Design of Rock Riprap for Bank Stabilization

Wednesday March 7, 2012

Presented by:
Paul Sanford, MSCE, PE, CFM
Applicability

- Lateral Migration Boundary
- Protection of In-Stream Structures
- Protection of Adjacent Infrastructure
Course Outline

- Project Scoping
- Hydraulic Principles for Riprap Design
- Erosion Mechanisms & Failure Modes for Bank Riprap
- Determining Appropriate Rock Size
- Filter Layer Concepts
- Specifying Riprap Gradations & Thickness
- Other Design Considerations
- Basic Specifications for Riprap
- Application of Different Methods
- Example
- Questions and Answers
Project Scoping
Project Scoping – Data Collection

- Gather & Review Existing Relevant Data
  - Flood Studies
  - Floodplain Maps
  - Hydrology
  - Topographic Data
- Site Reconnaissance
- Survey Data
  - Topography of Project Area
  - Cross-Sections
  - Horizontal & Vertical Datum
FEMA FIRM
NRCS Flood Study
Project Scoping – Permitting

- Floodplain Development Permit
- FEMA CLOMR/LOMR
- Clean Water Act (404)
- MT Natural Streambed & Land Preservation Act (310)
- MT Land Use License or Easement on Navigable Waters
- MT Short Term Water Quality
Project Scoping – Design

- Hydrology
- Hydraulics
  - Water Surface Profile Modeling
  - Scour
  - Shear Stress
- Rock Riprap Design
Project Scoping – Construction Documents

- Plans
- Specifications
- Bid Documents
Project Scoping – Construction Services

- Staking
- Inspection
- Certification
Hydraulic Principles for Riprap Design
Hydraulic Principles for Riprap Design

- Design Criteria – provide benchmarks by specifying quantifiable limits of performance
  - Infrastructure Protection
  - Channel Geometry
  - Vertical Stability
  - Lateral Stability
Hydraulic Principles for Riprap Design

• Hydrology

• Design Discharge
  • Infrastructure – 1% Annual Chance Flood typical

• Methods/Sources
  • Flood Insurance Study
  • USGS Gage Data
  • USGS Regression Equations
  • Rainfall Runoff (SCS Curve Number)
Hydraulic Principles for Riprap Design

- Hydraulics
  - Manning’s $n$
    - Handbook Method – calibrated photographs and other subjective methods
    - Analytical Methods – physically-based hydraulic roughness equations
    - Empirical – based on observation, experience, or experiment
Hydraulic Principles for Riprap Design

• Hydraulics (continued)
  • Tractive Force
    • “When water flows in a channel, a force is developed that acts in the direction of flow on the channel bed. This force, which is simply the pull of water on the wetted area, is known as the tractive force” (Chow, 1959)
    • \[ T = \gamma Y S = 62.4 \text{ pcf} \times \text{Depth in feet} \times \text{Slope of Water Surface} \]

From Chow, 1959
Hydraulic Principles for Riprap Design

• Hydraulics (continued)
  • Scour
    • “The enlargement of a flow section by the removal of boundary material through the action of fluid motion during a single discharge event. The results of the scouring action may or may not be evident after the passing of the flood event” (Pemberton & Lara, 1984)
  • Numerous Methods to Estimate Scour Depth
    • e.g. Scour at Bridges
      • HEC-RAS
      • HEC No. 18
Erosion Mechanisms & Failure Modes for Bank Riprap
Erosion Mechanisms & Failure Modes for Bank Riprap

- Particle Erosion
- Translational Slide
- Modified Slump
- Slump
Erosion Mechanisms & Failure Modes for Bank Riprap

• Particle Erosion
  • Tractive force of flowing water exceed bank material’s ability to resist movement
  • Initiated by abrasion, impingement of flowing water, eddy action, local flow acceleration, freeze/thaw action, ice, toe erosion

• Causes:
  • Stone size not large enough
  • Individual stones removed by impact or abrasion
  • Side slope of the bank too steep
Erosion Mechanisms & Failure Modes for Bank Riprap

• Translational Slide
  • Downslope movement of a mass of stones with fault line on a horizontal plane
  • Initiated when channel bed scours and undermines toe of riprap blanket
• Causes:
  • Bank side slopes too steep
  • Presence of excess hydrostatic pressure
  • Loss of foundation support at the toe of the riprap blanket caused by erosion of the lower part of the riprap blanket
Erosion Mechanisms & Failure Modes for Bank Riprap

- Modified Slump
  - Mass movement of material along an internal slip surface within the riprap blanket
- Causes:
  - Bank side slopes too steep
  - Material critical to the support of upslope riprap is dislodged by settlement of the submerged riprap, impact, abrasion, particle erosion, or some other cause.
Erosion Mechanisms & Failure Modes for Bank Riprap

• Slump
  • Rotational-gravitational movement of material along a surface or rupture that has a concave upward curve
  • Cause-related to shear failure of the underlying base material that supports the riprap
• Causes:
  • Non-homogeneous base material with layers of impermeable material that act as a fault line when subject to excess pore pressure
  • Side slope too steep and gravitational forces exceed the inertia forces of the riprap and base material along a friction plane
Determining Appropriate Rock Size
Determining Appropriate Rock Size

- Calculate Tractive Force
- Determine Permissible Tractive Force – maximum unit tractive force that will not cause serious erosion of the material forming the channel bed on a level surface
- If tractive force is greater than permissible tractive force, erosion occurs – use bigger rock
- Erosion Resistance
  - Depends on: stone shape, size, weight, and durability; riprap gradation and layer thickness; channel alignment, cross-section, gradient, and velocity distribution (USACE, 1994)
Determining Appropriate Rock Size

- Methods
  - Charts and Tables
  - Programs & Spreadsheets
    - E.g. Riprap Design System
Filter Layer Concepts
Filter Layer Concepts

• “A filter is a transitional layer of gravel, small stone, or fabric placed between the underlying soil and the structure.” (HEC-11)

• The purpose of a filter
  • Prevents the migration of fine soil particles through voids
  • Distributes the weight of the armor units, causing more uniform settlement
  • Permits relief of hydrostatic pressures within the soils
  • For areas above water line, prevents surface water from causing erosion beneath the riprap
Filter Layer Concepts

• When should a filter be used?
  • Whenever the riprap is placed on fine grained material subject to significant subsurface drainage

• Proper design is critical to bank riprap stability
  • If filter openings are too large, excessive flow piping through the filter can cause erosion and failure of bank material below filter.
  • If filter openings are too small, the build-up of hydrostatic pressures behind the filter can cause a slip plane to form along the filter, causing a translational slide failure
Filter Layer Concepts

• Gradation of filter layer
  • Filtration Criteria
    • $D_{15\text{filter}}/D_{85\text{soil}}$ should be less than 5 to assure adequate filtration/retention
  • Permeability Criteria
    • $D_{15\text{filter}}/D_{15\text{soil}}$ should be above 5 to assure adequate permeability/drainage
  • Uniformity Criteria
    • $D_{15\text{filter}}/D_{15\text{soil}}$ should be less than 40 to assure adequate uniformity
    • $D_{50\text{filter}}/D_{50\text{soil}}$ should be less than 25 to assure adequate uniformity

*additional retention/uniformity criteria for drainage filters by USBR & COE
Application of Different Methods

- Summary of Filter Design
  - \( \frac{D_{15 \text{coarse}}}{D_{85 \text{fine}}} < 5 < \frac{D_{15 \text{coarse}}}{D_{15 \text{fine}}} < 40 \)
Filter Layer Concepts

• Other Filter Design Parameters
  • Filters should be clean – less than 5 to 10% fines
  • Ideally, gradation curves for riprap and filters should be parallel

• Thickness of Filter Layer
  • Single layer – 6 to 15 inches
  • Multiple layers – 4 to 8 inches (each individual layer)
  • Multiply by 1.5 for underwater placement

• Personal Opinion
  • Rather than multiple layers to transition between coarse riprap and fine grained bank – can often justify thicker layer (say 24”) of well-graded pit run sandy gravel with cobbles – some natural armoring of the outer layer occurs as fines wash away from uppermost layer under the riprap
Filter Layer Concepts

- Geotextile Filters
  - Cheaper
  - Acceptable for smaller riprap, especially with significant thickness of riprap layer
  - Vulnerable to tearing with large riprap – don’t drop rock
  - Not uniform support for protected soil on steep slopes – especially with large riprap (sometimes there is soil movement under the geotextile)
  - Difficult to impossible to place under water, especially if in current
Specifying Riprap
Gradations & Thicknesses
Specifying Riprap Gradations & Thicknesses

• Specifying rock weight is alternative to gradation
• Three-point gradations are common
  • \(D_{100}, D_{50}, D_{15}\)
  • \(W_{100}, W_{50}, W_{15}\)
Specifying Riprap Gradations & Thicknesses

Gradations for MDT Riprap Classes

- Class I
- Class II
- Class III

Percent Smaller By Weight (%) vs. Diameter (ft)
Specifying Riprap Gradations & Thicknesses

- USACE Gradations
  - USACE Gradations shown for rock with a unit weight equal to 155 pcf
  - Gradations shown below were developed for riprap placement in the dry, for low turbulence zones

<table>
<thead>
<tr>
<th>D100 Max (in)</th>
<th>100% Lighter</th>
<th>50% Lighter</th>
<th>15% Lighter</th>
<th>D30 Min (ft)</th>
<th>D90 Min (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max (lbs)</td>
<td>Min (lbs)</td>
<td>Max (lbs)</td>
<td>Min (lbs)</td>
<td>Max (lbs)</td>
</tr>
<tr>
<td>12</td>
<td>81</td>
<td>32</td>
<td>24</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>15</td>
<td>159</td>
<td>63</td>
<td>47</td>
<td>32</td>
<td>23</td>
</tr>
<tr>
<td>18</td>
<td>274</td>
<td>110</td>
<td>81</td>
<td>55</td>
<td>41</td>
</tr>
<tr>
<td>21</td>
<td>435</td>
<td>174</td>
<td>129</td>
<td>87</td>
<td>64</td>
</tr>
<tr>
<td>24</td>
<td>649</td>
<td>260</td>
<td>192</td>
<td>130</td>
<td>96</td>
</tr>
<tr>
<td>27</td>
<td>924</td>
<td>370</td>
<td>274</td>
<td>185</td>
<td>137</td>
</tr>
<tr>
<td>30</td>
<td>1268</td>
<td>507</td>
<td>376</td>
<td>254</td>
<td>188</td>
</tr>
<tr>
<td>33</td>
<td>1688</td>
<td>675</td>
<td>500</td>
<td>338</td>
<td>250</td>
</tr>
<tr>
<td>36</td>
<td>2191</td>
<td>877</td>
<td>649</td>
<td>438</td>
<td>325</td>
</tr>
<tr>
<td>42</td>
<td>3480</td>
<td>1392</td>
<td>1031</td>
<td>696</td>
<td>516</td>
</tr>
<tr>
<td>48</td>
<td>5197</td>
<td>2078</td>
<td>1539</td>
<td>1039</td>
<td>769</td>
</tr>
<tr>
<td>54</td>
<td>7396</td>
<td>2958</td>
<td>2191</td>
<td>1479</td>
<td>1096</td>
</tr>
</tbody>
</table>
Specifying Riprap Gradations & Thicknesses

- FHWA Gradations
  - Assumes a specific gravity of 2.65
  - Based on AASHTO guidelines

<table>
<thead>
<tr>
<th>Riprap Class</th>
<th>Rock Size (ft)</th>
<th>Rock Size (lbs)</th>
<th>% of Riprap Smaller Than</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facing</td>
<td>1.30</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Light</td>
<td>1.80</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>1.30</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>1/4 Ton</td>
<td>2.25</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>1.80</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>75</td>
<td>10</td>
</tr>
<tr>
<td>1/2 Ton</td>
<td>2.85</td>
<td>2000</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>1 Ton</td>
<td>3.60</td>
<td>4000</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2.85</td>
<td>2000</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>2.25</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>2 Ton</td>
<td>4.50</td>
<td>8000</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>3.60</td>
<td>4000</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>2.85</td>
<td>2000</td>
<td>10</td>
</tr>
</tbody>
</table>
Specifying Riprap Gradations & Thicknesses

**Thickness Guidelines and Constraints**
- Normal range is 1.0 to 2.0 times $D_{100}$
- Thickness greater than 1.0 may allow a reduction in stone size due to increased layer thickness

**HEC-11 Guidance**
- “All stones should be contained reasonably well within the riprap layer thickness”
  - Should not be less than $D_{100}$ stone or less than 1.5 times $D_{50}$ stone
  - Should not be less than 12 inches for practical placement
  - Should increase thickness by 50% for underwater placement
  - Should increase thickness by 6-12 inches where riprap will be subject to floating debris, ice, waves, wind, or bedforms
Other Design Considerations
Other Design Considerations

- Material Quality
  - Rock riprap preferred
  - Broken concrete and other rubble – must control material quality and gradation
  - Shape – neither the width or thickness of a stone should be less than 1/3 the length
  - Consider rock density – denser is better
  - In terms of stability, angular rock is better than rounded

- Edge Treatment
  - Toe – extend below scour depth
  - Flanks
    - Smooth hydraulic profile at edges is important

- Bank Slope – 2H:1V maximum
Other Design Considerations

- Placement
  - Hand and machine placing
    - Expensive
    - Allows for steeper side slopes
  - Dumping – segregation and breakage can occur

- Longitudinal Extent
  - Dependent on site conditions
  - HEC-11 provides some guidance
Other Design Considerations

• Design Height
  • Consider
    • Wave action for impinging flow
    • Design discharge and water level
    • Superelevation in bends
    • Hydraulic jumps
    • Freeboard desired

• Ice Damage
  • Crushing, impact loading, shearing forces
  • Potentially increase stability factor if location has historic ice problems
Basic Specifications for Riprap
Basic Specifications for Riprap

• Examples
  • Montana Department of Transportation Standard Specifications for Road and Bridge Construction, 2006 Edition.
Basic Specifications for Riprap

• MDT Riprap Material Specifications
  • Furnish stone that is hard, durable, and angular in shape, resistant to weathering and water action, free from overburden, spoil, shale, structural defects, and organic material.
  • Each stone must have its greatest dimension not greater than three times its least dimension.
  • Do not use rounded stone or boulders from a streambed source as riprap. Do not use shale or stone with shale seams.
Basic Specifications for Riprap

- HEC-11 Riprap Material Specifications
  - Stone shall be hard, durable, angular in shape; resistant to weathering and water action; free from overburden, spoil, shale, and organic material.
  - Neither breadth nor thickness of a stone shall be less than one-third of its length.
  - Minimum unit weight shall be 155 lb/ft³
  - LA Abrasion Test: no more than 40% loss
Application of Different Methods
Application of Different Methods

- **USACE Method**
  - For flow in man-made or natural channels having low turbulence and slopes less than 2%.

- **Bed or Bank**

\[
D_{20} = S_f C_s C_v C_t K_1 \left( \frac{g_s \gamma_w}{g_s \gamma_w - g_w} \right)^{0.5} \left( \frac{V}{\sqrt{gd}} \right)^{2.5}
\]

Where:
- \(D_{20}\) = stone size, feet
- \(S_f\) = Safety Factor (see description later in this section)
  - 1.25 downstream of concrete channels, end of dikes, flow impingement
- \(C_s\) = stability coefficient for incipient failure
  - 0.30 for angular rock, 0.375 for rounded rock
- \(C_v\) = vertical velocity distribution coefficient
  - 1.0 for straight channels, inside of bends
  - 1.283 - 0.2 log(R/W), outside of bends (1 for R/W > 26)
  (see Figure 2.5 for a description of R/W)
- \(C_t\) = thickness coefficient
  - 1.0 for thickness = 1D_{100}(max) or 1.5D_{50}(max), whichever is greater
- \(d\) = local depth of flow at same location as \(V\), feet
- \(g_s\) = unit weight of stone, lbs/ft\(^3\)
- \(g_w\) = unit weight of water, lbs/ft\(^3\)
- \(V\) = local depth averaged velocity, \(V_s\), for sideslope riprap, ft/s
- \(g\) = acceleration of gravity, ft/sec\(^2\)
- \(K_1\) = sideslope correction factor = 1 for bottom riprap
  - 1.25 - 1.811/m + 3.343/m\(^2\) for sideslope riprap,

where \(m\) denotes the number of horizontal units per one vertical unit (7H:1V) of the sideslope.
Application of Different Methods

- **ASCE Method**
  - Uses Isbash equation with a modification to account for channel bank slope.

- **Bed or Bank**

\[
D_{50} = \left( \frac{6W}{\pi \gamma_s} \right)^{\frac{1}{2}}
\]

Where:

\[
W = \frac{0.000041G_s V^6}{(G_s - 1)^3 \cos^3 \theta}
\]

\[
\theta = \arctan(1/m)
\]

- \( D_{50} \) = stone size, ft
- \( W \) = weight of stone, lbs
- \( V \) = velocity, ft/s
- \( g_s \) = unit weight of stone, lb/ft\(^3\)
- \( g_w \) = unit weight of water, lb/ft\(^3\)
- \( G_s \) = specific gravity of stone, \((g_s / g_w)\)
Application of Different Methods

\[ D_{50} = 0.0122 V_a^{2.06} \]

Where:

- \( D_{50} \) = stone size, ft
- \( V_a \) = average channel velocity, ft/s

- USBR Method
  - Developed for estimating riprap size downstream of a stilling basin
  - Procedure developed using eleven prototype installations with velocity varying from 1 fps to 18 fps.
Application of Different Methods

\[ D_{50} = 0.01V_a^{2.44} \]

Where:

\[ D_{50} \quad = \quad \text{stone size, ft} \]
\[ V_a \quad = \quad \text{average velocity in cross section, ft/s} \]

- USGS Method
  - Equation resulted from field data taken from WA, OR, CA, NV, and AZ. Survey related hydraulic conditions to performance of riprap protection.
  - Surveys included 39 events of which 22 resulted in no riprap change. Of the 17 remaining events, 14 failures were caused by particle erosion.
Application of Different Methods

- **Isbash Method**
  - Developed for the construction of dams by depositing rock into running water.

- Turbulence level (low or high) is factored into equation.

\[ D_{50} = \frac{V_a^2}{2gC^2(G_s - 1)} \]

Where:

- \( D_{50} \) = stone size, ft
- \( V_a \) = average Channel Velocity, ft/s
- \( G_s \) = specific gravity of stone (\( g_s/g_w \))
- \( g \) = acceleration of gravity, \( \text{ft/s}^2 \)
- \( C \) = 0.86 for high turbulence zones
  - 1.20 for low turbulence zones
Application of Different Methods

\[ W = \frac{0.00002 V^6 G_s}{(G_s - 1)^3 \sin^3 (\rho - \theta)} \]

Where:

- \( W \) = Theoretical minimum stable rock weight of outside stone to resist flow forces, lbs
- \( V \) = Stream velocity to which bank is exposed, ft/s
- \( V_a \) = 4/3\( V_a \) for impinging flow
- \( V_a \) = 2/3\( V_a \) for parallel flow
- \( V_a \) = Average channel velocity, ft/s
- \( D \) = 70° for randomly placed rubble
- \( \theta \) = Bank angle, degrees
- \( G_s \) = Specific gravity of stone, \((\sigma/\rho)\)

- **Cal B & SP Method**
  - CA Dept. of Transportation developed this method to protect highway embankments.
  - Riprap embankments consist of one or more layers of rock.
  - Accounts for different types of flow (impinging or parallel) by modifying the average channel velocity.
Application of Different Methods

- HEC-11 Method
  - Developed for use in rivers or streams with non-uniform flow conditions and discharges normally greater than 50 cfs.
  - Bed or Bank
Application of Different Methods

\[ D_{50} = D'_{50} C_f C_s \]

Where:

\[ D'_{50} = \frac{0.001 V^3_a}{\sqrt{d} K_1^{1.5}} \]

\[ C_f = \left( \frac{\text{safety factor}}{1.2} \right)^{1.5} \]

\[ K_1 = \left( 1 + \frac{\sin^2 \theta}{\sin^2 \phi} \right)^{0.5} \]

\[ \theta = \arctan\left( \frac{1}{\text{Cotangent of sideslope}} \right) \]

\[ C_s = \frac{2.12}{(G_s - 1)^{1.5}} \]

- \( D_{50} \) = stone size, ft
- \( V_a \) = average channel velocity, ft/s
- \( \phi \) = material angle of repose, degrees
- \( G_s \) = specific gravity of stone, \((\rho_s/\rho_w)\)
- \( d \) = average flow depth, ft
Examples
Examples – Teton Creek

- Teton Creek Stream Restoration
  - Located in Teton County, Idaho
2009 Aerial Image of Project Reach
Project Background: Conceptual Cross-Section
Aerial View of Channelization

Why Was it Channelized?

1) To Control Floods???
2) To Fill in Wet Lands and Side Channels
3) Develop Infrastructure on Property
Phase 2 Construction: Fall 2010

Pre-Construction

Phase 2 Accomplishments:

1) Installed 2,700 linear feet of buried rock toe protection.

During Construction
Phase 2 Construction: Fall 2010

Runoff 2010

Buried Rock Toe Protection – Slope Preparation – November 2010
Examples – Teton Creek

- Teton Creek (continued)
  - Problem Input
    - $Q_{100} = 2050$ cfs
    - $n = 0.053$
    - Slope = 0.010 ft/ft
    - Channel & inset floodplain

- Riprap Design System
  - Ch. btm width = 40 feet
  - Inset FP side slope = 2:1
  - Size rock for buried bank protection at inset floodplain margin
• Teton Creek (cont.)
  • Riprap Design System
    • 160 pcf vs. 140 pcf riprap (USACE Method results shown)
Examples – Teton Creek

Alternative

As an alternative to the above Stone Mix A material specifications, rock from the River Rim source may be used. Stone will be hard and durable stone with less than 35 percent wear when tested for resistance to abrasion in conformance to ASTM C535. Bulk density will not be less than 140 pounds per dry cubic foot. The least dimension of any one piece will not be less than 1/3 the greatest dimension. Each load of Stone will be reasonably well graded from the smallest to the maximum size specified. Stone size gradation for this alternative stone will conform to the following gradation:

<table>
<thead>
<tr>
<th>Percent Lighter by Weight</th>
<th>Stone Weight, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>100</td>
<td>99</td>
</tr>
<tr>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

* The size is measured along the B-Axis, which is the second largest dimension of the stone (i.e., use the dimensions of length, height, and width to describe the stone; with length being the A-Axis and the longest dimension of the stone, then the B-Axis is the longer of the height and width dimensions).

• Teton Creek (cont.)
  • Riprap Design System
    • Gradation & Material Specification for Stone with $\gamma = 140$ pcf
Questions and Answers

paul@alliedengineering.com