V. STEEP SLOPE CHANNEL DESIGN

5.1 Introduction

The design of steep conveyance channels is a critical step in developing an adequate drainage network on a surface mine site. Steep slope conditions are typical of the natural watersheds in the mining regions of Appalachia. Additionally, man-made spoil fill slopes involve the conveyance of water on slopes of steep angle. The success or failure of these conveyances, typically intermittent or ephemeral streams, determines the sediment load delivered to the downstream environment. Therefore, steep slope conveyances must be adequately designed to insure the long-term success of the drainage network.

Achieving channel stability on steep slopes usually requires some type of channel lining. The only exception is a channel constructed in durable bedrock. In this case, the permissible velocity design approach given in Chapter VI can be utilized. Rock riprap is the most commonly used channel lining on surface mine sites, but adequate procedures for its design are not readily available. Most all riprap design procedures were developed for mild slope channels (typically less than ten percent) and their use in the steep slope conditions of Appalachia does not produce a reliable design.

Therefore, in this chapter a riprap design procedure developed exclusively for steep slope conditions is presented. The graphical design procedure is simple to apply and provides an accurate design based on the conditions that exist. The success of any riprap-lined channel depends on factors other than simply sizing the rock required. Of particular importance to a successful riprap-lined channel is the gradation and placement of the riprap (section 5.2.6). These two criteria are probably the most difficult to follow for surface mine operators in the Appalachia region. The blast rock typically used for riprap in steep channels is large enough, but usually not adequately graded to the smaller sizes. Placement of the large rock on the steep slopes is difficult to accomplish, particularly when constructing relatively small channel cross sections with the large rock. The steep slope riprap design procedure presented herein provides an adequate design, however, these other two criteria may determine the success or failure of a channel, and perhaps even the feasibility of designing and constructing such channels. The West Virginia alternative of chimney drains, even with the potential problems of plugging by sediment deposition, provides a viable alternative.

However, it is felt that additional research is needed to establish their long-term functioning.

Prior to presenting the steep slope design procedure, consideration is given to the other important concepts of riprap design. These concepts are applicable to both mild and steep slopes and are an integral part of any riprap design.

5.2 General Riprap Considerations

5.2.1 Definition of Riprap

Riprap consists of a layer of discrete fragments of durable rock possessing sufficient size to withstand the dynamic, erosive forces generated by the flow of water. The protective qualities of a riprap-lined channel lie somewhere between those of a grassed waterway and a concrete-lined channel. Dumped riprap is extensively used on surface mine sites due to the availability of rock, and the conduciveness of this method to placement by readily available mechanized equipment.

Proper design of a riprap channel lining requires consideration of many factors. The desired level of protection may not be provided by the riprap if design criteria concerning rock gradation, riprap thickness, and filter design are not considered. This section discusses general riprap design considerations applicable to riprap protection on both mild and steep slopes.

5.2.2 Types of Riprap

There are many means and methods by which riprap protection can be constructed and placed. Hydraulic Engineering Circular No. 11 (Searcy, 1967) entitled "Use of Riprap for Bank Protection" provided the following categorization of riprap materials and methods of placement:

- Dumped riprap
- Hand-placed riprap
- Wire-enclosed riprap
- Grouted riprap
- Concrete riprap in bags
- Concrete slab riprap

5.2.3 General Considerations

The important factors to be considered in designing rock riprap protection are:

1. Durability of the rock (Chapter VIII)
2. Density of the rock
3. Velocity (both magnitude and direction) of the flow in the vicinity of the rock
4. Slope of the bed or bankline being protected
5. Angle of repose for the rock
6. Size and weight of the rock
7. Shape and angularity of the rock
8. Filter considerations

Rock riprap should (Soil Conservation Service, 1977):

1. Assure stability of the protected bank as an integral part of the channel as a whole. For this major objective, the ideal condition for stability is a straight channel or a gently curved channel with its outer bank rougher and more erosion resistant than the inner bank.
2. Tie to stable natural bank or other fixed improvements with transitions designed to ease differentials in alignment, grade, slope and roughness of banks.
3. Eliminate or ease local irregularities so as to streamline the protected bank.

When available in sufficient size, dumped rock riprap is usually the most economical material for bank protection. Dumped riprap has many advantages over other types of protection, including its flexibility and the ease of local damage repair. Construction must be accomplished in a prescribed manner but is not complicated. When proper consideration is given to filter requirements and grading of the bed foundation problems will be minimal. Appearance of dumped riprap is natural, and after a time vegetation will grow between the rocks. Wave runup on rock slopes is usually less than on other types. Finally, in temporary channels when the usefulness of the protection is finished, the rock is salvageable. Additionally, most riprap used on surface mining operations is dumped riprap. Therefore the following discussion concentrates on this type of riprap.

5.2.4 Properties of Rock Used as Riprap

Riprap should be hard, dense and durable to withstand long exposure to weathering. Visual inspection by a knowledgeable inspector is most often adequate to judge quality, but laboratory tests may be made to aid the judgment of the field inspector (see section on rock durability).

Rocks used for riprap should be blocky in shape, as they will tend to "nest" together, providing greater resistance to movement. Riprap consisting of angular stones is more suitable than that consisting of rounded stones due to their greater angle of repose (see Figure 4.3). These criteria are reflected in stone shape limitations given by the U.S. Army Corps of Engineers (1970) which specify:

1. The stone shall be predominantly angular in shape.

2. Not more than 25 percent of the stones reasonably well distributed throughout the gradation shall have a length more than 2.5 times the breadth or thickness.

3. No stone shall have a length exceeding 3.0 times its breadth or thickness.

These limitations apply only to the stone within the riprap gradation and not to any durable spalls and waste that may be allowed. When a high percentage of durable wastes or spalls is allowed or quarry run stone is used that does not meet the above-listed limitations, an increase in riprap thickness should be provided.

5.2.5 Riprap Gradation and Placement

Lack of a proper riprap gradation is one of the most common causes of riprap failure. Riprap gradation simply implies that the riprap should be composed of a distributed size range of rock. With distributed size range, the interstices formed by the larger stones are filled with the smaller sizes in an interlocking fashion that prevents formation of open pockets. Open pockets in a riprap layer allow jets of water to contact the underlying soil, resulting ultimately in the erosion of material supporting the riprap layer.

Riprap gradation guidelines are commonly given by defining the D_{max} and the D_{10} or D_{20} size as some percentage of the D_{50} size. These three points (D_{max} , D_{50} and D_{10} or D_{20}) are then plotted on semilog graph paper and a smooth S-shaped curve drawn through them to define the entire gradation

range. Recommended values for the D_{max} size range from 1.3 to 2.0 times the D_{50} size, with 2.0 being the most commonly used. The value for the D_{10} to D_{20} size ranges from 0.20 to 0.30 times the D_{50} size.

These guidelines were developed for use with mild slope riprap design procedures where the D_{50} size is usually relatively small. Consequently, they produce adequate designs with a well distributed size range and D_{max} sizes that are reasonable. However applying this D_{max} criteria to a steep slope riprap design does not produce reasonable results. Due to the large D_{50} sizes typical of the steep slope riprap design procedure (see Section 5.3), the resultant D_{max} sizes are unrealistic and impractical particularly considering placement and channel excavation requirements (see Section 5.2.6). Additionally, the recommended steep slope riprap design procedure produces a conservative estimate of the D_{50} size. Therefore, the stability of the riprap should not require a large gradation above this size. In this situation it is more important to establish a smooth gradation to the smaller sizes to avoid large voids.

Therefore, the recommended riprap gradation for protection on steep slopes is that the maximum rock size D_{max} be no larger than 1.25 times the median size D_{50}. On mild slopes the upper limit for D_{max} should be increased to two times D_{50}. To maintain a large safety factor and a conservative design the ratio between the median diameter and the 10 to 20 percent size should be in a range of two to three for both steep and mild. Table 5.1 gives the suggested riprap gradation limits. Figure 5.1 qualitatively presents the gradation curves that result by using these guidelines and indicate their reasonableness. Control of the gradation of riprap is almost always made by visual inspection.

Improper placement of a properly designed riprap is another cause of failure. Riprap placement is usually by dumping directly from trucks. If riprap is placed during construction of the embankment, rocks can be dumped directly from trucks from the top of the embankment. To prevent segregation of sizes, rock should never be placed by dropping down the slope in a chute or pushed downhill with a bulldozer. With proper equipment dumped riprap can be placed with a minimum of expensive hand work. Poorly graded riprap with slab-like rocks requires more work to form a compact protective blanket without large holes or pockets. Draglines with orange peel buckets, backhoes and other power equipment can also be used advantageously to place the riprap.

Table 5.1. Recommended Riprap Gradation Limits*.

	Steep Slope	Mild Slope
$\frac{D_{max}}{D50}$	1.25	2
$\frac{D_{50}}{D_{10-20}}$	2-3	2-3

*i.e., if D_{50} is 12 inches for a steep slope riprap, then

$$\frac{D_{max}}{D_{50}} = 1.25; \quad D_{max} = 1.25\ (D_{50})$$

$$= 1.25\ (12) = 15 \text{ inches.}$$

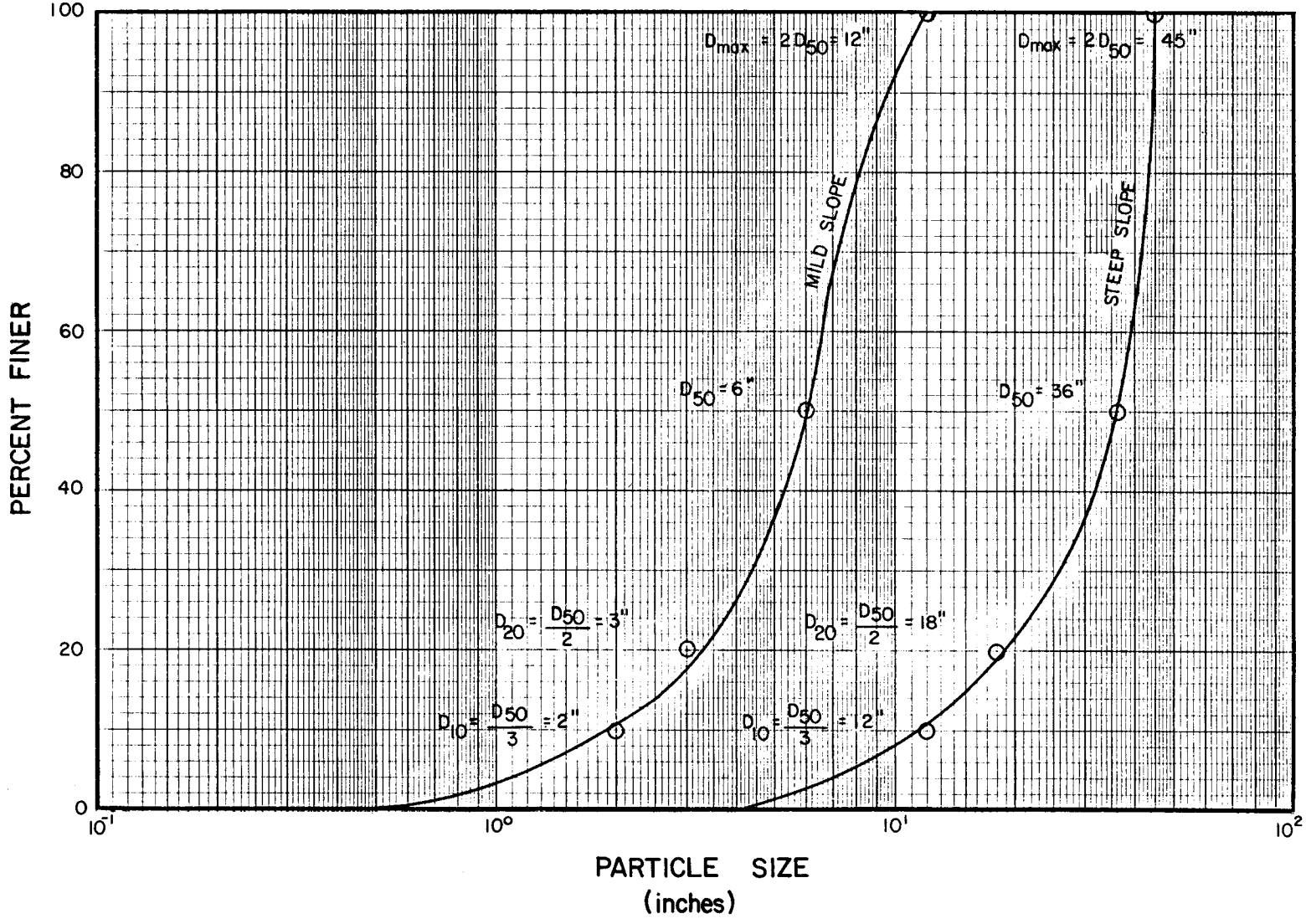

Figure 5.1. Definition sketch illustrating steep and mild slope riprap gradation based on recommended guidelines.

5.2.6 Riprap Thickness

The thickness of the riprap layer should be sufficient to accommodate the largest rock in the riprap material. Maximum resistance to the erosive forces of flowing water is obtained when individual stones are contained within the riprap layer thickness. Oversize stones that protrude above the riprap layer should be avoided since they reduce capacity and influence riprap stability. According to the Corps of Engineers (1970), "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." Where few oversize stones exist, these should be removed individually and replaced by appropriately sized rock. In instances where many oversized rocks exist, consideration should be given to remedial measures. Corrective actions could include using methods to remove the oversize stone, obtaining the stone from another source, or increasing the riprap layer thickness to contain the larger stone (Corps of Engineers, 1970).

The actual thickness of a riprap channel lining depends to a large extent upon experience and engineering judgment. Similar to gradation specifications, recommendations of layer thickness vary from about 1.3 to 2.0 times the median rock diameter D_{50} of the riprap in order to accommodate the D_{max} size. Therefore, for riprap linings on steep slopes a design value of 1.25 is recommended. A conservative riprap layer thickness of 2.0 times D_{50} is recommended for riprap applications on mild slopes.

In constructing the channel the depth of excavation must be adequate to accommodate the thickness of the riprap and filter layers. Therefore, any unnecessary increase in riprap thickness can significantly increase excavation and overall construction costs. If the design has been carefully and properly completed, there should be no need for the designer to recommend, nor the construction crew to build, a thicker lining.

5.2.7 Filter Layers

It is usually necessary to place a filter layer beneath riprap material to prevent leaching of the underlying soil and possible resultant bank stability problems. Without a filter layer the loss of underlying soil can occur in several ways. During high flows the lift and drag forces created by movement of water through the channel can create an uplift pressure. This

pressure can generate enough suction to draw soil particles vertically through the voids in the riprap. Also during high flows, turbulent eddies and jets can penetrate the riprap lining through the voids in the riprap causing detachment and erosion of the underlying soil. Finally, during all flows, but more visable during low flows, water can move at the interface between the riprap layer and the underlying soil. If large enough voids are present, erosion can be significant, particularly if the underlying material is an erodible fill. In all cases the loss of soil can result in the formation of cavities with potential failure from the loss of support. The use of a properly designed filter layer will minimize this occurrence and greatly increase riprap stability.

The actual need for a filter layer is dependent upon the gradation and cohesion of the bank material as well as the relative size difference between the riprap particles and soil particles. However, in most surface mine situations a filter layer will be necessary. Suitable material for the filter can usually be obtained from the same strata as the rock riprap since the blasting operation creates a variation in rock sizes (Plate 5.1). Figure 5.2 illustrates typical particle size gradation curves for three-inch diameter blastholes in hard shale and sandstone (U.S. Army Engineer Waterways Experiment Station, 1975). The larger rocks can be scalped off first and the remaining fines material saved and used as the filter material. In addition to natural graded filters, plastic filter cloth is also available. Guidelines for filter design are given in the following section.

5.2.7.1 Granular Filters

A layer or blanket of well-graded gravel should be placed over the channel bed prior to riprap placement. Sizes of durable particles in the filter blanket should be from 3/16 inches (5 mm) to an upper limit depending on the gradation of the riprap. Thickness of the filter may vary depending upon the riprap thickness, but should not be less than 6 to 9 inches (15-23 cm). It is recommended that the filter thickness equal the D_{max} of the filter with a minimum of nine inches.

Suggested filter gradation specifications have been developed on the basis of tests by Terzaghi's the Bureau of Reclamation, and the Corps of Engineers. Terzaghi's criteria relating gradation of filter cover to the particle size distribution of the underlying base or bed material is as follows:

Plate 5.1. Blasted durable rock along highwall. Note the gradation of particle sizes available for both riprap and filter materials.

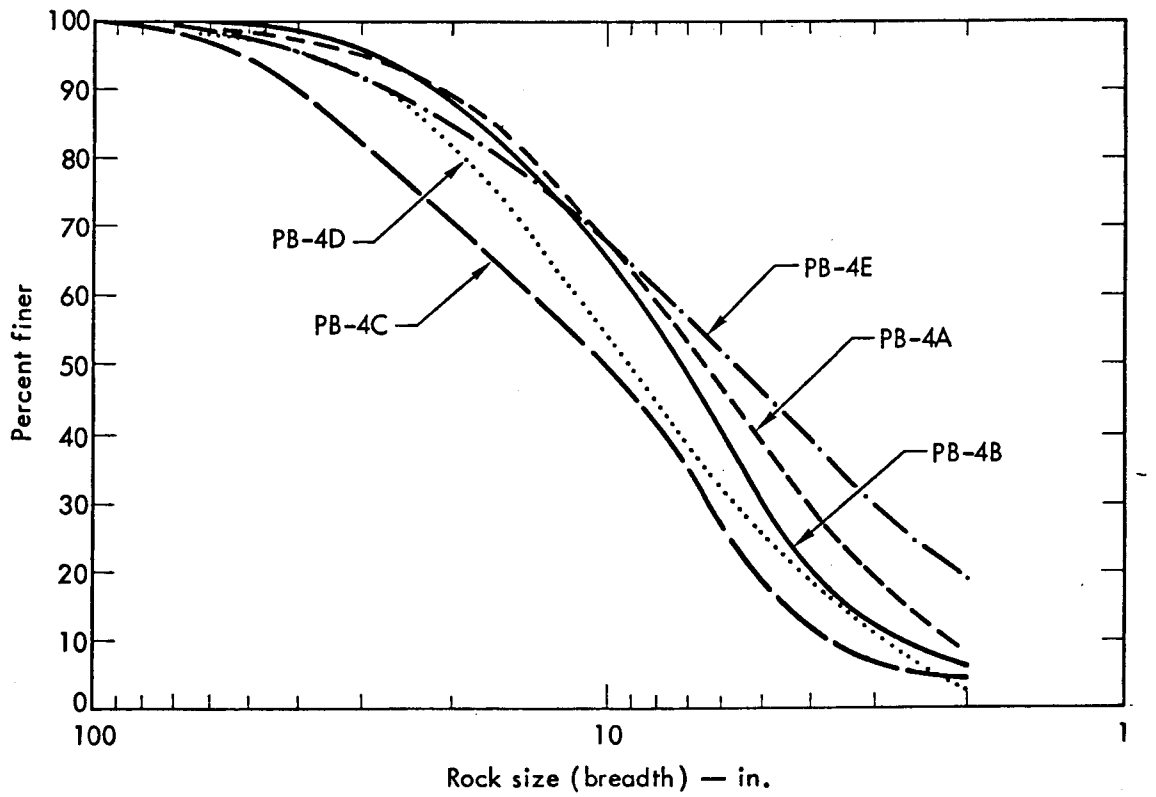

Figure 5.2. Gradation curves for three-inch diameter blast holes in hard shale and sandstone (U.S. Army Engineer Waterways Experiment Station, 1975).

$$\frac{D_{15}\ (\text{Filter})}{D_{85}\ (\text{Base})} < 5$$

$$4 < \frac{D_{15}\ (\text{Filter})}{D_{15}\ (\text{Base})} < 20 \qquad (5.1)$$

$$\frac{D_{50}\ (\text{Filter})}{D_{50}\ (\text{Base})} < 25$$

where the subscripts denote percentage of particles finer by weight.

The Corps of Engineers and Bureau of Reclamation filter gradation specifications have different limits, specifying (Anderson et al., 1970):

$$\frac{D_{15}\ (\text{Filter})}{D_{85}\ (\text{Base})} < 5$$

$$5 < \frac{D_{15}\ (\text{Filter})}{D_{15}\ (\text{Base})} < 40 \qquad (5.2)$$

$$\frac{D_{50}\ (\text{Filter})}{D_{50}\ (\text{Base})} < 40$$

Use of these criteria to evaluate the need for filter layers and their design is illustrated in the examples. Filter layers should not contain too many fines. A general guideline is that no more than five percent by weight of the particles in a filter sample should pass through a 200-mesh sieve. If more than one filter layer is required to adequately protect the base bed material, then the gradation criteria must be met by successive filter layers. When multiple granular filter layers are required, for example when the bed and banks are composed of very fine particles, the use of plastic filter cloths should be investigated. It may be possible to achieve the desired level of protection with one layer of filter fabric in place of several layers of granular filter material. Additionally, channel excavation costs would be decreased since the channel section would not have to be enlarged to contain several filter layers. The following section discusses the properties and design criteria for plastic filter cloths.

5.2.7.2 Plastic Filter Cloths

Plastic filter cloths are being used beneath riprap and other revetment materials, such as articulated concrete blocks, with considerable success. However, filter fabric is by no means a total substitute for granular filters. Filter fabric has the limitations of (1) filtering action is provided in only one direction, (2) only one Equivalent Opening Size (EOS) is maintained between the bed material and riprap, (3) fabric is less resistant to stone movement because of its relatively smooth surface, (4) additional of care must be exercised in placing riprap over plastic cloth filters to prevent damage, and (5) long term durability has not been proven.

The Denver Urban Flood Control District Drainage Design Criteria Manual (in print) specifies that plastic filter cloths should not be used when slopes are greater than 2.5 to 1. This is due to the reduced resistance to movement afforded by the smooth fabric. A six- to nine-inch layer of granular material is also recommended to be placed over fabric cloths to prevent tearing during placement of the riprap.

Care must be exercised in filter fabric installations where the seepage forces could be oriented parallel to the fabric. This could result in piping along the underside of the fabric and possible stability problems. Durability of filter cloths has not yet been established because they have been in use only since around 1967. However, inspections at various installations indicate little or no deterioration had occurred in the few (one to four) years that have elapsed since test installations.

Applications for filter fabric should be evaluated in terms of the specific advantages and/or disadvantages as compared to granular bedding. The economics associated with granular material availability, excavation, and placement of granular filters should be weighed against the economics of filter fabric. Obviously numerous site-specific factors determine the relative merits of each method; however, for long term design on a surface mine granular filter layers are generally preferred.

The following design criteria for plastic filter cloths were given by Normann (1975) in Federal Highway Administration Hydraulic Engineering Circular No. 15.

For filter cloths adjacent to granular materials containing 50 percent or less by weight fines (minus No. 200 material):

1. $$\frac{\text{85 percent size of material (mm)}}{\text{EOS (mm)}} > 1 \qquad (5.3)$$

2. Open area not to exceed 36 percent.

For filter cloths adjacent to all other soils:

1. EOS no larger than the opening in the U.S. Standard Sieve No. 70.

2. Open area not to exceed ten percent.

Note: No cloth specified should have an open area less than four percent or an EOS with openings smaller than the opening in a U.S. Standard Sieve Size No. 100. When possible, it is preferable to specify a cloth with openings as large as allowable by the criteria. It may not be possible to obtain a suitable cloth with the maximum allowable openings which also meets the strength requirements including tear resistance, however, due to the limited number of cloths available. Hydraulic Engineering Circular No. 15 describes the procedures for determination of Equivalent Opening Size (EOS) and open area.

5.3 Steep Channel Riprap Design

5.3.1 Introduction

The design of riprap for stabilizing steep conveyance channels with significant flow presents unique problems generally not encountered in riprap design study. Considering normal riprap design, the accepted methods are usually limited to slopes less than ten percent, where the velocities are slow enough and the depth of flow large enough (relative to the riprap size) that a reasonable estimate for the resistance to flow can be made. This resistance is generally characterized by Manning's n. However, on steep slopes the riprap size required to stabilize the channel is on the same order of magnitude or greater than the depth of flow. This creates difficulties in estimating roughness since Manning's relation is no longer valid. Without knowledge of the resistance to flow, an estimate of the velocity, needed for the design of the riprap, cannot be accurately determined.

Bathurst (1979) studied the hydraulics of mountain rivers where large roughness elements often exist in the flow. Based on flume studies, he was able to derive relationships for the resistance in channels where roughness elements are on the same order of magnitude as the depth of flow, often

breaking through the water surface. Using the general resistance equation developed by Bathurst, the velocity in a channel with a given size riprap can be determined. This velocity can then be used to evaluate the stability of the riprap. This approach is physically realistic since the hydraulics of a mountain river are similar to those of a steep slope diversion channel. In both situations the steep slopes require large diameter rock for stability since the flow tends to cascade around the rocks rather than flow over them. Consequently, the design procedure recommended in the follwoing section produces rock sizes and therefore, channel excavation requirements that may appear unrealistic for the design discharge and flow depth. However, the designer need only remember the hydraulics of the situation and the similarity to a steep mountain river to bring perspective to the design.

5.3.2 Simplified Design Procedures

Five sets of design curves (Figures 5.3-5.7) have been developed from Bathurst's relationship to simplify riprap design for steep conveyance channels. The design curves were developed for trapezoidal channels with 2 to 1 side slopes and bottom widths of 0, 6, 10, 14 and 20 feet. The 2 to 1 side slope was selected by considering angle of repose (Section 4.6) and channel excavation requirements. The 2 to 1 side slope is sufficiently less than the angle of repose for any particle size or shape. Side slopes less than 2 to 1 (i.e., 3 to 1) greatly increase excavation amounts without significantly increasing flow capacity for a given bottom width. Therefore, the 2 to 1 side slope was selected and is recommended for all steep slope channels. For a given channel bottom width, each curve represents the design for a given channel slope. The design curves were terminated at the point where flow velocities for a specific channel configuration and slope exceeded 15 ft/sec. A median rock diameter could be determined that would be stable at higher flows; however, rock durability at high flow velocity becomes of greater concern.

The procedure for entering the design curves with a known Q is illustrated on Figures 5.3 and 5.4. For practical engineering purposes, the D_{50} size specified for the design should be given in 0.25-foot increments. Therefore, the final design size is determined using Table 5.2. For the case where the bed slope (S) is not given on one of the design curves, linear interpolation is used to determine the riprap design. This can be done graphically by extending the horizontal line from the known discharge through

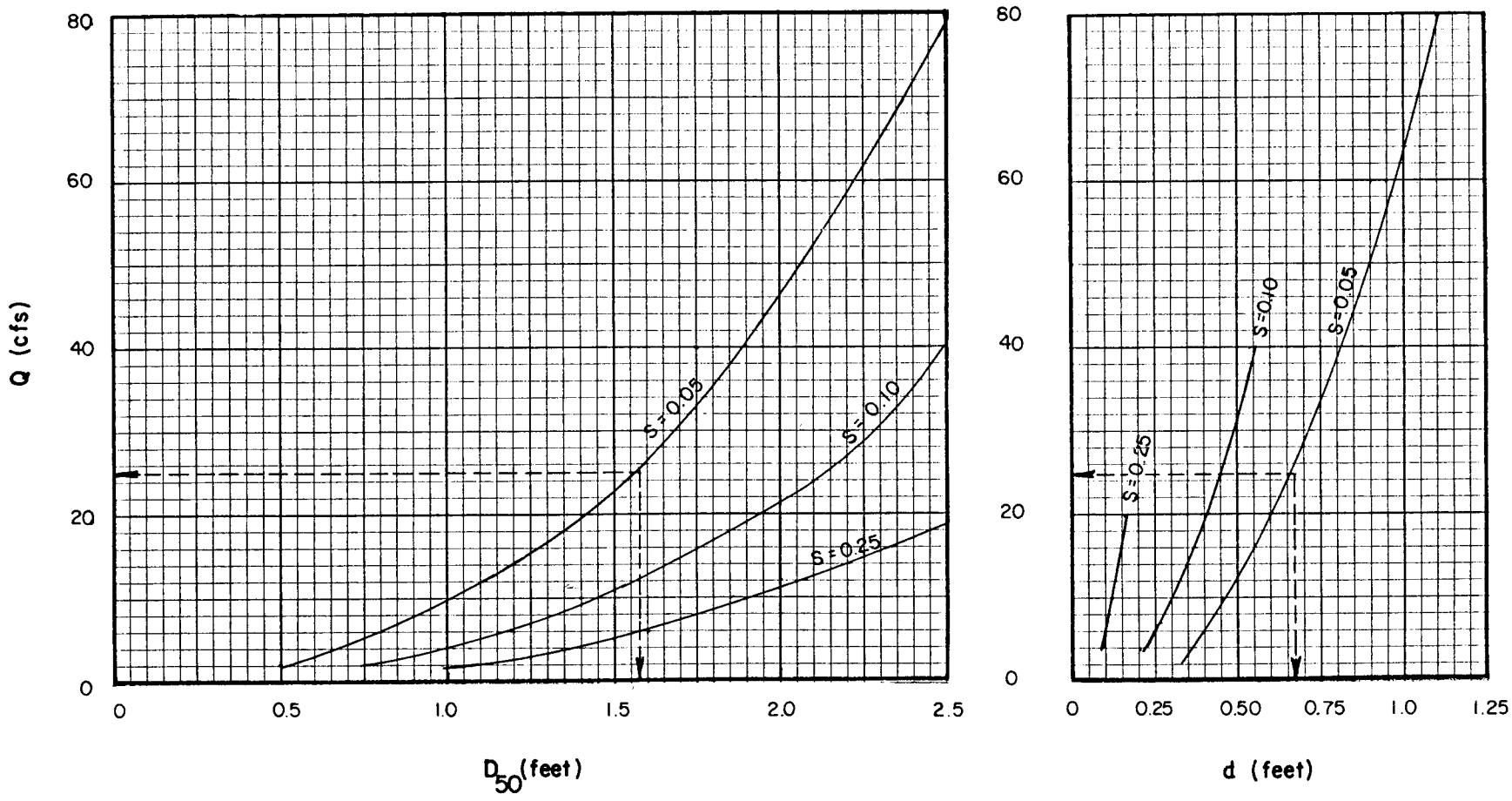

Figure 5.3. Steep slope riprap design, triangular channels, 2:1 sideslopes.

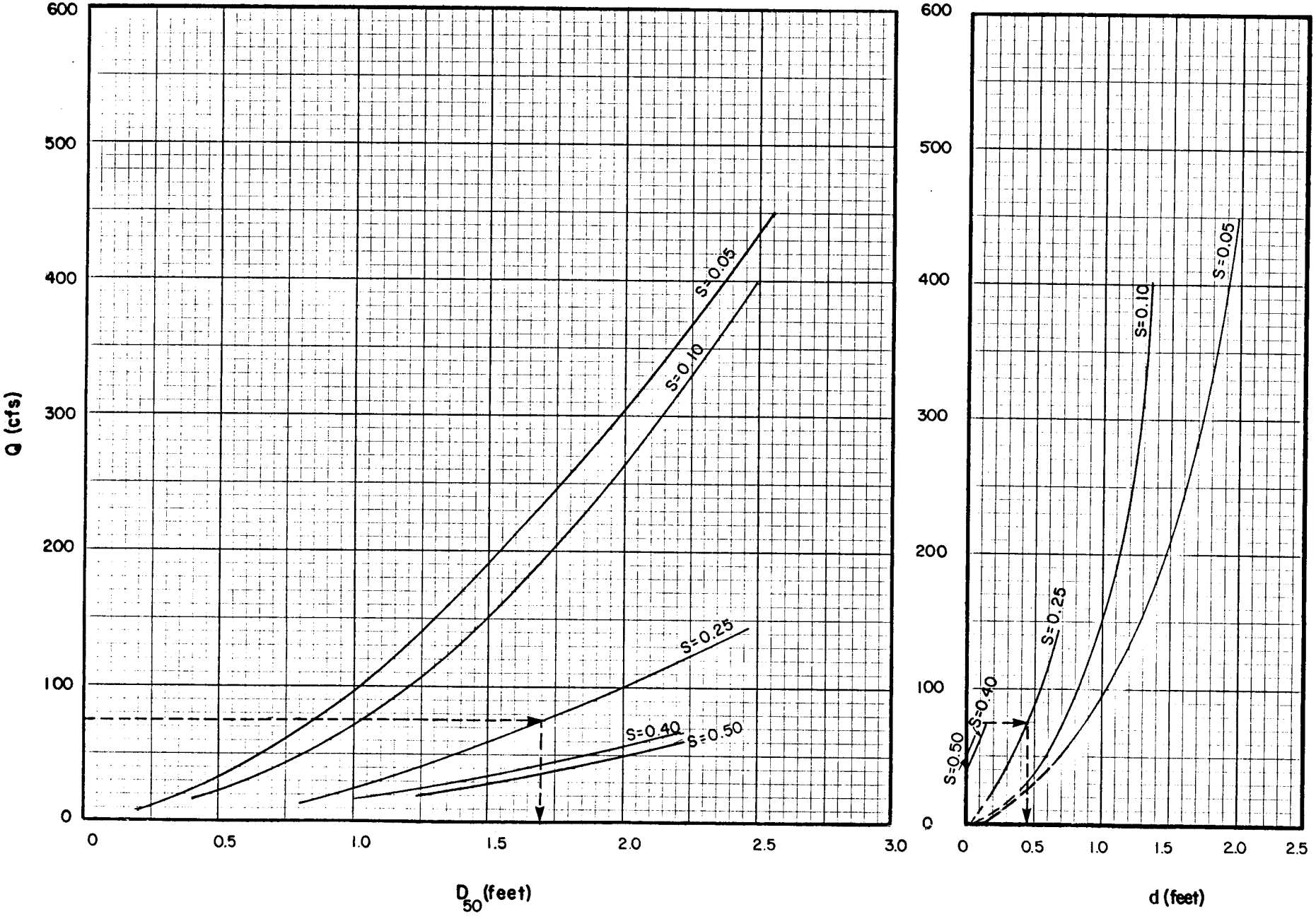

Figure 5.4. Steep slope riprap design, trapezoidal channels, 2:1 sideslopes, 6 ft base width.

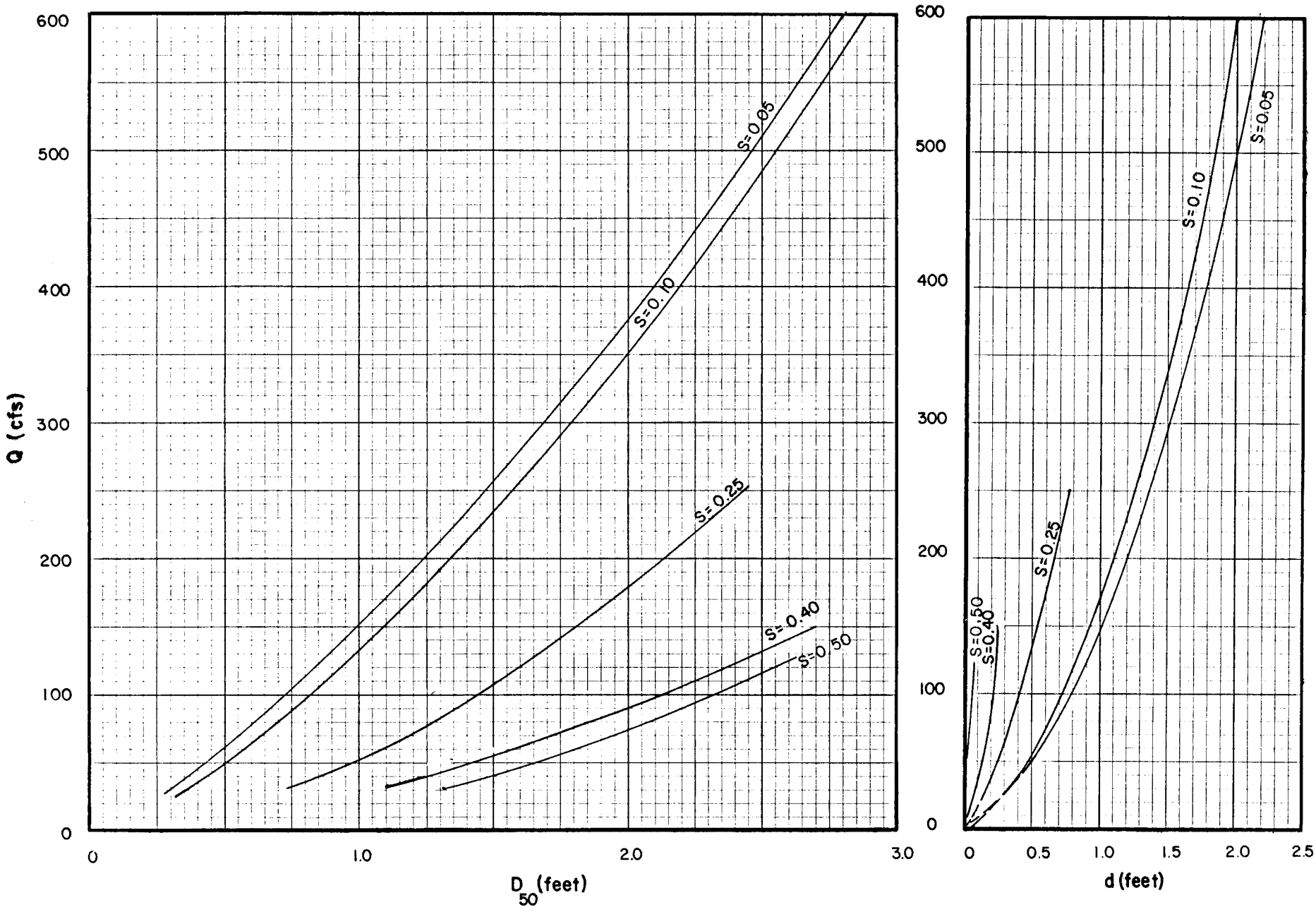

Figure 5.5. Steep slope riprap design, trapezoidal channel, 2:1 sideslopes, 10 ft base width.

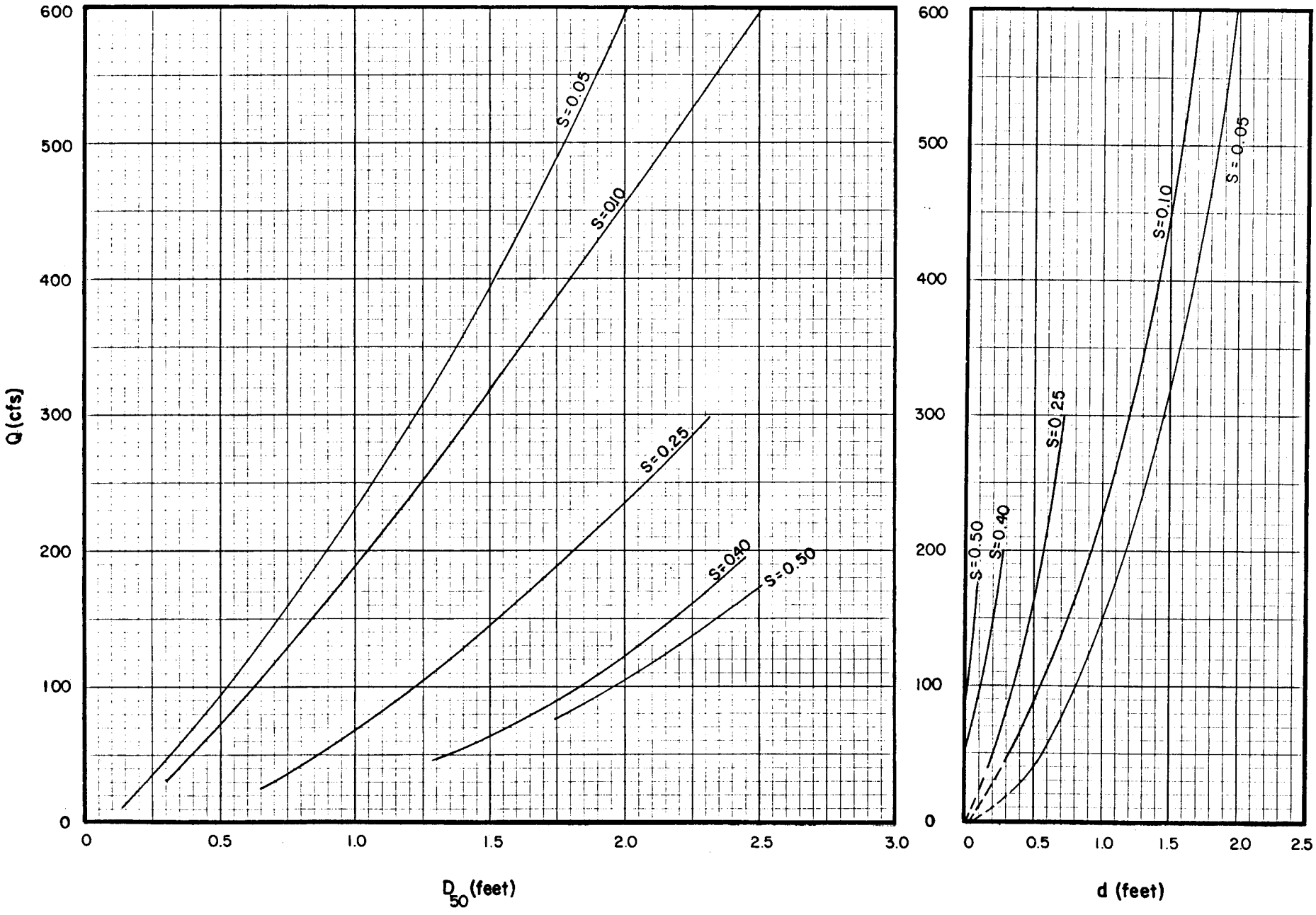

Figure 5.6. Steep slope riprap design, trapezoidal channels, 2:1 sideslopes, 14 ft base width.

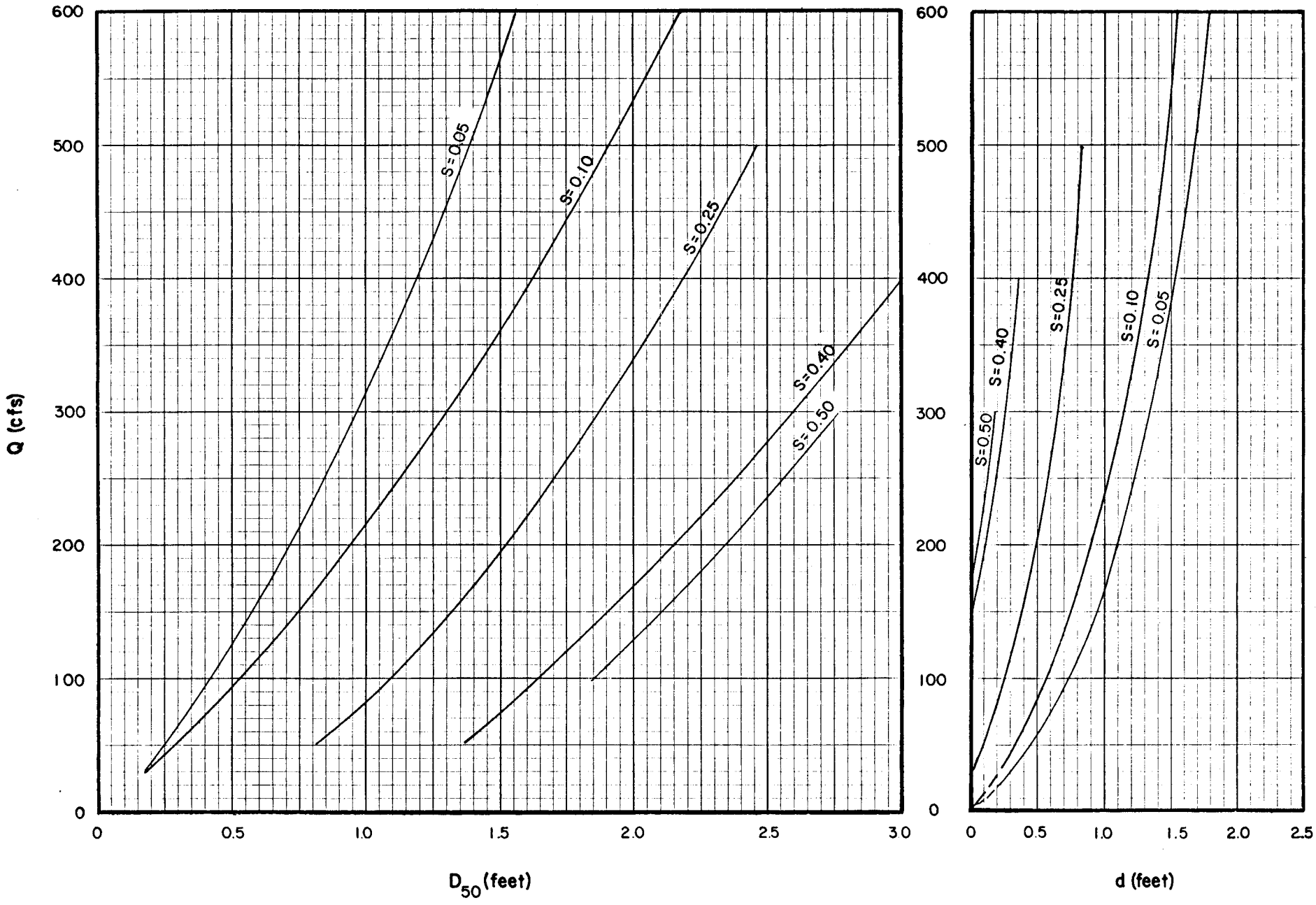

Figure 5.7. Steep slope riprap design, trapezoidal channels, 2:1 sideslopes, 20 ft base width.

Table 5.2. Design D_{50} Values.

D_{50} Determined From Design Curve (ft)	Design D_{50} (ft)
< 0.25	0.25
0.26 - 0.50	0.50
0.51 - 0.75	0.75
0.76 - 1.00	1.00
1.01 - 1.25	1.25
1.26 - 1.50	1.50
1.51 - 1.75	1.75
1.76 - 2.00	2.00
2.01 - 2.25	2.25
2.26 - 2.50	2.50
2.51 - 2.75	2.75
2.76 - 3.00	3.00

the curves with slopes bracketing the design slope. A point is then determined between the design curves by visual interpolation, and the D_{50} size is determined by a vertical line extended from this point. Similarly, for bottom widths other than the ones the graphs were prepared for, it is adequate to linearly interpolate using values from the graphs that bracket the desired bottom width.

5.4 Channel Entrances and Exits

When there is a transition from a steep to a mild slope, the flow changes from a supercritical (rapid) to a subcritical (tranquil) condition (see Section 4.2.5). Due to this change in the state of flow there is the possibility of formation of a hydraulic jump in the transition reach. The occurrence of a hydraulic jump is related to the Froude number (see Equation 4.7).

For the range of velocities and flow depths established in a channel by the steep slope riprap design procedure, Froude numbers on the steep slope will be less than four. In this Froude number range, violent hydraulic jumps do not form. For Froude numbers in the range of 2.5 to 4.5, surface waves are usually generated and a slight increase in water-surface elevation occurs; however, the violent hydraulic jump experienced at the base of a smooth surfaced spillway does not occur. Protection is still required in the transition length between a steep slope riprapped channel and a mild sloped channel to protect against local scour. Protection is required in the entrance due to the drawdown and increased velocity that results as flow transitions from a mild to steep slope. For simplicity, the length of protection estimated for the more critical exit section is also specified for entrance protection. A general rule for the length of protection required when Froude numbers are less than four is that transition length should be five times the uniform depth of flow computed for the downstream channel section; however, in no case should this length be less than 15 feet.

5.5 Design Procedures Summary

5.5.1 Criteria for Riprap Design

The design of riprap-lined channels with steep conveyance using the design curves requires the following steps:

1. Estimate the design flow based on hydrologic computations (Chapter III).

2. Determine the channel design slope based on topographic considerations. The channel design slope should be the uniform slope required to allow the channel to be constructed through slight changes in grade. If excavation amounts are too great too allow a uniform channel slope through changes in terrain slope, the channel can be designed to follow the changes in grade. For ease in construction, a single channel cross section adequate for each slope can be designed using the maximum slope to size the riprap required and the minimum slope to establish flow depth and freeboard requirements (transition requirements must be considered if this procedure is followed).
3. Determine a channel bottom width based on engineering judgment and available equipment.
4. Using the appropriate design curve, determine the required D_{50} size and flow depth.
5. Determine gradation and riprap thickness (Sections 5.2.5 and 5.2.6).
6. Evaluate filter requirements (Section 5.2.7).

   Granular Filter Design

   a. Determine gradation of channel bed and banks and gradation of granular material available.
   b. Evaluate adequacy of filter material by criteria in Section 5.2.7.
   c. Determine acceptable gradation for filter material.
   d. Determine thickness of filter layer.

   Plastic Filter Cloths

   a. Determine gradation of bed and bank material.
   b. Evaluate percent by weight of fines in bed material.
   c. Calculate allowable Equivalent Opening Size (EOS) of plastic filter cloth using criteria in Section 5.2.7.2.
   d. Select from available filter fabric meeting criteria.
7. Estimate freeboard required from Equation 4.20 and finalize cross section dimensions.
8. Evaluate entrance and exit protection required.

5.6 Design Examples - Using Step-By-Step Procedures Outlined Above

5.6.1 Design Example for Steep Slope Protection

1. Design discharge $Q = 75$ cfs
2. Assume a uniform slope of 0.25

3. Channel base width (b) selected as 6 feet
4. From Figure 5.4

   D_{50} = 1.70 ft Use D_{50} = 1.75 ft (Table 5.2)

   d = 0.45 ft

5. $D_{max} = 1.25\ D_{50} = 2.2$ ft
   Riprap Thickness = D_{max} = 2.2 ft
6. Evaluate filter requirements as discussed below.
7. Evaluate freeboard requirements. For steep slopes with riprap lining, Table 4.4 gives $c_{fb} = 1.0$.

   $c_{fb}(d) = (1)(0.45) = 0.45 \text{ ft} < 1.0 \text{ ft}$

   Therefore use 1.0 ft

   $$F.B. = c_{fb}(d) + \frac{1}{2}\Delta Z = 1.0 + 0 = 1.0 \text{ ft}$$

8. Figure 5.8 shows the channel section designed, including the granular filter (see next section).

5.6.2 Design Example for Granular Filter Layer

This example details procedures for determination and selection of an appropriate filter layer. The U.S. Army Corps of Engineers filter criteria are used because the limits are somewhat less restrictive than the Terzaghi filter criteria. The characteristics of the channel bed material and riprap protection are assumed to be:

D_{85} = 0.27 in

D_{50} = 0.1 in

D_{15} = 0.036 in

Riprap properties (determined from plotting gradation given in step 5 on semi-log paper; see Figure 5.9)

D_{85} = 26 in

D_{50} = 21 in

D_{15} = 9.5 in

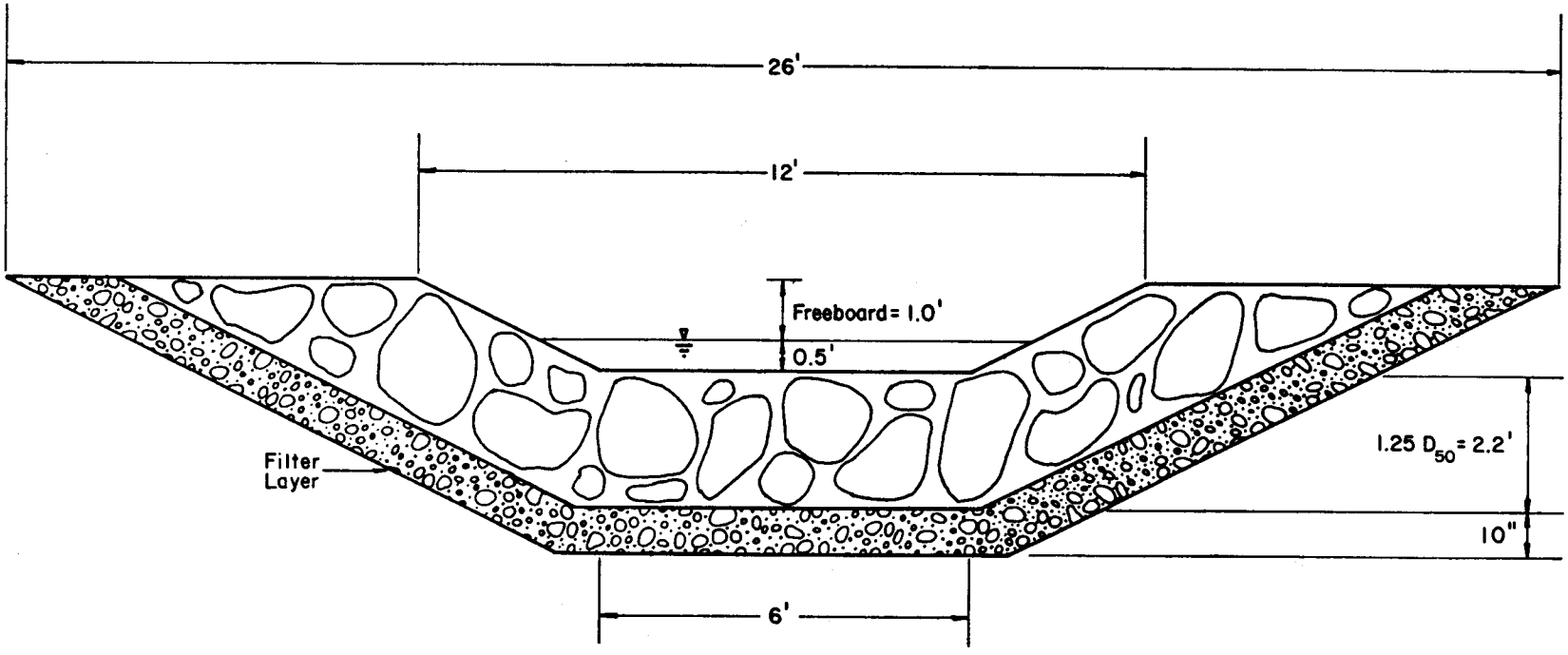

Figure 5.8. Final channel dimensions.

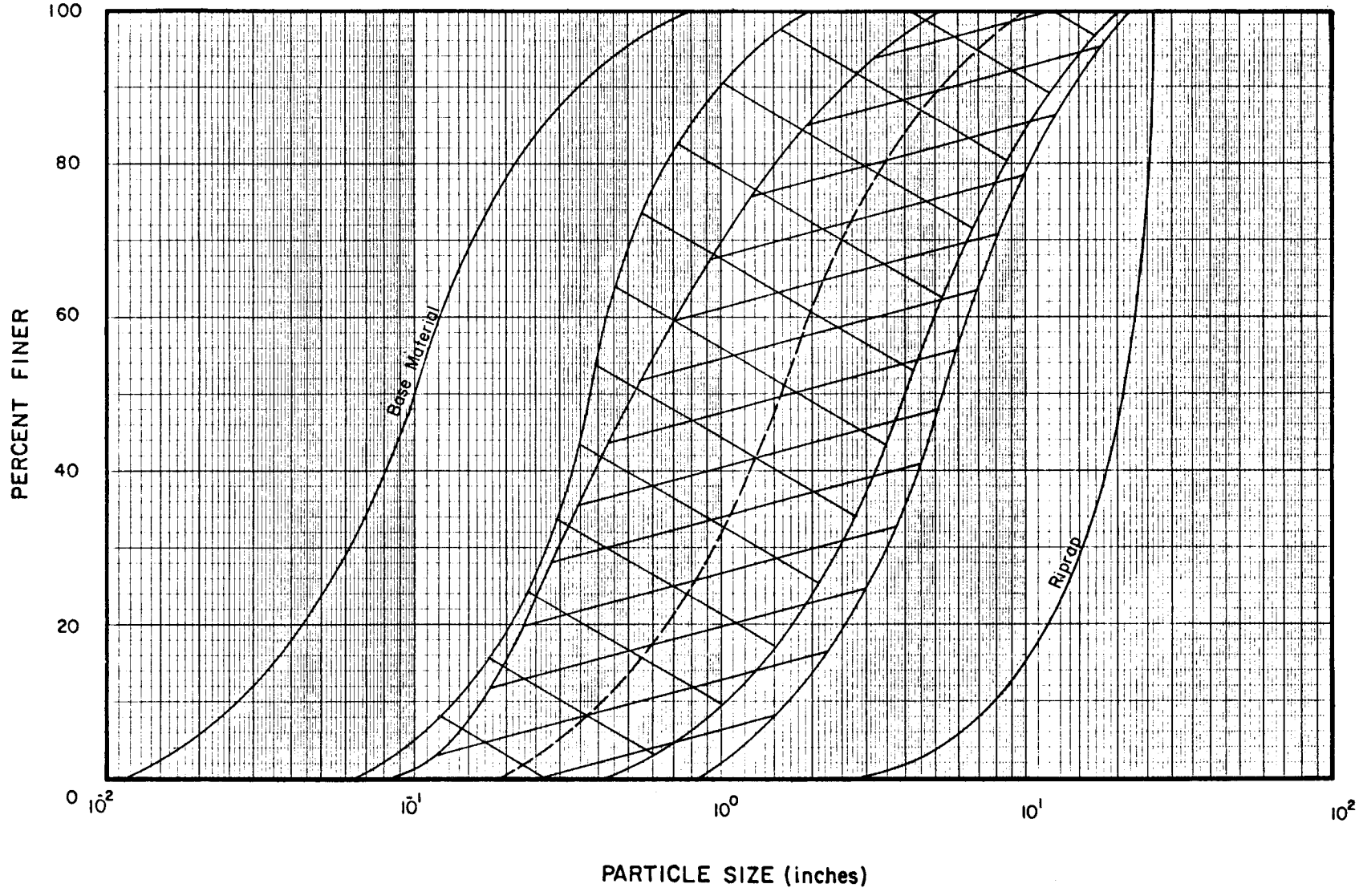

Figure 5.9. Gradations of filter blanket for design example.

Solution

1. Evaluate the need for a filter layer

$$\frac{D_{15}\ (\text{RIPRAP})}{D_{85}\ (\text{BASE})} = \frac{9.5}{0.27} = 35 < 5$$

Equation 5.2

$$\frac{D_{15}\ (\text{RIPRAP})}{D_{15}\ (\text{BASE})} \quad \frac{9.5}{0.036} = 264 < 40$$

Since filter criteria are exceeded, a filter layer is required.

2. The properties of the filter can be determined as follows

$$\frac{D_{50}\ (\text{FILTER})}{D_{50}\ (\text{BASE})} < 40, \quad \text{so} \quad D_{50}(\text{FILTER}) < 40 \text{ X } 0.1 = 4 \text{ in}$$

$$\frac{D_{15}\ (\text{FILTER})}{D_{15}\ (\text{BASE})} < 40, \quad \text{so} \quad D_{15}(\text{FILTER}) < 40 \text{ X } 0.036 = 1.4 \text{ in}$$

$$\frac{D_{15}\ (\text{FILTER})}{D_{85}\ (\text{BASE})} < 5, \quad \text{so} \quad D_{15}(\text{FILTER}) < 5 \text{ X } 0.27 = 1.35 \text{ in}$$

$$\frac{D_{15}\ (\text{FILTER})}{D_{15}\ (\text{BASE})} > 5, \quad \text{so} \quad D_{15}(\text{FILTER}) > 5 \text{ X } 0.036 = 0.18 \text{ in}$$

Therefore, with respect to the base material, the filter must satisfy

$$0.18 \text{ in} < D_{15}(\text{FILTER}) < 1.35 \text{ in}$$

$$D_{50}(\text{FILTER}) < 4 \text{ in}$$

3. Considering the riprap and a filter, the properties of the filter must satisfy

$$\frac{D_{50}\ (\text{RIPRAP})}{D_{50}\ (\text{FILTER})} < 40, \quad \text{so} \quad D_{50}(\text{FILTER}) > \frac{21}{40} = 0.5 \text{ in}$$

$$\frac{D_{15}\ (\text{RIPRAP})}{D_{15}\ (\text{FILTER})} < 40, \quad \text{so} \quad D_{15}(\text{FILTER}) > \frac{9.5}{40} = 0.2 \text{ in}$$

$$\frac{D_{15}\ (\text{RIPRAP})}{D_{85}\ (\text{FILTER})} < 5, \quad \text{so} \quad D_{85}(\text{FILTER}) > \frac{9.5}{5} = 1.9 \text{ in}$$

$$\frac{D_{15}\ (\text{RIPRAP})}{D15\ (\text{FILTER})} > 5, \quad \text{so} \quad D_{15}(\text{FILTER}) < \frac{9.5}{5} = 1.9 \text{ in}$$

Therefore, with respect to the riprap, the filter must satisfy

$$0.2 \text{ in} < D_{15} \text{ (FILTER)} < 1.9 \text{ in}$$

$$D_{50} \text{ (FILTER)} > 0.5 \text{ in}$$

$$D_{85} \text{ (FILTER)} > 1.9 \text{ in}$$

4. Figure 5.9 shows the limits of the filter material with respect to both the base and riprap material. The gradation curves for the filter layer have been extrapolated somewhat arbitrarily beyond the computed points. The ranges of suitable filter for both the riprap and the base have been crosshatched; any filter material that falls within the region where the cross-hatching overlaps will meet the criteria of both the riprap and the base material and will thus be suitable for the filter blanket.
5. The thickness of the filter layer can be determined for an assumed value of D_{max} of the filter. If filter material was available that had a gradation shown by the dotted line in Figure 5.9 then

   Assuming $D_{max} = 10$ in

   and filter layer thickness = $D_{max} = 10$ in

The channel section including the filter layer, was shown in Figure 5.8.

5.6.3 Plastic Filter Cloth Design Example

It is desired to design a plastic filter cloth suitable for application to base material having the gradation shown in Figure 5.8. Since no fines are present in the base material the design criteria are:

$$\frac{\text{85 percent size of material (mm)}}{\text{EOS (mm)}} > 1 \qquad (5.3)$$

Open area not to exceed 36 percent.

<u>Solution</u>

1. From Figure 5.8 $D_{85} = 0.27$ in = 6.8 mm
2. A filter cloth should be chosen that has:

   Equivalent Opening Size (EOS) < 6.8 mm of Plastic Filter Cloth

3. A layer of gravel should be placed over the filter cloth to provide protection during riprap placement.

5.6.4 Entrance and Exit Design Example

Determine the length of protection required above and below the channel section of the previous example. The downstream channel properties are:

1. $b = 6$ ft
2. $S = 0.002$
3. $D_{50} = 2$ in $= 0.17$ ft

<u>Solution</u>

Compute normal depth downstream

1. $n = 0.0395\ D_{50}^{1/6} = 0.0395(0.17)^{1/6} = 0.03$ Equation 4.18
2. From Figure C-1 in Appendix C for $Q_n = 2.25$ and

   $S = 0.002$

   $d = 2.4$ ft

   $V_n = 0.089;\ V = \frac{V_n}{n} = 3.0$ fps

3. Compute protection required

   length of protection

   $L = 5d = 12$ ft < 15 ft

   Therefore, length of protection = 15 ft

4. Figure 5.10 shows the entrance and exit protection

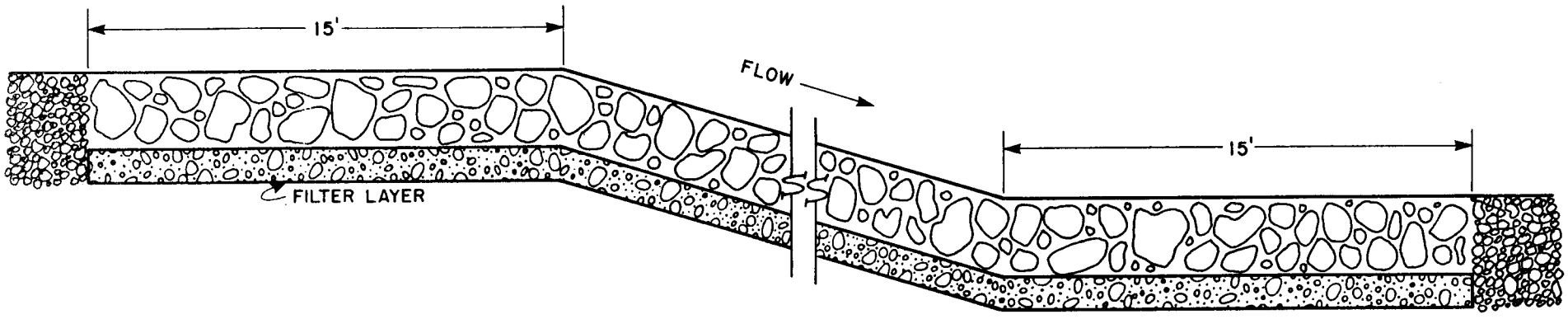

Figure 5.10. Entrance and exit protection on steep conveyance channel.

5.7 References

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