

Geocomposite Drains for Side Slope Stability in Landfill Covers

Aigen Zhao, Ph.D., P.E., Tenax Corporation, Baltimore, MD, USA

Gregory N. Richardson, Ph.D., P.E., G. N. Richardson and Associates, Raleigh, NC, USA

Abstract

The presence of a barrier layer within the 3H to 4H: 1V side slopes common to landfill final covers invites sliding failure of the cover due to a build up of pore water pressure above the barrier or landfill gas (LFG) pressures beneath the barrier. Both pore water and LFG pressures reduce the contact or effective stress acting on veneer interfaces and thus reduce the sliding stability of the final cover. Here limiting infiltration is not the primary concern, but stability is. To ensure stability, the designer must confirm that the interface friction between any two layers of the cover is adequate to resist the following:

- the reduction in contact stresses between the geomembrane and the overlying soil resulting from water infiltrating the cover and hydraulic head buildup, and
- the reduction in contact stresses between the geomembrane and the underlying soil resulting from LFG pressures.

This paper will focus on a review of the design of geocomposite drainage layers to satisfy these design considerations and demonstrates how geocomposite drains can be designed to control these stresses to ensure stability. Design examples will be presented in this paper.

Introduction

The design of final covers for lined landfills presents the designer with challenges related to soil erosion and slope stability. This section will focus on the design of geosynthetic drainage composites to ensure slope stability of the 3H to 4H: 1V side slopes common to landfill final covers. This topic has been the subject of recent academic studies at Geosynthetic Research Institute and was the topic of keynote presentation at the 6th International Conference on Geosynthetics in Atlanta (Koerner and Soong, 1998). Here limiting infiltration is not the primary concern, but stability is.

To ensure the stability of the cover slope, the designer must confirm that the interface friction between any two adjacent layers of the cover system is adequate to resist the following:

1. seepage forces, therefore, the reduction in contact stresses between the geocomposite drain and the overlying soil resulting from water infiltrating through cover and generating pore water pressures, and
2. the reduction in contact stresses between the geomembrane and the underlying soil resulting from LFG pressures.

This section will focus on a review of the design of geocomposite drainage layers to satisfy both design considerations.

Seepage Forces and Stability Equations

The authors feel that, with the exception of arid and semi-arid regions, the designer should assume that the vegetative layer becomes saturated during its service life due to extreme weather conditions. The greatest uncertainty in the design of the pore water drain is accurately predicting the maximum rate of water infiltration. The extreme weather generated by 'El Nino' has made this prediction easier. The high precipitation and mild weather that accompanied 'El Nino' produced saturated conditions in the vegetative layer in many regions of the United States that we previously would not have anticipated.

When the cover saturates, the maximum seepage forces in the cover soil layers using the infinite slope model shown on Figure 1. is given as follows:

$$F_{seep} = \gamma_w h \sin \beta \quad \text{Eq. 1}$$

Where β is the slope angle, h is the vertical thickness of the soil cover, and γ_w is the unit weight of water.

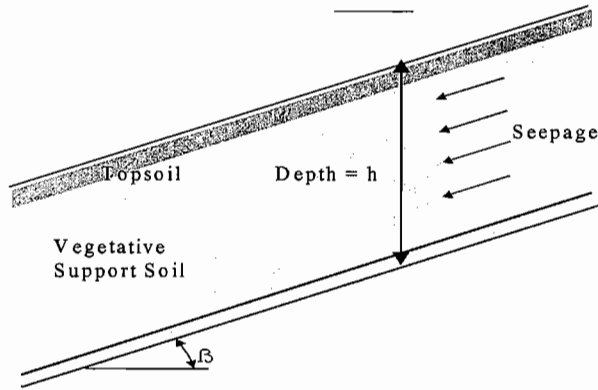


Figure 1 Infinite slope model

Surface water infiltrating through the vegetative layer will accumulate above the barrier layer and generate detrimental pore water pressures if it is not drained off. If the transmissivity of the geocomposite is inadequate, then pore pressures will develop in the cover soil layers. If the cover soil fully saturates, the slope stability factor of safety is given as

$$FS = \frac{\text{Resisting Forces}}{\text{Driving Forces}} = \frac{\gamma_b h \cos \beta \tan \delta}{\gamma_b h \sin \beta + \gamma_w h \sin \beta} = \frac{\gamma_b \tan \delta}{\gamma_{sat} \tan \beta} \approx 0.5 \frac{\tan \delta}{\tan \beta} \quad \text{Eq. 2}$$

Where δ is the minimum interface friction of between the geocomposite and soil or geocomposite and the geomembrane, γ_b and γ_{sat} are the buoyant and saturated unit weight of the cover soil. When such seepage forces are eliminated by using adequately drained geocomposite, the slope stability factor of safety, FS, becomes:

$$FS = \frac{\tan \delta}{\tan \beta} \quad \text{Eq. 3}$$

For common 4H:1V side slopes and $FS = 1.5$, this requires a minimum geocomposite/geomembrane interface friction angle of 20.5° when the cover soil is not saturated and 36.8° when it is saturated. The 20.5° interface friction angle is relatively easily achieved due to the "velcro" stick between nonwovens and most textured geomembranes. The 36.8° interface friction angle actually exceeds the internal friction angle of common soils used in landfill cover systems and demonstrates that seepage forces must be prevented.

Lateral Drainage Calculations

The design of the pore water pressure drain underlying a saturated cover soil layer was first presented by Thiel and Stewart at the Geosynthetics '93 conference in Vancouver, B.C.. Once the cover soil is saturated, the gradient, i , is equal to one (unit gradient) and the infiltration velocity is equal to the permeability of the soil. 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. Typical permeability values for vegetative systems range from 1×10^{-3} to 1×10^{-5} cm/sec. Tighter soils do not allow root penetration and soils looser do not provide adequate water storage. The basic lateral drainage model developed by Theil and Stewart is shown on Figure 2.

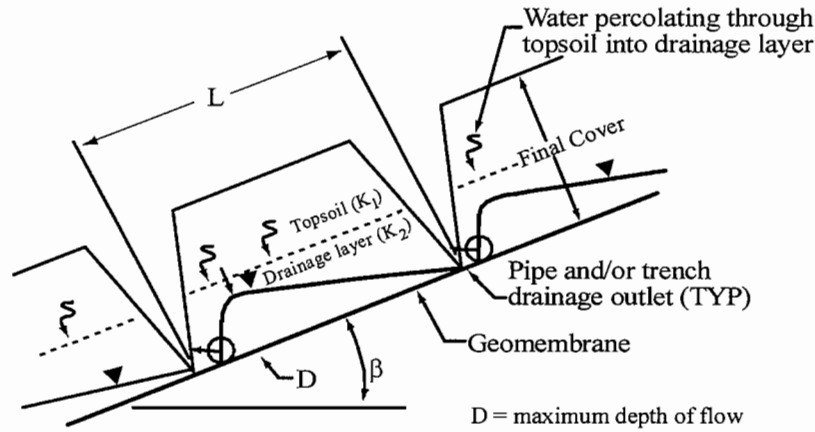


Figure 2 Schematic of head buildup in the drainage layer (Thiel and Stewart, 1993)

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

$$Q_{in} = k_{veg} L i \cos\beta \quad \text{Eq. 4}$$

Where k_{veg} is the permeability of the vegetative supporting layer of the cover, and L is the drainage length. The flow capacity of a drainage layer is solved for using Darcy's Law as follows:

$$Q_{out} = k_{veg} i A = k_{veg} i (t \times 1) = [k_{veg} t] i \quad \text{Eq. 5}$$

where t is the thickness of the drainage layer and $[k_{veg} t]$ is defined as transmissivity, Ψ . The transmissivity of a geocomposite drainage layer is obtained from laboratory testing per ASTM D 4716. It is important that Ψ 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, etc. must also be considered. Thiel and Stewart's model is limited to slopes steeper than 20%. For slopes flatter than this, the model developed by McEnroe (1993) should be used, and the design considerations were discussed by Zhao and Richardson (1998). Note that the Theil and Stewart approach is conservative for flat slopes.

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

$$FS_{dc} = Q_{out} / Q_{in} = \Psi i / (k_{veg} L \cos\beta) \quad \text{Eq. 6}$$

The authors recommend the Long-Term Reduction Factor $FS_{dc} = 8$ for lateral drainage systems in final covers. It is important to understand the impact of both Ψ and L on the hydraulic factor of safety. Design implementation of this equation is typically integrated into the side slope swale systems commonly used to limit surface erosion and slope length L , see Thiesen and Richardson, 1998. The geocomposite drainage layer is designed to drain into each swale. To ensure that L will be defined by the actual spacing of the swales, the drainage geocomposite must not be continuous across a swale. These two functional requirements can be accomplished using the side slope details shown on Figure 3.

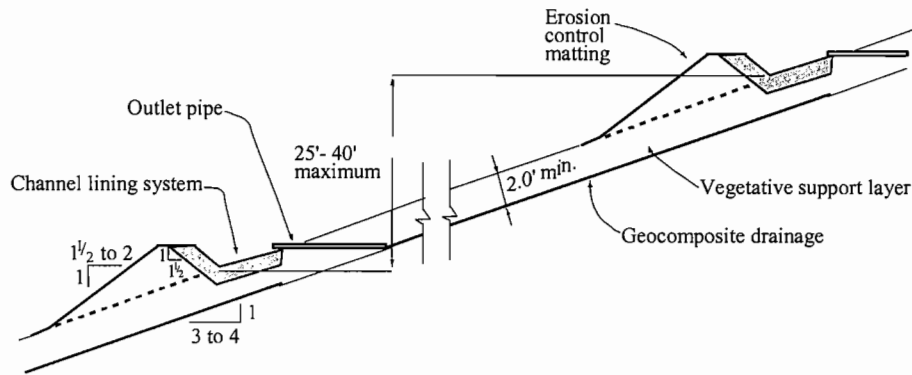


Figure 3. A schematic diagram of a side slope swale in a landfill final cover

Long-Term Reduction Factor, FS_{dc}

The need for the high long-term service reduction factor of 8 can be shown by examining the conditions that exist between full saturation of the cover soils and effective lateral drainage of the geonet. Soong and Koerner (1997) presented an analytically more rigorous analysis of side slope stability that relied on water balance and knowledge of the run-off coefficient to estimate the rate of infiltration. They defined the depth of saturation as compared to the overall thickness of the soil cover as the “Submergence Ratio”. As the zone of saturation rises, the submergence ratio approaches 1 and the cover soils experience increased seepage forces or pore water pressure. Figure 4.4 demonstrates the relations of cover soil stability, submergence ratio, and drainage safety factor as a function of transmissivity of the geocomposite for the following field conditions: slope length = 40m long, slope inclination angle = 14° (4H:1V), minimum interface friction angle (δ) = 22° , permeability of the vegetative cover soil = 5×10^{-4} cm/sec, precipitation = 60 mm/hr, and the run off coefficient = 0.4. For these same field conditions, the slope stability factor of safety, FS , is less than 1 under full saturation; the FS using Equation 2 is 0.8. As the geocomposite transmissivity increases, the depth of saturation and pore pressures are both reduced and the slope stability increases. When no pore pressures develop, the slope stability factor of safety calculated by Equation 3 equals 1.6. **Note from Figure 4 that the transition from excess pore pressure ($FS=0.8$) to no pore pressures ($FS=1.6$) occurs over a change in transmissivity from 7×10^{-4} to 8.8×10^{-4} $m^3/sec-m$. This is a minor change in transmissivity (25% reduction) considering the fact that transmissivity tests have significant variability (Koerner and Soong, 1998).**

This clearly demonstrates why the authors recommend that a high long-term service reduction factor be used in the design of lateral drainage systems in landfill covers. Failure of the designer to provide an adequate lateral drainage layer will result in catastrophic failure of the side slope if a single occurrence of cover saturation occurs during its service history. Given the uncertainties regarding cover soil properties, vegetative quality, and future precipitation, the designer has no option other than increasing the degree of safety factor used in their design.

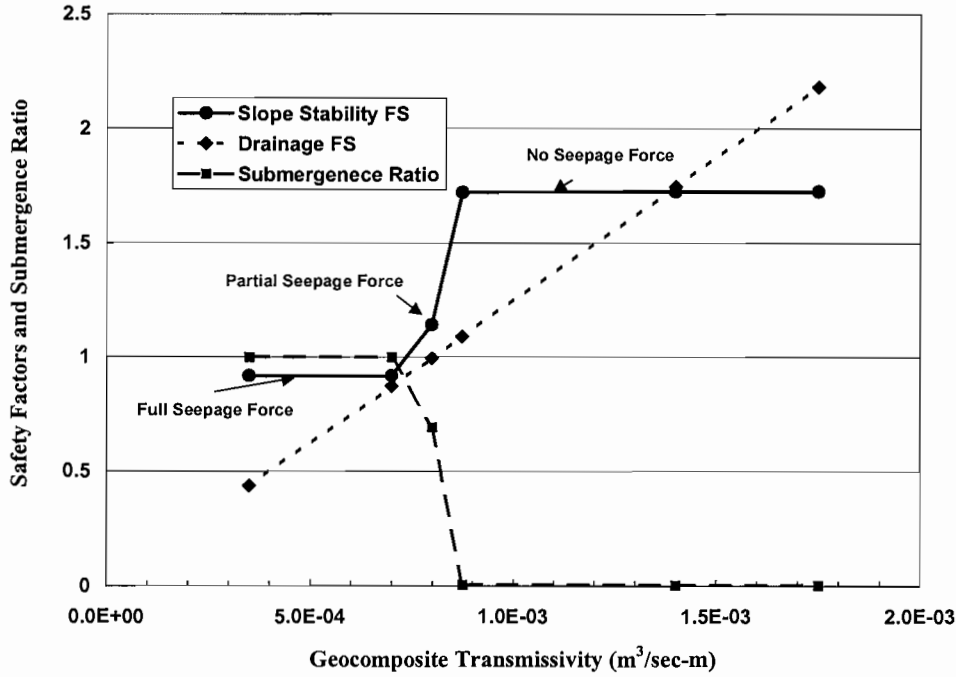


Figure 4. Safety factor for slope drainage, stability and geocomposite transmissivity

LFG Pressure Dissipation

LFG are generated during the biodegradation of fractions of the MSW. The actual rate of gas generation for a given landfill is dependent on the waste composition, waste moisture content, etc. such that a design engineer will have to make an assumption for the gas generation rate. For lined landfills that do not recirculate leachate, the gas generation rate, q_{gas} , can be typically assumed to equal $6.24 \cdot 10^{-3}$ m³/year/kg (0.1 scf/year/lb) of MSW. The rate of gas flux, Φ_{gas} (m³/year/m²), immediately beneath the final cover can be conservatively estimated as follows:

$$\Phi_{gas} = \frac{\text{Weight of Waste} \times q_{gas}}{\text{Area of Final Cover}} \quad \text{Eq. 7}$$

The gas flow capacity of the geocomposite should be evaluated in the laboratory using gas flows. However, such tests are exceptionally rare. An estimate for the airflow capacity of the drainage geocomposite can be calculated by *dividing* the water transmissivity by 14; for landfill gas divide by approximately 10. This conversion is based on an assumption of laminar flow and the ratio of the intrinsic viscosity of the gas to water. This relationship was confirmed for geocomposite drains by Thiel, 1998.

The assumption of laminar flow allows the use of Darcy's Law. This assumption allows the maximum pressure generated by the gas collected by a blanket drain, u_{max} , be defined as follows:

$$u_{max} = \frac{\Phi_{gas} \gamma_{gas}}{\Psi_{req}} \left[\frac{L^2}{8} \right] \quad \text{Eq. 8}$$

where γ_{gas} is the density of LFG which is approximately $1.28 \cdot 10^{-2}$ kN/m³, L is the length of the geocomposite drain, and Ψ_g is the required gas transmissivity. Calculation of the required transmissivity requires an assumption for the maximum gas pressure that can be allowed beneath the barrier layer in the

final cover. For example, typical landfill side slopes generally require the gas pressure remain below 75 mm water head or 0.75 kPa relative pressure beneath the barrier for stability considerations. The required transmissivity, Ψ_g , is then calculated as follows:

$$\Psi_g = \frac{\Phi_{gas} \gamma_{gas}}{u_{max}} \left[\frac{L^2}{8} \right] \quad \text{Eq. 9}$$

While the density of the LFG is greater than that of air ($\gamma_{air} = 1.18 \cdot 10^{-2} \text{ kN/m}^3$), the movement of LFG is essentially governed by gas pressure gradients and not gravity. Thus, the drainage length “L” dimension can be either vertical up the slope or horizontal to the slope.

Design Examples – Surface Water Infiltration

Example –1: Determine the required transmissivities for a geocomposite drainage layer for a final cover having the following properties:

- 25% slopes
- pipe horizontal spacing of 50 meters
- overall safety factor FS = 8
- 2-foot vegetative cover with $K = 1 \times 10^{-4} \text{ cm/sec}$
- Assume both HELP model infiltration rates and the saturated case

Typical “east coast” locations yield HELP peak impingement rate, $r = 9 \times 10^{-6} \text{ cm/sec}$. By using Equation 6, the required drainage transmissivity for the HELP case is

$$\Psi = FS_{dc} * k_{veg} L \cos \beta / i = 8 * (9 * 10^{-6} \text{ cm/sec}) (50\text{m}) / 0.24 = 1.5 * 10^{-4} \text{ m}^3/\text{sec-m}$$

For the saturated or unit gradient case, $r = 1 \times 10^{-4} \text{ cm/sec}$, the required transmissivity is

$$\Psi = FS_{dc} * k_{veg} L \cos \beta / i = 8 * (1 * 10^{-4} \text{ cm/sec}) (50\text{m}) / 0.24 = 1.7 * 10^{-3} \text{ m}^3/\text{sec-m}$$

Note that the HELP model significantly underestimates the transmissivity required if the cover saturates. The normal load acting on the geocomposite drainage blanket in this application is typically less than 25 kPa. The geocomposite drain is then selected using laboratory transmissivity test data with a flow gradient *equal to or greater than* the 25% field condition.

Example Two: Determine the drainage safety factor, slope stability safety factor for a landfill cover having the following properties:

- 3:1 slope, $\beta = 18.4^\circ$
- Slope length $L = 122 \text{ m}$
- Permeability of the cover soil $k = 5 \times 10^{-4} \text{ cm/sec}$
- Saturated unit weight of cover soil $\gamma_{sat} = 18 \text{ kN/m}^3$, hence $\gamma_b = 8.3 \text{ kN/m}^3$
- Transmissivity of the drainage composite $\Psi = 1.62 \times 10^{-3} \text{ m}^3/\text{sec-m}$
- Geocomposite/geomembrane interface friction angle $\delta = 25^\circ$

The unit gradient factor of safety for drainage is calculated by Equation 6 as

$$FS_{dc} = \frac{\Psi i}{kL \cos \beta} = \frac{1.62 * 10^{-3} * \sin 18.4^\circ}{5 * 10^{-6} * 122 \cos 18.4^\circ} = 0.88$$

It is more difficult to establish a 'typical' range of required gas transmissivity since the volume of waste impacts the calculation and will vary from site-to-site. Actual gas generation rates can be obtained by performing a NSPS (40 CFR Part 60) Tier 2 gas emissions survey.

Concluding Remarks

This paper presents design methods that allow the hydraulic properties of water and gas lateral-drainage systems to be conservatively calculated. These procedures allow a designer to conservatively design lateral drainage systems in final covers even when faced with significant uncertainties regarding the specifics of the soils to be used, the quality of vegetation that will be established, and future maximum precipitation events. The authors feel that these approximate methods are more appropriate than more rigorous methods given such uncertainties.

References:

Koerner, R.M and T.Y. Soong, (1998). "Analysis and Design of Veneer Cover Soils", *Proceedings of 6th International Geosynthetic Conference*, Atlanta, Vol. 1, pp. 1-23.

Koerner, G.R. and T.Y. Soong, (1998). "Scatter in Geosynthetics Performance Testing and Its Effect on Three Design Examples", *Proceedings of GRI-12th Annual Conference*, Philadelphia, PA, pp. 139-152.

McEnroe, B. M. (1993). "Maximum Saturated Depth over Landfill Liner", *Journal of Environmental Engineering*, ASCE, Vol.119, No. 2, March/April, pp. 262-270.

Theisen, M.S. and Richardson, G. N. "Geosynthetic erosion control for landfill final covers", *Geotechnical Fabrics Report*, May, pp. 22-27.

Soong, T.Y. and Koerner, R.M. (1997). "The Design of Drainage Systems over Geosynthetically Lined Slopes," GRI Report #19.

Thiel, R.S. (1998). "Design Methodology for a Gas Pressure Relief Layer below a Geomembrane Landfill Cover to Improve Slope Stability", *Geosynthetics International*, Vol. 5, No.6, pp. 589-617.

Thiel, R.S., and Stewart, M.G., (1993). "Geosynthetic Landfill Cover Design Methodology and Construction Experience in the Pacific Northwest", *Proceedings Geosynthetics '93*, Vancouver, IFAI, pp. 1131-1144.

Zhao, A. and Richardson, G. N. (1998). "Lateral Drainage Systems over Landfill Barrier Systems—flat Slopes," *Geotechnical Fabrics Report*, August, pp. 21-23.