisture Flux (q),Pore-Water Pressure Head (h) and Volumetric Water Content (θ_w)

Figure 11 shows the fluxes associated with input flow, q_P, (i.e., precipitation) and output flow (i.e., runoff, q_R; lateral diversion, q_L; and breakthrough, q_B). There was no runoff observed during the experiment, therefore q_R is not shown on the figure. Based on Fig. 11, it was observed that in the first stage the rate of water flow from lateral diversion increased gradually from the beginning of the simulation. However, in the second stage, the rate of lateral diversion increased slowly after 30 min into the experiment and subsequently increased rapidly at 120 min into the experiment. In these two stages, the maximum flux related to lateral diversion appeared to be nearly the same (7.50 mL/h) and neither runoff nor breakthrough was observed. The lateral diversion rate appeared to increase rapidly in the third stage and reached a maximum value of 9.33 mL/h before breakthrough occurred. The lateral diversion rate remained the same until the rainfall simulation stopped. Similar to the first two stages, there was no runoff observed during the third stage. The increase in the lateral diversion rate in the fourth and fifth stages appeared to be similar in pattern with that in the second stage and reached a maximum value at about 7.20 and 7.50 mL/h in the fourth and fifth stages, respectively. However, in the last two stages, the rate of lateral diversion did not decrease significantly after the rainfall application ended as happened in the first and second stages. The lateral diversion rate remained the same for about 65 min before gradually decreasing. Based on this observation, the behavior of the capillary barrier appears to change after the occurrence of breakthrough.

Figure 12 shows the variation of pressure head and volumetric water content at three different cross-sections along the fine sand (i.e., relatively fine) layer during the experiment. Section M was located at the middle part of the model, while Section B and Section T were located in the lower and upper parts of the model, respectively (see Fig. 8).

Variations in the pressure head at three different cross sections during the experiment appear to be similar in shape. Before precipitation was applied during each stage, the pressure heads on the relatively fine layer, as recorded by the tensiometers along the top row (or nearest to the surface) (i.e., T-24, T-34, and T-44) were lower than those recorded by tensiometers in the second row (i.e., T-23, T-33, and T-43). However, the values increased rapidly after 15 to 25 min of precipitation. Once the pressure heads in the second row (i.e., T-23, T-33, and T-43) increased to higher values than those in the top row (i.e., T-24, T-34, and T-44), the readings were always higher than those in the top row for the remainder of the experiment.

The pressure heads increased to the same value in the first and second stages; however, the readings were higher during the third stage. This trend occurred because the precipitation rate was the highest during the third stage. After breakthrough occurred (i.e., Stage IV and Stage V), the pressure heads increased to the same value as occurred in the stages before breakthrough (i.e., Stage I and Stage II). Hence, the changes in pressure head in the capillary barrier model were not affected by the occurrence of breakthrough. The maximum pressure head remained the same as that observed in the simulation conducted before and after the occurrence of breakthrough. It was noted that the shape of pressure head changes was similar to the shape of the $[q_P - (q_L + q_B + q_R)]$ curve (i.e., total flux in – total flux out). Similar to the changes in pressure head, changes in volumetric water content in the relatively fine layer follow the same trend as shown in Fig. 12.

Unlike the changes in pressure head and volumetric water content in the relatively fine layer, there was no significant change either in the pressure head or the volumetric water content of the relatively coarse layer (i.e., gravelly sand) during the experiment. This phenomenon was observed for all cross sections (i.e., TDR-1 to TDR-5). This indicates that breakthrough produced in the third stage of simulation occurred in the lower part of the model (i.e., lower than location of TDR-1).

Water Balance

The four main components of water balance are: cumulative precipitation, P (i.e., total water added to the system) and cumulative lateral diversion, L; cumulative breakthrough, B; and cumulative runoff, R (i.e., total water draining from the system) as illustrated in FIG.1.

The equilibrium equation for the water balance components can be expressed as follows:

$$P = (L + B + R) + \Delta S \tag{1}$$

where: ΔS is water storage changes in the capillary barrier system.

The measured components of water balance during the experiment are presented in Fig. 13*a*. Precipitation and water storage changes (ΔS) are positive, while lateral diversion and breakthrough are negative. The water storage changes, ΔS, were obtained by subtracting the amount of precipitation by the amount of lateral diversion, breakthrough, and runoff (Eq 1). For instant, at an elapsed time of 53 h (i.e., end of Stage III-W), the measured data for P, L, B, and R were 139.93 L, 129.29 L, 13.30 L, and 0 L, respectively. The water storage changes, ΔS, could then be calculated as 17.34 L. In this case, ΔS was calculated with reference to the initial conditions during the first stage of the experiment (i.e., end of steady-state infiltration).

Initially, the infiltrated water from precipitation was reflected as an increase in ΔS. Once lateral diversion was produced, the rate of increase in water storage, ΔS, decreased. The largest change in water storage recorded during Stages I, II, III, IV, and V were 8.31, 8.41, 17.34, 14.95, and 16.76 L, respectively. These values were reached before the precipitation in each stage ended and the maximum value (i.e., 17.34 L) occurred in Stage III when breakthrough commenced. From the comparison of ΔS before and after breakthrough (i.e., Stages II and IV), it was found that after breakthrough the largest change in water storage increased (i.e., 8.41 L during Stage II and 14.95 L during Stage IV). This suggests that the storage behavior of the capillary barrier model is affected by breakthrough. The largest change in water storage during the fifth stage was higher than that of the fourth stage (i.e., 16.76 L during Stage V and 14.95 during Stage IV) due to a longer rainfall duration during the fifth stage. In other words, the longer the duration of the rainfall, the higher the increase in storage.

From the porosity of the relatively fine layer (i.e., n = 41.1 %), the potential water storage (or the maximum water) that can be held in the relatively fine layer (i.e., under saturated condition) is 40.2 L. Therefore, the normalized storage changes with respect to the potential water storage measured during Stages I to V are 20.6, 20.9, 43.0, 37.1, and 41.5 %, respectively.

Total Water Storage

Changes in the water storage of the capillary barrier model can also be calculated from changes in volumetric water contents recorded in the relatively fine layer during the experiment. In this case, the water storage changes (ΔS) are equal to the changes in volumetric water content ($\Delta\theta_w$) multiplied by the total volume of the relatively fine soil. The volumetric water content of the relatively fine layer was obtained by averaging the individual measurements made in three locations in the middle part of the model (i.e., TDR-22, TDR-32, and TDR-42) as shown in Fig. 8. The comparison of the total water storage values obtained from the water balance measurements and the volumetric water content data are presented in Fig. 13*b*. In this figure, the water storage under initial conditions (i.e., after the steady-state infiltration or before the applied rainfall in the first stage) was assumed to be the same from both measurements. Therefore, the total water storage from the water balance measurements was obtained by adding the initial storage from water content measurements (i.e., 14.73 L) to the changes that occurred throughout the experiment (i.e., shown in Fig. 13*a*).

The discrepancy between the maximum water storage (i.e., 40.20 L) as compared with those recorded in the experiment (i.e., 38.56 L from water content data and 32.07 L from the water balance measurements) is believed to be related to incomplete saturation in the relatively fine layer when breakthrough occurred. As a result, the measured values of maximum water storage were lower than the potential water storage.

Based on these results, the storage capacity of the relatively fine layer was found to be one of the important parameters affecting the performance of the capillary barrier under the influence of high precipitation rates.

Scanning Curves of the Soil-Water Characteristic Curve

The volumetric water content and the pressure head data recorded by the TDR devices and the tensiometers from locations at close proximity can be plotted on the same graph. This plot can be used to investigate the path followed along the soil-water characteristic curve during the experiment. These paths also define a part of the scanning curves for the soil-water characteristic curve. Figure 14 shows three sets of scanning curves from the experimental data from Sections B, M, and T.

The scanning curves from the first and the second stages were almost on the same path as the wetting and drying curves from the independently measured soil-water characteristic curves. The results from the third stage (III-W and III-D) varied more widely but were still in the correct general region. The amount of the applied precipitation was higher during the third stage than those applied in the other two stages, thereby producing the observed deviation. The pressure head and the water content changes in Stage III were noticeably higher than those in other stages. After the occurrence of breakthrough (i.e., Stage IV and V), the scanning curves follow a different path than those observed before breakthrough. Thus, the behavior of the capillary barrier apparently changes after the occurrence of breakthrough.

If the scanning curves from different cross sections are compared, it can be seen that the curves from Section B have the largest volumetric water content range, while those from Section T have the smallest volumetric water content range. This change in behavior indicates that the infiltrated water flowed along the relatively fine layer and accumulated at the foot of the slope of the capillary barrier model.

Conclusions

A laboratory capillary barrier model can be used to study the mechanism and effectiveness of capillary barriers for slope stabilization purposes. The data obtained from different instruments were found to be consistent and in adherence to unsaturated soil behavior. The wetting and the drying paths of the soil-water characteristic curves determined from laboratory test were found to provide an envelope for the series of scanning curves obtained from the capillary barrier model experiment.

It can be concluded from the results of the experiments that the performance of the capillary barrier under the influence of high precipitation rates is mainly controlled by its storage capacity. The results also indicated that the behavior of the capillary barrier before and after the occurrence of breakthrough is slightly different. Further experimental studies are presently underway in order to provide a clearer understanding of the mechanisms of capillary barriers, particularly under the influence of high precipitation rates. A parametric study will also be conducted extending the laboratory model into a field-scale model.

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TABLE 1—*Controlling parameters for the experiments.*

Controlling Parameters	Stages				
	I	II	III	IV	V
Initial condition	SS	*	*	*	*
Intensities	8 mm/h	8 mm/h	20 mm/h	8 mm/h	8 mm/h
Duration	5 h	5 h	5 h	5 h	12.5 h
Total rainfall	40 mm	40 mm	100 mm	40 mm	100 mm

Notes : - * = simulation started after drying process of previous stage (19 h).
- SS = steady state infiltration at 1.8.

TABLE 2—*Summary of the testing program.*

Conditions Being Evaluated	Stages Being Compared				
	I	II	III	IV	V
- Different initial conditions, similar rainfall intensities and durations	X	X			
- Different rainfall intensities, similar initial conditions and rainfall durations		X	X		
- Different intensities and durations, similar initial conditions and total rainfalls			X		X
- Different rainfall durations, similar initial conditions and rainfall intensities				X	X
- Before and after brakthrough, similar rainfall intensities and durations		X		X	
- Restoration process under different amounts of storage			X	X	

Figure Captions

FIG. 1—*General arrangement of the infiltration box (solid and dash lines indicate signal line and water circulation direction, respectively).*

FIG. 2—*A view of laboratory setup for the experiment: RS = rainfall simulator; IB = infiltration box; DAS = data acquisition system; WB = collection tank above electronic weight balance; TDR = trase system & accessories; T = tensiometer body tube and pressure transducer attached; FS = fine sand layer; G = gravelly sand layer (magnetic flow meter not shown in photograph).*

FIG. 3—*Rainfall simulator type A.*

FIG. 4—*Spraying system for rainfall simulator Type B.*

FIG. 5—*Small tip type of tensiometer.*

FIG. 6—*Ceramic tip of the tensiometer and its detailed connector.*

FIG. 7—*TDR wave-guide and its connector.*

FIG. 8—*Location of the measuring devices.*

FIG. 9—*Grain-size distribution of the capillary barrier soils.*

FIG. 10—*Soil-water characteristic curves of the capillary barrier soils, experimental data from Yang (2002).*

FIG. 11—*Variation of input and output fluxes during the experimental series.*

FIG. 12—*Pore-water pressure head (h) and volumetric water content* (θ_w) *changes*: (a) *measured components of water balance;* (b) *total water storage.*

FIG. 13—*Water balance and total storage of the capillary barrier model during the experiments.*

FIG. 14—*Scanning and bounding curves of the soil-water characteristic curve from the experimental data.*