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Steep Stream Riprap Design

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Introduction and Objectives

Riprap design in steep streams requires consideration of factors such as flow impingement, downslope gravity forces, flow resistance on steep slopes, and alternate methods of estimating velocity that are not required for riprap design in a lower slope environment. For this paper, steep stream riprap design will be divided into the following three categories:

a. Single channels, nonimpinging flow, slopes less than 2 percent or 100 ft/mile.

b. Braided channels, impinging flow, slopes less than 2 percent or 100 ft/mile.

c. Single channels or overflow embankments, nonimpinging flow, slopes between 2 and 20 percent.

Riprap for category a streams can be designed using US Army Corps of Engineers guidance for riprap in flood control channels found in Engineer Manual (EM) 1110-2-1601 (Headquarters, US Army Corps of Engineers (HQUSACE), 1991). This guidance departs from the traditional guidance based on shear stress or tractive force and uses a procedure based on local depth-averaged velocity. While the new method can be derived from a modification of the shear stress equations, shear stress is not used explicitly in the new procedure. Local depth-averaged velocity was adopted primarily because local shear stress is difficult to visualize, compute, or measure. From EM 1110-2-1601 the equation for determining stone size is

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$$D_{30} = S_r C_s C_v C_T d \left[\frac{\gamma_w}{\gamma_s - \gamma_w} \right]^{1/2} \frac{V}{\sqrt{K_1 g d}} \quad (1)$$

2.5
B.5

where

- D_{30} - riprap size of which 30 percent is finer by weight
- S_r - safety factor, minimum - 1.1
- C_s - stability coefficient for incipient failure, thickness - $1D_{150}(\max)$ or $1.5D_{50}(\max)$, whichever is greater. $D_{85}/D_{15} = 1.7$ to 5.2
 - 0.30 for angular rock
 - 0.375 for rounded rock (EM 1110-2-1601 incorrect, gives 0.36)
- D_{15}/D_{15} - gradation uniformity coefficient
- C_v - vertical velocity distribution coefficient
 - 1.0 for straight channels, inside of bends
 - $1.283 - 0.2 \log (R/W)$ for outside of bends (1 for $R/W > 26$)
 - 1.25 downstream of concrete channels
 - 1.25 at end of dikes
- R - center-line radius of bend
- W - water-surface width at upstream end of bend
- C_T - blanket thickness coefficient
- d - local depth of flow
- γ_w - unit weight of water
- γ_s - unit weight of stone
- V - local depth-averaged velocity
- K_1 - side slope correction factor
- g - gravitational constant

Riprap designs for categories b and c require modification of the method presented in EM 1110-2-1601. The objective of this paper is to present riprap design for category b and c streams.

Riprap Design for Category b Streams

For braided streams having impinged flow, the EM 1110-2-1601 procedures require modification in two areas: the method of velocity estimation and the velocity distribution coefficient C_v . All other factors and coefficients presented in the EM are applicable.

The major challenge in riprap design for braided streams is estimating the imposed force at the impingement point. In the EM 1110-2-1601 method, the characteristic imposed force for side slope riprap is the depth-averaged velocity at 20 percent of the slope length up from the toe V_{20} . Although unproven, the most severe bank attack in braided streams is thought to occur when the water surface is at or slightly above the tops of the midchannel bars. At this stage, flow is confined to the multiple channels

that often flow into or "impinge" against bank lines or levees. At lesser flows, the depths and velocities in the multiple channels are decreased. At higher flows, the channel area increases drastically and streamlines are in a more downstream rather than into bank lines or levees. Therefore, a method was needed that allows estimation of the average channel velocity when the flow produces a stage at or just above the tops of the midchannel bars. This average channel velocity will be multiplied by an empirical factor to obtain V_{20} , just as in Plate B-33 in EM 1110-2-1601.

The first item that is needed in this method is the discharge that produces a stage near the tops of the midchannel bars Q_{mcb} . Q_{mcb} is probably highly correlated with the channel forming discharge concept. In the case of the Snake River near Jackson, Wyoming, Q_{mcb} is 15,000-18,000 cfs, which has an average recurrence interval of about 2-3 years.

The second item that is needed in this method is cross-section information at sites where the flow is concentrated into one channel against the bank line or levee. In the case of the Snake River, several locations could be found where cross sections had been measured and where the flow was concentrated into a single channel. Using cross-section data to determine the channel area below the tops of the midchannel bars and Q_{mcb} allows determination of the average channel velocity at the top of the midchannel bars V_{mcb} .

Field measurements at impingement sites were taken in 1991 on the Snake River near Jackson, Wyoming, and reported in Maynard (in preparation). Flow during these measurements ranged from 14,000 to 16,000 cfs, which produced a stage just below the tops of the midchannel bars. Velocities were measured with electromagnetic velocity meters suspended by a crane that could extend 40 ft from the bank line. Cross sections were not obtained during the 1991 field trip. At eight cross sections measured in 1988, the average channel area below the tops of the midchannel bars was about 2,000 sq ft. Using a Q_{mcb} of 15,000 cfs resulted in a V_{mcb} of 7.5 fps. The velocity measurements in 1991 resulted in V_{20} ranging up to 12 fps. The ratio $V_{20}/V_{mcb} = 12/7.5 = 1.6$, which is almost identical to the ratio shown in Plate B-33 for sharp bendways having $R/W = 2$ in natural channels, and this ratio is recommended for determining V_{20} for impinged flow.

Water-surface measurements on the Snake River at the impingement sites showed that the maximum local water-surface slopes measured over a 100-ft distance averaged 45 ft/mile and ranged from 19 to 82 ft/mile. The downvalley slope of the Snake River in this reach is 19-21 ft/mile.

As stated earlier, two areas of EM 1110-2-1601 require modification for use in impinged flow in braided streams. The second is the velocity distribution coefficient C_v , which varies with R/W in bendways as shown in Plate B-40 in EM 1110-2-1601. In straight

laboratory channels having 1V:2H side slopes and channel bottoms with the same riprap size, failure almost always occurred on the channel bottom in stability tests. In laboratory bendways of the Riprap Test Facility, US Army Engineer Waterways Experiment Station, having 1V:2H side slopes, failure generally occurred about halfway up the side slope. Preliminary results from ongoing studies of impinged flow having 1V:2H side slopes showed that failures were initiated higher up the side slope than in the bendway. This suggests that impinged flow has high velocities well up on the side slope, and the 1991 field study (Maynard, in preparation) confirms this observation. The laboratory study of impinged flow is trying to determine the appropriate value of C_v for impinged flow. Until that time a value of C_v of 1.25, which is close to a bendway having $R/W = 2$, is recommended.

For the Snake River near Jackson, Wyoming, the required riprap size using the procedures presented herein is as follows:

Input: $V_{20} = 1.6(15,000/2000) = 12$ fps, depth at $V_{20} = 10$ ft, specific weight = 155 pcf, $C_v = 1.25$, $C_s = 0.30$, $C_t = 1.0$, $S_z = 1.1$, 1V:2H side slope, thickness = $1D_{100}$, use ETL 1110-2-120 gradations given in Table 3-1 of EM 1110-2-1601.

Result: Required $D_{30} = 1.09$ ft, ETL $D_{30}(\text{min}) = 1.10$ ft, thickness = 27 in., $W_{50}(\text{min}) = 185$ lb.

This compares with the existing riprap that has an average size of less than 100 lb according to US Army Engineer District, Walla Walla (1987). New riprap placement along the Snake River generally uses riprap having $W_{50} = 400$ lb with thickness of 42 in. at the toe and 24 in. at the top.

→ Riprap Design for Category c Streams

→ For single channels or overflow embankments, slopes greater than 2 percent are outside the range of direct applicability of EM 1110-2-1601 because of the importance of the downslope gravity component and the effect of steep slopes on flow resistance. Overflow embankment riprap stability tests have generally been limited to a maximum slope of 20 percent. The most recent tests were conducted by Abt et al. (1986) and Abt et al. (1988). While a 20 percent slope may seem large for loose riprap, highway engineers have questioned this author about design guidance for riprap placed on slopes approaching 40 percent. Using Abt's data and dimensional analysis results in the following empirical equation

$$D_{50} = \frac{2.26S^{0.555}q^{2/3}}{g^{1/3}}$$

$$\frac{2.26}{1.95} = 1.16 = (2) \frac{D_{50}}{D_{30}}$$

or in terms of D_{30} used in EM 1110-2-1601

$$D_{30} = \frac{1.95S^{0.555}q^{2/3}}{g^{1/3}} \quad (3)$$

where S is the slope of the bed and q is the unit discharge. Both equations can be used in any consistent set of units, both fall on the conservative side of the data, and both are restricted to a thickness of $1.5D_{100}$, angular rock, specific weight of 167 pcf, 6-in. gravel filter beneath riprap, D_{85}/D_{15} from 1.7 to 2.7, slopes from 2 to 20 percent, uniform flow on a downslope with no tailwater, and average riprap size less than 6 in. The comparison of Equation 3 with the data is shown in Figure 1. One of the problems with this approach is that different specific rock weight, blanket thickness, and gradation uniformity cannot be used with this approach.

An alternative approach would be to use the EM 1110-2-1601 procedure to address other specific weights, thickness, and gradation but to include the appropriate factors for downslope gravity effects and a resistance equation for flow on steep slopes. From Ulrich (1987), the appropriate K_1 factor to use in Equation 1 is

$$K_1 = \cos \alpha \left[1 - \frac{\gamma_s \tan \alpha}{\gamma_s - \gamma_w \tan \phi} \right] \quad (4)$$

When α is the angle of the channel bottom from horizontal and ϕ is the angle of repose of the riprap revetment. From Maynard (1988) the appropriate ϕ for riprap revetments is about 53 degrees. Using Abt et al. (1986), flow resistance data and dimensional analysis result in the following modification of the Strickler equation

$$n = 0.07(D_{50}S)^{1/6} \quad (5)$$

which is applicable to slopes between 2 and 20 percent. Combining Equations 1, 4, and 5, using $q = Vd$, and $D_{50} = 1.2D_{30}$ results in

$$D_{30} = C' \frac{q^{2/3} S^{0.432}}{g^{1/3} K_1} \quad (6)$$

where

$$C' = 5.3(S_r C_v C_t C_s)^{0.785} \left[\frac{\gamma_w}{\gamma_s - \gamma_w} \right] \quad (7)$$

Abt
limits do
not apply

Note the similarity of Equation 6 and Equations 2 and 3 and that Equation 6 was derived without using Abt's et al. stability data. Also note that the slope effect in Equation 6 is also part of the K_1 factor in the denominator. Equation 6 is limited to slopes from 2 to 20 percent, angular rock, 6-in. gravel filter beneath riprap, uniform flow on downslope with no tailwater, and average riprap size less than or equal to 6 in. The comparison of Equation 6 using $S_f = 1.1$ (minimum safety factor), $C_v = 1$, $C_T = 0.84$ (for thickness = $1.5D_{100}$), $C_s = 0.30$ (for angular rock), specific stone weight = 167 pcf, and $\phi = 53$ degrees with Abt's et al. data is shown in Figure 1 as the modified EM 1110-2-1601 curve. Equation 6 fits the observed data as well as the empirical approach given by Equation 2 or 3 and allows variation of stone size with unit weight, blanket thickness, etc.

Abt et al. (1988) presents a flow concentration factor that varies from 1 to 3 that is multiplied by the unit discharge when the inflow is not uniform across the approach channel. Although guidance is lacking on the amount of flow concentration for a given geometry, some degree of flow concentration should be expected. Riprap on steep slopes should be relatively uniform with $D_{85}/D_{15} \leq 2.5$. Additional studies are needed to extend Equations 2, 3, or 6 to larger riprap sizes.

Consider a 10-ft-wide downslope having a 10 percent slope and a total discharge of 25 cfs. Rock protection will be placed to a thickness of $1.5D_{100}$, and have a unit weight of 165 pcf. Using a flow concentration factor of 1.25 results in a unit discharge of $1.25(25/10) = 3.13$ cfs/ft. Using Equation 3, the required $D_{30} = 0.37$ ft. Using the modified EM 1110-2-1601 procedure given by Equation 6, the required $D_{30} = 0.34$ ft. In either case, a typical gradation having $D_{30}(\text{min}) \geq 0.34$ ft would have $D_{100}(\text{max})$ of about 9 in. and a blanket thickness of $1.5(9) = 13-14$ in.

Summary and Conclusions

Riprap design for single channels, nonimpinging flow, and slopes less than 2 percent should use guidance presented in EM 1110-2-1601.

Riprap design for braided channels, impinged flow, and slopes less than 2 percent should use the velocity estimation method presented herein and $C_v = 1.25$ in the EM 1110-2-1601 procedure.

Riprap design for single channels or overflow embankments, nonimpinged flow, slopes between 2 and 20 percent, uniform flow on a downslope with no tailwater, and average rock size less than or equal to 6 in. should use either the empirical method in Equation 2 or 3 or the modification of the EM 1110-2-1601 method given in Equation 6.

Conversion Factors from U.S. Customary to SI Units

To convert (1)	To (2)	Multiply by (3)
Cubic foot per second (cfs)	Cubic meter per second (m ³ /s)	0.03
Degree	Radian	0.02
Foot (ft)	Meter (m)	0.31
Inch (in.)	Meter (m)	0.03
Pound (mass) (lb)	Kilogram (kg)	0.45
Pound (mass) per cubic foot (pcf)	Kilogram per cubic meter (kg/m ³)	16.02
Square foot (sq ft)	Square meter (m ²)	0.09

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