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Lessons learned from the failure of a landfill capping system

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ABSTRACT: The massive failure of a municipal solid waste landfill cap under construction is investigated and examined. The conclusions show that a number of factors led to the failure related to design issues, construction sequencing, and soil erodibility. This paper examines the causes of the failure, and provides solutions to prevent future construction related failures at this and other sites. Additionally, this paper presents design guidance that demonstrates the inevitable long-term failure of this final cover. A simplified, yet conservative, design procedure is recommended that will ensure successful long-term performance of similar final covers.

1 INTRODUCTION

Massive sliding of cover soils occurred after a major storm dropped 5” 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 14.1 hectares of cover. Investigation showed that the failure likely resulted from one or more of the following mechanisms: (1) Inadequate transmissivity in the drainage layer, leading to excessive pore water pressures in the cover soil; (2) Inadequate gas venting layer, causing LFG pressure buildup below the geomembrane; and (3) Highly erodible silty sands used in the vegetative support layer, causing soil mass loss, especially during storm events. Forensic investigation indicates that the failure of the cover soils highlighted significant design errors and construction sequence problems. Based on the forensic analysis, revised analysis methods and repair techniques for this failure are proposed. These repair techniques include increasing the hydraulic capacity of the drainage layer and reduction of the erosion potential during construction and service, and increasing the capacity of the gas pressure-relief layer. The paper concludes with a summary of the recommended replacement cover, revised analysis procedures, and required construction practices.

2 GEOCOMPOSITE TRANSMISSIVITY AND DRAINAGE SAFETY FACTOR

Evaluation of the failure is based on the following field conditions that existed at the time of failure:

- 3:1 slope, $\beta = 18.4°$
- Slope length L = 122 m
- Cover soil permeability, $k=5*10^{-3}$ cm/s
- Saturated unit weight of soil $\gamma_{sat} = 17.6$ kN/m^3
- Transmissivity of the composite lateral drainage layer, $\theta = 3.5*10^{-4}$ m^2/s
- Geocomposite/texture geomembrane interface friction angle $\delta = 22°$

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 of the slope occurred in response to a major storm that dropped 125 mm of rain on the site in a span of 5 to 6 hours. Failure occurred before the topsoil layer and associated grass could be placed.

Assuming saturation of the vegetative support sands, the quantity of water, Q_{in}, infiltrating into a unit width of drainage composite having a length L is given by:

$$Q_{in} = k_{veg} \times L \times 1 \quad (1)$$

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

$$Q_{out} = k \times i \times A = k \times i \times (t \times 1) = (k \times t) \times i \quad (2)$$

where t = thickness of the drainage layer and [k $\times$t] is defined as transmissivity, θ. A factor of safety for the *drainage capacity*, FS_{dc}, of the geocomposite drainage layer is defined as

$$FS_{dc} = Q_{out} / Q_{in} = \frac{\theta \times i}{k \times L} \quad (3)$$

A minimum factor of safety of 8 (overall drainage safety factor plus reduction factors) is recommended for lateral drainage systems in final covers. Substituting in site-specific values for the variables results in the following:

$$FS_{dc} = \frac{3.5 \times 10^{-4} \times 0.33}{5 \times 10^{-5} \times 122} = 0.019$$

Clearly, with an in-situ safety factor of 0.019, the transmissivity of the geocomposite is inadequate. The validity of the above analysis for saturated soils draining to a geocomposite drainage layer was previously established by Thiel and Stewart (1993), and by confirmed by more comprehensive studies by Giroud et al (2000). Note that Giroud demonstrated that the solution is valid only when the flow is unconfined and the maximum thickness of the flow layer is less than one tenth the slope height.

3 SEEPAGE FORCES AND COVER SOIL STABILITY

The seepage force in saturated cover soil layers is calculated by:

$$F_{seep} = \gamma_w \times a \times \sin\beta \tag{4}$$

where β is the slope angle and a is the vertical thickness of the soil cover. Using an infinite slope model, the factor of safety against slope failure is given by the following:

$$FS = \frac{\gamma_b \cos\beta \tan\delta}{\gamma_b \sin\beta + \gamma_w \sin\beta} = \frac{\gamma_b}{\gamma_{sat}} \frac{\tan\delta}{\tan\beta} \tag{5}$$

where β is the slope angle and δ is the interface friction angle between the soil and the underlying geosynthetic. This equation can be further reduced to

$$FS = \frac{\gamma_b}{\gamma_{sat}} \times \frac{\tan\delta}{\tan\beta} \tag{6}$$

Neglecting seepage forces, the sliding factor of safety of the cover soil was $\tan\delta / \tan\beta$ or 1.21. Including seepage forces, site conditions at this project results in FS = 0.44×tan 22°/tan18.4° or 0.53 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 geocomposite drain becomes saturated. The flow in the geocomposite drain must remain unconfined. Note that a minimum static sliding factor of safety of 1.5 is recommended. Thus, even the non-saturated condition was marginal at this site.

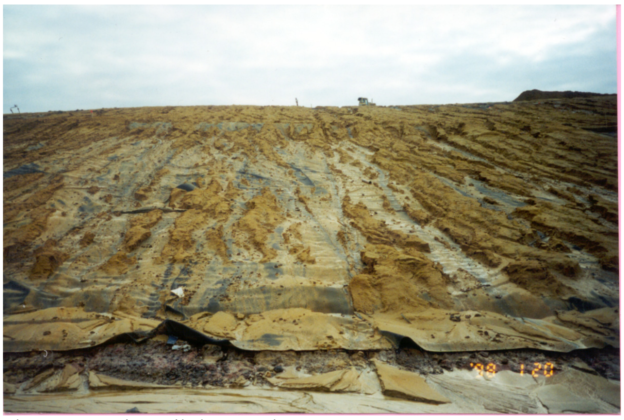

Photo 1. Massive soils loss on slopes

Photo 2. Standing water in the cover soil

4 EROSION OF THE COVER SOIL

The USDA universal soil loss equation (USLE) is a convenient tool used in evaluating erosion potential. The USLE predicts average annual soil loss as the product of six quantifiable factors. The equation is:

$$A = R \times K \times L \times S \times C \times P \tag{7}$$

where

– A = average annual soil loss, in tons/acre
– R = rainfall and runoff erosivity index (R= 175)
– K= soil erodibility factor, tons/acre (K=0.45)
– L = slope-length factor
– S=slope-steepness factor (SL=15)
– C = cover-management factor (C=1.0)
– P = practice factor (P=1.0)

The data input to this equation for this region is shown (ref Wishmeier. and Smith D.D., 1978). This indicates a potential annual soil loss of 2.7E6 Kg/Hectare/year. This dramatically exceeds the 4492 Kg/Hectare/year recommended design goals and indicates a significant soil loss potential due to surface erosion.

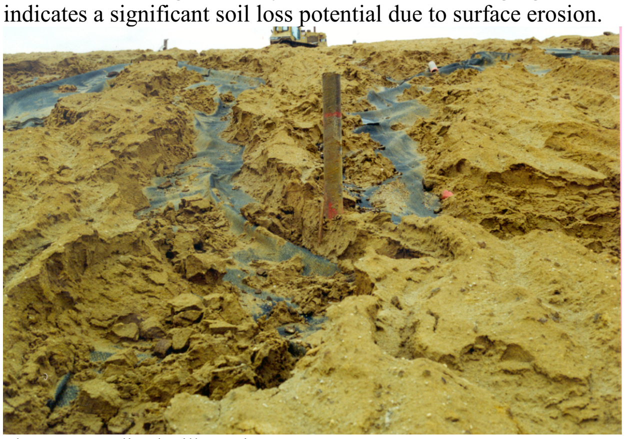

Photo 3. Localized Rill Erosion

Photo 4. Cover soil being washed away at the toe of the slope

5 REPAIR RECOMMENDATION FOR EXISTING SECTIONS

The current drainage geocomposite is inadequate and must be removed. Thus, the repair can at best salvage the existing geomembrane and gas collection blanket. The repairs must accomplish the following goals:

- 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.

5.1 *Drainage Layer Upgrade*

The drainage layer must provide a minimum total serviceability factor (drainage factor of safety multiplied by reduction factors) of 8, i.e.,

$$TSF = FS_{dc} \times RF_{in} \times RF_{cc} \times RF_{bc} \times RF_{cc} = 8 \quad (8)$$

where

- RF_{in} = reduction factor for intrusion of the adjacent geotextiles into the drainage channel.
- RF_{cr} = reduction factor for creep deformation of the drainage core and/or adjacent geotextile into the drainage channel.
- RF_{cc} = reduction factor for chemical clogging and/or precipitation of chemicals in the drainage core space.
- RF_{bc} = reduction factor for biological clogging in the drainage core space.

To achieve the above target serviceability factor, it is necessary to increase the transmissivity of the geocomposite, and reduce the length of slope that drains to it. This can be accomplished without removal of the geomembrane or regrading of the surface using 'tack-on' swales common to contemporary covers. The maximum design slope length is reduced to less than 45 m. For the 122 m slope this would mean using a top berm and two swales to produce maximum slope drainage lengths of 41 m. The required transmissivity is calculated from Equation 3 as follows:

$$\begin{aligned} \theta &= (FS_{dc} \times RF_{in} \times RF_{cc} \times RF_{bc} \times RF_{cc}) \times \frac{k \times L}{i} \\ &= 8 \times \frac{5 \times 10^{-5} \times 41}{0.33} = 5 \times 10^{-2}\ m^2/s \end{aligned} \quad (9)$$

This requires each length of geocomposite drainage layer to drain to the swale immediately beneath it.

5.2 *Erosion Upgrade*

The reduction of the slope length from 122 m to 41 m reduces the SL factor from 15 to approximately 9. This is not sufficient to eliminate the threat of erosion to the sand and means that topsoil and vegetation are required to achieve a satisfactory performance. Thus, it is recommended that the cover be constructed in a manner that no more than 0.5 hectare of sand is exposed at a given time. This will require building the cover in 'full section' as compared to constructing it in large individual layers as currently practiced.

5.3 *Gas Layer Upgrade*

While no data on gas pressures at this site currently exist, the 408 g/m^2 nonwoven is believed to be inadequate and should be supplemented by additional perforated pipe laterals and passive vents to limit the LFG pressure that can build up beneath the cover. Based on past calculations, adding the pipe laterals spaced at 12-m centers running up the slopes is recommended. These would be 'tied' to the gas blanket by cutting holes in the existing geomembrane and then cap stripping the pipes to the existing geomembrane. This is particularly important if the active system is ever turned off. A dramatic increase in gas pressure could develop and lead to a sliding failure of the cover.

Photo 5. Particular clogging in the geocomposite

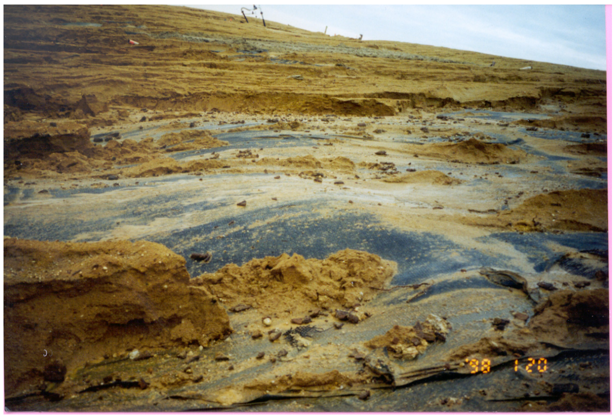

Photo 6. LFG buildup under the geomembrane

6 CONCLUDING REMARKS

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.

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