Riprap Design for Erosion Protection

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RIPRAP DESIGN FOR EROSION PROTECTION

Riprap consists of a layer of rock, typically dumped on an embankment or in a channel to limit the effects of erosion. It is the most common type of erosion protection used due to its general availability, ease of installation and relatively low cost.

The purpose of this course is to describe the forces that cause soil erosion and the forces associated with riprap that resist the erosion. It will provide information on proper sizing of riprap, proper gradation for riprap and appropriate thickness of riprap for applications including channel banks, bridge abutments, bridge piers, channel bottoms and aprons for culverts. An understanding of these design parameters allows engineers and managers to make appropriate decisions which will limit the potential for erosion.

DEFINING THE PROBLEM

Loss of soil due to erosion

Wherever there is water flowing across a surface that is not concrete or asphalt, there is the potential for erosion. If the surface is bare soils, the potential is much higher than it is if the surface is well-vegetated, but even a well-vegetated surface is subject to erosion. Riprap can be used to protect soils from erosion caused by the forces associated with flowing water.

There are a number of problems caused by erosion. When the bank of a channel is unprotected, erosion moves soil from the bank into the flowing water, which transports the soil downstream (see Figure 1). This results in a wider, shallow channel along with reducing the usable potential for the land adjacent to the water. This is particularly a problem on the outside of bends in the channel.

Figure 1.

When the channel bank is adjacent to a bridge, erosion of the channel can result in compromising the support structure for the bridge which can lead to catastrophic failure.

Erosion of the stream channel can also have significant consequences. One of the most common locations for significant erosion of a stream channel is at the downstream end of a culvert (see Figure 2). The flow in the pipe is contained by the walls of the pipe and the velocity in the pipe is typically higher than the velocity in the natural channel because the pipe is smaller than the natural channel. This higher velocity leaving the pipe results in greater ability to suspend and transport particles.

Figure 2 – Scour hole at downstream end of culvert

Erosion at the inlet to a culvert is also fairly common when no erosion protection is provided (see Figure 3). As water reaches the culvert entrance, it is necessary for the flow to contract into the culvert opening. This contraction creates turbulence around the inlet of the pipe, which can lead to significant erosion.

Figure 3 – Erosion at the inlet to a culvert

Forces that create movement

There are two primary forces that create movement of sediment. One of the forces is the buoyancy force. This force acts in an upward direction and tends to lift sediment particles from the stream channel and keep them suspended in the flowing water. The second force is a drag force, which acts parallel to the direction of flow. The flowing water creates friction on the soil particles, either on the channel bottom or the side of the channel. This friction tends to try to move the soil particles downstream.

Forces that resist movement

There are also two primary forces that resist movement of sediment. The first one is gravity, which acts in a downward direction and generally resists the buoyancy force. The second one is a drag force or friction force. When a sediment particle moves, it creates friction against adjacent particles. These resisting forces must be overcome by the forces that create movement in order for a particle to move.

RIPRAP SELECTION

One of the primary materials used to resist the erosive forces of flowing water is riprap. It is the most common type of erosion protection used due to its general availability, ease of installation and relatively low cost. For the riprap to be effective, however, it is important for the specifications to require appropriate materials. The following parameters need to be specified and provided for riprap to provide the desired erosion protection.

Dimensions and D_{50}

Determining the size of riprap is the first step in riprap selection but it is important to recognize that it is not the only step. Riprap sizing is generally based on the size of the D_{50} stone, which is the particle size where 50 percent of the rocks are larger and 50% of the rocks are smaller. Riprap is typically sized so that the D_{50} stone can resist the forces that can move the rocks, while providing an appropriate safety factor. The D_{50} for rocks is often calculated by taking the weight of the rock, dividing the weight by the density to obtain a volume, then calculating the sphere that would have that equivalent volume. The reality is that rocks are not spheres, so the overall dimensions are different than the D_{50}. Riprap stones should not be thin and platy, nor should they be long and needle-like. To account for this, most specifications limit the ratio of the largest dimension to the smallest dimension, also known as the shape factor, so that the largest dimension can't exceed the smallest dimension by more than this ratio. The most common shape factor is 3.

For example, a rock that has a D_{50} of 12 inches has a volume of 0.52 cubic feet (about 900 cubic inches). A rock that has dimensions of 6.7 inches x 6.7 inches x 20.1 inches would have a volume of about 0.52 cubic feet and meet the required ratio of largest dimension to smallest dimension. If the rock was a cube, each side would be about 9.7 inches.

The maximum size of rock, the ratio of largest dimension to smallest dimension and the thickness of the riprap layer are also important dimensions. While larger rocks are more resistant to movement, larger rocks can also create some issues with the thickness of the riprap layer. The thickness of the layer is often recommended to be at least twice the size of the D_{50} material. For example, if the D_{50} is 12 inches, the minimum layer thickness would be 24 inches. However, it is necessary to be sure that the largest allowable rock is smaller than the layer thickness. In this example, if the largest allowable rock had a D_{50} of 24 inches. Some designs indicate that the riprap layer should be 1.5 times the D50 of the riprap, which would indicate that some rocks could be larger than the total riprap thickness. In this case, a single rock would equal or exceed the required layer thickness, but a single rock does not provide adequate protection for the soil under the riprap layer.

Gradation

Graded riprap is more stable than uniform riprap because the range of sizes helps the riprap layer to interlock. Graded riprap also allows the smaller rocks to fill the voids between the larger rocks, providing much better protection for the soil below the riprap layers. Care must be taken during construction to ensure that the graded rocks are uniformly distributed. If large rocks roll to the base of the bank and the smaller rocks accumulate at the top, the benefits of using graded riprap will be lost. Also, a relatively uniform riprap surface will be more stable than an extremely uneven riprap surface. The uniform surface reduces the turbulence at the interface between the water and the riprap, which reduces the disruptive forces that could move the rocks.

One measure of the gradation is the uniformity ratio of D_{85}/D_{15}. This ratio should have a target value of 2.0 with an allowable range of 1.5 to 2.5. This additional requirement helps to ensure that the riprap is well graded so that there is a wide variety of rock sizes. If a uniformity ratio or other similar information on gradation is specified, it is possible that the riprap will consist of mostly rocks that are approximately equal to the D_{50} size, which will result in a poor riprap installation.

There are many different gradations published in design manuals. Each state DOT has a riprap gradation included in their standard specifications but there is a wide variation in these gradations. Table 1 presents a series of gradations included in FHWA Hydraulic Engineering Circular 23. Many design standards include only a small number of riprap sizes (typically three or four) and provide limited information on required gradations. Providing more information on the required gradation for riprap increases the likelihood that a better product will be provided. Standards that provide a larger number of gradations also encourage selection of riprap that is more appropriate for the specific condition.

Table 1. Minimum and Maximum Allowable Particle Size in Inches

Nominal Riprap Class by Median Particle Diameter		D_{15}		D_{50}		D_{85}		D_{100}
Class	Size	Min	Max	Min	Max	Min	Max	Max
1	6 in.	3.7	5.2	5.7	6.9	7.8	9.2	12.0
2	9 in.	5.5	7.8	8.5	10.5	11.5	14.0	18.0
3	12 in.	7.3	10.5	11.5	14.0	15.5	18.5	24.0
4	15 in.	9.2	13.0	14.5	17.5	19.5	23.0	30.0
5	18 in.	11.0	15.5	17.0	20.5	23.5	27.5	36.0
6	21 in.	13.0	18.5	20.0	24.0	27.5	32.5	42.0
7	24 in.	14.5	21.0	23.0	27.5	31.0	37.0	48.0
8	30 in.	18.5	26.0	28.5	34.5	39.0	46.0	60.0
9	36 in.	22.0	31.5	34.0	41.5	47.0	55.5	72.0
10	42 in.	25.5	36.5	40.0	48.5	54.5	64.5	84.0
Note: Particle size corresponds to the intermediate axis of the particle								

Materials

It is important to use appropriate materials for riprap. Most specifications require that riprap be hard, dense, durable and angular in shape. In addition, it should be resistant to weathering and water action (erosion), free from excess soils, spoil material, structural defects and organic material. Numerous testing protocols are available for testing riprap materials. Some of these include:

AASHTO T 335 – Standard Method of Test for Determining the Percentage of Fracture in Coarse Aggregate

AASHTO T85 - Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate

ASHTO T103 - Standard Method of Test for Soundness of Aggregates by Freezing and Thawing

ASTM D 3967 - Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens

ASTM D5519 - Standard Test Methods for Particle Size Analysis of Natural and Man-Made Riprap Materials

Some other recommended limitations on riprap material include that rounded stone or boulders from a streambed should not be used as a source. While these materials are likely durable, because they are round they tend to roll down the embankment and roll along the stream bottom so they don't provide the desired erosion protection. In some locations, round rocks are used because angular rocks are simply not available. There are two different approaches that can be used to reduce the potential issues with round rocks when they are the only material available. The first approach is to use a thicker layer of riprap. This approach is still temporary in nature because all of the round rock will eventually roll down the slope or down the channel, but a thicker layer extends the length of time that protection is available. No guidelines are available for how much additional riprap should be placed since it is very site specific. The second approach when only round rocks are available is to grout the space between the rocks. Figure 4 shows an example of grouted riprap. The grout provides a way for the rock rocks to more effectively interlock with adjacent rocks. However, the grout can deteriorate over time but additional grout can be sprayed over the rocks to rejuvenate the installation. In addition, the grout creates a rigid structure, rather than a flexible structure, so relatively small amounts of movement of the riprap can create much more significant problems.

In some locations, broken concrete is used as riprap. There are several issues associated with use of broken concrete to consider. The first is that in many instances, concrete has reinforcing steel (either rebar or mesh). This reinforcing steel must be removed or cut off to reduce the hazard potential of the material. Another issue is that many individuals want to use concrete removed from sidewalks or driveways for riprap. Large slabs do not make good riprap – the largest dimension exceeds the smallest dimension by much more than a factor of 3, so the slabs tend to slide down the slope. The third issue is that most concrete slabs are 4 to 6 inches in thickness, so proper processing results in riprap that is generally pretty small (a D_{50} less than 12 inches).

Figure 4 – Grouted riprap

Rocks comprised of appreciable amounts of clays, such as shales, mudstones and claystones are not acceptable for riprap

<u>Filter under Riprap</u>

It is very important to provide a filter component under the riprap layer. Geotextile filters or granular filters can be used. Granular filters were the historic approach but have been almost completely replaced by the use of geotextile filters due to lower cost and easier installation. The purpose of a filter is to retain the coarser particles of the subgrade while remaining permeable enough to allow water to move through the filter in both directions (infiltration and exfiltration). It is not necessary to retain all of the particle sizes in the subgrade, however.

Allowing some smaller particles to pass through the filter can result in a coarser substrate, which is an overall benefit. The filter prevents excessive migration of the base soil particles through the voids in the armor layer, permits relief of hydrostatic pressure beneath the armor, and distributes the weight of the armor to provide more uniform settlement.

When using a granular stone filter, the layer should have a minimum thickness of 6 inches or four times the D_{50} of the filter stone, whichever is greater. When placing a granular filter under water, it is recommended that the filter thickness be increased by at least 50%.

In flowing water, the placement of both granular and geotextile filters becomes challenging. Under these conditions, special materials and placement techniques have been developed to ensure that a quality filter installation is achieved.

Placing Geotextiles Under Water

Placing geotextiles under water is problematic for a number of reasons. Most geotextiles that are used as filters beneath riprap are made of polyethylene or polypropylene. These materials have specific gravities ranging from 0.90 to 0.96, meaning that they will float unless weighted down or otherwise anchored to the subgrade prior to placement of the armor layer. In addition, unless the work area is isolated from river currents by a cofferdam or other flow diversion structure, flow velocities greater than about 1.0 ft/s create large forces on the geotextile. These forces cause the geotextile to act like a sail, often resulting in wavelike undulations of the fabric (a condition that contractors refer to as "galloping") that are extremely difficult to control. In mild currents, geotextiles (precut to length) have been placed using a roller assembly, with sandbags to hold the fabric temporarily. Some geotextile fabrics are also available with a layer of sand encased on the fabric to provide additional weight and stability.

Installation

Riprap that is placed on a slope should be provided with a key below the bottom of the channel. This is sometimes referred to as a toe down (see Figures 5 and 6). The depth of the key should be at least as great as the depth of the anticipated long-term bed degradation plus the scour at the toe. In the case of a bridge abutment, this would be the combination of contraction scour plus abutment scour. In many cases under a bridge, the key also extends horizontally for a distance of 3 to 5 feet. This extended key provides additional protection against scour at the most critical location. In situations where a key is not feasible to construct, a mounded toe can be provided (see Figure 7).

The recommended freeboard for riprap depends on the infrastructure that is being protected. In many cases, the infrastructure is a roadway bridge which has very high value. In this case, riprap is often placed one to two feet above the design high water level (often the 100-year flood elevation).

Riprap should generally be placed starting at the toe of the slope and extending upward. The largest stones should be placed at the bottom, filling the gaps between the larger stones with smaller stones. The stones should be distributed evenly over the riprap area avoiding material segregation or substantial deviations from the design slope and grade. Riprap should be placed with a drop of less than 3 feet to avoid large tears in the geotextile and breaking the stones. Larger stones (greater than 250 pounds) should be carefully placed with no free fall.

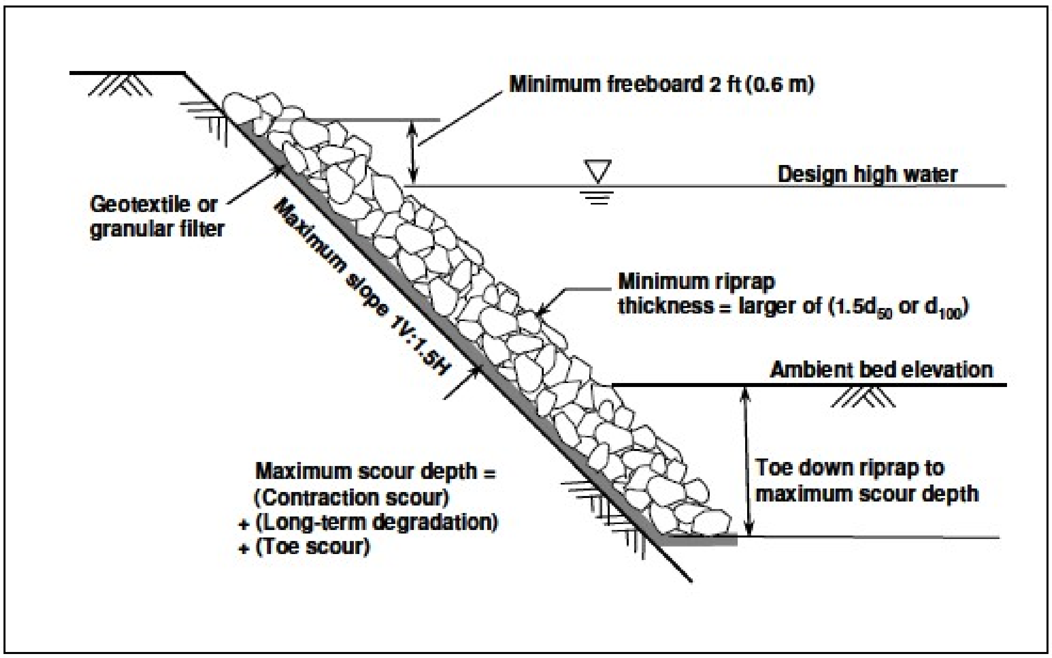

Figure 5 – Toe down for riprap

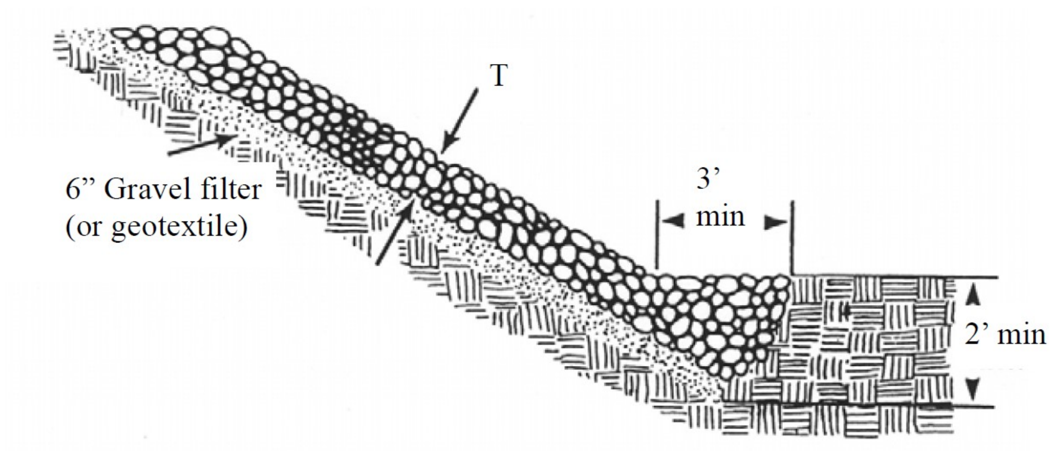

Figure 6 – Riprap Key

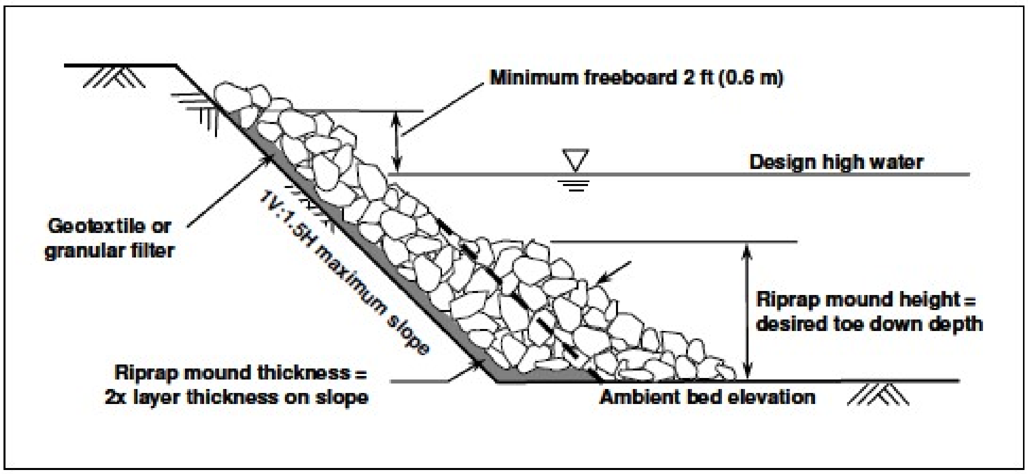

Figure 7 – Mounded toe at bottom of riprap

<u>Failure Modes</u>

Any successful riprap design must account for several possible modes of failure. These include riprap particle erosion, substrate material erosion and mass failure. Riprap particle erosion is minimized by sizing the riprap to withstand hydraulic and turbulence forces, but is also affected by riprap slope, impact and abrasion, ice, waves and vandalism. Substrate particle erosion occurs when the base material erodes and migrates through the riprap voids causing the riprap to settle. Substrate particle erosion is limited by placing a granular or geotextile filter between the riprap and the base material. Mass failure occurs when large sections of the riprap and/or base material slide or slump due to gravity forces. Mass failure can be caused by excess pore water pressures, bank steepness and loss of basal support through scour or channel migration. Also, a filter fabric that is too fine can clog and cause the buildup of pore water pressures in the underlying soil.

Riprap that is large enough to resist all the hydraulic forces can fail if channel migration or scour undermines the toe support. When the riprap toe is undermined it can shift and remain functional to some degree. Often an extra volume of riprap is included at the toe for this purpose, or the riprap toe is trenched to the depth of potential degradation and contraction scour.

REQUIRED SIZE OF RIPRAP

Riprap on Slopes

Riprap is commonly used on slopes to protect the underlying soils. It is used under bridges to protect the bridge foundation and along channel banks to protect the adjacent overbank from erosive forces. The following equation can be used to determine the appropriate size of riprap to use along an embankment.

- Riprap Size, $D_{50} = 0.001 * V_a^3 / (d_{avg}^{0.5} * K_1^{1.5})$
  - Where
  - D_{50} is median size of the riprap required (ft)
  - V_a is the average velocity in the main channel (ft/sec)
  - D_{avg} is the average flow depth in the main channel (ft)
  - $K1 = [1-(\sin^2\theta/\sin^2\varphi)^{0.5}]$
  - θ = bank angle with the horizontal
  - φ = riprap material's angle of repose (for angular riprap, this will be in the range of 42 degrees, for rounded rock it will be in the range of 38 to 40 degrees)

For example, find the required riprap size if the average channel velocity is 6 feet per second, the average flow depth is 4 feet, the bank is on a 2:1 slope (so θ = 26.6 degrees) and the material is angular riprap (so the angle of repose is 42 degrees).

$\sin^2\theta = 0.200$

$\sin^2\varphi = 0.448$

$K_1 = (1 – (0.200/0.448)^{0.5}) = 0.332$

$D_{50} = 0.001 * (6)^3 / ((4)^{0.5} * (0.332)^{1.5}) = 0.56$ ft.

For this application, the D_{50} riprap size should be at least 7 inches. Using the sizes noted in Table 1 would indicate that Class 2, with a D_{50} of 9 inches should be used. The thickness of the riprap should be at least twice the D_{50} size, or at least 18 inches. The gradation information in Table 1 indicates that the largest stones should have an intermediate dimension of 18 inches, so in some instances, the riprap thickness will equal the largest stone which doesn't provide for a very effective layer. To offset this issue, a minimum thickness of 24 inches should be considered.

Riprap at the end of Pipes

To protect the soil at the downstream end of a pipe, a riprap apron can be installed (see Figure 7). A typical design layout is shown in Figure 8. The riprap apron serves several purposes. The rocks help protect the underlying soil particles from erosion. However, the layer of riprap must be thick enough to allow multiple rocks between the surface and the underlying soil so the minimum thickness is generally recommended to be at least twice the average rock size (or twice the D_{50} size). The rocks also increase the surface roughness which causes turbulence and dissipates energy at the outlet of the pipe. Finally, the apron allows the flowing water to spread out, which reduces the depth of flow and lowers the velocity, while still providing protection for the natural soils.

Figure 7 – Riprap at downstream end of pipe

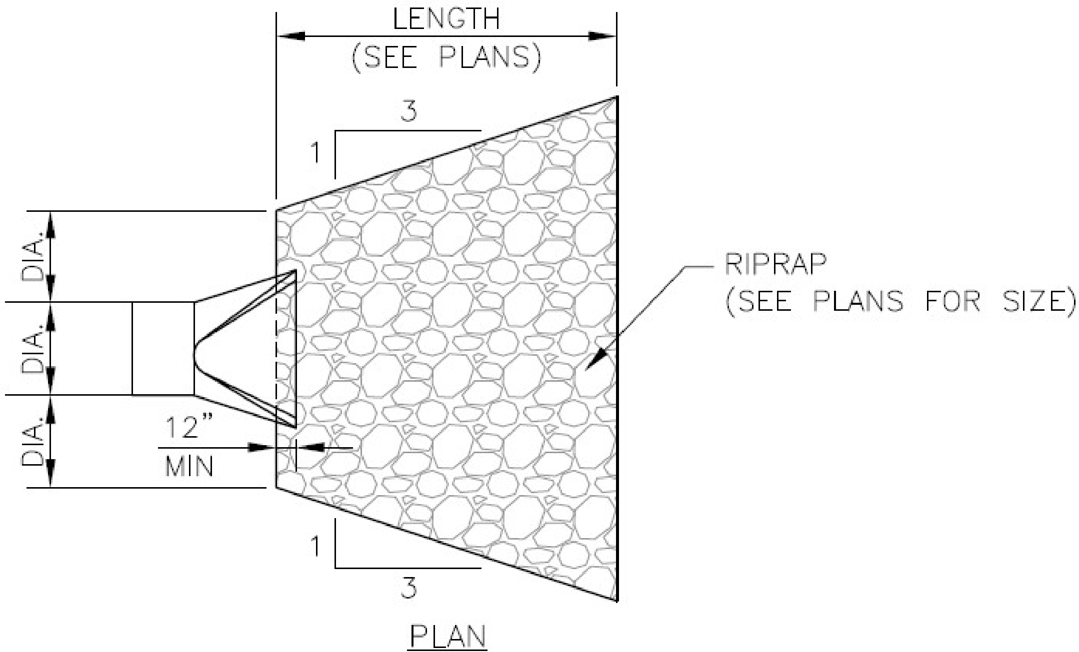

Figure 8 – Layout of Riprap Apron for Culvert End

To determine the appropriate size of riprap for an apron, the following equation can be used:

$D_{50} = 0.2 * D * (Q/(g^{0.5}*D^{2.5}))^{4/3} * (D/TW)$

- Where
- D_{50} is median size of the riprap required (ft)
- D is the diameter of the pipe (ft)
- Q is the flow rate (cfs)
- TW is the tailwater depth (ft), but not less than 0.4 * D

This equation is valid only for sub-critical flow, but this is a preferred condition at pipe outlets.

As an example, determine the required riprap size for a 48-inch diameter culvert with a design flow of 156 cfs.

TW = 4 ft * 0.4 = 1.6 ft (the actual tailwater value in a pond or a channel could be larger or smaller, but this is the minimum to use in the equation)

$D_{50} = 0.2 * 4 * (156/(32.2^{0.5}*4^{2.5}))^{4/3} * (4/1.6)$

D_{50} = 1.63 ft (about 20 inches)

The dimensions of the riprap apron can be estimated using the values in Table 2. For the example, with D50 = 20 inches, the length of the apron would be 7 times the pipe diameter, or 7 * 4 = 28 feet and the depth of the riprap would be 2.0 * D_{50} or 2.0 * 1.63 ft ~ 3.3 ft.

Class	D_{50} (in)	Apron Length[1]	Apron Depth
1	5	4D	3.5 D_{50}
2	6	4D	3.3 D_{50}
3	10	5D	2.4 D_{50}
4	14	6D	2.2 D_{50}
5	20	7D	2.0 D_{50}
6	22	8D	2.0 D_{50}

1 D is the culvert rise (or diameter)

Table 2. Example Riprap Classes and Apron Dimensions

PROTECTING BANKS

There are many situations where it is necessary to protect the bank of a stream channel. In reality it isn't necessary to protect the bank, but to protect whatever is adjacent to the stream bank. Figure 9 shows a recently completed installation where the stream was getting close to an existing highway. To protect the highway, riprap was placed on the stream bank to prevent the stream channel from migrating closer to the highway.

Figure 9 – Riprap protecting a highway embankment adjacent to a stream

Figure 10 – Riprap protecting a highway embankment adjacent to a lake

Riprap is also used for erosion protection around lakes and reservoirs. Figure 10 shows riprap being used along the shore of the lake to protect the bank from erosion which would threaten the integrity of the adjacent roadway. In a stream channel, the erosion is typically a function of the velocity of the water adjacent to the soil. In a lake, however, the erosive forces are a result of wave action against the soils, since the flow velocity is essentially zero. The erosive force of the waves is mostly a function of the height of the wave, which is a function of wind speed and the length of open water (fetch). Consequently, larger lakes will usually have higher waves and the resultant higher erosive forces.

Figure 11 – Riprap upstream from a bridge.

Figure 12 – Riprap guide bank upstream from a bridge

Riprap is commonly used to protect the stream embankments adjacent to a bridge, especially upstream of the bridge. Figure 11 shows the riprap immediately upstream of a bridge. This riprap is intended to protect the bridge abutment and help direct the water through the bridge opening. Figure 12 shows a guide bank upstream from a bridge. In this situation, a long extent of riprap was placed on the bank upstream from the bridge to ensure that the flow pattern in the channel properly lined up with the bridge opening.

Riprap is also used under the bridge to protect the bridge abutment (see Figure 13).

Figure 13 – Riprap protecting a bridge abutment

One of the most vulnerable locations of a riprap installation is at the end of the installation. At the upstream end, water can start to erode the soils just before the start of riprap and allow the flows to get behind the rock, compromising the installation. At the downstream end, water can start to erode the soils at the end of the riprap and allow the riprap to unravel, which will also compromise the installation. One of the most common ways to counteract these erosive forces at the ends of the installation is to provide a thicker layer of rock, excavated farther back into the bank, to protect the ends.

For bridge abutments, similar problems can occur. The solution for bridge abutments is to extend the riprap protection around the abutment slope. The riprap often extends beyond the end of the bridge by 20 feet or more (depending on the size of the stream).

Freeboard Requirements

When riprap is installed to protect an embankment from erosion, there is frequently a question about how much freeboard is necessary. Freeboard is commonly considered to be the distance between the maximum design water level and the top of the riprap.

Part of the decision-making process for determining the amount of freeboard is the value of the infrastructure being protected. If the infrastructure has very high value, such as a bridge, it is not uncommon for the freeboard to be 2 feet above the 100-year water level. If the infrastructure has lower value the freeboard could be reduced to a lower value, even below the 100-year water level.

Another part of the decision-making process for determining the amount of freeboard is the consequence associated with failure of the riprap and partial or complete loss of the infrastructure being protected. In the case of a bridge or roadway, the consequence of losing the infrastructure in related to the replacement value of the infrastructure along with the level of traffic on the roadway. Roadways will high traffic are more valuable to the general public and therefore usually receive a higher level of protection.

When the infrastructure being protected is an earthen dam, the consequence of failure may be substantially higher that the roadway condition.

PROTECTING BRIDGE PIERS

Another area that is very subject to erosion is adjacent to bridge piers. The piers (or pilings) create turbulence in the flow which re-directs the energy. Piers and piles are often extended to depths well beyond the expected scour. In some installations, this is not practical so riprap is sometimes used. Figure 14 shows an example of riprap placed around a series of pilings to protect the pilings. This riprap was installed as a maintenance measure after some scour had already occurred.

Figure 14 – Riprap around bridge pilings

There are several issues which limit the effectiveness of riprap for piers and pilings. In larger streams the velocities and erosive forces are high enough that the riprap can be displaced and moved downstream which eliminates the protection. In addition, debris can accumulate on the upstream side of the pier (see Figure 15). The debris increases the scour potential at the pier and also directs the erosive velocities farther away from the piers where riprap is less likely to be placed.

Figure 15 – Debris around bridge pilings

PROTECTING CHANNELS

Erosion can occur even in relatively small channels. To protect the soils in the bottom of these channels, riprap can be installed. Figure 16 shows an example of fine gravel placed in a roadside channel to provide erosion protection. Figure 17 shows an example of much larger rock placed in a roadside channel. When rock is used in a small channel to protect the soil from erosion, it is important to select an appropriate rock size. The calculations typically provide a minimum D_{50} for riprap. However, rock that is too large can be a problem because it is necessary to provide a thickness of rock that is at least twice the D_{50} size and with a small channel, this can resultant in substantial excess excavation, or a scattering of rocks that don't adequately protect the underlying soils.

Figure 16 – Channel with fine gravel for erosion protection

Figure 17 – Channel with riprap for erosion protection

CULVERT EXIT PROTECTION

The sizing for riprap at the end of a culvert was previously discussed. Similar to the issues with riprap for channel protection, riprap at the end of a culvert can be too large. One of the issues related with large individual rocks at the end of the culvert is they can collect debris which blocks the culvert outlet (see Figure 18). This figure also shows the large rock used is higher than the invert of the culvert which reduces capacity and creates additional potential for collecting debris.

The lateral and longitudinal extent of riprap can also be an issue. As noted in the discussion on sizing of a riprap apron, the purpose of the riprap apron is to spread out the flow and to dissipate energy. Figure 19 shows a long riprap apron that is very narrow. As the flow starts to spread out, the edges of the apron are subject to erosion. This figure is another example of the use of riprap that includes some rocks that appear to be much too large for the channel and the situation.

Figure 18 – Pipe outlet with debris accumulation

Figure 19 – Culvert outlet with riprap protection

REFERENCE

1. Federal Highway Administration, Hydraulic Engineering Circular 23, "Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance."

Riprap Design for Erosion Protection - Quiz

Updated: 10/19/2020

1. Erosion of a channel bank is most common in which location?
   a. On the inside of a bend
   b. On the outside of a bend
   c. It is common on both the inside and outside of a bend
   d. It is uncommon on either the inside or the outside of a bend.

2. What force acts in an upward direction and tends to lift sediment particles from the stream channel?
   a. Buoyancy force
   b. Drag force
   c. Gravity
   d. None of the above

3. What force resists movement of soil particles in a channel?
   a. Gravity
   b. Drag
   c. Both of the above
   d. None of the above

4. How is the shape factor for riprap calculated?
   a. It is the ratio of the largest dimension to the smallest dimension
   b. It is the ratio of the smallest dimension to the largest dimension
   c. It is the ratio of the largest dimension to the D_{50}
   d. It is the ratio of the smallest dimension to the D_{50}

5. What type of gradation of riprap is most effective?
   a. Rock of all the same size
   b. Rock with a variety of sizes (graded riprap)
   c. Gradation does not impact the effectiveness of riprap
   d. None of the above

6. Which of the following material properties is desirable for rock used for riprap?
   a. Hard
   b. Angular
   c. Dense
   d. All of the above.

7. How important is a filter under riprap?
    a. It is totally unnecessary
    b. It is required only in extreme conditions
    c. It is helpful but not usually necessary
    d. It is recommended for all installations

8. In general, how far should riprap extend down a channel bank?
    a. To the water line
    b. To the bottom of the channel
    c. To the bottom of the expected scour level
    d. None of the above

9. How does velocity impact the necessary size of riprap for bank protection?
    a. Higher velocity requires larger riprap sizes
    b. Higher velocity requires smaller riprap sizes
    c. Velocity is not a factor in determining riprap sizes
    d. Higher velocity may require either larger or smaller riprap sizes

10. What is the primary erosive force on the shore of a lake?
    a. Velocity of the water
    b. Wave action
    c. Buoyancy
    d. None of the above