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Prediction of Tilted Capillary Barrier Performance

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Abstract

Capillary barriers, consisting of tilted fine-over-coarse layers under unsaturated conditions, have been suggested as landfill covers to divert water infiltration away from sensitive underground regions, especially for arid and semi-arid regions. The Hydrological Evaluation of Landfill Performance (HELP) computer code is an evaluation tool for landfill covers used by designers and regulators. HELP is a quasi-two-dimensional model that predicts moisture movement into and through the underground soil and waste layers. Processes modeled within HELP include precipitation, runoff, evapotranspiration, unsaturated vertical drainage, saturated lateral drainage, and leakage through liners. Unfortunately, multidimensional unsaturated flow phenomena that are necessary for evaluating tilted capillary barriers are not included in HELP. Differences between the predictions of the HELP and those from a multidimensional unsaturated flow code are presented to assess the two different approaches. Comparisons are presented for the landfill covers including capillary barrier configurations at the Alternative Landfill Cover Demonstration (ALCD) being conducted at Sandia.

I. Introduction

The Alternate Landfill Cover Demonstration is a series of large-scale landfill test covers that have been constructed at Sandia National Laboratories in Albuquerque, New Mexico (Dwyer, 1995). Each cover is 13 m wide and 100 m long. The 100 m length is crowned in the middle, resulting in two 50 m long sections each with a 5% slope. One side is exposed to ambient conditions, while additional water is added to the other side to stress the barriers to the desired storm events. Two traditional cover designs and four alternatives, including tilted capillary barriers, are being tested and are shown in Figure 1. Plot 1, a RCRA Subtitle "D" cover, is simply topsoil over a compacted soil barrier layer. Plot 2 is a Geosynthetic Clay Liner (GCL) cover with topsoil, sand and a geomembrane on top of the GCL. Plot 3 is a compacted clay cover that simply replaces the GCL in Plot 2 with a compacted clay barrier layer, or a RCRA Subtitle "C" cover. Plot 4 is a tilted capillary barrier consisting of topsoil over sand and gravel layers followed by a barrier layer and another sand layer. Plot 5 is an anisotropic barrier consisting of 2 soil layers over sand and gravel. Finally, Plot 6 is an evapotranspiration cover and is simply topsoil over native soil. Assuming van Genuchten (1980) characteristic curves, properties for the various soils have been estimated and are summarized in Table 1. The wetting phase permeability as a function of capillary pressure, which is particularly useful in determining capillary barrier performance, is shown in Figure 2.

Prediction of the performance of the ALCD landfill covers should consider all unsaturated flow phenomena including precipitation, runoff and evapotranspiration under the arid conditions of Albuquerque, New Mexico. While the HELP model (Schroeder et al, 1994a,b) considers precipitation, runoff, and evapotranspiration, the simplified unsaturated flow modeling in HELP is inappropriate for tilted capillary barriers (Morris and Stormont, 1997). In addition, HELP has demonstrated a trend to overpredict percolation/leakage in semi-arid and arid conditions (Thompson and Tyler, 1984; Nichols, 1991; Fleenor and King, 1995), which are typical of capillary barrier applications. Because some of the covers may experience lateral diversion due to capillary barrier effects, and the ALCD is located in the arid environment of Albuquerque, HELP may not give accurate results. Conversely, many multidimensional unsaturated flow codes suitable for tilted capillary barriers do not have precipitation, runoff, and evapotranspiration models and the flexibility of HELP.

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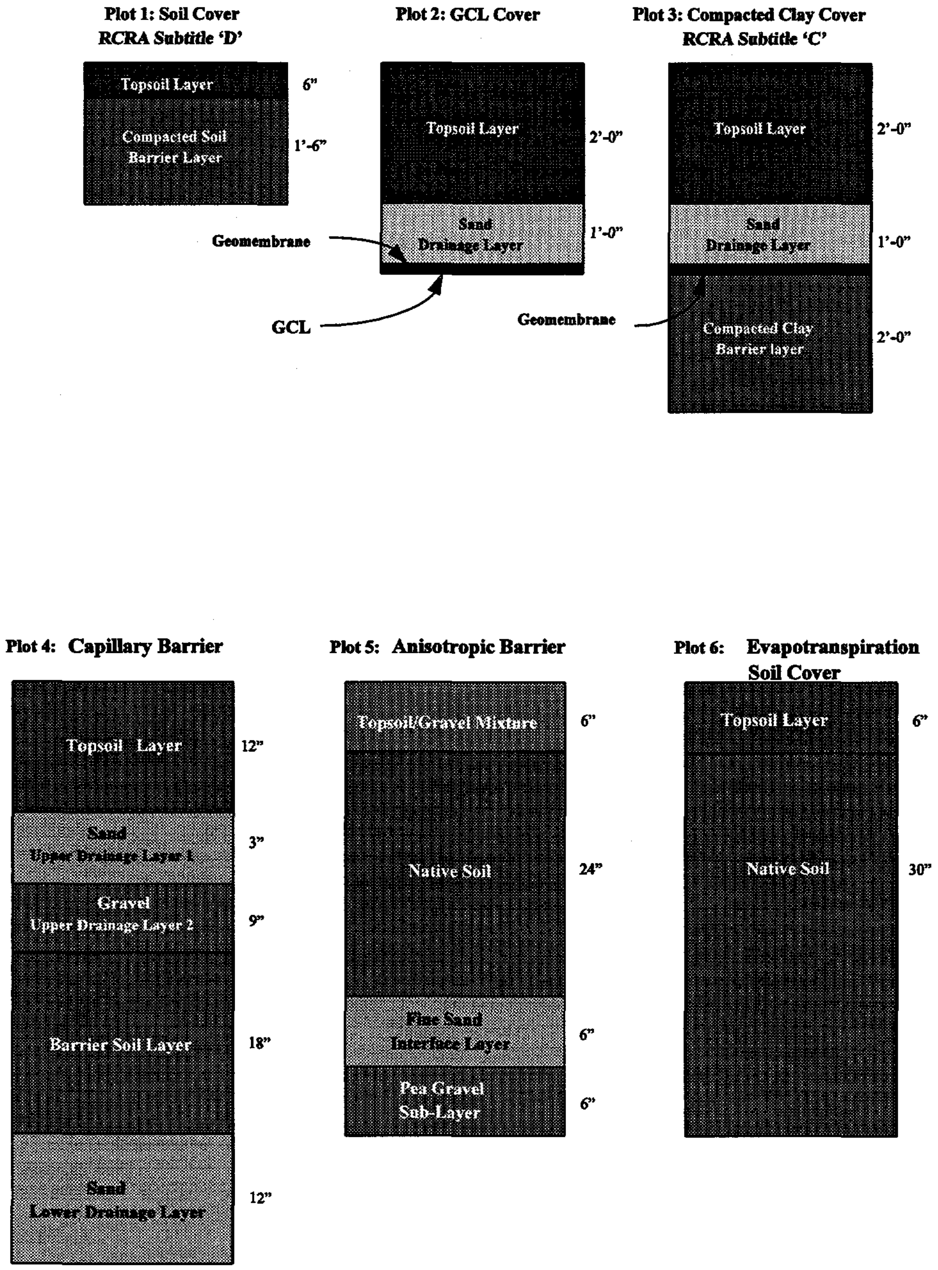
Plot 1: Soil Cover RCRA Subtitle 'D'

Plot 2: GCL Cover

Plot 3: Compacted Clay Cover RCRA Subtitle 'C'

Plot 4: Capillary Barrier

Plot 5: Anisotropic Barrier

Plot 6: Evapotranspiration Soil Cover

Figure 1
ALCD Landfill Covers

Table 1
Estimated Soil Properties

Soil Type	Saturated hydraulic conductivity (cm/s)[1]	Saturated Moisture Content	Residual Moisture Content	Capillary Pressure Parameter (1/cm)	Shape Parameter
Topsoil	3.0×10^{-4}	0.40	0.06	0.021	2.5
Native Soil	1.0×10^{-4}	0.40	0.08	0.018	2.0
Sand Layers	8.0×10^{-3}	0.39	0.04	0.018	3.3
Gravels	1.3	0.42	0.02	1.0	15.0
Compacted Clay and GCL	1.0×10^{-8}	0.45	0.20	0.005	1.5
Barrier Soil	1.0×10^{-6}	0.42	0.14	0.010	1.73
Geomembrane	4.0×10^{-13}	-	-	0.001	1.2
Topsoil/Gravel	2.0×10^{-2}	0.41	0.04	0.14	6.1

[1] - 1 cm/s ~ 1.03×10^{-9} m^2 for water at 20°C.

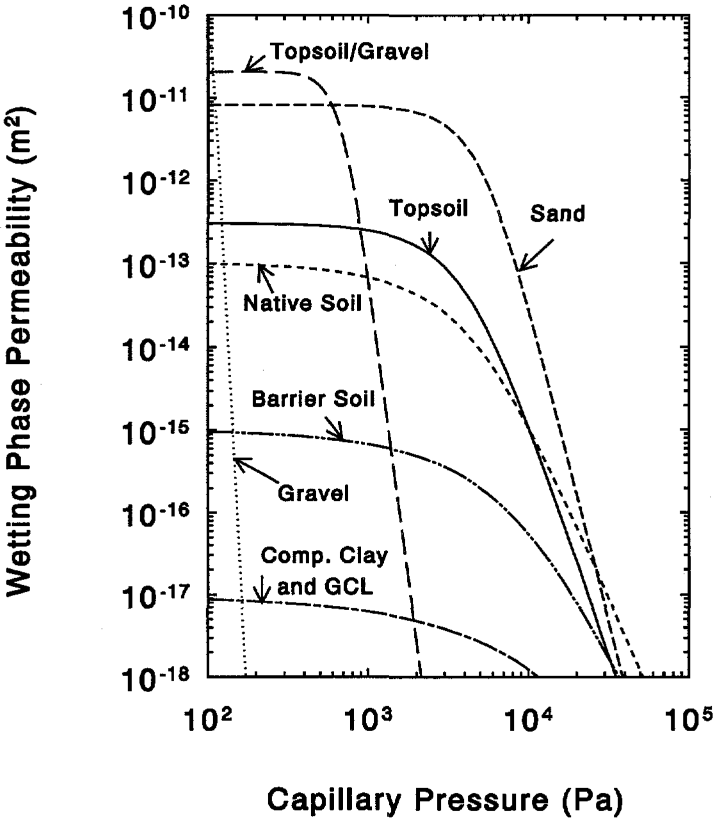

Figure 2
Wetting Phase Permeability vs. Capillary Pressure

In the current study, simulations for the ALCD landfill covers have been performed using HELP Version 3.06. In addition, two methods have been used to evaluate the capillary barrier diversion length of these covers; Ross' capillary barrier diversion formula (Ross, 1990) and detailed TOUGH2 simulations. The results from these approaches are compared for the various landfill covers including capillary barriers.

II. HELP Simulations

For the present study, the HELP simulations have been run for 5 years using Albuquerque precipitation and evapotranspiration assuming a maximum evaporation zone depth of 0.46 m (18 inches) and bare ground (Leaf Area Index = 0). Runoff, which is small for the present simulations, is calculated using a 5 percent slope and a length of about 50 m (150 ft); a soil texture of 5 (SCS Runoff Curve number = 84.5) has been assumed. Similarly, any lateral drainage layer had a 5 percent slope and a length of about 50 m (150 ft).

The layering sequence and appropriate properties for HELP input for each of the plots are summarized in Table 2. The field capacity and wilting point moisture content input parameters, which are used to define moisture storage and unsaturated hydraulic conductivity, are calculated using the van Genuchten two-phase characteristic curves and the parameters in Table 1 for capillary pressures of 0.33 and 15. bars, respectively, consistent with assumptions used in HELP. In all unsaturated layers, the initial moisture content is assumed equal to the wilting point value. In general, the layers are specified as vertical percolation layers. Subject to layering sequence restrictions in HELP, lateral drainage layers are also used. Lateral drainage in HELP is *not* equivalent to tilted capillary barrier behavior because it is based on saturated flow; capillary barrier diversion is an unsaturated phenomena and is much more complex. Nevertheless, lateral drainage layers were specified where possible.

The restrictions imposed by the HELP code for these simulations can be seen by comparing the layering sequences for Plots 4 and 5. In Plot 4, the gravel layer is a lateral drainage layer. In Plot 5, the gravel is specified as a vertical percolation layer even though the layering sequence of Plots 4 and 5 are very similar. The reason for this difference is that HELP does not allow a lateral drainage layer to be the bottom layer in a layering profile. While the layer sequence restrictions may be adequate for a horizontal landfill cap, which is after all the primary use of HELP, the restrictions may not be applicable to tilted capillary barriers, which HELP is *not* designed to model.

The average annual precipitation, runoff, evapotranspiration, lateral drainage, change in moisture content, and percolation/leakage for the simulations are summarized in Table 3 for the various covers. The percolation/leakage values span a wide range. For an average annual precipitation of 24.3 cm, the percolation/leakage for the various covers ranges between 0.002 cm to 15.9 cm. According to HELP, the most effective covers are Plots 2 and 3 due to the geomembrane with a percolation/leakage of 0.002 cm. Plot 5, which is a capillary barrier, is predicted to allow the highest leakage at 15.9 cm. As discussed above, lateral drainage could not be specified for this plot due to HELP restrictions on the layering sequence. Plot 4, which has a similar layering sequence to Plot 5, has a much lower percolation/leakage of 4.8 cm probably due to specification of the gravel as a lateral drainage layer.

III. Capillary Barrier Effect

To estimate the capillary barrier effect of the covers, Ross' formula (Ross, 1990) and the TOUGH2 code (Pruess, 1991) have been used to evaluate the steady-state diversion length of the covers. While Ross' original formula is only directly applicable to the quasi-linear two-phase characteristic curves, Webb (1997a) has recently extended Ross' equation to other two-phase curves including van Genuchten (1980). Comparison of Ross' formula with detailed numerical simulations shows good agreement (Webb, 1997b).

Table 2
Layering Sequences

Plot 1: Soil Cover RCRA Subtitle "D"

Layer	Properties	HELP Layer Type
Topsoil	Topsoil	Vertical Percolation
Compacted Soil Barrier	Barrier Soil	Vertical Percolation

Plot 2: GCL Cover

Layer	Properties	HELP Layer Type
Topsoil	Topsoil	Vertical Percolation
Sand	Sand	Lateral drainage
Geo-membrane	Geo-membrane	Membrane Liner Pinhole Density - 1 hole/acre Install Defects - 10 holes/acre Placement Quality - Good
GCL	GCL	Vertical Percolation

Plot 3: Compacted Clay Cover RCRA Subtitle "C"

Layer	Properties	HELP Layer Type
Topsoil	Topsoil	Vertical Percolation
Sand	Sand	Lateral Drainage
Geo-membrane	Geo-membrane	as above
Compacted clay barrier	Compacted clay	Vertical Percolation

Plot 4: Capillary Barrier

Layer	Properties	HELP Layer Type
Topsoil	Topsoil	Vertical Percolation
Sand	Sand	Vertical Percolation
Gravel	Gravel	Lateral Drainage
Barrier Soil	Barrier Soil	Barrier Soil
Sand	Sand	Vertical Percolation

Plot 5: Anisotropic Barrier

Layer	Properties	HELP Layer Type
Topsoil/Gravel	Topsoil	Vertical Percolation
Native Soil	Native Soil	Vertical Percolation
Sand	Sand	Vertical Percolation
Gravel	Gravel	Vertical Percolation

Plot 6: Evapotranspiration Soil Cover

Layer	Properties	HELP Layer Type
Topsoil	Topsoil	Vertical Percolation
Native Soil	Native Soil	Vertical Percolation

Table 3
Summary of HELP Simulation Results

	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6
Precipitation (cm)	24.3	24.3	24.3	24.3	24.3	24.3
Runoff (cm)	0.15	0.13	0.13	0.02	0.02	0.12
Evapotranspiration (cm)	17.4	6.0	6.0	2.9	8.4	13.1
Lateral Drainage (cm)	0	17.9	17.9	16.6	0.	0.
Change in Moisture Content (cm)	0	0.31	0.31	0.01	0.	0.
Percolation/Leakage (cm)	6.8	0.002	0.002	4.8	15.9	11.1

Table 4
Calculated Capillary Barrier Diversion Lengths

Net Infiltration Rate	Plot 1	Plots 2 and 3	Plots 4 and 5	Plot 6
20 cm/yr	3.4 m	220. m	210. m	0.
2.0 cm/yr	0.25 m	2200. m	2100. m	0.
0.2 cm/yr	0.035 m	17000. m	21000. m	0.

Table 4 presents the calculated capillary barrier diversion length of Plots 1-6 as a function of average net infiltration rate (precipitation minus runoff minus evapotranspiration); note that the average total precipitation from HELP is 24.3 cm/yr. Plot 1 shows a small capillary barrier effect at the topsoil/compacted soil interface which, interestingly, decreases with decreasing infiltration rate. This behavior is contrary to traditional fine-over-coarse tilted capillary barrier behavior which exhibits an increasing diversion length with decreasing infiltration. Plots 2 and 3 show no capillary barrier effect at the topsoil/sand interface. This behavior can be explained by comparing the characteristic curves for the two layers on Figure 2. Since the sand curve is above the topsoil curve, there is no capillary barrier effect for topsoil over sand using the present properties; the curve for the underlying layer must be below the curve for the overlying layer for a capillary barrier effect. Neglecting the geomembrane due to its low hydraulic conductivity and the possibility of local defects, the capillary barrier effect was calculated for the sand/GCL or compacted clay interface. Plots 2 and 3 are identical in this case because the GCL and compacted clay properties are the same. The calculated diversion length for this interface is hundreds of meters or more and is significantly greater than the length of the ALCD covers. Therefore, little, if any, percolation/leakage through the GCL or compacted clay is expected for Plots 2 and 3 due to the capillary barrier effect. While the reality of diversion lengths of 1000 meters or more is questionable, the magnitude of the calculated diversion length indicates a strong capillary barrier effect and minimal percolation/leakage. Similar to Plots 2 and 3, Plots 4 and 5 have no capillary barrier effect at the topsoil(native soil)/sand interface. Plots 4 and 5 *do* have a large capillary barrier effect at the sand/gravel interface; the predicted diversion length for Plots 4 and 5 is similar to Plots 2 and 3 and is significantly greater than the length of the ALCD covers. Finally, Plot 6 has no capillary barrier effect at all.

The results from TOUGH2 simulations show similar results. TOUGH2 is a multidimensional unsaturated flow code that is widely used for simulating flow and transport in fractured and porous media in nuclear waste, environmental, and geothermal applications (Pruess, 1991). Simulations were performed using TOUGH2 based on a net infiltration rate (precipitation minus runoff minus evapotranspiration) of 1, 10, and 100% of normal precipitation of 20 cm/yr for up to 10 years similar to Table 4. For Plots 1 and 6, minimal or no diversion was calculated by TOUGH2, while complete lateral diversion was predicted for Plots 2, 3, 4, and 5 consistent with the results from Ross' formula.

The advantage of using TOUGH2 compared to HELP is the mechanistic calculation of unsaturated conditions in the soil layers. Unfortunately, TOUGH2 does not include precipitation, runoff, or evapotranspiration models or have the flexibility of HELP. Morris and Stormont (1997) attempted to partially address the unsaturated flow issue by extracting the precipitation, runoff, and evapotranspiration data from HELP and using it as input to a mechanistic unsaturated flow code. However, this approach may not be adequate since the unsaturated conditions calculated by the unsaturated flow code were not fed back into HELP. Therefore, we are presenting planning to couple the precipitation, runoff, and evapotranspiration models of HELP with the unsaturated flow modeling of TOUGH2 (Webb, 1996). When this coupling is completed, a more comprehensive evaluation of the performance of the ALCD landfill covers, including capillary barriers, can be performed. Further evaluation is also anticipated when the experimental data from the ALCD become available.

IV. Conclusions

The predicted performance of the ALCD covers from the two approaches can be significantly different. For example, HELP predicts that Plot 5, a tilted anisotropic capillary barrier, allows the most percolation/leakage of any of the ALCD covers. In contrast, the capillary barrier results indicate that Plot 5 is one of the most effective configurations and will allow minimal or no percolation/leakage.

Evaluation of tilted landfill cover performance should consider possible capillary barrier effects. If there is little or no capillary barrier effect, HELP results may be appropriate, although questions about the applicability to semi-arid and arid regions remain. If there is a significant capillary barrier effect, the HELP results are not applicable. For the ALCD project, Plots 2, 3, 4, and 5 are expected to be the most effective designs due to the capillary barrier effect, and little or no percolation/leakage through these covers is expected. Plots 1 and 6 should allow significant percolation/leakage based on the HELP analysis; no significant capillary barrier effect is expected for these two plots.

In the future, HELP and TOUGH2 are planned to be coupled. When this work is completed, the effects of precipitation, runoff, and evapotranspiration based on HELP and the unsaturated flow modeling of TOUGH2 will be combined automatically and should give much more realistic results than either the HELP or TOUGH2 results by themselves.

Acknowledgment

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