RIPRAPPED BASINS FOR CULVERT OUTFALLS

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The sizing of riprap for culvert outlet basins is a difficult problem because the flow field at the outlets of many culverts is rapidly varied and 3-dimensional. Most available riprap design methods are primarily applicable to 2-dimensional uniform flow problems. For the purpose of developing more information on the behavior of riprap at culvert outlets, 288 model tests on basins for circular and rectangular culverts were conducted at Colorado State University. The models ranged in size from a 6- by 12-in. rectangular culvert with \( \frac{3}{4} \)-in. riprap to a 36-in. diameter pipe with 7-in. diameter rock. A method for the design of rock-riprapped basins for culvert outfalls was developed from a study of the model data. The method and design aids are presented in this paper. The method and aids are applicable for culvert flows with H2 or M2 water surface profiles near the brink, that is, mild sloping or horizontal culverts with drawdown at the outlet. The riprapped basin can be designed as a rigid-rock basin or, alternatively, as a scoured-rock basin if available rock is too small to prevent scour.

At many culvert outlets, it is necessary to reduce the kinetic energy of the flow and to match the flow velocity from the outlet basin with that of the downstream conveyance channel. There are available a number of good energy-dissipator designs, such as the St. Anthony Falls basin (1) and the Bureau of Reclamation stilling basin (2). The cost of these concrete structures can be relatively large in terms of the total cost of the culvert. Rock-lined outlet basins will be a feasible alternative for many culvert outlet structures. The question facing the designer is, "What size of rock and what basin dimensions are required for a rock-riprapped culvert outlet basin?"

The Wyoming State Highway Department, in conjunction with the Federal Highway Administration, sponsored a research program at Colorado State University to study riprapped basins at culvert outlets. The research program developed into an extensive model study program covering most of the range of culvert outlet flow conditions. A large portion of the tests were conducted with 6-in. diameter and 6- by 12-in. model culverts. For these small models, riprapped basins with \( \frac{1}{4}, \frac{1}{2}, 1, \frac{3}{4}, \) and 2-in. median sieve diameter rock were tested. Model-to-prototype scaling parameters were checked by tests on 12-, 18-, and 36-in. diameter culverts. The largest model involved 7-in. diameter rock that was tested with a flow of 100 ft\(^3\)/sec in the 36-in. diameter culvert. A study of the model test results developed into a methodology for the design of rock outlet basins.

The content of this paper is limited to the design of riprapped basins for circular and rectangular culverts without flared end sections in which the water surface profile is either an M2 or H2 profile. M2 and H2 water surface profiles are obtained in mild sloping and horizontal culvert barrels when the tailwater depth is less than the brink depth at the outlet. For culverts with M1 water surface profiles, the method presented by Watts et al. (3) should be used to size nonscouring rock basins. The design of rock basins for culverts on steep slopes has been presented elsewhere by Simons et al. (4).
DATA FOR DESIGN

The important variables that affect scour in rock at outfalls of culverts on horizontal or mild slopes are as follows:

1. The flow variables, where
   \( Q = \) culvert discharge,
   \( y_0 = \) flow depth at the plane of the culvert outlet, and
   \( d_t = \) tailwater depth at the plane of the culvert outlet;

2. The geometry of the culvert, where
   \( D = \) pipe diameter,
   \( H_o = \) height of the rectangular culvert, and
   \( W_o = \) width of the rectangular culvert;

3. The geometry of the scour hole or basin or both shown in Figure 1, where
   \( d_s = \) depth of scour,
   \( L_s = \) length of the scour hole,
   \( W_s = \) width of the scour hole,
   \( L = \) length of the basin,
   \( W_b = \) width of the basin, and
   \( h = \) height of mound; and

4. The properties of the rock, where
   \( d_e = \) effective grain size of the rock mixture.

Figure 1. Riprapped basin.
The effective grain size diameter is computed from the equation

\[ d_e = \left[ \frac{10}{\sum_{i=1}^{10} d_i^3} \right]^{1/3} \]

where

\[ d_i(1 = 1) = \frac{(d_0 + d_{10})}{2}, \]
\[ d_i(1 = 2) = \frac{(d_{10} + d_{20})}{2}, \]
\[ \ldots, \text{ and} \]
\[ d_i(1 = 10) = \frac{(d_{90} + d_{100})}{2}. \]

The \( d_0, d_{10}, \ldots, \) and \( d_{100} \) terms are the rock-size values taken from a plot of "percentage finer by weight" versus "sieve diameter" curve for the rock mixture.

The experimental programs, conducted at Colorado State University, have been reported by Stevens (5) and Chen (6). From the analyses of the experimental data, the following aids for the design of riprapped basins were prepared.

**Brink Depth at the Outlet**

For horizontal and mild-sloping culverts discharging onto basins built to the level of the barrel invert, the relationship between discharge, brink depth, and tailwater depth are shown in Figure 2. The dashed curves are estimates of the relationship for

![Figure 2](image-url)  

*Figure 2. Effect of tailwater on brink depth in horizontal and mild-sloping culverts.*
field-sized culverts. In 6-in. diameter models the curves are displaced because the zone of negative pressure at the crown near the outlet is much more pronounced than in large barrels. For 6-ft diameter barrels the influence of negative crown pressure is very small. This scale effect has been discussed by Simons et al. (4).

For rock-riprapped basins with widths greater than 2 culvert diameters, the tailwater level will be at the normal stream water surface elevation at the culvert outlet. This condition is not valid for the concrete basins studied by Watts (7).

Depth of Scour

The relations between the scour depth, $d_s$, rock size, $d_r$, tailwater depth, $d_t$, and the discharge, $Q$, are shown in Figure 3. The data were obtained from horizontal culvert models but are applicable to culverts on mild slopes.

It was found that, if the flow velocity at the outlet, $V_0$, tailwater depth, $d_t$, and the brink depth, $y_b$, were the same in a rectangular and circular culvert, then the scour depth, $d_s$, was approximately the same for a given rock size, $d_r$. The discharge ratios, $(Q/W_o)^{3/2}/(Q/D^{5/2})$, have been computed from the data shown in Figure 2 for the conditions that $y_b/H_o = y_b/D$ and $d_t/H_o = d_t/D$. The average values of the discharge ratios have been plotted as the curve shown in Figure 4. This curve can be used to convert rectangular culvert scour data to scour in equivalent circular culvert basins or vice versa. This conversion is illustrated in the accompanying design example.

Figure 3c shows the effect of the brink depth distortion on small models by the $Q/D^{2.5} = 4.04$ and 5.00 ft$^3$/sec/ft$^{5/2}$ curves. For these discharges in 6-in. models, the pipe flows nearly full at the outlet, but the upper streamlines are directed toward the bed of the basin in an abnormal manner. The effect of directing the upper streamlines toward the bed is an increased scour depth. Thus, the curves shown in Figure 3c for $Q/D^{2.5} = 4.04$ and 5.00 ft$^3$/sec/ft$^{5/2}$ indicate more scour than would be anticipated in interpolating between the $Q/D^{2.5} = 3.02$ and $Q/D^{2.5} = 6.28$ ft$^3$/sec/ft$^{5/2}$ curves, which are not affected by negative pressure at the crown near the outlet. The $Q/W_o H_o^{5/2} = 4.26$ ft$^3$/sec/ft$^{5/2}$ curve shown in Figure 3a is another example of the same effect. The brink depth distortion decreases as the pipe diameter is increased.

In a number of model tests, a phenomenon that has been labeled mound-controlled scour occurred. This type of scour is very evident in the results shown in Figure 3c. At very low tailwater depths, scour was less than at higher tailwater. For these tests, a relatively high mound of rock was formed that reduced the flow of water along the center of the basin and totally obstructed additional rock migration. The flow had the capacity to scour rock from the bed, but the rock could not be lifted over the top of the mound.

At greater tailwater depths, the relative height of the mound was less, and there was no movement of the bed material at the equilibrium depth of scour. However, when the mound was removed, the same flow scoured the basin to a greater depth.

Length of Scour Hole

The lengths of the scour holes for all tests on circular and rectangular culvert outlets are shown in Figure 5 for $d_t/d_s < 18$ and in Figure 6 for $d_t/d_s > 8$.

Length of Basin

The distance from the barrel outlet to the downstream end of the mound, $L_1$, is related to the length of the scour hole, $L_s$, and to the relative tailwater depth, $d_t/y_b$, as shown in Figure 7.

Width of Scour Hole

For circular and box ($W_o = H_o$) culverts, the width of the scour hole is primarily a function of the scour depth. The data shown in Figure 8 are for cases where $W_o/W_o$ or
Figure 3. Depth of scour for plain outlets.
Figure 4. Discharge ratios for equal scour depths.

Figure 5. Length of scour hole.
W_b/D was 4 or greater. With smaller relative basin widths, the scour hole was slightly wider.

For those rock basins that did not scour, model tests indicated that the jet would expand in the basin according to the relationships shown in Figure 9.

RECOMMENDED FIELD STRUCTURES

As the result of the model test program, 3 recommended rock-riprapped basins for culvert outfalls were developed. They are the nonscouring, the hybrid, and the scoured basins shown in Figure 10. The principal components of the 3 recommended basins are the apron, end slope, side slopes, underslope, and embankment slopes. For a given set of outlet conditions, the dimensions of these components are dependent on the rock size, d_s.
Nonscouring Basin

After the rations $\frac{Q}{W_bH_0 \sqrt{2g}}$ and $\frac{d_t}{H_0}$ have been computed, $\frac{y_t}{H_0}$ can be obtained from data shown in Figure 2. The depth of scour, $\frac{d_t}{H_0}$, can then be determined from data shown in Figure 3. If the available rock is of size $d_t$, so that $\frac{d_t}{H_0} = 0$, the dimensions of the components of the nonscouring basin are found in the following manner.

The lateral expansion rate, $\tan \theta$, is determined from data shown in Figure 9. The function of the rock basin is to reduce the outlet velocity, $V_o$, to the allowable downstream channel velocity, $V_{as}$. The continuity equation at the basin outlet requires that $V_{as} = \frac{Q}{W_b(d_t + LS/100)}$, where $S$ is the percentage of basin slope. If the basin width is approximately the same as the natural channel width, the term LS/100 should be dropped. Also $W_b = 2L\tan \theta + W_o$. The solution of these equations will yield the length of the apron, $L$, and the width of the basin, $W_b$, at the downstream end of the basin.

The apron should be placed at the elevation of the culvert invert at the outlet and on the same slope as the culvert barrel. The minimum recommended thickness of the apron, $T$, is either $2d_t$ or $d_{100}$, whichever is greater.

The end slope terminates the apron (Fig. 10) and provides protection against local scour at the end of the basin. If degradation is anticipated in the downstream channel, the end slope can be carried to a depth $E$ to give some protection to the structure. The recommended end slope is 2:1 with a thickness, $B$, equal to the greater of $d_{100}$ or $2d_t$, and a minimum drop, $E$, equal to $T$.

Riprap is required along the road embankment in the immediate vicinity of the outfall to protect against any splash or spray and to control the action of rollers that may form in the corners of the structure. The rock should be extended on the embankment slope to a height 1.5F above the invert. The value of F is the greater of $y_t$ or $d_t$. The thickness of the embankment slope, $B$, should be the greater of $2d_t$ or $d_{100}$.
Figure 9. Estimate of angle of lateral expansion for horizontal and mild-sloping culverts.
The underslope prevents movement of materials from under the culvert. A cutoff wall extending downward a distance $2T$ below the apron may be used in lieu of the underslope.

The side slopes extend from the culvert outlet to the termination point of the end slope. If the channel is not confined, the volume of riprap for the side slopes should be placed on the natural side slopes of the downstream channel or on the horizontal surface adjacent to the apron riprap.

Figure 10. Recommended riprapped basins.
The dimensions of a standard nonscouring basin for a circular pipe culvert are the same as those described earlier except that $W_o$ and $H_o$ are replaced by $D$, the pipe diameter.

If $dt/y_o \geq 1.0$, the average velocity at the culvert outlet is similar to that below the stilling basins studied by the Bureau of Reclamation (2). That is, there is no acceleration at the outlet when $dt/y_o \geq 1.0$. The Bureau's recommended rock size to prevent scour is given by the expression $V_o^{2/gd_a} = 2.5$ for rock with a specific weight of approximately 2.65. At Colorado State University in model tests on culverts with $dt/y_o \geq 1.0$, the $d_a$ required to prevent scour was less than that given by the Bureau. One possible explanation is that the turbulence level is much higher downstream of hydraulic jump stilling basins than it is below culvert outfalls in which there is no well-defined jump.

For the case in which $dt/y_o < 1.0$, the nonscouring basin can be sized by the method outlined earlier, but a better method has been given by Watts et al. (3). The 2 methods give approximately the same apron dimensions.

Hybrid Basin

The hybrid basin covers conditions where a basin scours slightly but not enough to give the efficient type of energy dissipation that results from basins with large scour holes. Then, if $0 < d_a/d_h < 2.0$, an additional volume of rock is added to the apron and underslope of the nonscouring basin (Fig. 10b) so that the jet will not penetrate the apron.

The determination of the dimensions $W_h$ and $L$ are in the design example. All other dimensions are the same as those for the nonscouring basin.

Scoured Basin

It is permissible to allow a riprapped basin to scour if the basin is sized correctly. Rather than preforming the scour hole, one will usually find it more convenient to construct the apron level with the culvert invert on the same slope as the barrel and to rely on the plunging jet to form the scour hole and mound (Fig. 10c).

The design of the embankment slope, side slopes, end slope, and underslope is the same as that for the previous 2 basins. The apron is now rectangular in plan and contains the major portion of the rock used in the structure.

For the scoured basin, the length of the basin is governed not by the allowable channel velocity downstream but by the need to provide a landing area for that rock moved from the scour hole. The mound is an integral part of the structure and, if it is somehow removed, the scour hole would deepen and penetrate the apron resulting in partial failure or failure of the basin. The design of a scoured basin is illustrated in the next section.

For circular barrels, the variables $W_o$ and $H_o$ are replaced by the pipe diameter $D$.

Filter Requirements

All side slopes about the outlet basin that are riprapped should be provided with suitable filters to prevent the movement of embankment materials through the riprap. That portion of the basin on the upstream side of the scour hole behind the embankment and underslope should always be provided with a filter. A filter is not recommended for the remainder of the basin when the riprap is well graded and the natural material is cohesive.

Authoritative discussions of riprap gradation and filter design are given by Sherard et al. (8) and by the Bureau of Reclamation (9).

**DESIGN EXAMPLE**

Consider a circular culvert on a mild slope (M2 profile), where slope $S = 1.7$ percent; discharge $Q = 680$ ft$^3$/sec; pipe (1,108-in. SPP) $D = 9$ ft; tailwater $d_t = 3.6$ ft; brink depth $y_o = 5.3$ ft; and allowable downstream velocity $V_{eh} = 8.8$ ft$^3$/sec.

The flow parameters at the outlet are as follows: $Q/D^{2.5} = 680/9^{2.5} = 680/243 = 2.80$ ft$^3$/sec/$ft^{1/2}$; $d_t/D = 3.6/9 = 0.40$; $d_t/y_o = 3.6/5.3 = 0.68$; and $y_o/D = 5.3/9 = 0.59$. 
Depth of Scour

From the curves shown in Figure 3, the depth of scour \( d_s \) is found for various mean rock diameters \( d_m \), as follows:

<table>
<thead>
<tr>
<th>( d_m / D )</th>
<th>( d_s ) (ft)</th>
<th>( d_s / D )</th>
<th>( d_s ) (ft)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.049</td>
<td>0.44</td>
<td>1.80</td>
<td>16.2</td>
<td>See following</td>
</tr>
<tr>
<td>0.0945</td>
<td>0.85</td>
<td>0.61</td>
<td>5.5</td>
<td>Figure 3c</td>
</tr>
<tr>
<td>0.205</td>
<td>1.85</td>
<td>0.0</td>
<td>0</td>
<td>Figure 3d</td>
</tr>
</tbody>
</table>

From data shown in Figure 3a, the depth of scour for \( d_m / D = 0.049 \) can be found by converting the flow parameter \( Q/D^{2/5} \) into its equivalent parameter for a box culvert, \( Q/W_c H_0^{3/2} \). \( (Q/W_c H_0^{3/2})/(Q/D^{2/5}) = 1.26 \) for \( y_0/D = 0.59 \) (Fig. 4). Therefore, the equivalent box culvert flow is \( Q/W_c H_0^{3/2} = 1.26 \times 2.80 = 3.53 \) ft\(^3\)/sec/ft\(^{5/2} \). \( d_s/H_0 = d_s/D = 1.80 \) for \( d_s/H_0 = d_s/D = 0.40 \) (Fig. 3). Hence, \( d_s = 1.8 \times 9 = 16.2 \) ft. A plot of \( d_s \) versus \( d_m \) is shown in Figure 11a.

Length of Scour Hole

The length of the scour hole is determined from data shown in Figures 5 and 6. Recall that \( d_s/y_0 = 0.68 \).

<table>
<thead>
<tr>
<th>( d_s ) (ft)</th>
<th>( d_s ) (ft)</th>
<th>( d_s/d_s )</th>
<th>( L_s/d_s )</th>
<th>( L_s/d_s )</th>
<th>( L_s ) (ft)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.2</td>
<td>0.44</td>
<td>37</td>
<td>9.5</td>
<td>154</td>
<td>Figure 6</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>0.85</td>
<td>6.5</td>
<td>80</td>
<td>-</td>
<td>68</td>
<td>Figure 5</td>
</tr>
<tr>
<td>2.4</td>
<td>1.20</td>
<td>2.0</td>
<td>44</td>
<td>-</td>
<td>53</td>
<td>Figure 5</td>
</tr>
<tr>
<td>0.0</td>
<td>1.70</td>
<td>0</td>
<td>00</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

The values of \( L_s \) and \( d_s \) are shown in Figure 11b, and a smooth curve is drawn through the computed points.

Required Length of Basin

When no long-term degradation is anticipated, the length of the basin, \( L_b \), is shown in Figure 7 (for \( d_s/d_s \approx 2.0 \)). The value of \( L_s \) is taken from the smoothed curve shown in Figure 11b.

<table>
<thead>
<tr>
<th>( d_s ) (ft)</th>
<th>( L_s ) (ft)</th>
<th>( L_s/L_s )</th>
<th>( L_b ) (ft)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>133</td>
<td>2.1</td>
<td>280</td>
<td>Figure 7</td>
</tr>
<tr>
<td>0.85</td>
<td>90</td>
<td>2.1</td>
<td>190</td>
<td>Figure 7</td>
</tr>
<tr>
<td>1.20</td>
<td>53</td>
<td>2.1</td>
<td>110</td>
<td>Figure 7</td>
</tr>
<tr>
<td>1.70</td>
<td>-</td>
<td>-</td>
<td>62.5</td>
<td>See following</td>
</tr>
</tbody>
</table>

For the rock size that does not scour \( (d_s = 1.7 \text{ ft}) \), the length of the basin will depend on the maximum allowable average velocity in the downstream channel, \( V_{oh} \). From data shown in Figure 9b, \( \tan \theta = 0.10 \) for \( d_s/y_0 = 0.68 \). The depth at the distance \( L \) downstream of the outlet is \( y = d_s \) if it is assumed that \( d_s \) is the normal depth for the design discharge. Then, \( L = [1/(2 \tan \theta)] \left[ (Q/d_s V_{oh}) - D \right] = 62.5 \text{ ft} \). The \( L \) versus \( d_s \) relationship is shown in Figure 11c.

Width of Scour Hole and Basin

The scour hole width is obtained from data shown in Figure 8, and the apron width, \( W_b \), is given by the equation \( W_b = W_s + 2D \).
For $d_s \geq 1.70$ ft, there is no scour, and the width of the basin, $W_b$, at a distance $L$ downstream of the pipe outlet is $W_b = 2L \tan \theta + D = 21.5$ ft. The $W_b$ versus $d_s$ curve is shown in Figure 11d.

**Volume of Riprap Required**

If the ratio $d_s/d_{100}$ is known, the volume of rock required for the different basins can be computed. A typical volume versus $d_s$ curve is shown in Figure 11e. Generally, the smallest rock size that will not scour yields the minimum rock-volume basin.

**Final Selection of the Basin**

The volume versus $d_s$ curve can be converted to a capital cost versus $d_s$ curve if the costs of each size of rock, delivered to the site, are known. From this information the most economical basin can be selected. Each basin will perform well at the given design discharge; however, scouring basins are more susceptible to failure than hybrid or nonscouring basins if the design discharge is exceeded. Simons et al. (4) have defined a safety factor against failure, and additional rock can be added to the apron so that all designs have the same safety factor. This additional rock would modify the volume versus $d_s$ and capital cost versus $d_s$ curves. The final decision could be made on the modified capital cost versus $d_s$ curve.

![Figure 11. Dimensions for design example basin.](image-url)
Multibarrel Culverts

The design of rock basins for multibarrel culverts is essentially the same as that for single-barrel culverts provided that all barrels are the same size. If there are equal discharges in all barrels, the depth of scour and the length of scour hole and basin are computed by using the same procedure that is outlined in the previous example; that is, the scour depth and the length of scour hole and basin for an n-barrel culvert carrying \( Q_t \) are the same as those for a single barrel discharging \( Q_t/n \). The width of the scour hole is given by the equation

\[
W_{sa} = W_s + (n - 1)(W_0 + S)
\]

or

\[
W_{sa} = W_s + (n - 1)(D + S)
\]

where

- \( W_{sa} \) = width of the scour hole for \( n \) barrels,
- \( W_s \) = width of the scour hole for a single barrel,
- \( n \) = number of barrels, and
- \( S \) = spacing between the barrels, assumed to be the same between all the barrels.

There is a greater chance of failure in the riprapped basin for multibarrel culverts than there is for single-barrel culverts. If one barrel of a multibarrel culvert is blocked with debris, the remaining barrels carry more water, and this increase in flow may be great enough to cause the rock basin to fail. The designer might consider riprapping multibarrel outlet basins with larger rock than the design procedure indicates.

CONCLUSIONS

A method for the design of rock-lined basins for culvert outfalls has been developed from model test data. The recommended rock-lined basins are suitable for single-barrel or multibarrel installations for both circular and rectangular outlets. The method provides for alternative rock basin designs depending on the size of the available rock. If the available rock will not prevent scour at the outlet, then a scoured basin design may be feasible. The cost of the most economical rock basin design should be compared with the cost of concrete and fabricated metal outlet structures before the outlet basin design is selected.

The design aids for riprapped culvert outlet basins were developed from model tests because the flow at the outfall is usually rapidly varied and 3-dimensional. Stable riprap sizes for such flow fields are different from those for uniform 2-dimensional flow. The information for scoured basin designs is presented because, in many cases, the rock size required to prevent scour is greater than the available rock sizes.

ACKNOWLEDGMENTS

We are indebted to the Wyoming State Highway Department and the Engineering Experiment Station at Colorado State University, joint sponsors of this project.

REFERENCES


