17 Bank Protection

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17.1 OVERVIEW AND PURPOSE

This chapter provides an overview of measures to protect highway embankments, bridge structures, culverts, and other infrastructure assets in and near rivers, creeks, streams, and other waterways (both natural and human-made). Guidance and standards outlined in this document are intended for use on and near state and federal highways maintained and managed by the Colorado Department of Transportation, and on all waterways adjacent or subject to influence by CDOT infrastructure.

Information presented herein originates from Federal Highway Administration means and methods outlined in "Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance," Hydraulic Engineering Circular No. 23 (HEC-23), Volumes 1 and 2, (2009). It is further supplemented by the Urban Drainage and Flood Control District's (UDFCD's) *Urban Storm Drainage Criteria Manual* (USDCM, Wright Water Engineers, 2016), and the CDOT *Drainage Design Manual* (DDM) Chapter 8 – Channels.

One of the hazards of placing a highway near a river, stream channel, or other water body is the potential for erosion of bridges, culverts, and highway embankments by moving water. Proper channel revetment, stream-instability countermeasures, or bank protection must be considered and strategically applied during design.

The guidelines in this chapter describe applicable revetments used as erosion and scour countermeasures for waterways with design discharges generally greater than 50 cfs. Waterways with smaller design discharges should follow procedures presented in the DDM Chapter 8 – Channels, and in the FHWA Hydraulic Engineering Circular No. 15 (HEC-15), "Design of Roadside Channels with Flexible Linings" (2005).

Four methods of protecting a highway embankment from bank erosion are available to the designer:

- Relocation - moving the highway away from the stream or water body;
- River Training - encouraging waterway channels to laterally migrate away from infratstructre assetes and facilities, such as bendway weirs, guidebanks, spurs, and other features not covered in this chapter, but are described in HEC-23 and other literarture;
- Waterway Alteration - moving the water body away from infrastructure assets and appurtenances; and
- Revetment - constructing engineered treatments to prevent erosion and scour.

Emphasis in this chapter has been placed on rock riprap revetments due to cost efficiency, flexibility of installation, self-healing during operation, and widespread acceptance within the transportation community across the nation. Table 2.1 of HEC-23 (reproduced in Appendix A) provides alternatives to traditional riprap installations, though riprap is preferred whenever possible. Gabions or gabion mattresses for revetment applications are not recommended for

Colorado due to severe weather considerations, freeze-thaw cycle destruction of wire systems, degradation of wire materials by oxidation, improper anchoring and installation, and the tendency for mass failure when one element of a gabion mattress is compromised.

In HEC-23 Hydraulic countermeasures are divided into four groups: transverse structures, longitudinal structures, areal structures, and revetments and bed armor. These groups are further broken down by application, suitable river environment, and maintenance. Other considerations include fish passage, recreational use, and resiliency considerations from a CDOT planning and programmatic level. Future revisions to this chapter will include the above structures, and will provide detail on matrix riprap installations.

Countermeasures must be designed and selected to accommodate or otherwise manage lateral migration of channels, long-term channel aggradation and degradation, scour, erosion, and other fluvial-geomorphologic conditions that must be considered for infrastructure in dynamic waterway systems. The identification of appropriate revetment is best accomplished through a combination of observation, historical data research, and quantitative analysis. Analytical and qualitative methods for assessing fluvial-geomorphologic conditions of a waterway are presented in FHWA's Hydraulic Engineering Circular No. 20 (HEC-20), "Stream Stability at Highway Structures" (2012). Scour calculation methods are presented in Hydraulic Engineering Circular No. 18 (HEC-18), "Evaluation Scour at Bridges" (2012).

17.2 REVETMENT TYPES

Revetment treatments commonly used for protecting highway infrastructure in Colorado include:

- Rock riprap;
- Matrix rock riprap (formerly called partially-grouted riprap);
- Fully-grouted rock riprap;
- Soil-filled riprap for plantings;
- Void-filled riprap using UDFCD methodology;
- Articulating concrete block (ACB);
- Concrete slope protection; and
- Biotechnical applications (vegetative plantings and hybrid revetements).

Rock riprap is the preferred material for protecting highway infrastructure features in and adjacent to CDOT facilities. Rock riprap, matrix riprap, and grouted rock are the most common applications. Examples of typical rock riprap applications are shown in Photos 17.1 and 17.2.

Photo 17.1 Rock riprap treatment along US 287 on the bank of the Cache la Poudre River in Larimer County, Colorado.

Photo 17.2 Rock riprap installed as pier-scour countermeasures at US 6 in the South Platte River near Merino, Colorado.

Other revetment applications such as ACBs and soil-cement means and methods can be implemented in accordance with HEC-23 standards, but they often require project-specific training, specifications, and unit prices that may not be consistent with design objectives or resiliency goals. Recent experiences in the 2013 Flood recovery zone in northeast Colorado (CDOT Region 4) have shown matrix riprap to be an effective and affordable alternative to large riprap, and in some cases on large project is more effective and efficient than standard riprap applications. All revetment designs require a filter system, discussed in HEC-23, Design Guideline 16. A matrix-riprap installation is shown during and after construction in Photos 17.3 and 17.4.

Photo 17.3 Construction of a matrix riprap revetment along the Big Thompson River on US 34, Larimer County, Colorado, near MP 72.

Photo 17.4 The completed matrix-riprap revetment from Photo 17.3 prior to landscaping.

Rubble, broken concrete, and other non-rock material should never be used as riprap revetment material. It was previously allowable to apply recycled materials as the primary feature in a revetment layer, but research by FHWA indicated this creates more damage than it prevents. Broken concrete may be crushed to specifications of aggregate mix for new concrete in other project applications.

Fully-grouted rock revetment consists of rock slope protection with voids filled with concrete grout forming a monolithic armor. Fully-grouted rock is a rigid revetment, it will not conform to changes in the bank geometry due to settlement. As with other monolithic revetments, fully-grouted rock is particularly susceptible to failure from undermining and the subsequent loss of the supporting bank material. Although it is rigid, fully-grouted rock is not strong. There is often underwater failure from the freeze/thaw cycle at the grout rock interface. The loss of even a small area of bank support can cause failure of large portions of the revetment. See Section 17.6.9 and Chapter 5 of HEC-23 for a detailed discussion of fully-grouted rock.

An alternative to fully-grouted rock is matrix riprap. It is used to increase the stability of riprap without sacrificing flexibility and has proven to be an efficient and effective method of protecting larger rock gradations.

In addition, soil-filled riprap can be used above ordinary high water and at emergency spillways for planting areas. Bioengineering, such as cuttings and rootwad, can be combined with riprap and void-filled riprap to provide ecological improvements and roughness.

17.3 DESIGN CRITERIA

Under certain conditions, it may be appropriate to establish the level of risk allowable for a site through risk and/or resiliency analysis, and design to a case-specific level of service or level of protection. In addition, design standards of other agencies having control or jurisdiction over the waterway or facility should be incorporated or addressed in the design. This includes permitting agencies with floodplain management standards, highway design criteria, stormwater management planning standards and community master plans. It is particularly relevant in the Denver metropolitan area where UDFCD criteria may require higher levels of service or protection. Scour standards published in HEC-18 and freeboard criteria in Chapter 10 – Bridges are also important to consider.

Design flow rates for design or analysis of infrastructure features in or near waterways have a recurrence interval range from the 10- to 500-year storm. Recommended design frequencies for various types of roads and drainage infrastructure are listed in Table 7.2 of Chapter 7 – Hydrology, but design frequencies for scour at bridges must be determined using methods found in HEC-18 and HEC-23.

In some instances, the worst-case revetment condition is incipient overtopping discharge, maximum pressure- flow discharge, or a combination of medium-flow flood events that generate worst-case scour or erosion conditions. Several discharge levels must be evaluated at bridges, culverts, roadway-overtopping sections, hydraulic structures, river training appurtenances, and adjacent waterway features to ensure the design is adequate to withstand hydraulic conditions for all discharges up to and including the design discharge.

17.4 ROCK RIPRAP DESIGN GUIDELINES

This Section presents guidelines for the design of rock-riprap revetment. The guidelines are based on Design Guideline 4 from HEC-23.

17.4.1 Riprap Size, Shape and Gradation

Rock riprap applications are standardized by a size classification known as a gradation, where the median grain size by density is specified as a d50 or D_{50}, typically in inches. The D_{50} for an individual particle is typically measured along the B-axis of an individual stone, which is identified as the median axis. Figure 17.1 shows the longest axis as the A-axis, and the narrowest as the C-axis.

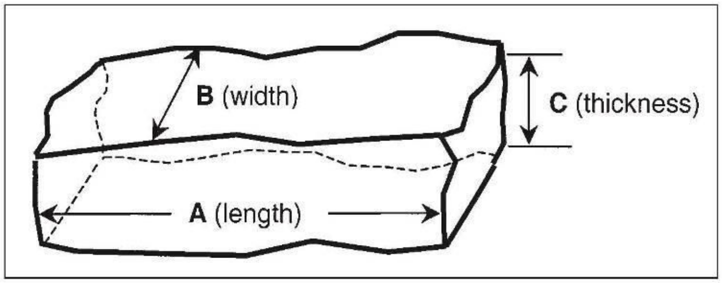


Figure 17.1 Riprap axes from HEC-23, Fig. 5.1.

It is important to note a standard riprap stone should be angular and somewhat irregular, despite the near brick shape illustrated in Figure 17.1. Riprap revetment should not be needle shaped like a curb stop, flat like broken sidewalk, or cubic where all three axes are nearly the same dimension. Angular rock riprap should follow the shape parameters of HEC-23, Chapter 5, Section 5.2.8 where an axis ratio of A/C $\leq$ 3.0 can be maintained, and a uniformity ratio is maintained as

$1.5 \leq D_{85} / D_{15} \leq 2.5$.

Round riprap is not recommended for CDOT channel revetment. It may be used as source material for habitat enhancement, or fine-graded channel features that can be disturbed by floods exceeding the bankfull or channel-forming discharges (see HEC-20). All riprap-revetment grain sizes must be measured using a Wolman pebble count at the quarry or in a field test pile before rock is accepted for construction installation. It is common for engineers and construction managers to “eyeball” riprap gradations delivered to project construction sites without confirming gradations. An example of a Wolman pebble count is provided in Photo 17.5.

It has been documented at CDOT that revetment installations tend to have an as-built D_{50} less than half of the designed and specified D_{50}. This can be prevented by inspection of delivered materials using Wolman pebble counts at construction sites during delivery and prior to placement. All Wolman counts should include 100 samples per site, be plotted on a standard gradation curve, and D_{50} calculated graphically. The standard gradation for riprap requires both

Photo 17.5. Collecting Wolman Counts of post-construction rock riprap at the Cache la Poudre River adjacent to US 287, Larimer County, Colorado, at MP 355.

smaller stones (closer to D_{10}) and larger stones (closer to D_{100}) to allow for a range of sizes within a revetment mattress. This allows partial interlocking of stones and prevents uniform voids from developing within the treatment area that could create a failure mechanism for water to escape through the revetment and attack the slope beneath.

The standard CDOT rock-riprap gradation is identified in Section 506, Table 506-2 in CDOT *Standard Specifications for Road and Bridge Construction* (2017). This table is reproduced as

Table 17.1. It is important to note the gradation specification does not exceed 24-in D_{50} materials. This is consistent with findings of investigations in CDOT Region 4 after the 2013 flood disaster, where reliable sources of D_{50} riprap gradations exceeding 24 in were not discovered in or near the state of Colorado. For applications where a D_{50} greater than 24 in is required, matrix riprap should be utilized per HEC-23 Design Guideline 12.

Table 17.1 Standard CDOT gradations for rock riprap.

Pay Item		Percent of Material Smaller Than Typical Stone[2]	Typical Stone Dimensions[3] (Inches)	Typical Stone Weight[4] (Pounds)
	Stone Size d50[1] (Inches)			
Riprap	6	70-100 50-70 35-50 2-10	12 9 6 2	85 35 10 0.4
Riprap	9	70-100 50-70 35-50 2-10	15 12 9 3	160 85 35 1.3
Riprap	12	70-100 50-70 35-50 2-10	21 18 12 4	440 275 85 3
Riprap	18	100 50-70 35-50 2-10	30 24 18 6	1280 650 275 10
Riprap	24	100 50-70 35-50 2-10	42 33 24 9	3500 1700 650 35

[1]d50 = nominal stone size
[2]based on typical rock mass
[3]equivalent spherical diameter
[4]based on a specific gravity = 2.5

Table 17.1 indicates rock riprap gradations can be specified by B-axis stone dimension (d50 or D_{50}), or by stone weight (W), where the conversion to weight is determined by Equation 17.1:

$$W = 0.85\left[\gamma_s\left(\frac{D}{12}\right)^3\right] \tag{17.1}$$

where: W = typical stone weight (lb)

γ_s = density of stone (lb/ft^3, or pcf)
D = size of stone on B-axis (in)

17.4.2 Riprap Design Calculations

Equation 17.2 was derived from HEC-23 equations in Volume 2, Design Guideline 3, and can be used for channel-revetment design calculations. Coefficients are included to account for the desired safety factor for design, specific gravity of the riprap stone, and bank slope.

$$D_{50} = 1.2y\left(S_f C_s C_V C_T\right)\left[\frac{V\,des}{\sqrt{K_1(Sg-1)(32.2)y}}\right]^{2.5} \qquad (17.2)$$

where:
D_{50} = riprap median stone size (in)
Y = depth of flow at the toe of slope (ft)
S_f = safety factor, typically 1.1, or 1.2 for steep waterways or debris (no units)
C_s = stability coefficient, 0.300 for angular rock, 0.375 for round rock (no units)
C_V = velocity distribution (see Eq. 17.3, no units)
C_T = blanket thickness coefficient, 1.0 (no units)
V_{des} = velocity 20% upslope of revetment toe (see Eqs. 17.4 and 17.5, ft/sec or fps)
V_{avg} = 1-dimensional cross section average flow velocity (ft/sec or fps)
K_1 = Side-slope correction factor (see Equation 17.6, no units)
R_C = centerline channel-bend radius of curvature (ft)
W = top width of upstream channel-bend water surface at approach (ft)
Sg = specific gravity of rock, use 2.50 for design (no units)
Θ = bank angle, never steeper than 2H:1V or 26.6° (degrees)
y = local depth of flow (ft)

For C_V, velocity distribution:

$$C_V = 1.0\ \textit{for straight channels or inside bends} \qquad (17.3)$$

$$C_V = 1.283 - 0.2\log log\left(\frac{R_C}{W}\right)\ \textit{on outside bends};\ \frac{R_C}{W>26}$$

$$C_V = 1.25\ \textit{downstream from concrete channels}$$

For V_{des} in natural channels:

$$V_{des} = V_{avg}\left(1.74 - 0.52\log log\left(\frac{R_C}{W}\right)\right) \qquad (17.4)$$

$$V_{des} = V_{avg}\ \textit{for}\ \frac{R_C}{W} > 26$$

For V_{des} in trapezoidal channels:

$$V_{des} = V_{avg}\left(1.71 - 0.78\log log\left(\frac{R_C}{W}\right)\right) \qquad (17.5)$$

$$V_{des} = V_{avg}\ \textit{for}\ \frac{R_C}{W} > 8$$

For K_1, side-slope correction factor:

$$K_1 = \sqrt{1 - \left(\frac{\sin(\theta - 14°)}{\sin 32°}\right)^{1.6}} \qquad (17.6)$$

Note the data required to solve Equations 17.2 through 17.6 must be derived from open-channel designs conforming to standards found in Chapter 8 - Channels, Section 8.4.

17.4.3 Design Thickness, Toe Depth and Longitudinal Extents

All stones should be contained within the riprap-layer thickness, with few or no oversized stones protruding above the surface of the riprap matrix. The following criteria are recommended based on typical CDOT practices and HEC-23 guidance, in order of preference:

1. Layer thickness should be twice D_{50} whenever possible.
2. Layer thickness should not be less than the spherical diameter of the D_{100} stone, or less than 1.5(D_{50}) stone at any point, whichever results in the greater thickness.
3. For practical placement layer thickness should never be less than 1.0 ft.
4. Layer thickness determined by the above criteria should be increased by 50% when the riprap is placed underwater to compensate for uncertainties associated with this placement condition.

Toe depth, or toe-down, is a critical design consideration to prevent hydraulic undermining of revetment-toe protection. This is one of the primary mechanisms of revetment failure that can be mitigated with detailed hydraulic analysis. In design of bank protection, estimates of depth of scour are needed to place the protective layer sufficiently low in the streambed to prevent undermining. Scour depths can include pier scour, abutment scour, contraction scour, bendway scour, vertical wall scour, and other HEC-18 scour types identified by laboratory and field research. The total depth of scour must be added to long-term channel degradation calculations and lateral migration projections to determine the total proper depth of treatment to prevent the undermining of engineered revetments.

The longitudinal extent of a design revetment is highly dependent on local site conditions. In general, the revetment should be continuous for a distance greater than the length affected by channel-flow forces that are severe enough to cause dislodging and/or transport of bank material. If the longitudinal extents are calculated too short, the entire treatment area could be flanked at the leading (upstream) or trailing (downstream) edge of treatment. This could lead to mass failure of large sections of protected waterways. Flanking of revetments is one of the most common failure mechanisms. It is better to be overly conservative with design and installation of a long bank protection structure than to come back and repair later. This failure mechanism was observed in CDOT Region 4 along the Cache la Poudre River at US 287 near LaPorte, Colorado, in flood events of 1999 and 2013, and can be prevented by conservative design of horizontal riprap extents supported by hydraulic analysis.

17.4.4 Vertical Freeboard

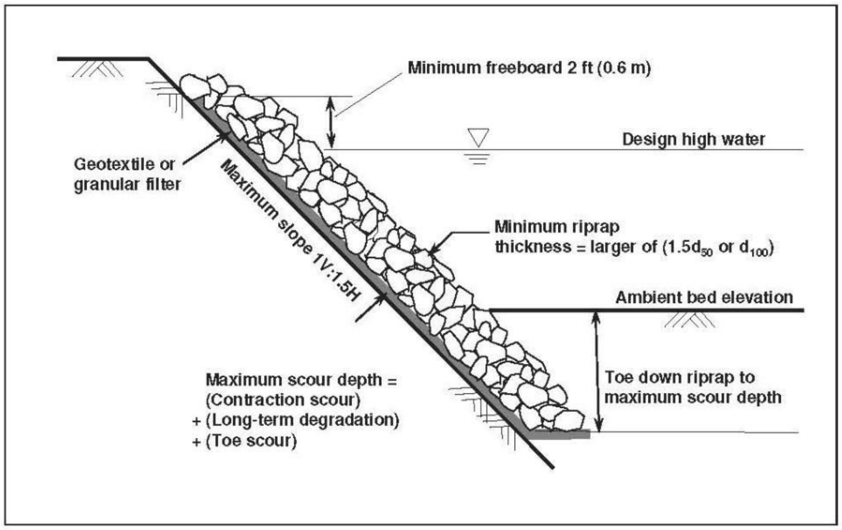
The minimum freeboard height of designed riprap is typically 2.0 ft on natural waterways. Treatments should be terminated at least 2.0 ft above the highest design water-surface elevation from detailed hydraulic analysis calculations and models. If computational procedures or resiliency measures indicate additional freeboard benefits a protected infrastructure system, the greater freeboard height should be used. For additional information on freeboard as well as computation procedures for freeboard at bridges, see Chapter 10 - Bridges.

17.4.5 Edge and End Treatments

Edge and end treatments are resiliency measures ensuring channel revetments with rock riprap perform as designed. HEC-23 applications in Design Guideline 4, Figure 4.2, are provided in

Figure 17.3 to illustrate proper termination of revetment toes, otherwise known as edge treatments.

End treatments are leading edge (upstream keys) and trailing edge (downstream keys) features that prevent flanking of revetments which cause mass failure by allowing flood flows to wrap behind rock riprap and destroy it from beneath the treatment. Proper upstream and downstream keys are described in HEC-23, Design Guideline 4, Figure 4.4, and included below in Figure 17.4.



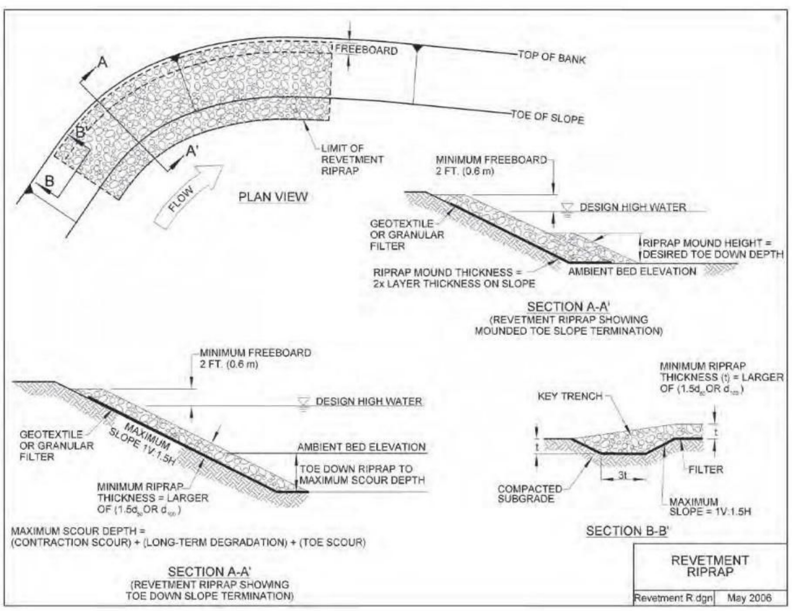


Figure 17.2 Edge treatments for proper toe-down of riprap revetment, from HEC-23.

Figure 17.3 End treatments for proper key-in of riprap revetment at upstream (Section A-A) and downstream (Section B-B) terminations, from

HEC-11. Note the design thickness of the riprap layer is denoted as T.

17.4.6 Riprap Placement

The common methods of riprap placement are hand placing and machine placing, such as from a skip, dragline, or some form of bucket. Dumping from trucks and spreading with a bulldozer is not an acceptable placement method. In the machine-placement method, sufficiently small increments of stone should be released no more than 3.0 ft above geotextile filter or granular bedding materials. Rehandling or dragging operations to smooth the revetment surface tend to result in segregation and breakage of stone and compromise filter layers beneath, which leads to failure below the rock matrix and compromises the design LOS.

17.4.7 Ice Damage

Ice can affect riprap linings in a number of ways. Moving surface ice can cause crushing and bending forces, and large-impact loadings. The tangential flow of ice along a riprap-lined channel bank can also cause excessive shearing forces. High-elevation applications of rock riprap have shown that freeze-thaw cycles can compromise the median grain size of a revetment application to fractions of original design sizes. This is especially true for riprap containing high volumes of sandstone or low-density minerals with low specific gravity. Design of high-elevation installations should consider riprap use of higher density and durability characteristics than sandstone materials.

17.5 RIPRAP FILTER DESIGN GUIDELINES

A filter is a transitional layer of gravel, small stone, or fabric placed between the underlying soil and the structure. The filter prevents migration of fine soil particles through voids in the structure. This distributes the weight of armor units and provides more uniform settlement that permits relief of hydrostatic pressures within the soils. A filter should be used whenever riprap is placed on non-cohesive material which is subject to significant subsurface drainage (e.g., in areas where water surface levels fluctuate frequently, and in areas of high groundwater levels). The filter should not contain organic material unless a void-filled riprap installation is prepared in accordance with UDFCD standards. Additional guidance on the selection, design, and specifications for filter material can be found in HEC-23, Design Guideline 16.

17.5.1 Granular Filter Designs

For rock riprap, a filter ratio ≤ 5 between layers will usually result in a stable condition. The filter ratio is defined as the ratio of the 15% particle size (D_{15}) of the coarser layer to the 85% particle size (D_{85}) of the finer layer. An additional requirement for stability is that the ratio of the 15% particle size of the coarser material to the 15% particle size of the finer material should exceed 5 but be less than 40. These requirements can be stated as:

$$\frac{D_{15}\ (coarser\ layer)}{D_{85}\ (finer\ layer)} < 5 < \frac{D_{15}\ (coarser\ layer)}{D_{15}\ (finer\ layer)} < 40$$

The first test of the inequality is intended to prevent piping through the filter. The second test provides adequate permeability for structural bedding layers. The right portion provides a uniformity criterion.

If a single layer of filter material does not satisfy filter requirements, one or more additional layers of filter material must be used. The filter requirement applies between bank material and the filter blanket, between successive layers of filter material if more than one layer is used, and between the filter blanket and riprap cover. In addition to filter requirements, grain-size curves for the various layers should be approximately parallel to minimize infiltration of fine material from the finer layer to the coarser layer. Not more than 5% of the filter material should pass the No. 200 sieve. Figure 17.4 can be used to aid in designing an appropriate granular filter.

The thickness of the filter blanket should range from 6 to 18 in for a single layer, or from 4 to 8 in for individual layers of a multiple-layer blanket. Where gradation curves of adjacent layers are approximately parallel, the thickness of blanket layers should approach a minimum. The thickness of individual layers should be increased above the minimum proportionately as the gradation curve of material comprising the layer departs from a parallel pattern.

17.5.2 Geotextile Filter Designs

Synthetic geotextile filters are frequently used as an alternative to granular filters. Since the first erosion-control application of geotextile in 1957, it has been used successfully on thousands of projects. Advantages of using geotextile filters include:

- Installation is generally quick and labor-efficient;
- Geotextile filters are more economical than granular filters;
- Geotextile filters have a more consistent and reliable material quality; and
- Geotextile filters have higher inherent tensile strength.

Disadvantages include:

- Geotextiles can be difficult to install underwater;
- Geotextiles have widely variable hydraulic properties and must be designed based on project-specific conditions and performance requirements;
- Geotextile filter performance is sensitive to construction procedures;
- Special installation and inspection procedures may be necessary when using geotextile filters; and
- Geotextile can tear during placement and, depending on the material, may not last over time.

The design of geotextile filters closely follows traditional graded granular-filter design principles and should consider:

- Soil retention (piping resistance);
- Permeability;
- Clogging; and
- Survivability.

It is very important that individual site conditions and performance requirements be established in conjunction with the geotextile design. Generalized geotextile requirements should be used only on very small or non-critical / non-severe installations where a detailed analysis is not warranted. AASHTO has developed materials and construction specifications (AASHTO Specification M-288) for routine, non-critical / non-severe geotextile applications. Details of geotextile-filter design for all levels of project severity and criticality are presented in FHWA's *Geosynthetic*

Design and Construction Guidelines. Detailed guidance on specifying and installing geotextiles for a variety of transportation applications is provided. The American Society for Testing Material, Committee D-35, has developed standard testing procedures for approximately 35 general, index, and performance properties of geosynthetics. These procedures are recommended for use in design and specifications when using geosynthetics.

17.5.3 Geotextile Installation Procedures

To provide good performance, a properly-selected geotextile should be installed considering the following:

- The area should be graded and debris removed to provide a smooth, fairly-even surface;
- Geotextile should be placed loosely, laid with the machine (generally roll) direction, in the same direction as anticipated water flow or movement; and
- The geotextile should be seamed, or a minimum overlap of 12 in should be used.

The maximum-allowable slope on which a riprap-geotextile system can be placed is equal to the lowest soil-geotextile friction angle for the natural ground, or stone-geotextile friction angle for cover (armor) materials. Additional reductions in slope may be necessary due to hydraulic considerations and possible long-term stability. For slopes greater than 1V:2.5H, special construction procedures are required.

For streambank and wave-action applications, geotextile must be keyed in at the bottom of the slope. If the system cannot be extended a few feet above the anticipated high-water level, the geotextile also should be keyed in at the crest of the slope.

The revetment (cushion layer and/or riprap) should be placed over the width of the geotextile in a manner that avoids puncturing it.

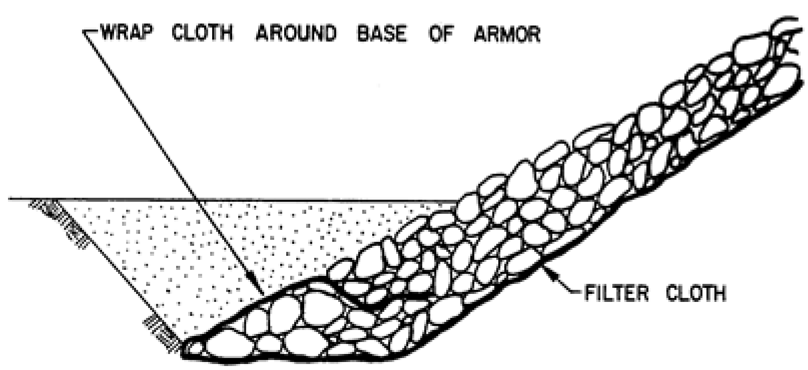


Figure 17.4 Geotextile Filters

17.6 Software for Designing Bank Protection

Current software for designing bank protection is listed in Table 17.2. The software listed is public domain software, or software CDOT has purchased. For the most-current versions of software and software documentation, the hydraulic engineer should consult the software source.

Table 17.2. Software for riprap revetment design assistance.

Software Name	Features	Source
SMS v12.3	The Surface Water Modeling System (SMS) is a comprehensive environment for one- and two-dimensional hydrodynamic modeling. A pre- and post-processor for surface-water modeling and design, SMS includes two-dimensional finite element and finite difference analyses, and finite volume analysis with the addition of SRH-2D. The analysis package SRH-2D includes options for modeling bridges, culverts and highways in three-dimensions with two-dimensional output, and has a calculator function that allows HEC-23 equations to be programed directly into a post-processed solution.	Aquaveo website at www.aquaveo.com
FHWA Hydraulic Toolbox 4.4	The FHWA Hydraulic Toolbox software is a stand-alone suite of calculators that perform routine hydrologic and hydraulic computations (see the software section of Chapter 8 - Channels). The channel-lining-design calculator uses HEC-15 tractive-force methods for determining rock size for rock lining, and for assessing gabions. The riprap-design calculator includes the HEC-23 riprap-sizing equations for channel revetment, bridge piers, bridge abutments or guide banks, channel spur, embankment overtopping, open-bottom culvert, and wave attack. The calculator also includes culvert-outlet riprap-sizing equations from HEC-14, and filter design.	FHWA

Riprap can be designed using the FHWA Hydraulic Toolbox or the USACE CHANLPRO software. Bank protection for uniform channels can be designed using the FHWA Hydraulic Toolbox, channel analysis, or WMS, channel calculator (see the Software section of Chapter 8 - Channels).

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APPENDIX A ·eam instability and bridge scour countermeasures matrix

Count							Cou		
							SUITA		
							River Type	Stream Size	Bend Radius
						s	B = braided M = meandering S = straight	W = wide M = moderate S = small	L = long M = moderate S = short
GROUP 1. HYDRAULIC COUNT									
GROUP 1.A. RIVER TRAINING S									
TRANSVERSE STRUCTURES									
Impermeable spurs (jetties, groins, wing dams)	◗	◗	○	○	●	○	B, M	W, M	L, M
Permeable spurs (fences, netting)	◗	◗	○	○	●	○	B, M	W, M	L, M
Transverse dikes	○	○	○	○	●	○	B, M	W, M	✓
Bendway weirs/Stream barbs[1]	◗	◗	○	○	●	○	M	✓	M, S
Hardpoints	○	○	○	○	●	○	✓	✓	✓
Drop structures (check dams, grade control)	◗	◗	◗	●	○	○	✓	✓	✓
Embankment Spurs	◗	○	◗	○	○	○	✓	✓	✓
LONGITUDINAL STRUCTURES									
Longitudinal dikes (crib/rock toe/embankments)	◗	○	○	○	●	◗	✓	✓	L, M
Retards	◗	○	○	○	●	○	✓	✓	L, M
Bulkheads	●	○	○	○	●	○	✓	✓	✓
Guide banks	●	◗	◗	○	◗	◗	✓	W, M	✓
AREAL STRUCTURES/TREATMENTS									
Jacks/tetrahedron jetty fields	○	○	○	○	●	○	B, M	W, M	L
Vanes	○	◗	○	○	●	○	B, M	W, M	L, M
Channelization	◗	◗	○	○	●	○	B, M	✓	✓
Flow relief (overflow, relief bridge)	◗	◗	●	○	○	●	✓	✓	✓
Sediment detention basin	○	○	○	●	○	○	✓	✓	✓
GROUP 1.B. ARMORING COUNTE									
REVETMENTS AND BED ARMOR									
Rigid									
Soil cement	●	●	◗	◗	●	●	✓	✓	✓
Roller compacted concrete	●	◗	●	●	●	●	✓	✓	✓
Concrete pavement	◗	○	●	◗	●	◗	✓	✓	✓
Rigid grout filled mattress/concrete fabric mat	◗	○	◗	◗	●	◗	✓	✓	✓
Fully grouted riprap	○	○	○	○	◗	○	✓	✓	✓
Flexible/articulating									
Riprap	●	●	◗	◗	●	◗	✓	✓	✓
Self launching riprap (windrow)	○	○	○	○	◗	○	✓	✓	✓
Riprap fill-trench	◗	○	○	○	●	○	✓	✓	✓
Gabions/gabion mattress[2]	●	●	◗	◗	●	◗	✓	✓	✓
Wire enclosed riprap mattress (rail bank/sausage)	●	○	○	○	●	○	✓	✓	✓
Articulated blocks (interlocking and/or cable tied)	●	●	●	◗	●	●	✓	✓	✓
Concrete/grout mattress (fabric-formed)	●	◗	●	◗	●	◗	✓	✓	✓
Partially grouted riprap	●	●	◗	◗	●	○	✓	✓	✓
LOCAL SCOUR ARMORING									
Riprap (fill/apron)	●	●	N/A	N/A	N/A	N/A	✓	✓	✓
Fully grouted riprap	◗	○	N/A	N/A	N/A	N/A	✓	✓	✓
Concrete armor units (Toskanes, tetrapods, etc.)[3]	◗	◗	N/A	N/A	N/A	N/A	✓	✓	✓
Grout filled bags/sand cement bags	●	◗	N/A	N/A	N/A	N/A	✓	✓	✓
Gabions/gabion mattress[2]	●	●	N/A	N/A	N/A	N/A	✓	✓	✓
Articulated blocks (interlocking and/or cable tied)	●	●	N/A	N/A	N/A	N/A	✓	✓	✓
Sheet pile/cofferdam	◗	◗	N/A	N/A	N/A	N/A	✓	✓	✓
Partially grouted riprap	●	●	N/A	N/A	N/A	N/A	✓	✓	✓

● well suited/primary use

◗ possible application/secondary use

○ unsuitable/rarely used

N/A not applicable

✓ s

Table 17.3 Stream instability and bridge scour countermeasures matrix (continued)

	Abutments	Piers[4]	Channel	Vertical	Lateral	Embankments	River Type B = braided M = meandering S = straight	Stream Size W = wide M = moderate S = small
GROUP 2. STRUCTURA								
FOUNDATION STRENGTHENING								
Crutch bents/Underpinning	○	●	●	●	◗	N/A	✓	✓
Cross bracing	○	●	●	●	○	N/A	✓	✓
Continuous spans	○	●	●	●	○	N/A	✓	✓
Pumped concrete/grout under footing	●	●	◗	◗	◗	N/A	✓	✓
Lower foundation	●	●	●	●	●	N/A	✓	✓
PIER GEOMETRY MODIFICATION								
Extended footings	N/A	●	N/A	N/A	N/A	N/A	✓	✓
Pier shape modifications	N/A	●	N/A	N/A	N/A	N/A	✓	✓
Debris deflectors	N/A	●	N/A	N/A	N/A	N/A	✓	✓
Sacrificial piles/dolphins	N/A	●	N/A	N/A	N/A	N/A	✓	✓
GROUP 3. BIOTECHNICA								
Vegetated geosynthetic products	○	○	○	○	●	◗	M, S	M, S
Fascines/woody mats	○	○	○	○	●	○	✓	M, S
Vegetated riprap	○	○	○	○	●	◗	✓	✓
Root wads	○	○	○	○	●	○	✓	M, S
Live staking	○	○	○	○	●	○	✓	M, S
GROUP 4. M								
FIXED INSTRUMENTATION								
Sonar scour monitor	◗	●	●	●	◗	○	✓	✓
Magnetic sliding collar	●	●	●	●	◗	○	✓	✓
Float out device	●	●	●	●	●	●	✓	✓
Sounding rods	◗	●	●	●	◗	○	✓	✓
PORTABLE INSTRUMENTATION								
Physical probes	●	●	●	●	●	○	✓	✓
Sonar probes	●	●	●	●	●	○	✓	✓
VISUAL MONITORING								
Periodic Inspection	●	●	●	●	●	●	✓	✓
Flood watch	●	●	●	●	●	●	✓	✓

● well suited/primary use
◗ possible application/secondary use
○ unsuitable/rarely used
N/A not applicable

NOTES:

1. There is limited but successful field experie
2. Performance of welded vs. twisted wire, an
3. There is limited but successful field experie
4. Piers at new bridges cannot rely on counter
5. Biotechnical countermeasures are only inte fully grown, with well-established root syste material, as discussed in Chapter 6 of this d