Design of Riprap for Slope Protection against Wave Action

Introduction

This article is intended to provide practical guidance to engineers for the design and construction of riprap for embankment dams, particularly small embankment dams. This article is not intended to be an all-inclusive guide. A list of commonly used references on the topic is provided at the end of this article.

As discussed in the previous article of this issue, earthen embankment dams can be subject to erosion by wave action within the reservoir. In 1983 the USDA developed a technical release (TR-69) that describes procedures for the design of rock riprap protection for earthen embankments to protect against wave action. TR-69 was used as the basis for this article. Detail not found herein can be found in TR-69 and the associated references. As mentioned in the previous article the design procedures described in TR-69 are generally limited to reservoirs having an effective fetch length of less than 10 miles and significant wave height of less than 5 feet.

Additional relevant publications for guidance on the design of riprap slope protection include Chapter 7 of "Embankment Dams" (Reclamation 1992), "Design of Small Dams" (Reclamation 1987), "Design of Coastal Revetments, Sea Walls, and Bulkheads" (USACE 1995) and "Design of Riprap Revetment" (FHWA 1989).

Why Riprap?

Slope armoring acts as primary protection against embankment erosion caused by wind and wave action within the reservoir. Excessive erosion of a dam embankment can lead to embankment failure. Inadequately designed or installed riprap can pose a dam safety risk. For successful performance, a riprap layer must be designed to:

- Protect the individual rock particles from displacement by the wave force, and
- Keep the protected earth, filter, and bedding underlying the riprap from being washed out through the voids in the riprap.

Figures 1 and **2** are examples of the embankment erosion that can occur without adequate protection against wave action.

Figure 1: Erosion of a small embankment dam in Montana caused by wave action.

Figure 2: Erosion of a small embankment dam in Montana caused by wave action.

Riprap is one material commonly used as armoring for upstream slope protection. There are other commercially available armoring materials, each with their own design considerations and methodologies.

Some of these alternate materials include articulated concrete blocks, cellular concrete mats, and in some low wave-energy sites, vegetation or geosynthetic reinforced vegetation. This article focuses on the design of riprap armoring, as it is the most commonly preferred and installed material.

Procedure

In general terms and in TR-69, the procedure for the design of riprap can be summarized as a flow chart as shown on **Figure 3**. This procedure is described in the following sections of this article and an example (Example #2) is provided at the end of this article. Example #2 is a continuation of Example #1 from the previous article in this newsletter.

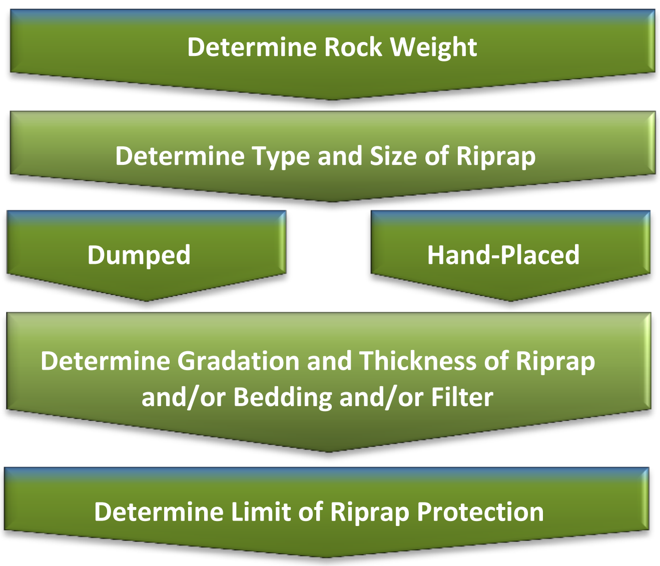

Figure 3: Summary flow chart procedure for design of riprap.

Determining Rock Weight

In accordance with TR-69, the equation to estimate the required riprap rock weight (W_{50}) can be given as:

$$W_{50} = \frac{19.5\ G_S\ H_S^3}{(G_S-1)^3 \cot\ \alpha} \qquad \text{Eq.1}$$

G_S = Specific Gravity
H_S= Significant Wave Height (See previous article for calculation method)
cot α = Horizontal Component of Embankment Slope

Rock weight can also be estimated using Figure 8 in TR-69. As the embankment slope and or significant wave height increases, the calculated W_{50} rock weight also increases. Conversely as the embankment slope and or significant wave height decreases, the calculated W_{50} rock weight reduces.

Determining Type, Size, Thickness and Gradation

There are two types of rock placement described in TR-69:

- Type 1 – Dumped (Equipment-Placed) Rock
- Type 2 – Hand-Placed Rock

Dumped rock is regarded as superior to hand-placed rock because of historically low maintenance costs. Experience has also shown that in most cases dumped rock provides the best upstream slope protection at the lowest ultimate cost. For these reasons, only dumped rock is discussed further in this article.

The procedure for determining the physical riprap characteristics described in TR-69 for Type 1 (dumped) rock is as follows:

- Size: using the W_{50} weight of rock, find rock size (D_{50}) using Figure 9 (TR-69) or the equations provided with the figure. Usually the equation for spherically shaped rock is used to estimate rock size for riprap as follows:

$$D_{50} = 1.24 \sqrt[3]{\frac{W_{50}}{62.4\ G_S}} \qquad \text{Eq.2}$$

Where, G_S = Specific Gravity

- Gradation: using the rock size, find the gradation limits using Figure 10 (TR-69).
- Thickness: two times the D_{50} rock size.

According to the hazard category of the dam a safety factor can also be applied to the calculated D_{50} rock size and this is described in “Slope Protection for Dams and Lakeshores” (USDA 1989). Alternative methods for determining riprap size, thickness, and gradation are described in Chapter 7 of “Embankment Dams” (USBR 1992).

Generally riprap should be hard, dense angular stone, graded as designed, comprising sound fragments resistant to abrasion and weathering and be free of cracks, seams, clay, organic material and other defects. Rounded boulders or cobbles are not generally acceptable as riprap.

Bedding and Filters

Once the gradation of the riprap is determined, the gradation and thickness of the bedding layer should be determined. In principal, the bedding layer provides a foundation for the riprap placement and also provides a filter-compatible transition layer to finer, underlying embankment materials. The finer embankment material underlying the riprap could be washed out through the rock particles during reservoir fluctuations and wave action. Retention of the underlying embankment materials is attained by placing a finer-grained layer of bedding under the riprap. Where very large riprap is used, a progressively finer two-stage bedding/filter layer may be required. The bedding layer needs to be filter-compatible with both the underlying embankment material and overlying riprap to limit the potential of erosion and washout of both embankment and bedding material between the voids of the riprap.

Generally bedding should be a well-graded mixture of gravel and sand that is filter-compatible with both the riprap and the embankment materials. There is some general guidance on developing the filter-compatible gradation and the recommended thickness provided in Chapter 7 of Embankment Dams (Reclamation 1992) and in Design of Riprap Revetment (FHWA 1989). The general guidance for bedding thickness is summarized in **Table 1**.

Table 1: Bedding layer thickness according to riprap layer thickness.

Riprap Layer Thickness	Bedding Layer Thickness
12-24”	9”
27-36”	12”
Over 36”	15”

Limit and Layout of Riprap Protection

According to TR-69, the lower limit of the riprap protection should be 1.5 times the significant wave height (H_s) below the reservoir normal water level at the lowest ungated opening, or below the lowest controlled outlet.

The upper limit of riprap is described by TR-69 as the vertical distance above the reservoir still water flood pool level equal to the sum of the wave runup (R) and wind setup (S). This can be calculated as described in the previous article. The lower limit of riprap is determined by the lower of either the (a) vertical distance of 1.5 times H_s below the still water flood pool, or (b) lowest controlled outlet elevation.

The upper and lower limits of riprap are shown on **Figure 4**.

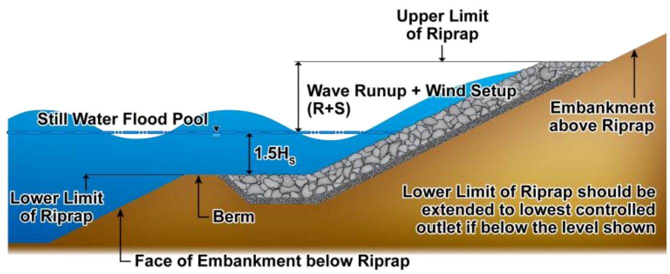

Figure 4: Typical upper and lower limits for riprap placement.

For owners of existing small dams the extent of a riprap revetment may be limited by the budget available to complete the project. When this is the case the owner and designer should carefully consider where the riprap can offer best value from a dam safety and operational perspective. Priorities could include, but may not be limited to, providing riprap on sections of the embankment where erosion has previously occurred, is deemed likely to occur (i.e., adjacent to concrete structures and other infrastructure), and or in horizontal bands at the reservoir normal water level or normal operational water level. Experience has shown that dam embankments built with interior or exterior bends or at angles that are perpendicular to prevailing winds, can be more susceptible to erosion. Armoring of these areas should be a priority.

Placement

According to TR-69, for dumped rock, the placement of bedding and riprap on a dam embankment should be as shown on **Figure 5**. This figure shows the riprap supported by a level berm (also refer to **Figure 4**), which facilitates placement.

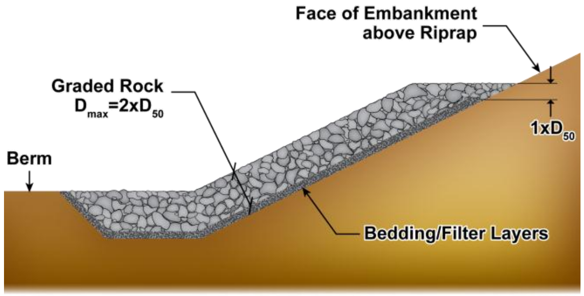

Figure 5: Dumped rock placement detail.

Where construction of a berm is impractical or on an existing slope, keying of the riprap into the slope is recommended to prevent displacement of riprap down the slope. A reference published by the Minnesota NRCS state office titled "Slope Protection for Dams and Lakeshores" (USDA 1989) provides alternatives for keying riprap into existing slopes where the riprap will not extend the full height or length of the dam.

The placement of riprap should be done by mechanical means, such as a hydraulic excavator. Dumping riprap from a truck down an embankment should be avoided as it can cause segregation of the rock by size and result in unsuitable gradation. Placement should be performed to produce a well-graded, even mass of rock with uniform cover and minimal voids. Laborers should be provided during placement for rearrangement of loose rock fragments, "chinking" of void spaces, and hand-placement as needed to provide a well-keyed and stable layer of riprap.

Figure 6 shows dumped riprap being placed over bedding on the upstream slope of a small dam in South Dakota.

Figure 6: Placing riprap bedding and riprap on the upstream slope of a small dam in South Dakota.

Conclusion

Properly designed and installed riprap can provide erosion protection from wave action that would otherwise cause significant damage of earthen embankment dams. For riprap to be effective the designer must calculate the required riprap weight, size and gradation, and specify acceptable material properties. The designer must carefully consider bedding and/or filter requirements to ensure that they are compatible with the embankment material and the riprap itself.

References (with Links where available)

To aid the designer through the process, the following is a list of design references that can be used:

- USDA (1983), Technical Release No. 69: Riprap for Slope Protection against Wave Action.
- USDA (1989), Minnesota Technical Note 2: Slope Protection for Dams and Lakeshores.
- Reclamation (1992), "Design Standards No. 13: Embankment Dams", Chapter 7 – Riprap Slope Protection, U.S. Department of Interior, Bureau of Reclamation, Technical Service Center, Denver, CO. *Look for the revised version of this reference at the following link soon:* Reclamation Dam Design Standards
- Reclamation (1987), "Design of Small Dams", U.S. Department of Interior, Bureau of Reclamation.
- FHWA (1989), "Design of Riprap Revetment", Federal Highway Administration, McLean, Virginia.

Example #2:

Design embankment riprap protection for the dam described as Example #1 in the previous article of this newsletter. The upstream dam embankment slope is 3H:1V, the significant wave height (H_S) was calculated as 3.2 ft and the specific gravity (G_s) of the riprap source is 2.65.

Calculations:

1. Determine the required W_{50} rock weight for the riprap using **Equation 1**:

$$W_{50} = \frac{19.5 * 2.65 * 3.2^3}{(2.65 - 1)^3 * 3.0}$$

$$W_{50} = 126\ lbs$$

2. Using the W_{50} rock weight determine the D_{50} rock size for the riprap using **Equation 2**:

$$\mathrm{D}_{50} = 1.24 \sqrt[3]{\frac{126}{62.4 * 2.65}}$$

$$\mathrm{D}_{50} = 1.15\ \text{feet}$$

   The riprap layer thickness and maximum rock size is calculated as two times the D_{50} rock size. Using the D_{50} rock size of 1.15 feet, D_{MAX} is 2.3 feet.

3. Using the D_{50} rock size estimate the gradation limits using Figure 10 (TR-69). Gradation limits for a riprap with a D_{50} rock size of 1.15 feet are shown in Table 2.

Table 2: Gradation limits for a D_{50} rock size of 1.15 feet.

Rock Passing Sieve	Size
100%	21 to 28”
85%	19 to 26”
50%	14 to 20”
15%	2 to 9”

4. Using the guidance on the bedding layer thickness provided in Chapter 7 of “Embankment Dams” (Reclamation 1992), adopt the bedding layer thickness as 12”. Determine the gradation of the bedding and any requirements for a filter layer in accordance with the aforementioned reference, TR-69 and “Design of Riprap Revetment” (FHWA 1989).

5. Determine the limit and layout of the riprap protection. Consider the limits described in this article and in TR-69.