SIMPLIFIED DESIGN GUIDELINES FOR RIPRAP SUBJECTED TO OVERTOPPING FLOW

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Abstract

Riprap, or some type of rockfill, is commonly used to prevent erosion of the downstream face of dams during rainfall events. Often, it is expected to be able to protect a dam during small overtopping events. It is generally an inexpensive method proposed to provide stability while rehabilitating dams expected to overtop. Rock channels may also be used as spillways for releases from dams. River restoration projects often use riprap drop structures to prevent degradation of the channel invert.

Previous large-scale testing by Reclamation and Colorado State University produced initial guidelines for designing steep riprap slopes subjected to overtopping. Additional test data from 1997 have been incorporated into this previous work allowing verification of initial design guidelines. Input from embankment dam designers has prompted investigation into simplification of the initial guidelines into a more "user-friendly" form. The errors introduced by assuming a generic coefficient of uniformity, D_{60}/D_{10}, to eliminate determinating three rock sizes, have been computed and use of a safety factor specified. This will produce less concern about obtaining the specified rock gradation during inspection of an existing or construction of a new riprap overlay.

Another important aspect of the design is establishing the use of the guidelines over the full range of riprap slopes. Overtopping flow on embankments with slopes less than or equal to 0.25 (4H:1V) covers the riprap. For slopes greater than 0.25, the overtopping flow must be contained within the layer of riprap for stability, although an insignificant amount of highly-aerated water splashes and cascades over the top of the riprap. The design guidelines specify procedures to deal with both slope situations to provide the designer confidence in using the guidelines.

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.

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A brief summary of suggested new riprap design criteria for protecting embankments during overtopping are 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.

Background

Riprap, or zone 3 rockfill, is the most common cover material for embankment dams, including those owned by Reclamation. Often engineers need to know the riprap will provide adequate protection should the dam overtop. However, flow hydraulics on steep embankment slopes protected with 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]. Other fairly recent investigations have resulted in empirical riprap design criteria based upon small scale testing on mild slopes and the assumption that uniform flow equations can be applied to these cases [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 need for 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 three 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. The results of the 1994 and 1995 test programs were reported at the 1997 Association of State Dam Safety Officials (ASDSO) conference [4]. This paper discusses the final tests and presents the modifications made to the previously given riprap design criteria.

Test Program

Test programs with large riprap were completed in the Overtopping Facility at CSU in Fort Collins CO during 1994,1995, and 1997. The test facility, instrumentation, data acquired, and results are described in the following sections, with emphasis on the 1997 tests and results.

Facility

The test facility consists of a concrete head box, chute, and tail box. The chute is 3 m wide and has a 15 m vertical drop on a 2:1 (H:V) slope (Figure 1). The walls of the flume are 1.5 m high and extend the full length of the chute. Plexiglass windows, 1 m by 1 m, are located near the crest brink, mid-point, and toe of the flume along one wall. Water is supplied by a 0.9 m 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 4.5 m^3/s, which includes an additional 0.8 m^3/s added by a pump that recirculates flow from the tail box to the head box.

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. Discharge and head data were collected for each test. In addition, the flow depth and interstitial flow velocities were recorded at up to four stations down the flume slope.

Interstitial flow velocities were recorded by using a salt injector and two conductivity probes at each of the 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.

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

Figure 1. - Embankment overtopping research facility with riprap protection. Each 1.5 m wide band of rock was painted a different color to assist with observations of rock movement during the 1997 tests. (fig1.bmp)

Riprap Characteristics

The riprap test sections covered the full width of the chute and were placed over typical bedding material. 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 12 mm 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 large riprap with D_{50} of 386 mm placed 0.6-m-thick over a 203-mm-thick gravel bedding material. The riprap layer extended 18 m down the slope from the crest and ended on the slope. The riprap size was selected based upon extrapolation of previous design equations [2]. The bedding layer thickness and size were designed according to standard Reclamation criteria.

The riprap tests performed in 1995 utilized the first test bed with a second, 0.6 m thick layer of relatively uniformly graded rock with D_{50} of 655 mm, 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 1997 tests utilized the results of the previous tests to check the design curves. The previous rock material was removed from the flume and bedding with a D_{50} of 48.3 mm and riprap with a D_{50} of 271 mm was installed. The bedding and riprap covered the entire flume slope and extended 1.8 m horizontally at the toe of the slope, as per embankment dam designer recommendations. The 1997 riprap gradation is shown in Figure 2. The surface layer of riprap shown in Figure 1 is painted different colors in stripes 1.5 m wide to provide visual evidence of movement.

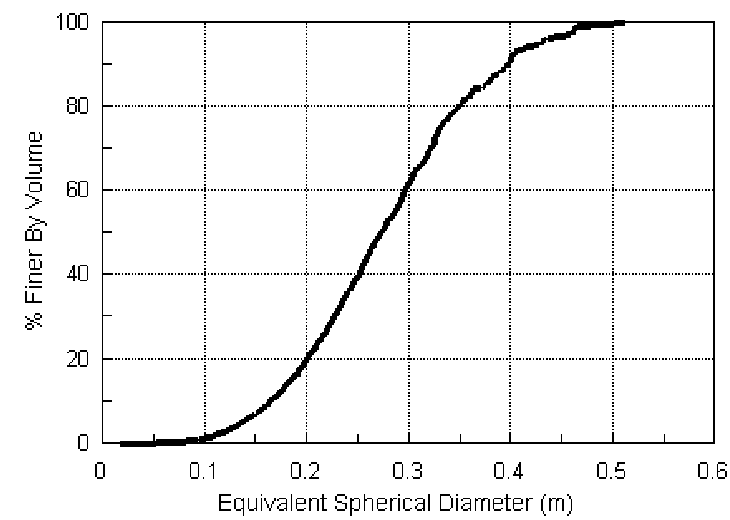

Figure 2. - Gradation curve for 1997 tests. (97grad.wpg)

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, mid point, and near the toe of the riprap 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, with even a few bubbles in the bedding layer. The flow was extremely turbulent with eddies forming behind some rocks and jets impinging on others. 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 flow intermittently cascades over the surface then penetrates into the riprap layer. Continual increase in the discharge results in forces 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.

Figure 3 shows the flow conditions over the riprap protected embankment in the 1997 tests. The majority of the flow is interstitial in spite of the very large amount of spray and splash observed during these tests.

Interstitial Velocities, Flow Depth, and Discharge Relationships

The velocity at a given depth in the rock layer and down the slope is relatively constant for a wide range of discharges, provided that the flow is purely interstitial. During the 1997 riprap tests, the average interstitial velocity was about 0.7 m/s in the riprap layer and about 0.5 m/s in the bedding layer. The average flow depth in the riprap layer during the tests was below the top of the layer at failure on this steep 2:1 slope. The interstitial velocity is used later to determine the thickness of the required riprap layer with respect to the depth of flow before failure.

Figure 3. - Overall view, looking down the slope, of the 1997 riprap material with q=0.09 m^3/s/m. The pipes extending through the riprap were used to measure interstitial velocities. (Fig3.bmp)

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. Channelization occurs, with rock movement and well-developed flow paths forming over the surface of the rock, prior to failure of the slope. 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 solid water depth still below the surface of the 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. This became a very important observation for later determination of riprap layer thickness.

In the 1997 tests, a large hole formed in the riprap layer exposing the bedding layer at a distance 12.1 m down the slope from the crest. The riprap layer was considered to have failed at a unit discharge of 0.20 m^3/s/m. Many stones had repositioned or had been removed until, at failure, the bedding layer underneath the larger stones was exposed in several locations. The definition of failure is one reason for discrepancies when comparing data from various investigators.

Design Criteria

Data gathered during the tests performed under this program provided information on larger size rock on steeper slopes than previous test programs. The task was then to verify existing riprap design equations for overtopped embankments or to develop new design guidelines.

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

[2,4,5,6]. A set of curves shown in Figure 4 for different embankment slopes combines the rock properties of the riprap material, discharge, and embankment slope. Each curve represents the point of incipient failure for a particular embankment slope, S, for a design unit discharge, q, and median stone size, D_{50}. C_u on the y-axis is the coefficient of uniformity of the material which is the ratio of the material D_{60} to D_{10}. The curves on figure 4 are based on the riprap material having an angle of internal friction, F , of 42^E. The design curves combine empirical data with accepted sediment transport equations and are not simply a best fit of the data. A safety factor is not included in the graph, but left to the judgement of the designer to apply as needed.

Further investigation of the data used to determine these design curves can lead to some simplification of the design, such as eliminating the coefficient of stability, C_s, from previous design information [4]. Plotting the data with the design curves on linear axes shows that there is little difference in D_{50} when the embankment slope is 0.1 or less. Also, determination of the coefficient of uniformity is often difficult. This can lead to concerns by the designer trying to identify rock sizes for use with the design procedure. A sensitivity analysis was performed by varying the coefficient of uniformity from 1.5 to 2.1 and found to produce a ±5 percent difference in the computed median stone size.

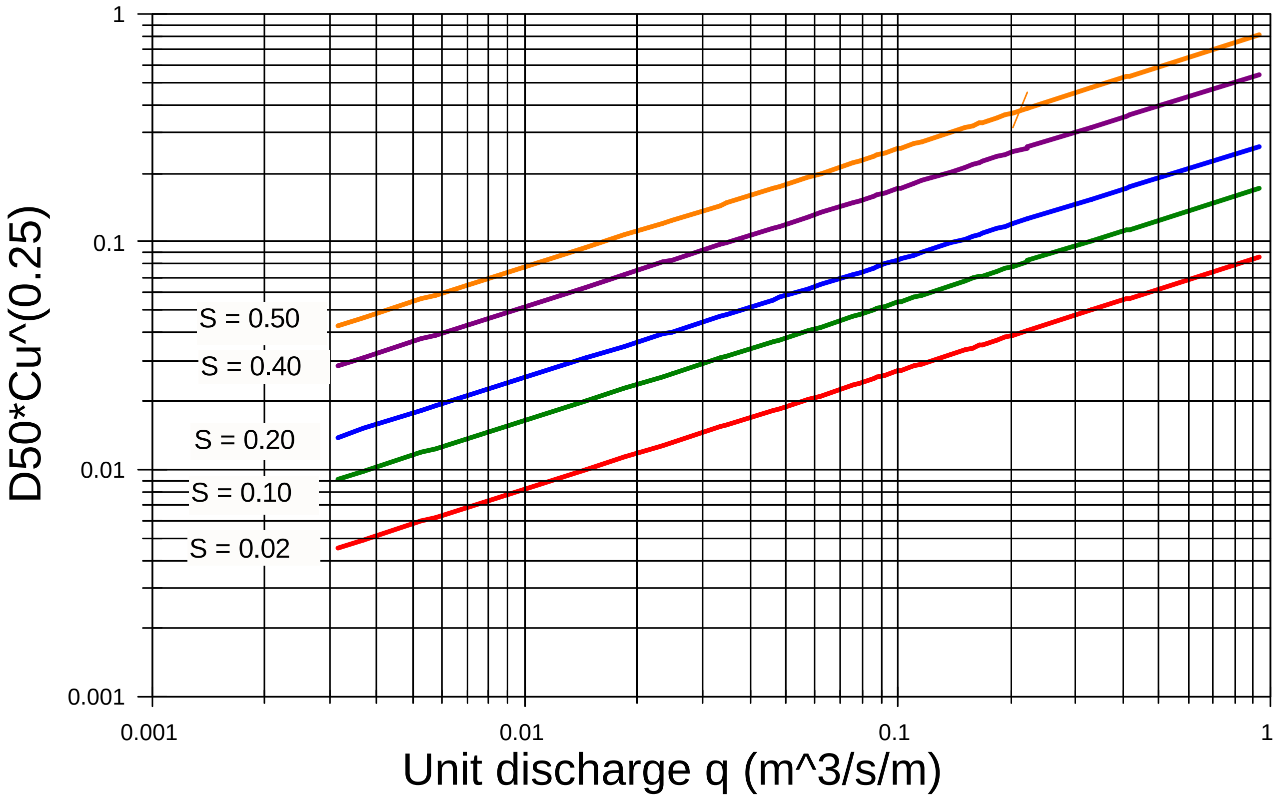

Figure 4. - Design curves to size riprap protection on embankments of various slopes. These curves represent the point of incipient failure as described previously. No safety factor has been included. (Fig4.wpd)

Riprap Layer Thickness

Thickness of protective riprap layers generally is specified as a minimum of twice the D_{50} or equal to the D_{100} size rock in the layer. Interstitial velocity data obtained from the test program, combined with data from previous tests conducted at CSU [2], has produced an analytical approach to determining the required riprap layer thickness. The following non-dimensional relationship has been developed between the interstitial velocity, the median stone size, slope, and the coefficient of uniformity:

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

Where: v_i = interstitial velocity (m/s)
D_{50} is initially determined from the design curves of Figure 4
g = gravitational constant (9.81 m/s^2)
S = embankment slope
and C_u= coefficient of uniformity = D_{60}/D_{10}

This approach uses the interstitial velocity, v_i, porosity, n_p, and continuity to determine the appropriate riprap layer thickness, t. The average velocity, v_{ave} can be determined using the porosity and the interstitial flow velocity determined from $v_{ave}= v_i n_p$. The average flow depth, y, is then determined from continuity using the design unit discharge and the average velocity, $y=q/v_{ave}$. The required thickness, t, of the riprap layer is determined using this flow depth and observations about the relationship between the embankment slope, the median rock size, D_{50}, and the subsequent allowable surface flow.

First some “rules of thumb” regarding riprap layer thickness; 1) the minimum thickness of the riprap layer is $2D_{50}$, 2) the maximum practical limit is $4D_{50}$. A methodology has been developed to determine the appropriate riprap layer thickness based upon the interstitial flow depth and embankment slope.

If the average water depth, y, 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 (as was the case with our tests) and the $2D_{50}$ criteria will be met with possibly a few iterations on the D_{50} rock size. However, this is not always the case. At milder slopes, less than 0.25, water has been observed to flow through and over smaller size riprap [2] and will approach the practical placement limit of $4D_{50}$. In cases where the embankment slope is less than 0.25 and the flow depth, y, exceeds the $2D_{50}$ criteria, an estimate of the flow depth and discharge that can safely pass over the riprap surface must determined. The surface flow depth is determined using standard flow equations for the flow over rough surfaces, and Manning’s and Shield’s equations, to assure that 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 $n=0.0414D_{50}^{1/6}$ based upon previous experimental data [2] and the initial design D_{50}. This surface 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. The difficulty of any design using riprap is the quality control of the rock material properties, size and gradation. For large riprap sizes, specifications are easily written, but from a practical standpoint, it is difficult to verify the riprap properties at the site. A factor of safety may be applied by the designer, as necessary. For example, if the design is for the probable maximum flood, no factor of safety may be required. However, if the design is for the 100-year flood over the service spillway, a factor of safety may be required based on agency policy or experience or judgement of the designer.

Toe Treatment

The riprap protection tested in 1994 and 1995 stopped on the slope with an open frame wall to hold the material in place. Designers expressed concern that perhaps the toe would be the weak point in the design and that the riprap should extend down the entire slope to a horizontal toe berm. As a result, bedding and riprap were placed horizontally at the toe of the slope with a berm equal to twice the riprap layer thickness placed parallel to the slope over the toe. The riprap failed on the slope first with no noticeable movement of the toe treatment throughout the test program. After failure on the slope had occurred the berm thickness over the toe was progressively reduced to equal the slope thickness. Rock movement occurred but no failure of the toe. These tests included flows with and without tailwater over the toe.

The riprap on the slope was then stabilized by covering the rock with anchored wire mesh and the discharge increased to determine the point of incipient failure for the toe. However, in spite of the stabilizing procedure, the rock at the crest dislodged and was removed down to the floor of the flume, causing failure of the entire slope such that testing of the toe could not continue. No specific guidelines are given, but clearly riprap on the slope is less stable and will be the point of failure, not the toe protection.

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 in metric or S.I. units. Flood and embankment properties that are known or assumed are listed in the following table:

Property	Parameter	Value
Overtopping discharge	Q	65 m^3/s
Embankment length	L	304.8 m
Overtopping unit discharge	q	0.213 $m^3/s/m$
Angle of repose of material	f	42^o

Property	Parameter	Value
Embankment crest width	W	6.1 m
Discharge coefficient	C	1.57
Embankment slope	S	23% or 0.23
Embankment angle	%	13^{o}
Coefficient of uniformity	C_u	1.95
Porosity	n_p	0.45
Specific gravity of riprap	G_s	2.65
Specific gravity of water	G_w	1.00

Step 1: Many designers like to know the depth of the overtopping discharge, therefore, the overtopping depth, H, is found using:

$$Q = CLH^{1.5}$$

$$H = (Q/CL)^{2/3} = \left(\frac{65}{1.57\,x\,304.8}\right)^{0.67} = 0.262\,m$$

Step 2: Find the median rock diameter, D_{50} , from the design curves (0.213 m^3/s/m and an embankment slope of 0.23),

$$D_{50}\,C_u^{0.25} = 0.14 \qquad D_{50} = 0.12\,m$$

Step 3: Find the interstitial velocity, v_i,

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

$$v_i = 2.48(0.23)^{0.58}\,(1.95)^{-2.22}\,\sqrt{9.81(0.12)} = 0.26\,m/s$$

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

$$v_{ave} = v_i \times n_p = 0.26 \times 0.45 = 0.12\ m/s$$

Step 4: Determine the average depth of water, y, at the point of incipient failure of the riprap,

$$y = q / v_{ave} = 1.78\, m$$

Check to see if the average depth, y, is less than, or equal to $2D_{50}$, in which case the design is complete and the design depth of riprap is $2D_{50}$. If not, then the embankment slope and practical limitations on overall placement thickness of $4D_{50}$ will determine the next steps taken. If the slope is less than or equal to 0.25, proceed with step 5 to determine the amount of the flow that can safely flow over the riprap surface. If the slope is greater than 0.25, go to step 10, and choose a larger D_{50} size for performing further iterations.

$$y = 1.78\, m > 0.24\, m = 2D_{50}$$

Slope = 0.23, so proceed to step 5

Step 5: Find the depth of water, h, that can flow over the surface of the riprap without causing critical shear stress [7],

$$0.97 hS = 0.06(G_s - G_w) D_{50} \tan(\phi)$$

Using the appropriate values of the parameters, and solving for h,

$$h = \frac{0.06(2.65 - 1.00)(0.12)(0.900)}{0.97\,(0.23)} = 0.048\, m$$

Step 6: Calculate Manning's roughness coefficient, n,

$$n = 0.0414\, D_{50}^{1/6} \qquad n = 0.0414(0.12)^{1/6} = 0.029$$

Step 7: Calculate the unit discharge, q_1, that can flow over the riprap layer from Manning's equation,

$$q_1 = \frac{1}{n} h^{1.67} S^{1/2} = 0.10\, m^3/s/m$$

Step 8: Calculate the unit discharge, q_2, flowing through the riprap,

$$q_2 = q - q_1 = 0.21 - 0.10 = 0.11\, m^3/s/m$$

Step 9: Determine the interstitial flow depth through the riprap,

$$h_2 = \frac{q_2}{V_{ave}} = 0.92\,m \geq 4D_{50} = 0.48\,m$$

At this point, because the interstitial flow depth, h_2, is greater than $4D_{50}$, the stone size must be increased, therefore, go to step 10.

Step 10: Increase D_{50} by 10%. The new D_{50} is now 0.13 m.

Other iterations, with 10 percent increases in D_{50}, are presented in the following table until the interstitial depth of water is less than the chosen limit of placement thickness of the riprap layer:

Step	Parameter	1st iteration D_{50} = 0.13 m		2nd iteration D_{50}=0.14 m		3rd iteration D_{50}=0.154 m	
		Value	Comments	Value	Comments	Value	Comments
5	h (m)	0.052		0.056		0.062	
6	n	0.029		0.03		0.03	
7	q_1 (m^3/s/m)	0.117		0.13		0.152	
8	q_2 (m^3/s/m)	0.096		0.083		0.061	
9	v_i (m/s)	0.271	use Step 3	0.281	use Step 3	0.295	use Step 3
	v_{ave} (m/s)	0.122	use Step 3	0.13	use Step 3	0.133	use Step 3
	h_2 (m)	0.786	$>4D_{50}=0.52$	0.638	$>4D_{50}=0.56$	0.466	$<4D_{50}=0.62$

After the third iteration, the portion of the flow, q_2, and depth, h_2, that is carried interstitially is less than $4D_{50}$, therefore, the required thickness, t, of the riprap layer is:

$$t = 4D_{50} = 4 \times 0.154 = 0.62 \text{ m}$$

Thus, the required median stone size at the point of incipient failure is 0.154 m for this discharge and slope. A factor of safety should be applied, as necessary.

Conclusions

Design criteria for large riprap are presented. The design provides a means to determine the point of incipient failure of the riprap for a given overtopping unit discharge and the required thickness of $2D_{50}$ or $4D_{50}$ based on the slope of the embankment, the interstial flow, and surface flow. 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 failure is estimated to begin. 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 $2D_{50}$, $3D_{50}$, or $4D_{50}$. A factor of safety can be provided by the design engineer to meet specific applications. The design criteria can be used for new designs and to evaluate the adequacy of riprap protection on existing dams.

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