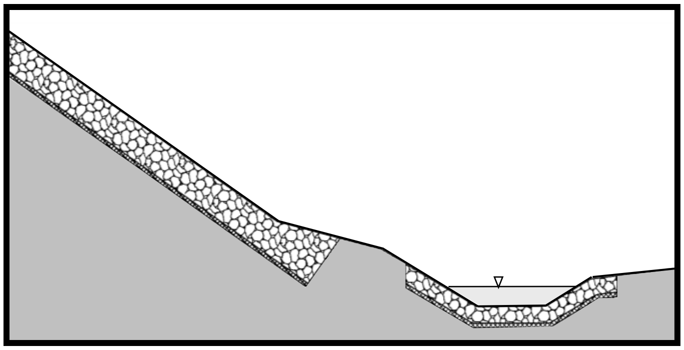
ACTIVITY: Riprap	ES – 23



CITY OF KNOXVILLE

Targeted Constituents				
● Significant Benefit	◗ Partial Benefit	○ Low or Unknown Benefit		
● Sediment	○ Heavy Metals	○ Floatable Materials	○ Oxygen Demanding Substances	
○ Nutrients	○ Toxic Materials	○ Oil & Grease	○ Bacteria & Viruses	○ Construction Wastes

Description

Riprap is the controlled placement of large rock material that will resist movement and erosion. Riprap is used to protect culvert inlets and outlets, streambanks, drainage channels, slopes, or other areas subject to erosion by stormwater erosion. This practice will significantly reduce erosion and sediment movement.

Suitable Applications

- Along a stream or within drainage channels, as a stable lining resistant to erosion.
- On shorefronts and riverfronts, or other areas subject to wave action.
- Around culvert outlets and inlets to prevent scour and undercutting.
- In channels where infiltration is desirable, but velocities are too excessive for vegetative or geotextile lining.
- On slopes and areas where conditions may not allow vegetation to grow.

Approach

Riprap may be used in many different locations and many different ways. It is very resistant to erosion and has relatively few drawbacks when installed correctly. Riprap does not prevent erosion or sedimentation from occurring, but it can help to create a stable channel lining and to reduce velocities. In the Knoxville area, limestone rock is readily available and relatively inexpensive. Other types of riprap material can also include cement bags (with sand/aggregate added) or concrete blocks, as described in TDOT Standard Specifications for Road and Bridge Construction (reference 172)

Stone riprap can either be placed as graded machine riprap (layers that can be placed by machine and then compacted) or as rubble (large pieces of rock are placed by hand). Graded riprap is often used for channel linings because it is flexible and can be compacted to a dense structure without manual sorting or placement. Rubble-stone riprap can be used for an attractive landscaped appearance but lacks flexibility to adapt to settlement, washing out of material, burrowing animals, etc.

Oftentimes there may be a "green" solution for slope stabilization problems or for drainage channels that would have typically required riprap. Erosion control matting, geotextiles, and flexible mattresses are just a few examples of how geosynthetics are providing alternatives for channels traditionally lined with riprap and concrete. Some alternatives to riprap for slopes include surface roughening, terracing, and mulching.

The selection of whether to use riprap may be dependent upon safety and maintenance considerations. Riprap could pose a hazard from snakes or burrowing animals for children who play in ditches or streams. Children may also be tempted to throw or drop rocks into water to see a big splash. Large rocks could settle or dislodge, endangering anyone in the immediate vicinity. Weeds may be difficult to control.

As a rough guideline, riprap can be specified for a design flow velocity which is over 5 feet per second (approximate upper limit of most vegetative channel linings). The upper limit for design flow velocity of a riprap channel lining depends primarily on the size of riprap specified and methods used for securing riprap material in place. Graded machined riprap is usually less expensive to install than hand-placed riprap and tends to be more flexible in case of settlement or movement.

Two common misuses of riprap:

- It is often specified incorrectly as an erosion control method just because the project designer has not performed drainage calculations. The project designer incorrectly assumes that a certain amount of "hard" material in a drainage channel will create a stable, non-eroded channel lining that is maintenance-free.
- Riprap is often installed incorrectly as a channel lining. A contractor may form and grade a drainage channel, and then dump some rock into it as an afterthought. This makes the channel have a much smaller flow capacity than was originally designed. If riprap is dumped without proper placement and compaction, it will act somewhat as a rock check dam. This will allow sedimentation to occur even more and thus further reduce flow capacity.

Materials

Riprap shall generally consist of machined shot rock which is angular and clean. Do not use rounded stones or cobbles for riprap (although cobble stones may be used in grouted channels for architectural appearances). Riprap shall not contain sand, dust, organic material, excessive cracks, mineral lenses and intrusions, or other impurities. Riprap is usually solid durable limestone rock quarried locally, which is generally resistant to erosion and to normal stream chemistry. Riprap material which is of questionable origin may be given a sodium sulfate soundness test to determine its durability. Riprap material shall have at least 2.5 specific gravity.

Table ES-23-1
Machined Riprap Specifications (TDOT Classification)

Class A-1	Class A-3	Class B	Class C
2" to 15" diameter (0.5 to 169 lbs) Dumped	2" to 6" diameter (0.5 to 11 lbs) Dumped	3" to 27" diameter (1.5 to 985 lbs) Dumped	5" to 36" diameter (6 to 2335 lbs) Dumped
20% by weight shall be at least 4" size (3 lbs) Typical thickness is 18" with a surface tolerance of 3"	20% by weight shall be at least 4" size (3 lbs) Typical thickness is 12" with a surface tolerance of 2"	20% by weight shall be at least 6" size (11 lbs) Typical thickness is 30" with a surface tolerance of 4"	20% by weight shall be at least 9" size (36 lbs) Typical thickness is 42" with a surface tolerance of 6"

The different classes of machined riprap are shown in Table ES-23-1 and are taken directly from the TDOT specifications. Gradations are commonly specified in terms of a specified percentage by weight being smaller than a diameter. For example, TDOT calls for Class B riprap to have a D_{20} of at least 6 inches. D_0 would be the smallest allowable size and D_{100} would be the largest allowable size for any specified gradation.

Alternate riprap sizes are listed in City of Knoxville Technical Specification #25 (available on Civil Engineering Division webpage) as shown in Table ES-23-2. These classes are relatively narrow gradations for use as riprap placed by hand.

Table ES-23-2
Hand-Placed Riprap Specifications (Knoxville Classification)

Class I	Class II	Class III	Class IV
1.5” to 5” diameter Hand-placed 75% by weight shall be at least 4” size 12” thickness	6” to 10” diameter Hand-placed 75% by weight shall be at least 8” size 12” thickness	9” to 12” diameter Hand-placed 75% by weight shall be at least 11” size 18” thickness	12” to 18” diameter Hand-placed 75% by weight shall be at least 15” size 24” thickness

Other types of riprap materials are shown in Table ES-23-3. Rubble-stone riprap can be very attractive as well as functional, but requires a great deal of hand labor and time. Manufactured concrete products such as interlocking blocks, articulated blocks, and revetment mattresses can resist very high flow velocities and are usually designed to be flexible for handling settlement and subgrade irregularities. Sacked riprap (essentially a concrete lining) is also labor-intensive and expensive to install. Concrete linings are generally discouraged because they do not allow for wildlife habitats and may contribute to downstream drainage problems such as high velocities.

Table ES-23-3
Non-Machined Riprap Specifications (TDOT Classification)

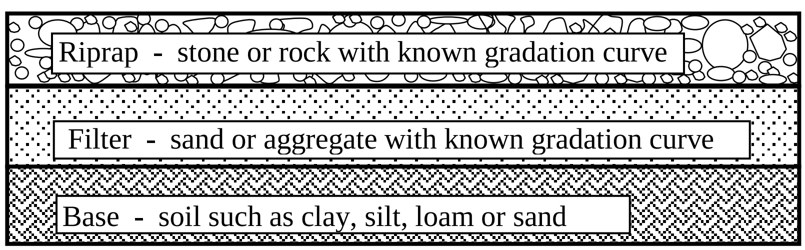
Rubble-stone (plain)	Rubble-stone (grouted)	Concrete blocks	Sacked riprap (sand-cement)
Min 2” diameter (min 0.5 lbs) Placed by hand	Min 2” diameter (min 0.5 lbs) Placed by hand	Rectangular shapes that can be placed in the specified dimensions by hand	Approx 1 cubic ft (approx 100 lbs) Placed by hand
80% by weight shall be at least 10” in any dimension (prefer rectangular) Remainder is 2” to 4” size for chinking Typical thickness is 12” with surface tolerance of 2”	80% by weight shall be at least 10” in any dimension (prefer rectangular) Remainder is 2” to 4” size for chinking Typical thickness is 12” with surface tolerance of 2”	Class A concrete with 3000 psi 28-day strength Various thickness from 4” upwards Design and install per manufacturer’s recommendations	Sacks should be cotton or jute cloth that retains sand and dry cement mix Mix 1 bag cement (94 lbs) with 5 cubic feet of sand Typical thickness is 10” with a surface tolerance of 2”

For smaller aggregates (less than 2 inches across), gradation is normally determined by mechanically shaking several pounds of material through a set of progressively smaller sieves. Then it can be stated that a certain percentage (by weight) is finer than a particular sieve with a defined opening size, which is then equated with an average diameter. However, riprap material cannot be mechanically shaken through sieves and thus it is more difficult to quantify the average size.
A geotextile filter fabric is usually placed beneath riprap to maintain separation from underlying soils. Also, geotextile filter fabric is necessary within stream channels to avoid loss of fine-grained soils. In particular, use geotextile filter fabric at the inlet and outlet of culverts, where turbulence is normally expected. Typical properties are listed in ES-12, Geotextiles. The equivalent opening size (EOS) of a geotextile filter fabric is typically between US standard sieve size No. 40 and No. 70 for use with most soils. The minimum recommended size for a geotextile filter fabric is No. 100, intended for use with fine-grained silts and clays. The geotextile filter fabric should be anchored securely using anchor trenches, stakes, staples, sewing or a combination of methods.

A layer of aggregate or sand can also be placed beneath riprap to maintain separation from underlying soils, either in addition to filter fabric or in place of filter fabric. The layer of aggregate or sand acts as a smooth bed to allow easier placement of riprap, and it can be used as a granular filter. The granular filter permits water to drain out or seep through it without allowing the adjacent soil or aggregate to bleed through. In general, a geotextile filter fabric will perform this function more reliably and with much smaller installation costs.

A granular filter should have the following properties with relation to the base soil underneath. The first and second properties are an application of the well-known filter criteria used by dam builders and other civil engineers for over a century. The third and fourth properties help ensure that the gradation curve of the granular filter is approximately the same shape as the gradation curve of the soil base.

1. D_{15} of filter must not be more than five times D_{85} of base.
2. D_{15} of filter must not be less than five times D_{15} of base.
3. D_{15} of filter must not be more than forty times D_{15} of base.
4. D_{50} of filter must not be more than forty times D_{50} of base.



The relationship of the riprap to an underlying granular filter layer should follow the same filter criteria as between the granular filter and the base soil. In other words, the term “filter” refers to the larger-grained material and the term “base” refers to the smaller-grained material. Due to the many problems associated with carefully placing 6” layers of graded aggregate or sand, the use of geotextile filter cloth is greatly preferred.

Design

There are many methods available for choosing riprap size, particularly for riprap channel linings. There are methods which make use of only one equation or nomograph, which can only account for 3 or 4 factors using assumptions and various rule-of-thumb guidelines. There are many methods which try to account for forces and momentum more exactly, with several equations and nomographs being used for factors such as rock specific gravity, stream tractive force, drag force, etc.

Riprap design shall generally be performed by a professional engineer using drainage computations, field conditions, quality of materials, and construction placement. If possible, it is recommended that a few design methods should be used to verify reasonable results.

River Shorelines: Riprap for use on river or lake shorelines should be designed to conform with standards by Tennessee Valley Authority (TVA) or the US Army Corp of Engineers. Large riprap with approximate average sizes of 24 to 36 inches should be used, depending on locations of nearby bridges or other factors affecting velocity. The rivers within the City of Knoxville are regulated by dams so that maximum and minimum river elevations are generally known.

Slopes: Riprap applications for slope stabilization, where wave action or flowing water is not a concern, should be sized for stability. The natural angle of repose is defined as the angle at which material can be placed without sliding downhill due to gravity. Angular riprap or crushed rock typically has in the neighborhood of 40°, so that a slope of 1.5 to 1 for most slopes is reasonable when not subject to flowing water. Rounded stones such as river gravel have a lower angle of repose. See Figure ES-23-1 for angle of repose based on average stone size, D_{50} (using a chart from reference 153).

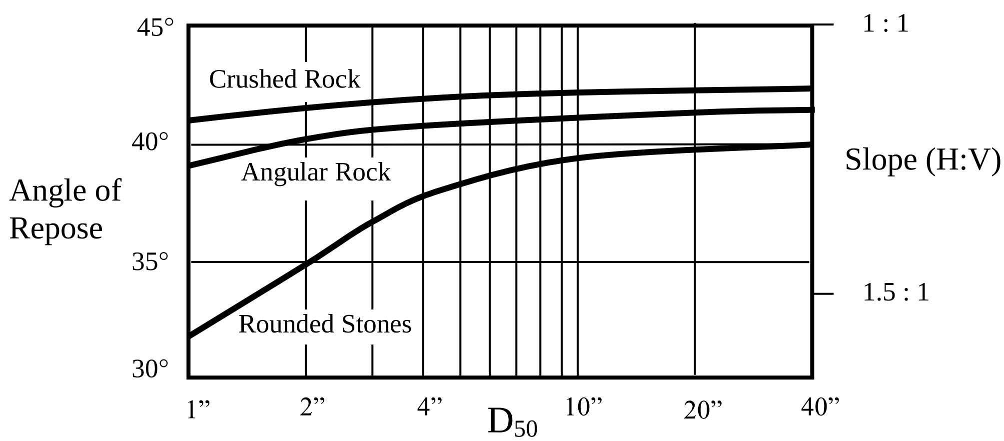


Figure ES-23-1
Angle of Repose for Riprap Based on Average Stone Size

The angle of repose does not take into account any external forces (such as vehicles, people, storms, groundwater, earthquakes, other ground vibrations). Also, sliding will often occur at the interface between two layers, particularly on a geotextile filter fabric which is not sufficiently anchored. Slope stability analyses should be performed by a professional engineer for all sloped areas which are critical or potentially hazardous.

Channels (HEC-15 design method):

The following design method for sizing riprap is taken from Hydraulic Engineering

Circular 15, Design of Stable Channels With Flexible Linings, by the Federal Highway Administration (1975). The mean riprap size is computed for tangent sections and curved sections of trapezoidal channels. Drainage computations are used to determine channel shape, channel slope, surface width, and design flow depth by using the Manning's n roughness coefficient equal to:

$$n = 0.0395 \times (D_{50})^{1/6}$$

1. Compute the channel bottom D_{50} riprap size based on the following equation where D_{50} and the maximum design flow depth have the same units (inches or feet) and channel slope is expressed in feet per foot:

$$\text{Bottom } D_{50} = 12.5 * \text{Depth} * \text{Channel Slope}$$

2. If the channel side slopes are steeper than 3:1, then the side slope D_{50} riprap size will be adjusted using the following equation where K_1 is obtained from Figure ES-23-2 and K_2 is obtained from an equation:

$$\text{Bottom } D_{50} \times K_1 / K_2 = \text{side slope } D_{50}$$

$$K_2 = (1 - \sin^2(\varphi)/\sin^2(\theta))^{0.5}$$

The side slope D_{50} is the riprap size necessary for the sides slopes of tangent sections where side slope is steeper than 3:1 (18.5°), φ is the angle of the side slope in degrees, and θ is the angle of repose in degrees.

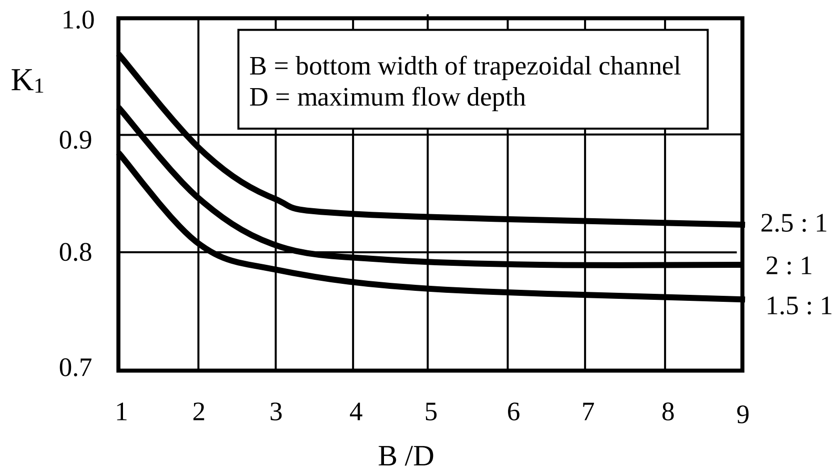


Figure ES-23-2
Distribution of Boundary Shear For Trapezoidal Channels

3. For curved sections of channel, compute the ratio Δ_C which is the internal angle that differentiates between a short bend and a long bend. The value R_O is the radius of the channel centerline bend, and the value R_D is the average radius of the channel outside bend as computed by the following equation using T (top width of the channel) and B (bottom width of trapezoidal channel):

$$R_D = R_O + 0.25 (T + B)$$

$$\Delta_C = \cos^{-1}(R_O / R_D)$$

4. Long bend (bend angle Δ is more than Δ_C): The tangent D_{50} riprap size (from Step 1 if side slopes are not steeper than 3:1, or Step 2 if side slopes are steeper than 3:1) will be adjusted using the coefficient K_3 which is obtained from an equation with V

being the average velocity (using Manning's flow equation):

$$\text{Curved } D_{50} = K_3 \times \text{tangent } D_{50}$$

$$K_3 = 4 \times V^2 / R_D$$

5. Short bend (bend angle Δ is less than Δ_C): The tangent D_{50} riprap size (from Step 1 if side slopes are not steeper than 3:1, or Step 2 if side slopes are steeper than 3:1) will be adjusted using the coefficient K_4 which is obtained from an equation using K_3 as computed above:

$$\text{Curved } D_{50} = K_4 \times \text{tangent } D_{50}$$

$$K_4 = 1 + (K_3 - 1)(\Delta / \Delta_C)$$

The selection of a mean riprap size D_{50} will basically specify a gradation curve. The maximum riprap size should be 1.5 times the D_{50} riprap size. The riprap layer thickness should be approximately 1.7 to 2.0 times the D_{50} riprap size, in accordance with the TDOT riprap classifications in Table ES-23-1.

The minimum freeboard for a riprap channel shall generally be at least 6 inches, depending upon the type of computations and potential for damage. Always provide additional freeboard at culvert inlets and outlets, areas of potential turbulence, changes in slope or direction, etc. Superelevation of the flow surface may occur on the outside bank of a channel bend. The amount of superelevation, Δ_Y, can be estimated using the following equation where g is equal to 32.2 feet per second per second and the other terms have already been defined:

$$\Delta_Y = (V^2 T) / (g R_O)$$

Installation

Installation of riprap should be accomplished within a short time frame (1 or 2 days) to minimize potential for damage from stormwater runoff.

General Subgrade Preparation

- Clear and grade the area of trees, brush, vegetation and unsuitable soils. Provide equipment access as necessary for earthwork and handling of large rocks.
- Prepare the subgrade to the specified depth necessary for installation of riprap. Compact subgrade firmly to prevent slumping or undercutting. Excavate anchor trenches as necessary for installation of geotextile filter fabric.
- Install geotextile filter fabric to maintain separation of rock material with the underlying soil. Geotextile filter fabric should be placed so that it is not stretched tight and conforms closely to the subgrade. Secure filter fabric by using anchor trenches, stakes, staples, sewing or any other means necessary according to manufacturer's recommendations.
- Place a layer of aggregate or sand (if specified by design for use as a bedding layer or as a granular filter) so that the layer is smoothly graded and well-compacted. A typical layer of aggregate or sand is 4 inches thick when used only as a bedding material. A granular filter of aggregate or sand is usually 6 inches thick.

Rubble-Stone Riprap

Rubble-stone riprap is usually placed as one layer (12" deep), two layers (6" deep), or an interlocking mixture of one and two layers. Rubble-stone riprap should be hand placed so that the stones are close together, are staggered at all joints as far as possible, and are placed so as to reduce the voids to a minimum. The larger rocks should be thoroughly chinked or anchored in place by using 1” to 3” stones or aggregate by placing over the surface and compacting in any manner practical.

When rubble-stone riprap is constructed in layers, the layers should be thoroughly tied together with large stones protruding from one layer into the other. The average depth is usually determined by frequent measurements throughout installation. Any change in thickness should be accomplished gradually.

Installation of grouted rubble-stone riprap includes hand placement of large rocks, chinking with smaller rocks and aggregate, filling with grout, surface finishing, and curing. When grouting is used, care should be taken to prevent earth or sand from filling the spaces between the stones before the grout is poured. Grout should be composed of one part portland cement and four parts of sand measured by volume, and then mixed thoroughly with sufficient water to a consistency so that the grout can flow into and completely fill the voids.

Immediately before pouring grout, the stones should be wetted by sprinkling. Starting at the lower portion of the riprap channel, carefully pour grout into the voids between the stone and at a slow rate to prevent oozing to the surface. Do not pour grout over the entire surface of the riprap, but insert grout mixture by using vessels, chutes, tubes, or hoses of adequate size and shape. Carefully finish the grouted riprap surface using small hand tools. Remove excess grout without disturbing riprap structure. Allow grout to harden and set before any stormwater is received. Keep grout moist with water that is free from salt or alkali for a period of not less than 72 hours.

Sacked Riprap (Sand-Cement)

Sand for sacked riprap may be either manufactured or natural clean sand, free from impurities and conforming to requirements for either cement sand or mortar sand. The basic requirements for sand are a maximum size (or D_{100}) to be approximately 3/8 inches and a minimum size (or D_0) to be equal to the No. 200 sieve or larger (i.e. no dust or clay). Portland cement should be manufactured dry powdered hydraulic cement without impurities. Do not use hydraulic cement which is caked or otherwise moist. Sacks should be of either cotton or jute standard grade cloth which is able to hold the sand-cement mixture without leakage during handling and tamping.

Sand and hydraulic cement should be mixed dry, with a mechanical mixer, in the proportion of one bag (94 pounds) of cement to 5 cubic feet of dry sand, until the mixture is uniform in color. The sand-cement mix should be poured into sacks of approximately 1 cubic foot capacity until the sacks are approximately ¾ full. The sacks should then be securely fastened with hog rings, by sewing, or by other suitable methods that prohibit leakage of the mixture from the bags.

The sacks of sand-cement should be bedded by hand on the prepared grade with all the fastened ends on the grade and in a staggered pattern, with a minimum thickness of 10 inches. The sacks should be rammed and packed against each other in such a manner as to form close contact and secure a uniform surface. Immediately after placement, sand-cement sacks should be thoroughly soaked by sprinkling with water (but not high-pressure water flows). Sacks that are ripped or broken in placement should be removed and replaced before being soaked with water.

Machined Riprap

Machined riprap material is generally dumped and placed by the use of appropriate power equipment. Placement should avoid segregating material by minimizing drop heights and by dumping material in large quantities. Riprap is then graded and compacted (using hand or mechanical tamping) to produce a surface uniform in appearance. Handwork may be required to correct irregularities. Place riprap carefully to avoid puncturing or displacing geotextile fabric.

Typical layer thickness and allowable surface tolerances are shown in Table ES-23-1. Class A-2 machined riprap is the same as Class A-1 riprap except that the depth may be decreased to 12 or 15 inches when placed by hand in accordance with rubble-stone installation procedure. Other classes of hand-placed riprap are listed in Table ES-23-2.

Inspection

The final step in riprap installation is to verify proper construction methods are used and that the specified gradation was installed. Visually inspect machined riprap to ensure that at least 20 percent of surface area consists of the D_{20} stone sizes specified within the materials section. Check that 50 percent of the surface area consists of stones no smaller than one-half of the maximum size specified.

Table ES-23-4 provides a rough guide to estimating the weight and equivalent diameter size of riprap material. A unit weight of 165 pounds per cubic foot is the same as a specific gravity of 2.65 with respect to water. Rectangular dimensions in a ratio of 3:2:1 are also listed as a frame of reference.

Maintenance

- Check riprap slopes and channel linings after major storm events for slumping, displacement, scour or undermining of riprap. Replace or reposition riprap as necessary, making a note of any damage for future reference.
- Periodically check for excessive growth of bushes, trees, weeds and other vegetation. Remove vegetation as necessary to maintain channel flow capacity and to prevent damage to channel linings.
- If properly constructed, riprap requires minimal maintenance. If long-term problems are noted, a major redesign and construction effort may be necessary.

Table ES-23-4
Weight and Size Equivalents of Riprap
(assuming a unit weight of 165 pounds per cubic foot)

Weight	Equivalent diameter (spherical)	Rectangular dimensions (assuming 3:2:1 ratio)
1 pound	2.7 inches	3.6” x 2.4” x 1.2”
2 pounds	3.4 inches	4.6” x 3.0” x 1.5”
5 pounds	4.6 inches	6.2” x 4.1” x 2.1”
10 pounds	5.8 inches	7.8” x 5.2” x 2.6”
20 pounds	7.4 inches	9.8” x 6.5” x 3.3”
30 pounds	8.4 inches	11.2” x 7.5” x 3.7”
40 pounds	9.3 inches	12.4” x 8.2” x 4.1”
50 pounds	10.0 inches	13.3” x 8.9” x 4.4”
75 pounds	11.4 inches	15.2” x 10.1” x 5.1”
100 pounds	12.6 inches	16.8” x 11.2” x 5.6”
150 pounds	14.4 inches	19.2” x 12.8” x 6.4”
200 pounds	15.9 inches	21.2” x 14.1” x 7.1”
250 pounds	17.1 inches	22.8” x 15.2” x 7.6”
300 pounds	18.2 inches	24.2” x 16.1” x 8.1”
500 pounds	21.5 inches	28.7” x 19.1” x 9.6”

Limitations

- Displacement may occur if the slope is too steep or if riprap is too small.
- If no geotextile filter cloth is used, then scour may quickly occur and damage channel. Scour may also occur for improperly designed or installed geotextiles.
- Riprap which is too small may experience movement within a drainage channel. This may create downstream blockages and excess sedimentation, in addition to allowing the channel to erode.

References **33, 34, 35, 141, 159, 161, 162, 167, 172, 179** (see BMP Manual Chapter 10 for list)

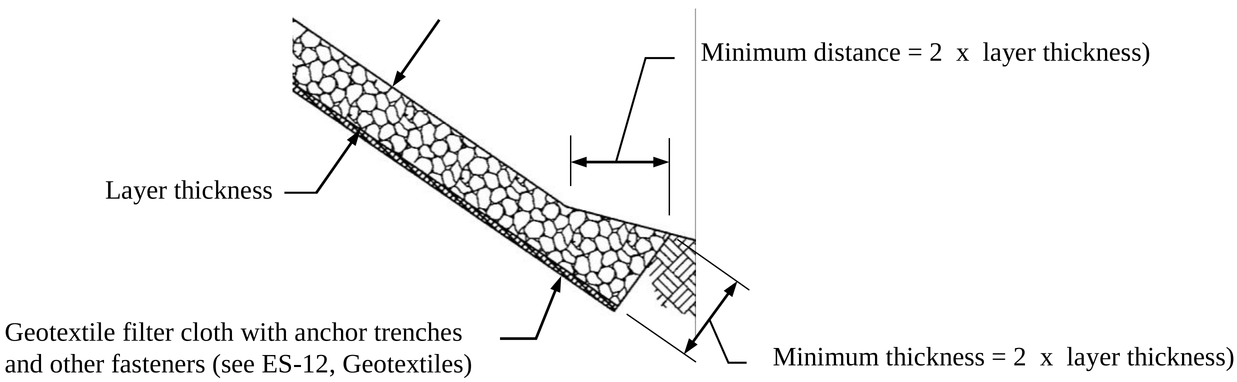


Figure ES-23-3
Base of Riprap Slope Protection