Anderson, Clifford; Wall, Steve

Erosion Protection at Landfill Slopes Greater than 10%

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/100229

Vorgeschlagene Zitierweise/Suggested citation:
Anderson, Clifford; Wall, Steve (2010): Erosion Protection at Landfill Slopes Greater than 10%. In: Burns, Susan E.; Bhatia, Shobha K.; Avila, Catherine M. C.; Hunt, Beatrice E. (Hg.): Proceedings 5th International Conference on Scour and Erosion (ICSE-5), November 7-10, 2010, San Francisco, USA. Reston, Va.: American Society of Civil Engineers. S. 1064-1073.

Standardnutzungsbedingungen/Terms of Use:
Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.
Erosion Protection at Landfill Slopes Greater than 10%

Clifford Anderson¹, M. ASCE, PE, PhD, D.WRE and Steve Wall²

¹Department of Engineering, Central Connecticut State University, 1615 Stanley Street, New Britain, CT 06050-4010, USA, email: cliff@ahymo.com

²Office of Pollution Prevention and Solid Waste (WST-7), US EPA Region 9, 75 Hawthorne St., San Francisco, CA 94105, USA, email: Wall.Steve@epamail.epa.gov

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 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:

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

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
- \( s \) 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:

\[
d_h = \left( \frac{Q_{200}}{F/n} \right)^{0.375} s^{-0.1875} \tag{2}
\]

where:
- \( F \) is the width-to-depth ratio. (Use a value of 40)
- \( n \) 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:

\[
q_f = \frac{Q_{200}}{b}
\]

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:

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

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 GRAVER 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
SCOUR AND EROSION

the nearest 6.4 mm (0.25 inch).

- specify a design maximum $D_{100}$ ($D_{100\text{-max}}$) at 200% of the $D_{50\text{-min}}$, 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 $D_{15}$ ($D_{15\text{-min}}$) at 45% of the $D_{50\text{-min}}$, rounded to the nearest 6.4 mm (0.25 inch).

- specify a design maximum $D_{15}$ ($D_{15\text{-max}}$) at 80% of the $D_{50\text{-min}}$, 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 ($Y_{\text{min}}$) at the 2.0 times the $D_{50\text{-min}}$, or 1.0 times the $D_{100\text{-max}}$ 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/m$^3$ (165 lbs/ft$^3$). If any rock with a smaller average specific gravity is proposed for use, the size of the $D_{15}$, $D_{50}$, $D_{100}$, and $Y_{\text{min}}$ 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 $D_{85\text{-min}}$) at 20% of the maximum veneer $D_{15}$ ($D_{15\text{-max}}$), rounded to the nearest 0.25 mm (0.01 inch).

- specify a minimum Filter $D_{50}$ (Filter $D_{50\text{-min}}$) at 4% of the maximum veneer $D_{50}$ ($D_{50\text{-max}}$), rounded to the nearest 0.25 mm (0.01 inch).

- specify a design minimum Filter $D_{60}$ (Filter $D_{60\text{-min}}$) at 140% of the minimum Filter $D_{50}$ (Filter $D_{50\text{-min}}$), rounded to the nearest 0.25 mm (0.01 inch).

- specify a design minimum Filter $D_{10}$ (Filter $D_{10\text{-min}}$) at the minimum Filter $D_{60}$ (Filter $D_{60\text{-min}}$) divided by 3.5, rounded to the nearest 0.25 mm (0.01 inch).

- specify the Filter coefficient of uniformity (Filter $C_u = Filter D_{60} / Filter D_{10}$) with an allowable range between 2.0 and 3.5.

- specify the minimum Filter layer thickness (Filter $Y_{\text{min}}$) 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 $D_{50\text{-}min}$ is 100 mm (4.0 inches) or less. The Type B Granular Soil Filter can generally be used when the veneer $D_{50\text{-}min}$ is between 100 mm (4.0 inches) and 180 mm (7.0 inches). A somewhat finer filter could be specified for cases where the $D_{50\text{-}min}$ is smaller than 65 mm (2.5 inches). For each gravel veneer size, the Filter $D_{85\text{-}min}$, Filter $D_{50\text{-}min}$, and Filter $D_{10\text{-}min}$ 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                     | Passing                     |
| 75 mm (3 inch)              | 100%                        |
| 20 mm (3/4 inch)            | 30 to 90%                   |
| 10 mm (3/8 inch)            | 10 to 70%                   |
| #4 (0.475 mm)               | 0 to 20%                    |
| #200                        | 0 to 3%                     |
| 100 mm (4 inch)             | 100%                        |
| 25 mm (1 inch)              | 30 to 80%                   |
| 10 mm (3/8 inch)            | 5 to 40%                    |
| #4 (0.475 mm)               | 0 to 20%                    |
| #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 D15 at 40% to 60% of the D50. The percentage of riprap size material in a proposed gradation can be determined from the percentage of material passing the computed "25% of the D50", where:

\[
\%\text{Riprap} = 100\% - \% \text{passing "25\% of D}_{50}\]
\[
\text{[5]}
\]

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:

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

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:

\[
\%\text{passing riprap portion} = 100\% \left( 1 - \frac{(100\% - \%\text{passing})}{\%\text{Riprap}} \right)
\text{[7]}
\]

Using the grain size values for the riprap portion, the D15 \text{rip rap}, D50 \text{rip rap}, D85 \text{rip rap} and D98 \text{rip rap} of the riprap can be computed. The basic riprap layer thickness is computed as:

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

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

whichever is smaller, but not less than:

\[
T_{\text{rip rap-1}} = 2 \times \text{computed D}_{50}
\text{[10]}
\]

When the D15 \text{rip rap} is smaller than 40% of the computed D50, 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:

\[
T_{\text{rip rap-2}} = \left[ 1 - \left( \frac{0.15 \left( \ln(D_{15 \text{rip rap}}) - \ln(25\% \text{comp D}_{50}) \right)}{\ln(40\% \text{comp D}_{50}) - \ln(25\% \text{comp D}_{50})} \right) \right] \left( \frac{T_{\text{rip rap-1}}}{0.85} \right)
\text{[11]}
\]
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:

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

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

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

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

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

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 $\text{Min } \% \text{ Filter}$ 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 $\text{Minimum } \% \text{ Filter}$ does not exceed the $\% \text{ Filter}$ provided by the gradation, the computed $T_{\text{Riprap}}$ 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:

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

with $T_{\text{Layer}}$ never less than $T_{\text{Riprap}}$.

**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, $T_{\text{Layer}}$, applicable to a single slope and length condition. With a single thickness and slope used to compute the $T_{\text{Layer}}$, 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 $T_{\text{Layer}}$. 
APPLICATION OF DESIGN PARAMETERS

A riprap-filter mix was applied to a typical landfill side slope in an arid climate. A multiple page spreadsheet was used to perform the computation. A section of the side slope with an area of 0.468 ha (1.157 ac) and a uniform slope of 0.20 m/m was considered. A summary of the design parameters are given below:

- Design storm for erosion stability = 200-year frequency (0.5% per year)
- Top slope = 0.20 m/m (20%)
- Overland flow slope length = 137 m (449 ft)
- Peak flow = 0.319 m$^3$/s (1.396 ft$^3$/s)
- Maximum channel velocity = 2.11 m/s (6.92 ft/s)
- Hydraulic depth of channel flow = 62 mm (0.202 ft)
- Computed $D_{50}$ of riprap portion = 96 mm (3.79 in.), use 95 mm (3.75 in.)
- Required thickness of riprap only = 0.203 m (8.00 in.)
- Computed thickness of riprap-filter layer, $T_{Layer} = 0.254$ m (10 in.)

The design admixture gradation for the 0.468 ha area at a slope of 0.20 m/m is shown on Figure 1.

![Figure 1. Combined Riprap-Filter Gradation](image)

The design admixture gradation from Figure 1 with a layer thickness, $T_{Layer}$, of 0.254 m (10 in) and slope of 0.20 m/m (20%) can also be applied to a spreadsheet analysis for slopes from 0.10 to 0.30 m/m (10 to 30%). Slopes flatter than 0.20 m/m will allow larger runoff areas and longer overland flow slope lengths, and slopes steeper than 0.20 m/m will require smaller runoff areas and shorter overland flow slope lengths. Table 2 shows values for the runoff areas and overland flow lengths that can be applied to the Figure 1 gradation with a 0.254 m (10 in) layer thickness.
Table 2. Riprap-Filter Mix Runoff Areas and Overland Flow Lengths

| Layer thickness (m) | Max. Area at ≤12% slope (ha) | Max. Area at ≤14% slope (ha) | Max. Area at ≤16% slope (ha) | Max. Area at ≤18% slope (ha) | Max. Area at ≤20% slope (ha) | Max. Area at ≤22% slope (ha) | Max. Area at ≤26% slope (ha) | Max. Area at ≤30% slope (ha) |
|---------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 0.254               | 1.024                         | 0.808                         | 0.660                         | 0.551                         | 0.468                         | 0.406                         | 0.313                         | 0.251                         |
| Max. Length at ≤12% slope (m) | Max. Length at ≤14% slope (m) | Max. Length at ≤16% slope (m) | Max. Length at ≤18% slope (m) | Max. Length at ≤20% slope (m) | Max. Length at ≤22% slope (m) | Max. Length at ≤26% slope (m) | Max. Length at ≤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 geomorphic equations to compute channelized flow. Procedures commonly applied to determine riprap size and filter gradation can then 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 could be readily adapted to any slopes were rock veneers are warranted.

REFERENCES

Abt, S. R. and Johnson, T. L. (1991). “Riprap Design for Overtopping Flow.” Journal of Hydraulic Engineering, 117 (8), pp 959-972.

Simons, D. B., Li, R. M., et al. (1980). Watershed and Stream Mechanics, prepared for the US Department of Agriculture, Soil Conservation Service, Washington, D.C.

Simons, Li and Associates (1982). Engineering Analysis of Fluvial Systems, Fort Collins, CO.

US Federal Highway Administration (1989). Design of Riprap Revetment, Hydraulic Engineering Circular No. 11, FHWA-IP-89-016, Washington, D. C.