APPENDIX C

METHODS FOR RIPRAP DESIGN

Sizing riprap is complicated by the wide range of variability in river channel characteristics. Because of this variability, designers often resort to simple equations and nomographs. Typically these methods use an average water velocity as the main criterion. There are limitations with this approach. A velocity-only method does not account for other river characteristics, such as flow depth, that influence rock size. Another factor is that the velocities used in these approaches represent the average velocity across the cross-section.

Bank erosion is a function of the tractive force, which involves flow depth and velocity, and the characteristics of the flow immediately adjacent to the streambank. The velocities typically used for design purposes are often computed using one-dimensional analytical techniques such as HEC-2. A one-dimensional analysis, however, does not account for flow variations across the width of the channel, or for local hydraulic phenomena such as helical flow at the outside of bends. These factors, which are often not quantified in the design technique, are usually left to the judgement of the designer.

Based on the level of experience of the designer and the complexities of the site, the computed size of the rock is frequently rounded up to the next standard class as a factor of safety. King County's *Surface Water Design Manual* (1990), for example, provides specific procedures and a nomograph, developed by the U.S. Army Corps of Engineers (Corps), for computing the median stone size based on flow velocity. The manual then cautions the user that, "If the rip rap [specified using this methodology] is to be used in a highly turbulent zone...the median stone should be increased from 200 to 600 percent depending on the severity of the locally high turbulence." Depending on the designer's judgement, an extremely high variance in the design size of the rock may result.

An additional complication exists in that the computed rock size (usually specified in terms of the median stone size or D_{50}) does not always precisely match riprap classifications (e.g., light loose riprap). King County commonly uses two classes of riprap: light loose and heavy loose riprap. The classes, taken from the Washington State Department of Transportation's (WSDOT) specifications, delineate the size range and gradation for each class. In practice, the actual size of rock obtained varies with the quarry from which it is acquired.

Placement of the riprap may also effect how well the design specifications are met. In the past, the County's usual method of placing riprap was to grade the bank, end dump the riprap, then shape the rock layer with a dragline. The largest material from the delivered gradation was used in the toe section. While the concept of placing the largest rock at the toe is valid, it unfortunately reduces the amount of large rock available for the upper bank. This results in a facing that does not meet the specifications for either light or heavy loose riprap.

RIPRAP SIZING

Many agencies have developed various approaches to sizing riprap. These methods should be applied carefully to western Washington rivers as many of them were derived from laboratory studies and tested in other regions of the country. Three recommended methods for sizing riprap are discussed below. Two of these methods were developed by the U.S. Army Corps of Engineers. The first method was developed by Maynord et al. (1989); the second is an updated method, based on the research of Maynord et al., that incorporates a larger number of variables in the operative equations (USACOE 1991). The third method discussed is that of Richardson, Simons and Julien (1990). For a detailed discussion of these methodologies, the reader is referred to the original publications.

MAYNORD METHOD

Maynord et al. propose using a single layer of riprap on top of a filter. In their analysis, failure was defined as the exposure of the material underlying the riprap. This method does not define a riprap size that will not be removed during the design event, but a gradation that will effectively sort and lock together so as not to expose the filter layer or natural channel bank. The riprap size found to best characterize the gradation was the D_{30}. It is defined as follows:

$$\frac{D_{30}}{Y} \geq SF * C * \left(\frac{\Gamma_w}{\Gamma_s - \Gamma_w}\right)^{1.25} * \left(\frac{V}{(gY)^{0.5}}\right)^{2.5}$$

Where:

D_n = Riprap particle size in feet; n percent of riprap is finer by weight. This particle size, which is considered the equivalent spherical diameter, is the common method of specification. Because the rock will not be spherical, the actual dimensions will vary.

Y = Depth of water in feet.

SF= Factor of safety. Use 1.20.

C = Stability coefficient. For $Z = 2$ or flatter, use $C = 0.30$; for $1.5 \leq Z \leq 2$, use $C = 0.6 - 0.15*Z$.

Z = Channel side slope (horizontal offset for one foot vertical increase).

Γ_w = Specific weight of water.

Γ_s = Specific weight of stone.

V = Local velocity (fps). If unknown, use $1.5 * V_{avg}$.

g = Gravitational acceleration (32.2 feet per second squared).

It is important to note that Maynord et al. use D_{30} as the characteristic size while other methodologies use D_{50}. From laboratory tests, they found if D_{30} was used as the characteristic size that the coefficient

C was constant regardless of gradation. To calculate D_{50} accurately, this coefficient must be varied as it depends on the gradation used.

The acceptable range of gradations meet the following criteria (assumptions listed in design equation above.):

$$1.8\ D_{15} \le D_{85} \le D\ 4.6\ D_{15}$$

Unfortunately, specifications for D_{15}, D_{30}, and D_{85} do not correlate well with the rock gradations commonly used in western Washington. Until revised standards for King County are developed, the WSDOT's specifications are the most efficient to use. Listed below are the WSDOT classification for computing each D_{30}. This listing was derived by comparing WSDOT specifications with gradations proposed by Maynord et al. and the Corps.

For $D_{30} \le$ 3-inch, use quarry spalls.

For 3-inch < $D_{30} \le$ 15-inch, use light loose riprap.

For 15-inch < $D_{30} \le$ 18-inch, use heavy loose riprap.

For D_{30} > 18-inch, the rock gradation must be explicitly specified.

Maynord et al. assume only a single layer of riprap of thickness D_{100} (with necessary filters). Qualitatively, there is an inverse relationship between necessary stone size and necessary blanket thickness. Thus, if a thicker riprap blanket is used, then a smaller D_{30} can be chosen. This approach, however, may cause movement of more of the smaller rock at the design discharge, and may therefore require more frequent maintenance.

The ability to use vegetative methods such as joint planting is diminished by additional riprap depth. It is recommended that the stone size be based on the analytical technique developed by Maynord et al., and the blanket then be designed to a thickness of D_{100} (i.e., the riprap layer should be as thick as the largest rock in the sample). For the three standard WSDOT gradations, the blanket thickness should be as follows:

Quarry spalls, minimum thickness = 8-inch

Light loose riprap, minimum thickness = 30-inch

Heavy loose riprap, minimum thickness = 36-inch

A potential limitation in using this procedure for sizing riprap for King County rivers is that the experimental data used in its development were limited to channel slopes of less than two percent and Froude numbers less than 1.2. For extremely steep rivers with turbulent flow, further analysis and study may be required. While Maynord et al. did not rule out the application of this method to rivers outside these limits, they suggest that care be taken since the user would be extrapolating rather than interpolating from the experimental data.

Additional analysis of the laboratory testing and modeling conducted by Maynord et al. resulted in updated design equations (USACOE 1991). The basic equation in Maynord et al. was updated as follows:

$$D_{30} = SF * C_S * C_V * C_T * Y \left[\left(\frac{\Gamma_w}{\Gamma_s - \Gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5}$$

All variables are the same as in the previous equation, with the following additions:

C_s = Stability coefficient for incipient failure. Use 0.30 for angular rock; 0.36 for rounded rock.

C_V = Vertical velocity distribution coefficient. Use 1.0 for straight channels, 1.25 for ends of dikes and downstream of concrete channels; and 1.283-0.2 log(R/W) for outside of bends (1 for R/W > 26).

where:
R = center-line radius of bend
W = water surface width

C_T = Thickness coefficient. Use 1 for blanket thickness of 1 D_{100}. For other thicknesses, refer to USACOE (1991) to determine the coefficient.

K_1 = Side slope correction factor

$$= \sqrt{1 - \frac{\sin^2\Theta}{\sin^2\Phi}}$$

where:
Θ = angle of side slope with horizontal
Φ = angle of repose of riprap material (normally 40°)

This equation adds considerable complexity to Maynord et al.'s original method. Perhaps because of this, the Corps suggest a slightly decreased factor of safety of 1.1. This factor should be increased when unusual characteristics exist such as high potential for impact forces from debris. The safety factor could also be increased to account for other circumstances such as expected inaccuracies in computation of hydraulic parameters or difficult placements.

RICHARDSON, SIMONS, AND JULIEN (1990).

This method is based on flow velocities and depths, and involves a trial-and-error approach beginning with an assumed D_{50}. The designer then uses the nomograph in Figure C.1 to compute the velocity against the stone. The ratio of the velocity against the riprap, V_s, to the mean channel velocity, V_m, is related to the ratio of the stone diameter, D_{50}, to the flow depth, y_o, by the curve in the nomograph. When the total depth of flow exceeds approximately ten feet, the ratios should be computed using 0.4 of the actual flow depth instead of the depth itself. This will yield a riprap size sufficient throughout the cross section. After defining the velocity against the stone using Figure C.1, the next step is to determine the D_{50}. This is accomplished using Figure C.2, which is based on both velocity and riprap side slope. If the D_{50} computed in this manner does not agree with that originally assumed, then the process must be repeated. These nomographs assume that the unit weight of the rock is 165 pounds per cubic foot. If the rock is of a different weight, then the stone size should be corrected using the following equation:

$$D'_{50} = \frac{102.5 * D_{50}}{\Gamma_s - 62.5}$$

where:

D'_{50} = actual stone size for unit weight being used

D_{50} = stone size computed from nomographs

Design velocities should be increased for installations protecting banks from direct flow impingements such as at the outside of sharp bends. Richardson, Simons and Julien provide two estimates of the necessary increase in velocities. One is from the California Division of Highways, who recommend doubling the velocity against the stone for sharp bends. The other estimate is from Lane, whose analysis would require the velocity against the stone to be increased by 22 percent for very sinuous channels. In any case, the velocity should be increased to account for the bend. A factor between 1 and 2 is recommended, depending on the severity of the attack.

Because this method computes the D_{50} rather than the D_{30}, the correlations to the WSDOT classifications differ from those listed previously.

For $D_{50} \leq$ 4-inch, use quarry spalls

For 4-inch $< D_{50} \leq$ 22-inch, use light loose riprap

For 22-inch $< D_{50} \leq$ 30-inch, use heavy loose riprap

For $D_{50} >$ 30-inch, the rock gradation must be explicitly specified

Figure C.1 Nomograph for determining D_{50} based on velocity and flow depth. (From FHWA 1967.)

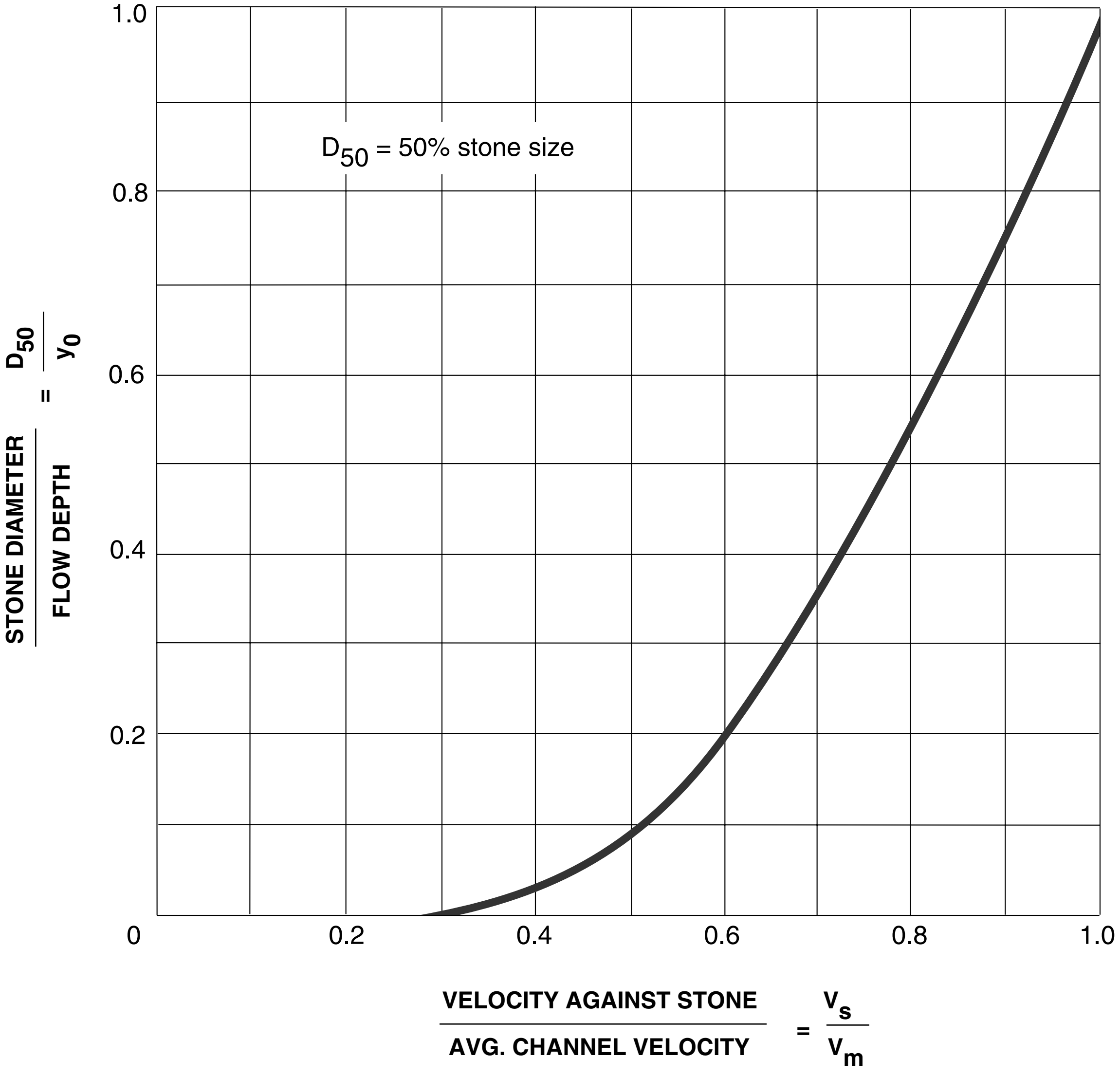
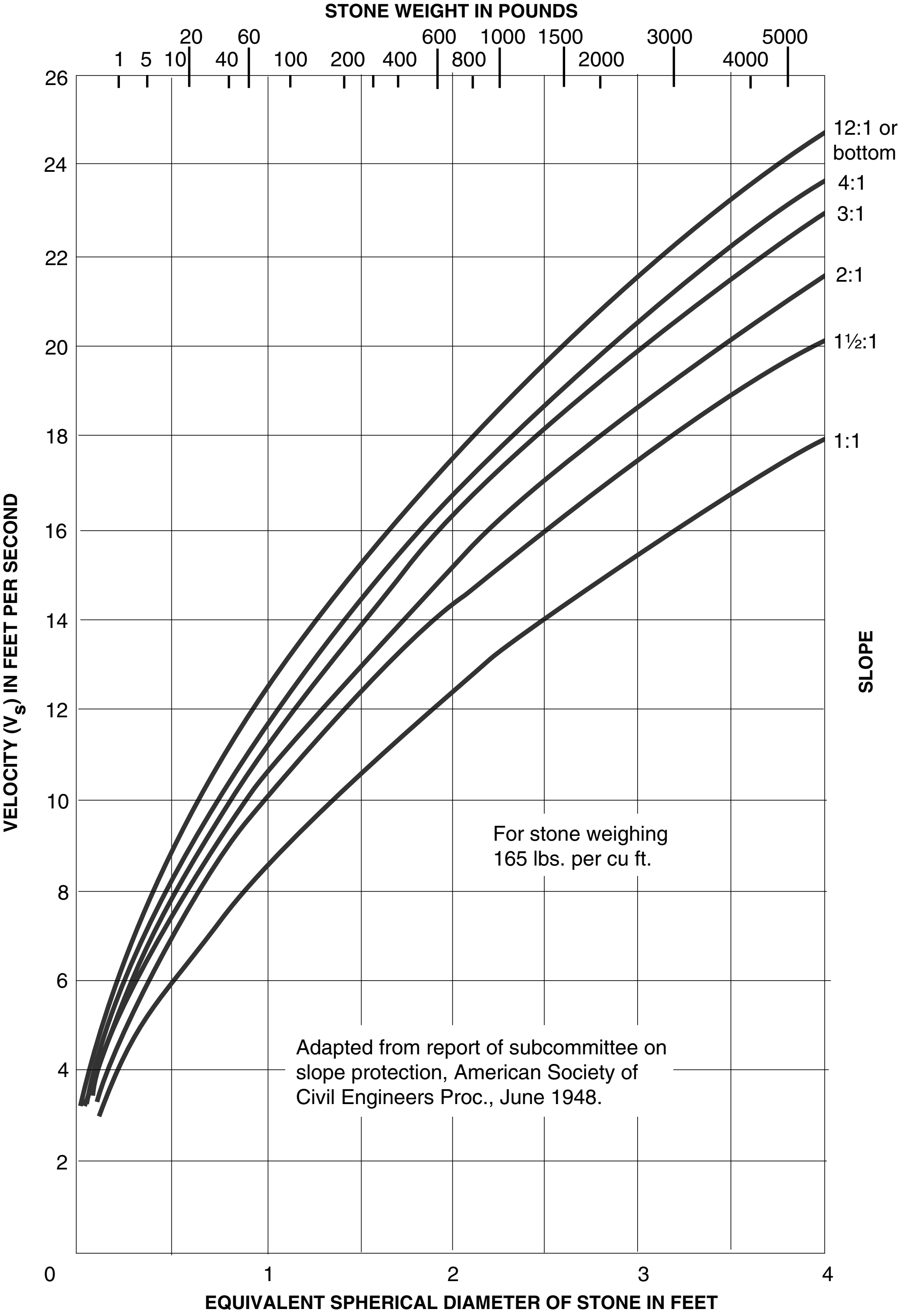


Figure C.2 Nomograph for determining the stone size based on velocity and side slope. (From FHWA 1967.)



FILTER DESIGN

While the King County *Surface Water Design Manual* allows the use of a filter fabric, it does not specify fabric selection. The manual provides criteria for design and evaluation of filter material (well-graded gravel) under riprap. A set of relationships, listed below, has been established for analyzing the adequacy of the material interface between the armor layer and the protected material underneath. For large riprap such as heavy loose, a filter layer will generally be necessary. If the natural channel banks consist of a fine alluvium, it may be advantageous to place a filter fabric, then a rock filter layer, and finally the riprap itself. The *Surface Water Design Manual* does not specify the filter blanket thickness. In practice, a well-graded 8-inch thick layer of quarry spalls and smaller material should work well as a filter layer for light or heavy loose riprap .

The relationships themselves are useful when increased precision is desired. To use these relationships, analyze the interface between the natural bank material and the armor layer to be utilized. If the relationships are not satisfied, a filter layer (or layers) must be added so that they hold true across each material interface. The relationships are as follows:

$$D_{15} \leq 5\ d_{85}$$

$$4\ d_{15} \leq D_{15} \leq 20\ d_{15}$$

$$D_{50} \leq 25\ d_{50}$$

where:

D_n = Armor-layer particle size; (n percent of armor layer material is finer by weight.)

d_n = Protected or filter layer particle size; (n percent of protected layer material is finer by weight.)

SPECIAL CASES

When the practice of placing the largest rock of the gradation at the toe results in smaller than specified rock for the face, the designer can order 80 percent of the rock using one of the usual classifications, and the other 20 percent as sorted, large rock (often known as “rockery rock”). This toe rock would then be of fairly uniform gradation, computed to be large enough to withstand expected erosive forces, while the face of the structure would still have stone that meets the desired specifications. The large sorted rock would tend to be more expensive, but using it for only 20% of the overall project would limit the increase in costs.

The riprap design methods discussed above may not be appropriate for sizing riprap used in combination with large woody debris in the toe section of the bank to provide cover for fish. Rather than cable the root wads or logs into the bank, they can be anchored with large individually placed rocks. A method for sizing this rock is needed as it is not part of a blanket layer and must therefore withstand the force of the flow by itself. The method must examine the incipient motion conditions, i.e., the velocity and/or force required to begin to move the individual rock, either through sliding or rolling. If the rocks are large enough, they can provide habitat benefits in the form of cover and refuge for anadromous fish during high flows.

SUMMARY TABLES

The following four tables provide information on riprap specifications and gradations related to rock diameters discussed in the design methods above. These tables will aid the designer in specifying riprap gradations and also will assist in correlating the sizes in the design gradations to standard rock specifications.

Table C.1 Riprap sizes and corresponding weight.

Equivalent Diameter (inches)	Weight[1] (pounds)
3	1
6	11
9	36
12	86
15	170
18	290
21	460
24	690
27	980
30	1350
33	1800
36	2300
39	3000
42	3700
48	5500
54	7900
60	10800

[1] Assumes spherical rock at 165 pounds per cubic foot.

Table C.2 King County riprap specifications by weight and least dimension. (King County 1987.)

Specification	Weight Range (pounds)	Least Dimension (inches)
Two-man rock	300 to 600	13
Three-man rock	800 to 1200	16
Four-man rock	1500 to 2200	18

Table C.3 **Washington State Department of Transportation riprap specifications related to D_{30} and D_{50} diameters. (Adapted from WSDOT 1991.)**

Class	Specification	Interpreted D_{30} (inches)	Interpreted D_{50} (inches)
Quarry Spalls	100% must pass 8 in. sieve 40% max must pass 3 in. sieve 10% max must pass 0.75 in. sieve	$D_{30} < 3$	$D_{50} < 4$
Light Loose Riprap	20 to 90% should be between 300 lbs. (2 cu. ft. to 0.5 cu. yd.)	$3 < D_{30} < 15$	$4 < D_{50} < 22$
	80% should be between 50 lbs. to 1 ton (0.33 cu. ft. to 0.5 cu. ft.)		
Heavy Loose Riprap	10 to 20% should have a maximum size of 50 lbs. (spalls)	$15 < D_{30} < 18$	$22 < D_{50} < 30$
	40 to 90% should have a maximum size of 1 ton (0.5 cu. yd.)		
	70 to 90% should have a minimum size of 300 lbs. (2 cu. ft.)		
	10 to 30% should have a maximum size of 50 lbs. (spalls)		

Table C.4. Comparison of riprap gradations recommended by various agencies.[1]

	Relationship to D_{30} Diameter		Relationship to D_{50} Diameter		
Diameter	USACOE (1991)	Richardson et al. (1990)	USACOE (1991)	Richardson et al. (1990)	Washington Dept. of Ecology (1992)
D_0	NS[2]	0.38	NS	0.25	0.25
D_{15}	0.75	0.66	0.64	0.43	NS
D_{30}	1.00	1.00	0.85	0.65	NS
D_{50}	1.17	1.54	1.00	1.00	1.00
D_{85}	1.40	2.70	1.20	1.75	NS
D_{100}	1.50	3.08	1.28	2.00	1.25 to 1.5

1. The values for these gradations have been adapted and interpreted from the cited references.
2. Not Specified.

RECOMMENDED SOURCES FOR ADDITIONAL INFORMATION

Richardson, E.V., D.B. Simons, and P.Y. Julien. 1990. Highways in the River Environment, Federal Highway Administration.

Maynord, S.T., J.F. Ruff, and S.R. Abt. 1989. Riprap Design. Journal of Hydraulic Engineering. American Society of Civil Engineers.

King County Dept. of Public Works. 1990. Surface Water Design Manual. Surface Water Management Division. Seattle, Wash.

U.S. Army Corps of Engineers. 1991. Hydraulic Design of Flood Control Channels, July 1, 1991. EM 1110-2-1601.