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Parametric Study of Unsaturated Drainage Layers in a Capillary Barrier

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Abstract: Unsaturated drainage layers (UDLs) have been demonstrated to greatly increase the lateral diversion capacity of capillary barriers. The inclusion of a UDL allows native soils suitable for vegetation growth to be used as the finer soil as lateral drainage properties of the layer no longer need to be considered. A comprehensive numerical study was conducted to investigate the influence of the interface slope and the UDL material on the system's ability to laterally divert downward moving moisture. A capillary barrier system with and without a UDL was simulated for 10 years using daily varying climatic data for three locations in the United States. Three different sands were simulated as the UDL and were modeled at slopes of 5, 10, and 20%. The numerical results confirm that the inclusion of an unsaturated drainage layer at the fine/coarse interface of a capillary barrier can provide significant improvements in the performance of the cover system by laterally draining water. This improvement in performance may allow the system to be successfully implemented in climates wetter than previously were thought suitable. The diversion length (the distance water is diverted laterally with no downward flow through the fine/coarse interface) of a capillary barrier with a UDL was found to be proportional to the slope of the fine/coarse interface. In addition, a relationship between lateral diversion lengths in a capillary barrier and the UDL material was developed and found to be dependent on the unsaturated flow characteristics of the UDL. These relationships allow the performance of a variety capillary barrier UDL designs to be calculated knowing the behavior of one system for a given location.

INTRODUCTION

Capillary barriers, consisting of relatively fine-over-coarse soils, have been suggested as an alternative to traditional compacted soil covers for containment of buried wastes in arid and semiarid environments (Daniel 1994; Hakonson et al. 1994; Benson and Khire 1995). The finer soil layer of a capillary barrier holds infiltrating water by capillary forces and thus serves as a barrier to downward flow. Failure occurs when the moisture content of the finer soil at the interface approaches saturation and the soil suction approaches the water entry value of the coarser layer. Thus, capillary barriers are stressed the most during winter and early spring when precipitation events can be large and evapotranspiration (ET) minimal. Advantages of capillary barriers include their expected longevity, principally because they do not rely upon degradation-susceptible compacted soil layers, and their relatively low-cost due to their simple configuration.

The simplest design approach for a capillary barrier is to ensure that it can store the infiltration expected from precipitation until it can be subsequently removed by ET. The principal variable for this design is the thickness of the finer soil layer, as the amount of ET that can be expected is largely fixed by the local climate. A more complex capillary barrier design includes the use of a sloping fine-coarse interface to promote lateral flow of moisture in the finer layer under unsaturated conditions. The use of unsaturated lateral drainage to remove water from the system provides a mechanism for water removal that is independent of local climate and seasonal variations. Lateral flow (diversion) in a capillary barrier is principally a function of the unsaturated hydraulic conductivity of the finer soil material, as well as the slope of the fine/coarse interface. The shape of the moisture characteristic curve strongly influences the ability of a soil to conduct water under unsaturated conditions.

Experimental studies of capillary barriers as covers have achieved mixed results depending on design, application, and climate (Nyhan et al. 1990; Hakonson et al. 1994; Khire et al. 1994; Woyshner and Yanful 1995). These studies all report significantly increased moisture contents in the capillary barrier systems during periods of high precipitation and low ET, which in some cases led to failure of the barrier and subsequent production of leachate. In those cases where the capillary barriers were sloped, little lateral diversion occurred because the hydraulic conductivity of the finer soil was too low.

Significant increase in the lateral diversion capacity can be accomplished by modifying the finer layer, and hence its unsaturated flow characteristics. This has often been accomplished by constructing the layer using specially selected (and often imported) soil. This soil may not be suitable as a rooting medium; hence the addition of a vegetative layer may also be required in the cover system. However, as the bulk of the lateral flow occurs near the fine/coarse interface, a relatively thin intermediate layer between the overlying soil and the underlying coarser material can be used to increase lateral diversion. The material of the intermediate layer should be conductive enough to laterally divert downward moving water, yet remain unsaturated to preserve the capillary break with the underlying coarser material. Such an intermediate layer is termed a transport layer or unsaturated drainage layer (UDL) (Stormont and Morris 1997). The use of the UDL allows native soils to be used as the finer layer of the system, which acts as both a vegetative and storage medium in the cover system. This configuration may be significantly less expensive to construct.

The concept and use of a UDL in capillary barrier systems will be discussed in this paper. The use of three materials as the UDL will be examined for three sites, with the results of numerical simulations compared with a traditional capillary barrier cover for three interface slopes. The results of the simulations will be discussed, focusing on the role of the UDL in enhancing the performance of a capillary barrier system. Finally, it will be shown that the use of a suitable UDL can significantly reduce the amount of water flowing through the cover and extend the climatic regions in which a capillary barrier can be successfully used as a cover system.

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LATERAL DIVERSION IN CAPILLARY BARRIERS

Lateral diversion is essentially gravity-driven unsaturated drainage within the finer layer of a sloped capillary barrier. Because the water content of the finer soil typically increases with depth, lateral diversion is concentrated at the fine/coarse interface where the hydraulic conductivity is the greatest. Laterally diverting water will cause an increase in moisture in the downslope direction, which may result in failure of the barrier. The distance downslope that the water can be diverted before breakthrough (inflow) into the coarser layer occurs is called the diversion length, as shown in Fig. 1.

The simplest capillary barrier design is a homogeneous finer layer of local, near-surface soil over a coarser sand or gravel. In this design, the finer layer of a sloping barrier system serves three main purposes: (1) As a rooting medium for plants; (2) as a soil water storage medium; and (3) as a lateral diversion medium (Stormont 1996). The finer layer simulated in this project consists of the top layer of a soil from Albuquerque, N.M. and, thus, is suitable to act as a vegetative layer for native plants. Field tests and numerical simulations of capillary barriers with homogeneous finer layers of typical soils indicate that the diversion lengths are <10 m (Hakonson et al. 1994; Morris and Stormont 1997a). These short diversion lengths are due to the relatively low hydraulic conductivity of the finer soil prior to breakthrough compared to the infiltration rate during stressful periods when the soil is relatively wet (e.g., spring snowmelt). Thus, local soils that are suitable as rooting and water storage media, and are relatively inexpensive, may not be conductive enough to laterally divert substantial amounts of water downslope and out of the system (i.e., their diversion lengths may be short).

The diversion capacity of a capillary barrier system can be increased by utilizing a UDL within the fine layer (Stormont 1995b; Morris and Stormont 1997a). A UDL is a relatively conductive layer that drains water laterally within the fine soil while remaining unsaturated. Because soil water tends to accumulate near the fine/coarse interface and unsaturated conductivity increases with water content, a UDL at the interface will be most effective in removing water from the system through lateral diversion.

The function of a UDL can be explained by considering a system comprised of a silty soil as the finer soil layer, a fine-grained sand as the UDL, and a gravel as the coarser layer. The unsaturated hydraulic conductivities (derived from the moisture characteristic curves) as a function of soil suction for these materials are given in Fig. 2. The sand layer can serve as either a capillary barrier or as a UDL depending on the value of the suction head at the interface with an overlying soil layer. Above about 400-mm suction, the soil is more conductive than the sand, and a capillary barrier is formed. Once the suction head at the interface decreases to about 400 mm, the sand layer no longer impedes downward flow and can accommodate as much water as the overlying soil layer can provide. The sand layer hydraulic conductivity is about two orders of magnitude greater than that of the overlying soil layers at suction heads of 300 mm and less. Because the sand layer is underlain by the gravel, it will retain water until the suction head decreases to about 10 mm (the water entry head of the gravel) when breakthrough into the gravel will occur. Therefore, between soil suctions of 300 and 10 mm, the sand will be relatively conductive in the lateral direction but will not pass water across the interface with the underlying gravel. It is under these conditions that the sand can laterally divert substantial quantities of water and thus serve as a UDL.

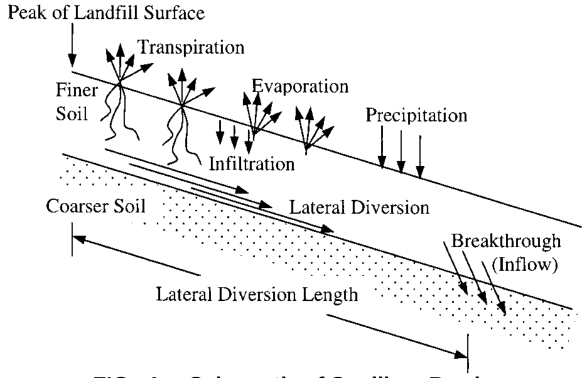

FIG. 1. Schematic of Capillary Barrier

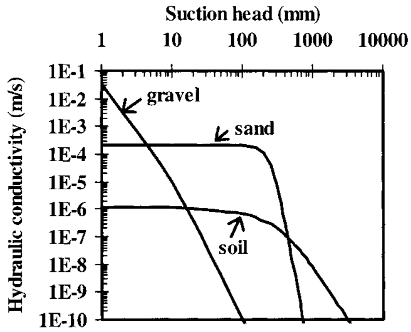

FIG. 2. Hydraulic Conductivity versus Soil Suction for Three Soils

PREVIOUS WORK

The concept of a UDL has been validated using numerical modeling, laboratory experiments, and pilot-scale field tests. Schulz et al. (1995) conducted laboratory experiments using several types of soils in a system that simulated flow in a capillary barrier to determine transport distances under steady infiltration conditions. They found that diatomaceous earth provided the best performance. Results suggested that at flow rates up to 4.2×10^{-3} mm/s, water would remain under tension for any diversion length for slopes of 1:5 and greater. They also concluded that small imperfections or pockets in the fine-coarse interface would not collect water and allow leakage. Based on their experimental results, Schulz et al. (1995) concluded that a conductive layer placed over a capillary break (above the interface) would provide significant protection against infiltrating moisture and proposed using this type of system by itself or in conjunction with an overlying compacted soil cover to provide additional protection.

Stormont (1995b, 1996) conducted pilot-scale water balance tests on 7-m-long capillary barriers sloped at 5 and 10% to investigate the ability of a UDL to remove moisture from the system. The barriers consisted of a 900-mm-thick fine layer over a 250-mm-thick coarse gravel bed. For each slope two barriers were constructed; one with a homogeneous finer layer comprising silty sand only; and the other barrier included horizons of a fine-grained, uniform sand, one of which was placed at the fine/coarse interface. Water was added to the barriers at a rate of 5 and 10 mm/day for the 5 and 10% sloped barriers, respectively, with no lateral flow at the soil surface. In both tests, the homogeneous barriers failed with water moving into and through the gravel, whereas this moisture was diverted laterally in the layered barriers and no breakthrough occurred. After the period of imposed infiltration, the barriers on the 10% grade were exposed to ambient atmospheric conditions for more than 200 days. During this period 70 mm of precipitation fell. The barrier with UDLs successfully diverted all infiltration, whereas the homogeneous barrier failed with moisture flow into the underlying gravel layer.

Numerical simulations have been conducted to investigate the potential drainage capacity of UDLs (Stormont and Morris 1997). The simulations utilized a modeling approach that ac-

counted for near-surface, climate-dependent processes as well as transient, unsaturated flow (Morris and Stormont 1997a). This numerical approach has been demonstrated to satisfactorily simulate unsaturated water movement associated with capillary barriers, including reasonably reproducing the previously described field tests (Morris and Stormont 1997b).

The field experiments and numerical studies discussed above have demonstrated the potential of UDLs in laterally diverting water at the fine-coarse interface and thus limiting percolation through a capillary barrier. However, these studies did not include a systematic investigation into the influence of the UDL material properties or the interface slope on the diversion capacity of the UDL.

SIMULATIONS OF LATERAL DIVERSION

Material Properties

In this study we numerically investigate three soil types for the UDL: (1) A 100-mesh, uniform sand; (2) a concrete sand that has a less uniform grain size; and (3) a Plainfield sand described by Yeh et al. (1994). The grain size distributions for the materials used in the test are shown in Fig. 3, with the exception of the Plainfield sand. Only the unsaturated flow characteristics for the Plainfield sand have been found in the literature; thus the physical characteristics are unknown. The Plainfield sand was chosen as a possible UDL due to its relatively high conductivity under unsaturated conditions compared with the concrete and 100-mesh sands. These sands are used as the transport layer in barriers with interface slopes of 5, 10, and 20%. The transport layer was 200 mm in thickness and was placed between the finer and coarser layers in the capillary barrier system as shown in Fig. 4. The finer layer (also called the vegetative layer) was 0.66 m of a finer, uncompacted soil, and the coarser layer was a medium gravel. An uncompacted finer layer was used because there is no need to minimize the hydraulic conductivity of this soil. This is an advantage of the capillary barrier system over conventional covers, which translates to simpler, less expensive construction costs.

The properties of the soils used in this study are given in Table 1 using the van Genuchten functions (van Genuchten 1980). These functions were chosen because they are widely used and accepted, are easy to implement in numerical schemes, and provide a reasonable match to a wide range of experimental data. The moisture content θ and the soil suction h are related by means of

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{-m} \qquad (1)$$

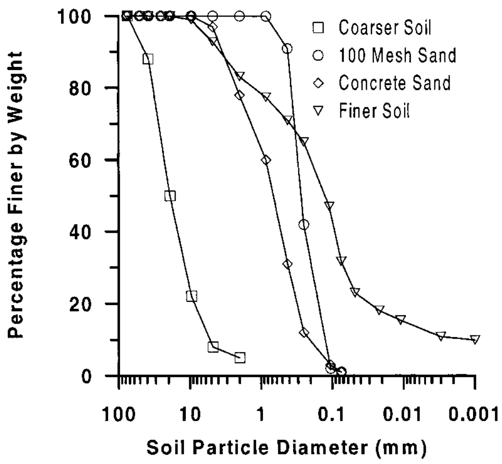

FIG. 3. Grain Size Distribution of Soils

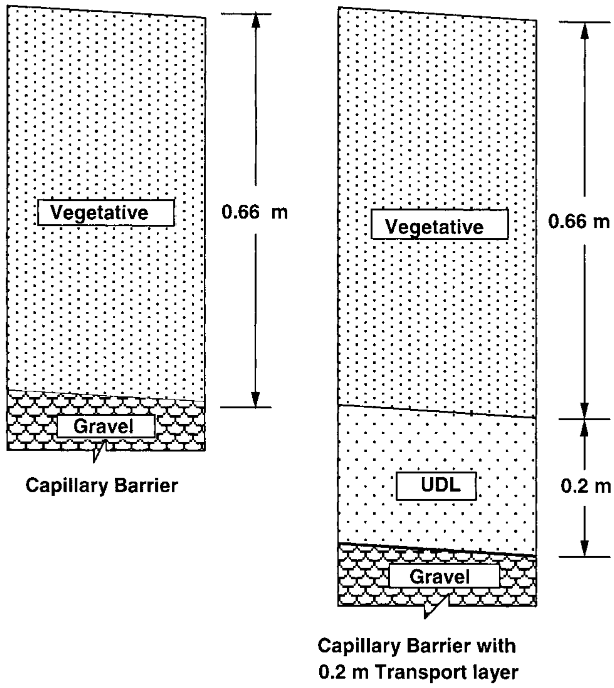

FIG. 4. Schematic of Cover Systems

TABLE 1. van Genuchten Parameters for Cover System Soils

Soil/layer (1)	k_s (m/s) (2)	θ_s (3)	θ_r (4)	α (mm^{-1}) (5)	n (6)
Vegetative	1.4×10^{-6}	0.442	0.077	0.0015	2.03
Construction sand	1.6×10^{-4}	0.37	0.0077	0.063	2.12
100-Mesh sand	2.1×10^{-4}	0.39	0.031	0.0038	4.95
Plainfield sand	3.0×10^{-4}	0.36	0.030	0.2408	15.04
Gravel	0.1	0.42	0.005	0.493	2.19

and the hydraulic conductivity is given as

$$k = k_s\Theta^{1/2}(1 - (1 - \Theta^{1/m})^m)^2 \qquad (2)$$

where Θ = dimensionless water content; k_s = saturated hydraulic conductivity; θ_s = saturated moisture content; θ_r = residual moisture content; $m = 1 - 1/n$; and n and α are fitting parameters.

The soil properties for the finer layer were based on soil samples taken from Sandia National Laboratories, Albuquerque, N.M., as determined by McTigue (1994). The gravel layer properties were taken from Stormont (1995b), and the Plainfield sand properties were from Yeh et al. (1994). The properties of the concrete and 100-mesh sands were measured and reported by Pease (1995). Though the finer layer soil properties were taken from a New Mexico soil, they were not changed for the sites modeled in this study. The parameters of this soil are likely to be similar to other silty soils found in other locations and were not the focus of this study. In addition, a direct comparison between sites was desired so that the influence of climate on UDL material performance could be established.

Model

The computer code used to perform the numerical simulations was TRACER3D, described by Travis and Birdsell (1991). The finite-difference code is capable of simulating 3D saturated and unsaturated flow behaviors in porous media. Minor modifications were made to the code to allow distribution of ET from the surface and within the root zone of the model,

to allow large source/sink files to be used, and to provide the output in an easy to use format. The distribution of ET followed the methodology used in the HELP model, which was based on work by Penman, Ritchie, and Knisel and is described in detail in Schroeder et al. (1994). The distribution accounts for both direct evaporation from the soil and for plant transpiration from throughout the root zone. Previous work by Morris and Stormont (1997b, 1998a,b) showed that the program is capable of simulating capillary barrier performance providing there is reasonable agreement with both analytical and field data. Details of the modeling process used are described in Morris and Stormont (1997a).

The model simulated 2D flow and had an horizontal extent of 100 m and a vertical extent of 1.03 m. A uniform grid was used, consisting of 50 cells in the horizontal direction and 31 cells in the vertical direction to simulate the cover system. The top 21 cells of the model were designated to be the finer soil, with the next 6 cells being the UDL. The remaining 4 cells were assigned the attributes of the gravel. The characteristics of the soils used are listed in Table 1. The top cell of the system was used only as a source of infiltration, with the ET sink being allocated to the next 20 cells in the model (cells 2–21). Because each cell was 0.033 m in depth, ET took place in the top 0.66 m of the system. The ET term was distributed through the cover to a depth of 0.66 m (the chosen rooting depth) using the algorithm described in the HELP engineering manual (Schroeder et al. 1994).

The model boundary conditions were no-flow on the right, front, back, and top and ambient on the left and bottom of the model. The ambient boundary condition (analogous to a constant head boundary) maintains the designated cells at their initial condition throughout the simulation. A schematic of the model is shown in Fig. 5. The lower boundary is analogous to a landfill system where the gravel layer of the capillary barrier would be underlain by a layer of unsaturated soil, which is placed over the compacted waste. In effect, the boundary condition prevented moisture from accumulating in the gravel layer and did not alter the system behavior at the interface. The model was sloped to the left allowing lateral drainage out of the system. The area of study was 50 m in length, leaving 50 m to eliminate the influence of the downslope boundary on lateral flow. Moisture flow into the second layer of cells in the coarse layer of the capillary barrier system was tracked and tabulated on a 2-week basis for the 10-year simulation period. The moisture flow into the monitored cells was designated to be the amount of breakthrough (inflow) produced for the lateral diversion distance and scenario being simulated. It should also be noted that the ET term became inactive when the soil moisture in a cell was below the ''wilting point'' (15-bar matric potential), with the demand being passed to the next deeper cell in the system. If the entire root zone area was dried to the wilting point, the ET term was ignored. This scenario was again based on the method used in the HELP code.

The initial conditions used for the simulations were identical for all simulations and were as follows: vegetative layer and

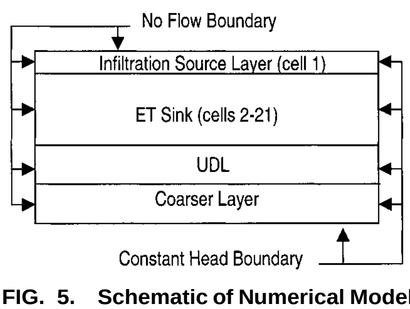

FIG. 5. Schematic of Numerical Model

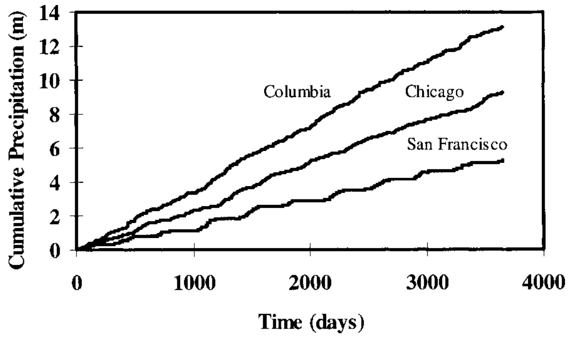

FIG. 6. Cumulative Rainfall

UDL—10% saturation; and gravel layer—1% saturation. Because the focus of the research was a comparison between systems with and without a UDL and for different UDL materials, the writers felt that using the same initial condition for each scenario was important. The initial condition used for the gravel layer (1% saturation) was chosen based on the assumption that water would readily drain from the layer and that the moisture content near the interface would be very low. Increasing the gravel layer saturation by 10% in the simulations increased breakthrough (inflow) by <1%, which was considered to be insignificant. Similarly, increases in the initial saturation of the finer soil also led to insignificant increases in breakthrough.

A similar model of a capillary barrier without a UDL was used as a baseline against which the various scenarios were compared. The model used for comparison was identical in the top 21 cells and varied only in that the 6 cells designated as the transport layer were switched to be part of the coarser layer, eliminating the UDL. Because the capillary barrier behavior is essentially independent of the coarser layer thickness, any difference in performance is completely attributed to the presence or lack of the UDL.

RESULTS

The simulations of the capillary barrier system were conducted for three sites in the United States: San Francisco; Chicago; and Columbia, S.C., which represent a variety of climates, with the precipitation patterns for the modeled period shown in Fig. 6. [Data for Fig. 6 was obtained from the HELP model (Schroeder et al. 1994).] Arid and semi-arid sites were also modeled (Albuquerque, Salt Lake City, and Denver) in the initial work on the project; however, failure of the simple capillary barrier system did not occur at these sites so that the addition of a UDL would serve no purpose. The data from these locations was of limited use in this parametric study and, thus, was not included.

Three UDL soils were tested at three interface slopes to determine the influence of slope and material on their ability to laterally divert water. All simulations were conducted for a 10-year period so that the cumulative effects of precipitation and ET were accounted for. This long period of modeling is important for capillary barriers because one of the major moisture removal processes is ET. If ET is lower than precipitation, moisture can accumulate in the system over several years and, if not removed by lateral diversion, may result in a large breakthrough event. At each site the 5-year period with the highest cumulative precipitation was chosen from the 100-year record so that the systems were subjected to the highest realistic infiltration stress. This 5-year record was preceded by 3 years of data and followed by an additional 2 years, for a total modeling period of 10 years. This methodology allowed the soil moisture contents to come to equilibrium prior to the 5-year high precipitation period and to examine the effects of the high

precipitation period on later system behavior. At the present time, there is no prescribed or agreed upon duration for modeling cover system behavior and no consensus on what type of climatic conditions should be included to demonstrate performance. The 10-year period, which included the 5-year period with the highest precipitation out of 100, was chosen for two reasons: the writers believed that it probably provided the highest stress that the systems would encounter; and the human and machine time required to perform each simulation was reasonable. Each simulation took 3–6 h of computational time on a high-end UNIX system when successful. It should also be noted that though actual diversion lengths are provided and discussed, the lengths are not an exact distance at which flow into the underlying coarser soil begins. The concept of diversion length is discussed in detail by Ross (1990) and is the basis upon which distances are chosen in this study. The goal of this study was to predict trends and establish comparative performance of the systems modeled using a uniform set of variables, not to provide an absolute value of diversion length for each scenario.

San Francisco represents a site that has large seasonal variations in precipitation and ET. The bulk of the moisture falls during the winter and spring months when ET is low, with little, if any, rain falling during the rest of the year when potential ET is high. This combined precipitation and ET pattern leads to high soil moisture contents during the wet months and very dry soil by the end of the summer. The total rainfall over the 10-year period simulated was 5.2 m, or an average of 520 mm/year. The average total percolation through a simulated 5% sloped capillary barrier without a UDL was 1.28 m (Fig. 7), which is approximately 25% of the total precipitation that fell on the site during the 10-year simulation period. The average total percolation is the total percolation divided by the surface area of the barrier. The average value is used because the quantity of percolation increases with downslope distance.

The amount of breakthrough in the capillary barrier at San Francisco is a function not only of the interface slope but also of the UDL material. The 100-mesh sand and the Plainfield sand have a significantly greater ability to laterally divert downward moving moisture compared with the concrete sand, as seen in Fig. 7. Percolation through the cover system can be significantly reduced or eliminated by using either the 100 mesh sand or the Plainfield sand as the UDL layer. The 5% sloped, 100-mesh sand UDL allowed an average of only 228 mm of water (4% of the total precipitation) to move through the cover over the 50-m length during the 10-year simulation. Water movement through the capillary barrier system can be

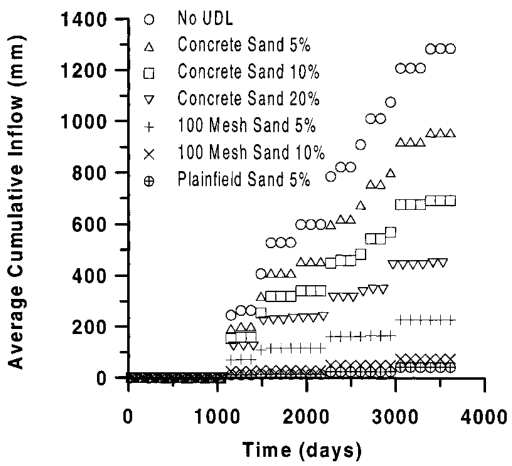

FIG. 7. Average Cumulative Inflow for San Francisco (Note: No Inflow for 100-Mesh 20% or Plainfield Sand 10 and 20% Simulations)

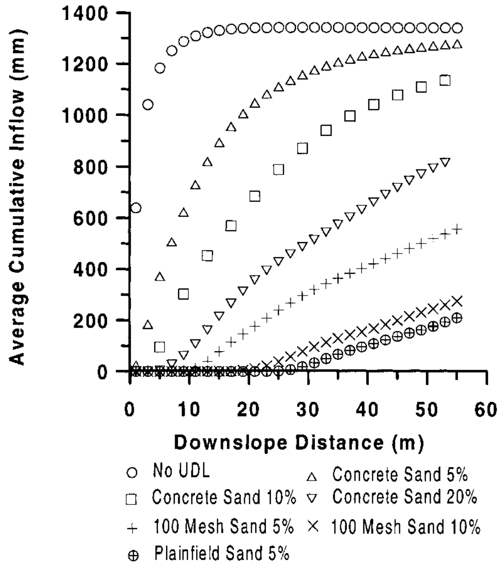

FIG. 8. Diversion Length Data for San Francisco (Note: Diversion Lengths for 100-Mesh 20% or Plainfield Sand 10 and 20% Simulations Were >50 m)

virtually eliminated through the use of steeper interface slopes and/or Plainfield sand as the UDL material.

The second item that is important in the utilization of a UDL is the distance water can be diverted before breakthrough occurs. This diversion distance was determined for each of the 10 scenarios simulated for San Francisco, with the results shown in Fig. 8. The diversion length is the distance over which the total percolation into the coarser layer for the 10-year modeling period is insignificant; hence all downward moving water was laterally diverted into this portion of the cover. This diversion length varies from being <2 m for the system without a UDL and for the 5% sloped concrete sand to over 50 m for the 10 s and 20% sloped Plainfield and UDLs. The diversion length, like the cumulative percolation, is a function of both the UDL material and the interface slope. Based on these simulations, percolation of moisture through a capillary barrier system can be reduced to near zero or eliminated over a 50-m length by the use of a UDL constructed of Plainfield sand at a slope of 10% or greater. Due to the timing of precipitation at San Francisco, moisture removal by ET is limited; therefore the use of a UDL significantly increases the ability of the capillary barrier system to prevent movement of moisture into the coarse layer and the waste below.

The precipitation at Chicago, the second site modeled, was greater than at San Francisco but was spread more evenly throughout the year. Total precipitation over the 10-year period was approximately 9.28 m (928 mm/y) or about 1.75 times that of San Francisco. A plot of the average cumulative percolation through the capillary barrier systems modeled is shown in Fig. 9. The performance of each system at Chicago was significantly better than at San Francisco, despite the increased precipitation. The benchmark capillary barrier without a UDL allowed only 89 mm of precipitation to breakthrough into the underlying coarser layer, which is about 1% of the total precipitation at the site. The inclusion of a UDL in the cover system markedly reduces percolation through the barrier, with significant percolation occurring only for the concrete sand transport layer. No water moved into the coarser layer of the system when the 100-mesh and Plainfield sands were used as the UDL; hence, only the 5% slope 100-mesh sand results are shown in Fig. 9.

The diversion lengths for the concrete sand UDLs at Chicago are shown in Fig. 10, and again we see that they are <20

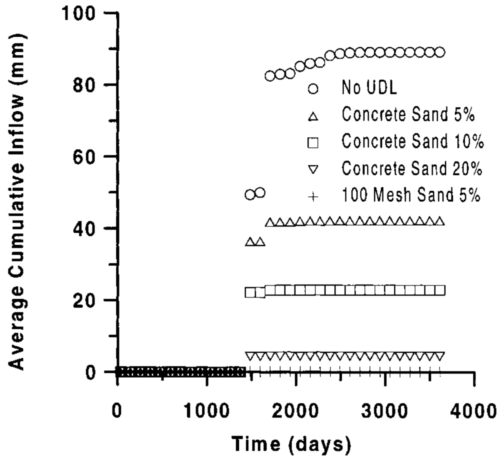

FIG. 9. Average Cumulative Inflow for Chicago (Note: No Inflow for 100-Mesh 10 and 20% or for Plainfield Sand 5, 10, or 20% Simulations)

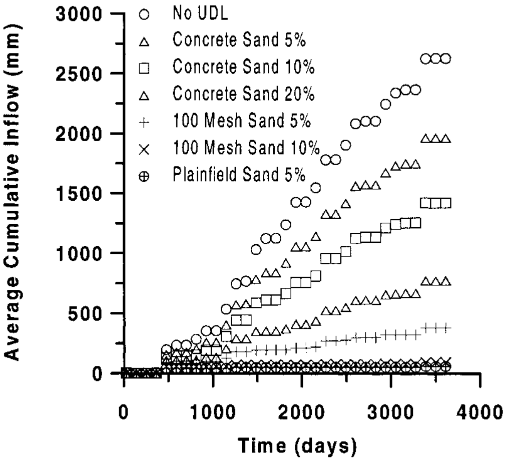

FIG. 11. Average Cumulative Inflow for Columbia (Note: No inflow for 100-Mesh 20% or Plainfield Sand 10 and 20% Simulations)

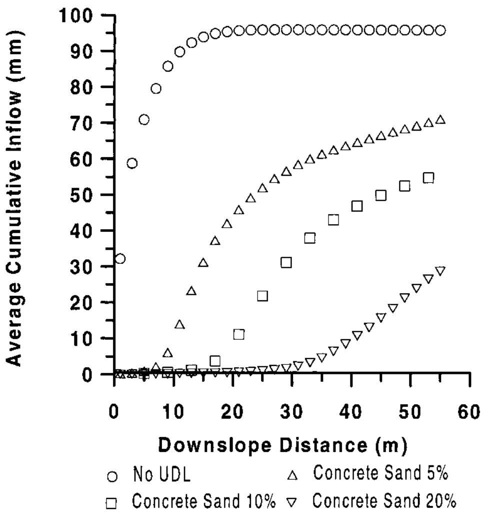

FIG. 10. Diversion Length Data for Chicago (Note: Diversion Lengths for 100-Mesh and Plainfield Sands Simulations Were >50 m)

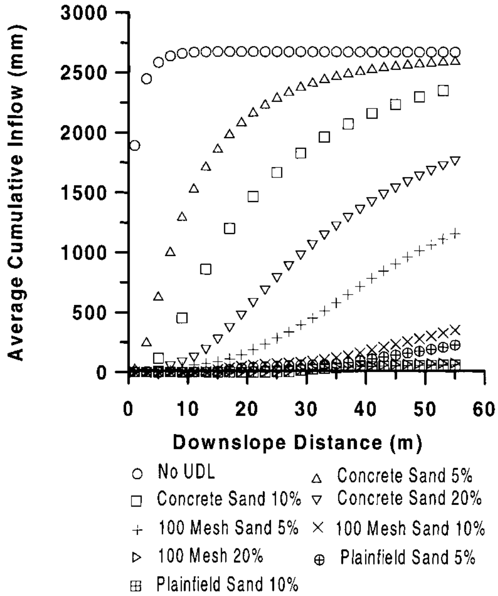

FIG. 12. Diversion Length Data for Columbia (Note: Diversion Length for Plainfield Sand 20% Simulation Was >50 m)

m even for the 20% sloped system. The diversion lengths of the 10 and 20% sloped 100-mesh and Plainfield sands used as UDLs are not shown since they exceeded the 50-m test distance for all cases.

Similar reductions in percolation are seen for Columbia, where the precipitation over the 10-year simulation period was approximately 13.10 m or 1.4 times that at Chicago and 2.5 times greater than at San Francisco. The average cumulative percolation for the site is shown in Fig. 11 for the capillary barrier systems modeled at Columbia. The benchmark barrier system without the UDL produced 2.630 m of breakthrough over the 10-year period, which was 20% of the total precipitation. The addition of the UDL to the capillary barrier reduces percolation significantly over the 50-m test length but only eliminates it completely using the Plainfield sand at a 20% slope.

The diversion lengths for the 10 UDLs simulated at Columbia are shown in Fig. 12. The concrete sand again shows the shortest diversion lengths, all being <5 m, followed by the 100-mesh sand with diversion distances of 5–23 m and the Plainfield sand with diversion lengths of 13 to >50 m. The Plainfield sand was able to prevent percolation into the coarse layer for the 20% sloped test system over the 50-m barrier length.

DISCUSSION

The results presented in the previous section demonstrate that a capillary barrier with a UDL can significantly reduce or eliminate water movement into underlying waste, providing protection that is superior to a traditional capillary barrier. These results are not unexpected when we look at the characteristics of the UDL soils and the factors that govern the diversion length in a capillary barrier system.

Ross (1990) developed an analytical expression for calculating the diversion length of a capillary barrier that was modified by Steenhuis (1991) and Stormont (1995a). The modified equations express the diversion length L of a sloping capillary barrier as a function of both the soil characteristics and the slope of the finer/coarser interface (Steenhuis et al. 1991)

$$L \leq \tan \phi \left[a^{-1}\left(\frac{K_s}{q} - 1\right) + \frac{K_s}{q}(h_a - h_w^*) \right] \quad (3)$$

where q = constant or steady-state infiltration rate; h_w^* = water entry head of the coarse layer; ϕ = inclination of the fine-coarse interface; h_a = air entry head; K_s = saturated hydraulic conductivity; and a = constant called the sorptive number. Though this expression was developed for steady-state infil-

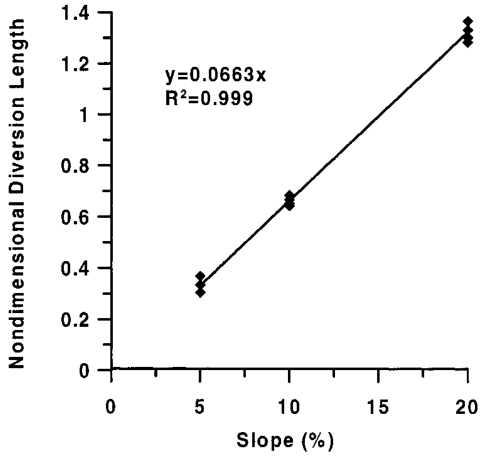

FIG. 13. Nondimensionalized Diversion Length Data for All Sites

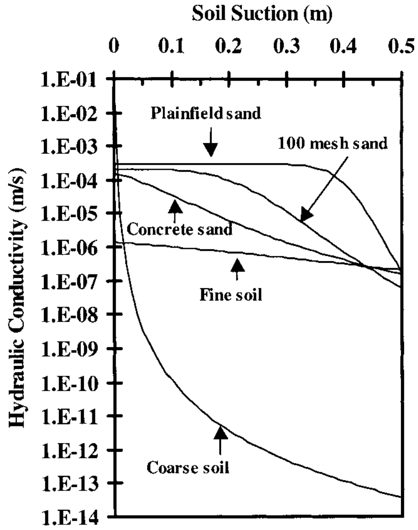

FIG. 14. Hydraulic Conductivity versus Soil Suction for Soils Used in Simulations

tration, we can infer from it that, for all conditions, diversion length is proportional to the interface slope. Because the precipitation and, hence, the infiltration into the covers simulated in this study were variable over the 10-year period, the above equation cannot be applied. A diversion length could be defined as a function of time if q at the interface is known for each time step and for each cell; however, this was not undertaken in this study. It should also be noted that results from modeling steady-state infiltration into a sloped capillary barrier using a variety of numerical models are comparable to analytical expression shown in (3) (Webb 1997, 1998; Morris and Stormont 1998a).

The simulation diversion lengths shown in Figs. 8, 10, and 12 follow this behavior over the range of slopes of 5–20% tested. Doubling the gradient doubled the diversion length for that material at the location being simulated. Using Columbia and the 100-mesh sand as an example, we see that for a 5% slope the diversion length was approximately 6 m. This length increased to 12 m for the 10% slope test and to 25 m for the 20% test, demonstrating the linear dependence. To verify that the linear relationship is valid for the three UDL materials and for all three simulation sites, all diversion length data were nondimensionalized and plotted versus slope as shown in Fig. 13. To nondimensionalize the data, each diversion distance in a set of simulations (e.g., San Francisco and the 100-mesh sand) was divided by the difference between the longest and shortest diversion length for that set (28, which is the difference between 8 m for the 5% slope and 36 m for the 20%). As is seen in Fig. 13, the data for the three material types and three locations follows a linear relationship. In Fig. 13, data points for 18 of the 27 simulations are plotted, with each point representing the nondimensionalized diversion length at a given slope for a given UDL material and test location. In nine of the tests no breakthrough occurred, while six of the tests produced identical nondimensionalized results and, thus, are not distinguishable. The linear relationship seen in Fig. 13 appears to be independent of location and UDL material type, providing a reasonable comparison between the different materials and test sites.

Though this result was expected, it is important for two reasons: first, it demonstrates that the numerical simulations conducted in this study provide similar results to those predicted by the analytical approximation developed by Ross (1990) and extended by Steenhuis et al. (1991); and second, it demonstrates that numerous simulations or field tests at different slopes are not required to predict diversion lengths for a given system. Results from a single test for a particular site and UDL material in which the diversion length is accurately measured can be extrapolated to estimate barrier performance for a variety of slopes.

The second important variable of interest in evaluating the lateral diversion capacity of a capillary barrier is the UDL material. In this study, three materials were analyzed, and in all cases the Plainfield sand provided the greatest lateral diversion for a given interface slope, followed by the 100-mesh sand and the concrete sand. This behavior follows from Fig. 14 in which hydraulic conductivity is plotted versus soil suction. The Plainfield sand curve remains at a relatively high conductivity from saturation to a soil suction of approximately 0.35 m whereas conductivity of the 100-mesh sand begins dropping at 0.15 m, and that of concrete sand begins decreasing when the soil suction increases above zero. As discussed in the lateral diversion section of this paper, the Plainfield sand should be able to drain significantly more water laterally than either the 100-mesh sand or concrete sand, because it has a higher conductivity over a larger soil suction range. The results from the simulations support this interpretation in all cases.

What is not apparent from looking at Fig. 14 and (3) is how to relate diversion length data for different UDL materials at a given site. From (3) it is seen that diversion length is dependent on the saturated hydraulic conductivity, the sorptive number, and the air entry value of the UDL material and on the water entry value of the coarse layer. One method of relating the diversion capabilities of different materials is to determine their capacity to transmit water over the range in which they will be operating and comparing the results. The maximum diversion capacity of a soil can be expressed as follows (Ross 1990):

$$Q_{max} = K_s \tan \phi \int k_r \, dh = \tan \phi \int k_w \, dh \tag{4}$$

where ϕ = angle of the fine-coarse interface with respect to the horizontal; h = soil suction; k_w = wetting-phase conductivity ($K_s^*k_r$); K_s = saturated hydraulic conductivity; and k_r = relative hydraulic conductivity function that varies with the soil suction. The limits of the integration are the suction heads at the top and bottom of the layer through which the water is flowing.

Lateral diversion will occur preferentially within the UDL material without breakthrough when the soil suction is between the values designated by the crossing of the UDL curve with the coarse and fine layer soils as shown in Fig. 14. However, the maximum flow will occur when the soil suction at

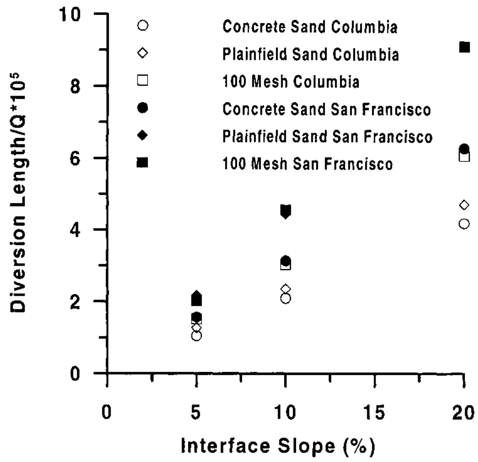

FIG. 15. Diversion Length Divided by *Q* versus Slope for San Francisco and Columbia

the interface is slightly higher than the water entry value of the underlying coarser layer h_w^*, which in this study was approximately 10 mm. If the soil suction at the interface is h_w, then the soil suction at the top of the UDL is just $h_w + z$, where z is the elevation of the top of the UDL above the interface. Therefore, Q_{max} can be found using (4) with limits of integration. This integral is simply the area under the curve between the soil suctions of 10 and 210 mm, in Fig. 14, for the UDL material in question. If the flow of moisture to the interface is less than Q_{max}, the soil suction at the bottom of the UDL will be >10 mm and, thus, will be >210 mm at the top boundary of the UDL. For this scenario, the diversion flow rate Q will simply be the flow rate of water to the interface. The diversion length can then be calculated by simply dividing Q_{max} by the infiltration rate q. If the calculated diversion length exceeds the length of the capillary barrier, then the system would be expected to prevent breakthrough.

To investigate the relationship between diversion length and material type, a composite Q was determined by numerically integrating the curves representing the three UDL materials shown in Fig. 14 using a lower limit of 10 mm. The upper limit of integration was set to be the soil suction at the point at which the UDL and the fine soil curves cross in Fig. 14. This upper limit was chosen to account for lateral diversion that occurred when the suction at the interface was greater than h_w^*. The diversion length data for each site were divided by the corresponding composite UDL Q. These data were then plotted versus the interface slope as shown in Fig. 15 for Columbia and San Francisco. The plots indicate that the composite Q obtained by integrating the curves over the range in which the UDL is active is a significant measure of the lateral diversion capability of the material. If Q were not a measure of lateral diversion capability, the data from the three different UDL materials would not tend to coalesce into a single straight line. The diversion length data used in Fig. 15 are based on the entire 10-year modeling period and not on just a single breakthrough event, and thus the scatter is reasonable. This relationship between the composite Q for different UDL materials and lateral diversion lengths is very important because it allows performance predictions to be made based on data from one set of tests in which good quality data are obtained.

CONCLUSIONS

This study demonstrated through the use of a numerical model that the inclusion of an UDL at the finer/coarser interface of a capillary barrier could provide significant improvements in the performance of the cover system. The use of UDLs in the system allows large quantities of water to be removed from the fine soil layer by lateral diversion, increasing the ability of a capillary barrier to prevent percolation events during periods of high infiltration and low ET. The climatic range in which capillary barriers can be used can also be expanded to wetter climates because reliance on ET to remove moisture from the cover system is reduced.

This project also verified that the diversion length of a capillary barrier is directly related to the slope of the fine/coarse interface. If the interface slope is doubled, the diversion length will also double. This verification reduces the number of field tests or numerical simulations that need to be conducted to develop a suitable capillary barrier cover for a site.

Finally, the writers developed a relationship between lateral diversion lengths in a capillary barrier and the material in which the lateral diversion is occurring. This, again, is an important relationship because it allows estimates of diversion length to be made for a variety of materials based on data from tests or numerical simulations that used a different material for lateral transport.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

a = sorptive number for quasi-linear approximation;
h = suction head;
h_a = air entry suction head;
h_w^* = water entry suction head;
I = infiltration;
k = hydraulic conductivity;
k_r = relative hydraulic conductivity;
k_s = saturated hydraulic conductivity;
k_w = wetting-phase conductivity;
L = diversion length;
m = 1 - 1/n, van Genuchten function parameter;
n = van Genuchten function parameter;
Q = lateral flow in diversion layer;
$Q_{\max}$ = maximum lateral flow in diversion layer;
q = infiltration rate;
α = van Genuchten function parameter;
Θ = dimensionless water content;
θ_r = residual moisture content;
θ_s = saturated moisture content; and
ϕ = slope of fine-coarse interface.