DESIGNER'S FORUM

Geosynthetic erosion control for landfill final covers

By Marc S. Theisen and Gregory N. Richardson

SIGNIFICANT ATTENTION HAS been focused on the veneer stability of final covers, yet little has been written about protection of their slopes against erosion failures. This no doubt reflects the civil engineer's comfort with free-body diagrams and great discomfort with systems that require agricultural or botanical knowledge to succeed. This article will focus on the engineering process required to limit erosion to an acceptable level on landfill final covers.

A proactive program of controlling erosion, readily accomplished by most good designers, complements the passive methods of sediment control required by most states. Landfill final covers are critical applications for developing basic erosion-control concepts, since they are expensive to construct, expensive to repair, and very expensive when they fail.

Traditionally, landfill final covers are designed to limit maximum soil loss to less than two tons/acre/year. Thus, over the 30-year post-closure monitoring/performance life of a cover, nearly 60 tons of soil could be lost per acre. Such a restrictive soil loss would result in the depletion of less than ½ in. of cover over the landfill's three-decade service life.

This criterion is the legacy of RCRA (Resource Conservation and Recovery Act) Subtitle-C hazardous waste landfills. Such landfills typically have final covers with slopes flatter than 8%—not as significant of an erosion challenge as most municipal solid-waste landfills where slopes commonly reach 33%.

Soil-loss prediction

By understanding predictive methods for soil loss, the designer can predict the soil-loss rate and understand the role of various erosion-control products and field techniques in limiting the process. The Universal Soil Loss Equation (USLE), developed by the U.S. Soil Conservation Service in the 1930s in response to the great dust storms of that time, is the most common method of estimating soil loss (Wishmeier and Smith 1978).

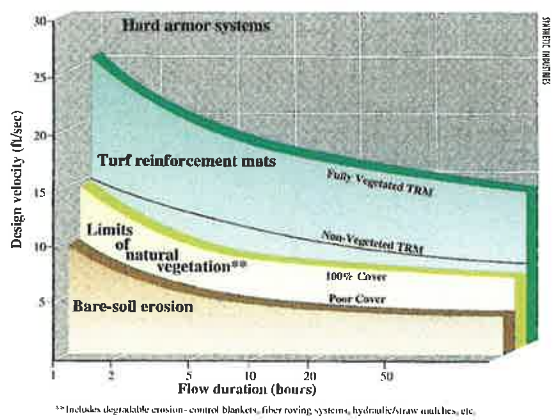

Figure 1. Erosion-control performance guidelines: velocity vs. duration, based on long-term (50-hour) flow data.

Photo 1. An ECB protects a 5H:1V slope at the Super Gro landfill, serving as a mulch while reducing erosion.

This equation has been modified regionally to fit historical experiences and is currently undergoing revision. It continues to be the primary tool in service and provides a simple vehicle for a discussion of erosion-control basics. The USLE is expressed as follows:

$$X = RKSLCP$$

where X is the annual soil loss in tons per acre; R is a rainfall-erosion index that reflects the erosion potential from regional precipitation; K is the soil-erodibility factor; S is the slope-gradient factor; L is the slope length; C is a crop or vegetation factor; and P is an erosion-control practice factor that reflects the facility's maintenance activities.

Based on USLE, the civil engineer traditionally limits landfill final-cover erosion by minimizing several of the variables as follows:

Soil erodibility, K: Resistance of a soil to erosion increases with both particle size and soil plasticity. Thus, silts are the most erodible of soils, since they lack both factors. Armoring techniques, such as riprap, are used as an obvious attempt to dramatically decrease K.

Slope, S: As previously discussed, soil loss can be limited by requiring initial slopes to be lower than some nominal amount, e.g., 8% for hazardous-waste landfills. This practice, however, may not be economical in municipal landfill-cover slopes, which are designed to maximize airspace. Often, waste in these landfills is highly susceptible to future subsidence; steeper slopes minimize settlement concerns.

Slope length, L: Landfill designers have long been aware that erosion on side slopes is significantly greater than that which is predicted when sheet flow is assumed. For this reason, side slopes are reduced in "erosion length" by placing drainage swales or terraces/benches at 25–50-ft vertical spacings. This typically reduces the effective slope length to less than 120 feet. Some form of engineered conveyance must be used to bring waters collected in the swales down the slope.

Crop-management factor, C: To a civil engineer, this means grass. This variable can range from a value of 0.45 for no ground cover, to as low as 0.003 for 100% grass coverage. Many erosion problems vanish on paper through manipulation of this factor. Unfortunately, the field steps required to develop and maintain a high-percentage of healthy, robust ground cover are rarely implemented on final covers. Here, erosion-control products may play a very important role.

Erosion-control practice, P: Due to a lack of clear guidance and experience on how landfill maintenance relates to agricultural or botanical practices, this is commonly assumed to be in the 0.9–1.0 range.

Geosynthetic erosion-control products can be used to increase the long-term erosion resistance of an engineered feature, e.g., lining a down chute, or providing a short-term solution until a self-sustaining vegetative cover is established. The application-service life, or "functional longevity," is important to consider during the selection of an erosion-control material, since the field life of ultraviolet- (UV-) protected products is significantly greater than that of natural products. Non-UV-stabilized geosynthetics may have field lives comparable to the natural materials. **Figure 1** (p.22) shows the relationship between surface water-flow velocity and duration on the selection of many of the erosion-control systems illustrated in this article.

There are two basic types of rolled erosion-control products (RECPs): temporary degradable and long-term nondegradable. Temporary degradable RECPs are used to protect newly seeded areas from environmental forces such as wind, rain and intense sunlight, and to enhance vegetation growth. Once established, the vegetation itself must be able to resist erosive forces, since temporary products will degrade.

Long-term nondegradable RECPS, constructed of UV-stabilized synthetic materials, also protect the seed and inhibit erosion prior to germination. In addition, these products provide permanent vegetation reinforcement capable of withstanding much higher velocities and shear stresses than vegetation alone (Lancaster and Austin 1994).

Short-term erosion-control

In the mid 1960s, only one type of erosion-control blanket (ECB) existed. A state soil conservationist discovered that jute, used to wrap cotton bales, could be used to prevent soil erosion. The material consisted of a woven mesh of thick natural yarns, which, when applied on the soil surface, provided thousands of tiny check dams to help keep soil from washing away.

Jute blankets allow vegetation to become established on steeper slopes and in higher flow swales than the traditional hydraulic, straw and hay mulches. A similar material remains in use today.

However, jute has drawbacks: Its open-weave construction leaves soil exposed, the organic material tends to shrink and swell under changing moisture, and it is extremely flammable. To achieve optimum results, straw or hay mulch must be placed beneath the jute.

A one-step, rollout mulch blanket was needed. The first versions involved a very dense mat of curled, barbed aspen wood (excelsior) fibers. The material stayed together but was too dense to allow vegetative growth.

Next, a twisted kraft-paper net was placed above a thinner mat of excelsior fibers. Vegetation grew through the blanket but performance of the paper netting was very inconsistent; it often broke down too quickly and was lifted by the vegetation or worse yet, allowed the blanket to be washed away before vegetative establishment. A stronger, non-moisture-sensitive, more durable netting was needed. Plastic was the answer.

Combining a dense mat of excelsior with a plastic netting lead to the first successful excelsior RECPs. Field trials with nets, fiber lengths and glue patterns resulted in essentially the same excelsior blankets we see today. The key to the improved performance of excelsior over jute blankets has been the plastic-net backbone of the product.

The most recent development in ECBs has been the introduction of parallel-lock stitching with cotton, polyester or polypropylene threads, which hold mulch fibers in place more firmly . These newer-generation "stitched" straw, excelsior and coconut blankets show clear performance advantages over their "glued" predecessors.

Short-term degradable RECPs limit eroion and prevent seed loss on sites subjected low or medium surface-water-flow velocities until a mature vegetative cover is established. Here the goal of the erosion-control product is to provide an acceptable value of the crop-management factor, C, while vegetation is developing.

Table 1 presents a description of various short-term erosion-control systems designed for low to medium flows. It is important to note that these products are designed for a short service life and flow velocities of less than 1-6 fps, with a duration of less than four hours. Such systems are commonly used with hydro-seeding/mulching, dry-land mulches and/or organic or asphalt tackifiers/adhesives to provide enhanced short-term performance. Alternative tools available to limit immediate erosion include dozer tracks or gouges to reduce the slope length, L, and rock or natural mulches to improve the soil erodibility, K.

Long-term erosion-control

Long-term nondegradable RECP systems are required when the velocity (or shear stress) and duration of the design surface-water flow exceed the capacity of mature vegetation. Such design conditions require the use of supplemental armoring to improve or replace that of the vegetation. Turf reinforcement is a method or system that uses geosynthetic materials to enhance plants' natural ability to protect soil from erosion. A flexible three-dimensional matrix retains seeds and soil, stimulates seed germination, accelerates seedling development and, most importantly, synergistically meshes with developing plant roots and shoots.

In laboratory and field analyses, biotechnically reinforced systems have resisted flow rates in excess of 4 ft/sec for durations of up to two days, *providing twice the erosion protection of unreinforced vegetation* (Carroll et al 1991). Such performance has resulted in the widespread use of turf reinforcement as a "soft armor" alternative to concrete, riprap and other armor systems in the protection of open channels, drainage ditches, detention basins and steepened slopes.

Permanent geosynthetic mattings are composed of durable, synthetic materials stabilized against UV degradation and inert to the chemicals normally encountered in a natural-soil environment. They consist of a web of mechanically or melt-bonded polymer nettings, monofilaments or fibers that are entangled to form a strong and dimensionally stable matrix. Polymers include polypropylene, polyethylene, nylon and polyvinyl chloride.

Figure 1 shows the approximate performance guidelines for soft- and hard-armor long-term erosion-control systems. **Table 2** (p. 26) provides a summary of commonly used soft- (RECP) and hard-armor long-term erosion-control systems.

Flow duration is of key importance. For open-channel analysis, it is defined as the time difference between 90% of the peak duration on the rising limb of the flood hydrograph, minus 90% of the peak on the falling limb. Note in Figure 1 that the allowable flow velocities decrease with increasing flow duration, an important consideration for comparing performance data from manufacturers. Many manufacturers may express the erosion resistance of their products in terms of maximum allowable flow velocities or shear stress. Though unstated, such flow limits may be for very short durations (minutes, not hours). Design flows for landfill covers have durations of hours. Be sure to obtain the design recommendations for long-term design events, i.e., 25- or 100-year, 24-hour storm events.

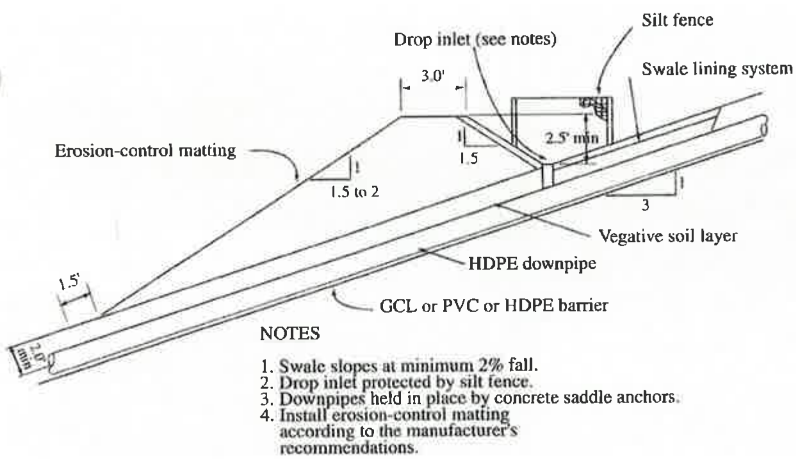

Figure 2. Side-slope swale detail

Application to landfill final covers

Landfill final covers include specific applications of short- and long-term erosion-control applications. Three components of landfill final covers deserve specific discussion regarding erosion control: side-slope surfaces, swales used to subdivide the slopes, and the down chutes used to drain the swales.

Side slopes: Swales commonly are spaced in a way that limits the distance sur-

TABLE 1. SHORT-TERM EROSION-CONTROL SYSTEMS[1] (FROM CARROLL; DODSON; HEWLETT; KELLER; THEISEN 1991, 1992; CHEN)

Type	Description	Flow velocity range, fps	Installed cost $/yd²
Hay/straw/ hydraulic mulches	Typically machine applied over newly seeded sites	1–3	$0.20–$0.30
BOP (Biaxially oriented process nets)	PP or PE nets, used to anchor loose fiber mulches, such as straw, or as a component of erosion-control blankets	2–5[2]	$0.50–$0.75
ECM (woven erosion-control meshes)	Twisted fibers of PP, jute, or coir, woven into a dimensionally stable blanket. Excellent for bioengineering or sod reinforcement	3–6[2]	$0.50–$.75 PP $1–$2 jute $4–$10 coir
ECB (erosion-control blankets)	BOP stitched or glued on one or both sides of a biodegradable fiber blanket composed of straw, wood, excelsior, coconut, etc.	3–6[2]	$1–$3

PP = polypropylene PE = polyethylene

[1] Shear-stress ranges have been omitted because comprehensive data for these materials is not readily available. Long-term shear stresses are limited to the performance of natural vegetation, which ranges from 0.35–3.70 lb/ft², depending upon composition height and density. Class C vegetation, 6"-12" bluegrass, may be expected to resist 1.0 lb/ft² of shear stress.

[2] Depending on vegetation, composition, and density

face water can flow over a slope. For example, a vertical swale spacing of 30 feet for a 4H:1V side slope produces a slope length of less than 125 ft. This results in a USLE-SL factor of less than 5.4. By working the USLE backwards for typical final covers and 24-hour design rain events east of the Mississippi River, the following results are produced:

X (2 ton/acre/yr max) = R(250 avg) K(?) SL(5.4) C(.45 initial, .01 final) P(.90)

The soil loss, X, equals approximately 550 x K initially and 125 x K after vegetation is established. The long-term goal—less than 2 tons/acre/year soil loss—is achieved for soils with a K value of less than 0.16. Such soils are commonly well graded and limited in the percentage of silts and fine sand-size particles.

Clearly, however, dramatic soil loss can occur before the vegetation develops. Assuming a K of 0.16, the USLE predicts a short-term soil-loss rate of approximately 90 tons/acre/year. Here, the use of an erosion-control system may be beneficial if significant precipitation is anticipated before the vegetation becomes established.

Photo 1 (p. 22) shows the placement of a light ECB on a 5H:1V sandy side slope at a South Carolina Superfund site. The material used, Amoco SuperGro, consists of a light, non-UV-stabilized net that supports a very light polypropylene nonwoven. The site was prepared and seeded; the ECB then was stapled over the ground. As with typical installations, the ECB was watered (or rained upon), forcing the nonwoven fibers into the ground's surface. At this point, the stabilizer net played a minimal role.

The ECB performed the role of a mulch by enhancing the germination of the vegetation while reducing rain-related erosion. Several rills did develop within the ECB-stabilized zone, but the overall benefit from the material easily can be recognized from the photo. The installed price of this ECB is approximately \$1.20/yd^2.

Side-slope swales: The "tack-on" swale (detail shown in **Figure 2**, p. 24) is placed on the side slope to reduce effective slope lengths. It offers the advantages of increased air space and ease of post-settlement adjustment relative to more traditional benches or terraces. The "tack-on" swale does generate erosion concerns both in the steep $1\frac{1}{2}$H:1V–2H:1V exterior slopes and in the ≈ 4% drainage channel formed by the swale. Obviously, the related erosion-control systems must be designed for long-term performance.

The exterior slopes of swales are steeper and shorter than those commonly addressed by USLE-SL factors. It is reasonable to assume, however, that the value of SL will be 2–3 times that assumed for the 4H:1V side slopes. Such a large SL value generally precludes acceptable levels of soil loss without the use of a turf-reinforcement mat (TRM).

At the Fresh Kills Landfill on New York's Staten Island, Synthetic Industries' Landlok TRM 450 permanent turf-reinforcement mat protects recently constructed side-slope swale exteriors on the cap. This UV-stabilized product is a dense, three-dimensional web of green polypropylene fibers placed between two high-strength nets and stitched together. The installed cost at this site was approximately \$5.50/yd^2 less than for riprap-lined channels. The City of New York realized over \$412,500 in savings over the 75,000 yd^2 of TRM installed in drainage swales.

Side-slope swales are typically laid out to provide initial 3–4% drainage to the down conveyance. The average flow velocity within the swale is given by Manning's equation as:

$$V = 1.49R^{2/3}\,S^{1/2}/n$$

where n is Manning's roughness coefficient; R is the hydraulic radius, equal to the cross-section area divided by the wetted perimeter; and S is the slope of the channel (French 1985). Figure 1 and Table 2 can be used to select the appropriate erosion-control system. In general, cost-effective TRM systems are adequate for these moderate channel gradients.

Alternatively, the tractive (shear) force approach can be used to design the channel. The tractive force, τ, is equal to:

$$\tau = \gamma D S$$

where τ is the unit weight of water (62.4 lb/ft³); D is the maximum depth of flow, and S is the average bed slope or energy slope. Thus, this simplified shear-stress analysis may easily be manipulated by adjusting bed slope or maximum depth of flow.

Design criteria based on flow velocity may be limited because maximum velocities vary widely with channel length (L), shape (R), and roughness coefficients (n). In reality, it is the force developed by the flow, not the flow velocity itself, that challenges erosion-control system performance. Tractive forces caused by flowing water over the ground surface create shear stresses that can be used as a design parameter, independent of channel shape and roughness. Moreover, the higher stresses developed in channel bends or other changes in stream-channel geometry can be quantified by simplified shear-stress calculation, providing a higher degree of design confidence than otherwise possible (Dodson 1990; Chen and Cotton 1988).

Critical shear-stress determinations are meant to be used with velocity calculations to pre-screen channel-lining designs. Manning's equation remains the primary hydraulic research and design tool. However, as everyday practice has determined, a simplified screening criteria, such as maximum shear stress, is necessary to ensure properly engineered design of erosion-control systems for channel lining. Shear-stress ranges have been omitted purposely from Table 2 because comprehensive data is not available for the range of products/materials described. We urge designers to contact individual manufacturers for specific performance and cost data. Several manufacturers now offer computer software capable of performing velocity, shear stress and USLE analyses.

Down chutes: Surface water drains from the swales and is conveyed downslope through down-pipes or down chutes. The down-chute flow capacity is calculated using Manning's equation, as previously discussed. However, these features must handle the aggregate flow of many swales at the full side-slope angle. Here, flow velocities will commonly exceed 15 fps and hard and/or soft armoring systems must be used.

The advantage of a TRM system is clearly shown on Figure 1. Even prior to establishing vegetation, the TRM system can tolerate flow velocities of 7–12 fps. Once vegetated, the long-term flow velocity increases to more than 14 fps.

Photo 2 shows a Pyramat three-dimensional geotextile being installed within a down chute at a Pennsylvania landfill. The chute has slopes ranging from 3H:1V–2H:1V and an overall total length of 200 feet. Just days after placement of the TRM, this down chute experienced a design storm that resulted in only minor damage to the matting and allowed continued operation of the down chute.

Photo 2. This three-dimensional geotextile, which lines a Pennsylvania-landfill down chute, saved more than $20,000 over riprap.

Use of the TRM in this application reduced the cost of the down chute from $40,000 for a riprap design to less than $15,000. Beyond the significant cost reductions, the TRM gives the down chute a more aesthetically appealing appearance than could be achieved with an armored riprap system. In this case, it also lessened the threat of damage to the geosynthetic cap during construction.

TABLE 2 LONG-TERM EROSION CONTROL SYSTEMS[1] (FROM CARROLL; DODSON; HEWLETT; KELLER; THEISEN 1991, 1992; CHEN)

	Type	Description	Flow velocity, range, fps²	Installed Cost $/yd²
Soft armoring systems	GCS (Vegetated geocellular containment)	Polymeric honeycomb-shaped 3-D-cell systems filled with soil and vegetation	4–6³	$20–$40
	FRS (UV-stabilized fiber roving systems)	Strands of PP or fiberglass fiber blown onto the ground surface, then anchored in place using emulsified asphalt	6–9	$1–$2
	TRM (Turf-reinforcement mats)	A 3-dimensional matrix of PP, PE, or nylon fibers or yarns, mechanically stitched, woven or thermally bonded. Designed to be seeded, then filled with soil.	10–25	$6–$15
	CBS (Vegetated concrete-block systems)	Articulated or hand-placed concrete blocks filled with soil, then vegetated	10–25³	$40–$60
Hard armoring systems	GCS (Geocellular containment systems)	Polymeric honeycomb cells filled with gravel or concrete	6–25³	$30–$60
	FFR (Fabric-formed revetments)	Geotextiles filled with grout or slurry	15–25	$15–30
	CBS (Concrete-block systems)	Articulating or hand-placed concrete blocks	15–25	$40–$60
	Gabions	Rock-filled wire baskets	15–25	$45–$75
	Riprap	Quarried rock of sufficient density	6–30 (depends on mean diameter)	$15–$80

¹ Shear-stress ranges have been omitted because comprehensive data for the range of materials is not readily available. Contact the manufacturer for specific performance and cost data.
² Some systems with greater mass and/or ground cover may exceed these upper limits.
³ Depending on infill material.

Summary

Geosynthetic erosion-control systems provide the flexibility that is important on subsidence-prone final covers and is difficult to obtain in more traditional armoring systems. These systems frequently offer cost advantages and improved aesthetics over more traditional designs. Designers who convey run-off through a vegetated erosion-control system also benefit from improved water quality and the broadening of the run-off hydrograph, which lessens the impact of a storm on the sediment-control basin.

Results from one GRI study indicated that geosynthetic erosion-control products reduce sediment yield by 60% (Rustom and Weggel 1993). With more stringent mandates (and enforcement) of U.S. EPA NPDES (National Pollutant Discharge Elimination System) Phase 2 guidelines looming, vegetated erosion-control systems have become a preferred Best Management Practice for landfill final-cover systems.

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