INCREASING THE DIVERSION LENGTH OF CAPILLARY BARRIERS

R.E. Pease[1] and J.C. Stormont[2], [1]GeoSciences, RE/SPEC, Inc., 4775 Indian School Rd., NE, Albuquerque, NM, 87110, and [2]Civil Engineering Department, University of New Mexico, Albuquerque, NM, 87131

ABSTRACT The diversion length of a capillary barrier is increased with the introduction of a well-sorted sand layer immediately above the fine/coarse interface. Various soils were evaluated as “transport layer” materials using numerical simulation. Infiltration and evapotranspiration were simulated for one year of an Albuquerque, NM, climate. The infiltration and evapotranspiration varied daily in the simulations with the use of a daily effective flux. The baseline simulation without a transport layer diverted moisture 5 m. The diversion length was increased to 37 m with the use of a construction sand layer, and a layer of 100-mesh sand did not allow any moisture to penetrate the barrier. The simulation results are consistent with the field test results of Stormont [1], which indicate an increase of capillary barrier diversion length with the introduction of a sand transport layer. A capillary barrier may be an inexpensive and stable method of improving performance of cover systems in semi-arid regions.

KEYWORDS: capillary barriers, unsaturated flow, lateral diversion landfill covers

INTRODUCTION

Surface barriers

Surface covers are a component of all waste-containment facilities. Their primary purpose is to isolate the waste from the environment, prevent infiltration, improve the aesthetic value of the landfill, and prevent biointrusion and gas emanation. Cover designs range from simple compacted soil layers to multi-component, engineered systems. Materials used for surface barriers commonly include soils of various grain sizes, geosynthetics, and compacted soils. Figure 1 presents the possible components of an engineered surface barrier [2]. The infiltration barrier layer is the critical component of the surface barrier. The barrier layer minimizes infiltration through the cover due to its greatly reduced hydraulic conductivity. The surface barrier promotes storage in the overlying layers until the moisture may be removed by evapotranspiration or internal drainage.

Advantages and disadvantages of barrier layer materials

In the following sections, some strengths and limitations of the three most common barrier layers are given.

Low-permeability soil layers

Compacted, low-permeability soil layers offer the advantages of low cost, familiarity, and material availability. The addition of bentonite to local soil allows these layers to achieve the low saturated hydraulic conductivity that may be required by regulatory agencies. Disadvantages include desiccation-induced cracking, effects of freeze-thaw, and the effects of differential settlement. These effects may produce channels of preferential flow that greatly increase the hydraulic conductivity through the cover [3].

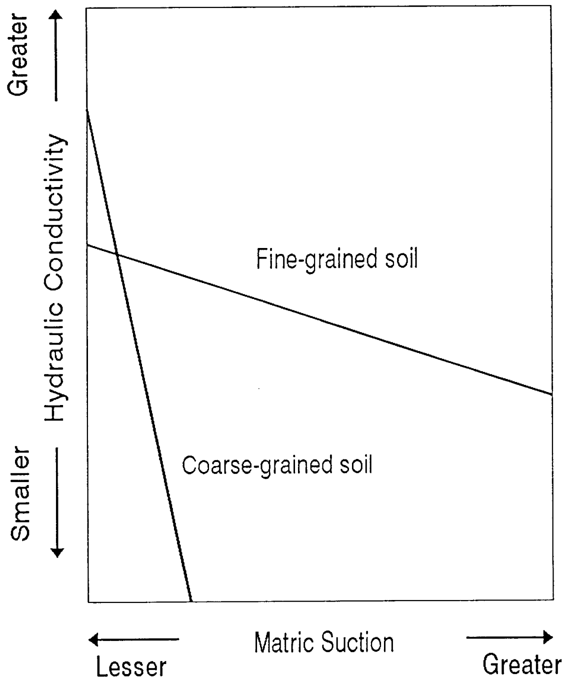

FIGURE 1. MATRIC SUCTION VS. HYDRAULIC CONDUCTIVITY FOR COARSE AND FINE SOILS.

Geomembranes

Geomembranes are thin sheets of plastic (i.e., polyvinyl chloride or polyethylene) used to limit infiltration into (cover) or out of (liner) subsurface waste. Geomembranes are not as affected by differential settlement as other materials. They have a high ductility and will deform to some extent without tearing. The main concern with geomembranes is installing them without compromising their integrity by puncture holes or defects in the seams. The seams must be “welded” together flawlessly to prevent moisture from penetrating into the underlying layers. Holes or seam defects will increase the effective hydraulic conductivity through the cover.

Geosynthetic clay liners

A geosynthetic clay liner (GCL) is a thin layer of bentonite (approximately 5 mm) supported by geotextiles and/or geomembranes. GCLs are convenient since they are rolled out at the project site. Overlapping of the seams allows them to be self-sealing upon hydration through expansion of the bentonite clay. A principal concern with GCLs is their long-term stability due to their low interfacial shear strength. The angle of internal friction of bentonite clay is significantly reduced from dry to wet conditions. An important consideration for all of these materials is their long-term ability to limit infiltration into the underlying waste. Alternative designs and methods should be investigated to find the most dependable and economical cover design.

Capillary barriers

Capillary barriers are being examined as an alternative design for surface barriers in semi-arid regions. A capillary barrier consists of a fine-grained soil overlying a coarse-grained soil. The interface between the two materials is the barrier which prevents moisture from infiltrating through the system and is a result of the hydraulic conductivity vs. matric suction characteristics for the different soils. Figure 1 shows the hydraulic conductivity vs. matric suction relationships typical for a fine-grained soil and a coarse-grained soil. Figure 1 shows that at most values of matric suction, the hydraulic conductivity of the coarse soil is negligible compared to that of the fine soil. Matric suction in soil is a function of moisture content. If the soil is saturated, the matric suction is zero. As the moisture content decreases, the matric suction becomes larger. Due to reasons of continuity, the value of matric suction in the coarse soil immediately below the fine soil layer will assume the same value as that of the fine soil layer. If this value of matric suction is large enough, (i.e., water content less than saturation) the moisture in the fine layer will be limited from entering the coarse layer. This effect becomes more pronounced as the matric suction increases (i.e., the moisture content decreases). The value of matric suction at which water enters the coarse layer is the water entry pressure value of the coarse soil. Removal of water from the fine layer can occur by evaporation, transpiration, or drainage. Capillary barriers are most often considered for semi-arid climates due to the high evapotranspiration rate and low infiltration rates. Drainage may occur if the fine/coarse interface is sloped with inclusion of an interface angle (φ) between the fine and coarse soil. This angle introduces a gravity force on the moisture which will help drive it in the "down-dip" direction of the slope. The moisture content increases in the down-dip direction, which keeps the soil in the "up-dip" portion of the interface from reaching near saturation conditions.

Capillary barrier performance

An important consideration for design of a capillary barrier as a protective cover is the diversion length of the barrier. The diversion length is only applicable to sloped capillary barriers since an unsloped barrier does not divert water. Diversion length is defined in this report as the length of interface in the down-dip direction until breakthrough occurs. Breakthrough occurs at the point along the interface where the matric suction in the fine layer becomes equal to the water entry pressure of the coarse layer. At this point water will begin to enter the coarse layer and the flowrate will increase as the matric suction decreases. Ross [4], on the other hand, defined breakthrough as the point along the barrier where the flowrate into the coarse soil layer was equal to the constant infiltration rate applied to the top of the fine-soil layer.

Field tests performed on capillary barriers indicate that diversion lengths may be relatively short (i.e., less than 10 m). Using an analytical solution, Ross [4] estimated the diversion lengths to range from 5 to 50 m depending on the infiltration rate and the material properties. For capillary barriers to be effective at laterally diverting water over distances needed for many cover applications, designs are needed to increase diversion lengths.

Research objectives

The purpose of this research was to investigate means of increasing the diversion lengths of capillary barriers. The approach for increasing diversion length was to include a hydraulic transport layer between the fine/coarse interface. The transport layer has a greater hydraulic conductivity than the fine layer at near saturation conditions. When the moisture accumulates in the fine layer, the increased hydraulic conductivity of the transport layer helps to laterally divert the moisture in the down-dip direction.

This thesis examined the results of various soils tested as transport layers in a capillary barrier. The research showed that a well-sorted, fine to medium sand used as a transport layer may give the capillary barrier an acceptable diversion length required to cover a subsurface waste containment facility.

LITERATURE REVIEW

There is substantial literature on capillary barrier concepts. The literature summarized here focuses on the diversion length of capillary barriers.

Analytical solutions

Ross [4] studied the concepts of the capillary barrier for potential use as a landfill cover. Ross defined the concepts of an up-dip limit, which is the upper boundary of the fine/coarse interface where horizontal flow is zero, and a down-dip limit which is "far away" and has a means of removing laterally diverted moisture. Ross developed analytical solutions for diversion length and diversion capacity of sloped capillary barriers. The diversion length is the length in the down-dip direction to a point where the barrier does not divert any additional water; a downward flux is experienced in both the fine and coarse soil. The diversion capacity is the amount of water flowing laterally in the asymptotic down-dip limit that is the most that the barrier can divert. Ross's equations are based on numerous assumptions including steady state infiltration, semi-infinitely thick soil layers, and the quasi-linear approximation (see Theoretical Considerations) for the hydraulic properties of the soil. Ross's solutions provide useful information about lateral diversion for the design of capillary barriers. Ross also analyzed the horizontal flux as a function of distance above the fine/coarse interface. He derived a relation which predicts the effective thickness of the fine layer where most of the moisture is laterally diverted.

Steenhuis, *et al.* [5], proposed extensions for Ross's solution of diversion length. They mention that the interface between the fine and coarse layers does not necessarily produce a stable wetting front, and fingers will normally appear at the structural interface. They also suggest that the quasi-linear approximation for hydraulic conductivity is not reliable for moisture contents near saturation. They revised Ross's solution for diversion length by using a different estimate of hydraulic conductivity as a function of matric suction.

Stormont [6] expanded on Ross's solution to incorporate the effect of a constant hydraulic conductivity anisotropy of the fine layer. Stormont's solution contains the diversion due to the capillary barrier (as expressed by Ross) which is summed with the lateral water movement as a consequence of the anisotropy of the fine layer. Stormont found that the increased diversion length considering anisotropy is approximately proportional to the ratio of the principal hydraulic conductivities in the fine layers.

Numerical modeling

Oldenburg and Pruess [7] used numerical methods to investigate the behavior of capillary barriers. Their work seems to support the theoretical presentation by Ross [4] and validates the use of the quasi-linear approximation. At the same time, they point out that the breakthrough develops gradually and appears to be much more complicated than the assumptions of Ross. The breakthrough is characterized by a large downward flux through the contact. This large leakage tends to dry out the fine layer, and the barrier becomes effective again in the down-dip direction. They also develop a relationship between the breakthrough and the contrast in sorptive numbers (see Theoretical Considerations) between the layers.

Field tests

Miyazaki [8] performed experiments to determine lateral flow at an inclined interface between a fine-grained soil and a coarse-grained soil. He performed laboratory box tests, containing a sandy loam as the fine soil, with either a sandwiched plant layer or gravel layer for the coarse soil. Miyazaki observed that the advance of the wetting front from a constant infiltration rate stopped at the interface between the fine soil and the second plant or gravel layer and entered the second and third layers at the lower edges of the slopes. Miyazaki points out that the water flow from the fine to coarse layer is diverted laterally along the interface. Miyazaki illustrated the concept of lateral diversion of moisture from an inclined interface of a capillary barrier.

Nyhan, *et al.* [9], performed a three-year field study to compare the performance of an improved landfill cover including a capillary barrier to a conventional landfill cover. The conventional cover consisted of 20 cm of topsoil over 108 cm of crushed tuff. The improved design contained from top to bottom: 71 cm of topsoil, a geotextile on a 5% slope, 46 cm of gravel, 91 cm of cobble, and 38 cm of tuff with a drain. The purpose of the geotextile was to create a sharp interface between the capillary barrier layers. The cobble layer was used to minimize biointrusion. The improved landfill cover had a reduced percolation through the entire cover of more than a factor of four compared to the conventional landfill cover. Nyhan attributes the reduced percolation of the improved cover to the capillary barrier effect of retaining moisture in the fine layer. This moisture is then available for evapotranspiration and helps to sustain the vegetation present on the cover which in turn reduces erosion of the cover. The study illustrates some of the positive effects of a capillary barrier, but in practical terms, the improved cover is 246 cm thick as opposed to the 128 cm conventional cover. This improvement would greatly increase the cost of placement and reduce the space for waste within the facility.

Hakonson, *et al.* [10], presented results of a field demonstration of various capping experiments conducted at Hill AFB, Utah. The field experiments were performed with lysimeters and involved four designs: a typical soil cover to serve as a baseline, a modified Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) cover, and two variations of a Los Alamos design, each of which contained erosion control measures, vegetative covers and a capillary barrier. The field test was subjected to ambient precipitation. The capillary barriers consisted of a sandy loam over a gravel with a geotextile as a filter between the layers. All of the layers were on a 4% slope to divert flow laterally. Hakonson reported that 24% of the total precipitation passed through the typical soil cover. The capillary design with enhanced vegetation reduced leachate production by about a factor of 2, but the barriers failed during the spring time with rapid soil wetting. The RCRA cap (clay hydraulic barrier) was most effective in reducing leachate production. Hakonson's comments on the capillary barriers were, "The ability of the capillary barrier to divert soil water laterally is a strong function of the hydraulic conductivity of the fine grained topsoil immediately above the gravel capillary break and on the slope angle on the topsoil and gravel interface. Two possible capillary barrier design options to further improve leachate control might be to increase the slope on the capillary barrier and/or to use a layer of material (i.e., sand) with a higher hydraulic conductivity, just above the capillary break, to promote faster lateral soil water flow rates."

Stormont [1] reported on field tests performed on two capillary barriers. The capillary barriers were constructed in boxes with a length of 7.0 meters, and the interface between the fine and coarse layers had a 5% slope. One barrier maintained a 90 cm, homogeneous, fine soil layer over a 25 cm gravel. The other barrier had a fine soil layer that was layered: three layers of fine soil, 20 cm each, and three layers of fine-grained sand, 10 cm each. This entire layer was above 25 cm of gravel. The barriers were subjected to a constant infiltration rate of .5 cm/day. Stormont found that the layered design was much more effective in laterally diverting water than the barrier with the homogeneous profile. Ninety-nine percent of the water which moved out of the non-homogeneous fine layer was laterally diverted beyond a 6 m length.

Schultz, *et al.* [11], reported on field tests being performed at a humid region site at Beltsville, Maryland. The performance of three different cover designs in various combination were being compared for use as surface barriers. One cover was the combination of a resistive clay layer overlying a conductive barrier (capillary barrier). The barrier was made of diatomaceous earth as the fine layer and gravel as the coarse layer. The resistive layer kept flow rates less than 10^{-6} cm/s from entering the capillary barrier. The barrier performed without moisture entering the coarse layer for three to four years. After three to four years .13 cm of water passed through cover. The research illustrates the performance of a capillary barrier in a humid region where the infiltration rate into the barrier is controlled. In this study, lateral diversion was the main mechanism to remove the moisture from the fine layer of the capillary barrier. The fine layer served as a transport layer to laterally divert the moisture. The conductive barrier used in these tests did not perform as well as expected by the researchers. The cover system was expected to limit all moisture from passing through the cover.

The field tests on capillary barriers indicate that lateral diversion can be achieved in practice. The literature also indicates that diversion lengths must be increased for the barriers to be practical. The barriers need to have the capacity to divert water during the months of high infiltration from rainfall and snowmelt.

Stormont's [1] field tests are the only experimental work based on a transport layer concept. Hakonson, *et al.* [10], point out that the hydraulic conductivity of the soil immediately above the interface needs to be increased for better diversion performance. A combination of Stormont's [1] field work and the recommendation of Hakonson, *et al.* [10], suggest a capillary barrier with a layer of sandy material (with increased hydraulic conductivity compared to that of the fine layer) placed over the interface to improve the lateral flow capacity of the barrier.

THEORETICAL CONSIDERATIONS

Ross [4] developed analytical relationships for the diversion length (L) and the diversion capacity (Q) of a capillary barrier. Ross [4] used equations based on constant infiltration into the fine layer and semi-infinite layers of soil. The relationships for diversion length and diversion capacity were based on a quasi-linear approximation of the hydraulic conductivities of the materials [12]. The quasi-linear approximation is a simplified relation between the saturated and the unsaturated hydraulic conductivities of the porous media being considered.

Quasi-linear approximation:

$$K = K_s e^{a\psi} \tag{1}$$

where K = hydraulic conductivity (L/T), K_s = saturated hydraulic conductivity (L/T), a = sorptive number (1/L), and ψ = matric suction (L).

Steenhuis, *et al.* [5], used a more realistic relationship for the hydraulic conductivity than the quasi-linear approximation. Ross's solution for the upper bound of the effective length of the capillary barrier as modified by Steenhuis, *et al.* [5], is

$$L \le \tan\phi \left[a^{-1}\left(\frac{K_s}{q} - 1\right) + \frac{K_s}{q}\left(h_a - h_w^*\right)\right] \tag{2}$$

where ϕ = dip angle of the interface from the horizontal, q = infiltration flux (L^2/T), h_a = effective air entry value (L), h_w = effective water entry value (L), and * = denotes properties of the coarse layer.

The sorptive number (a) indicates the relative effects of gravity and capillary forces on the fluid flow within the material void space. If the sorptive number is small, then capillary forces dominate. If the number is large, then gravity forces dominate, indicating a coarser-grained soil with larger diameter pore spaces.

Stormont [6] adapted Ross's solution to accommodate the effects of constant anisotropy on the fine-layer.

$$L \le \frac{K_{xx}^s \tan\phi}{q\ a}\left[\left(\frac{q}{K^{s*}}\right)^{\frac{a}{a^*}} - \frac{q\cos\xi}{K_{zz}^s \cos\phi}\right] + \left(\frac{K_{xx}^s}{K_{zz}^s} - 1\right)(\tan\phi\cos\xi)(b) \tag{3}$$

where K_{xx}^s and K_{zz}^s are the saturated hydraulic conductivity parallel and normal to the dip direction, respectively (L/T), ξ = angle between vertical and the direction normal to the dip direction, and b = width of the fine layer (L).

Stormont's derivation suggests that an increase in the hydraulic conductivity in the down-dip direction could increase the length and diversion capacity of the system. The increased length is approximately proportional to the ratio of the principal hydraulic conductivities. By increasing the ratio of the hydraulic conductivities parallel and normal to the dip direction, the effective length of the barrier increases.

Ross [4] considered the effect of layer thickness on the diversion length of capillary barriers. Although his derivations were based on semi-infinite layers of soil, he derived a relationship for lateral flux as a function of the distance above the fine-coarse interface:

$$q_h = \left[\left(\frac{q}{K_s^*}\right)^{\frac{a}{a^*}} - \frac{q}{K_s}\right] K_s e^{a\cos\phi\, z} \cos\phi \sin\phi \tag{4}$$

where z = distance in the direction normal to the dip direction from the fine-coarse interface (L) and q_h = lateral flux (L^2/T)

From Equation 4 we see that the horizontal flux is a strong function of vertical distance (z). The distance (z) is zero at the fine/coarse interface, and the negative direction is towards the ground surface of the capillary barrier. By a distance of 3 $(\alpha \cos\phi)^{-1}$, the flux is only 5% of that at the interface. For typical soils, the sorptive number (a) is on the order of .05 cm^{-1} to .2 cm^{-1} [13]; for a sand, .1 cm^{-1} is appropriate. Most interface slopes are less than 10 degrees; we can assume cos(ϕ) approaches 1. Thus, a sand may effectively divert the majority of the flow in a region of thickness of about z = $(\alpha \cos\phi)^{-1}$ = 10 cm immediately above the interface. Nearly all of the flow will occur within a distance of two or three times the distance $(\alpha \cos\phi)^{-1}$ from the interface. This result suggests that rather than constructing an anisotropic fine layer, a relatively thin layer with a relatively great hydraulic conductivity (a transport layer) could dramatically increase the diversion length [1].

Ross's [4] derivation of lateral flux as a function of vertical distance suggests that only one layer of material is necessary. Stormont's [1] field tests indicate that a sandy material may prove successful as a transport layer. The layer should be located above the interface, and the thickness of the layer is dependent on the sorptive number of the material considered. For sands, this distance is expected to be on the order of 10 cm or less. Different materials should be considered to find the most effective transport layer.

SELECTION OF SOILS

This section describes analysis of various soils to determine which materials are the most appropriate for use as a hydraulic transport layer material within the capillary barrier. Properties of all of the soils are presented.

Preliminary considerations

The goals of the transport layer are to increase the diversion length of the capillary barrier as much as possible, but it must be economically feasible for large scale construction. The most inexpensive soil to use at a landfill site would be the local soil. The local soil can be "tailored" by sieving out portions of the grain-size distribution to produce a suitable transport layer. Sands used for concrete and construction are relatively inexpensive and may also be candidates for the hydraulic transport layer.

Material used for fine soil layer

For reasons of availability and convenience, the first soil to consider for use as the fine layer for a capillary barrier would be the local soil at the site of construction. The fine layer considered in this study is a composite of soil samples obtained from a test landfill site at Sandia National Laboratories, Albuquerque, NM. Nine soil samples were obtained from the site. An equal portion (by weight) of the nine samples were combined to produce a composite mix (denoted as MIX), which is classified as a silty sand by the USCS classification. The sample was split with the US sieve #4 (4.75 mm) and the large particle portion was discarded. Desorption data and saturated hydraulic conductivity data were obtained for the sample to use in numerical modeling as the fine soil layer. van Genuchten parameters describe the hydraulic conductivity vs. matric suction relations for a soil. They are derived from a non-linear regression of the moisture characteristic curve of a sample.

Material used for coarse soil layer

The coarse layer considered in this study is a gravel. Moisture characteristics of the coarse soil (van Genuchten parameters) are obtained from Fayer, *et al.* [14].

Transport layer material

The soil sample taken from the SW corner of the experimental landfill site was chosen as the local soil to be tailored for transport layers. The decision was based on availability of the soil, and the SW sample had a grain-size distribution that closely resembled the composite sample MIX, which was used for the fine layer. The SW sample was sieved through the #4 U.S. standard sieve size (4.75 mm) and material passing was used. This was necessary to provide a more well-sorted sample. The material passing the #4 sieve was further tailored by discarding of the fine portion of the material. Four samples were obtained, all of the material passed the #4 sieve and was retained on either the #200, #140, #60, or the #40 sieves.

To determine which tailored soils might perform well as transport layer material, hydraulic conductivies were approximated using Schlichter's method [15]. At near

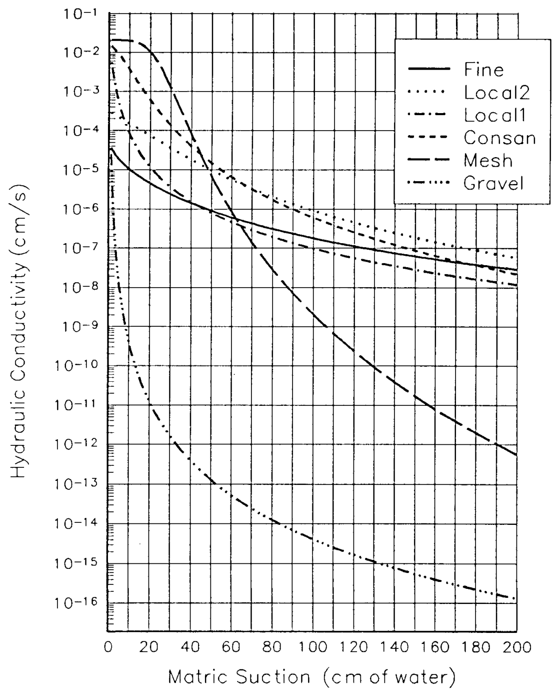

FIGURE 2. HYDRAULIC CONDUCTIVITY VS. MATRIC SUCTION.

saturation conditions (i.e., low matric suction values), the sample retained on the #200 sieve and the sample retained on the #60 sieve had hydraulic conductivity values smaller than the other two samples. The sample retained on the #200 sieve and the sample retained on the #60 sieve were discarded. The soil retained on the #40 sieve (local1) and the soil retained on the #140 sieve (local2) would be considered as potential transport layer materials.

Stormont's [1] field tests indicate that a sandy soil may function well as a transport layer. Two sands were chosen for simulation: a construction sand (Consan) and a 100-mesh sand (Mesh).

Local1

Local1 was a soil tailored from the SandiaSW sample and is classified as a SM (silty sand) by the USCS classification system. Only the material passing the #4 sieve and retained on the #40 sieve was used. The USCS classification of this tailored soil was an SP with gravel (poorly graded sand with gravel). The coefficient of uniformity (C_u) was 3.3, and the coefficient of concavity (C_c) was .76.

$$C_u = \frac{D_{60}}{D_{10}} \quad and \quad C_c = \frac{(D_{30})^2}{(D_{10})\,(D_{60})}$$

where C_u = coefficient of uniformity, C_c = coefficient of concavity, and D_x = diameter of particle (mm) where x percent is finer.

The coefficients are used to determine whether the sample is well-graded or poorly graded. A sample must have a $C_u \geq 4$ and a $1 < C_c < 3$ to be considered well-graded.

Over 50% of this soil was composed of fine gravel; the rest was coarse sand with only about 8% of the sample falling into the medium sand category.

van Genuchten properties were determined from hanging column tests. The sample had van Genuchten properties of θ_r = .4%, α = .274, and n = 1.42. The saturated hydraulic conductivity of the sample was .028 cm/s with a porosity of almost 50%. Due to the large, well-sorted particles, packing ability was minimal. The hydraulic conductivity vs. matric suction curve for this soil may be observed in Figure 2. The hydraulic conductivity of the Local1 soil was approximately half of an order of magnitude greater than that of the fine soil at 15 cm of water matric suction. The hydraulic conductivity of the Local1 soil approached the hydraulic conductivity of the fine layer as matric suction values increased. At 40 cm of water matric suction, the fine and Local1 soils had the same value of hydraulic conductivity. At matric suction values greater than 40 cm of water, the Local1 soil had hydraulic conductivity values smaller than that of the fine soil layer.

Local2

As with the Local1 soil, the Local2 soil was tailored from the SandiaSW sample. The sample contained material passing the #4 sieve and retained on the #140 sieve. The soil had a $C_u = 2.27$ and a $C_c = .524$. The USCS classification was an SP (poorly graded sand) with gravel. Unlike the Local1 soil, the Local2 soil contained about 50% fine sand. The other portions consisted of 20% fine gravel, 10% coarse sand, and 20% medium sand. The soil had van Genuchten properties of $\theta_r = 2.36\%$, $\alpha = .026$, and n = 1.9. The saturated hydraulic conductivity measured 3.1 x 10^{-4} cm/s with a porosity of 41.3%. The hydraulic conductivity vs. matric suction can be viewed in Figure 2. The hydraulic conductivity of the Local2 soil had an effective range of greater hydraulic conductivity than the fine layer from about 60 cm to 1 cm; yet the hydraulic conductivity was only about 1 magnitude greater.

Consan

The construction sand was classified as an SP (poorly graded sand). It had a $C_u = 4.25$ and a $C_c = .94$. The soil had a little more than 20% fine gravel, 35% coarse sand, 35% medium sand, and 10% fine sand.

The van Genuchten properties of the sand were $\theta_r = .77\%$, $\alpha = .0634$, and n = 2.12. The sand had a saturated hydraulic conductivity of .016 cm/s with a porosity of 37%. The sand was more well-graded than the other samples and could reach a density of 1.8 g/cc with simple vibratory compaction (i.e., shaking on a table in a graduated cylinder). The sand had a tendency to assume a denser state than the other samples. The matric suction and hydraulic conductivity relationship is presented in Figure 2. Figure 2 shows the Consan to have a greater hydraulic conductivity than the fine soil from 50 cm of water to 1 cm of water (i.e., saturation). At 50 cm of water matric suction, the Consan had a hydraulic conductivity one order of magnitude greater than the fine soil. At 15 cm of water matric suction, the hydraulic conductivity of the Consan was over 2.5 orders of magnitude greater than that of the fine soil layer.

Mesh

The sand was classified as an SP (poorly graded sand) with a Cu = 2.5 and a Cc = 1.11. The soil contained about 5% coarse sand, 65% medium sand, and 30% fine sand.

The soil had $\theta_r = 3.15\%$, $\alpha = .0375$, and n = 4.944. The saturated hydraulic conductivity was .021 cm/s with a porosity of 46%. The 100-mesh sand contained particles that were well-rounded and very similar in diameter size. They do not pack as well as a better graded sample. The matric suction vs. the hydraulic conductivity is presented in Figure 2. Figure 2 shows that the hydraulic conductivity of the 100-mesh sand is over 1.5 orders of magnitude greater than the fine layer at 40 cm of matric suction. The difference increased as matric suction dropped, and around the water-entry value of the coarse layer (≈ 15 cm) the hydraulic conductivity of the Mesh was 3 orders of magnitude greater than the fine layer. The Mesh appeared to be the most promising material for an effective transport layer.

NUMERICAL MODELING

The numerical code used to simulate the capillary barrier was TRACR3D [16]. The program uses an implicit finite difference solution scheme and models time-dependent mass flow and chemical species transport in a three-dimensional, deformable,

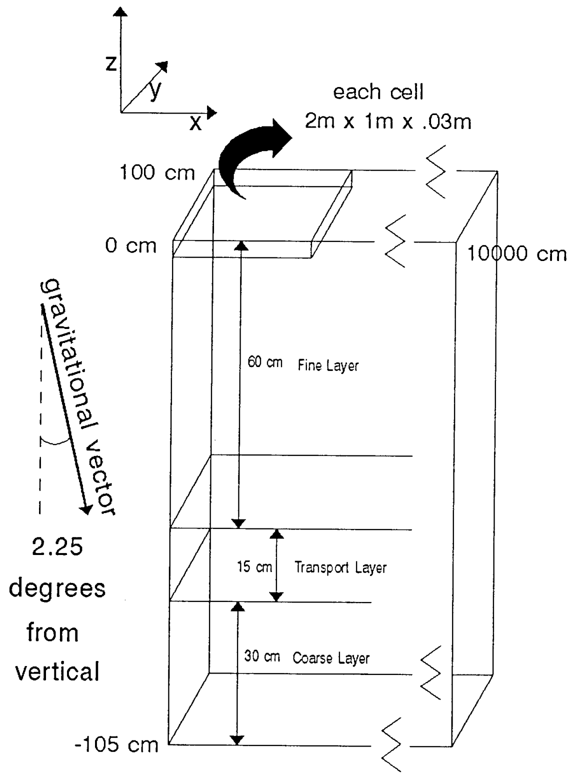

FIGURE 3. FINITE DIFFERENCE MESH USED FOR SIMULATIONS.

heterogeneous, sorptive porous medium. The code will calculate water or air flow for steady or transient, one-, two-, or three-dimensional geometries, saturated or unsaturated conditions. The main equations of the program are the mass and chemical species conservation equations, a reduced form of the momenta equations, and an equation of state plus several constitutive relationships. For the purposes of this study, the van Genuchten parameter option was used in the program to model the hydraulic conductivity properties of the soil.

Figure 3 is an illustration of the finite difference mesh used for the simulations. The mesh was one cell wide in the y-direction and, therefore, represented a two-dimensional configuration. The vertical (z-direction) component of the mesh corresponded to a capillary barrier 105 cm thick: 60 cm of fine layer soil, 15 cm of transport layer material, and 30 cm of coarse layer soil. For the baseline simulation, the transport layer was converted to fine layer material, thus representing a 75 cm fine layer overlying a 30 cm coarse layer. The x-direction was the axis of down-dip length and measured 100 m for the simulation. The point x = 0.0 cm was the up-dip limit, and x increased in the down-dip direction. Each cell of the mesh measured x = 100 cm, y = 200 cm, and z = 3 cm, thus there were 100 cells in the x-direction, 1 cell in the y-direction, and 35 cells in the z-direction. Of the 35 cells located in the z-direction, 20 were in the fine soil layer, 5 cells were in the transport layer, and 10 cells were in the coarse layer. Cells of particular interest were centered at z = -73.5 cm. These were the cells in the transport layer adjacent to the coarse layer/transport layer interface. The matric suction values in this layer of cells was indicative of a possible failure of the capillary barrier. Also, the layer of cells centered at z = -76.5 cm were significant. These were the cells located in the coarse layer adjacent to the transport layer. Any flux of moisture into this layer of cells indicated that moisture was entering the coarse layer from the transport layer and constituted failure of the capillary barrier. The simulation was performed with a fine/coarse interface angle of 2.25 degrees. The interface angle was simulated by redirecting the gravity vector 2.25 degrees from the vertical axis.

A significant aspect of the simulation was the method of unsteady infiltration introduced. Analytical solutions to determine diversion lengths (e.g., [4]) assume a constant infiltration rate into the top of the fine soil layer. A constant infiltration rate is not a realistic representation of the daily variations in climate experienced for a near surface cover system. Therefore, data representative of the Albuquerque, NM, climate for one year was implemented into the simulations. The method used a daily effective flux (DEF), which is dependent on the climate. The DEF is explained by Morris and Stormont [17] as the amount of moisture into or out of the cover each day.

$$DEF = PI - RO - ET \tag{5}$$

where DEF = daily effective flux (cm), ET = evapotranspiration (cm), RO = runoff (cm), and PI = potential infiltration (cm).

Morris and Stormont [17] used the Hydrologic Evaluation for Landfill Performance (HELP) model developed by the Environmental Protection Agency (EPA) to generate climate data for New Mexico for one year. The HELP model cannot simulate a capillary barrier since the model considers moisture under the influence of gravitational force and does not consider the matric suction forces which can dominate in an unsaturated media. Equation 5 shows that the DEF is a function of the potential infiltration. Potential infiltration is not dependent on a particular cover design; it is dependent on the climate only. It is affected by factors such as air and soil temperature, precipitation quantity and form, solar radiation, wind speed and duration, and plant type and growth. Equation 5 shows that the DEF is also a function of the evapotranspiration and the runoff. Both the evapotranspiration and runoff are design-dependent parameters. Factors such as the slope of fine layer surface, vegetation, soil types, and densities will affect the runoff and evapotranspiration. Therefore, the DEF is a design-dependent parameter and must be produced for each particular cover design.

The design was simulated by the HELP model to produce evapotranspiration and runoff data. The evapotranspiration is dependent on the amount of moisture present in the rooting depth thickness of the cover. Morris and Stormont [17] produced a year of infiltration and evapotranspiration data from the HELP model typical of the Albuquerque, NM, climate. The data was produced by simulating a pseudo capillary barrier in the HELP model. The model could not model the capillary forces dominant in unsaturated flow in a real capillary barrier, so the interface was modeled as a sloped moisture barrier. When the fine layer nears saturation in a capillary barrier, failure occurs; likewise, in the HELP model simulation, when saturation was reached, water began to drain along the barrier at the bottom of the fine layer. The drainage removed water that would have broken through into the coarse layer for a real capillary barrier. The HELP model was used to determine appropriate daily values of infiltration and evapotranspiration (a function of moisture content) for the pseudo capillary barrier. The values obtained from the HELP model were entered into the TRACR3D simulations as daily source/sink terms. The annual rainfall for the year of data was 25 cm; the average annual precipitation for Albuquerque is 28.37 cm. Therefore, the yearly precipitation simulated was slightly lower than average. The rooting depth (portion of the cover affected by evapotranspiration) was 60 cm, the vertical depth of the fine layer.

The advantage of the DEF was to allow pulse infiltration into the cover and the evapotranspiration terms to model that of the actual climate.

The barrier was simulated using TRACR3D. The output of flux into the coarse layer and output of matric suction values of the transport layer were analyzed to evaluate the performance of the capillary barrier without a transport layer and with different materials used as the transport layer to increase the diversion of moisture at the fine/coarse interface.

RESULTS

Baseline simulation

The baseline simulation was of a capillary barrier without a transport layer. The cells which were designated as the transport layer were assigned material properties identical to the fine layer, thus increasing the fine layer by 15 cm. The fine layer was 75 cm thick in the vertical direction, overlying a 30 cm thick gravel layer. The fine soil was at 80% initial water saturation. Integrated flux is reported in units of length and represents the volume of water that entered the cell divided by the surface area of the face of the cell perpendicular to the flux. Distance increased in the down-dip direction. The performance of each cell was evaluated by the integrated flux entering that cell. Since each cell was located at the top of the coarse layer, a flux of moisture represented moisture entering from the fine layer (i.e., failure of the interface to act as a barrier to moisture migration). A value of "breakthrough" for the simulations were the first signs of integrated flux into the coarse layer (i.e., breakthrough > 0.0).

The first signs of failure of the barrier occurred on day 127 at a distance of 5 m in the down-dip direction. Integrated flux increased dramatically on day 295 with a value of about 1 cm. Although a diversion length of 5 m was apparent on day 127, by day 295 the barrier showed no diversion length, with a integrated flux of .4 cm at a distance of 1m. The baseline response indicated that a simple capillary barrier will not prevent breakthrough for the conditions and assumptions of the simulations.

To increase the diversion length of the system, eight simulations were performed with different transport layer material. Diversion length was defined as the distance in the down-dip direction until the first signs of integrated flux into the coarse layer were present. Four simulations were performed with different transport layer materials beginning with 80% initial saturation. The same configurations were used for a second simulation, only the initial saturation of the transport layers was 20%. Matric suction values in the transport layer were observed for the four simulations at transport layer initial saturation of 20%. Matric suction data for the simulations at 80% initial moisture saturation were not obtained.

Local1

The capillary barrier was modeled with a layer consisting of the Local1 soil. Local1 soil was derived from the SandiaSW sample: material passing the #4 sieve and retained on the #40 sieve. At 80% initial saturation, the water in the transport layer moved into the coarse layer within the first time iteration, corresponding to two weeks. The coarse layer began receiving moisture at 169 days at a length of 5 m. A substantial increase of coarse layer moisture occurred after 295 days. Integrated flux on day 295 ranged from .10 to .25 cm along the interface. By day 295, the diversion length of 5 m that was displayed at 169 days had disappeared and an integrated flux of about .10 cm was present at a length of 1 m.

To understand the behavior of moisture migration into the coarse layer, matric suction values of the finite difference cells in the transport layer directly above the interface were considered as a function of length and time. The matric suction at a time of 0 days with a saturation of 20% was 180 cm of water, which followed directly from the moisture retention characteristics of the material. After 15 days, some of the moisture initially present in the fine layer had entered the transport layer. Failure occurred when the matric suction values dropped to approximately 14 cm of water. This corresponded to the water entry pressure of the coarse soil. On day 15, matric suction values had dropped to about 18 to 19 cm of water in the bottom of the transport layer. The Local1 material did not prove to be an effective transport layer. This conclusion was supported with Figure 2. Figure 2 illustrates the hydraulic conductivity vs. matric suction behavior of the Local1 soil compared to that of the fine layer. The hydraulic conductivity of the Local1 soil was about 1 order of magnitude greater than that of the fine layer soil at 10 cm of water matric suction. The curves crossed at a matric suction value of 40 cm of water and the value of hydraulic conductivity for Local1 was greater than that of the fine layer until saturation. Therefore, the transport layer did not improve the ability of the capillary barrier to divert moisture until a matric suction value of 40 cm of water was reached and, as the layer became wetter, the improvement in hydraulic conductivity over the fine layer was never more than 1 order of magnitude. The relationship between hydraulic conductivity and matric suction supported the results obtained from the numerical modeling.

Local2

The capillary barrier was modeled with a transport layer composed of the Local2 material. The Local2 material was derived from the SandiaSW sample using the material passing the #4 sieve and retained on the #140 sieve. Thus, the soil contained more fines than the Local1 soil. The first simulation with the Local2 soil was performed with an initial saturation of 80% for the transport layer. Moisture began to enter the coarse layer by 99 days, with a flux of 5.0×10^{-5} cm at a length of 11 m. A gradual increase in the moisture entering the coarse layer occurred until day 281, with a integrated flux of about .25 cm of water. A large increase in coarse layer moisture occurred on day 295 with integrated flux values of 0.8 to 0.9 cm of water at lengths of 20 m and greater. A flux of 4.0×10^{-4} cm of water occurred at a length of 3 m on day 295. Therefore, the initial diversion length of 11 m observed on day 99 had decreased to 3 m by day 295.

The second simulation using the Local2 soil was performed with an initial saturation of 20% for the transport layer. The simulation showed no signs of moisture entering the coarse layer. The matric suction did not drop below 30 cm of water for the 1 year simulation. The water entry value of the coarse layer was approximated at 14 cm of water from earlier simulations. Thus, water entry into the coarse layer was not expected. On day 295 the matric suction value at a length of 1 m was 37 cm of water and at a length of 9 m it had decreased to 31 cm of water and remained at 31 cm of water for the 73 m of interface length considered in the simulation. The matric suction decrease of 6 cm of water from 1 m length to 9 m length implied that the soil was wetter in the down-dip direction for the first 9 m. Therefore, diversion was occurring for the first 9 m of length in the down-dip direction. This was consistent with the first simulation of the Local2 soil as the transport layer, which showed an initial diversion of moisture 11 m on the 99th day.

Figure 2 shows the hydraulic conductivity as a function of matric suction of the Local2 soil compared to that of the fine soil layer. The hydraulic conductivity of the Local2 soil was about 1 order of magnitude greater than that of the fine soil layer for matric suction values of 100 cm of water to saturation (0 cm of water). The Local2 soil had better hydraulic conductivity properties as compared to the fine soil than did the Local1 soil as shown in Figure 2. The Local1 soil did not have a hydraulic conductivity value 1 order of magnitude greater than that of the fine soil layer until the soil had a matric suction value of about 10 cm of water. This supported the simulations which found that the Local2 soil performed better than the Local1 soil for moisture diversion in the capillary barrier.

Consan

The Consan soil was a typical concrete sand, readily available and relatively inexpensive. The material was simulated as the transport layer in the capillary barrier. The first simulation was with the transport layer at 80% initial saturation. The initial moisture content was so great, that the matric suction value was smaller than the water entry value of the coarse layer and the moisture entered the coarse layer within the first time iteration.

The second simulation was performed with the transport layer at initial saturation of 20%. Moisture entered the coarse layer on day 295, at a length in the down-dip direction of 37 m and a flux of 7.5×10^{-6} cm of water. The integrated flux increased to a value of 1.1×10^{-4} cm of water at a down-dip length of 37 m by the end of the simulation on day 365. The same day yielded an integrated flux of .01 cm of water at a down-dip length of 55 m The first signs of flux into the coarse layer occurred on day 295 at a length of 37 m, which corresponded to a matric suction value of about 14 cm of water. The matric suction value of 14 cm of water was consistent with the results from the simulation of the Local1 soil as the value of matric suction which corresponded to the water-entry value of the coarse layer. The flux into the coarse layer began to decrease on day 309 as the matric suction began to rise in the transport layer. The rise in the matric suction of the transport layer was due to the moisture removed from the transport layer in the form of flux into the coarse layer.

Figure 2 compares the hydraulic conductivity vs. matric suction for the Consan to the fine layer soil and the other soils considered as transport layer material. At matric suction values of 50 cm of water, the Consan had a hydraulic conductivity of about 1 order of magnitude greater than that of the fine layer soil. At matric suction values of 14 cm of water (corresponding to the water-entry value of the coarse layer), the Consan had a hydraulic conductivity of 2 orders of magnitude greater than that of the fine soil layer. This was consistent with the data in Figure 2, which suggested that the Consan should perform better at *diverting* water than the Local1 and the Local2 soils. The Local2 soil displayed a greater storage capacity than the Consan by not breaking through at 20% initial moisture saturation. The Consan showed a diversion length of 37 m before any moisture entered the coarse layer.

Mesh

The 100-mesh sand was a finer, more well-sorted and a more expensive material than the construction sand. The Mesh soil was used as the transport layer material for the capillary barrier. The first simulation was performed at an initial saturation of 80%. There was no flux into the coarse layer during the 365-day simulation.

The second simulation had an initial saturation of 20% in the transport layer. The coarse layer showed no flux of water entering for the one-year simulation. The lowest value of matric suction occurred on day 295 at a down-dip length of 73 m with a value of 25 cm of water. The 25 cm of water was greater than the 14 cm of water entry value for the coarse layer, and flux into the coarse layer should not have occurred. The matric suction values at a length of 1 m were about 20 cm of water greater than the values at a down-dip length of 73 m for any particular time step. This showed that the water content was increasing in the down-dip direction and lateral diversion was occurring.

Figure 2 compares the hydraulic conductivity vs. matric suction relationship for the transport layer materials including the Mesh soil and the fine layer soil. The Mesh material had a hydraulic conductivity about 1 order of magnitude greater than that of the fine layer soil at a matric suction value of 50 cm of water. The hydraulic conductivity value of the Mesh soil increased to about three orders of magnitude greater than that of the fine layer soil at a matric suction value of 14 cm of water, which corresponded to the water entry value of the coarse soil. The hydraulic conductivity vs. matric suction relationship for the Mesh material indicated that the Mesh soil should have performed well compared to the other transport layer materials at laterally diverting moisture. This supported the simulation results that showed no moisture entering the coarse layer for the down-dip length of 55 m and the 365-day time length of the simulation. The fact that no breakthrough occurred implied that the Mesh soil had the ability to divert moisture a down-dip length greater than the 55 m used for the simulation.

DISCUSSION

Performance of materials

The Local2 soil had greater values of moisture content at matric suction values greater than 30 cm than any of the other transport layer materials considered. At 20% initial moisture saturation, the value of matric suction is 310 cm of water for the Local2 soil. The values of matric suction at 20% saturation for the Mesh, Consan, and Local1 were: 44 cm, 72 cm, and 182 cm, respectively. Therefore, the Local2 soil has greater amounts of moisture at most values of matric suction than the other soils. This implies a greater storage capacity of moisture for the Local2 soil. Thus, the Local2 soil was able to store moisture without reaching breakthrough for the simulation at 20% initial saturation. The simulation at 80% initial saturation lowered values of matric suction in the Local2 soil to the water entry value of the coarse layer, and breakthrough was displayed. Thus, the Local2 soil may provide adequate performance in an unsloped barrier (i.e., moisture removed only by evapotranspiration, not lateral diversion), but it does not perform well in terms of moisture diversion.

The Mesh soil attains a great storage capacity at 14 cm of water (i.e., the water entry value of the coarse soil). At 15 cm of matric suction the moisture content of the Mesh, Consan, Local2, and Local1 soils are .45, .27, .38, and .27, respectively. This implies that before breakthrough occurs, the Mesh sample was able to store a large portion of water within the transport layer. This supports the results of no breakthrough encountered for the Mesh soil at 80% initial saturation.

The diversion length for the simulations is the horizontal length water travels until first signs of moisture entry from the transport layer into the coarse layer. At an arbitrary length of 37 m, all of the samples except the Mesh were allowing moisture migration into the coarse layer. Although all of the materials had failed in that they permitted breakthrough, the amount of moisture entering the coarse layer from the Consan soil was considerably smaller than that of the other materials considered. The Consan soil reached a maximum cumulative flux of about 1.0 x 10^{-4} cm of water whereas the other samples ranged from 0.4 cm of water to 1.0 cm of water cumulative flux into the coarse layer at the same time of 365 days.

Comparison of materials

The Mesh and the Consan were similar materials. The Mesh and the Consan were both SP (poorly graded sands). Both materials contained about 1% fines, yet the Mesh soil contained greater portions of finer material than the Consan. The Consan was more "well-graded" with a C_u of 4.25 whereas the Mesh had a C_u of 2.5.

It appears that the amount of fines has an impact on the performance of the materials. As the amount of fines in the soil increased, the capacity of the soil to laterally divert water increased.

An important consideration for the design of a capillary barrier is the cost of producing or obtaining the transport layer materials in the field. The Mesh sand is relatively expensive as compared to the Consan; a similar material to the Consan could be purchased at any construction material supply yard. The process of tailoring materials on-site may become expensive due to the cost of sieving and the material yield for a particular grain-size portion. For example, the Local1 soil was derived from the SandiaSW sample, yet the portion of the SandiaSW sample between the #4 and the #40 was approximately 10% of the entire sample. Therefore, it would take 10 tons of local soil to produce 1 ton of transport layer material.

CONCLUSIONS

The Mesh soil appears to have performed the best as a transport layer material. Although a diversion length was not defined from the simulations, the matric suction values indicate that lateral diversion of moisture is occurring in the transport layer and the diversion length may be greater than 73 m. The Consan soil performed well enough to be considered as a possible design material. The diversion length of the Consan was defined as 37 m, although the amount of moisture entering the coarse layer at 37 m was significantly smaller then the calculated fluxes from the Local1, Local2, and baseline simulations. The Local2 soil outperformed the Consan and Local1 soils in terms of storage capacity. Storage capacity is an important parameter for unsloped barriers.

The results show that the implementation of a transport layer in the bottom of the fine soil layer of a capillary barrier can significantly increase the diversion length of the capillary barrier. A capillary barrier performs well in semi-arid regions where the evapotranspiration is high and the infiltration is low. The simulations modeled actual climate behavior for Albuquerque, NM, by introducing unsteady infiltration and evapotranspiration. Experimental verification of the transport layer concept should be carried out with various materials used in the transport layer for the Albuquerque, NM, climate.

REFERENCES

1. J.C. Stormont, The performance of two capillary barriers during constant infiltration, Landfill Closures, ASCE Special Geotechnical Publication No.

53, Annual ASCE Convention, October 1995, San Diego, CA, 1995, pp. 77-91.

2. D.E. Daniel, Surface barriers: Problems, solutions, and future needs, Thirty-third Hanford symposium on health and the environment, In-situ remediation: Scientific basis for current and future technologies, part 1, November 7-11, Pasco, Washington, 1994, pp. 441-487.

3. D.E. Daniel and Y.-K. Wu, Compacted clay liners and covers for arid sites, J. Geotech. Engrg., 119:2 (1993) 223-237.

4. B. Ross, The diversion capacity of capillary barriers, Water Resour. Res., 26:10 (1990) 2625-2629.

5. T.S. Steenhuis, J.-Y. Parlange, and K.-J.S. Kung, Comment on “the diversion capacity of capillary barriers” by Benjamin Ross, Water Resour. Res., 27:8 (1991) 2155-2156.

6. J.C. Stormont, The effect of constant anisotropy on capillary barrier performance, Water Resour. Res., 31:3 (1995) 783-785.

7. C.M. Oldenburg and K. Pruess, On the numerical modeling of capillary barriers. Water Resour. Res., 29:4 (1993) 1045-1056.

8. T. Miyazaki, Water flow in unsaturated soil in layered slopes, J. Hydrol., 102 (1988) 201-214.

9. J.W. Nyhan, T.E. Hakonson, and B.J. Drennon, A water balance study of two landfill cover designs for semiarid regions, J. Environ. Qual., 19 (1990) 281-288.

10. T.E. Hakonson, K.V. Bostick, L.J. Lane, G. Trujillo, R.W. Warren, W. Wilson, J.S. Kent, and K.L. Manies, Hydrologic Evaluation of Four Landfill Cover Designs at Hill Air Force Base, Utah, Los Alamos National Laboratory report LAUR-93-4469, 1994.

11. R.K. Schultz, R.W. Ridky, and E. O’Donnell, Control of Water Infiltration into Near Surface LLW Disposal Units, U.S. Nuclear Regulatory Commission, USA, NUREG/CR-4918(8), 1995.

12. J.R. Phillip, Theory of infiltration, Adv. Hydrosci., 5 (1969) 215-296.

13. A.J. Pullan, The quasi-linear approximation for unsaturated porous media flow, Water Resour. Res., 26 (1990) 1219-1234.

14. M.J. Fayer, M.L. Rockhold, and M.D. Campbell, Hydrologic modeling of protective barriers: Comparison of field data and simulation results, Soil Sci. Soc. Am. J., 56 (1992) 690-700.

15. M. Vukovic and A. Soro, Determination of Hydraulic Conductivity of Porous Media from Grain-Size Composition, Water Resources Publications, Littleton, Colorado, 1992.

16. B.J. Travis and K.H. Birdsell, TRACR3D: A model of flow and transport in porous media — Model description and user’s manual, Los Alamos National Laboratory, LA-11798-M: April 1991.

17. C.E. Morris and J.C. Stormont, Capillary Barriers and Subtitle D Covers: Estimating Equivalency, Journal of Environmental Engineering, accepted for publication, 1995.