SEEPAGE INDUCED LANDFILL CAPPING FAILURES AND A CONSERVATIVE METHOD FOR DESIGNING LANDFILL LATERAL DRINAGE LAYER

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ABSTRACT

The long-term stability of landfill final covers becomes a challenge when a combination of significant slopes and geomembranes are present together. The extreme weather generated by 'El Nino' has generated significantly higher precipitation than what USEPA HELP model predicts. The resulting large amount of infiltrating water produces a zone of saturation that generates significant seepage forces in the overlying soil. These seepage forces will result in a slope failure during a design surface water event. Such failures have proven to be very costly. This paper focuses on a review of the design of geocomposite drainage layers to satisfy critical design considerations and demonstrates how geocomposite drains can be designed to control these seepage stresses. Design examples are presented in this paper. Actual examples of landfill failures resulting from inadequate drainage are described, and design changes that would have alleviated problems are also discussed.

INTRODUCTION

The design of final covers for lined landfills presents the designer with challenges related to soil erosion and slope stability. 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:

- seepage forces, therefore, the reduction in contact stresses between the geocomposite drain and the overlying soil;
- the reduction in contact stresses between the geomembrane and the underlying soil resulting from landfill gas pressures.

This paper focuses on the design of geosynthetic drainage composites to eliminate seepage forces that are critical to 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).

Drainage geocomposites are presently widely used in the landfill closures as the surface water collection layer over the barrier layer. The two geocomposite lateral drainage layers in the surface water collection layer, side slope drain, and the top drain as shown in Figure 1, act to reduce the hydraulic head acting on the underlying barrier system. The impact of the failure of one of these two systems is dramatically different. On the flatter slopes associated with the top of typical cover systems, the higher head will result in an increase in the infiltration rate through the barrier. A similar failure of the lateral drainage layer on the side slope will result in a catastrophic slope failure of all layers above the barrier system.

Fig. 1 Geocomposite drainage layers in a landfill cover

SEEPAGE FORCES AND STABILITY EQUATIONS

With the exception of arid and semi-arid regions, the designer should assume that the vegetative layer of a landfill cover 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 in which 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 2 is given as follows:

$$F_{seep} = \gamma_w h \sin\beta \tag{1}$$

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

Surface water infiltrating through the vegetative layer will accumulate above the barrier layer and generate detrimental pore water pressures if it is not drained. 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

$$FS = \frac{\gamma_b h \cos\beta \tan\delta}{\gamma_b h \sin\beta + \gamma_W h \sin\beta} = \frac{\gamma_b \tan\delta}{\gamma_{sat} \tan\beta} \approx 0.5\frac{\tan\delta}{\tan\beta} \tag{2}$$

Fig. 2 Infinite slope stability model

Where δ the interface friction angle between the geocomposite and soil or geocomposite and the underlying 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:

$$FS = \frac{\tan\delta}{\tan\beta} \tag{3}$$

For common 4H:1V side slopes and *FS*=1.5, this requires a minimum geocomposite/geomembrane interface friction angle of 20.6° when the cover soil is not saturated and 36.9° when it is saturated. The 20.5° interface friction angle is relatively easily achieved due to the "velcro" stick between nonwoven geotextiles and most textured geomembranes. The 36.9° 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. Once the cover soil is saturated, the infiltration gradient is equal to one (unit gradient) and the velocity is equal to the permeability of the soil. The rate of water infiltration into the geocomposite drain can then be readily calculated under a unit gradient. Typical permeability values for vegetative systems range from 1 x 10^{-3} to 1 x 10^{-5} cm/sec. Tighter soils do not allow root development and looser soils do not provide adequate water storage. A simple water balance equation can be used to determine the drainage safety factor.

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

$$Q_{in} = k_{veg} \times L \times 1 \tag{4}$$

where k is the permeability of the vegetative supporting layer of the cover, and L is the drainage length, measured horizontally.

While the quantity of water, Q_{out}, exiting from the drainage layer is calculated by Darcy's Law as follows:

$$Q_{out} = k_d \times i \times A = k_d \times i \times (t \times 1) = \left[k_d \times t \right] \times i = \theta \times i \tag{5}$$

where k_d is the permeability of the drainage layer, and t is the thickness of the drainage layer. [k_d x t] is defined as hydraulic transmissivity, θ. The required transmissivity for the geocomposite drain can then be calculated

$$\theta_{req} = \frac{k_{veg} \cdot L}{i} = \frac{k_{veg} \cdot L}{\sin \beta} \tag{6}$$

The transmissivity of a geocomposite is evaluated using a laboratory transmissivity test (ASTM D-4716). This test is performed using the transmissivity box that allows a range of normal loads and boundary conditions to be applied to the upper surface of the geocomposite. The head acting across the 300 mm by 300 mm square sample can be varied to create a range of gradients that simulate field slope conditions. In general, transmissivity decreases with increasing normal loads and increases with decreasing flow gradients. Laboratory measured transmissivity of a geocomposite drain does not take into account of potential reduction factors during its design life. GRI-GC8 standard (2001) requires the allowable transmissivity being determined under simulated condition for 100-hour duration using the following formula:

$$RF_{CR} = \left[\frac{\left(t_{CO} / t_{virgin}\right) - (1 - n_{virgin})}{\left(t_{CR} / t_{virgin}\right) - (1 - n_{virgin})} \right]^3 = \left[\frac{t_{CO} - \frac{\mu}{\rho}}{t_{CR} - \frac{\mu}{\rho}} \right]^3$$

$$\theta_{allow} = \theta_{100} \frac{1}{RF_{CR} \times RF_{CC} \times RF_{BC}} \tag{7}$$

where

θ_{allow} = allowable transmisisivity
θ_{100} = laboratory measured transmissivity determined under simulated conditions for 100-hour duration
RF_{CR} = reduction factor for creep to account for long term behavior
RF_{CC} = reduction factor for chemical clogging
RF_{BC} = reduction factor for biological clogging

The creep reduction factor RF_{CR} is based on 10,000 hour compressive creep data and calculated according to the following equation developed by Giroud et. al (2000):

Where:

t_{CO} = thickness after load application for 100 hours
t_{virgin} = initial thickness
t_{CR} = thickness at the time period of interest (for instance, thickness at 50 year design life, extrapolated from the 10,000 creep curve)
n_{virgin} = initial porosity
μ = mass per unit area of the considered geonet
ρ = density of the polymeric compound used to make the geonet

Range of clogging reduction factors is provided by GRI-GC8, as shown in below table. A higher reduction factor for biological clogging is recommended for landfill capping to account for the growth of biological organisms or by roots growing through the overlying soil and extending downward, through the geotextile filter layer, and into the drainage geonet core.

Application	Chemical Clogging (RF_{CC})	Biological Clogging (RF_{BC})
Sports field	1.0 - 1.2	1.1 – 1.3
Capillary breaks	1.0 - 1.2	1.1 – 1.3
Roof and plaza decks	1.0 - 1.2	1.1 – 1.3
Retaining walls, seeping rock and soil slopes	1.1 - 1.5	1.0 – 1.2
Drainage blankets	1.0 - 1.2	1.0 – 1.2
Landfill caps	1.0 - 1.2	1.2 – 3.5
Landfill leak detection	1.1 - 1.5	1.1 – 1.3
Landfill leachate collection	1.5 – 2.0	1.1 – 1.3

Combining equations (6) and (7), a drainage safety factor, FS_{dc}, of the geocomposite drainage layer can then be calculated as follows:
□□□

$$FS_{dc} = \frac{\theta_{allow}}{\theta_{req}} = \theta_{allow}\frac{\sin\beta}{k \times L} = \theta_{100} \times \frac{1}{RF_{CR} \times RF_{CC} \times RF_{BC}} \times \frac{\sin\beta}{k \times L} \qquad (8)$$

The selection of drainage FS-value is dependent upon the design life and criticality of the project, 2 – 3 is recommended by Giroud et al (2000). The combination of drainage safety factor and reduction factors are sometimes called the Long-Term Services Factor. In the absence of measured data, a minimum long-term services factor of 8 is recommended for landfill capping drainage layer (design drainage safety factor (2), creep (1.2), biological clogging (3.0), and chemical clogging (1.1), i.e., 2*1.2* 3.0*1.1 = 7.92).

Drainage, Submergence Ratio and Slope Stability

The need for the minimum long-term service 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 a 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 3 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), cover soil thickness = 1m, saturated unit weight of cover soil = 21kN/m3, permeability of the vegetative cover soil = 5×10^{-4} cm/sec, and minimum interface friction angle (δ) = 22°.

For these same field conditions, the slope stability factor of safety, FS, is less than 1 under full saturation; the FS is 0.92 per equations by Soong and Koerner, and using infinite slope Equation 2 FS = 0.86. 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 Soong and Koerner equation = 1.72, and the FS by infinite slope Equation 3 equals 1.62. Note from Figure 3 that the transition from excess pore pressure (FS=0.81) to no pore pressures (FS=1.62) occurs over a change in transmissivity from 7 x10^{-4} to 8.8 x10^{-4} m^3/sec-m. This is a minor change in transmissivity (20% reduction) considering the fact that transmissivity tests have significant variability (Koerner and Soong, 1998).

Fig. 3. Safety factor for slope drainage, stability and geocomposite transmissivity

DESIGN EXAMPLES

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
- long-term service reduction factor FS_{dc} = 8
- vegetative cover with k = 2.5 x 10^{-4} cm/sec

For the saturated or unit gradient case, by using equation 6, the required transmissivity is

$$\theta_{req} = \frac{k_{veg} \times L}{\sin\beta} = \frac{2.5\times10^{-4}\,cm/s\times50m}{0.24} = 5.2\times10^{-4}\,m^2/\sec$$

The transmissivity that takes into account for drainage safety factor and reduction factors can be determined by equation 8

$$\theta_{100} = (FS_{dc}\times RF_{CR}\times RF_{CC}\times RF_{BC})\times\theta_{req}$$
$$= 8\times5.2\times10^{-4}\,m^2/\sec = 4.2\times10^{-3}\,m^2/\sec$$

The normal load acting on the geocomposite drainage blanket in this application is typically less than 48 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, β=18.4°
- Slope length L= 122 m
- Permeability of the cover soil k = 5x10^{-4} cm/sec
- Saturated unit weight of cover soil γ_{sat} = 18 kN/m^3
- Transmissivity of the drainage composite θ □=1.62x10^{-3} m^3/sec-m
- Geocomposite/geomembrane interface friction angle δ=26°

The safety for drainage is calculated by Equation 9 as

$$FS_{dc} = \theta\frac{\sin\beta}{k\times L} = 1.62*10^{-3}\,\frac{\sin18.4^{o}}{5*10^{-6}\times122} = 0.84$$

The drainage safety factor is below 1.0, the cover soil is fully saturated and subjected to seepage force. The factor of safety against slope failure is given by Equation 2 as follows:

$$FS_{dc} = \frac{\gamma_b \tan\delta}{\gamma_{sat} \tan\beta} = \frac{(18-9.8)\times\tan 26^o}{18\times\tan 18.4^o} = 0.67$$

Clearly the transmissivity of the geocomposite is inadequate. The slope would be unstable if the cover soil becomes fully saturated.

By limiting the slope length to 30m, and a minimum long-term service reduction factor of 8, the required transmissivity for geocomposite selection can be calculated by Equation 9

$$\theta_{100} = (FS_{dc}\times RF_{CR}\times RF_{CC}\times RF_{BC})\frac{k\times L}{\sin\beta} = 8\times\frac{5\times10^{-6}*30}{0.3156} = 3.8*10^{-3}m^2/\sec$$

The drainage capacity of the geocomposite with above transmissivity is sufficient to drain away the infiltrated water and keep the cover soil unsaturated; the factor of safety against slope failure utilizing Equation 3 becomes:

$$FS = \frac{\tan\delta}{\tan\beta} = \frac{\tan 26^o}{\tan 18.4^o} = 1.5$$

indicating a stable condition of the cover soil on the slope.

LESSIONS LEARNED FROM LANDFILL CAPPING FAILURES

A Landfill Cover Failure in Maryland

This failure is particularly interesting in that it occurred on a relatively gentle slope. Photo 1 shows the base of the cover slope looking to crest, note vegetative blocks resulting from sliding. Photo 2 demonstrates that cracks widening between sliding blocks. Photo 3 and 4 show the erosion of vegetative soil between sliding blocks, vegetative supporting soil was washed to slope base. Initially this failure was thought to a surface erosion problem since the slope was minor. However no erosion ‘gullies’ running down the slope are visible and the vegetation on the cover is excellent. This led to suspect that something other that run off erosion was occurring.

Photo 1. Base of landfill cover slope looking to crest
(vegetative blocks resulting from sliding)

Photo 2. Cracks widening between sliding blocks

Photo 3. Base of landfill cover slope looking to crest
(Erosion of vegetative soils between sliding blocks)

Photo 4. Vegetative support soils washed to the slope base

The details of the cover are as follows:

- slope angle = 8.5 degrees, slope length = 94 m
- cover profile: 15cm top soil, 45cm silty sands ($k=5*10^{-4}$ cm/sec), single bonded geocomposite drainage net, and a smooth HDPE geomembrane.
- geocomposite transmissivity = $8*10^{-4}$ m^2/sec

A HELP analysis indicated that the top soil and sand did not saturate and a peak flow into the geocomposite of 2.5 cm per day, $r = 2.9x10^{-5}$ cm/sec. Thus the peak flow into the geocomposite was calculated = $2.7*10^{-5}$ m^3/sec-m ($2.9*10^{-7}$ m/sec * 94 m * 1). The drainage capacity of the geocomposite is calculated = 1.2 $*10^{-4}$ m^3/sec-m ($8*10^{-4}$ m^3/sec-m * sin(8.5^o)). This results in a predicted factor of safety of $1.2*10^{-4}/2.7*10^{-5} = 4.5$. However, inspection of the failed cover clearly indicated that the cover had saturated. Thus the flow into the geocomposite should not have been calculated using HELP model and should have been calculated using unit gradient design. This produces a peak inflow into the geocomposite of $4.7*10^{-4}$ m^3/sec-m ($5*10^{-6}$ m/sec * 94 m * 1) and an actual factor of safety of $1.2*10^{-4}/4.7*10^{-4} = 0.26$! Clearly the drainage layer was under-designed and the final cover was subject to saturation. As a note, this cover was 'repaired' by removing all materials over the geomembrane and rebuilding with a larger capacity geocomposite and perforated pipes that reduced the effective collection length of the geocomposite to approximately 30 m.

A Landfill Cover Failure in New Jersey

Massive sliding of cover soils occurred after a major storm dropped 120mm of rain on an East Coast municipal solid waste landfill cap construction project. The rainfall occurred within a span of 5 to 6 hours and damaged approximately 14 hectares of cover. Photo 5 shows massive cover soil loss along the slope, Photo 6 is a close look at localized erosion, and Photo 7 demonstrates landfill gas pressure built-up under the geomembrane.

Photo 5. Massive Soils Loss on Slopes

Photo 6. Localized Rill Erosion

Photo 7. LFG buildup under the geomembrane

Investigation showed that the failure likely resulted from one or more of the following mechanisms:

(a) Inadequate transmissivity in the drainage layer, leading to excessive pore water pressures in the cover soil. Evaluation of the failure is based on the following field conditions that existed at the time of failure:

3:1 slope, β = 18.4°
Slope length L = 122 m
Cover soil permeability, k = 5*10^{-3} cm/sec
Saturated unit weight of soil γ_{sat} = 17.6 kN/m^3
Transmissivity of the composite lateral drainage layer, θ□=3.5*10^{-4} m^2/sec
Geocomposite/texture geomembrane interface friction angle δ=22°

Field observations and laboratory testing indicated that the in-place soil was saturated. This soil was composed of fine sugar sand containing a high percentage of silt fines. The Unified Classification for this soil is SP-SM. The soil was to function as a vegetative support layer immediately above the final cover geomembrane and drainage composite. The vegetative support layer was to be covered with 150 mm of topsoil supporting grass. Failure occurred before the topsoil layer and associated grass could be placed.

Assuming saturation of the vegetative support sands, the factor of safety for the *drainage capacity*, FS_{dc}, of the geocomposite drainage layer can be calculated by equation (8), substituting in site-specific values for the variables results in the following:

$$FS_{dc} = 3.5\times10^{-4}\times\frac{0.32}{5\times10^{-5}\times122} = 0.018$$

Clearly, with an in-situ safety factor of 0.019, the transmissivity of the geocomposite is inadequate. Using equation (2), site conditions at this project results in

$$FS = \frac{\gamma_b}{\gamma_{sat}}\frac{\tan\delta}{\tan\beta} = \frac{(17.6-9.8)}{17.6}\frac{\tan 22^o}{\tan 18.4^o} = 0.54$$

Thus, the slope is unstable if the drainage capacity of the drainage net is exceeded**.** No existing geocomposite drains or geotextiles prove sufficient interface friction to enable a cover soil to remain in place for such a steep slope if the cover soil becomes saturated. However, when seepage forces are eliminated, the slope factor of safety of the cover soil per equation (3) was = $\tan\delta / \tan\beta$ or 1.21. Note that a minimum static sliding factor of safety of 1.5 is typically recommended. Thus, even the non-saturated condition was marginal at this site.

In addition to a lack of adequate transmissivity, there were problems of: (b) inadequate gas venting layer, causing LFG pressure buildup below the geomembrane; and, (c) highly erodible silty sands used in the vegetative support layer, causing soil mass loss, especially during storm events.

The failure of the cover soils highlighted significant design errors and construction sequence problems. Each of the mechanisms evaluated above are sufficient to have caused major damage to the partially constructed cover. With the exception of facilities in arid climates, geocomposite lateral drainage systems must be designed assuming the overlying soils become saturated. Given the unusual weather trends that have dominated the past decade, long-term performance of these facilities must accommodate such weather extremes.

The construction problems are related to construction in layers versus full sections. This conventional practice leaves very large and highly erodible soil surfaces exposed for extended periods. Severe storms will cause major damage to construction when such practices are used. This is independent of the design adequacy of what is being constructed. Many contracts now limit the area of exposure allowed for erodible soil layers unless the contractor can demonstrate that excessive erosion will be mitigated. Incremental slope stability and soil loss evaluations will force this practice.

Based on the forensic analysis, revised analysis methods and repair techniques for this failure are proposed. These repair techniques include

- Reduction of the effective slope length of the drainage layer
- Increase in transmissivity of the drainage layer.
- Decrease the erosion potential of the soils.
- Increase the capacity of the existing gas collection blanket.

CONCLUDING REMARKS

This paper presents design methods that allow a designer to conservatively design lateral drainage systems in final 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.

REFERENCES:

ASTM D4716, (2001), "Test method for determining the (in-plane) flow rate per unit width and hydraulic transmissivity of a geosynthetic using a constant head".

GRI-GC8 (2001), "Standard guide for determination of the allowable flow rate of a drainage geocomposite." Geosynthetic Research Institute.

Giroud, J.P., Zhao, A. and Richardson, G.N. (2000), "Effect of thickness reduction on geosynthetic hydraulic transmissivity", *Geosynthetics International*, Special Issue on Liquid Collection Systems, Vol. 7, Nos.4-6, pp. 433-452.

Giroud, J.P., Zornberg, J.G. and Zhao, A. (2000), "Hydraulic design of geosynthetic and granular liquid collection layers", *Geosynthetics International*, Special Issue on Liquid Collection Systems, Vol. 7, Nos.4-6, pp. 285-380.

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

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

Richardson, G. N. and Zhao, A. (1998), "Issues on geosynthetic drainage systems in landfills," *Proceedings of the 12th GRI Conference "Lessons learned from geosynthetics case histories*", pp. 177-196, Philadelphia.

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

Theisen, M.S. and Richardson, G. N. "Geosynthetic Erosion Control for Landfill Final Covers", *Geotechnical Fabrics Report*, May, pp. 22-27.

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., (2000), "Geocomposite drains for side slopes stability in landfill covers," *Proceedings of International Conference on filters and drainage in geotechnical and environmental engineering*, A. A. Balkema, Rotterdam, Warsaw, Poland, 289 – 293.