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Percolation through landfill final covers

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It seems that more of our time is now spent evaluating alternative final cover systems, rather than alternative liner systems for landfills. This probably speaks highly for geosynthetic clay liners (GCLs), since they now dominate the alternative composite liner applications. This past year, we completed the third year of a final cover monitoring program for a North Carolina facility and thought that the data to date provides both support for our design procedures and a look into design alternatives. With that in mind, this article will quickly review the monitoring program, the results of three years of monitoring and implications of the data to both final cover analysis and design.

Monitoring program

The monitored landfill is owned and operated by the City of High Point in the central Piedmont region of North Carolina. The site provides us with significant quantities of "almost" liner clays, e.g. permeability ranges in the mid 10^{-7} cm/sec range. The initial composite liner for this facility was constructed in 1991 using bentonite amended on-site clay to achieve the required 1 x 10^{-7} cm/sec permeability. Subsequent cells use a GCL to reduce liner costs. The first lift of the initial lined landfill was ready for partial closure late in 1996. Since this cell actually preceded implementation of RCRA Subtitle D, the state allowed us great latitude in cover design for these 3.5H:1V side-slopes and associated drainage benches.

Final cover test sections using the following five cover systems were constructed over the interim cover layer:

- 2% bench: 18" vegetative support layer (VSL)
- 2% bench: 18" VSL over 18" compacted soil barrier (CSB)
- 3.5H:1V side slope: 18" VSL
- 3.5H:1V side slope: 18" VSL over 18" CSB
- 3.5H:1V side slope: 6" VSL over 18" CSB

***Photo 1**. Partial view of four-Lysimeter installation.*

The CSB had a saturated permeability of mid 10^{-6} to high 10^{-7} cm/sec. Note that none of the sections included a "geo" component. However, the percolation through each test section was measured using a system of four pan lysimeters placed on the interim cover soil layer prior to construction of the final cover section. The lysimeters were constructed using a drainage composite placed over a PVC geomembrane that collected all percolation and drained it to a collection/measuring sump. **Photo 1** shows four lysimeters placed beneath one of the two bench test covers. Each lysimeter was attached to a nonwoven geotextile to prevent it from shifting during placement of cover and drained to a collection bottle “sump,” **Photo 2**. To minimize the potential for the lysimeter itself to act as a capillary break and limit the volume of percolation collected, each sump was saturated initially at a positive pore water pressure and allowed to gradually normalize.

Site weather

As with most of the United States, the weather during the past three years can only be described as weird. Climatic phenomena recorded by the National Climatic Data Center, (see National Oceanic and Atmospheric Administraion(NOAA)), include the high precipitation that occurred just before and during Hurricane Fran in September 1996. Winter and spring 1998 brought record warm temperatures and precipitation, influenced by the global El Nino phenomenon, followed by a moderate to severe drought extending from mid-1998 to mid-1999. The recent study period ended with Hurricane Floyd, which brought unofficial record rainfall to the region during September 1999. This amounted to three 100-year and one 500-year rain events in the three-year monitoring period.

Photo 2*. Lysimeter monitoring “sumps.”*

Their potential effect on final cover soil-moisture conditions is not adequately represented by either temperature or precipitation data alone. Two agricultural regional-scale climatic indices are considered: the Palmer Modified Drought Index (PMDI) and the Palmer Z Index (Z), NOAA 1994 **(Table 1)**. The PMDI indicates the balance between moisture supply and demand based on precipitation and evaporation-transpiration (ET), corrected for temperature, solar radiation and vegetation states (e.g. whether it is the growing season, or not). The Z index shows short-term precipitation relative to “normal” conditions. **Figure 1** presents plotted values for High Point.

The PMDI can be used to evaluate long-term drought and wet spells that would necessarily affect (or reflect) the water balance in the landfill cover soils. One would expect infiltration to be lower when PMDI values are negative (when ET is higher and ambient soil moisture tends to be lower), while infiltration should be higher when the PMDI values are positive (due to generally wetter conditions). The Z index data is used in this context to substantiate the PMDI in terms of rainfall volumes, but the Z index can reveal abnormally wet conditions during a prolonged drought. Sudden “spikes” in the precipitation data **(Figure 1)** are reflected by the Z index and can sometimes be seen in the infiltration data. At present, the au-

Range PMDI			Range Z	
3.00	3.99	Severe Wetness	2.5	3.49
1.50	2.99	Mild to Moderate Wetness	1	2.49
-1.49	1.49	Near Normal	-1.24	0.99
-1.50	-2.99	Mild to Moderate Drought	-1.25	-1.99
-3.00	-3.99	Severe Drought	-2	-2.74
<-4.00		Extreme Drought	<-2.75	

TABLE 1. EXPLANATION OF PALMER INDEX VALUES

thors are not aware of an infiltration model that uses these specific parameters, but the Palmer indices are useful in making qualitative comparisons between regional climate and the infiltration data.

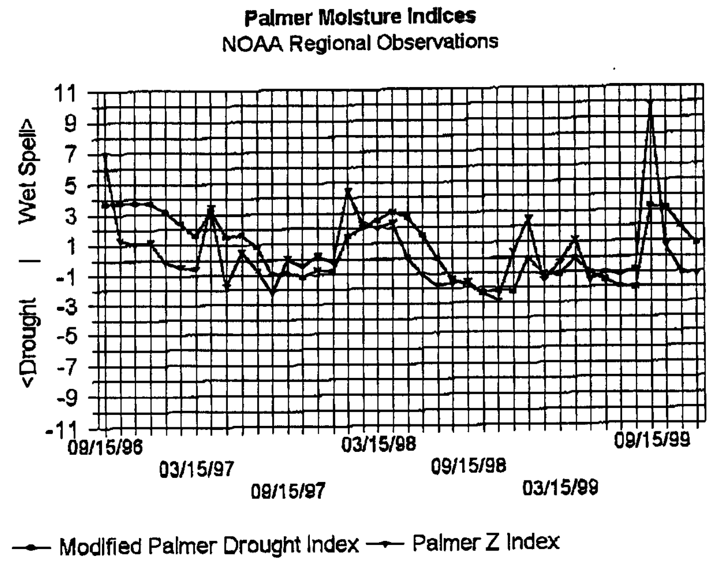

Figure 1*: Palmer agricultural indices over monitoring period*

Precipitation and percolation

Rainfall was measured at the site as it occurred and converted to gallons/acre/day corresponding to the lysimeter readings. The lysimeters were read monthly during the wet periods. Some months were skipped during dry spells. The practicality of the units of gallons/acre/day is that the data may be collected at uneven time intervals and “normalized” as a unit value based on a 30-day interval. The “normalized” rainfall and precipitation data are plotted on the middle of each month in **Figure 2**. The highest monthly rainfall recorded in a single 30-day period was over 13 in. The average unit precipitation during the study period is about 3,200 gallons/acre/day.

The total annual precipitation and infiltration through the covers is presented in **Table 2**. Infiltration measured in the second and third years is significantly higher than the first year as the cover sections wet up. The total infiltration on the side slope reaches a “peak” value of approximately 1 in. per 30-day monitoring period during the winter of 1997-98. After the initial wet spell, the total infiltration fluctuates with seasonal changes below this value, but does not exceed 1 in. per 30-day monitoring period for successive wet spells. Note that the infiltration on the slope is significantly greater than on the bench. While this is converse to expected behavior, the authors feel that the soils along the bench received higher levels of compaction than those on the slope and were thus less permeable.

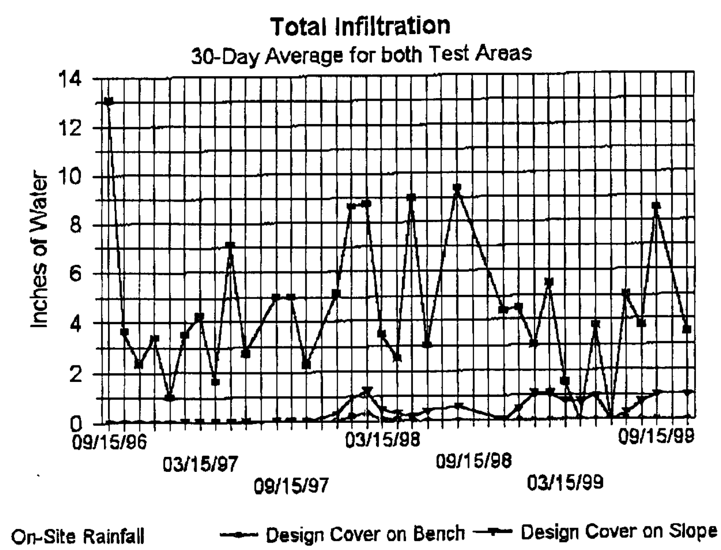

Figure 2*: 30-day average precipitation and percolation*

While a detailed evaluation of the monitored weather trends verses the measured percolation is beyond this article, it was observed that an approximately one-month lag between rainfall and percolation existed the initial year. As the VSL increased in moisture, the lag time reduced until it was reduced to virtually nothing by the end of the third year.

	Year 1	Year 2	Year 3	Total
On-Site Rainfall, inches	47.65	57.14	45.88	150.67
18" VSL on Bench	0.011	1.803	1.188	3.002
18" VSL over 18" CSB on Bench	0.0	0.708	0.064	0.772
18" VSL on Side Slope	0.129	4.304	7.528	11.961
6" VSL over 18" CSB on Side Slope	0.654	7.051	9.268	16.991
18" VSL over 18" CSB on Side Slope	0.874	7.954	10.926	19.754

TABLE 2. TOTAL ANNUAL PERCOLATION THROUGH FINAL COVERS

Meaning of peak percolation rates

The peak infiltration rates shown on **Figure 2** for both the slopes and the 2% bench are approximately 1 inch (1 x 10^{-6} cm/sec) and 0.3 inch (3 x 10^{-7} cm/sec) per 30-day monitoring period, respectively. This is approximately equal to the saturated permeability of the CSB. This observation is important, since it confirms the unit-gradient design process for lateral drainage systems in final covers. The unit-gradient design was first discussed by Thiel and Steward (1993) and has been recommended by the first author for the all closures except those in arid regions. This design method was discussed in a previous *Designer's Column* by Richardson and Zhao (1998). The rate of water infiltration into the geocomposite drain can be readily calculated under a unit-gradient, since the infiltration velocity is equal to the permeability of the vegetative layer. The basic lateral drainage model developed by Thiel is shown on **Figure 3**.

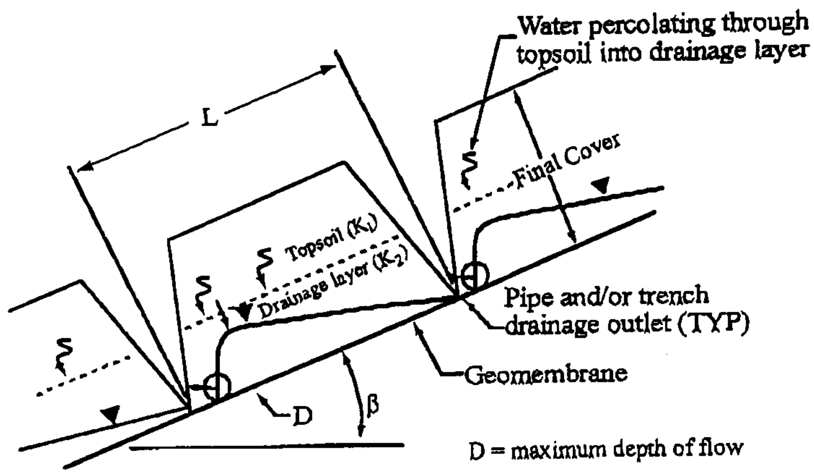

***Figure 3**: Schematic of head buildup in the drainage layer Thiel and Stewart (1993)*

The quantity of water, Q_{in}, infiltrating into a unit width of drainage composite having a length L is given by

$$Q_{in} = k_{veg} L\ 1 \cos \beta$$

The flow capacity of a drainage layer is solved for using Darcy's Law as follows:

$$Q_{out} = kiA = ki\ (tx1) = [kt]\ i = \theta\ t$$

where t is the thickness of the drainage layer, i is the flow gradient, and [kt] is transmissivity, θ. For slopes, the gradient i is equal to sin β, where β is the slope angle. The transmissivity of a geocomposite drainage layer is obtained from laboratory testing. It is important that θ be obtained at normal stress levels, boundary conditions and gradients that reflect actual field conditions. Additional reduction factors for creep deformation of the drainage core, biological clogging of the geotextile and so on may also be considered. Thiel and Stewart's model is generally limited to slopes steeper than 20% for sand or gravel drains. It is not limited for geonets because of the very low head associated with these products. It should be noted, however, that the simple model developed by Thiel and Stewart is conservative at the flatter slopes and therefore could be used in design of such slopes.

A factor of safety for the drainage capacity, FS_{dc}, of the geocomposite drainage layer can be defined as follows

$$FS_{dc} = \frac{Q_{out}}{Q_{in}} = \frac{\theta i}{k_{veg} L \cos\beta} = \frac{\theta \tan\beta}{k_{veg} L}$$

The first author recommends a minimum factor of safety of 8 (overall drainage safety factor plus reduction factors) for lateral drainage systems in final covers.

Comparison of HELP model prediction and measured final cover performance

Total infiltration was estimated using the HELP model for the design cover section on the 2% grade erosion control bench and the 3.5H:1V side slope. The total annual infiltration as a percentage of annual precipitation calculated by the HELP model was 6.3% for the side slopes and 0.2% for the 2% bench. For the three-year average, the annual infiltration as a percentage of annual precipitation measured was 6.31% for the side slopes and 0.33% for the 2% bench. While the HELP model gave a very accurate prediction of the average total infiltration, it failed to predict the prolonged periods of saturation of the VSL. This is in agreement with the observations of Koerner and Soong, (1998) who observed that the HELP model can underestimate the quantity of water collected in lateral drainage systems by up to two orders of magnitude. The impact of this error on slope stability can be catastrophic.

Summary

The use of the unit-gradient design method is supported by field data obtained in the mid-Atlantic region. Conversely, the HELP model is shown to provide an accurate prediction of the long-term average annual infiltration but does not accurately predict the peak flows in lateral drainage systems in final covers. Since such peak flows can adversely impact the slope stability of a final cover, the use of the HELP model in stability evaluations is not recommended.

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