7.9 Design Guidelines – Rock Riprap

7.9.1 Rock Riprap

This section contains design guidelines for the design of rock riprap. Guidelines are provided for bank slope, rock size, rock gradation, riprap layer thickness, filter design, edge treatment and construction considerations. In addition, typical construction details are illustrated. In most cases, the guidelines presented apply equally to rock and rubble riprap. Guidelines for other types are presented in HEC-11.

7.9.2 Bank Slope

A primary consideration in the design of stable riprap bank protection schemes is the slope of the channel bank. For riprap installations, normally the maximum recommended face slope is 1V:2H.

7.9.3 Rock Size

The stability of a particular riprap particle is a function of its size, expressed either in terms of its weight or equivalent diameter. In the following sections, relationships are presented for evaluating the riprap size required to resist particle and wave erosion forces.

7.9.4 Particle Erosion

Two methods or approaches have been used historically to evaluate a material's resistance to particle erosion. These methods are the permissible velocity approach and the permissible tractive force (shear stress) approach. Under the permissible velocity approach the channel is assumed stable if the computed mean velocity is lower than the maximum permissible velocity. The tractive force (boundary shear stress) approach focuses on stresses developed at the interface between flowing water and materials forming the channel boundary.

7.9.5 Design Relationship

A riprap design relationship that is based on tractive force theory yet has velocity as its primary design parameter is presented in Equation 7.36. The design relationship in Equation 7.36 is based on the assumption of uniform, gradually varying flow. Figure 7-25.1 presents a graphical solution to Equation 7.36. Equation 7.37 can be solved using Figures 7-26 and 7-27.

$$\mathbf{D_{50} = 0.005\,94\ V_a^{3} / (d_{avg}^{0.5}\ K_1^{1.5})} \qquad \mathbf{(\ D_{50} = 0.001\ V_a^{3} / (d_{avg}^{0.5}\ K_1^{1.5})\ )} \qquad \mathbf{(7.36)}$$

Where: D_{50} = the median riprap particle size, m (ft)
C = correction factor (described below)
V_a = the average velocity in the main channel, m/s (ft/s)
d_{avg} = the average flow depth in the main flow channel, m (ft)

K_1 is defined as:

$$\mathbf{K_1 = [1-(\sin^2\theta/\sin^2\Phi)]^{0.5}} \qquad \mathbf{(7.37)}$$

Where: $\boldsymbol{\theta}$ = the bank angle with the horizontal
$\boldsymbol{\Phi}$ = the riprap material's angle of repose

The average flow depth and velocity used in Equation 7.36 are main channel values. The main channel is defined as the area between the channel banks (see Figure 7-24 below).

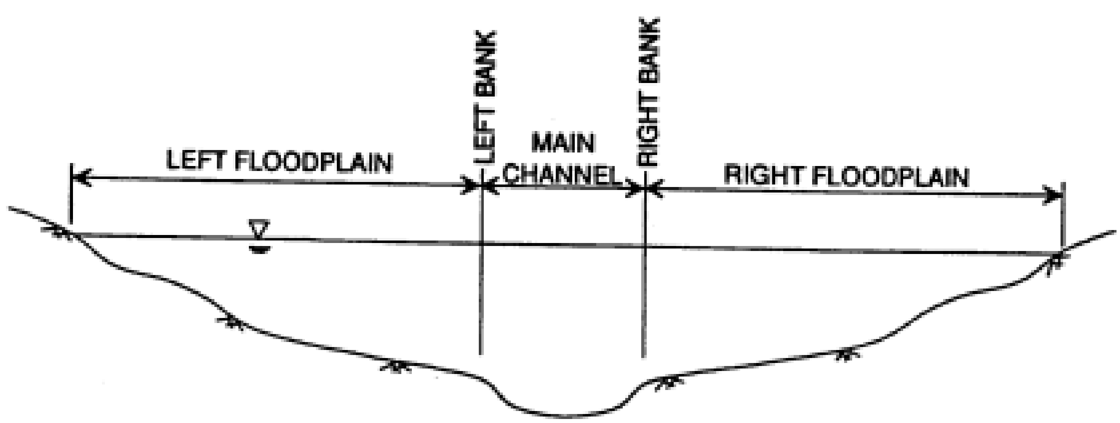


Figure 7-24 Definition Sketch; Channel Flow Distribution

Equation 7.36 is based on a rock riprap specific gravity of 2.65, and a stability factor of 1.2. Equations 7.38 and 7.39 present correction factors for other specific gravities and stability factors.

$$\mathbf{C_{sg} = 2.12/(S_s - 1)^{1.5}} \qquad \textbf{(7.38)}$$

Where: S_s = the specific gravity of the rock riprap

$$\mathbf{C_{sf} = (SF/1.2)^{1.5}} \qquad \textbf{(7.39)}$$

Where: SF = the stability factor to be applied.

The correction factors computed using Equations 7.38 and 7.39 are multiplied together to form a single correction factor C. This correction factor, C, is then multiplied by the riprap size computed from Equation 7.35 to arrive at a stable riprap size. Figure 7-28 provides a solution to Equations 7.39 and 7.38 using correction factor C.

The stability factor, SF, used in Equations 7.38 and 7.39 requires additional explanation. The stability factor is defined as the ratio of the average tractive force exerted by the flow field and the riprap material's critical shear stress. As long as the stability factor is greater than 1, the critical shear stress of the material is greater than the flow induced tractive stress, the riprap is considered to be stable. As mentioned above, a stability factor of 1.2 was used in the development of Equation 7.36.

The stability factor is used to reflect the level of uncertainty in the hydraulic conditions at a particular site. Equation 7.36 is based on the assumption of uniform or gradually varying flow. In many instances, this assumption is violated or other uncertainties come to bear. For example, debris and/or ice impacts, or the cumulative effect of high shear stresses and forces from wind and/or boat generated waves. The stability factor is used to increase the design rock size when these conditions must be considered. Table 7-7 presents guidelines for the selection of an appropriate value for the stability factor.

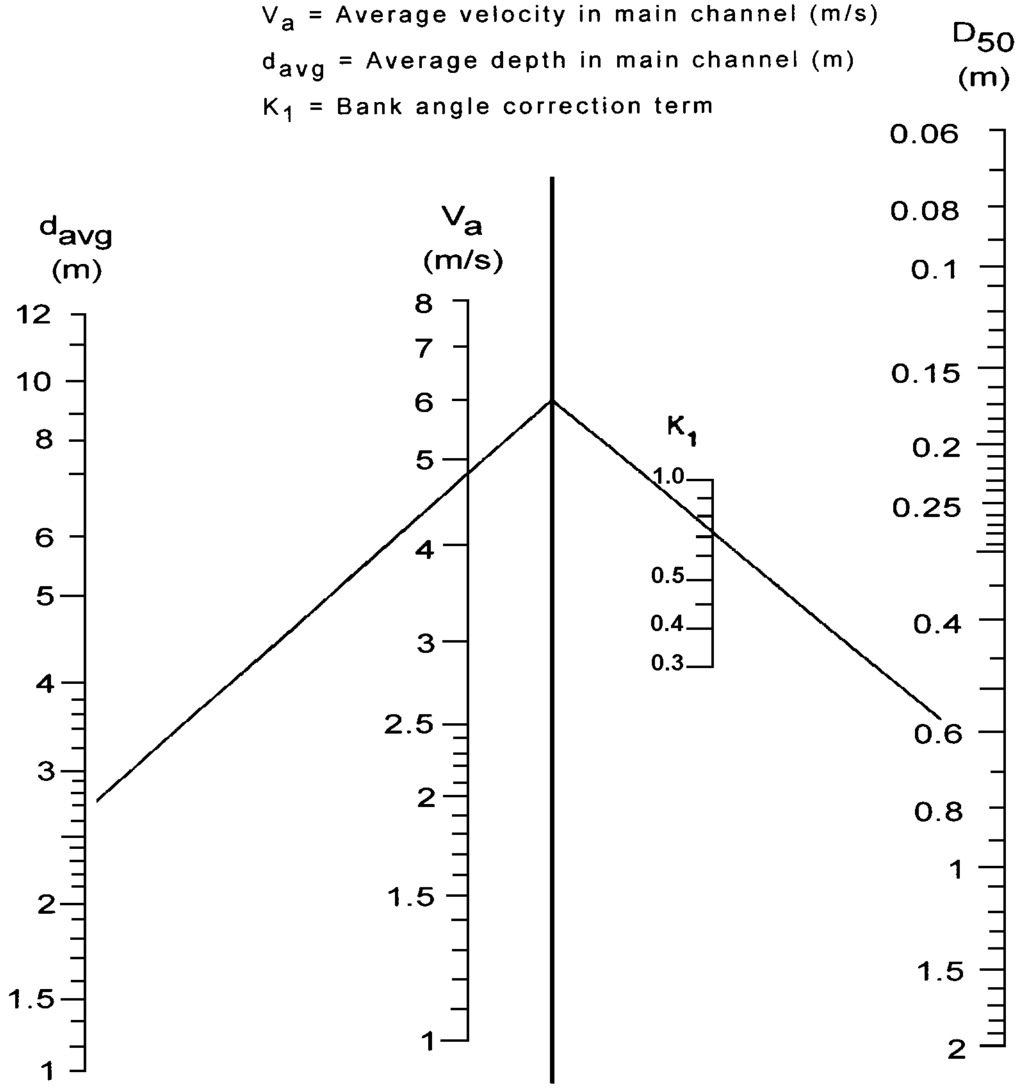
$$D_{50} = 0.005\,94\, V_a^3 / (d_{avg}^{1/2} K_1^{3/2})$$

D_{50} = Median Riprap Size (m)

V_a = Average velocity in main channel (m/s)

d_{avg} = Average depth in main channel (m)

K_1 = Bank angle correction term



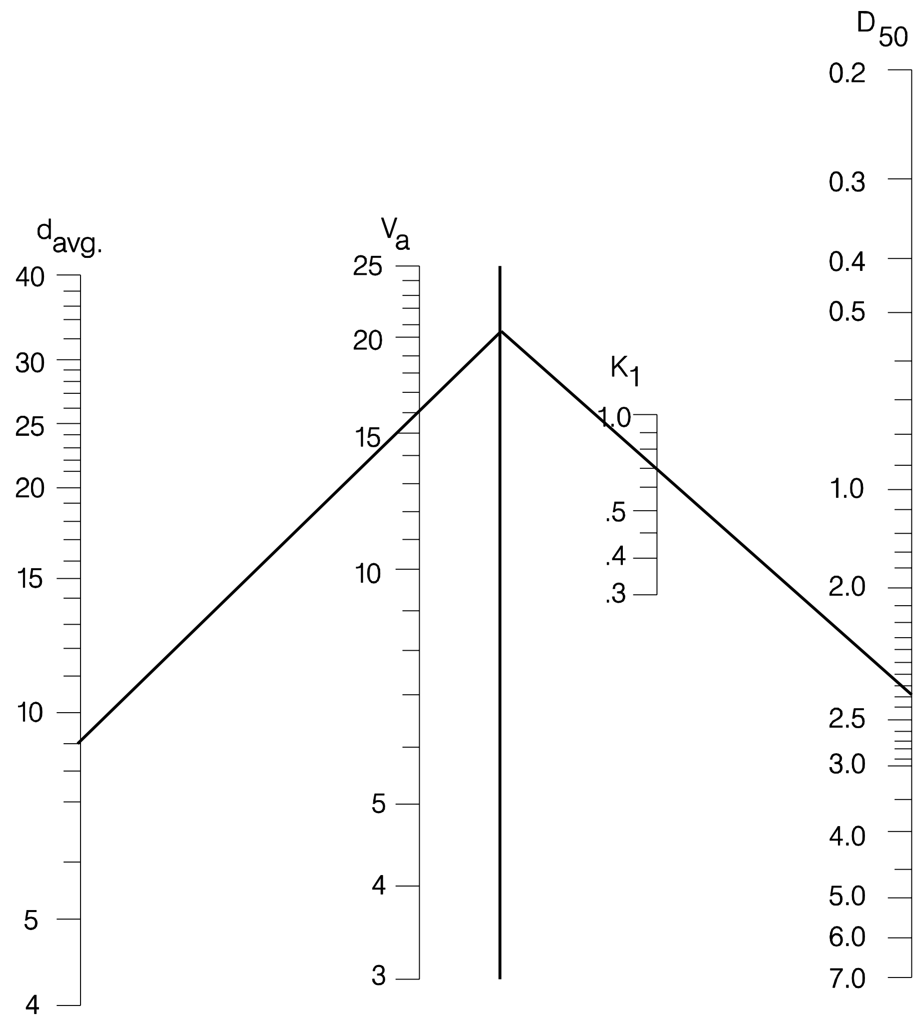
Example

Given:	Find:	Solution:
V_a=4.9 m/s	D_{50}	D_{50}=0.69 m
d_{avg}=2.75 m		
K_1=0.72		

Figure 7-25 Riprap Size Relationship (metric units)

$$D_{50} = 0.001\, V_a^3 / (d_{avg.}^{1/2} K_1^{3/2})$$

D_{50} = Median Riprap Size (ft.)
V_a = Average velocity in main channel (ft/sec)
$d_{avg.}$ = Average depth in main channel (ft.)
K_1 = Bank angle correction term



Example:

Given:

V_a = 16 ft/sec.
$d_{avg.}$ = 9 ft.
k_1 = 0.72

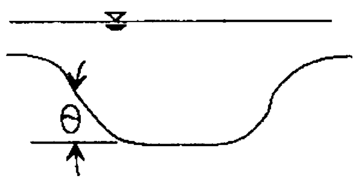
Find:

D_{50}

Solution:

D_{50} = 2.25

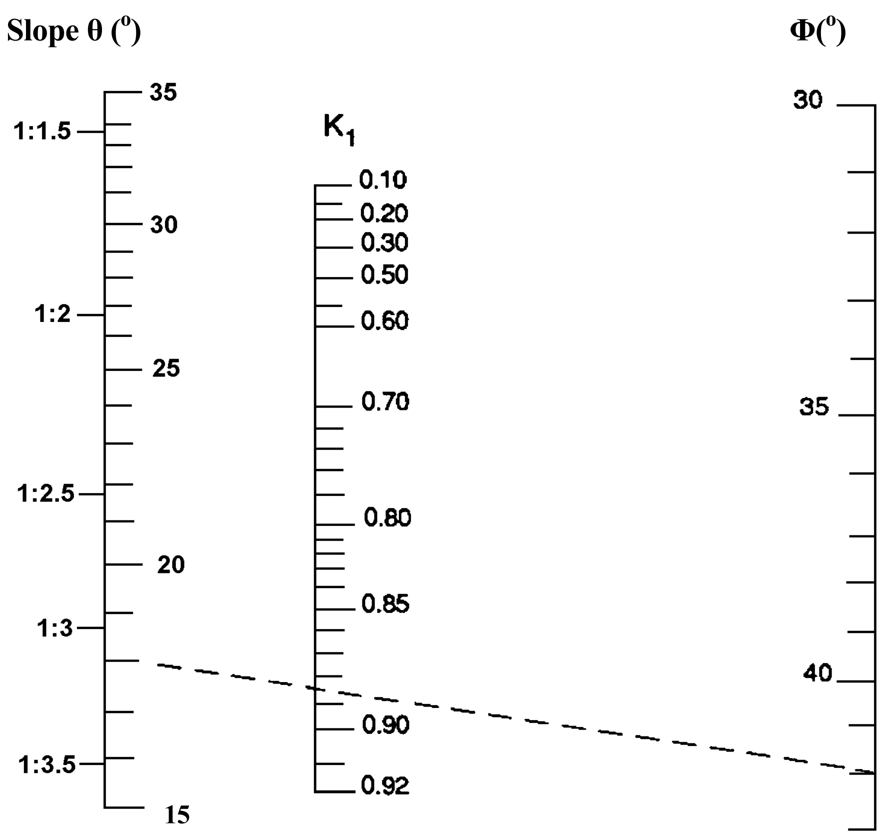
Figure 7-25.1 Riprap Size Relationship (English units)



$$K_1 = \left[1 - \frac{\sin^2\theta}{\sin^2\Phi}\right]^{0.5}$$

θ = Bank angle with horizontal

θ =Bank angle with horizontal
Φ = Material angle of repose
See Figure 7-27 or 7-27.1



Example

Given:	**Find:**	**Solution:**
$\theta = 18^o$	**K_1**	**$\Phi = 42^o$**
Very angular		**$K_1 = 0.885$**
D_{50} = 457 mm (1.5 ft)		

Figure 7-26 Bank Angle Correction Factor (K_1) Nomograph

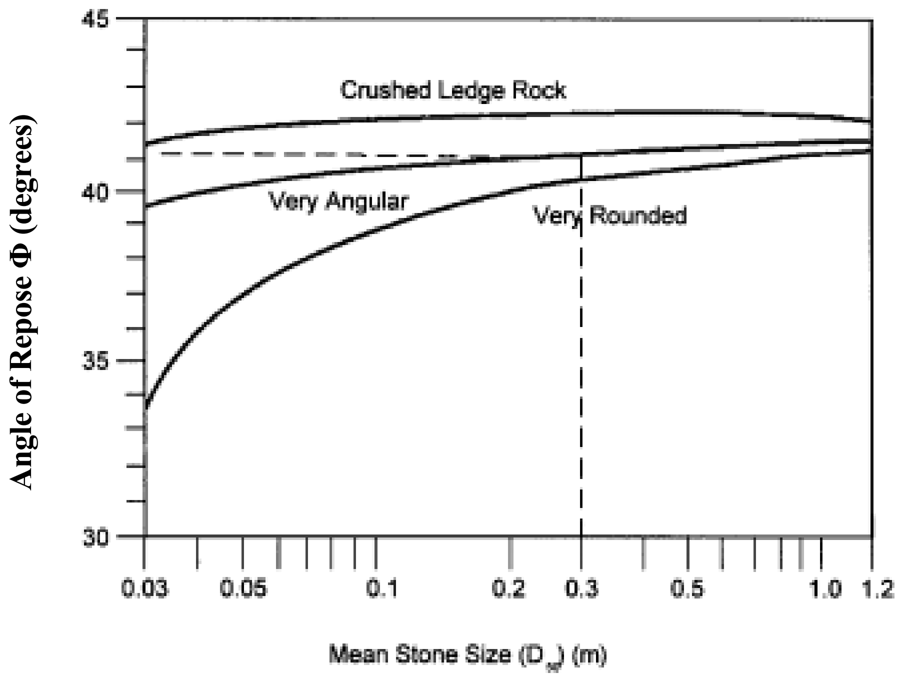


Figure 7-27 Angle Of Repose Of Riprap In Terms Of Mean Size And Shape Of Stone (metric units)

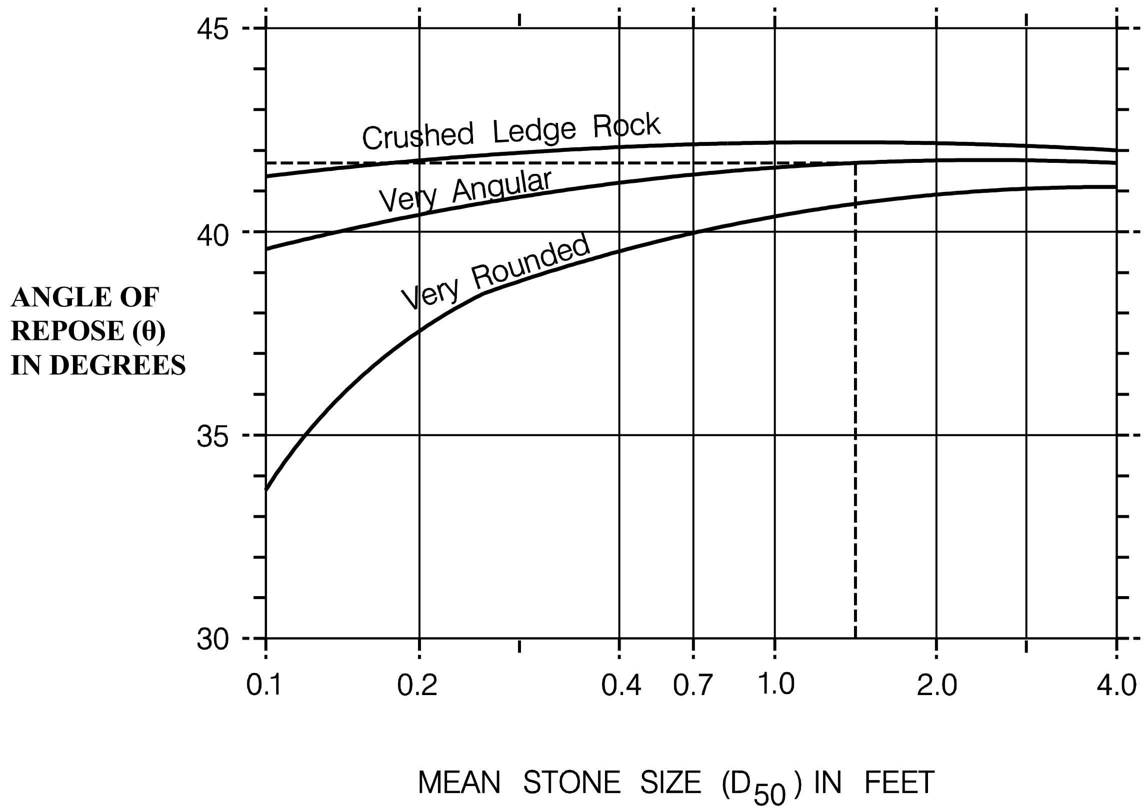
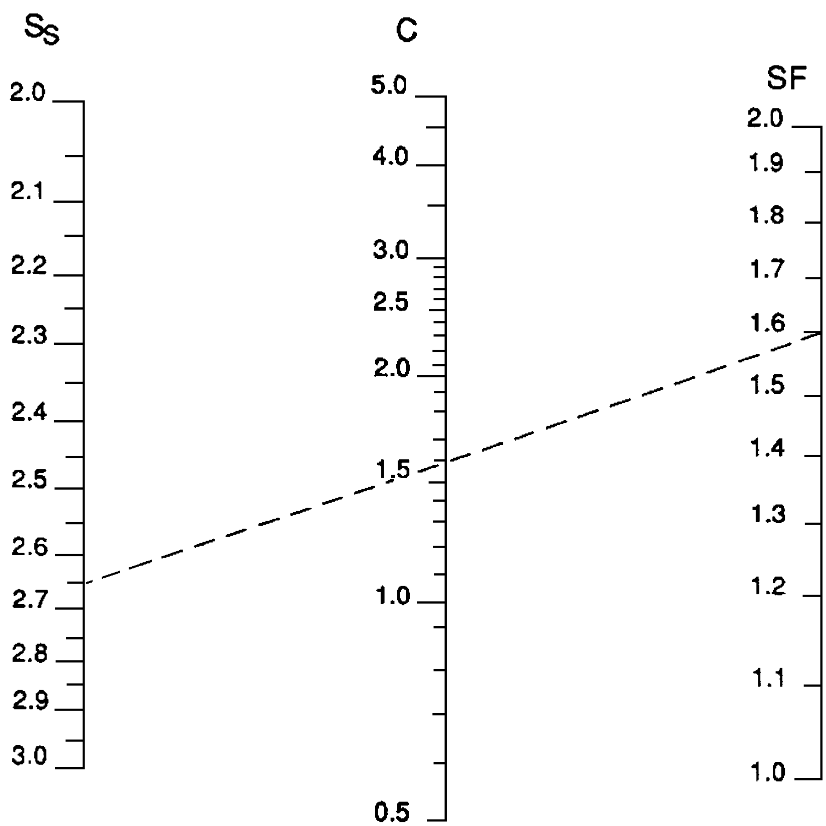


Figure 7-27.1 Angle Of Repose Of Riprap in Terms Of Mean Size and Shape Of Stone (English units)

$$C=1.61SF^{1.5}/(S_S-1)^{1.5}$$

CORR=D_{50}CORRECTION FACTOR
SF = STABILITY FACTOR
S_S= SPECIFIC GRAVITY OF ROCK



Example:

Given:	Find:	Solution:
S_S=2.65	C	C=1.59
SF= 1.60		

Figure 7-28 Correction Factor For Riprap Size (metric or English)

Table 7-8 Guidelines For The Selection Of Stability Factors

Condition	Stability Factor Range
Uniform flow; Straight or mildly curving reach (curve radius/channel width > 30); Impact from wave action and floating debris is minimal; Little or no uncertainty in design parameters.	**1.0 - 1.2**
Gradually varying flow; Moderate bend curvature (30 >curve radius/channel width > 10); Impact from waves or floating debris moderate.	1.21 - 1.6
Approaching rapidly varying flow; Sharp bend curvature (10 > curve radius/channel width); Significant impact potential from floating debris and/or ice; Significant wind and/or boat generated waves (0.3 - 0.6 m (1-2 ft)); High flow turbulence; Turbulently mixing flow at bridge abutments; Significant uncertainty in design parameters.	1.61 - 2.0

7.9.6 Application

Application of the relationship in Equation 7.36 is limited to uniform or gradually varying flow conditions that are in straight or mildly curving channel reaches of relatively uniform cross section. However, design needs dictate that the relationship also be applicable in nonuniform, rapidly varying flow conditions often exhibited in natural channels with sharp bends and steep slopes, and in the vicinity of bridge piers and abutments.

To fill the need for a design relationship that can be applied at sharp bends and on steep slopes in natural channels, and at bridge abutments, it is recommended that Equation 7.36 be used with appropriate adjustments in velocity and/or stability factor as outlined in the following sections.

Wave Erosion

Waves generated by wind or boat traffic have also been observed to cause bank erosion on inland waterways. The most widely used measure of riprap's resistance to wave is that developed by R. Y. Hudson "Laboratory Investigations of Rubble-Mound Breakwaters," 1959. The so-called Hudson relationship is given by the following equation:

$$W_{50} = (\gamma_s H^3) / (2.20 [S_s - 1]^3 \cot \theta) \qquad \textbf{(7.40)}$$

Where: W_{50} = weight of the median particle, kg (lb)
γ_s = unit weight of riprap (solid) material, kg/m^3 (lb/ft^3)
H = the wave height, m (ft)
S_s = specific gravity of riprap material
θ = bank angle with the horizontal

Assuming:

$S_s = 2.65$ and $\gamma_s = 2643$ kg/m^3 (165 lb/ft^3), Equation 7.40 can be reduced to:

$$W_{50} = 267.4\, H^3/\cot \theta \qquad \mathbf{(}\, W_{50} = 16.7\, H^3/\cot \theta\, \mathbf{)} \qquad \textbf{(7.41)}$$

In terms of an equivalent diameter Equation 7.41 can be reduced to:

$$D_{50} = 0.57H/\cot^{1/3} \theta \qquad \mathbf{(}D_{50} = 0.75H/\cot^{1/3} \theta\, \mathbf{)} \qquad \textbf{(7.42)}$$

Where: D_{50} = median riprap size, m

Methods for estimating a design wave height are presented in Appendix A of this chapter. Equation 7.42 is presented in nomograph form in Figure 7-29. Equations 7.41 and 7.42 can be used for preliminary or final design when H is less than 1.5 m (5 ft), and there is no major overtopping of the embankment.

7.9.7 Steep Slopes

Flow conditions in steep sloped channels are rarely uniform, and are characterized by high flow velocities and significant flow turbulence. In applying Equation 7.36 to steep slope channels, care must be exercised in the determination of an appropriate velocity. When determining the flow velocity in steep sloped channels, it is recommended that Equation 7.43 be used to determine the channel roughness coefficient. It is also important to thoughtfully consider the guidelines for selection of stability factors as presented in Table 7.8.

On high gradient streams it is extremely difficult to obtain a good estimate of the median bed material size. For high gradient streams with slopes greater then 0.002 m/m (ft/ft) and bed material larger than 0.06 m (0.2 ft) (gravel, cobble, or boulder size material), it is recommended that the relationship given in the following equation be used to evaluate the base Manning's n.

$$\mathbf{n = 0.32\ S_f^{0.38}\ R^{-0.16} \qquad (n = 0.39\ S_f^{0.38}\ R^{-0.16})} \qquad \mathbf{(7.43)}$$

Where: S_f = friction slope, m/m (ft/ft)
R = hydraulic radius, m (ft)

7.9.8 Bridge Piers

For recommendations, see Chapter 9, Bridges.

7.9.9 Ice Damage

Ice can affect riprap linings in a number of ways. Moving surface ice can cause crushing and bending forces as well as large impact loadings. The tangential flow of ice along a riprap lined channel bank can also cause excessive shearing forces. Quantitative criteria for evaluating the impact ice has on channel protection schemes are unavailable. However, historic observations of ice flows in New England rivers indicate that riprap sized to resist design flow events will also resist ice forces.

For design, consideration of ice forces should be evaluated on a case by case basis. In most instances, ice flows are not of sufficient magnitude to warrant detailed analysis. Where ice flows have historically caused problems, a stability factor of 1.2 to 1.5 should be used to increase the design rock size. Please note that the selection of an appropriate stability factor to account for ice generated erosive problems should be based on local experience.

7.9.10 Rock Gradation

The gradation of stones in riprap revetment affects the riprap's resistance to erosion. The stone should be reasonably well graded throughout the riprap layer thickness. Table 7-9 presents the median particle size of three types of riprap which have gradations defined in the ConnDOT standard specifications. All designs should consider using the ConnDOT standard gradations, however if a design requires a non-standard median particle size, then the AASHTO guidelines for rock gradations as presented in HEC-11 should be used.

Table 7-9 D_{50} of Available Riprap

Riprap Type	D_{50} mm
Modified	125 (5 inches)
Intermediate	200 (8 inches)
Standard	380 (15 inches)

7.9.11 Layer Thickness

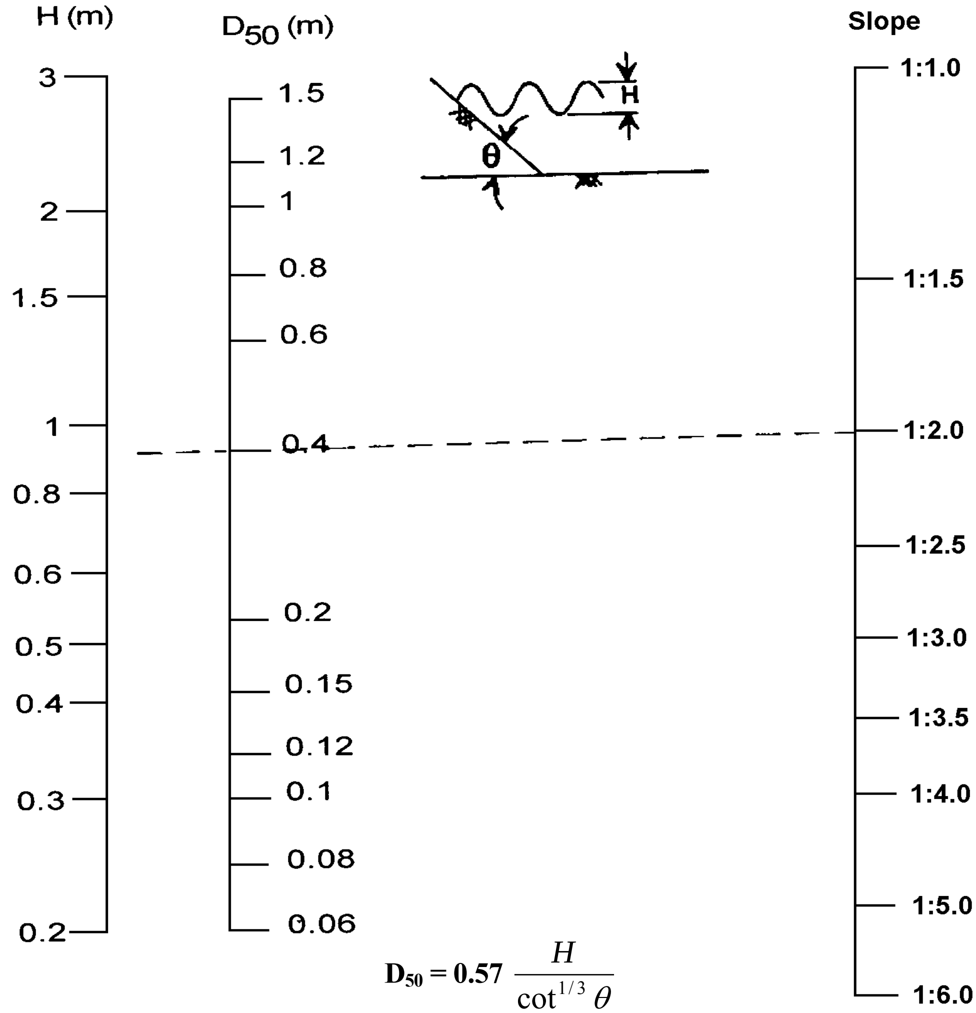
All stones should be contained reasonably well within the riprap layer thickness to provide maximum resistance against erosion. Oversize stones, even in isolated spots, may cause riprap failure by precluding mutual support between individual stones, providing large voids that expose filter and bedding materials, and creating excessive local turbulence that removes smaller stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones. The following criteria apply to the riprap layer thickness.

1. It should not be less than the spherical diameter of the D_{100} stone, or less than 2.0 times the spherical diameter of the D_{50} stone, whichever results in the greater thickness.
2. It should not be less than 300 mm (12 in) for practical placement.
3. The thickness determined by either of the above criteria should be increased by 50% when the riprap is placed underwater to provide for uncertainties associated with this type of placement.
4. An increase in thickness, accompanied by an appropriate increase in stone sizes, should be provided where riprap revetment will be subject to attack by floating debris or ice, or by waves from boat wakes, wind, or bedforms.

The typical layer thickness for riprap (ConnDOT gradations) revetment is shown in Table 7-10.

Table 7-10 Riprap Layer Thickness

Riprap Type	Riprap Layer Thickness mm
Modified	300 (12 inches)
Intermediate	450 (18 inches)
Standard	900 (36 inches)



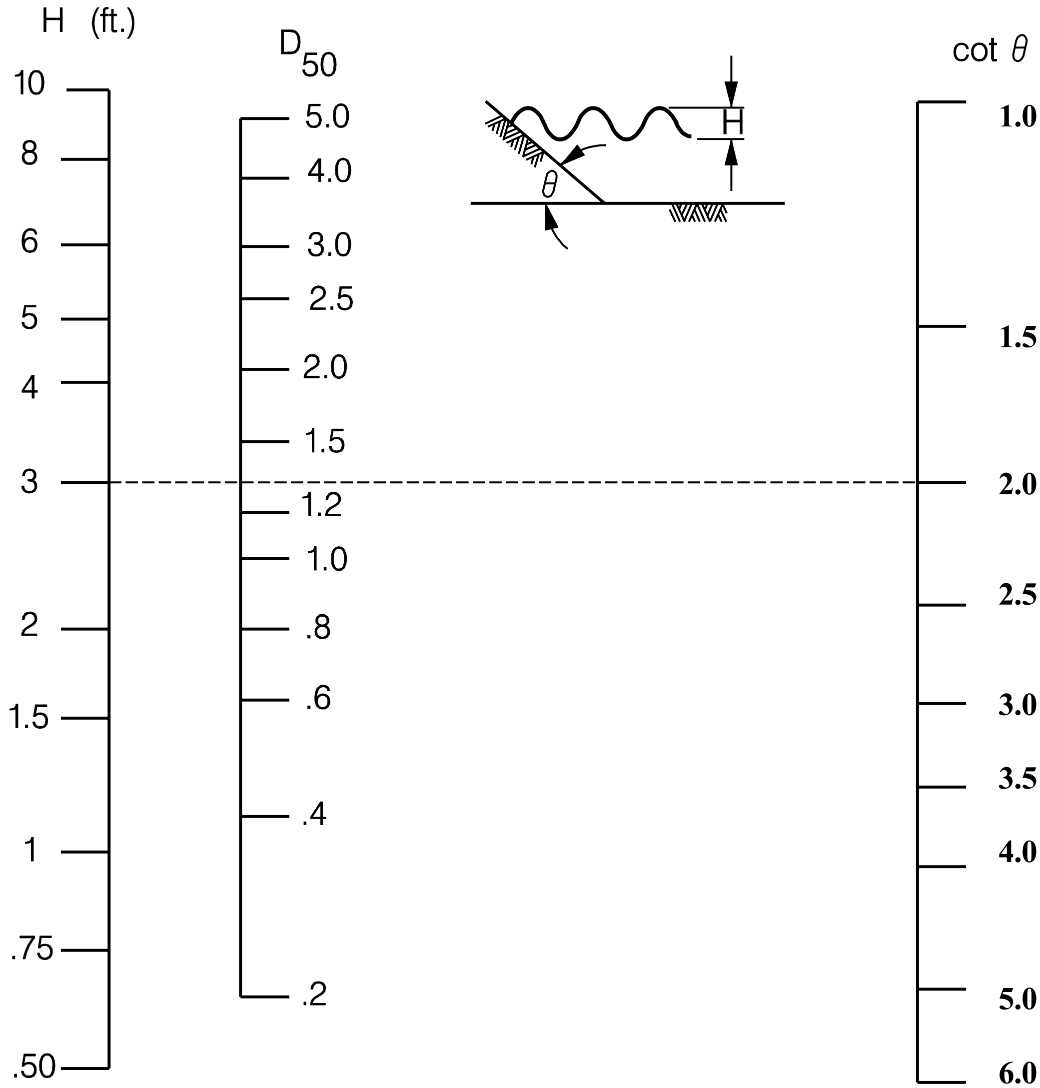
$$D_{50} = 0.57 \frac{H}{\cot^{1/3} \theta}$$

D_{50} = Median Riprap Size
H = Wave Height
θ = Bank Angle with Horizontal

Example

Given:	Find:	Solution:
Slope = 1V:2H	D_{50}	D_{50} = 0.4 m
H = 0.91 m		

Figure 7-29 Hudson Relationship For Riprap Size Required To Resist Wave Erosion – metric units



$$D_{50} = 0.57 \frac{H}{\cot^{1/3}\theta}$$

D_{50} = Median Riprap Size
H = Wave Height
θ = Bank Angle with Horizontal

Example:

Given:	Find:	Solution:
$\cot\theta = 2:1$	D_{50}	$D_{50} = 1.33$ ft.
$H = 3$ ft.		

Figure 7-29.1 Hudson Relationship For Riprap Size Required To Resist Wave Erosion – English units

7.9.12 Filter Design

A filter is a transitional layer of gravel, small stone, or fabric placed between the underlying soil and the structure. The filter prevents the migration of the fine soil particles through voids in the structure, distributes the weight of the armor units to provide more uniform settlement and permits relief of hydrostatic pressures within the soils. A filter should be used whenever the riprap is placed on noncohesive material subject to significant subsurface drainage (such as in areas where water surface levels fluctuate frequently and in areas of high groundwater levels).

Granular Filters

Typical riprap installations use granular filters as a transitional layer between the riprap and underlying soil. This layer shall consist of the item "Granular Fill" which is found in the standard specifications. The required thickness of the granular fill layer based on the ConnDOT riprap type is shown in Table 7-11.

Table 7-11 Granular Fill Filter Thickness

Riprap Type	Granular Fill Filter Thickness (mm)
Modified	150 (6 inches)
Intermediate	150 (6 inches)
Standard	300 (12 inches)

In some cases further analysis of the granular filter layer may be warranted. Guidelines for granular filter design are found in HEC-11.

Fabric Filters

Synthetic fabric filters have found considerable use as alternatives to granular filters. The following list of advantages relevant to using fabric filters have been identified:

- Installation is generally quick and labor-efficient
- Fabric filters are more economical than granular filters
- Fabric filters have consistent and more reliable material quality
- Fabric filters have good inherent tensile strength
- Local availability of suitable granular filter material is no longer a design consideration when using fabric filters

Disadvantages include the following.

- Filter fabrics can be difficult to lay underwater
- Installation of some fabrics must be undertaken with care to prevent undue ultraviolet light exposure
- Bacterial activity within the soil or upon the filter can control the hydraulic responses of a fabric filter system

- Experimental evidence indicates that when channel banks are subjected to wave action, non-cohesive bank material has a tendency to migrate downslope beneath fabric filters; this tendency was not observed with granular filters
- Fabric filters may induce translational or modified slump failures when used under rock riprap installed on steep slopes if not properly keyed into the top of slope

Filter Fabric Design

The filter cloth (geotextile) design should consider the following performance areas.

- Soil Retention (Piping Resistance)
- Permeability
- Clogging
- Survivability

It is extremely desirable that individual site requirements be used to establish the necessary requirements. Generalized geotextile requirements should be used only on very small or non-critical/non-severe installations where a detailed analysis is not warranted. A discussion of the above special considerations is found in Hydraulic Engineering circular No. 11.

The design process generally consists of the following design steps:

Step 1 - Evaluate the application site.
Step 2 - Obtain and test soil samples
Step 3 - Evaluate possible armor choices
Step 4 - Calculate flow through geotextile
Step 5 - Determine geotextile requirements:

a. Soil Retention
b. Permeability
c. Clogging
d. Survivability

Filter Fabric Placement

To provide good performance, a properly selected cloth should be installed with due regard for the following precautions:

- Heavy riprap may stretch the cloth as it settles, eventually causing bursting of the fabric in tension. A 150mm (6 inch) gravel bedding layer should be placed beneath standard riprap.
- The filter cloth should not extend into the channel beyond the riprap layer; rather, it should be wrapped around the toe material as illustrated in Figure 7-30.
- Adequate overlaps must be provided between individual fabric sheets.
- The filter should be installed loosely to allow for any stretching under settlement.
- Securing pins with washers are recommended at 0.6m to 1.5m (2 to 5 ft) intervals along the midpoint of the overlaps.

- Proper stone placement on the filter begins at the toe and proceeding up the slope. Dropping stone from heights greater than 0.6m (2 ft) can rupture fabrics (greater drop heights are allowable under water).
- “Drop height” of riprap must be limited to avoid tearing the fabric

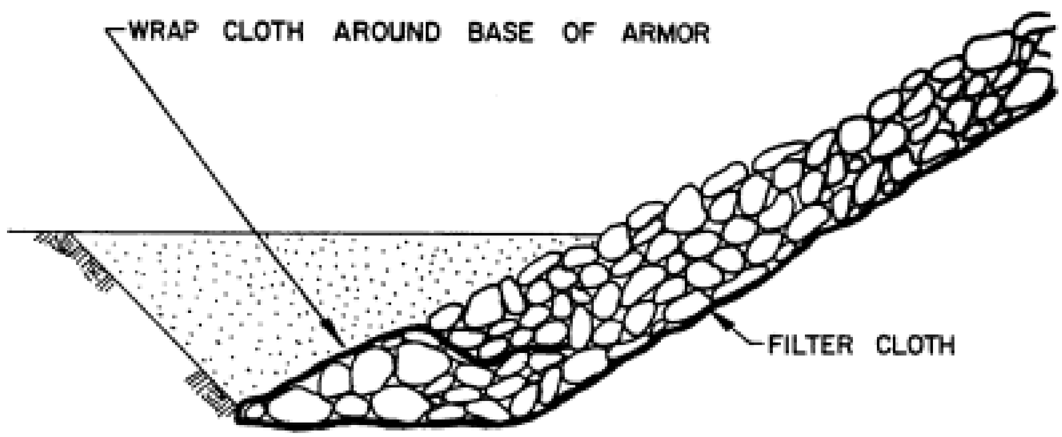


Figure 7-30 Filter Fabric Placement

7.9.13 Edge Treatment

The edges of riprap revetments (flanks, toe and head) require special treatment to prevent undermining. The flanks of the revetment should be designed as illustrated in Figure 7-31. The upstream flank is illustrated in Section A-A and the downstream flank in Section B-B of this figure. A more constructible flank section uses riprap rather than compacted fill.

Undermining of the revetment toe is one of the primary mechanisms of riprap failure. The toe of the riprap should be designed as illustrated in Figure 7-32. The toe material should be placed in a toe trench along the entire length of the riprap blanket.

Where a toe trench cannot be dug, the riprap blanket should terminate in a thick, stone toe at the level of the streambed (see alternate design in Figure 7-32). Care must be taken during the placement of the stone to ensure that the toe material does not mound and form a low dike; a low dike along the toe could result in flow concentration along the revetment face which could stress the revetment to failure. In addition, care must be exercised to ensure that the channel's design capability is not impaired by too much riprap in a toe mound.

The size of the toe trench or the alternate stone toe is controlled by the anticipated depth of scour along the revetment. As scour occurs (and in most cases it will) the stone in the toe will launch into the eroded area as illustrated in Figure 7-33. Observation of the performance of these types of rock toe designs indicates that the riprap will launch to a final slope of approximately 1V:2H.

The volume of rock required for the toe must be equal to or exceed one and one-half times the volume of rock required to extend the riprap blanket (at its design thickness and on a slope of 1V:2H) to the anticipated depth of scour. Dimensions should be based on the required volume using the thickness and depth determined by the scour evaluation. The alternate location can be used when the amount of rock required would not constrain the channel. Establishing a design scour depth is covered in Section 7.8.8.

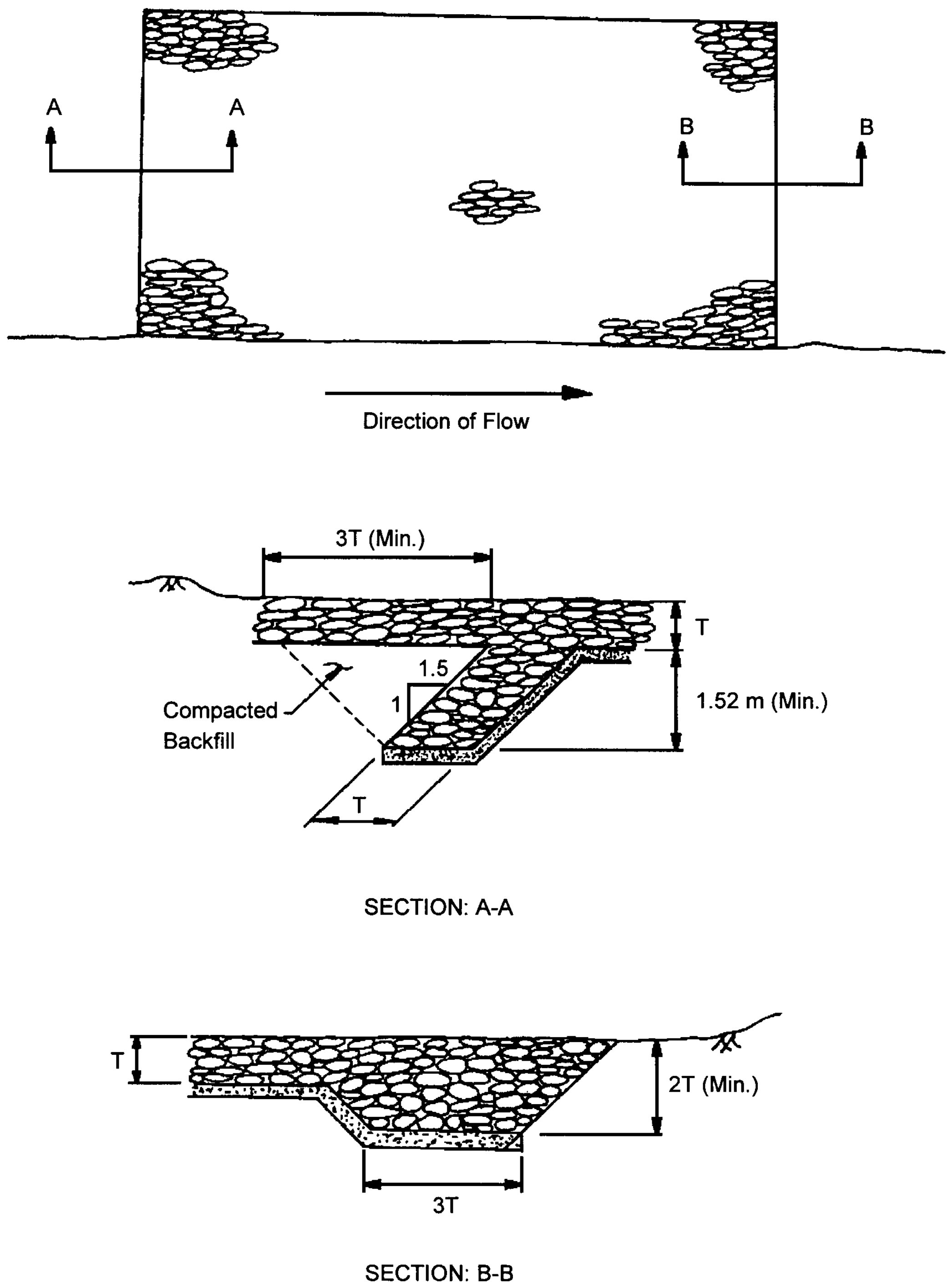


Figure 7-31 Typical Riprap Installation: Plan and Flank Details

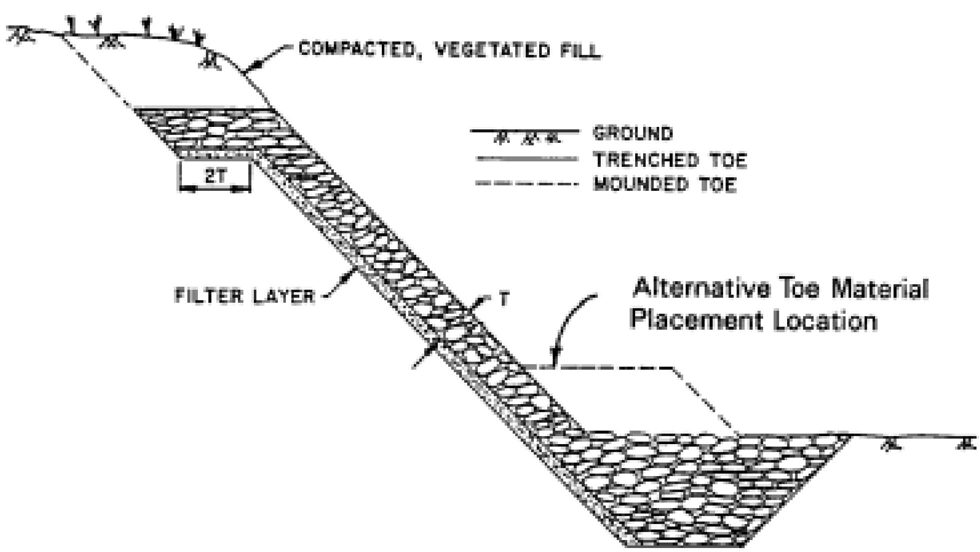


Figure 7-32 Typical Riprap Installation: End View (Bank Protection Only)

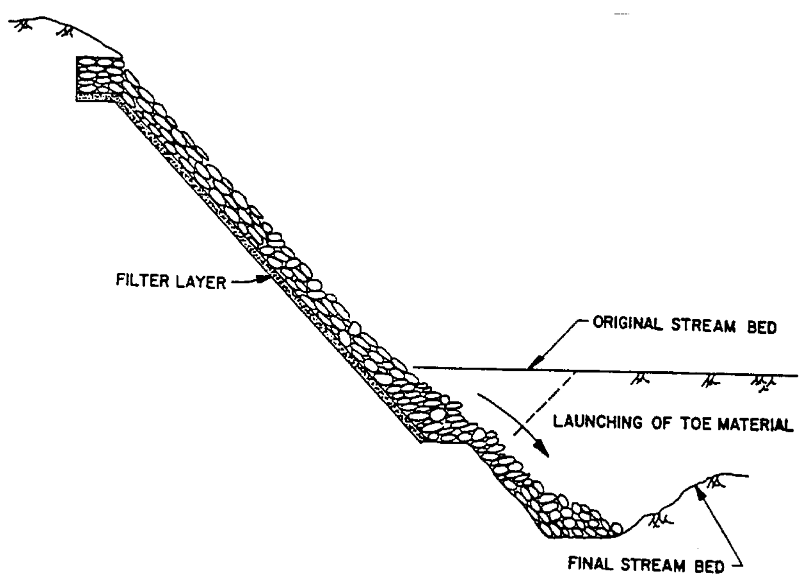


Figure 7-33 Launching Of Riprap Toe Material

7.9.14 Rock Riprap Design Procedure

Rock riprap design procedure outlined in the following sections is comprised of three primary sections: preliminary data analysis, rock sizing and revetment detail design. The individual steps in the procedure are numbered consecutively throughout each of the sections. Figure 7-34 provides a useful format for recording data at each step of the analysis.

Preliminary Data

Step 1 Compile all necessary field data including (channel cross section surveys, soils data, aerial photographs, history of problems at site, etc.).

Step 2 Determine design discharge.

Step 3 Develop design cross section(s). Note: The rock sizing procedures described in the following steps are designed to prevent riprap failure from particle erosion.

Step 4 Compute design water surface.

A. When evaluating the design water surface, Manning's n should be estimated. If a riprap lining is being designed for the entire channel perimeter, an estimate of the rock size may be required to determine the roughness coefficient.

B. If the design section is a regular trapezoidal shape, and flow can be assumed to be uniform, design procedures in Section 7.7.3 can be used.

C. If the design section is irregular or flow is not uniform, backwater procedures must be used to determine the design water surface.

D. Any backwater analysis conducted must be based on conveyance weighing of flows in the main channel, right bank and left bank.

Step 5 Determine design average velocity and depth.

A. Average velocity and depth should be determined for the design section in conjunction with the computations of step 4. In general, the average depth and velocity in the main flow channel should be used.

B. If riprap is being designed to protect channel banks, abutments, or piers located in the floodplain, average floodplain depths and velocities should be used.

Step 6 Compute the bank angle correction factor K_1 (Equation 7.37, Figures 7-26 and 7-27).

Rock Sizing

Step 7 Determine riprap size required to resist particle erosion (Equation 7.36, Figure 7-25).

A. Initially assume no corrections.

B. Evaluate correction factor for rock riprap specific gravity and stability factor ($C = C_{sg}C_{sf}$).

C. If designing riprap for piers or abutments see Chapter 9, Bridges.

Step 8 If entire channel perimeter is being stabilized, and an assumed D_{50} was used in determination of Manning's n for backwater computations, return to step 4 and repeat steps 4 through 7 with the revised D_{50}.

Step 9 If surface waves are to be evaluated:

A. Determine significant wave height.

B. Use Figure 7-29 to determine rock size required to resist wave action and Table 7-7 for correction factor).

Step 10 Select final riprap.

Revetment Detail Design

Step 11 Determine longitudinal extent of protection required (section 7.8.8).

Step 12 Determine appropriate vertical extent of revetment (section 7.8.8).

Step 13 Design filter layer (section 7.9.12).

A. Determine appropriate filter material size, and gradation.

B. Determine layer thickness.

Step 14 Design edge details (flanks and toe) (section 7.9.13).

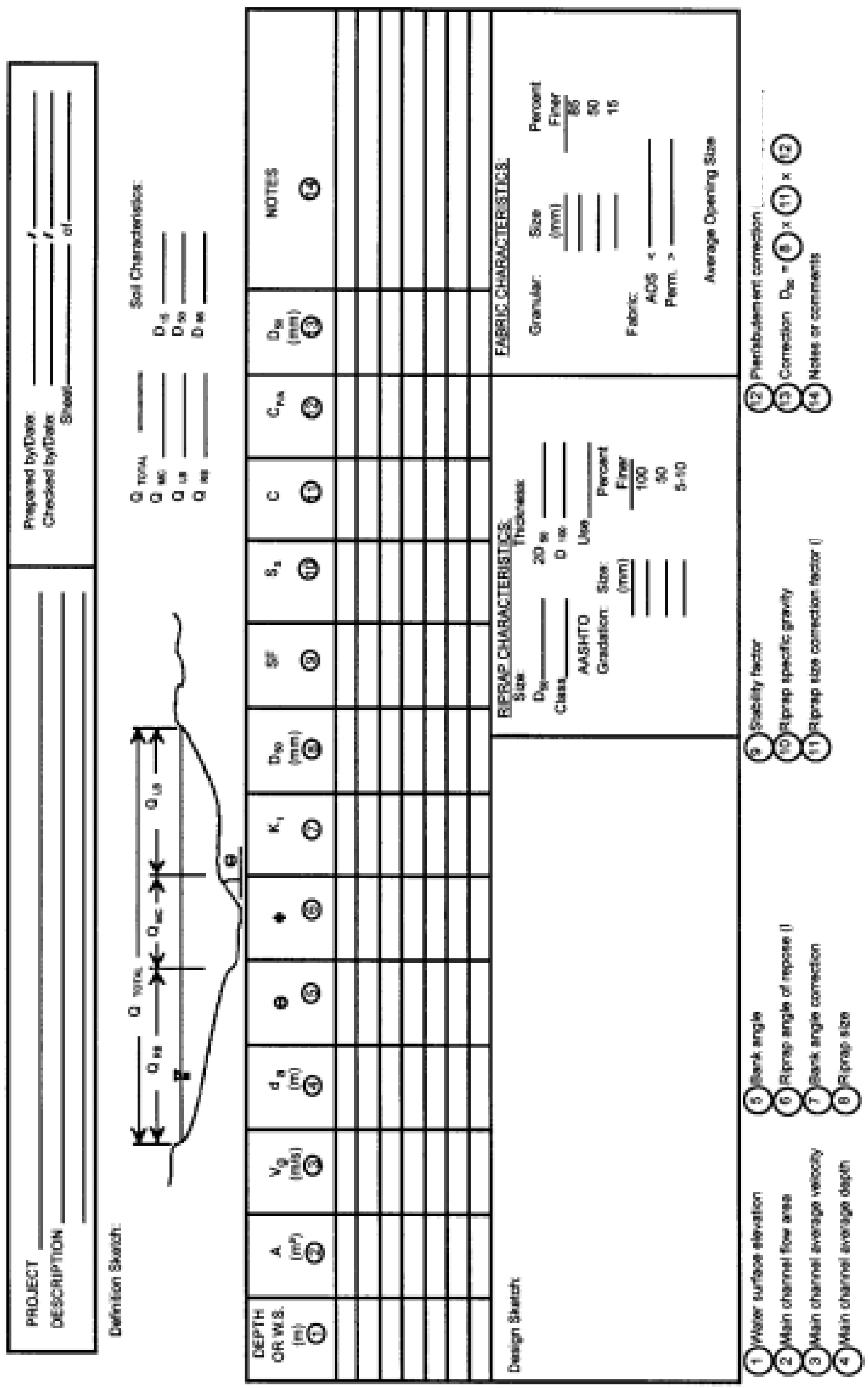


Figure 7-34 Riprap Size Particle Erosion – metric units

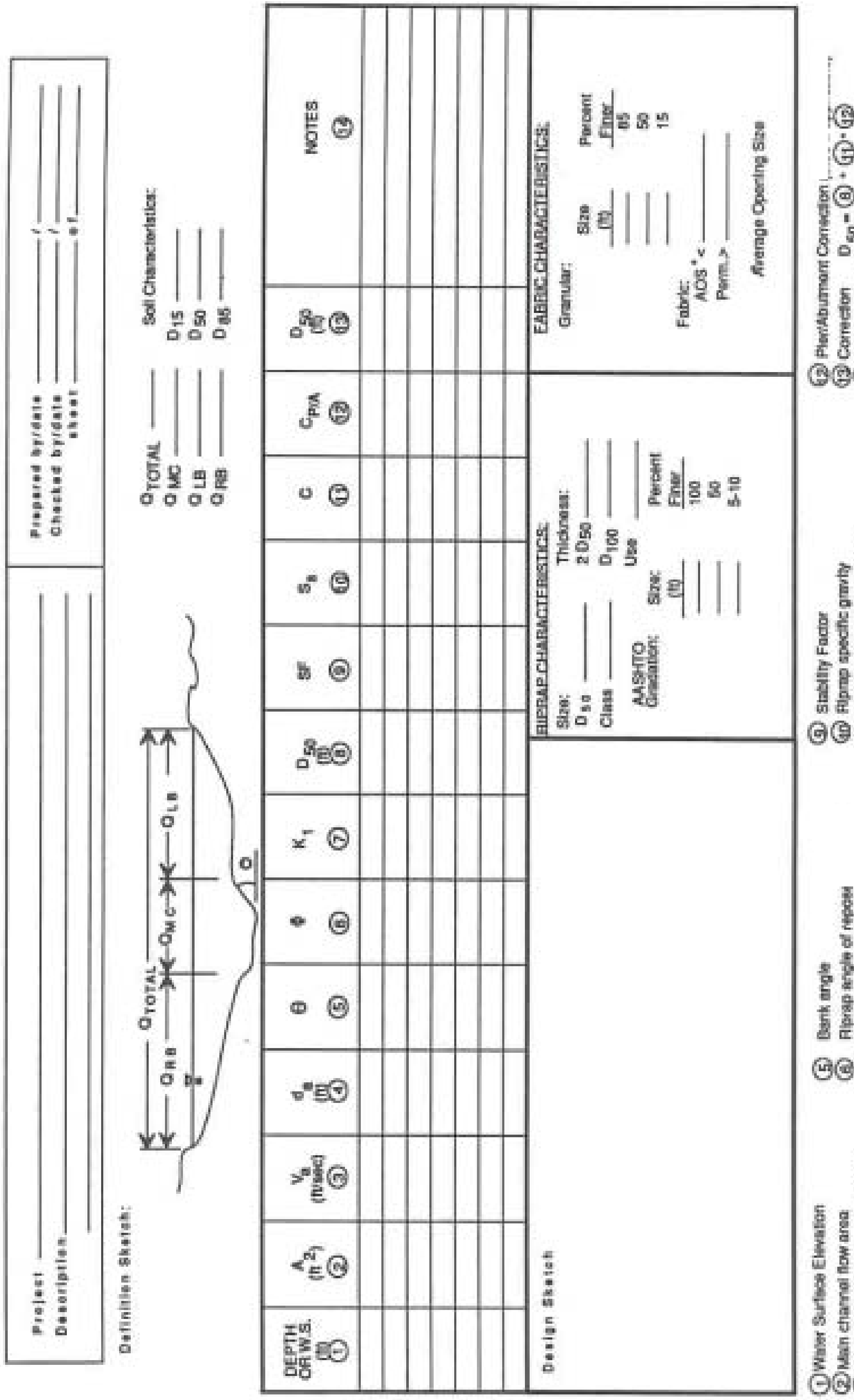


Figure 7-34.1 Riprap Size Particle Erosion – English units