Gravel Admixtures for Erosion Protection in Semi-Arid Climates

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Abstract

Erosion of surface soils is a particular concern in climates with high intensity storms and low native plant density such as the semi-arid Southwestern US. In this case, erosion may occur by the formation of rills and gullies that can result in significant maintenance expense and/or the loss of function of the soil layer. For example, significant erosion from a surface cover system designed to isolate buried wastes will compromise their barrier function. Estimates of erosion from single precipitation events in semi-arid climates suggest that erosion from a single 100-year event can be more than five times the average annual erosion. Thus, there is a need to design for specific storm events rather than using annual averages.

An effective erosion barrier for conditions associated with semi-arid climates can be designed by combining gravel with native soils into a gravel admixture layer. As finer portions of the soil are removed by erosive forces, the larger particles remain behind and form an “armored” layer that inhibits the formation of deep rills and gullies. The area of armored layer formation is restricted to zones where erosive flows are concentrated. This process is observed in nature in the formation of armored layers in sand and gravel bed arroyos. In dry climates, a gravel admixture layer can have advantages over other treatments such as rip-rap, gravel veneers, vegetation and geosynthetics. For example, in contrast to some other treatments, an admixture will have little impact on vegetation or the soil-water balance.

A procedure for design of gravel admixtures is given. Input to the design includes physical properties of the surface layer (slope, length) and the intensity of the
application of the water (precipitation rates, infiltration – runoff relationship, and off-site flows). The design results include the size of the gravel, percentage of gravel and depth of the admixture layer. In addition, modification of the hydraulic properties of the native soils from the added gravel can be estimated.

The successful application of a gravel admixture layer into a cover system for a Superfund site is described. The gravel admixture layer was designed to provide protection from a 100-year precipitation event and included the following specifications: 50% gravel (1:1 by weight with soil), size gravel at 1.6 to 3.2 cm; and a 16 cm layer thickness. After seven years, the cover shows no signs of significant rill formation or other degradation.

**Introduction**

Regulations for closure of municipal waste landfills typically follow the Federal regulations established by the Resource Conservation and Recovery Act (RCRA, 1976, Subtitle D program, 40 CFR 258). These regulations require the top soil layer to have a slope not less than 0.03 m/m, and not greater than 0.05 m/m. This minimum slope is required because the surfaces of a landfill are subject to substantial local settlement due to the normal process of decomposition of solid waste. Covers for hazardous waste remediation will generally have similar slopes. The application of minimum slope criteria provides for a surface that is relatively free of local depressions and pond areas where excess precipitation can accumulate. To minimize the future occurrence of ponding and to limit infiltration, it is common for designers and regulators to consider slopes approaching the 0.05 m/m limit. Steeper slopes of 0.08 or 0.10 m/m have been considered for some sites.

In some climate zones, a vegetative cover will form a protective blanket that effectively prevents erosion on a cover system. But for arid and semi-arid areas in the southwest United States, minimal rainfall and warm climate creates sparse vegetation. In many areas the natural vegetation will cover only 10 to 20 percent of the surface. The native plants commonly establish root systems that collect moisture from wide areas and store moisture during drought periods. It is possible to provide revegetation with nonnative species to provide a higher plant density, but such attempts are frequently not sustainable. In order to maintain the nonnative species supplemental watering may be required, but introduction of water is not normally advisable for long-term post-closure of landfills.

If native plants are used for southwestern landfill cover systems, a continuous erosion blanket is not likely to be created. Much of the land surface will be exposed to the impacts of rainfall and surface runoff, with the resulting transport of soil through erosion. Surface erosion is a function of the intensity of rainfall and the steepness of the terrain. The impact from raindrops initiates local soil movement, but it is the conveyance across slopes that causes local soil movement to become erosion. The creation of greater cover slopes can have consequences for erosion that will become obvious only after severe rainfall events.
Erosion will not usually occur as a uniform lowering of the surface, but by the formation of rills or small gullies. Rills are the smallest channels formed by runoff, and gullies are the somewhat deeper channels. The distinction between the two is not precise, but both are formed where no defined channel originally existed. Rills and gullies have the potential to cut through the top soil (erosion) layer of a cover system and damage the underlying barrier soil layer or liner. Such damage would compromise the cover system protection.

To assess the impact of potential surface slopes, a typical cover environment in southeastern New Mexico was investigated. Here, erosion was estimated using both an empirical equation and mathematical modeling of the physical processes. These procedures were applied to a New Mexico location.

**Estimating Erosion with the Revised Universal Soil Loss Equation**

An empirical procedure applicable to landfill erosion evaluation is the Revised Universal Soil Loss Equation (RUSLE). This equation is described in detail in *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)* (Renard, et al., 1997). The RUSLE was derived from the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The RUSLE has been used throughout the United States and is particularly directed to the prediction of erosion from agricultural lands, but the procedures do include methodology for use in pasture, range and idle land, and for areas disturbed by construction. The RUSLE equation is:

\[ A = R KLSCP \]

where A is the computed soil loss per unit area, R is a rainfall runoff erosivity factor, K is a soil erodibility factor, L is a slope length factor (a ratio of field length to a 22.1 m test plot), S is a slope steepness factor (a ratio of field slope to a 0.09 meter per meter slope), C is cover management factor, and P is a support (conservation) practice factor. The RUSLE is limited to the determination of average annual erosion rates and cannot establish erosion from specific events and peak erosional years. Additionally, there is no method within the RUSLE procedure to determine the depth or magnitude of gully or rill erosion that may be an integral part of the erosion process.

**Erosion Modeling with AHYMO and WEPP**

There is no known procedure that presents an accurate measure of the physical processes concerning erosion on a cover. However, there are several procedures that combine modeling of some physical processes along with application of empirical equations. One applicable methodology includes the determination of storm water runoff hydrographs using hydrologic modeling, the estimation of sediment wash loads (fine silts and clays that can be suspended in runoff) using the storm-based Modified Universal Soil Loss Equation (Williams, 1975), and estimation of
channelized sediment transport rates using regression equations developed from more complex sediment transport procedures. This computational methodology has been included in the AHYMO Computer Program (Anderson, 1997). The sediment volume for any storm event can be computed from the above procedure. All of the runoff events for a period can be accumulated to obtain an average annual volume. An average annual sediment yield can also be computed by using a statistically weighted function of the 2, 5, 10, 25, 50 and 100-year sediment yields.

The Water Erosion Prediction Project (WEPP) model is a process-based model that considers rill and interrill erosion (Flanagan and Nearing, 1995). For a slope without a pre-existing channel, runoff rates and durations are used to calculate delivery of interrill sediment quantities, and rill erosion and deposition are estimated assuming rectangular rill geometry and a rill density statistic. Databases containing soil properties, climate parameters, and land treatments are available within the program. Surface and subsurface hydrology, winter processes, irrigation, plant growth and residual decomposition are included in the program. The program is capable of developing sediment yield estimates from single storm events (such as the 10-year event) or continuous climate conditions to produce annual values.

Site specific conditions are required to utilize modeling with the AHYMO and WEPP programs. A typical site in southeastern New Mexico was selected in order to provide a comparison of predicted erosion using the empirical RUSLE procedure and modeling methods.

**Input Parameters for Erosion Simulations**

In order to simulate runoff from a typical landfill using numerical methods, it was necessary to establish some physical parameters that would be used in the models. For this erosion potential analysis the following values were selected: cover system area at 2.02 ha (5.0 acres), surface dimensions at 142.2 m by 142.2 m, a coarse sandy loam or loamy fine sand surface soil, median bed material gradation ($D_{50}$) of 0.50 mm, and a ground cover with 10-percent native grass cover. Surface slopes of 0.02, 0.05 and 0.08 m/m were used to simulate three potential surface configurations.

Rainfall is the driving condition for most moisture and erosion that can impact a cover system. While snow melt may also produce moisture, it is of lesser consequence for erosion throughout much of the southwest US. The 24-hour precipitation amounts for a site in New Mexico were obtained from the *Precipitation Frequency Atlas of the Western United States, Volume IV-New Mexico (NOAA Atlas)* (National Weather Service, 1973) as shown in Table 1.
Table 1. Precipitation for 24-hour storm

<table>
<thead>
<tr>
<th>Return period</th>
<th>From NOAA Atlas maps</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-year</td>
<td>4.95 cm</td>
</tr>
<tr>
<td>10-year</td>
<td>8.13 cm</td>
</tr>
<tr>
<td>100-year</td>
<td>12.70 cm</td>
</tr>
</tbody>
</table>

For erosion event computation, extreme rainfall events must be accurately represented. Therefore, revised synthetic precipitation data was created using the Extreme Value Type I distribution and procedures described in *Applied Hydrology* (Chow, et al, 1988). This resulted in 137 daily events greater than 2.2 cm for a 100-year simulation, and extreme event values in agreement with the NOAA Atlas.

The simulation of runoff and erosion required that the depth of cumulative precipitation be simulated throughout a 24-hour period, with special concern about the rainfall intensity during the peak hour. Table 2 shows the distribution of a typical rainfall event based on the 24-hour and 1-hour values from the NOAA Atlas. The data from Table 2 was applied to each of the 137 daily rainfall quantities to form 137 rainfall distribution tables.

<table>
<thead>
<tr>
<th>Table 2. Rainfall distribution factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Percent of 24-hour</td>
</tr>
<tr>
<td>Percent of 1-hour</td>
</tr>
</tbody>
</table>

Results from the Revised Universal Soil Loss Equation Analysis

The average annual sediment yield from the RUSLE is tabulated in Table 3. These values are based on a rainfall-runoff factor (R) of 80; a length-slope factor (LS – with a high ratio of rill to interrill erosion) of 0.51 at a 0.02 m/m slope, 1.69 at a 0.05 m/m slope, and 2.97 at an 0.08 m/m slope; a soil erodibility factor (K) for coarse sandy loam or loamy fine sand of 0.20; a cover factor for 10-percent native grass of 0.30; and a conservation practice factor of 1.0. Table 3 summarizes the results from the RUSLE for the 2.02 ha (5.0 acre) site.

<table>
<thead>
<tr>
<th>Table 3. Average annual sediment yields based on the RUSLE (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope = 0.02 m/m</td>
</tr>
<tr>
<td>11100</td>
</tr>
</tbody>
</table>
Results from the AHYMO and WEPP Modeling

When the 137 largest rainfall events of the 100-year period were evaluated with the AHYMO computer program, only 115 events showed measurable runoff. A summary of the AHYMO sediment yields is contained in Table 4. The average annual sediment yields computed by the AHYMO program are within about 15 percent of the values computed with the RUSLE.

<table>
<thead>
<tr>
<th>Event frequency</th>
<th>24-hr rain (cm)</th>
<th>Sediment (kg) at 0.02 m/m slope</th>
<th>Sediment (kg) at 0.05 m/m slope</th>
<th>Sediment (kg) at 0.08 m/m slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-year</td>
<td>12.70</td>
<td>54800</td>
<td>184300</td>
<td>326500</td>
</tr>
<tr>
<td>10-year</td>
<td>8.13</td>
<td>23400</td>
<td>79400</td>
<td>141600</td>
</tr>
<tr>
<td>2-year</td>
<td>4.95</td>
<td>6200</td>
<td>21500</td>
<td>38800</td>
</tr>
<tr>
<td>Average annual</td>
<td>-----</td>
<td>9300</td>
<td>31800</td>
<td>57000</td>
</tr>
</tbody>
</table>

The WEPP program was also used to compute storm water runoff and sediment yields for the 2, 10 and 100-year events as well as the annual average for 100 years of simulated climate. Table 5 presents sediment yields computed with the WEPP model for the 0.02, 0.05 and 0.08 m/m slopes. The sediment yields computed by the WEPP program are substantially lower than the values computed with the RUSLE and the AHYMO program. These results highlight the variability of erosion estimates made with different methods, and suggest caution when utilizing estimated erosion quantities.

<table>
<thead>
<tr>
<th>Event frequency</th>
<th>24-hr rain (cm)</th>
<th>Sediment (kg) at 0.02 m/m slope</th>
<th>Sediment (kg) at 0.05 m/m slope</th>
<th>Sediment (kg) at 0.08 m/m slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-year</td>
<td>12.70</td>
<td>16800</td>
<td>50500</td>
<td>85100</td>
</tr>
<tr>
<td>10-year</td>
<td>8.13</td>
<td>8600</td>
<td>28700</td>
<td>49300</td>
</tr>
<tr>
<td>2-year</td>
<td>4.95</td>
<td>1900</td>
<td>12900</td>
<td>22900</td>
</tr>
<tr>
<td>Average annual</td>
<td>-----</td>
<td>1800</td>
<td>8600</td>
<td>15400</td>
</tr>
</tbody>
</table>

The sediment values from RUSLE and AHYMO all exceed the conventional regulatory limit of annual permissible sediment loss of 4500 kg/ha (2 tons/acre), whereas the WEPP results suggest that only the steepest slope exceeds this annual limit. Another observation from these results is that results from single storm events from both WEPP and AHYMO can be many times the annual amount.

If the sediment yield computed for a 100-year event were uniformly distributed over the entire 2.02 ha area the effect on a typical cover would be minimal, with a loss of 0.05 to 0.17 cm for a 0.02 m/m slope, 0.16 to 0.57 cm for a 0.05 m/m slope, and .25
to 1.0 cm for a 0.08 m/m slope. However, rill or gully erosion is likely to be concentrated over 2 to 5 percent of the cover area, resulting in average rill or gully depths 20 to 50 times the values computed for uniform erosion. For all surface slopes, gullying could adversely affect cover performance.

**Design of Erosion Protection**

In dry climates, a surface gravel veneer or gravel admixture layer (Waugh and Petersen, 1994) can be utilized to provide erosion protection. A gravel veneer is constructed by placing a 2 to 5 cm thick layer on the soil surface. The gravel must be of sufficient size that it will not be substantially displaced during a major storm event. Rounded gravel with a diameter of 1.3 to 5 cm (½ to 2 in.) is typically used. A gravel layer will reduce surface erosion due to runoff and wind erosion, hold seed in place until it can germinate, and moderate the temperature of the underlying soil. In addition, moisture may increase in the upper most layer of soil allowing vegetation to become established. Experimental studies have shown that a gravel mulch can significantly reduce sediment yield from a cover (Finley et al., 1985; Wischmeier and Smith, 1978).

A gravel veneer can reduce the evaporation rate and may create a habitat for deep-rooted plants (Waugh and Petersen, 1994; Kemper et al., 1994). This reduced evaporation may discourage the use of a surface gravel veneer. For some climate conditions, the increased moisture may increase plant evapotranspiration and offset the loss in direct evaporation. There is no published information revealing whether the added evapotranspiration will offset the reduced evaporation. The use of a gravel veneer may need to be a site specific decision.

An alternative to a surface gravel layer is a gravel admixture. A gravel admixture can be used in combination with vegetative treatments. Waugh and Petersen (1994) suggest that moderate amounts of gravel mixed into the cover topsoil will control both water and wind erosion with little effect on vegetation or soil-water balance. Brakensiek and Rawls (1994) have evaluated the effects of rock and soil mixtures on permeability and unsaturated soil properties. The design of a gravel admixture layer should be based on the need to protect the soil cover from water and wind erosion. A gravel admixture generally protects a cover from long-term wind erosion; the protection from water erosion will depend on the depth, velocity, and duration of water flowing across the landfill cover. These flow values can be established from the physical properties of the cover (slope, convex or concave grading, slope uniformity, and length of flow paths) and the intensity of the application of water (precipitation rates, infiltration - runoff relationship, and off-site flows). For the arid and semi-arid Southwest, runoff from severe storm events usually presents the critical stress on gravel admixture stability.

Based on the above concerns, the gravel admixture for a landfill cover should be based on maintaining long term ecological stability and protection of the soil cover from runoff generated by a major storm event. The design condition for the major
storm event will be to prevent rill or gully erosion from penetrating into the soil layer. The following steps can be used to design a gravel admixture:

a) Establish physical parameters for the cover including area, maximum slope and slope length. Estimate the width of the surface that contributes to individual gully formation. A width of approximately 25% of the slope length is appropriate for many uniformly graded surfaces at slopes less than 10%. The slope length and width establishes the area contributing to formation of a rill or rill zone.

b) Determine rainfall quantities for the design storm from historic information, such as the NOAA Atlas 2. Determine 5, 10, 15, 30 and 60-minute rainfall intensities. Select an appropriate design storm; commonly a 10-year to 100-year event is used.

c) Using appropriate surface infiltration conditions, establish a runoff hydrograph for the design storm event. Runoff based on the rational method, the initial abstraction-uniform infiltration method or the Green-Ampt method is commonly used.

d) Compute sheet flow erosion using the MUSLE (Williams, 1975) with a wash load factor based on local climate conditions.

e) Compute rill or channelized erosion quantity from the runoff hydrograph based on the Meyer-Peter, Muller-Woo (MPM-Woo) Method (Mussetter, et al., 1994) or other total sediment load equation, calibrated for local conditions.

f) Compute the rill geometry using the flow rate and soil grain relation by Simons, Li and Associates (1982, equation 5.7):

\[
b = 37 \left( Q_m^{0.38} / M^{0.39} \right)
\]

where \(b\) is the width of flow in feet, \(Q_m\) is the dominant discharge in cfs and \(M\) is the percentage of silt and clay. For arid alluvial conditions use \(Q_m\) at 10 to 20% of the peak flow, \(Q\). For shallow sections:

\[
b = 0.5 \left( b / d_h \right)^{0.6} F_r^{-0.4} Q^{0.4}
\]

where \(d_h\) is the hydraulic depth in feet, \(F_r\) is the Froude number (assumed to be approximately 1.0 for moderately steep natural channels) and \(Q\) is the peak flow in cfs. From these equations the following equations can be derived to estimate the rill properties:

\[
d_h = (1 / 12.03) M^{0.2597} Q_m^{0.4136}
\]

\[
b = 363.6 M^{-0.6285} d_h^{0.9188}
\]
When $F_r$ is computed to be much less than 1.0, the equations should be modified to use the computed $F_r$ value. Use locally calibrated geomorphologic factors to estimate channelized flow spacing and channel width-to-depth ratios.

g) From the hydraulic analysis of the cover surface, compute the critical particle size, $D_c$, using the Shield's relation (Graf, 1971):

$$D_c = \frac{\tau}{F^* (\gamma_s - \gamma)}$$

Where $\tau$ is the bed shear stress in psf, $F^*$ is Shield’s dimensionless shear stress (0.047 is commonly used), and $\gamma_s$ and $\gamma$ are the unit weights in pcf of the particle and the water. The bed shear stress, $\tau$, is given by:

$$\tau = \gamma_d h S$$

where $S$ is the bed slope in m/m. The $D_c$ is the minimum size required to maintain an armored or stable channel configuration for the design flow event.

h) Based on the percentage of gravel in the gravel admixture layer, compute the depth of scour, $Y_s$, necessary to establish an armor layer with the equation:

$$Y_s = Y_a \left(1 + P_c - 1\right)$$

where $Y_a$ is the armor layer thickness and $P_c$ is the decimal fraction of material greater than the incipient particle size. The value of $Y_a$ should be 3 to 4 times the $D_c$, with a value of 4 times $D_c$ commonly used for small diameters ($D_c < 75$ mm).

i) Compute the total thickness of the gravel/soil admixture layer, $Y_{total}$, as:

$$Y_{total} \geq Y_s + Y_a$$

The thickness of the gravel/soil admixture layer will also depend on the maximum diameter of the gravel, $D_{max}$, in the admixture layer so that:

$$Y_{total} \geq Y_s + (2 D_{max})$$

The value of $D_{max}$ should generally be less than 6 to 8 times $D_c$.

Additionally, the total recommended depth for the gravel admixture may incorporate design safety factors based in uncertainty in material properties, runoff quantities and geomorphologic factors. This gravel admixture design procedure is not appropriate for channels or locations where surface flows are intentionally concentrated. Further, application of the procedure may not be appropriate for slopes in excess of 0.1 m/m.
Application of Design Parameters

A gravel admixture layer was applied in 1997 to a 0.31 ha (0.76 ac) demonstration landfill cover at a Superfund site near Farmington, New Mexico. The surface slope in this cover was at 0.05 m/m. The gravel admixture was designed to provide protection from a 100-year precipitation event and included the following specifications: proportion of gravel to total at 50 percent (1 part gravel to 1 part soil); size at 1.6 to 3.2 cm (0.65 to 1.3 in.); and thickness of layer at 16 cm (6 in.). After seven years, the cover shows no signs of significant rill formation. During this period 11 rainfall events greater than 1 inch in 24-hours occurred. No events near the 100-year magnitude have been measured.

A summary of the design parameters are given below:

- Design storm for erosion stability = 100-year frequency (1% per year)
- Top slope = 0.05 m/m (5%)
- Percentage of gravel = 50% of total (1 part gravel to 1 part soil)
- Cover soils = silty clayey sand with D50 = 0.20 mm.
- Overland flow slope length = 61 m (200 ft.)
- Peak flow = 0.23 m³/s per ha (3.32 cfs per acre)
- Maximum channel velocity = 0.64 m/s (2.11 ft/s)
- Hydraulic depth of channel flow = 25.6 mm (0.084 ft.)
- Bed shear stress = 1.28 kg/m² (0.262 psf)
- Critical particle diameter = 16.5 mm (0.054 ft.), use 19 mm (0.75 in.)
- Required thickness of armor layer = 8 cm (3.0 in.)
- Scour depth = 8 cm (3 in.)
- Thickness of gravel/soil admixture layer = 16 cm (6 in.)
- Gravel gradation = 1.9 to 3.8 cm (% to Wz in.)

Conclusions

The function of a landfill can be improved by construction measures designed to control erosion. The slope of a final cover can have a profound impact on the amount of erosion and on the size of rills or gullies. In arid and semi-arid climates, a significant percentage of erosion and formation of rills may come from single events that are represented by 10-year to 100-year storms. A single 10-year storm can to produce erosion quantities more than two times the average annual erosion and a 100-year storm can produce five times the average annual erosion. While mitigative measures such as revegetation and application of organic mulches may reduce erosion, mechanical stabilization by a gravel veneer or a gravel admixture layer will likely be required to prevent water erosion in the arid and semi-arid Southwest. The design method for gravel admixtures presented here may serve as an outline for further erosion investigations and provide guidance for future designs of gravel-soil admixture layers.
GSP 135 Erosion of Soils and Scour of Foundations

References


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