Unsaturated Performance Comparison of Compacted Clay Landfill Liners

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Abstract

Tests were conducted to determine the variation in volumetric water content and pore water suction for a variety of compacted clay soils used in the construction of landfill liners. The fit of the experimental data to an existing parametric model was investigated for two different fitting techniques. The first technique involves the use of the retention curve computer program (RETC) developed for the U.S. EPA. The second technique employs the Solver subroutine included in Microsoft Excel. The parametric models resulting from either technique correlated well to the experimental data. However, the individual curve fit parameters varied significantly. The effect of these variations on the unsaturated behavior of compacted clay liners was evaluated using the Hydrologic Evaluation of Landfill Performance (HELP) model. The curve fit parameters resulting from both the RETC and the Solver techniques were used as input to the HELP routine for simulation of variably saturated flow through a cover liner. There were no significant differences in the volume of leakage or rate of leakage predicted using the input from the two curve-fitting techniques. However, there was significant soil-dependent variation in the HELP output. Examination of the HELP output provides information regarding variation in the volumetric water content of the cover liner soil. This information can be used to predict pore water suction variations and susceptibility to desiccation cracking.

Introduction

The primary function of a cover liner at a landfill is to limit the migration of moisture to the underlying waste, thereby reducing the volume and rate of leachate production. Cover liners are constructed at volumetric water contents less than the saturated value, and during the life of the containment system moisture is added to and removed from the cover liner. Therefore, it is expected that, for at least a portion of it's life, the cover liner will be operating in an unsaturated mode. The governing equation for flow through a variably saturated liner, assuming one-dimensional, vertical flow is:

$$C(\psi)\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z} + 1\right)\right] \tag{1}$$

where t is the time (sec); z is the elevation assumed positive upward; ψ is pore water suction head (m), $K(\psi)$ is unsaturated hydraulic conductivity (m sec^{-1}), and $C(\psi)$ is specific water capacity (m^{-1}). $C(\psi)$ relates pore water suction to volumetric water content and is equivalent to the slope of the soil-water characteristic curve (SWCC). The data necessary to construct a SWCC is typically determined using pressure plate apparatus (ASTM, 1994). The resulting data can be fit to existing parametric models of the SWCC (Brooks and Corey, 1964; Fredlund and Xing, 1994). One common model is the van Genuchten (van Genuchten, 1980) equation

$$\frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + \left(\frac{\psi}{a}\right)^n\right]^m} \tag{2}$$

where the optimized parameters are θ_s, θ_r, a, n, and m. The effect of the parameters a, n, and m on the shape of the SWCC is provided by Leong and Rahardjo (1997). Van Genuchten (1980) suggested a simplifying relation between the parameters m and n (i.e., m = 1-1/n). However, in the present investigation the parameters m and n are assumed to be independent for more flexibility in the curve-fitting procedure.

The SWCC can be used to provide insight to the potential for desiccation cracking of a cover liner soil. During desiccation, the saturation of a liner is reduced, and the remaining pore water is held at increasingly large suctions. If the volumetric water content is known, or has been predicted, the SWCC can be used to determine the pore water suctions corresponding to the known volumetric water content. Previous research (Miller et al., 1998) has shown that the onset and resulting amount of cracking is correlated to a soil-specific critical suction level. Hence the maximum pore water suction expected in the cover liner can be compared to the critical suction level to estimate susceptibility to desiccation cracking.

The landfill cover liner problem is not the only environmental application that requires modeling of unsaturated conditions. A similar problem involves surface spills that migrate through the unsaturated zone towards an unconfined aquifer. In general,

the solution of pollutant migration through the unsaturated zone is a much more difficult problem than contaminant transport through the aquifer. In the aquifer, the pore water pressure is linearly related to depth below the free surface and the hydraulic conductivity is assumed constant. However, in the vadose zone, the presence of the air phase impacts the relationship between pore water pressure and volumetric water content, as well as hydraulic conductivity and volumetric water content.

This study was conducted to investigate the impact of variations in the characterization of the unsaturated behavior of a cover liner soil on the performance of that liner. The liner performance was evaluated using water balance output from a landfill simulation model.

Materials and Methods

The materials used in this study consist of six clay soils used as landfill cover liners at five municipal solid waste landfills in the metropolitan Detroit vicinity. One of the sites had two active excavation regions, yielding two distinct clay soils. Samples of the liner materials were retrieved from the excavation areas used as borrow sources for liner construction at each site. Table 1 provides a summary of the geotechnical characterization of each soil. In subsequent discussions, the six soils will be referred to using the numerical designation provided in column one of this table, i.e. the clay liner from Auburn Hills will be designated Soil 1.

Table 1 - Geotechnical Characterization of the Clays

Soil	Saturated Hydraulic Conductivity (m/sec)*10^{-10}	Distribution of Fines (% of total)		Max. Dry Density (kN/m^3)	Opt. Moisture Content (% by wt)	Plasticity Index	Liquid Limit
		Clay	Silt				
1	6.32	32	31	21.1	8.6	10	22
2	3.40	28	43	20.4	10.2	10	26
3	1.80	36	41	20.2	9.4	14	30
4	4.83	31	47	20.1	10.3	13	35
5	6.40	36	32	20.3	9.1	16	32
6	0.51	64	34	16.7	22.5	60	83

Note: Soil designations 1-6 refer to soil from the following locations: Auburn Hills, Woodland Meadows (brown clay), Woodland Meadows (gray clay), Evergreen, Canton, and Smith's Creek (with 25% by weight bentonite added), respectively.

Although mineralogical analysis was not included in the scope of this research, previous investigations (Salim et al., 1996) suggest that the mineralogical make-up of clay soils in southern Michigan are fairly similar and that site-specific mineralogical analysis may be unwarranted. A typical mineralogical composition shows the clay fraction to be dominated by three minerals with 60% illite, 12% kaolinite, and 9% chlorite.

Volumetric pressure plate and pressure membrane extractors were used to determine the soil-water characteristic curve (SWCC) during the drying cycle for remolded samples of each of the six soils. The methodology is described in ASTM Standards D2325 (ASTM, 1993) and D3152 (ASTM, 1994) for the plate and membrane apparatus, respectively. The samples were remolded using modified Proctor compactive effort at moisture conditions approximately 2% wet of optimum. The volumetric water contents were used together with the applied suctions to develop the SWCCs.

Data collected was fit to the models described by Eq. 2. An optimization routine was used to fit the parametric models to the measured data by altering the fitted parameters using an iterative process until the difference between the predicted SWCC and the measured data was minimized. The quantity to be minimized is the Sum of the Squared Residuals (SSR):

$$SSR=\sum_{i=1}^{n} w_i\left(\theta_{wi}-\theta_{ci}\right)^2 \qquad (3)$$

where w_i is the weighting factor which is equal to 1.0, θ_{wi} is the measured volumetric water content, which is defined as θ_{wi} = nS (n=soil porosity and S=saturation corresponding to θ_{wi}), and θ_{ci} is the calculated volumetric water content from each model. The minimization process for SSR was performed using two techniques: a standard statistical package included with Microsoft Excel® and an optimization package developed specifically for this purpose by van Genuchten et al. (1991). Detailed information regarding the curve fit for each soil and each optimization technique is presented in Table 2. In all cases, the SSR is less than 10^{-3}, which is similar to the SSR values obtained by Leong and Rahardjo (1997). Each of the optimization approaches provides an acceptable fit to the experimental data, with similar values of the SSR. The individual curve fit parameters, however, vary significantly between approaches.

Table 2. van Genuchten Curve Fit Parameters

Soil	Technique	a (kPa x 10^{-2})	n	m	θr	θs	SSR
1	Solver	0.0035	0.7131	31.6122	0.1449	0.2419	$9.60X10^{-6}$
	RETC	0.2856	1.0050	1.5980	0.1408	0.2304	$10.22X10^{-6}$
2	Solver	0.5809	56.9445	0.0185	0.2424	0.3351	$23.54X10^{-6}$
	RETC	0.5828	150.7430	0.0067	0.2408	0.3351	$23.77X10^{-6}$
3	Solver	0.1125	0.8311	0.3465	0.0003	0.3106	$121.59X10^{-6}$
	RETC	0.1525	1.0050	0.4697	0.1186	0.3065	$10.47X10^{-6}$
4	Solver	0.0102	0.8711	11.8146	0.1962	0.3231	$3.12X10^{-6}$
	RETC	0.1560	1.0050	1.0896	0.1702	0.3202	$3.31X10^{-6}$
5	Solver	0.0121	1.6752	166.8758	0.2700	0.3485	$42.67X10^{-6}$
	RETC	0.0117	1.6768	178.7306	0.2700	0.3485	$49.06X10^{-6}$
6	Solver	0.3668	2.0737	0.5178	0.3488	0.5525	$36.75X10^{-6}$
	RETC	0.3456	2.0848	0.5203	0.3525	0.5525	$49.06X10^{-6}$

It was observed that the best-fit saturation volumetric water content (θ_s) was relatively independent of the approach used, although there was significant variation in the value between the six soils. The maximum variation in θ_s between optimization techniques was 5% for Soil 1. The maximum variation in θ_s among the soils was greater than 100%, representing the variation between Soil 1 and Soil 6. For a saturated soil, the saturated volumetric water content, θ_s, is equal to the soil porosity Thus, it was expected that there would be significant variation in θ_s among the soils.

The optimized value of the irreducible volumetric water content, θ_r, showed greater variation between techniques than the θ_s variation. The variation between optimization methods was on the order of 15% for all soils, with the exception of Soil 3 which showed a much greater dependence on optimization technique and a variation on the order of 100%. The variation in θ_r between soils was on the order of 50%, except for Soil 3 which exhibited a θ_r much less than the others.

The other curve fit parameters a, n, and m represent the shape and offsets of the SWCC. These parameters, especially the latter two, show significant variation between soil types and between optimization approaches. However, the curve shapes that result from the two approaches appear very similar, as shown in Figure 1 The parameter set defining the shape of the SWCC is not unique The similarities observed in the SWCCs from the two techniques suggests that the added effort in using the RETC program is unwarranted Operation of the RETC requires knowledge in DOS and Fortran formatting of input files. On the other hand, the Solver subroutine does not require formatted input and has a Windows interface

Modeling of flow in the unsaturated zone requires input of the SWCC, usually in a form similar to that in Eq 2, along with the associated curve fit parameters (θ_s, θ_r, a, n, and m, in this case) Therefore, it is expected that alternative data sets for these parameters will result in variable model output. This hypothesis is tested using the HELP model for prediction of landfill cover liner performance

Leakage Predictions

The HELP model (Schroeder et al., 1994) was used to simulate the variably saturated conditions in a hypothetical landfill cover liner of one acre surface area. HELP is a computer program developed by the U.S. Army Engineer Waterways Experiment Station for the analysis of a landfill water budget. The model includes precipitation, surface runoff, evapotranspiration, and snow melt in calculation of the site water budget. Excess moisture acts as additions to soil moisture storage in the cover soil while moisture deficits reduce soil moisture storage in the cover soil The model simulates four different types of soil layers, subdivided based on their functions vertical percolation layers, lateral drainage layers, barrier soil liners, and combination geomembrane/barrier soil liners. The transport process for each layer is one-dimensional The model simulates quasi-steady state and quasi-two-dimensional flow (Khanbilvardi et al., 1995).

The landfill cover system was modeled simplistically as a two-component system, comprised of a 60 cm thick upper sandy layer above a 90 cm thick compacted clay layer. The upper sandy layer was modeled as a *vertical percolation layer* of 60 cm thickness with good vegetative cover, a surface slope of 3% and slope length of 305 meters. The run-off curve number corresponding to these surface layer conditions was determined internally in HELP to be 67. The climatological conditions (precipitation, temperature, and solar radiation) simulated were those included in the HELP database as 100 years synthetic data for Detroit, MI.

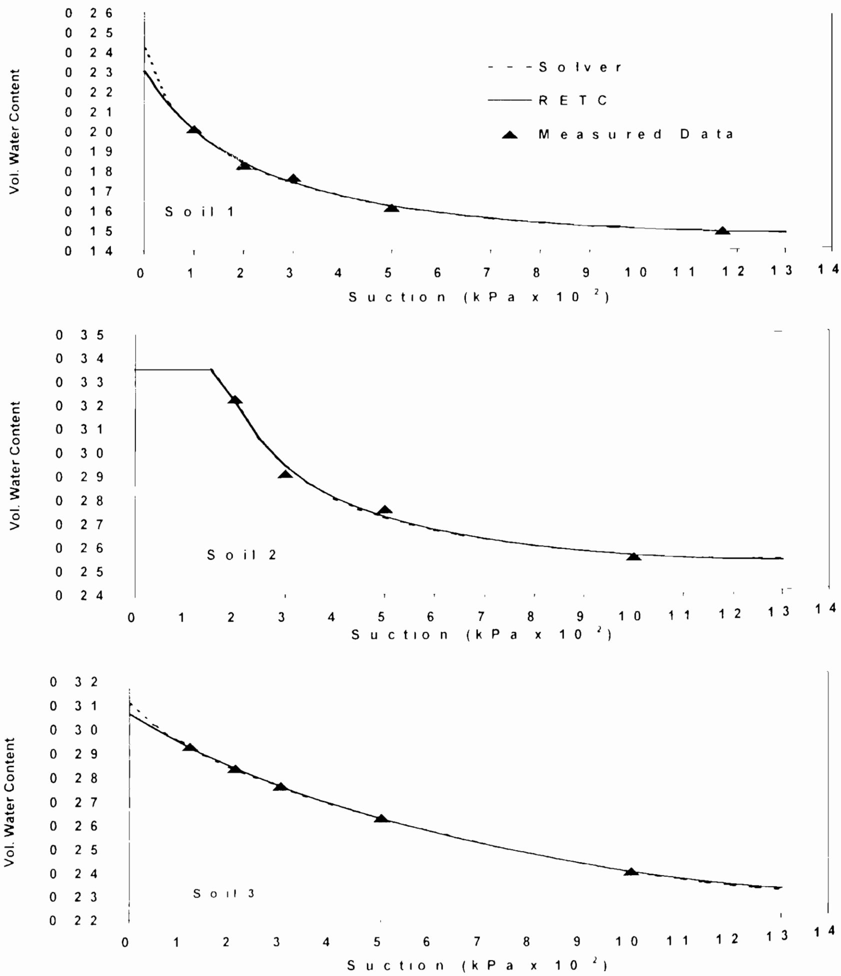

Figure 1a Van Genuchten Curve-Fit for SWCC for Soils1-3

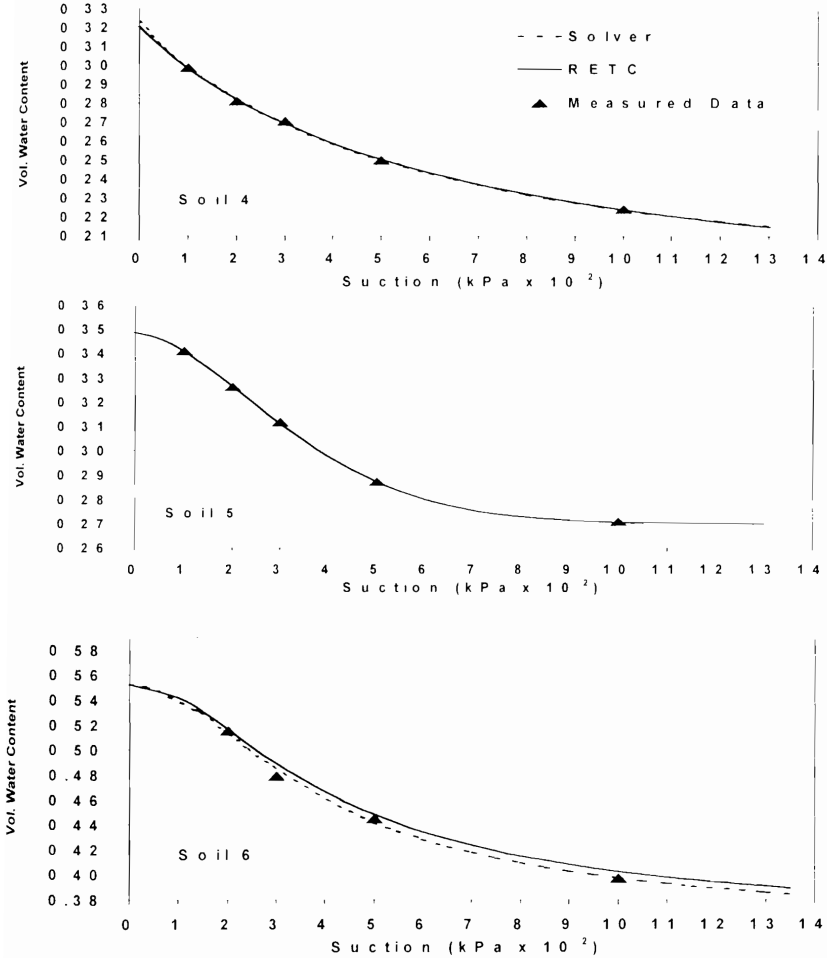

Figure 1b. Van Genuchten Curve-Fit for SWCC for Soils 4-6

It is typical to designate a compacted clay liner as a *barrier soil layer* for HELP modeling. However, the barrier soil layer module assumes the cover liner to be saturated for the entire simulation. Therefore, for all runs performed, the 90 cm thick clay layer was simulated as a vertical percolation layer which allows for variably saturated conditions. This approach allowed the use of the SWCC parameters for the cover liner and permitted the simulation of variably saturated conditions within the cover liner

The saturated hydraulic conductivity and the volumetric saturated water content (or porosity) used for each soil was that provided in Tables 1 and 2, respectively. The initial moisture condition for all simulations corresponded to a constant moisture profile throughout the clay liner, with the volumetric water content equal to the field capacity. The field capacity is defined as the volumetric water content at a pore water suction of 0.33 Bar while the wilting point is the volumetric water content at 15 Bar (Schroeder et al., 1994). The volumetric water contents corresponding to these pore water suctions were determined using the RETC and Solver best-fit techniques for the van Genuchten formulation of the SWCC (Eq.1) for each of the six cover liner soils. These values are provided in Table 3. The unsaturated characteristics determined using the two curve fitting techniques were used to test the sensitivity of model results to the curve-fit procedure adopted. In each comparative run, the only input parameters varied were the field capacity and wilting point. All other quantities remained at the base run values.

Table 3 – Input Parameters for HELP Simulation

Soil	Technique	FC	WP
1	Solver	0.2203	0.1475
	RETC	0.2185	0.1470
2	Solver	0.3351	0.2519
	RETC	0.3351	0.2514
3	Solver	0.3039	0.2248
	RETC	0.3023	0.2259
4	Solver	0.3130	0.2116
	RETC	0.3123	0.2104
5	Solver	0.3480	0.2700
	RETC	0.3472	0.2700
6	Solver	0.5512	0.3810
	RETC	0.5514	0.3855

Results and Discussion

Figure 2 shows the cumulative leakage over a five year period for each of the cover liners simulated using the HELP model with the Solver parameters, while Figure 3 shows similar information for HELP runs using the RETC parameters. Table 4 presents the cumulative output at the end of the five year simulation for each of the six cover liners and both curve-fitting techniques.

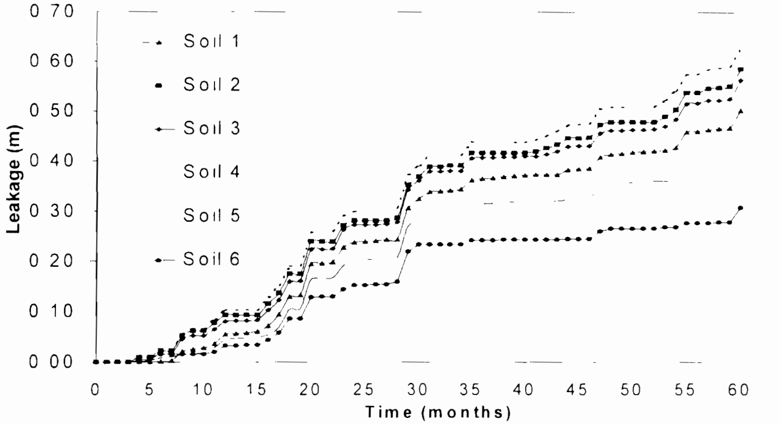

Figure 2. Leakage from each Soil Liner Using the Solver Parameters

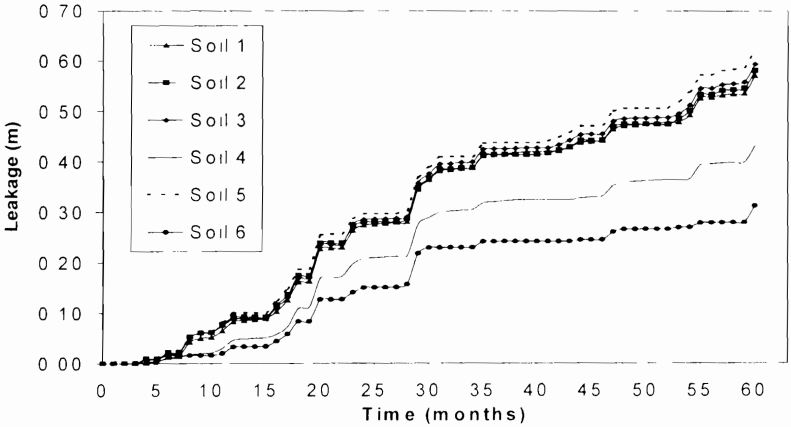

Figure 3. Leakage from each Soil Liner Using the RETC Parameters

Variation due to soil type

Although the cumulative leakage varies between soils (Table 4), the monthly patterns are similar (Figures 2 and 3). For all soils, the leakage was greatest during months 17, 19, and 28 The leakage did not reach steady state conditions during the 60 months simulated. For the entire period of the simulation, leakage through the cover liner constructed with Soil 6 was significantly less than that of the other cover liners. At the end of the simulation period, the leakage through Soil 6 was approximately 60%

less than any of the other cover liners. The diminished leakage can be attributed to a variety of factors, including the decreased value of saturated hydraulic conductivity for Soil 6 and the shape of the SWCC (suctions increase significantly as the volumetric water content is reduced). The leakage through Soil 5 exceeded that of all other soils considered in the simulation. The variation in leakage predicted in these simulations is similar to that reported by Khire et al (1998).

Table 4 Water Balance Components from HELP Simulation

Soil	Technique	Cumulative Output (m)			
		Leakage	ET	Runoff	Δ Storage
1	RFTC	.5712	2.097	1.471	-0.0358
	Solver	.5038	2.0971	1.4714	0.0379
2	RFTC	.5811	2.0567	1.4706	-0.0016
	Solver	.5865	2.0567	1.4706	-0.0075
3	RFTC	.5941	2.0693	1.4789	-0.0387
	Solver	.5630	2.0693	1.4789	-0.0047
4	RFTC	.4313	2.2078	1.4730	-0.0057
	Solver	.4238	2.2078	1.4730	0.0026
5	RFTC	.6227	2.0435	1.4434	-0.0030
	Solver	.6274	2.0435	1.4434	-0.0081
6	RFTC	.3127	2.3900	1.4172	-0.0142
	Solver	.3072	2.3946	1.4179	-0.0139

The cumulative evapotranspiration and run-off also are soil-dependent. The evapotranspiration component of the water balance was greatest for Soil 6. Soil 6 was most successful at preventing moisture movement through the cover liner, which increased the moisture available for evapotranspiration. Surface runoff was almost identical for all soils. This is expected due to the identical runoff curve numbers and precipitation history that were used in simulating all six conditions.

Variation due to optimization technique

Differences in the predicted leakage due to the optimization technique adopted for the curve-fitting routine were not significant. The maximum variation in the predicted leakage between the two techniques occurred for Soil 1 and was approximately 13%. The evapotranspiration and runoff components of the water balance were not affected by the optimization technique

Moisture fluctuations

The HELP model does not provide direct output of the calculated volumetric water content changes in the cover liner soil, except on an annual basis. Monthly changes in soil moisture storage were calculated using the water balance equation:

$$\Delta \text{ Soil Moisture} = P - RO - ET - L - \Delta SW \quad (4)$$

where the quantities on the right hand side of the equation reflect the cumulative monthly values of precipitation, runoff, evapotranspiration, leakage, and change in snow water, respectively. The snow water term accounts for that portion of the precipitation occurring when local temperatures are below freezing. Changes in the volumetric water content of the clay cover liner were calculated for Soil 1 and 6. The variation on a monthly basis is shown in Figure 4. Although both soils were subjected to identical climatological conditions, the resulting moisture states were very different. The volumetric water content spans significantly different ranges for the two soils. The volumetric water content for the cover liner using Soil 1 varies between 0.15 and 0.24 while this range for Soil 6 is between 0.50 and 0.55. Soil 6 was much more effective at preventing leakage, and thus a significantly larger fraction of the available moisture was stored above the liner to meet the evapotranspiration demands. Therefore, the liner constructed with Soil 6 maintained comparatively higher values of volumetric water content than Soil 5, which allowed greater leakage.

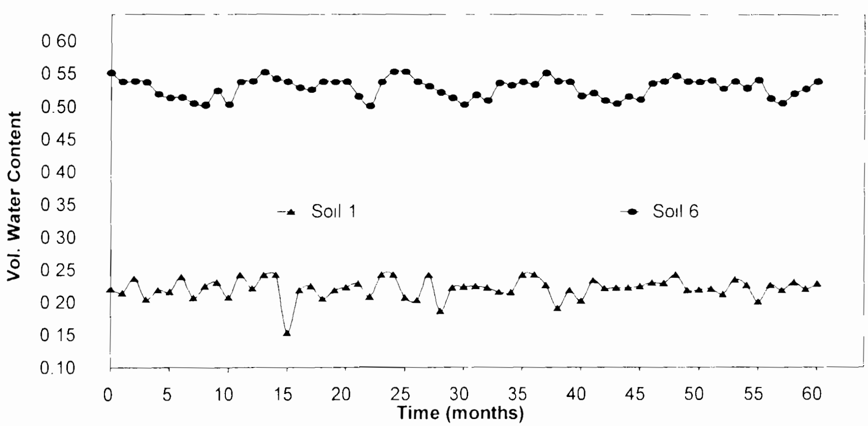

Figure 4. Volumetric Water Content Fluctuations in the Soil Cover Liner

Using the SWCC, the volumetric water contents of Fig. 4 can be converted to values of pore water suction. Previous research by the authors (Miller et al., 1998) has shown that the onset of desiccation cracking may be related to a soil-specific critical suction value. If that value is known for the cover soil under investigation, it would be possible to use the HELP output to determine the likelihood that the cover liner will

experience suctions equal to or greater than the critical value. With this information, it would be possible to predict the onset of desiccation cracking. For example, if the critical suction is determined to be 200 kPa for Soils 1 and 6, the HELP simulation suggests that Soils 1 and 6 are subjected to desiccation cracking 2% and 12% of the time, respectively.

Further details regarding moisture conditions within the cover liner soil are provided in Table 5. Although Soil 1 experienced significantly lower volumetric water contents than Soil 6, it did not exceed the critical suction as frequently as did Soil 6. Therefore, it is expected that Soil 6 is more susceptible to desiccation cracking than Soil 1. However, this limited analysis provides no methodology to predict the extent of cracking.

Table 5 - Details Regarding Moisture Conditions Encountered in Clay Cover Liner

Soil	Minimum Volumetric Water Content	Maximum Pore Water Suction (kPa)	% of Time Saturated	% of Time Critical Suction Exceeded
1	1572	880	18.34	1 7
6	5004	240	10.00	11 7

Table 5 indicates that the cover liners constructed with Soil 1 and Soil 6 are expected to reach saturation during 18.3% and 10.0% of the 5 year simulation duration, respectively. This prediction suggests that analyses of clay cover liners that rely on the assumption of saturated conditions may be inappropriate. Such assumptions likely result in over-estimates of the amount of leakage through the cover liner, while under-estimating the potential for desiccation cracking.

Summary and Conclusions

The variably saturated performance of six compacted clay soils as cover liners was compared using the HELP model. The relationship between the unsaturated volumetric water content and pore water suction was determined in the laboratory for each soil using the pressure plate apparatus. The data was fit to the van Genuchten model of the soil-water characteristic curve (SWCC) using two different optimization techniques. The shape of the two resulting SWCCs were very similar for each of the six soils, although the values of the individual curve-fit parameters varied significantly (exceeding 100% in some cases). The variation in the shape of the resulting SWCCs for the six soils was much greater than the variation due to optimization technique.

The cover liner was modeled as a *vertical percolation layer* rather than the typical approach of using the HELP option for a *barrier soil layer*. This was done to overcome the assumption of continuous saturated conditions inherent in the *barrier soil layer* specification. The design of each cover liner simulated was identical, the only variable being the input data set used for specification of the saturated and unsaturated soil characteristics. Two simulations were completed for each of the cover liner soils

that included the parameter sets resulting from both types of SWCC curve-fitting routines.

The results from the HELP simulations showed that the monthly patterns of leakage were similar for all cover liner soils. In addition, leakage through the cover liner was relatively unaffected by the SWCC curve-fitting routine adopted. However, the leakage varied significantly from one soil to another. The cover liner constructed with Soil 5 exhibited the greatest leakage, while the cover liner constructed with Soil 6 exhibited the least leakage. Although it is well known that the relationship between volumetric water content and pore-water pressure is hysteretic, only the drying limb of the soil water characteristic curve was used in these simulations. There may be great variation in the soil water characteristic behavior on the wetting and drying sides of the hysteretic curve. Therefore, it may be unrealistic to adopt the drying curve for simulation of the infiltration process.

Evapotranspiration and runoff were much less variable than the leakage component. There was essentially no variation attributed to the different optimization approaches, with only minor variations due to cover liner soil specification.

Changes in soil moisture storage were calculated on a monthly basis for Soils 1 and 6. The range in volumetric water contents predicted for each soil was very different. The volumetric water contents were converted to pore water suctions using the SWCC and compared to an assumed critical value of 200 kPa. Critical conditions were exceeded 1.7% and 11.7% of the time for Soil 1 and Soil 6, respectively. Both soils were predicted to be unsaturated during a significant portion of the five year simulation period (82% and 90% of the time for Soils 1 and 6, respectively). Simulation of the variably saturated nature of the flow through the cover liner is important to realistically predict leakage behavior

Acknowledgement

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