U.S. Army Corps of Engineers Riprap Design for Flood Channels

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The U.S. Army Corps of Engineers riprap design guidance for flood channels is presented, and the limitations and basis of several empirical coefficients are discussed. The method is based on depth-averaged velocity rather than shear stress, which was the basis of the previous guidance. The effects of bends, blanket thickness, side-slope angle, particle shape, and gradation on riprap stability are addressed in the design guidance.

The U.S. Army Corps of Engineers guidance for design of riprap in flood control channels is found in Engineer Manual (EM) 1110-2-1601 (*1*). This guidance is a departure from the traditional guidance based on shear stress or tractive force and uses a procedure based on local depth-averaged velocity. Although the new method can be derived from a modification of the shear stress equations, it does not use shear stress explicitly. Local depth-averaged velocity was adopted primarily because local shear stress is difficult to visualize, compute, and measure. Various methods, discussed in this paper, are available for estimating depth-averaged velocity. The objective of this paper is to provide assistance in application of the new procedure. Limitations of the method and several example problems will also be presented.

BASIC EQUATION

The basis and derivation of the basic equation used to determine stone size can be found in works by Maynord (*2,3*) and Maynord et al. (*4*). From EM 1110-2-1601 (*1*) the equation for determining stone size is

$$D_{30} = S_f C_S C_v C_T d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5} \quad (1)$$

where

D_{30} = riprap size of which 30 percent is finer by weight (for some gradations, use D_r);
D_r = $D_{85}(\min)[D_{15}(\min)^2]$;
S_f = safety factor (minimum = 1.1);
C_S = stability coefficient for incipient failure, thickness = $1D_{100}(\max)$ or $1.5D_{50}(\max)$, whichever is greater (D_{85}/D_{15} = 1.7 to 5.2),
= 0.30 for angular rock, and
= 0.375 for rounded rock [note: EM (*1*) is incorrect, giving 0.36];
D_{85}/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, and
= 1.25 at end of dikes;
R = centerline radius of curvature of bend;
W = water-surface width at upstream end of bend;
C_T = blanket thickness coefficient (see Figure 1);
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; and
g = gravitational constant.

The power of 2.5 in this equation was based on laboratory data from straight, tilting flumes. The extreme values of the power in Equation 1 are from 2 to 3. A power of 2 results in the Isbash equation (no dependence on depth) and is generally used when there is no boundary layer development. A power of 3 results from application of existing shear stress and the Manning-Strickler equations and represents the condition of completely developed boundary layer and a relative roughness (roughness size/depth) that is low enough to yield a constant Shields coefficient. Because most bank and channel riprap protection problems fall somewhere between these two extremes, the 2.5 power was adopted for all bank and channel riprap protection problems, not just the straight, tilting flumes from which it was derived.

INPUT/OUTPUT DESCRIPTION AND LIMITATIONS

General

The method described herein is limited to what is normally referred to as "low turbulent flow": the method is applicable to sizing riprap in rivers and channels except those immediately downstream of hydraulic structures that create highly turbulent flow. Data used in the development of this method were limited to slopes less than or equal to 2 percent. Data are also limited to $D_{30}/d \geq 0.02$, which means that the method has not been verified for relatively deep flows.

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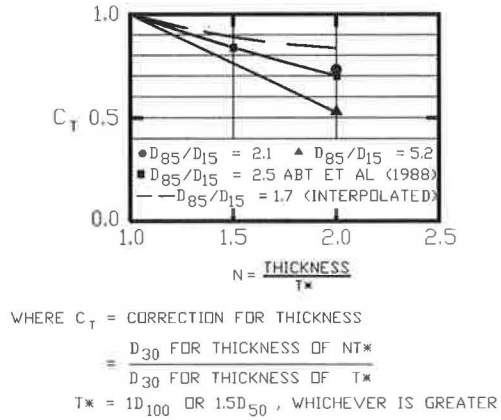

FIGURE 1 Correction for riprap blanket thickness.

Design Conditions

Riprap should be designed for the combination of velocity and depth that gives the largest rock size. This combination is not always the design discharge. In many cases bank-full discharge produces the combination of velocity and depth that results in the largest rock size. Rock size in bendways is normally based on the maximum velocity-depth combination found along the bend. Bendways having stable upstream conditions could be designed with a variable rock size along the bend. This is generally not done because specifying multiple gradations has been found in some cases to increase construction costs.

Velocity Estimation

As stated earlier, the primary reason for adopting a design procedure based on depth-averaged velocity is that several techniques exist for estimating this velocity. Velocity is also easier to visualize and measure than is shear stress. Any riprap design problem has two parts: the first part is to estimate the imposed force, and the second is to use the imposed force and determine riprap size. The most difficult and most uncertain part of riprap design lies in estimating the imposed force, whether it be local depth-averaged velocity or shear stress. When riprap is designed for a channel bottom, local depth-averaged velocity is a straightforward concept even if it is difficult to determine. When side-slope riprap is designed, local depth-averaged velocity varies greatly from the toe of slope to the waterline, and near-bank velocity is meaningless unless the position is specified. The EM 1110-2-1601 method (*1*) uses depth-averaged velocity at a point 20 percent upslope from the toe V_{ss} for side-slope riprap design. The 20 percent point was selected because straight channel side-slope stability tests resulted in the same stability coefficient C_S as straight channel bottom stability tests with this position on the side slope and the appropriate adjustment for side-slope angle. This point is consistent with the location of maximum side-slope shear stress from straight channel studies.

Various tools exist to estimate depth-averaged velocity for use in riprap design and include the following with some of their limitations:

1. Two-dimensional (2D) depth-averaged *numerical models* have been shown to be unconservative in prismatic bends. Bernard (*5*) has developed a correction method for 2D depth-averaged models, and a version is available that can be used with 386 personal computers (PCs). This model has compared well with data from trapezoidal channels and is being tested against data from natural channels.
2. *Physical models* are rarely available for bank protection projects because of cost. If available, near bank velocity distributions should be measured to obtain V_{ss}.
3. *Empirical methods* must be applied only to cases similar to the data from which they were derived.
4. *Analytical methods*, which are based on conveyance [such as the ALPHA method given in EM 1110-2-1601 (*1*)], should be limited to straight channels because secondary currents cause ALPHA to be unconservative. Thorne and Abt (unpublished data) discuss additional analytical methods that incorporate the effects of secondary currents.
5. *Prototype data* normally require extrapolation to design conditions but are usually not available.

This paper focuses on the application of the empirical method given in EM 1110-2-1601 (*1*), presented in Figure 2. Figure 2 is applicable only for estimating characteristic side-slope velocity (V_{ss}) in straight or curved channels at 20 percent of slope length up from the toe. Figure 2 was derived from velocity data taken in physical models and prototypes. The amount of scatter in this type of data is large, and the curves were drawn on the conservative side of the data. In the case of bendways, Figure 2 is based on bends having fully devel-

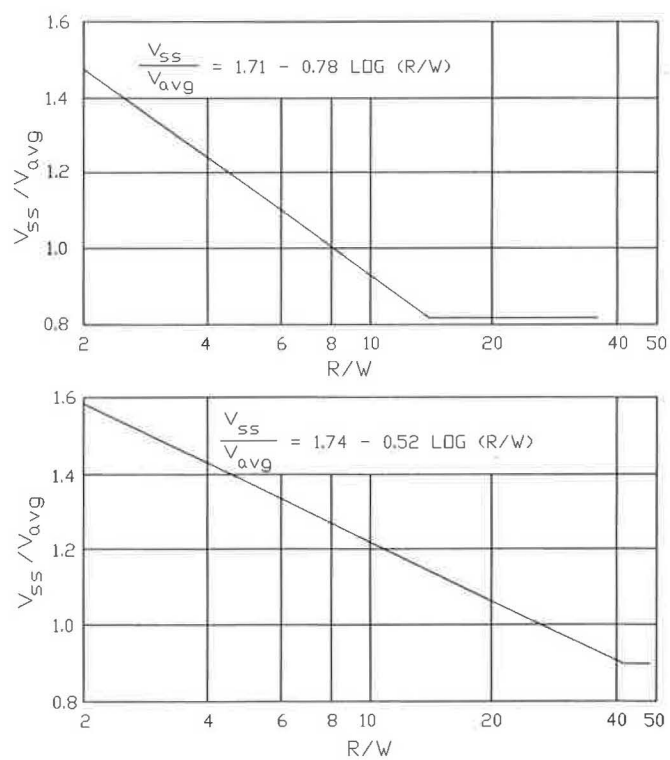

FIGURE 2 Velocity estimation based on EM 1110-2-1601 (*1*): *top*, trapezoidal channel; *bottom*, natural channel.

oped bend flow, which means that the bend angle is sufficiently large to develop close to the maximum velocity for that value of R/W. To use the minimum V_{ss}/V_{avg} in Figure 2 for straight channels requires that the channel be far enough downstream of bends, constrictions, or other devices that might create an imbalance of flow across the channel. Consequently one should be very cautious about specifying a straight channel—some investigators will not use $V_{ss}/V_{avg} < 1$. Figure 2 estimates V_{ss} from only average channel velocity V_{avg}, R, W, and channel type (natural or trapezoidal). The effects of other factors such as bend angle, bank angle, and bed/bank roughness have not been determined. It is important to note that V_{ss}/V_{avg} has rarely been found to exceed 1.6 in any alluvial or man-made fixed bed channel and is a minimum of 0.82 in straight trapezoidal channels and 0.9 in straight natural channels. Thus the designer is simply defining where in the range of V_{ss}/V_{avg} = 0.82 to 1.6 to design the protection. Figure 2 assists in that determination and generally provides a conservative estimate. Since Figure 2 is valid only for estimating side-slope velocity, velocity estimation for all problems other than bank protection (such as channel bottom protection) must use some other technique to determine local depth-averaged velocity, such as the numerical model described previously.

Average channel velocity is used only in the EM method (*1*) in conjunction with the empirical velocity estimation technique and is determined from discharge/channel area (Q/A). Area and discharge should be restricted to the main channel and should not include overbank areas.

Bend Radius and Water-Surface Width

The centerline radius of curvature of the bend and the water-surface width at the upstream end of the bend are used to characterize the bendway in both the EM rock sizing techniques (*1*) and the scour depth estimation techniques. The centerline radius and the width should be based on flow in the main channel and should not include overbank areas.

Natural Versus Trapezoidal Channel

In the empirical velocity estimation technique shown in Figure 2, two channel types, natural and trapezoidal, are used. Trapezoidal channels are often man-made with a smooth alignment; sediment transport is not sufficient to build point bars, which can concentrate flow against the outer bank. The data used in developing the trapezoidal channel curve were from clearwater channel models having riprap bottom and banks and aspect ratios (top width/average depth) ranging from 11 to 22. Though many trapezoidal channels have aspect ratios greater than 22, secondary currents in the channels with lower aspect ratios will provide more velocity concentration along the outer bank than those with higher aspect ratios.

In contrast, the natural channel curve in Figure 2 is applicable to channels having irregular alignment with sediment transport leading to point bars and toe scour that concentrate the flow along the outer bank.

Characteristic Particle Size for Gradation

One of the most controversial changes from the old to the new guidance has been the adoption of a characteristic particle size of D_{30}. A gradation plot in Figure 3 illustrates concepts such as the lower and upper gradation limits (also referred to as minimum and maximum) as well as D_{100}(max), D_{30}(min), and so forth. Stability tests conducted at a thickness of $1D_{100}$, which is the most commonly used thickness for bank protection, showed that gradations ranging from uniform to highly nonuniform exhibited the same stability if they had the same D_{30}. Maynord provides details of the comparison of D_{50} and D_{30} and documents other investigators who found a characteristic size less than the commonly used D_{50} (*2*). It is likely that if the tests had been conducted at another thickness, such as $1.5D_{100}$, the resulting characteristic size would have been different, probably larger. The use of D_{30} instead of D_{50} requires that the designer determine which of the available gradations has a D_{30}(min) greater than or equal to the computed D_{30} rather than to D_{50}. One of the results of this finding is that uniform gradations use the least volume of rock to achieve the same stability because the thickness is equal to the maximum stone size. One of the troubling aspects of these results is that an investigator of riprap subjected to channel flow has not yet been found who has been able to confirm the commonly held notion that a range of sizes gives increased stability due to better interlock.

If the designer prefers to work in terms of D_{50}, the approximate relation of D_{30} is

$$D_{50} = D_{30}(D_{85}/D_{15})^{0.32} \tag{2}$$

The use of a single particle size to characterize a gradation, whether D_{30}(min) or D_{50}(min), does not reflect all characteristics of that gradation. The following equation can be used to determine if D_{30}(min) is representative or if D_r(min) should be used as the characteristic particle size:

$$D_r(\text{min}) = \sqrt[3]{D_{85}(\text{min})[D_{15}(\text{min})^2]} \tag{3}$$

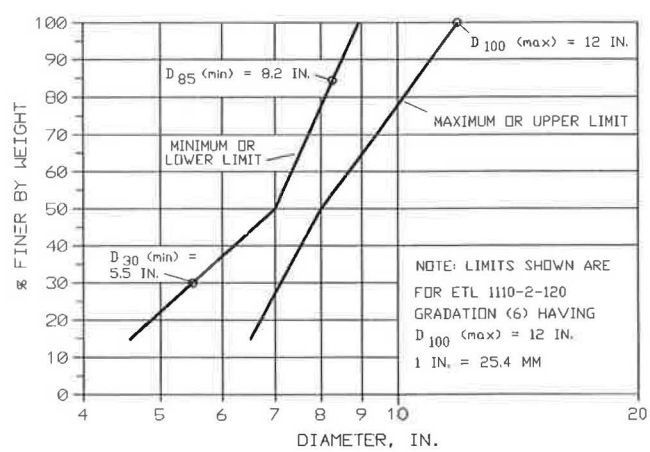

FIGURE 3 Explanation of gradation terminology.

If D_r(min) is significantly different from D_{30}(min), use D_r(min). The significance of Equation 3 is explained elsewhere (*3*).

One factor that should be considered is the impact of gradation on filter requirements. If a granular filter is used, the lower sizes of the riprap gradation must properly interface with the upper sizes of the filter. Consequently it is difficult to use a large uniform riprap and economically interface it with a granular filter. With geotextiles, this is not a problem, but a bedding layer is sometimes used on top of the geotextile to prevent damage from placing the riprap.

Unit Stone Weight

Unit stone weight is generally within the range of 2402 to 2803 kg/m³ (150 to 175 lb/ft³). Rock weighing less than 2402 kg/m³ (150 lb/ft³) can be used, but this is not very close to the unit weights that have been used in stability tests. When rock sizes required for different unit weights are compared, it is not correct simply to use equal rock weights and the relationship between size and weight of a sphere or cube. These comparisons must be made using the stone-sizing Equation 1 because this addresses the increased drag that would occur on a less dense but larger piece of riprap.

Riprap Blanket Thickness

Blanket thickness is generally measured in terms of the maximum stone size D_{100}. The minimum allowable blanket thickness is $1D_{100}$, and many streambank protection projects use this thickness. Only for very uniform gradations ($D_{85}/D_{15} \leq 2$) must the thickness also be at least $1.5D_{50}$. Stability tests show that uniform gradations must meet this requirement of $1.5D_{50}$(max) for equivalent stability. Stability tests have shown that a thickness greater than T^*, where T^* is the greater of $1.5D_{50}$ or $1.0D_{100}$, results in increased stability. Figure 1 shows guidance given in EM 1110-2-1601 (*1*) for thickness effects. The interpolated curve having $D_{85}/D_{15} = 1.7$ is applicable to the gradations in Table 1 (*6*). (This curve was interpolated between the curve for $D_{85}/D_{15} = 2.5$ and $D_{85}/D_{15} = 1$, which was conservatively assumed to have no increase in stability for increased thickness.) Gradations having $D_{85}/D_{15} \geq 5.2$ should use the curve for 5.2. When greater blanket thickness is used to increase stability, it must be realized that some rock movement will occur before the revetment becomes stable.

Local Flow Depth

The procedure presented in EM 1110-2-1601 is based on local depth-averaged velocity and local depth of flow. For channel bottoms, the local depth of flow is simply the depth at the point of interest. For side slopes the characteristic velocity and local depth are located 20 percent up the slope from the toe. At this point the local depth is 80 percent of the depth over the toe.

Side-Slope Angle

Stability studies have shown that the decrease in stability that occurs from placing a revetment on a side slope is not as significant as suggested in some of the previous guidance. This is probably because the angle of repose of a revetment is greater than the angle of repose of a rock dike. The relation of K_1 versus side-slope angle from EM 1110-2-1601 is shown in Figure 4. The solid line should be used for revetments. The least volume of riprap per foot of bank line is used when revetments are placed on slopes between 1V:1.5H and 1V:2H. For slopes flatter than 1V:4H, rock stability is not affected by the slope angle for revetments subject to channel flow. Slopes steeper than 1V:1.5H are not recommended.

Velocity Profile Correction

An evaluation of the velocity profile over bottom riprap in straight channels resulted in the following equation:

TABLE 1 Gradations for Specific Stone Weight of 165 lb/ft3, from ETL 1110-2-120 (*6*)

D_{100}(max) (in.)	Limits of Stone Weight for Percentage Lighter by Weight (lb) 100 Max	100 Min	50 Max	50 Min	15 Max	15 Min	D_{30}(min) (ft)	D_{90}(min) (ft)
12	86	35	26	17	13	5	0.48	0.70
15	169	67	50	34	25	11	0.61	0.88
18	292	117	86	58	43	18	0.73	1.06
21	463	185	137	93	69	29	0.85	1.23
24	691	276	205	138	102	43	0.97	1.40
27	984	394	292	197	146	62	1.10	1.59
30	1,350	540	400	270	200	84	1.22	1.77
33	1,797	719	532	359	266	112	1.34	1.96
36	2,331	933	691	467	346	146	1.46	2.11
42	3,704	1,482	1,098	741	549	232	1.70	2.47
48	5,529	2,212	1,638	1,106	819	346	1.95	2.82
54	7,873	3,149	2,335	1,575	1,168	492	2.19	3.17

NOTE: 1 lb/ft³ = 16.018 kg/m³; stone weight limit data from ETL 1110-2-120 (*6*). Relationship between diameter and weight is based on the shape of a sphere.

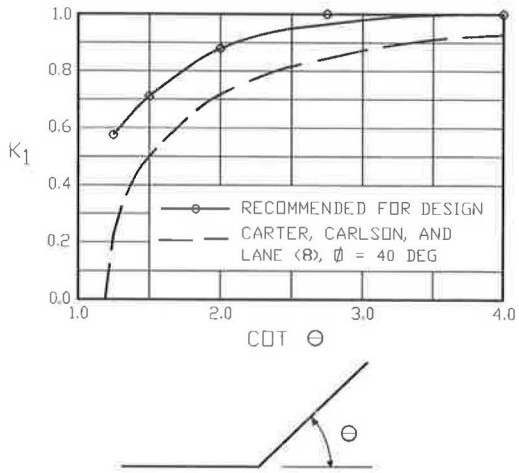

FIGURE 4 Side-slope correction coefficient.

$$\frac{V(y)}{V} = (1 + N)\left(\frac{y}{d}\right)^N \tag{4}$$

where

$V(y)$ = velocity at y,
N = 0.25 for d/D_{90} from 3 to 20, and
y = distance from top of riprap.

The velocity profile given by Equation 4 is the profile for which the stability coefficient for angular rock was found to be 0.30. In both bendways and just downstream of concrete channels, the profile is more nearly vertical with velocity in the upper zone (near the surface) less than Equation 4 and velocity in the lower zone (near the bottom) greater than Equation 4. For the same depth-averaged velocity, the vertical velocity profile in bends and just downstream of concrete channels tends to have a greater capacity to move the riprap because the velocities near the riprap and the shear stress are larger. For riprap just downstream of concrete channels, the velocity profile has not adjusted from the smooth concrete surface to the rough riprap. For bendways, secondary currents are suspected of causing the change in velocity profile.

In either case, an increased stone size is required. Two choices are available for making this increase. The first of these would involve returning to the basic shear stress equations, developing a velocity profile relationship for the bend or the area downstream of the concrete channel, and determining a new relationship between the shear stress, relative roughness, Shield's coefficient, and applicable velocity profile. Because this is a formidable task and would have made the design procedure difficult to use, the second choice—a completely empirical approach to velocity profile effects—was selected. For riprap just downstream of concrete channels, an empirical velocity profile correction C_V of 1.25 should be used in Equation 1. This increased size need be carried downstream only until the velocity profile has adjusted to the rougher riprap; 5 to 10 flow depths should be adequate. For riprap in channel bends, the velocity profile correction is dependent on the strength of the secondary currents, which is generally related to the parameter R/W. From stability tests in the Riprap Test Facility (RTF), U.S. Army Engineer Waterways Experiment Station, the empirical velocity profile correction to be multiplied by the computed rock size was found to be 1.2 for $R/W = 2.5$. The relationship used for the velocity profile correction given in EM 1110-2-1601 is

$$C_V = 1.283 - 0.2 \log (R/W) \tag{5}$$

where C_V is equal to 1 for $R/W \geq 26$.

A third area where the velocity profile departs significantly from Equation 4 is riprap on the nose of a rock dike. The constricting effect of the dike causes the flow to accelerate rapidly around the dike. Because of the short distance, the flow is affected by the dike and the boundary layer has no chance to grow and is continually being reduced by the flow acceleration. Limited tests show that the velocity profile correction to be multiplied by the rock size should be 1.25 for riprap on the nose of a dike.

Stability Coefficient

Stability coefficients defining the onset of unacceptable rock movement were determined from large-scale laboratory tests. These laboratory tests attempted to simulate mechanically placed riprap on a filter fabric without tamping or smoothing after placement. For thickness = $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater, $C_S = 0.30$ for angular rock. Limited tests show that $C_S = 0.375$ for rounded rock. Note that EM 1110-2-1601 incorrectly gives $C_S = 0.36$ for rounded rock.

Safety Factor

The minimum safety factor to account for nonhydraulic factors and other uncertainties is 1.1. The general tendency in riprap design is to estimate velocity conservatively, which adds in a safety factor. (Figure 2 is generally conservative because the design curve is drawn near the top of the data scatter.) Having to select an available gradation having D_{30}(min) greater than or equal to the computed D_{30} often adds another safety factor. For these reasons, the minimum safety factor is set low, at 1.1. One factor that cannot be easily quantified is the consequence of failure. A larger safety factor should be used for protection works in urban areas than would be used for protection of rural areas.

RIPRAP PACKING

Some Corps districts tamp or pack riprap after placement with a heavy plate or a wide-tracked dozer to achieve increased stability. This action tends to produce a more compact mass of riprap having greater interlock. Limited tests showed that tamping allowed a size reduction 10 percent over normal placement techniques (*3*).

EFFECTS OF FILTER TYPE

The stability tests used in the determination of $C_S = 0.3$ were conducted on a filter fabric. Limited tests showed that place-

ment of riprap on a granular filter allowed a size reduction of 10 percent compared with placement on a filter fabric (*3*). This reduction is considered applicable only to the minimum blanket thickness equal to the maximum stone size ($1D_{100}$). Greater rock thickness would tend to minimize the impact of the filter.

VARIATION OF VELOCITY AND ROCK SIZE UP SIDE SLOPE

In some cases the variation in velocity up the side slope is needed in design, especially when smaller riprap or vegetation is used on the upper slope. Velocity data have been collected in the RTF showing the variation of velocity over the side slope for a bank having the same riprap size from toe of slope to waterline. These data could be used to give an indication of velocities on the upper slope for smaller riprap or vegetation, recognizing that there will be some differences due to the difference in roughness. Figure 5 presents dimensionless depth-averaged velocities over the side slope that were replotted from Maynord for Stations 1+78 and 2+81 in the RTF (*7*). Station 1+78 is at the downstream end of a long straight reach and is unaffected by upstream disturbances. Station 2+81 is at the downstream end of the first bend and is the approximate location of most riprap failures during stability tests in the first bend. Station 2+81 is a severe bend condition because of the large bend angle, large bed roughness, small R/W, and small aspect ratio. These factors combine to produce strong secondary currents that concentrate flow against the outer-bank side slope. Thus Stations 1+78 and 2+81 represent two extremes in terms of secondary current or bend effects. Most bends should fall within these two curves. Figure 5 can be used with Figure 2 to estimate the distribution of maximum depth-averaged side-slope velocity in the bend. The use of depth-averaged velocity distribution given in Figure 5 provides a reasonable estimate of the distribution of forces along the side slope. However, use of the detailed velocity distributions presented in Maynord will provide a better description of forces not only up the side slope but along the bend (*3*).

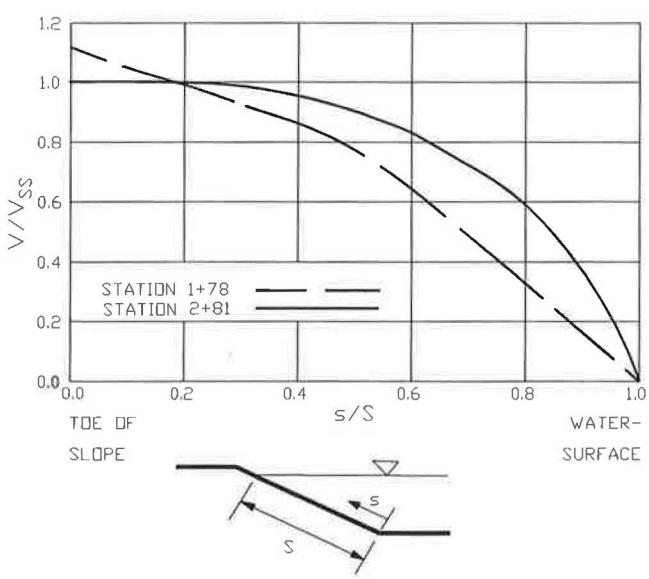

FIGURE 5 Dimensionless side-slope velocity.

EXAMPLE PROBLEMS

The following examples demonstrate the application of the EM 1110-2-1601 procedures. Gradations shown in Table 1 are used for demonstration in some of the examples, but they should not be taken as a recommendation.

Example 1: Bank Protection Only

Problem

Determine stable riprap size for the outer-bank side slope of a natural channel bend in which the maximum velocity occurs at bank-full flow. Water-surface profile computations at bank-full flow show an average channel velocity of 2.2 m/sec (7.1 ft/sec) and a depth at the toe of the outer bank of 4.6 m (15 ft). The channel is wide enough that the added resistance will not significantly affect the computed average channel velocity. A nearby quarry has rock weighing 2643 kg/m^3 (165 lb/ft^3) and can produce the D_{100}(max) gradations of 0.30, 0.38, 0.46, 0.53, and 0.61 m (12, 15, 18, 21, and 24 in.) given in Table 1. A bank slope of 1V:2H has been selected on the basis of geotechnical analysis. A typical blanket thickness of $1D_{100}$(max) will be used in this design with the minimum safety factor of 1.1. Centerline bend radius is 189 m (620 ft), and water-surface width is 61.0 m (200 ft).

Solution

Using Figure 2 with R/W = 189/61 = 3.1 results in V_{ss}/V_{avg} = 1.48 for a natural channel bend. The resulting V_{ss} = 1.48(2.2) = 3.2 m/sec (10.5 ft/sec). Using Equation 1 with C_t = 1, C_V = 1.18 (from Equation 4), K_1 = 0.88, and d = 0.8(4.6) = 3.7 m (12 ft) results in a computed D_{30} = 0.19 m (0.63 ft). Table 1 indicates that of the available gradations, the 0.46-m (18-in.) D_{100}(max) gradation is the smallest, having D_{30}(min) ≥ computed D_{30}. This gradation should be placed to a thickness of $1D_{100}$(max) or 0.46 m (18 in.). This example demonstrates that the actual safety factor is often larger than 1.1 because available gradations are used. In this case the actual safety factor is 0.73/(0.63/1.1) = 1.27.

Example 2: Total Channel Protection

Problem

Determine stable riprap size in a bend of a trapezoidal channel with essentially uniform flow. Bank slope is 1V:2H, and both the bed and banks will be protected with the same size of riprap. The bottom width is 42.7 m (140 ft), channel slope is 0.0017 m/m (0.0017 ft/ft), and the design discharge is 382.6 m^3/sec (13,500 ft^3/sec). Use $1D_{100}$(max) thickness and a nearby

quarry having stone with a unit weight of 2643 kg/m³ (165 lb/ft³) that can produce the D_{100}(max) gradations of 0.30, 0.46, and 0.61 m (12, 18, and 24 in.) given in Table 1. Centerline bend radius is 152.4 m (500 ft).

Solution

In this problem the solution is iterative; flow depth, velocity, and rock size depend on one another because a significant part of the channel perimeter is covered with riprap. Use Strickler's equation $n = 0.036\ [D_{90}(\text{min})]^{1/6}$ from EM 1110-2-1601 to estimate Manning's resistance coefficient. Bend velocity is determined using Figure 2. The solution technique is as follows: assume trial gradation and obtain uniform flow computations in Table 2, and use velocity estimation and riprap size equations to obtain riprap size in Table 3.

This example demonstrates that the increasing rock size for the three trial gradations results in increasing depth and decreasing velocity. The minimum acceptable gradation is the 0.46-m (18-in.) D_{100}(max) gradation placed to a blanket thickness of 0.46 m (18 in.).

Example 3: Design for Thickness Greater Than $1D_{100}$

If a thickness greater than $1D_{100}$(max) is specified, smaller gradations can be used if available. This option frequently requires that the blanket thickness be larger than the thickness for rock placed to $1D_{100}$(max). Using Example 1 and specifying a thickness parameter N of 1.2 in Figure 1 (determined by trial and error) results in a computed D_{30} = 0.18 m (0.59 ft) and an 0.46-m (18-in.) blanket thickness of the Table 1 gradation having a D_{100}(max) = 0.38 m (15 in.). Although both the gradations from Example 1 and this example will remain stable for the design conditions of Example 1, the two gradations are not equal in stability because the real safety factor for the D_{100}(max) = 0.38 m (15 in.) gradation placed to a thickness of 0.46 m (18 in.) is 0.61/(0.59/1.1), or 1.14.

Using Example 1 again, suppose a gradation has a unit weight of 2643 kg/m³ (165 lb/ft³), D_{85}/D_{15} equals 5.2, D_{30}(min) equals 0.12 m (0.40 ft), and D_{100}(max) is 0.43 m (17 in.). Since a D_{30}(min) of 0.12 m (0.4 ft) is less than the required D_{30} of 0.19 m (0.63 ft), a thickness of $1D_{100}$(max) will not be stable. What thickness would be required to maintain stability for the conditions of Example 1? Try various thickness parameters N from Figure 1 to determine the minimum stable thickness. Table 4 gives the results of this trial-and-error analysis. Use of this alternative gradation for Example 1 would require a blanket thickness of 0.76 m (30 in.) because the D_{30}(min) of 0.12 m (0.4 ft) is equal to or greater than the required D_{30} of 0.12 m (0.40 ft). This gradation placed to a 0.76-m (30-in.) thickness satisfies the requirements of Example 1 but is not exactly equal in stability to the previously determined gradations in Table 1 because the actual safety factor is different.

TABLE 2 Uniform Flow Computations

Trial D_{100}(max) (in.)	Manning's n	Normal Depth (ft)[b]	Water-Surface Width (ft)	Average Velocity (fps)[a]	Side Slope Depth, ft
12	0.034	10.6	182.4	7.9	8.5
18	0.036	11.0	184	7.6	8.8
24	0.038	11.3	185.2	7.3	9.0

[a]1 in. = 25.4 mm.
1 ft = 0.305 m.
[b]From iterative solution of Manning's equation
$Q/A = (1.49/n)R^{2/3}S^{1/2}$

TABLE 3 Velocity Estimation and Riprap Size

Trial D_{100} (max) (in.)	Thickness (in.)	V_{ss}[b] (fps)	Computed D_{30}[c] (ft)	D_{30} (min) of trial[d] (ft)
12	12	10.8	0.73	0.48
18	18	10.4	0.66	0.73
24	24	10.0	0.59	0.97

[a]1 in. = 25.4 mm.
1 ft = 0.305 m.
[b]From Figure 2 using trapezoidal channel.
[c]From Equation 1.
[d]From gradation information given in Table 1.

TABLE 4 Alternative Thickness Computations

N = Thickness / D_{100} (max)	Thickness, (in[a])	C_T from Figure 1	Required D_{30} (ft)
1.5	26	0.76	0.48
1.75	30	0.64	0.40
2.0	34	0.53	0.33

[a]1 in. = 25.4 mm.
1 ft = 0.305 m.

Example 4: Riprap Downstream of Concrete Channel

Problem

The channel shown in Figure 6 suffered riprap failure at Point A and a sediment deposit at Point B. Because the concrete channel is expanding faster than the flow can expand, an eddy formed on the left side of the downstream end of the concrete channel. Observers reported that the left third of the channel had upstream flow. The average velocity (Q/A, where A is total area) at the end of the concrete was 2.4 m/sec (8 ft/sec) and flow was subcritical. Use a unit stone weight of 2643 kg/m^3 (165 lb/ft^3), thickness of $1D_{100}$(max), and flow depth at Point A of 4.6 m (15 ft). Determine stable gradation from Table 1 for riprap placed just downstream and estimate how far to extend downstream.

Solution

The most difficult and uncertain aspect of this problem is estimating the velocity at Point A. Prototype data do not exist, and numerical or physical models cannot be justified. This problem is caused by the flow concentration caused by the eddy, which makes the effective cross-sectional area less than the actual area, and by the abrupt change in roughness from the concrete to the riprap. Assuming that only two-thirds of the channel area at the downstream end of the concrete channel is passing flow, then the average velocity through this effective area will be 2.4/(2/3), or 3.7 m/sec (12 ft/sec). If 3.7 m/sec (12 ft/sec) is the average, then higher velocity should be found near the center of the effective area, which is the location of the previous failure at Point A. A depth-averaged velocity of 4.0 m/sec (13 ft/sec) will be used for this design. Figure 2 does not apply to cases such as this example. Using Equation 1 where $K_1 = 1.0$, $C_t = 1.0$, $C_V = 1.25$, and $d = 4.6$ m (15 ft) results in a required D_{30} of 0.27 m (0.90 ft). This requires the gradation in Table 1 having D_{100}(max) of 0.61 m (24 in.) and D_{30}(min) of 0.30 m (0.97 ft) placed to a thickness of 0.61 m (24 in.). To allow the vertical velocity profile to adjust, the larger rock should be placed 5 to 10 channel depths downstream. To allow the flow to achieve a uniform distribution across the channel, the larger rock should be placed 3 to 5 channel widths downstream. The larger of the two values (5 to 10 channel depths or 3 to 5 channel widths) should be used in design.

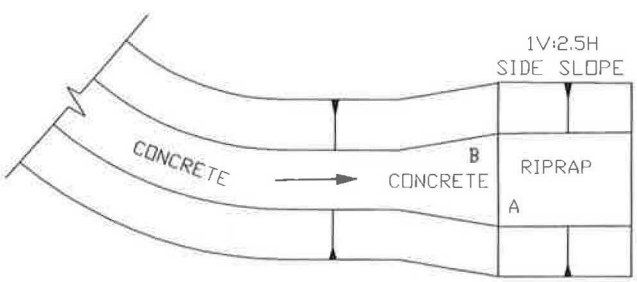

FIGURE 6 Plan view of channel in Example 4: (*a*) riprap failure, (*b*) sediment deposition.

PC PROGRAM

A PC program, RIPRAP15, incorporating these procedures has been developed and is available from the author.

SUMMARY AND CONCLUSIONS

The riprap design procedure presented herein is applicable to bank and channel protection in low-turbulence environments. Local depth-averaged velocity was selected over shear stress as the basis for this procedure because methods are available for estimating depth-averaged velocity and because many designers will not use procedures that are based on shear stress.

This method has several empirical coefficients analogous to the Shields coefficient that take into account the effects of rock shape, blanket thickness, and side-slope angle. The traditional Carter et al. relationship is more conservative than the empirical curve presented herein for side-slope effects (*8*). Another empirical coefficient is used to account for changes in the vertical velocity profile such as those occurring in bendways or downstream of concrete channels. This empirical approach was chosen because a theoretical approach would have been unfriendly to most users of riprap design guidance.

Gradation effects are addressed by using D_{30} as the characteristic particle size in lieu of the commonly used D_{50}. Equation 2 relates D_{50} to D_{30} and D_{85}/D_{15} for designers who prefer to use D_{50}.

Blanket thickness and gradation must both be specified to define the stability of a revetment. A uniform riprap can be placed to a large thickness with only a small increase in stability over the minimum blanket thickness. However, a nonuniform riprap placed to a large thickness will be much more stable than the minimum thickness of the same gradation. The method presented herein defines the stability of a wide

range of gradation and thickness, and design examples show how the method is applied to several cases.

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