Design of GCL Barrier for Final Cover Side Slope Applications

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Abstract

During the middle to late 80's, geosynthetic clay liners (GCL) were used as barrier layers on CERCLA covers to limit long term infiltration. This usage is increasing due to further regulatory driven need to limit infiltration on all waste containment systems and concerns about long-term dessication of compacted clay barriers. The addition of the GCL to a final cover system on a side slope creates the potential for failure of the slope caused by pore water pressure buildup immediately above the GCL and internal shearing of the GCL. This paper presents guidelines for (1) estimating the surface water infiltration rate above the GCL, (2) evaluate the shear stress in the GCL, (3) evaluating the acceptable level of pore water pressures above the GCL, and (4) estimating the actual leakage through the GCL. The ratio of the percentage of water infiltrating through the GCL to the total surface water infiltrating the cover system is termed the GCL efficiency. Laboratory data relating GCL efficiency to slope angle, infiltration rate, and pore pressure relief layer properties are presented.

Introduction

Geosynthetic Clay Liners (GCL) have been used in the USA and Europe since the late 80s to limit surface water infiltration at environmental restoration sites. Their uniformity as a manufactured product, speed of construction, relative insensitivity to freeze-thaw, and economy have led to an increasing use in the closure of both new lined landfills and in final cover systems over environmental restoration projects. The simplest GCL final cover system for side slopes is shown on Figure 1. The primary components of this system include (1) an erosion resistant vegetative layer that commonly includes a top soil layer and a vegetative support layer, (2) a pore water pressure relief layer, (3) the GCL infiltration barrier, and (4) a structural fill layer. The most important design parameter is the maximum rate of water infiltration through the vegetative layer to the pore water pressure relief layer. The final design must provide a minimum static factor of safety against sliding failure greater than 1.5, and provide an acceptable level of infiltration through the GCL. Each of these design consideration is presented in this paper.

Evaluation of Infiltration Rate

The maximum rate that surface water infiltrates to the pore water pressure relief layer on the side slope cab be estimated using either of the two following methods:

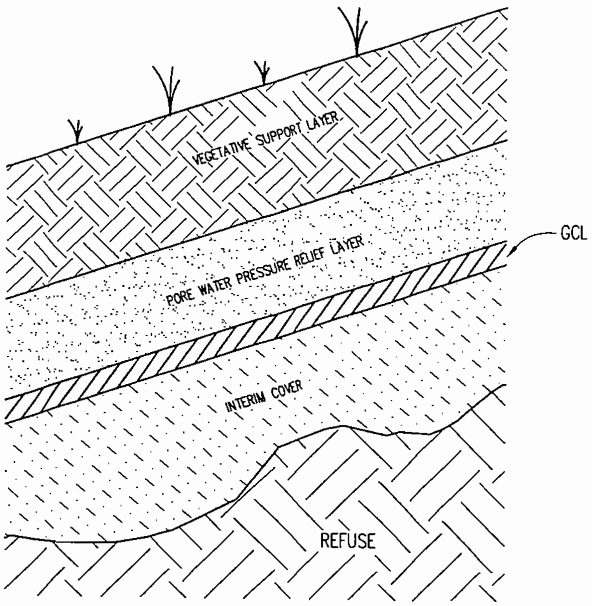

Figure 1. Typical GCL Final Cover System on Side Slope

Method One - HELP3 Analysis ---- In the latest version of HELP, Schroeder (1) has incorporated the research of Woolhiser, et al(2), to allow a conservative estimate of the rate and quantity of water infiltration through the side slopes. This method modifies the SCS runoff coefficient, CN, based on the following equation:

$$CN_{II}=100-(100-CN_{IIo}) \cdot \left(\frac{L^{*2}}{S^{*}} \right)^{CN_{IIo}^{-0.81}} \tag{1}$$

where L^* is a standardized dimensionless length, (L/500 ft), S^* is a standardized dimensionless slope, (S/0.04), and CN_{IIo} is the runoff coefficient for a mild slope under average soil moisture conditions. The peak daily rate of water infiltration through the vegetative layer can quickly be determined using the HELP model. HELP analyses performed in the southeast, assuming a good grass stand, predicted peak monthly infiltration through the vegetative layer ranging from 4 to 7 inches. This corresponds to equivalent infiltration velocities from 4 to 7 x 10^{-6} cm/sec. Note that the HELP based impingement rates are orders of magnitude less than predicted based on unit gradient method recommended by Thiel and Steward (3) for the Pacific Northwest. The difference with unit gradient assumption becomes less with good quality vegetation and increased permeability of the vegetative support layer. Vegetative cover layers that are not loams, e.g., sandy soils common to coastal regions, may approach the unit gradient condition.

Method 2 - Unit Gradient ---- Thiel and Steward (3) showed a vertical unit flow gradient exists for landfills in the northwest that are observed to have a vegetative layer that saturates during the winter months. Under the unit gradient, the apparent vertical rate of infiltration, v, is given by Darcy's Law as follows:

$$Q = v \cdot A = K \cdot I \cdot A = K \cdot A \rightarrow v = K \tag{2}$$

Thus for the 4H:1V slope previously evaluated using the HELP model the infiltration rate would be equal to the permeability of the vegetative layer, or 1×10^{-4} cm/sec. Comparing the infiltration rates predicted by Method 1 and Method 2 clearly shows that the unit gradient assumption is very conservative when saturation of the final cover surface layers does not occur.

Evaluation of Maximum Allowable Pore Water Pressure

The stability of the soil veneers above the GCL can be evaluated by the following general equations for the stability of an infinite slope by Matasović[(4)]:

$$FS = \frac{c/(\gamma \cdot z \cdot \cos^2\beta) + \tan\phi\left[1 - \gamma_w(z-d_w)/(\gamma \cdot z)\right] - k_s \cdot \tan\beta \cdot \tan\phi}{k_s + \tan\beta} \tag{3}$$

where FS = factor of safety, k_s = seismic coefficient, γ =unit weight of slope material(s), γ_w= unit weight of water, c = cohesion, ϕ = angle of internal friction of the assumed failure interface or surface, z = depth to the assumed failure interface or surface, and d_w = depth to the water table (assumed parallel to the slope). The above equations yield the factor of safety explicitly for both cohesive ($c \neq 0$) and cohesionless soils ($c = 0$). If there is no surface water infiltration, the depth to the water table, d_w, is set equal to the depth to the assumed failure plane, z.

Setting the seismic coefficient and cohesion equal to zero, and defining the pore water pressure, p_w, as $\gamma_w(z-d_w)$, Equation 3 reduces to the following expression:

$$FS = \frac{\tan\phi\left[1 - p_w/(\gamma \cdot z)\right]}{\tan\beta} \tag{4}$$

The allowable pore water pressures for a minimum slope stability factor of safety of 1.5 are shown on Figure 2 as a function of slope angle, β, and the interface friction angle, ϕ. For typical applications of a GCL on a side slope, e.g., $\beta = 14°$ and $\phi = 22°$, the allowable pore water pressure is only 30 psf or approximately 0.2 psi.

Internal Shear on GCL Barrier

The maximum shear stress, τ, acting on the GCL can be calculated[(5)] as follows:

$$\tau = W_T \sin\beta \tag{5}$$

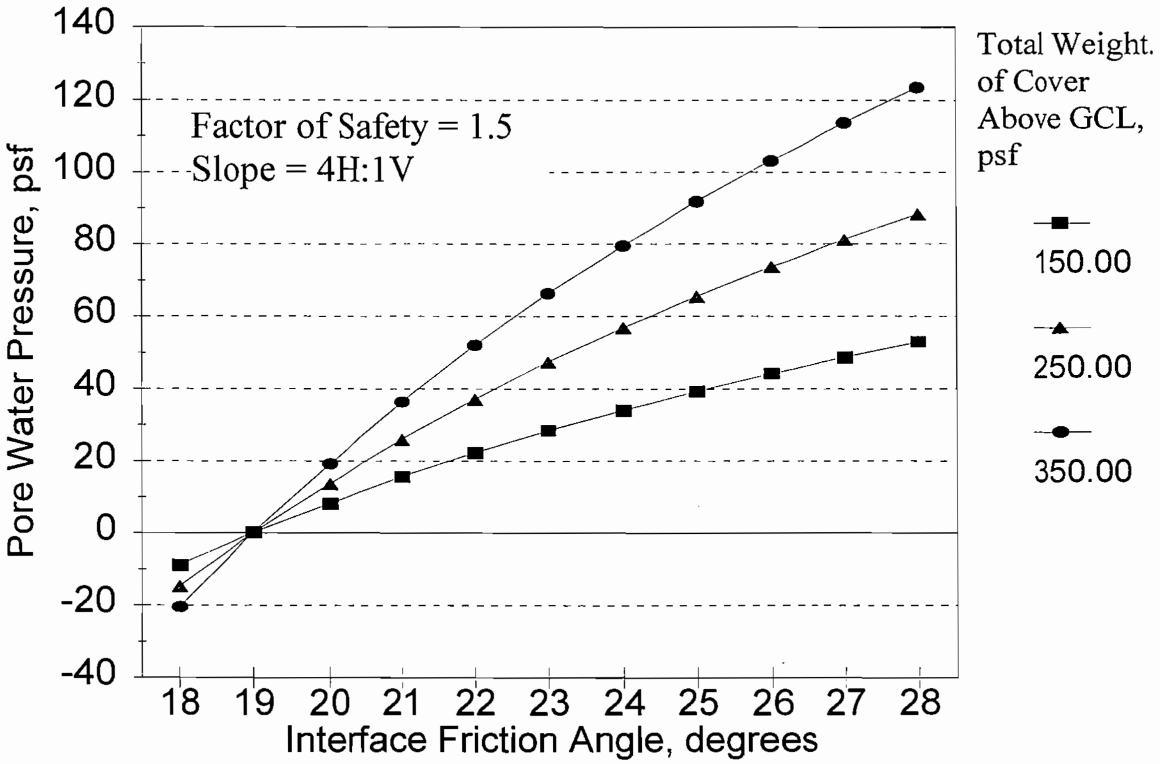

Figure 2. Allowable Pore Water Pressure on Side Slopes

where W_T is the total weight of the cover system over a unit area of the GCL and β is the slope angle. This relationship is shown on Figure 3 for a range of typical slope angles and cover unit weights. Use of a reinforced GCL having a post-hydration shear strength of 500 psf satisfies most typical cover applications. The use of an unreinforced GCL is not recommended since the possibility for full hydration and resulting loss of shear strength of the GCL exists.

Transmissivity of Pore Water Pressure Relief System

Thiel(3) showed that the minimum permeability, K_{pwr} , of the pore water relief layer is given by the following:

$$K_{pwr} = (v \cdot L) / D \cdot \sin \beta \qquad (5)$$

where L is the slope distance between drainage outlets on the pore pressure relief system and D is the maximum head acting on the barrier. For pore water relief layers constructed with sand, the maximum head acting on the system is controlled by slope stability considerations and is found by dividing the allowable pore water pressure determined from Figure 2 by the density of water, γ_w. For pore water relief layers constructed with geonets, the minimum acceptable transmissivity of the geonet is given by the product of $K_{pwr} \cdot D$. The actual transmissivity of the geonet is commonly an order of magnitude greater than the minimum requirement.

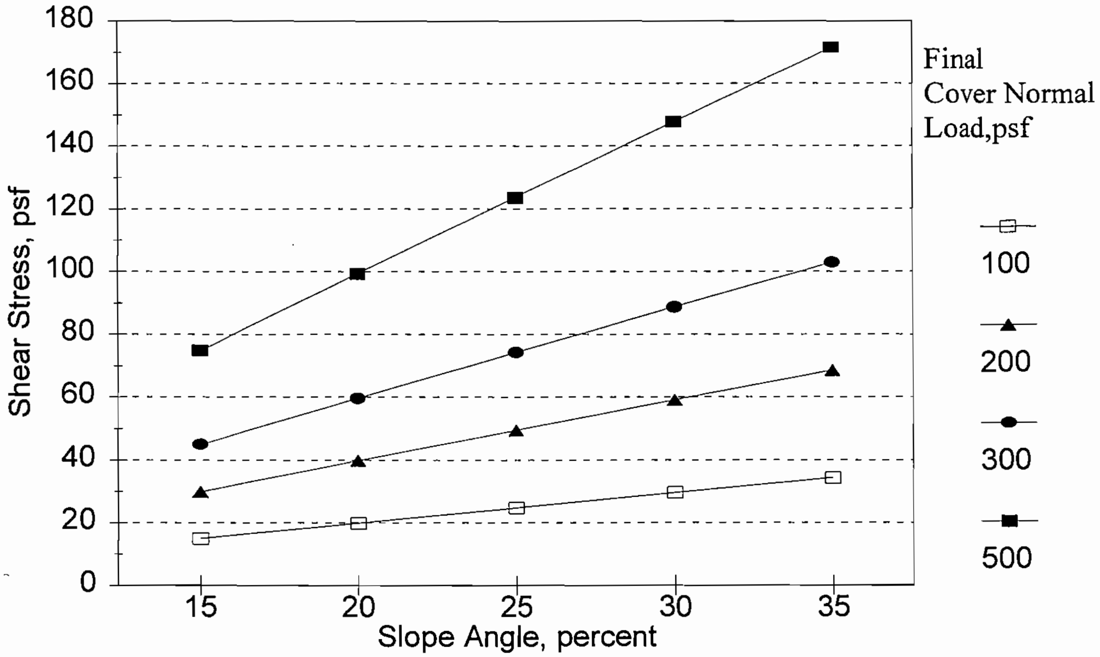

Figure 3. Shear Stress Acting on GCL on Side Slopes

Infiltration Through GCL

The maximum head acting on the GCL can be obtained from Figure 3. The average head acting on the GCL will be approximately half of the maximum head since the pore water pressure will be approximately zero at the drainage outlets at the top and bottom of the slope. The average flow gradient, $I = \Delta H/\Delta L$ acting across the GCL will then be given by $I = D/2t_{GCL}$, where t_{GCL} is the thickness of the GCL. Using Darcy's Law, the flow through the GCL, Q_{GCL}, can be expressed as follows:

$$Q_{GCL} = K_{GCL} \cdot \frac{D}{2 \cdot t_{GCL}} \cdot L \cdot 1 = \frac{K_{GCL} \cdot D \cdot L}{2t_{GCL}} \tag{7}$$

By substituting Equation 5 into Equation 6, we can produce a general expression for the flow through a GCL side slope barrier as follows:

$$Q_{GCL} = \frac{K_{GCL} \cdot v \cdot L^2}{K_{PWR} \cdot 2 \cdot t_{GCL} \cdot \sin\beta} \tag{8}$$

The percentage of side slope infiltration water that actually penetrates the GCL, referred to as barrier efficiency, E, by the author, can be calculated by comparing Q_{GCL} to the total infiltration, v·L·1. The efficiency of the GCL, E_{GCL} can be given as

$$E_{GCL} = [1 - \frac{K_{GCL} \cdot L}{K_{PWR} \cdot 2 \cdot t_{GCL} \cdot \sin\beta}] \cdot 100\% \tag{9}$$

The GCL efficiency based on Equation 8 is presented on Figure 5 for a range of typical side slope conditions. For the majority of common side slope conditions, the GCL barrier clearly limit infiltration to less than 1% of the actual total side slope infiltration using clean sands or a geonet in the pore water pressure relief layer. For most of the southeast, the side slope infiltration represents less than 25% of the total precipitation. Thus the maximum infiltration anticipated through the side slope GCL is less than .25% of the total annual precipitation.

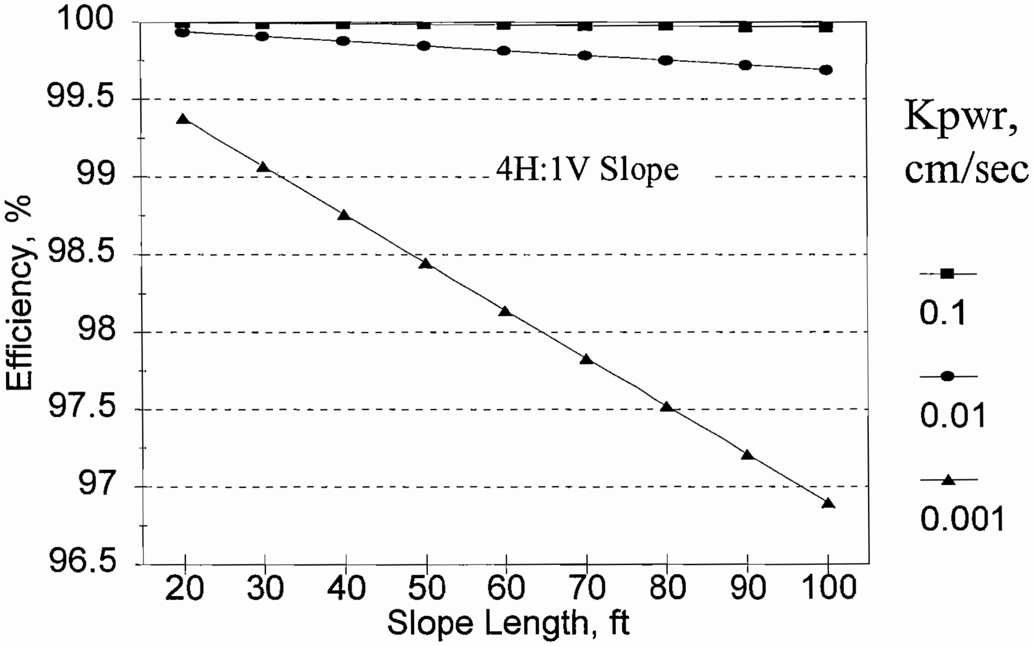

Figure 4. GCL Side Slope Infiltration Efficiency

Laboratory Evaluation of GCL Efficiency

A limited series of laboratory tests were performed to verify the relative magnitude of both leakage through the GCL and actual GCL efficiency as predicted by the above equations. These tests were performed in small (90x60 cm) flow boxes. Details of the flow boxes are shown on Figure 5. The flow boxes were mounted so that the slopes could vary from

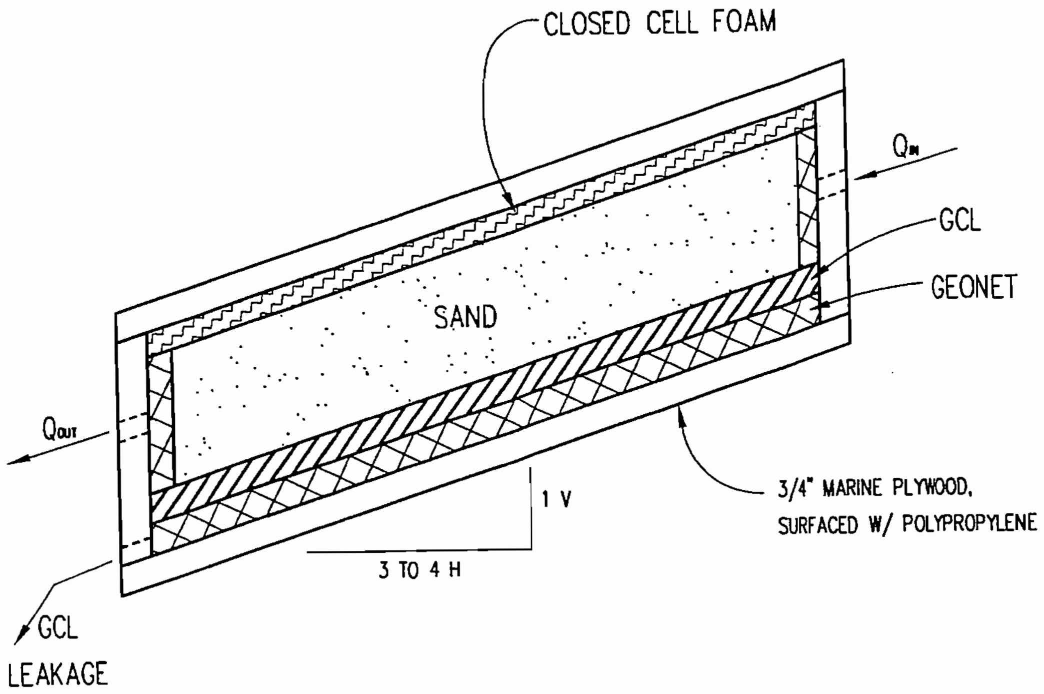

Figure 5. Laboratory GCL Efficiency Test Cell

4H:1V(14.0°) to 3H:1V(18.4°). Water was pumped into the flow boxes at a rate ranging from 0.6 to 1.5 gallons per minute. The sand is a clean, relatively uniform sand commonly used for construction of water well sand filters. The sand has a D_{10} grain size of 0.10 cm. Based on Hazen's formula, $k(cm/sec) = 100\,D_{10}^2$, the sand has a permeability of $\approx$ 1.0 cm/sec.

The GCL efficiency can be calculated from Equation 9 assuming the permeability of the GCL is 5×10^{-9} cm/sec and that the thickness of the GCL is 0.5 inch. The GCL thickness was measured as samples of the as-tested GCL was removed from the flow boxes and average 12 mm. The GCL efficiency predicted based on Equation 9 is equal to approximately 100%, i.e., no infiltration. Test data from the flow boxes is given on Table 1 for several measured flow rates. The quantity of water infiltrating through the GCL is so small that it had to be captured in a sealed bottle to prevent evaporative loss from destroying it.

It should be noted that minor infiltration through the GCL did occur for the initial 24-hours of each test. This was the time required for the bentonite granules to hydrate sufficiently that such that the GCL sealed. The GCL efficiency predicted based on Equation 8 is equal to approximately 99.99%. The measured efficiency for these tests ranged from 98.4 to 100%, but could not be quantified to the accuracy of Equation 9. The majority of GCL samples tested had no measurable infiltration through the GCL after the initial 24 hour wetting cycle. What infiltration that did occur is thought to be due to difficulties in sealing the GCL edges during the tests.

Table 1 Laboratory GCL Efficiency Test Data

Slope	Series Description, (Box 1or 2 - Series)	Supply Rate, liter/min	Leakage Rate cc/min	Efficiency %
4H:1V	Coarse Sand-1-A	2.3	38	98.4
	Coarse Sand-2-A	3.0	0	100
	Coarse Sand-1-B	5.7	12	99.8
	Coarse Sand-2-B	5.7	0	100
	Fine Sand-1-A	.25	0	100
	Fine Sand-1-B	.25	5	98.0
3H:1V	Coarse Sand-1-A	2.3	14	99.4
	Coarse Sand-2-A	2.3	0	100
	Coarse Sand-1-B	5.7	0	100
	Coarse Sand-2-B	5.7	0	100

Unfortunately, the GCL's are inherently so efficient that longer slope lengths are required to collect measurable flow through the GCL. The tests were repeated using a finer sand having a permeability of approximately .01 cm/sec. Under the same circumstances, the finer sand produced no discernable increase in leakage through the GCL even though the head acting on the GCL was increased.

Example Application

Design a GCL side slope barrier cover for a landfill located near Raleigh, North Carolina. Assume a 4H:1V side slope, a minimum interface friction value between the GCL and the sand pore water relief system of 22 degrees, a sand drain layer permeability of 1 x 10^{-2} cm/sec, and that the cover section includes a 24-inch thick vegetative support layer and a 9-inch thick sand pore water relief layer over the GCL.

- Evaluation of Infiltration Rate : The design infiltration rate is obtained based on HELP analysis as 6.1 x 10^{-6} cm/sec.

- <u>Evaluation of Maximum Allowable Pore Water Pressure</u> : The unit weight of the soil overlying the GCL is approximately 100x(24+9)/12= 366 psf. Using an interface friction of 22° and a unit weight of ≈350 psf, the maximum allowable pore water pressure is obtained from Figure 2 as 52 psf or approximately 10 inches of water.

- <u>Evaluate the Actual Pore Water Pressure</u> : The actual head acting on the GCL can be calculated from Equation 5 by assuming a drainage length, L. For most covers in the East, it is common to place side slope swales every 20 foot vertical which results in a maximum drainage length of approximately 82.5 feet. Equation 5 can be modified as follows:

  $$D = v \cdot L / (K_{pwr} \cdot \sin \beta) \qquad \textbf{(10)}$$

  Substituting site values into Equation 5, the calculated maximum head acting on the GCL is ranges from 2 feet for a 1 x 10^{-3} cm/sec sand to 0.2 feet for a 1 x 10^{-2} cm/sec sand in the pore water pressure relief system. Obviously, the head of water must be less than the thickness of the pore water pressure relief layer. For this example, we will assume a 1 x 10^{-2} cm/sec sand is available such that the maximum head acting on the GCL is 0.2 feet.

- <u>Calculate Infiltration Through GCL</u> : The leakage through the GCL can be found using Equation 7 with K_{GCL} = 5 x 10^{-9} cm/sec, D_{AVE} = 0.2/2 = 0.1 feet, L = 82.5 feet, and the thickness of the GCL, t_{GCL}, assumed equal to 12 mm. The resulting flux is equal to 6.8 x 10^{-8} ft^3/sec or 0.00053 gal/ft^2/day.

- <u>Calculate the GCL Efficiency</u>: The efficiency of the GCL can be calculated from Equation 9 with K_{GCL} = 5 x 10^{-9} cm/sec, K_{PWR} = 1 x 10^{-2} cm/sec, L = 82.5 feet, and the thickness of the GCL, t_{GCL}, equal to 12 mm. Substituting these values predicts an efficiency of 99.78%.

Summary

This paper presents a general methodology for the design of GCL barriers on side slope applications. The design procedure accounts for slope stability and infiltration considerations and can be adapted for side slopes of varying steepness. Additionally, the result of the numerical analysis and limited laboratory test program indicate that the use of a GCL barrier in such systems is capable of limiting infiltration through the cover to less than 1% of the surface infiltration. Since less than 25 % of the site precipitation typically infiltrates such slopes the total infiltration may be less than 0.25% of site precipitation. Thus in most applications, the use of a GCL barrier alone will provide adequate control of infiltration and eliminate stability problems associated with the use of composite barriers on side slopes.

References

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SI Conversions

1 inch = 2.54 cm
1 psf = 0.04788 kilonewtons/square meter
1 pcf = 5.787 kilonewtons/cubic meter
1 gallon = 0.00037854 cubic meter