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New Riprap Design Criteria to Prevent Embankment Dam Failure During Overtopping

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NEW RIPRAP DESIGN CRITERIA TO PREVENT EMBANKMENT DAM FAILURE DURING OVERTOPPING

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Abstract

The Bureau of Reclamation (Reclamation) and Colorado State University (CSU) are currently investigating the effectiveness of using riprap on the downstream face of an embankment dam as an overtopping protection method. Existing theoretically and empirically developed design criteria to size riprap for overtopping protection often predict widely varying rock sizes for use on a given dam. The existing criteria have been developed from small scale tests and are not well defined for steeper slopes, larger size rock, and the unit discharges often associated with overtopping designs. An extensive test program with large riprap on a 2:1 slope has been conducted.

The result of these tests, combined with data from many other investigators, is the development of a preliminary design procedure for use in predicting the riprap size and layer thickness needed to prevent dam failure during overtopping events. The new criteria are suggested for use by the dam safety community to both evaluate the capability of riprap on existing dams and for designing new small riprap-covered embankments to safely pass small magnitude overtopping flows. Evaluating the capability of the riprap protection on an existing dam to pass overtopping flow without failure is also the first step in a risk assessment dealing with the possibility of dam breach and eventual failure.

A brief summary of suggested new riprap design criteria for protecting embankments projected to overtop will be presented. The paper will illustrate the use of the design information by presenting the design of a stable riprap cover for a small embankment dam.

Further tests will be conducted in the summer of 1997 with the riprap covering the entire flume slope to allow investigation of appropriate toe treatments. Results from these tests will be incorporated with the existing database to ensure quality design recommendations.

Background

Riprap is the most common cover material for most embankment dams, including those owned by Reclamation. Often engineers want to know if it will provide adequate protection should the dam overtop. However, flow hydraulics on steep embankment slopes protected with

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riprap cannot be analyzed by standard flow and sediment transport equations. Reclamation currently takes a relatively conservative stance on the stability of a riprap armored embankment dam subjected to overtopping [1]. Several other researchers have proposed empirical riprap design criteria based upon small scale testing on fairly mild slopes and the assumption that uniform flow equations can be applied [2,3].

Predicting riprap stone sizes from these previous works produces widely varying results. Overestimating of the stone size needed to protect a dam can lead to excessive costs during construction of the project. Underestimating the stone size can lead to catastrophic failure of the dam and loss of life.

Introduction

There continues to be a real need to determine a reliable method to predict riprap stone sizes for the flow conditions associated with dam overtopping. To address this need, a multi-year program to develop design criteria for riprap subjected to overtopping flows is being funded by Reclamation's Dam Safety and Research and Technology Development Programs. The program has two main objectives:

- Perform large scale testing of riprap on a steep slope.
- Determine criteria for riprap size and layer thickness needed to protect an embankment dam during overtopping.

These objectives have been met by the completion of two test programs with large size riprap on a 2:1 slope, comparison with other experimental data, and compilation of the results into proposed new criteria for riprap size and layer thickness to provide adequate protection during overtopping.

Test Program

Test programs with large riprap were completed in the Overtopping Facility at CSU in Fort Collins CO during 1994 and 1995. The test facility, instrumentation, data acquired, and results are described in the following sections.

Facility

The test facility consists of a concrete head box, chute, and tail box. The chute is 10 ft wide and has a 50-ft vertical drop on a 2:1 (H:V) slope (Figure 1). The walls of the flume are 5 ft high and extend the full length of the chute. Plexiglass windows, 3- by 3-ft, are located near the crest, mid-point, and toe of the flume along one wall. Water is supplied by a 3-ft-diameter pipe from Horsetooth Reservoir. The supply pipe diffuses into the head box below a broad flat crest that replicates overtopping conditions. The facility has a maximum discharge capacity of about 160 ft^3/s, including an additional 30 ft^3/s added by a pump that recirculates flow from the tail box. The unit discharge, 16.0 ft^2/s, is determined by dividing the total discharge capacity by the variable width of the facility, that is currently set at 10 ft. The unit discharge may be increased by reducing the flume width.

Figure 1. - The Overtopping Facility at CSU is 10 ft wide with a 50-ft drop over a 2:1 slope. Shown is the empty flume with water flowing down the concrete floor of the flume.

Instrumentation and Data Acquisition

The facility provided the opportunity to gather important data regarding flow through large size riprap. The visual observations provided information on the aeration, interstitial flow, stone movement, and the failure mechanism on the slope. Of course, discharge and head data were collected for each test. In addition, the flow depth and interstitial flow velocities were recorded at three stations down the flume slope.

Interstitial flow velocities were recorded by using a salt injector and three conductivity probes at each of the three stations down the slope. The velocities were obtained by injecting salt water into the flow and measuring the time until the wave front arrived at each of the downstream probes. Each injector and probe had three different elevations to inject or record, respectively. The voltage decreased at each conductivity probe as the salt wave arrived. This trace was recorded with a commercially available data acquisition unit with software for use with a personal computer.

Depth was measured using water manometers inserted through the floor of the flume into a tower attached normal to the floor. The data recorded were the depths of solid water flowing interstitially between the rocks, not the highly aerated flow skimming the surface.

Riprap Characteristics

The riprap test section covered the full width of the chute and extended 60 ft down the slope from the crest. Three-inch angle iron ribs were installed across the chute floor to retain the bedding on the slope. The angle iron was bolted to the chute with a 0.5-in space underneath to provide a flow path at the chute surface. An open frame retaining wall was located at the downstream end of the test section to hold the toe in place. The riprap layers were placed by dumping.

Tests were first conducted in 1994. The first test section consisted of an 8-in-thick gravel bedding material with a 2-ft overlay of large riprap. The bedding layer thickness and size were designed according to standard Reclamation criteria. The gradation curve for the riprap tested in 1994 is shown on Figure 2. The riprap porosity was 0.45.

The riprap tests performed in 1995 utilized the first test bed with a second, 2-ft-thick layer of relatively uniformly graded rock, placed over the existing material. Most rocks were dumped into the flume; however, because of the rock size, some hand readjustment was necessary to even out the surface and avoid damaging the instrumentation. The bedding and riprap material from the previous tests basically became the bedding material for the larger riprap of the 1995 tests. The gradation curve for the top riprap layer tested in 1995 is shown on Figure 3, and again, the riprap porosity was 0.45.

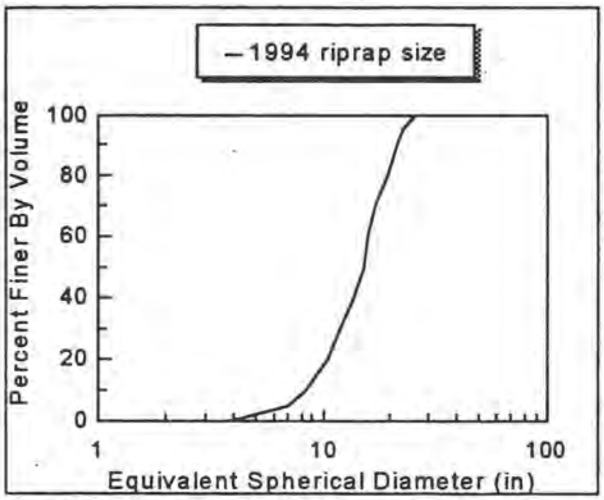

Figure 2 - Gradation curve for 1994 riprap tests.

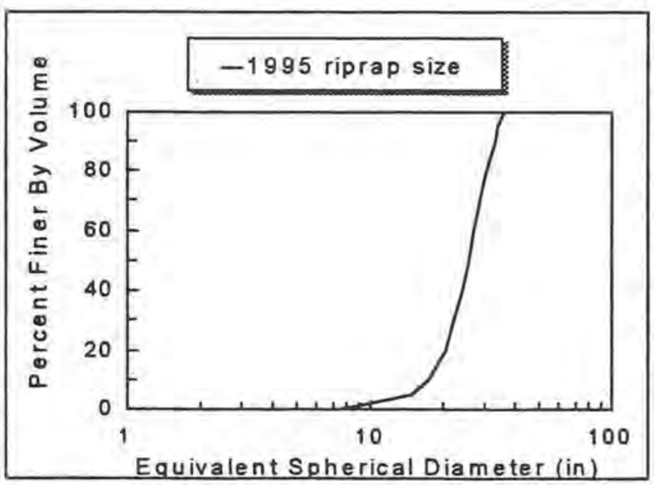

Figure 3 - Gradation curve for 1995 riprap tests.

Results

Important observations and physical information were gathered during the tests of each size riprap. Observations of flow conditions provided needed insight into the physical data. The interstitial flow velocities and depths were analyzed with the stone properties and flow equations to produce meaningful results.

Riprap Flow Conditions

Flow conditions through riprap covering an embankment are a function of the rock size distribution, embankment slope, and discharge. Flow conditions were well documented by making observations from the surface and through the side windows located at the crest brink and near the toe of the riprap on the slope.

During low flow conditions, the flow comes over the flat concrete crest and dives down into the riprap layer. There is no flow visible over the surface of the rock layer and the flow is entirely interstitial. Viewing from the side windows indicated that the flow was very aerated, even with a few bubbles in the bedding layer. The flow was extremely turbulent with eddies forming behind some rocks and jets impinging on other rocks. Failure of the riprap layer would be unlikely during these low flow conditions because the water level is well below the top layer of the riprap.

As the flow increases, the water still dives down into the riprap layer at the crest, but soon thereafter, reappears on the surface and is frothy and highly aerated. The flow intermittently cascades over the surface then penetrates into the riprap layer. Flow in the bedding layer is obviously of a lesser velocity, with turbulence increasing towards the surface where skimming flow is

Figure 4. - View looking down onto the surface of the 1994 riprap layer with q=2.0 ft^3/s/ft.

occurring. Flow patterns and forces begin forming that will eventually lift or move surface rocks from the protective layer. During this phase small rocks begin moving on the surface, but failure has not occurred.

The flow conditions for the 1994 season tests are shown in Figure 4. This view of the surface shows highly aerated flow with stones still visible just before failure.

Figure 5 shows the flow conditions for the 1995 season tests with the second larger layer of riprap placed over the previous 1994 riprap layer. The lower level of riprap carried a large portion of the flow with the flow through the upper layer very aerated and highly turbulent. A transition in flow conditions is visible between the two different size rock layers. The flow continues to be well aerated throughout the depth for a discharge of 8.0 ft^3/s/ft. The majority of the flow is interstitial in spite of the very large amount of spray and splash observed during these tests.

Figure 5. - Overall view of 1995 riprap material with q=8.0 ft^3/s/ft.

Interstitial Velocities, Flow Depth, and Discharge Relationships

The measured interstitial velocities and flow depths produced some interesting results, particularly when combined with visual observations of the flow. The results are shown schematically on Figure 6 for both test programs. The figure shows a representation of the bedding and rock layers with general indications of the velocity profiles, transition points and flow depths measured during the tests.

The velocity for a specific level in the rock layer is relatively constant for a wide range of discharges, provided that the flow is purely interstitial. The average measured interstitial velocity in 1994 is about 1.9 ft/s throughout this riprap layer. The velocity in the bedding layer is less, and the velocity of the skimming surface flow is much greater. The zones of constant and transitional interstitial velocity are shown schematically on Figure 6 by the plot of velocity, V, versus depth, Y. Velocity was relatively constant down the slope of the facility indicating that the flow was not continuing to accelerate.

There were two distinct zones of flow and velocity for the 1995 large riprap tests. Interstitial velocities measured in 1995 in the lower layer underneath the larger stones averaged about 2.1 ft/s. More flow passed through this layer than in the previous tests because of the protective layer of larger stones on top. The conductivity probes were not fully submerged in the upper layer of large rock, preventing the direct measurement of the interstitial velocity. Velocities in the upper layer were determined by extrapolating the depth and unit discharge plot, Figure 6. The linear relationships shown in Figure 6 between unit discharge, q, and flow depth, Y, for the various layers of material were developed from the flow depth data. These schematics also indicate constant velocity within each respective layer of material, as the velocity would be equal to the slope of the line. The velocities represented by the slope of the line are similar to the measured interstitial velocities in the 1994 and lower 1995 rock layers. The change in slopes of these lines corresponds to the change in velocity as different layers of material or the free surface are encountered. Therefore, the interstitial velocity of about 5.6 ft/s was determined for the upper layer of rock by using the depth and discharge data. This increase in velocity is due to less resistance associated with the very large size rock. The average flow depth in the riprap layer measured during these tests never reaches the top of the layer before failure of the rock slope. The interstitial velocity is used later to help determine the thickness of the required riprap layer with respect to the depth of flow before failure.

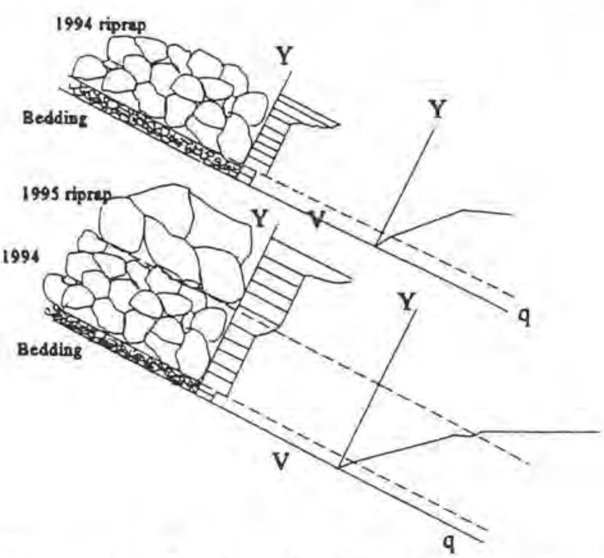

Figure 6. - Schematic of rock layers, velocity profiles, and discharge versus depth profiles for both test programs.

Failure

Prior to failure of the riprap slope, many individual stones moved or readjusted locations throughout the test period. Movement of these stones is referred to as incipient motion. This occurs when the displacing or overturning moments exceed the resisting moments. The force in the resisting moment is given by the component of the weight perpendicular to the embankment and interlocking between stones in the matrix. The overturning forces are the drag (or the jet impact on a stone), the lift, buoyancy, and to a lesser degree, the component of the weight parallel to the embankment depending on the point(s) of contact with other stones. Even though buoyancy plays an important role in the removal of rocks, the hydrodynamic forces have the major role in producing failure of the protective layer. This observation is supported by the depth measurements which revealed that the stones on the surface are not submerged.

Failure of the riprap slope was defined as removal or dislodgement of enough material to expose the bedding material. Failure of the riprap layer occurred with the measured water depth still below the surface of the upper protective rock layer. Highly aerated water consistently flows over the surface of the riprap, but represents only a small portion of the flow and is not measurable by water manometers.

A large bathtub-shaped hole was formed in the 1994 riprap layer down to the bedding layer at a distance of about 55 ft down the slope. Failure was less defined in the large 1995 material placed over the top of the previous riprap layer. Many stones were repositioned during the tests, and five stones were dislodged from the slope and caught in the trap below. The riprap layer was considered to have failed between a unit discharge of 10-13 $ft^3/s/ft$. Many stones had repositioned or had been removed, such that the layer underneath the large stones was significantly exposed in several locations.

Design Criteria

The objective of the test program was to verify existing riprap design equations for overtopped embankments or to develop new design guidelines. The data gathered during the tests performed under this program have provided information on larger size rock on steeper slopes than any previous test program.

Design Procedure to Predict Stable Stone Size

A new design procedure to predict median stone size for a protective riprap layer has been developed from the test program and compilation of data from previous investigations [1,2,3,4]. A set of curves shown in Figure 7 for different embankment slopes combines the rock properties of the riprap material, discharge, and embankment slope. The curves provide an estimation of the point of initial failure of the riprap.

Where: q = unit discharge - $ft^3/s/ft$
S = embankment slope
C_s = coefficient of stability = $0.75+(\log C_u^{6})^{-2}$ [3]
and C_u= coefficient of uniformity = D_{60}/D_{10}

The design curves combine empirical data with accepted sediment transport equations. Because this is the median stone size where incipient motion will begin, a safety factor can be provided by the designer, if required.

Figure 7. - Design curves for riprap protection on embankments.

Riprap Layer Thickness

The thickness of protective riprap layers has historically been assumed to be twice the D_{50} or equal to the D_{100} size rock in the layer. The information obtained from the test program, combined with data from other experimenters, has produced an analytical approach to determining the required riprap layer thickness. This approach involves using the interstitial velocity, porosity, and continuity to determine the appropriate riprap layer thickness, t. The following relationship between the interstitial velocity, the median stone size, slope, and the coefficient of uniformity:

$$\frac{v_i}{\sqrt{gD_{50}}} = 2.48 S^{0.58} C_u^{-2.22}$$

is being proposed, where D_{50} is initially determined from the design curves.

The average velocity can be determined using the porosity and the interstitial flow velocity determined by the previous equation from $v_{ave} = v_i n_p$. The average depth, y, is then determined from continuity using the design unit discharge and the average velocity, $y = q/v_{ave}$. This depth is used to determine the required thickness, t, of the riprap layer. The thickness of the riprap layer must always be at least $2D_{50}$. If the riprap layer thickness is less than $2D_{50}$, then the flow is entirely interstitial and the D_{50} stone size is satisfactory for the design discharge. If not, then a portion of the discharge is flowing over the riprap and a larger stone size and/or a thicker layer would be required to accommodate the entire flow depth.

In general, for steeper slopes, the majority of the flow will be interstitial and the $2D_{50}$ criteria will be met; however, this is not always the case. For smaller stone sizes on milder slopes, the riprap thickness is often greater than $2D_{50}$ and often approaches a practical limit of $4D_{50}$. At milder slopes, less than about 0.25, water has been observed to flow through and over the riprap, producing a large required layer thickness. In cases where the flow depth exceeds the $2D_{50}$ criteria, an estimate of the discharge above the riprap must be made using standard flow equations for the flow over rough surfaces, and Manning's and Shield's equations, to assure that the flow over the surface will not exceed the critical shear stress for the design D_{50}. Manning's n value is determined from the equation $n=0.034D_{50}^{1/6}$ based upon previous experimental data [3] and the initial design D_{50}. The depth of flow that can safely pass over the riprap surface and the associated discharge are then determined. This flow is subtracted from the total flow to determine the interstitial discharge and depth that meets the $2D_{50}$ to $4D_{50}$ thickness criteria.

This analytical approach to determining the thickness of the riprap layer provides a design where the riprap layer is at the point of failure for the design discharge. A factor of safety may be applied by the designer, as necessary.

Design Example

The following design example illustrates the use of the proposed method for sizing stable riprap on a typical embankment dam slope. Computations for the median stone size and minimal thickness of the protective riprap layer are shown. A riprap embankment protection is designed for this imaginary dam using the following procedure. Flood and embankment properties that are known or assumed are listed below:

Property	Parameter	Value
Overtopping discharge	Q	2000 ft^3/s
Embankment length	L	1000 ft
Overtopping unit discharge	q	2.0 $ft^3/s/ft$
Angle of repose of material	ϕ	42°
Embankment crest width	W	20 ft
Discharge coefficient	C	2.8
Embankment slope	S	20% or 0.20
Embankment angle	$\propto$	11.31°
Coefficient of uniformity	C_u	2.1
Porosity	n_p	0.45

Step 1: (optional) Many designers like to know the depth of the overtopping discharge; from Q find the overtopping depth using:

$$Q = CLH^{1.5} \qquad \text{or} \qquad H = (Q/CL)^{2/3} = \left(\frac{2000}{2.8X1000}\right)^{0.67} = 0.8ft$$

Step 2: From C_u find the coefficient of stability,
$C_s = 0.75 + (\log C_u^{6})^{-2} = 0.75 + (\log (2.1)^{6})^{-2} = 1.02$

Step 3: Find the median rock diameter, D_{50}, from the design curves for q=2 ft³/s/ft and an embankment slope of 0.20,

$$D_{50}C_S^{0.667} = 0.40 \qquad \text{so} \qquad D_{50} = \frac{0.40}{(1.02)^{0.667}} = 0.39ft$$

Step 4: Find the interstitial velocity, v_i, from

$$v_i = 2.48(0.2)^{0.58}(2.1)^{-2.22}\sqrt{32.2(0.39)} = 0.67ft/s$$

from v_i find the average velocity, v_{ave} using

$$v_{ave} = v_i * n_p = 0.67(0.45) = 0.30ft/s$$

Step 5: Determine the average depth of water, y, at the point of incipient movement of the riprap,

$$y = q/v_{ave} = \frac{2}{0.30} = 6.67ft$$

Check to see if the average depth, y, is less than or equal to $2D_{50}$. If it is, then the design depth of riprap at the point of failure is $2D_{50}$ and the design is completed. If the depth, y, is greater than $2D_{50}$, proceed with Step 6.

$$y = 6.67 > 0.72 = 2D_{50}$$

Step 6: Find the depth of water that can flow over the surface of the riprap without causing critical shear stress.

$$0.97h_1 S = 0.06(\gamma_s - \gamma)D_{50}\tan\phi \qquad h_1 = \frac{0.06}{0.97}(2.65-1)\frac{0.39}{0.2}\tan 42° = 0.18ft$$

where γ_s = specific gravity of rock
γ = specific gravity of fluid
h_1 = depth of water over the riprap.

Step 7: Calculate Manning's roughness coefficient, n

$$n=0.034D_{50}^{1/6} \qquad n=0.034(0.39)^{1/6}=0.029$$

Step 8: Calculate the unit discharge, q_1, that can flow over the riprap layer.

$$q_1=\frac{1.486}{n}h_1^{1.67}S^{1/2}=\frac{1.486}{0.029}(0.18)^{1.67}(0.2)^{1/2}=1.31ft^3/s/ft$$

Step 9: Calculate the unit discharge, q_2, flowing through the riprap.

$$q_2=q-q_1=2.00-1.31=0.69ft^3/s/ft$$

Step 10: Determine a new riprap thickness based on flow through the riprap.

$$h_2=\frac{q_2}{V_{ave}}=\frac{0.69}{0.30}=2.30ft>4D_{50}=1.56ft$$

Step 11: $h_2 > 4D_{50}$, therefore, increase D_{50} by 10%. In this case, increase size to D_{50} = 0.43 ft and proceed through Steps 4 to 10 again.

Second iteration D_{50} = 0.43 ft			
Step	Parameter	Value	Comments
4	v_i	0.70 ft/s	
5	y	6.25 ft	6.25 > 2 D_{50}
6	h_1	0.20 ft	
7	n	0.030	
8	q_1	1.51 ft^3/s/ft	unit discharge over riprap interstitial discharge
9	q_2	0.49 ft^3/s/ft	
10	h_2	1.72 ft	new flow depth through riprap

Required thickness, t, of the riprap layer is the final ND_{50} calculated which exceeds h_2.

$$t = ND_{50} = 4\ (0.43) = 1.72 \text{ feet} \qquad \text{where} \qquad 2 \leq N \leq 4,\ D_{50} = 0.43 \text{ ft}$$

The riprap layer thickness should never be less than $2D_{50}$. There should be a well-graded bedding layer with a specified D_{50} under the riprap layer. A filter cloth (geotextile) or filter layer should be placed under the riprap if there is no bedding layer. Riprap with the designed D_{50} should be placed on top of the bedding layer.

The riprap thickness criterion is based upon the surface flow not causing critical shear stress and the remainder of the flow passing through the riprap with a thickness of $2D_{50}$ to $4D_{50}$. The median stone size determined from the proposed design curves computes the size at which incipient motion begins. The design requires an iterative procedure involving the design D_{50} and the riprap layer thickness for a given design unit discharge. The riprap layer thickness will be given as an integer multiple of D_{50} such as 2 D_{50}, 3 D_{50}, 4 D_{50}, etc.

Continuing Research

This riprap testing program has developed a design criteria for riprap protection used on earth embankments subjected to overtopping flows. Data gathered for the interstitial flow velocity and depth have produced the remarkable ability to predict riprap stone size and layer thickness. Additional tests are being performed in the summer of 1997 to provide additional support for the new theories discussed here and to determine appropriate treatments for the toe of dams protected by riprap. The results of the 1997 tests will provide a definitive equation and a comprehensive set of curves to design riprap protection on any embankment slope based upon the size and gradation of the riprap.

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