Riprap – RR

DEFINITION

A permanent, erosion-resistant ground cover of large, loose, angular stone with a geotextile or granular underlining.

PURPOSE

Riprap is used to protect culvert inlets and outlets, stabilize stream banks, stabilize drainage channels, and protect slopes and other areas subject to erosion by storm water, where vegetative or geotextile measures are not adequate or appropriate. This practice significantly reduces erosion and sediment movement.

CONDITIONS

Riprap may be used in many different locations and many different ways:

- Along a stream or within drainage channels, as a stable lining resistant to erosion.
- On lakefronts 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.

Riprap protection of banks and channels of streams, rivers, and lakes requires authorization from the Tennessee Division of Water Pollution Control and United States Army Corps of Engineers. **For more information, see Appendix C and: http://www.state.tn.us/environment/permits/arap.htm**

DESIGN CRITERIA

Riprap applications for channel or slope stabilization should be designed by a professional familiar with the design of storm water conveyance structures.

Stone riprap can either be placed as machine-graded riprap (layers that can be placed by machine and then compacted) or as rubble (large pieces of rock that 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. Hand placed riprap is typically two-dimensional. Each piece is “keyed” into each other and the displacement of one piece may lead to the failure of surrounding pieces. Machine placed riprap layers are typically thicker, providing more structural integrity.

Riprap should be used only when other methods of protection or stabilization are not appropriate. Erosion control matting, geotextiles, and flexible mattresses are examples of geosynthetics that provide an alternative to channels lined with riprap or concrete. Some alternatives to riprap for slopes include surface roughening, vegetation, terracing, and mulching as found elsewhere in this manual.

As a rough guideline, riprap can be specified for a channel design flow velocity that 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. Sound engineering practice should be used when considering flow velocity in the design of channels. 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.

CONSTRUCTION SPECIFICATIONS

Quality of Stone: Riprap should generally consist of machined shot rock that 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 should not contain sand, dust, organic material, excessive cracks, mineral lenses and intrusions, or other impurities.

Riprap is usually solid durable limestone rock, which is generally resistant to erosion and to normal stream chemistry. Riprap material that is of questionable origin should be given a sodium sulfate soundness test to determine its durability. Riprap material should have a specific gravity of at least 2.5.

Gradation: Different classes of machined riprap are shown in Table 1 taken from the TDOT Standard Specifications for Road and Bridge Construction. 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. This means that for Class B riprap, 20% of the stones, by weight, would be 6 inches in diameter or larger. D_0 would be the smallest allowable size and D_{100} would be the largest allowable size for any specified gradation.

Other types of riprap materials are shown in Table 2. 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 discouraged because they do not allow for wildlife habitats and may contribute to downstream drainage problems such as high storm water velocities.

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. The different classes of aggregates are shown in Table 3 and are taken directly from the TDOT Standard Specifications for Road and Bridge Construction.

Machined Riprap Specifications

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 surface tolerance of 3"	20% by weight shall be at least 4" size (3 lbs) Typical thickness is 12" with 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 beat least 9" size (36 lbs) Typical thickness is 42" with a surface tolerance of 6"

Table 1

Non-Machined Riprap Specifications

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 Placed 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	80% by weight shall be at least 10" in any dimension (prefer rectangular) Remainder is 2" to 4" size for chinking	Class A concrete with 3000 psi 28-day strength Various thickness from 4" upwards	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 12" with surface tolerance of 2"	Typical thickness is 12" with surface tolerance of 2"	Design and install per manufacturer's recommendations	Typical thickness is 10" with a surface tolerance of 2"

Table 2

Source: TDOT Standard Specifications for Road and Bridge Construction

Machined Aggregate Specifications

Size number	1	2	24	3	357
Nominal size square openings	90 to 37.5 mm (3 1/2" to 1 1/2")	63 to 37.5 mm (2 1/2" to 1 1/2")	63 to 19 mm (3 1/2" to 3/4")	50 to 25 mm (2" to 1")	50 to 4.75 mm (2" to No. 4)
Size number	4	467	5	56	57
Nominal size square openings	37.5 to 19 mm (1 1/2" to 3/4")	37.5 to 4.75 mm (1 1/2" to No. 4)	25 to 12.5 mm (1" to 1/2")	25 to 9.5 mm (1" to 3/8")	25 to 4.75 mm (1" to No. 4)
Size number	6	67	68	7	78
Nominal size square openings	19 to 9.5 mm (3/4" to 3/8")	19 to 4.75 mm (3/4" to No. 4)	19 to 2.36 mm (3/4" to No. 8)	12.5 to 2.36 mm (1/2" to No. 4)	9.5 to 2.36 mm (1/2" to No. 8)
Size number	8	89	9	10	
Nominal size square openings	9.5 to 1.18 mm (3/8" to No. 8)	4.75 to 1.18 mm (3/8" to No. 16)	4.75 to 1.18 mm (No. 4 to No. 16)	4.75 mm (No.4 to No.100)	

Table 3

Source: TDOT Standard Specifications for Road and Bridge Construction

Geotextile: A geotextile should be placed beneath riprap to maintain separation from underlying soils. It is also necessary within stream channels to avoid migration of fine-grained soils from the subgrade into the riprap. In particular, use geotextile at the inlet and outlet of culverts, where turbulence is normally expected. Refer to the specification **Geotextiles - GE**

Granular Filter: A layer of aggregate or sand can also be placed beneath riprap to maintain separation from underlying soils, either in addition to geotextile or in place of geotextile. 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 migrate through. In general, a geotextile will perform this function more reliably and with lower installation costs.

A granular filter (Figure 1) should have the following properties with relation to the base soil underneath:

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 is greatly preferred.

There are many methods available for choosing riprap size, particularly for riprap channel linings. There are methods that make use of only one equation, 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 should be performed by a professional using drainage computations, which consider 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.

Riprap for River Shorelines: Riprap for use on river or lake shorelines should be designed to conform to standards by Tennessee Valley Authority (TVA) or the US Army Corps of Engineers.

Riprap for 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 an angle of repose in the neighborhood of 40°, so that a slope of 1.5 to 1 is reasonable for most slopes when not subject to flowing water. Rounded stones such as river gravel have a lower angle of repose. See Figure 2 for angle of repose based on average stone size, D_{50}.

The angle of repose does not take into account any external forces (such as vehicles, people, storms, groundwater, earthquakes, or other ground vibrations). Failure will often occur at the interface between two layers, such as on a geotextile filter fabric that is not sufficiently anchored or where hydraulic forces exceed the sheer strength of the base and/or filter layer. A professional engineer should perform slope stability analyses for all sloped areas that are critical or potentially hazardous. See Figure 3 for base of riprap slope protection.

Riprap at Outlets: Design criteria for sizing stone and determining the dimensions and installation of riprap pads used at the outlet of drainage structures are contained in the specification **Storm Drain Outlet Protection - OP**

Typical Granular Filter

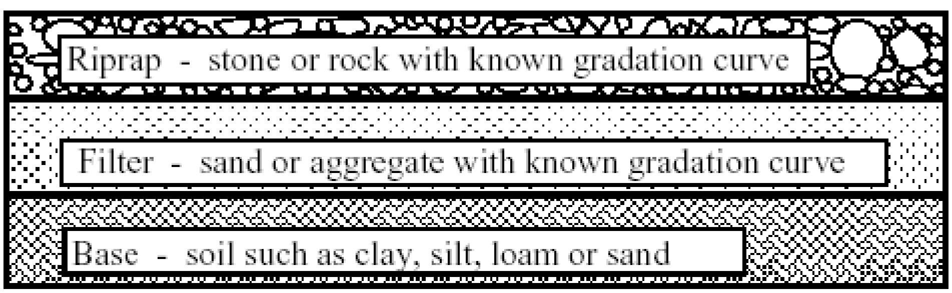

Figure 1

Source: Knoxville Engineering Department

Angle of Repose for Riprap Based on Average Stone Size

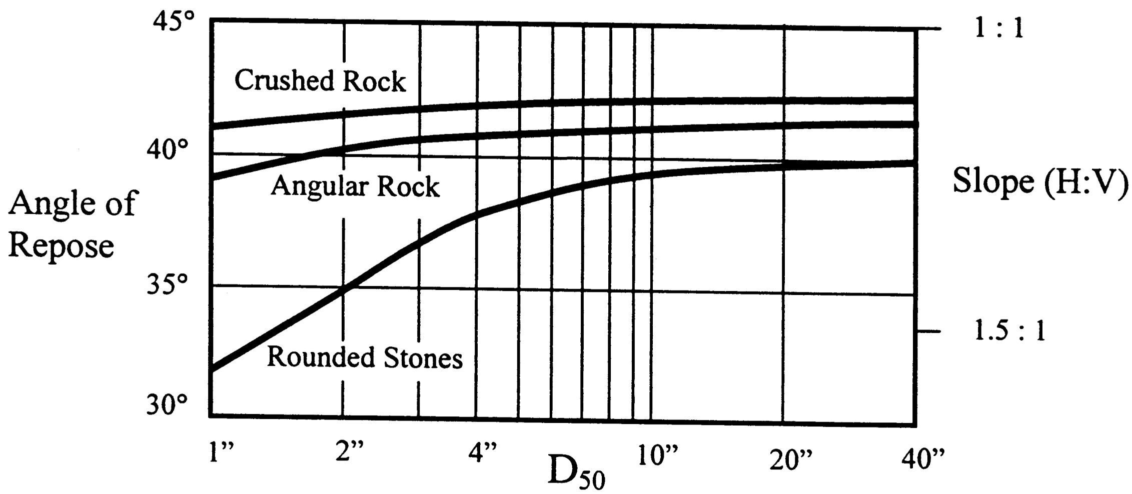

Figure 2

Source: Knoxville Engineering Department

Base of Riprap Slope Protection

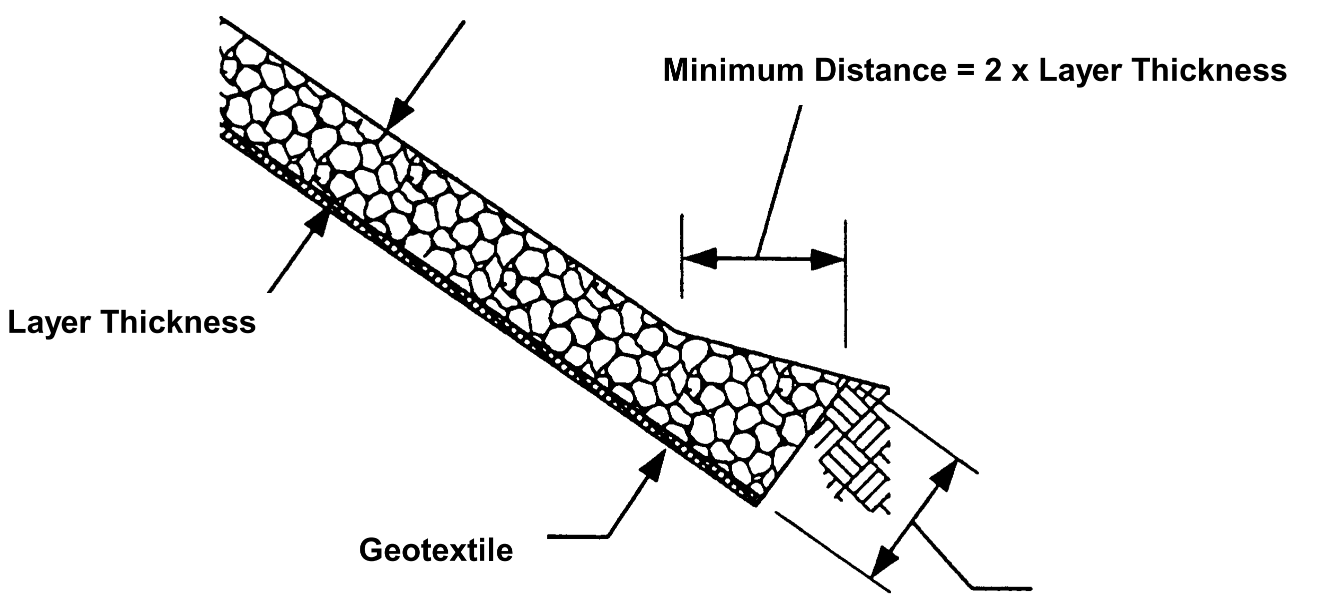

Figure 3

Source: Knoxville Engineering Department

Riprap for Channel Stabilization (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 (H:V):

$$\text{Bottom } D_{50} = 12.5 \text{ X depth X Channel Slope}$$

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 4 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 side 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

3. For curved sections of channel, compute the ratio $\triangle_c$ that 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):

$$R_D = R_O + 0.25\,(T+B)$$
$$\triangle_C = \cos^{-1}(R_O / R_D).$$

Distribution of Boundary Shear For Trapezoidal Channels

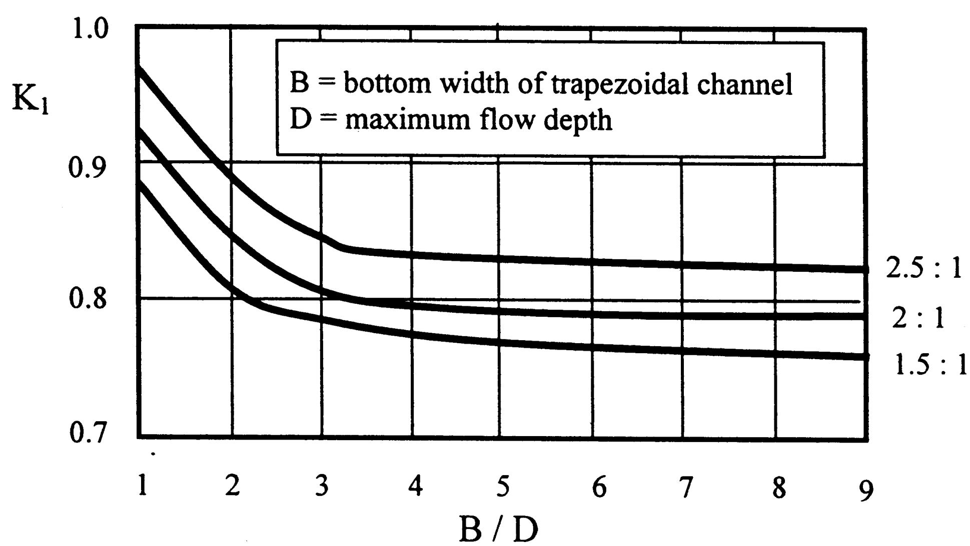

Figure 4

Source: Knoxville Engineering Department

4. Long bend (bend angle $\triangle$ is more than $\triangle_c$): 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 that 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 $\triangle$ is less than $\triangle_c$): The tangent D_{50} riprap size (from Step I 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 that is obtained from an equation using K_3 as computed above:

$$\text{Curved } D_{50} = K_4 \times \text{tangent } D_{50}$$
$$K_4 = I + (K_3 - 1)\ (\triangle / \triangle_c)$$

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 1.

The minimum freeboard for a riprap channel should 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, $\triangle_Y$, 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:

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

INSTALLATION

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

General Subgrade Preparation

1. The area should be cleared of trees, brush, vegetation, unsuitable soils, and graded. Access for equipment that will be necessary for earthwork and handling of large rocks should be provided.

2. The subgrade should be prepared 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.

3. Install geotextile to maintain separation of rock material from the underlying soil. Geotextile should be placed so that it is not stretched tight, and it 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.

4. 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 (2 @ 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 I" 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.

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 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 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 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:I are also listed as a frame of reference.

MAINTAINANCE

Riprap slopes and channel linings should be checked 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.

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"

Table 4

Source: Knoxville Engineering Department