Lessons learned from failure: landfill covers

Developing better drainage systems for cover side slopes by studying failed ones

During the initial year of service, excessive erosion occurred in a final cover over a military landfill. Subsequent investigation showed that the erosion was not due to conventional surface water forces but was caused by the failure of the underlying lateral drainage system and the use of highly erodible vegetative support soils. Subsequent remedial work on the cover also revealed that the geocomposite used to form the lateral drain was significantly clogged by roots from the overlying vegetation. This paper reviews the design calculations required to properly design the geocomposite lateral drain and postulates on means of lessening the potential for root-related damage.

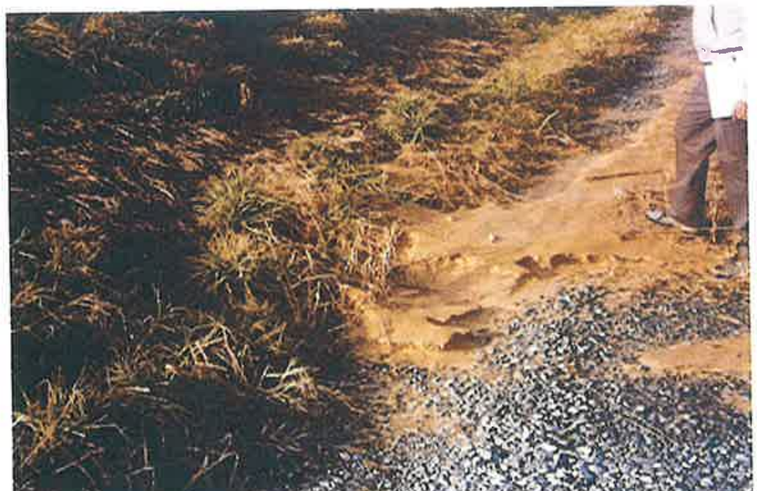

Photo 1. Silt drainage at toe of slope.

Photo 2. Crack observed in cover.

Introduction

In the spring of 1996, United States Department of Defense (USDOD) officials conducted a routine inspection of several recently constructed landfill covers at a U.S. Navy installation. While inspecting one of the landfill covers, engineers noticed that a relatively minor amount of soil had migrated from the vegetative support layer of the cover system and deposited along a road at the perimeter of the landfill (**Photo 1**). Further inspection revealed several small erosion gullies on some of the steeper slopes of the landfill cover surface. In general, the vegetation on the cover was in excellent condition, and initially this appeared to be a simple erosion problem. Previous measures to address the erosion, including placement of riprap along the toe of the steepest slopes and some drainage feature modifications, appeared adequate.

In the spring of 1997, the landfill cover was again inspected by USDOD. Soil deposits on the perimeter road had increased significantly, and the erosion rills and gullies along the steeper slopes were larger and deeper. Erosion rills were up to 1 m (40 in.) wide and up to 60 cm (24 in.) deep. At this time, the authors were brought in to evaluate the cover; one working for the contractor who had constructed the cover and one with the U.S. Army Corps of Engineers (USACE), who provide technical assistance to USDOD. Representative samples were taken of the landfill cover's vegetative support layer material and the soil deposited on the perimeter road to help determine the cause of the soil migration problem. Subsequent to analysis of the cover system

By Gregory N. Richardson, Ph.D., P.E., and K.L. Pavlik

presented in this paper, a permanent solution to the problem was designed and constructed in late 1998.

Landfill geometry and cover section

The landfill contains typical military installation waste materials, consisting primarily of construction and base maintenance debris and municipal wastes. The landfill is approximately 5.7 hectares (14.1 acres) in size with a maximum vertical relief of 22.6 m (74 ft.) and side slopes varying from 1 vertical to 6 horizontal (IV:6H) to 1V:1.5H. The landfill's perimeter is approximately 1,070 m (3,500 ft.).

The cover system cross-section consisted of, from top to bottom:

- 152 mm (6 in.) of topsoil
- 457 mm (18 in.) of vegetative support soil layer
- geocomposite drainage layer
- 1.0 mm (40 mil) thick HDPE geomembrane
- geocomposite gas venting layer
- 610 mm (24 in.) foundation soil layer
- waste

The geocomposite drainage layer consisted of a geotextile attached to one side of a geonet on slopes flatter than (<IV:3H) and a geotextile attached to both sides of a geonet on slopes equal to or steeper than IV:3H. A textured geomembrane was used on the slopes steeper than 1V:3H, while the remainder of the slope was covered with a smooth geomembrane.

The entire landfill perimeter, with the exception of approximately 105 m (345 ft.), was constructed with an anchor trench drainage system. Where the anchor trench drainage system was not present, the drainage layer was daylighted into a wetland. Three anchor trench drainage system pipe outlets were constructed initially, one at each of the anchor trench drainage system termination points and one intermediate. The anchor trench drainage system was constructed with typical dimensions of 610 mm (2 ft.) wide by 915 mm (3 ft.) deep. A 200 g/m^2 (6 oz./yd.^{2}) nonwoven needlepunched geotextile with an apparent opening size (AOS) of 0.212 mm (#70 U.S. sieve) wrapped the anchor trench. A flexible perforated drainage pipe varying from 100–200 mm (4–8 in.) in diameter was placed in the bottom of the anchor trench drainage system followed by placement of an AASHTO No. 5 gravel (1 in. sieve: 100–90% passing; .75 in.: 55–20%; .5 in: 10–0%; 3/8 in.: 5–0%).

Location/Number of Samples	ESCS Classification	Percent Finer Than 4.75mm (#4)	Percent Finer Than 0.07mm (#200)
USACE Composite Samples			
Cover	SP-SM	100	10
Erosion	ML	100	52
USACE Cover Samples (8 total)			
6	SM	96–100	46–58
1	SP–SM	96	46
1	ML	100	58
Contractor Samples			
On-Site	SM	97	40
Off-Site	SM	100	37

Table 1. **Summary of cover soil particle size analysis—vegetative support soil.**

Historical drainage problems and repairs

Hydroseeding of the landfill cover with grass was completed in late May 1995. Prior to vegetation establishment, precipitation in late May 1995 caused severe erosion rills. Also, subsequent storms in the summer of 1995 resulted in significant cover and vegetative support soil erosion on steep areas of the cover. The capacity of the anchor trench drainage system at the base of the drainage layer was reported as being exceeded during this time. Soil from the cover also appeared to be moving into the anchor trench drainage system.

Based on the observed drainage problems, modifications to the anchor trench drainage system were made in 1996. These modifications consisted of constructing a second intermediate anchor trench drainage system pipe outlet to reduce hydrostatic pressure and replacement of the 200 mm (8 in.) diameter "cover-soil-choked" drainage pipe. In an effort to reduce potential hydrostatic pressure in the vegetative support soil layer, 100 and 150 mm (4 and 6 in.) diameter drainage pipes were installed within the layer in a "T" configuration upslope from the landfill toe in these areas. The geotextile portion of the geocomposite was reported to be free of soil everywhere except on steeper slopes. Repairs revealed vegetative support soil fines, which had passed through the geotextile, were deposited on the geomembrane.

Two storms occurred in late October 1995, causing a cover material veneer failure in the steepest areas without an anchor trench drainage system. To minimize the chance of future veneer failures, four 30.5 m (100 ft.) long pipe laterals and a downchute in a "Y" configuration were constructed. This configuration was constructed on top of the cover geomembrane/drainage composite to collect surface and vegetative support soil internal water and relay it down slope in the steepest portion of the landfill.

In February 1996, a warm front and precipitation caused melting of the snowfall accumulated on the landfill, resulting in additional erosion and cracking. The following repairs were made to the steep slope areas:

- A trench drain was constructed at the toe to improve drainage away from the landfill cover.

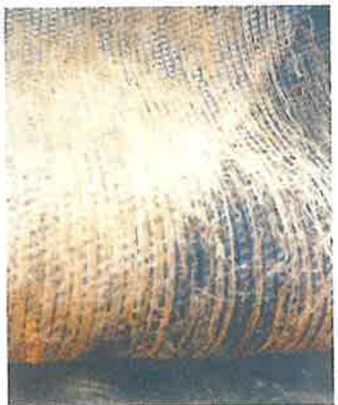

Photo 3. Root penetration of drainage composite.

- The site access road was raised and extended to create a continuous landfill cover perimeter road.
- Four additional "T" drains were installed in the vegetative support soil layer.
- Riprap was placed to provide additional slope stabilization.

The repairs proved to be unsuccessful, and major drainage problems at the site continued. By the fall of 1996, significant new cracks were observed in the steep slope area of the landfill (**Photo 2**).

Analyses

After the failure of repairs made in 1996, the authors were independently brought in early in 1997 to evaluate the failure of the cover. One evaluation was performed for the contractor who built the cover. The second was conducted by USACE for the USDOD, who owned the cover. The findings of these studies are presented in this section.

Properties of cover soils

As part of the initial USACE investigation in April 1997, composite samples of the existing vegetative support soil layer material and eroded soil, which had been deposited on the perimeter road, were obtained. In June 1997, additional samples of the existing vegetative support soil layer material were collected. The thickness of both topsoil and vegetative support soil layers were also determined. Samples were obtained by hand excavation on a grid pattern over the majority of the landfill cover system. The investigation consisted of 48 excavations down to the geosynthetics and obtaining 33 vegetative support soil layer soil samples.

All vegetative support soil layer samples were sent to a USACE laboratory for classification testing. Gradation and hydrometer tests were performed on the two composite samples collected in April 1997, and eight gradations were performed on representative samples from the 33 samples collected in June 1997. Two contractor vegetative support soil layer gradations and hydrometer analyses were made available to the USACE. One of the cover material analyses was for on-site borrow material and the other for the more commonly used off-site borrow material. All samples consisted of very fine uniformly graded non-plastic sand with high silt contents. **Table 1** provides sample particle size data. **Figure 1** presents the range of particle size gradations obtained for the silty sand used in the vegetative support soil layer. Laboratory testing by both the USACE and the contractor indicates that the vegetative support soil layer soil has a D_{85} of 0.300–0.150 mm (≈50–100 U.S. Sieve) opening size and a contractor determined permeability of approximately 5 x 10^{4} cm/sec.

Filter analysis

The geotextile manufacturer reports the fabric has an apparent opening size (AOS) for which 95% are smaller (O_{95}) of 0.212 mm (≈70 U.S. sieve). Based on the USACE test results, the vegetative support soil layer material had an 85% passing (D_{85}) of 0.300–0.150 mm (≈50–≈100 U.S. sieves). This results in a O_{95}/D_{85} ratio of only 0.7–1.4. This is below Carroll's criteria for O_{95}/D_{85} of 2–3 (Koerner 1998). Having a coefficient of uniformity (D_{60}/D_{10}) of approximately 1.1, the Federal Highway Administration (FHWA) standards (Holtz 1997) recommends that $O_{95} \leq D_{85}$. Thus, the sand marginally meets the FHWA requirements.

However, the uniform gradation of the vegetative support soil layer makes formation of a soil filter bridge near the geotextile portion of the geocomposite difficult. With approximately 50% of the vegetative support soil layer material being able to pass through the geotextile component of the geocomposite, a significant amount of fines could pass through the geotextile before the larger particles could form a filter bridge. *Based on observed problems, the drainage system was not adequately designed with respect to soil particle retention.* Therefore, the use of Carroll's or the FHWA criteria without consideration of the internal stability of the soil may be a potential problem.

The permittivity of the geotextile was reported to be in excess of 1.0 sec^{-1}. FHWA standards for permittivity requirements (Holtz 1997) are based on the percentage of the soil passing the 0.075 mm (#200 U.S. sieve). For material with more than 50% passing the 0.075 mm opening size (#200 U.S. sieve), a permittivity greater than or equal to 0.1 sec^{-1} is recommended. Based on this, the permittivity of the geotextile is adequate for the vegetative support soil layer soil.

Drainage analysis

The geocomposite drainage layer was constructed to run the full length of the slope without having any intermediate exit points to dissipate excess water pressures. Construction quality assurance (CQA) tests of the geocomposite drainage material for the contractor indicated a transmissivity of approximately 7.0×10^{-4} $m^3/s/mm^2/s$ (3.35 gal./min./ft.) under a unit gradient. The minimum acceptable design transmissivity for the lateral drainage system was evaluated based on the field observation that the cover soil layers had saturated. This was blamed on the high precipitation and mild weather that accompanied that year's "El Nino."

Saturation simplifies the analysis, since, under saturated conditions, the vertical seepage gradient, i, is equal to 1 (unit gradient). Therefore, infiltration velocity is equal to the permeability of the soil, k_{veg}. The design of the sand drainage underlying a saturated vegetative layer, and stability analyses, were first presented by Thiel and Stewart (1993). For geocomposite drains, the flow rate of water, Q_{in}, infiltrating into a unit of drainage composite having a length L is given by:

Equation 1

$$Q_{in} = k_{veg} * L * 1$$

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

Equation 2

$$Q_{out} = k_g * i * A = k_g * i * (t * 1) = (k_g * t) * i = \theta * i$$

where k_g and t are permeability and thickness of the geocomposite respectively, and "θ" is the required transmissivity of geocomposite.

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

Equation 3

$$FS_{dc} = Q_{out}/Q_n = \theta * i/(k_{veg} * L)$$

With regards to transmissivity reduction factors, Koerner (1997) recommends the following:

Equation 4

$$FS = \frac{\theta_{allow}}{\theta_{req'd}}$$

Equation 5

$$\theta_{allow} = \frac{\theta_{ultimate}}{RF_{in} \bullet RF_{cr} \bullet RF_{cc} \bullet RF_{bc}} = \frac{\theta_{ultimate}}{\pi RF}$$

where FS is the overall safety factor for drainage, θ_{allow} is the allowable transmissivity of the drainage geocomposite, $\theta_{req'd}$ is the required transmissivity, and $\theta_{ultimate}$ is the transmissivity measured in accordance with ASTM D4716. *It is important that $\theta_{ultimate}$ is evaluated in the laboratory using boundary conditions, normal stress levels, and gradients that represent actual field conditions.* Thus, the test must be performed using the actual drainage geocomposite, adjacent soils or geomembranes, and at true field gradients, (Williams et al. 1984). Service reduction factors are not intended to account for variations in these factors. The reduction factors and their default values include RF_{in} for intrusion of adjacent geotextile (1.3–1.5), RF_{cr} for creep deformation of the geonet (1.1–1.4), RF_{cc} for chemical clogging or precipitation of chemicals (1.0–1.2), and RF_{bc} for biological clogging (1.2–1.5).

The geocomposite drainage layer was designed to run the full length of the slope without having any intermediate exit points to dissipate excess water pressures. The details of the longest slope of the cover are as follows: slope angle = 8.5°, slope length = 94 m (300 ft.). A HELP (version 3.04) analysis of this slope indicated that the topsoil layers did not saturate and predicted a peak flow into the geocomposite of 2.5 cm/day (2.9×10^{-5} cm/sec). Based on this inflow, the peak flow into the geocomposite was calculated to be 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 using **Equation 2** is 1.03×10^{-4} m^3/sec-m (7×10^{-4} m^3/sec-m * sin(8.5°)). This results in a HELP model predicted factor of safety of 3.8 ($1.03 \times 10^{-4}/2.7 \times 10^{-5}$).

However, assuming the cover had saturated, the flow into the geocomposite should have been calculated using **Equation 1** with k_{veg} = 5×10^{-4} cm/sec. *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 $1.03 \times 10^{-4}/4.7 \times 10^{-4} = 0.22$!* Clearly, the final cover will become unstable when the vegetative soil layer saturates.

Conclusions

The failure of this small final cover clearly supports two fundamental concerns that have been expressed well by others. The first concern relates to potential dangers of clogging caused by fines migrating through sands is discussed by Giroud et al. (1998) related to leachate collection systems but is clearly also appropriate for drainage layers in cover systems. The use of a soil that does not readily achieve a stable internal filter must be avoided if lateral drains are to remain serviceable. Recall that the vegetative support soils used to construct this cover contain up to 50% silt size fraction that readily passes through the geotextile. The second concern is raised by the work of Soong and Koerner (1997) that shows the use of the HELP model can lead to a significant underestimation of required transmissivity for the drainage layer.

Additionally, the recent removal of the old geocomposite drainage system during reconstruction exposed many areas of the drain that were totally clogged by root penetration (**Figure 3**). Root penetration had not been detected during either of the failure studies. This raises concern regarding the common thickness of soil layers above the lateral drain and the limitations of current transmissivity reduction factor. For this site, the 60 cm (24 in.) soil depth was not adequate to prevent grass root penetration. This is, however, a typical cover soil thickness and indicates that root penetration could be a larger problem than currently recognized. Based on this example, the authors recommend that a minimum factor of safety of 8 should be used in **Equation 5** to determine the transmissivity of a lateral composite drainage element in a final cover. While no research data is available to support the premise, the authors feel that a very conservatively designed drainage layer would not contain sufficient free moisture to draw the roots into the drainage net.

Recommendations

- The use of an "unstable" soil next to a lateral drainage geocomposite can significantly reduce the available transmissivity due to a failure of the geotextile to retain fines. The ability of a soil to form an internal filter must be confirmed before it is used adjacent to a geocomposite drain. The use of Carroll's or FHWA particle retention criteria with unstable soils is not recommended.
- The design inflow to a lateral drain in a final cover system should be estimated by assuming that the cover soils have saturated. The HELP model can significantly underestimate the rate of inflow to the drainage layer.
- Drainage layers on long slopes must be designed with intermediate drains to reduce the effective slope length to less than 50 m (165 ft.) or excessive design transmissivities will be required.
- The potential for root penetration into the geocomposite must not be neglected. This may require evaluation of roots

depths of plants native to the site and corresponding adjustment of the cover soil thickness. Additionally, it is felt that an over-designed drainage layer will not contain sufficient available moisture to attract roots.

- A minimum combined service reduction factor, ϑRF, of 8 should be used in **Equation 5** when determining the design transmissivity of a lateral composite drainage element in a final cover. GFR

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Greg N. Richardson is president of G.N. Richardson & Associates, Raleigh, N.C.; www.gnra.com.

K.L. Pavlik is a civil engineer with the U.S. Army Corps of Engineers, www.usace.gov.