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Erosion Protection at Landfill Slopes Greater than 10%

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ABSTRACT

In arid climates the steep side slopes of a landfill can be sources of severe erosion. The amount of vegetation that can be sustained commonly does not provide significant erosion protection, and alternative erosion protection measures are required. The commonly used side slope terrace drains can be difficult to construct and maintain. A method is presented to compute the gradation and thickness of a rock surface erosion protection layer that will allow for longer slope lengths than has been commonly applied. The procedure considers peak flow, slope and the formation of surface channelization. Criteria for applying a granular filter are also considered. As an alternative to separately placed riprap and granular filter layers, a combined mixture could serve the same function as separate layers, and reduce construction costs. A gradation range is considered for a combined mixture, and a series of gradations within the range is examined to determine the critical layer thickness. Examples of a resulting side slope design are presented.

INTRODUCTION

The steep side slopes of a landfill can be sources of erosion if surface runoff is allowed to accumulate on the steep slopes and the side slope surfaces are constructed with erosive materials. In some climates, vegetation can be utilized to reduce runoff velocities and stabilize surface soils. In arid climates the amount of vegetation that can be sustained commonly does not provide significant erosion protection, and alternative erosion protection measures are required. One erosion protection method commonly used limits the slopes to short lengths by the construction of side slope terrace drains, with additional protection provided by the addition of gravel armoring to the slopes. Side slope terrace drains can be difficult to construct and maintain, and their placement on existing slopes may provide additional construction difficulties. The procedures described in this document can be used to guide the design of a rock surface erosion protection layer that will allow for longer slope lengths than has been commonly applied. The longer slope lengths may greatly reduce or eliminate the need for side slope terrace drains.

It is desirable to reduce the amount of surface water that can enter the zone of fill, and this is typically accomplished by construction of a barrier layer above the area of fill. Studies in arid climates have shown that a thick soil layer can provide a superior barrier layer, because of the moisture storage properties of the soil, and high rates of evaporation and plant transpiration. Some studies have indicated that placement of a surface gravel layer will increase surface infiltration and reduce

evaporation so that the efficiency of a soil barrier layer is reduced. However, for very steep slopes the runoff percentages will be much higher than for flatter slopes, and the effects of surface gravel on overall evaporation will be minimized. When slopes are at 10% or steeper, and the base soil does not allow for the rapid infiltration of surface water, a gravel layer or "veneer" can provide surface erosion protection without significantly reducing the function of the soil barrier layer.

The size of the gravel and layer thickness is normally based on a constructed watershed condition and a critical design slope. The design of a gravel veneer to protect steep side slopes from erosion requires evaluation of small watershed hydrology and hydraulics, and the design of the conveyances where water is expected to flow. In the case of steep uniformly graded or gradually varying embankment slopes, a fixed flow path or channel may not be constructed on the surface, but channelization will occur because of normal construction variability, settlement, and on-going erosion processes. Site physical conditions and experience at similar existing sloped areas can be used to establish surface flow criteria using geomorphologic equations. The resulting flow rates and velocities based on geomorphology will generally be larger than when only existing or constructed site topography is used.

Construction of a gravel veneer commonly includes a separately placed finer filter soil below the gravel, but construction could be simplified if the filtering material could be placed concurrently with the gravel. The design of a combined gravel-filter erosion layer is described in this document.

Using critical flow depth, velocity and slope criteria, a single gravel veneer gradation and thickness can be designed. When slopes and runoff areas vary widely, an alternative approach is to use preliminary analyses to determine veneer gradations, then to use this information as a guide for selection of material gradations that can be efficiently produced. Each selected gradation can then be evaluated to determine the range of site conditions where the gradation can be safely applied.

PEAK FLOW AND UNIT DISCHARGE

Erosion of landfill side slopes is most problematic during severe precipitation when erosion can remove waste from a landfill and convey it to downstream areas. For a landfill side slope in the arid and semi-arid areas of the southwest United States a 200-year event is a suggested design flow condition, because of the significant environmental damage that can result from side slope erosion. Special site requirements and waste materials may warrant use of more severe event frequencies. For any given watershed, the 200-year frequency event peak flow (Q_{200}) can be determined from a basic hydrologic analysis, such as with the Rational Method or NRCS Curve Number (CN) procedure. Peak flow during the storm event is the most important hydrologic property to accurately predict erosion. For a planar surface with an identified length, but a width that can be identified only after erosion has occurred, the recommended watershed width for runoff computations should be 25% of the watershed length. The dominant discharge peak flow (Q_m) can be evaluated by considering the statistically weighted average of the peak runoff occurring over a long period, for example 100 years. In the arid southwestern the Q_m can be estimated at 10% of Q_{100} . For any given watershed, the relationship between the 200-year

frequency event peak flow (Q_{200}) and the 100-year frequency event peak flow (Q_{100}) can be determined from a basic hydrologic analysis. Therefore, the value of Q_{100}/Q_{200} will have a fixed value for any single watershed. The ratio of Q_m/Q_{200} can be determined from Q_m/Q_{100} and Q_{100}/Q_{200} . For example, if the Q_{100}/Q_{200} is determined to be 0.78, the Q_m can be estimated as 7.8% of Q_{200} .

By following the analysis procedure described in "Design of Erosion Protection at Landfill Areas with Slopes Less than 10%" (Anderson and Wall, 2010, this volume), and substituting the Q_{200} for the Q_{100} , the hydraulic depth equation is:

$$d_h = (43.7)^{-0.6} \left(\frac{Q_m}{Q_{200}} \right)^{-0.6} Q_m^{0.372} \left[0.0488 \left(\frac{D_{50}}{1000} \right)^{0.167} \right]^{0.6} s^{-0.3} M^{0.234} \quad [1]$$

where: d_h is the hydraulic depth (m),
 Q_{200} is the peak flow at 200-year frequency (m^3/s),
 Q_m is the dominant discharge (m^3/s),
 D_{50} is the median size of the rock riprap (mm).
 M is the percentage of silt and clay in the channel perimeter
 and s is the slope of the channel profile (m/m).

Equation [1] describes the flow width based on the geomorphologic equation of Simons, Li and Associates (1982, and Simons and Li, 1980). Except for the D_{50} , all of the values in this equation can be estimated from physical watershed properties. This equation and Manning's equation can also be used to compute the 200-year event unit discharge, Q_{200}/b , and the width-to-depth ratio, b/d_h . While the dominant discharge, Q_m , is used in equation [1], the computed hydraulic depth, d_h , represents the depth from a 200-year frequency event.

A second geomorphologic parameter is the width-to-depth ratio of the flowing water. For arid and semi-arid conditions a maximum width-to-depth ratio of 40 is recommended. If the width-to-depth ratio, b/d_h , exceeds 40, the b and the d_h must be re-computed to maintain a width-to-depth ratio of 40. The width-to-depth relation can be used to obtain an alternate equation for the hydraulic depth as:

$$d_h = [(Q_{200} n)/F]^{0.375} s^{-0.1875} \quad [2]$$

where: F is the width-to-depth ratio. (Use a value of 40)
 and n is the Manning's roughness coefficient.

Equation [2] describes the flow width and depth based on a defined width-to-depth ratio. Equation [2] should be used whenever the b/d_h computed from equation [1] exceeds 40. Using Manning's equation and equation [1] or [2], the flow velocity, V_{100} , the Froude number, F_r , the width of flow, b , and the unit discharge, q_f , can be computed.

RIPRAP ROCK SIZE

With the flow properties established, the S. R. Abt and T. L. Johnson equation

(1991) can be used to solve for the median rock size of the gravel veneer. The basic Abt and Johnson equation provides a prediction of the flow conditions when failure is expected to occur, but for constructed applications, failure at the design flow is not tolerable. "Riprap design should be directed toward preventing stone movement and to insure the riprap layer does not fail" (Abt and Johnson, 1991, page 962). Abt and Johnson state that the values from the basic equation "should be adjusted to prevent stone movement" (Abt and Johnson, 1991, page 967). In addition, actual construction is expected to be somewhat more variable than the hand placement of rock in a controlled laboratory experiment, and minor construction variability could cause failure prior to the conditions identified in the Abt and Johnson field laboratory testing. Abt and Johnson recommend that factor of safety of 1.2 be applied to the rock size equation (page 967).

The Abt and Johnson equation uses the unit discharge, and profile slope to compute the median rock size when failure is expected to occur. The unit discharge is computed using the smallest b derived using Manning's equation and equation [1] or [2] so that the computed unit discharge is the maximum value computed from the two equations. The equation for unit discharge is:

$$q_f = Q_{200}/b \quad [3]$$

where: q_f is the unit discharge or unit flow rate (m^2/s).

The Abt and Johnson equation with the addition of the recommended factor of safety and converted to metric form is:

$$D_{50} = (1.2 \times 502.9) s^{0.43} q_f^{0.56} \quad [4]$$

where: D_{50} is the median rock size of the gravel veneer (mm).

The physical testing by Abt and Johnson did not use slopes steeper than 20% (0.20 m/m) and the extension of the procedure to slopes steeper than 33% (0.33 m/m) is not recommended. Abt and Johnson's paper suggested that the gravel layer thickness should be 1.5 to 3.0 times the D_{50} . However, only two of their 26 tests had a layer thickness less than 2.0 times the D_{50} . All of their tests were for separately placed riprap and granular filter layers.

CRITERIA FOR GRAVEL VENEER RIPRAP AND FILTER

The D_{50} computed from equation [4] can be used to determine the rock gradation for the gravel veneer and the total thickness of the veneer layer. The following procedure is recommended:

- specify a construction minimum D_{50} (D_{50-min}) based on the computed value from equation [4] rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{50} (D_{50-max}) at 140% of the D_{50-min} , rounded to the nearest 6.4 mm (0.25 inch).
- specify a minimum D_{100} ($D_{100-min}$) at 150% of the D_{50-min} , rounded to

the nearest 6.4 mm (0.25 inch).

- specify a design maximum D_{100} ($D_{100-max}$) at 200% of the D_{50-min} , rounded to the nearest 6.4 mm (0.25 inch). The constructed veneer can have a larger value with an appropriate adjustment in the layer thickness.
- specify a minimum D_{15} (D_{15-min}) at 45% of the D_{50-min} , rounded to the nearest 6.4 mm (0.25 inch).
- specify a design maximum D_{15} (D_{15-max}) at 80% of the D_{50-min} , rounded to the nearest 6.4 mm (0.25 inch).
- specify the coefficient of uniformity ($C_u = D_{60} / D_{10}$) with an allowable range between 1.75 and 3.0.
- specify the minimum rock layer thickness (Y_{min}) at the 2.0 times the D_{50-min} , or 1.0 times the $D_{100-max}$, whichever is larger.

The Abt and Johnson physical testing used rock with an average specific gravity of 2.66. In order to use equation [4] without adjustment, the rock in the gravel veneer should have an average specific gravity of 2.65 or larger. This is equivalent to a particle unit weight of 2650 kg/m³ (165 lbs/ft³). If any rock with a smaller average specific gravity is proposed for use, the size of the D_{15} , D_{50} , D_{100} , and Y_{min} would need to be adjusted based on the ratio of the buoyant weight of the rock.

The gravel veneer in the Abt and Johnson testing used a granular filter immediately below the rock layer. Filter material is placed below the rock layer to prevent loss of material below the layer which would cause failure of the erosion layer. The size of the granular bedding must be based on size of the gravel in the erosion layer. Some guidelines on granular filter design can be found in the US Federal Highway Administration, Hydraulic Engineering Circular No. 11 (1989, FHWA-IP-89-016). The following procedure is recommended:

- specify a minimum Filter D_{85} (Filter D_{85-min}) at 20% of the maximum veneer D_{15} (D_{15-max}), rounded to the nearest 0.25 mm (0.01 inch).
- specify a minimum Filter D_{50} (Filter D_{50-min}) at 4% of the maximum veneer D_{50} (D_{50-max}), rounded to the nearest 0.25 mm (0.01 inch).
- specify a design minimum Filter D_{60} (Filter D_{60-min}) at 140% of the minimum Filter D_{50} (Filter D_{50-min}), rounded to the nearest 0.25 mm (0.01 inch).
- specify a design minimum Filter D_{10} (Filter D_{10-min}) at the minimum Filter D_{60} (Filter D_{60-min}) divided by 3.5, rounded to the nearest 0.25 mm (0.01 inch).
- specify the Filter coefficient of uniformity (Filter $C_u = \text{Filter } D_{60} / \text{Filter } D_{10}$) with an allowable range between 2.0 and 3.5.
- specify the minimum Filter layer thickness (Filter Y_{min}) at 0.152 m (6.0 inches).

For the range of gravel veneer sizes that are likely to be required for steep landfill slopes, a typical roadway aggregate base will typically contain a higher percentage of finer grained soils than is recommended to meet granular filter criteria. Table 1 provides two granular filter gradations that might be considered with steep

sloped rock layers. The Type A Granular Soil Filter in Table 1 can generally be used when the veneer D_{50-min} is 100 mm (4.0 inches) or less. The Type B Granular Soil Filter can generally be used when the veneer D_{50-min} is between 100 mm (4.0 inches) and 180 mm (7.0 inches). A somewhat finer filter could be specified for cases where the D_{50-min} is smaller than 65 mm (2.5 inches). For each gravel veneer size, the *Filter* D_{85-min} , *Filter* D_{50-min} , and *Filter* D_{10-min} should be examined to verify that the appropriate Granular Filter Soil (Type A or B) is used.

Table 1. Suggested Granular Filter Gradations

Granular Filter Soil - Type A		Granular Filter Soil - Type B	
Passing	% by weight	Passing	% by weight
75 mm (3 inch)	100%	100 mm (4 inch)	100%
20 mm (3/4 inch)	30 to 90%	25 mm (1 inch)	30 to 80%
10 mm (3/8 inch)	10 to 70%	10 mm (3/8 inch)	5 to 40%
#4 (0.475 mm)	0 to 20%	#4 (0.475 mm)	0 to 20%
#200	0 to 3%	#200	0 to 3%

A SINGLE RIPRAP-FILTER LAYER

As an alternative to separately placed riprap and granular filter layers, a combined material layer could serve the same function as the separate layers, and reduce construction costs. With a riprap-filter mixture the resulting material properties need to be examined to determine if the erosion protection and the filtering criteria can be met. With the riprap-filter mix, it is possible to perform some material selection and processing to produce different classes of mix, but more refined material selection may not be feasible.

Rather than specify detailed rock and filter gradations applicable to a single design flow and slope, a preliminary design to determine rock and filter gradations can be used in selecting a riprap-filter mixture that can be efficiently produced. Even with material from a single source area, it is expected that there will be variability of test results. The arithmetic mean and standard deviation of the test data are important measurements to obtain a specified gradation range. It may be desirable to specify a wider range of particle sizes than would be indicated by statistical sampling of a single source in order to allow greater flexibility in material source selection and processing. However, a larger range of values will change the layer erosion protection capability and may reduce the design efficiency. There are limits to the range of allowable gradations. For example, if there is not a sufficient quantity of particles that resist the erosive forces, no additional thickness can compensate for this deficiency.

With a specified riprap-filter mix the gradation of the portion of the mix that can be considered to as riprap must be considered. Particles sizes at "25% of the D_{50} " can carry only 8.4% of the unit discharge of particles at "100% of the D_{50} ". Based on examination of riprap guide specifications from several sources, particle sizes in the riprap-filter mix that are smaller than 25% of the computed D_{50} , should not be included in the riprap portion of the mix. The US Dept. of Transportation, Federal Highway Administration, *Design of Riprap Revetment* (Hydraulic Engineering

Circular, FHWA-IP-89-016, 1989, p.36) recommends D_{15} at 40% to 60% of the D_{50} . The percentage of riprap size material in a proposed gradation can be determined from the percentage of material passing the computed "25% of the D_{50} ", where:

$$\%Riprap = 100\% - \% \text{ passing "25\% of } D_{50}" \quad [5]$$

Using a similar procedure, the percentage of effective filtering material can be determined. For the range of gravel sizes expected, any particle sizes that pass a #10 sieve (2.0 mm) should not be considered as contributing to riprap filtering. Therefore the percentage of filter material in a gradation can be computed as:

$$\% Filter = \% \text{ passing "25\% of } D_{50}" - \% \text{ passing \#10 sieve (2.0 mm)} \quad [6]$$

With the % *Riprap* and % *Filter* established, it is also possible to use the total grain size distribution to obtain an equivalent riprap grain size distribution for the portion of the particle sizes that can be considered as riprap. The individual sieve size percent passing values for the riprap portion are computed as:

$$\% \text{ passing riprap portion} = 100\% \left(1 - (100\% - \% \text{ passing}) / \% \text{ riprap} \right) \quad [7]$$

Using the grain size values for the riprap portion, the $D_{15 \text{ riprap}}$, $D_{50 \text{ riprap}}$, $D_{85 \text{ riprap}}$ and $D_{98 \text{ riprap}}$ of the riprap can be computed. The basic riprap layer thickness is computed as:

$$T_{Riprap-1} = 1.6 \times D_{50 \text{ Riprap}} \quad \text{or} \quad [8]$$

$$T_{Riprap-1} = (0.6 \times D_{90 \text{ Riprap}}) + (0.9 \times D_{85 \text{ Riprap}}) \quad [9]$$

whichever is smaller, but not less than:

$$T_{Riprap-1} = 2 \times \text{computed } D_{50} \quad [10]$$

When the $D_{15 \text{ riprap}}$ is smaller than 40% of the computed D_{50} , there is more small size material than is recommended for a normal riprap gradation and the riprap layer thicknesses should be adjusted for the excess of smaller material by the following equation:

$$T_{Riprap-2} = \left[1 - \left(\frac{0.15 (\ln(D_{15 \text{ Riprap}}) - \ln(25\% \text{ comp } D_{50}))}{\ln(40\% \text{ comp } D_{50}) - \ln(25\% \text{ comp } D_{50})} \right) \right] \left(\frac{T_{Riprap-1}}{0.85} \right) \quad [11]$$

When the sample $D_{50 \text{ riprap}}$ is smaller than the computed D_{50} , the average size of the riprap is too small and the riprap layer thickness is adjusted by the following equation:

$$T_{\text{Riprap-3}} = \left[1 - \left(\frac{0.50 (\ln(D_{50 \text{ Riprap}}) - \ln(25\% \text{ comp } D_{50}))}{\ln(40\% \text{ comp } D_{50}) - \ln(25\% \text{ comp } D_{50})} \right) \right] \left(\frac{T_{\text{Riprap-1}}}{0.50} \right) \quad [12]$$

The riprap layer thickness then is the largest value, or:

$$T_{\text{Riprap}} = \text{Maximum} (T_{\text{Riprap-1}}, T_{\text{Riprap-2}}, T_{\text{Riprap-3}}) \quad [13]$$

The minimum percentage of filter in the gravel-soil mix is determined from the following equation derived from typical riprap filter designs:

$$\text{Min \% Filter} = \% \text{Riprap} \times (15\% \text{ of } D_{50}) / 4.0 \quad [14]$$

but not less than $0.10 \times \% \text{ Riprap}$ or more than $0.25 \times \% \text{ Riprap}$. The computed $\% \text{ Filter}$ material is compared with this sample value, and if the $\text{Min \% Filter}$ is greater than the $\% \text{ Filter}$ provided, the total layer thickness is adjusted.

If the percentage of the material finer than the Riprap size in the sample gradation does not exceed 25%, and the *Minimum \% Filter* does not exceed the $\% \text{ Filter}$ provided by the gradation, the computed T_{Riprap} will also be the computed layer thickness. When these conditions are not met, the total layer thickness must be adjusted to account for filter bulking or $\% \text{ Filter}$ deficiency. The following equation is used:

$$T_{\text{Layer}} = \left[\text{Max} \left(\frac{75\%}{\% \text{Riprap}}, 1 \right) \right] \times \left[\text{Max} \left(\frac{\text{Min \% Filter}}{\% \text{Filter}}, 1 \right) \right] \times T_{\text{Riprap}} \quad [15]$$

with T_{Layer} never less than T_{Riprap} .

GRAVEL RIPRAP-FILTER SELECTION FOR A GRADATION RANGE

The procedure for the riprap-filter mix can be used to test a single specified gradation and determine the applicable layer thickness appropriate to that gradation. It does not directly give the appropriate thickness when a gradation range is specified for a given location. When a gradation range is identified, the material that could be supplied may fall anywhere within the gradation band. Checking the computed thickness for only the minimum and maximum gradations does not provide a thorough examination of the possible gradations. A series of nine gradation scenarios within the gradation range is examined to determine the critical admixture layer thickness, T_{Layer} , applicable to a single slope and length condition. With a single thickness and slope used to compute the T_{Layer} for a specified gradation, it is also possible to examine a range of slopes and lengths from 10% to 30% that can utilize the same gradation and T_{Layer} .

Table 2. Riprap-Filter Mix Runoff Areas and Overland Flow Lengths

Layer thickness (m)	Max. Area at $\leq 12\%$ slope (ha)	Max. Area at $\leq 14\%$ slope (ha)	Max. Area at $\leq 16\%$ slope (ha)	Max. Area at $\leq 18\%$ slope (ha)	Max. Area at $\leq 20\%$ slope (ha)	Max. Area at $\leq 22\%$ slope (ha)	Max. Area at $\leq 26\%$ slope (ha)	Max. Area at $\leq 30\%$ slope (ha)
0.254	1.024	0.808	0.660	0.551	0.468	0.406	0.313	0.251
Layer thickness (m)	Max. Length at $\leq 12\%$ slope (m)	Max. Length at $\leq 14\%$ slope (m)	Max. Length at $\leq 16\%$ slope (m)	Max. Length at $\leq 18\%$ slope (m)	Max. Length at $\leq 20\%$ slope (m)	Max. Length at $\leq 22\%$ slope (m)	Max. Length at $\leq 26\%$ slope (m)	Max. Length at $\leq 30\%$ slope (m)
0.254	202	180	162	148	137	127	112	100

CONCLUSIONS

Measures to control erosion at the steep side slopes of a landfill are critical for safe function. Mechanical stabilization of steep slopes by a combined riprap-filter layer can be used to prevent water erosion. Standard rainfall-runoff procedures can be combined with geomorphologic equations to compute channelized flow. Procedures commonly applied to determine riprap size and filter gradation can then be modified to establish requirements for a single riprap-filter layer. The resulting riprap-filter gradation can then be evaluated for a range of slope and watershed conditions to determine applicable layer thicknesses. The design method presented here was prepared to guide the construction of erosion protection for steeply sloped areas on a landfill in the arid and semi-arid Southwest. However, the method implements design concepts that are commonly applied at steep slopes, and the design method could be readily adapted to any slopes where rock veneers are warranted.

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