Design of Low Tailwater Riprap Basins for Storm Sewer Pipe Outlets

by

Michael A. Stevens, Consultant
Ben Urbonas, Urban Drainage & Flood Control District
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Introduction

The Urban Storm Drainage Criteria Manual's Volume 2, *Major Drainage* (USDCM) of the Urban Drainage and Flood Control District provides guidance for the design of scour protection downstream of culvert outlets. This guidance was intended for culvert crossings of major drainageway channels and assumed that the culvert is in line with the channel. It also assumed there was significant tailwater that partially inundated the culvert's outlet. This guidance does not work for storm sewer pipes discharging into open drainageways when the flow depth in the drainageway provides a low tailwater at the pipe's outlet. Thus, when tailwater is low, scour protection at the outlet of a storm sewer has to be designed differently than for culverts crossing major drainageways. For storm sewer outlets low, tailwater is defined when:

$$y_t \leq \frac{D}{3} \qquad \text{or} \qquad y_t \leq \frac{H}{3}$$

in which: y_t = depth of tailwater at the time the pipe is discharging its design flow, in feet; D = the diameter of a circular pipe, in feet; H = the height of a rectangular pipe, in feet.

Stevens (1969) reported on a series of studies describing the scour geometry in riprap located at pipe outlets. Quantifiable relationships were found between flow depth and velocity at the outlet, the scour hole geometry, and the rock size. Figure 1 describes the geometry of a pre-shaped scour hole downstream of a pipe fitted with a flared end section. Refer to this figure when reading the rest of this article.

Finding Flow Depth and Velocity at Storm Sewer Pipe Outlets

The first step in the design of a scour protection basin at the outlet of a storm sewer is to find the depth and velocity of flow at the outlet. Pipe-full flow can be found using sing *Manning's* and the pipe-full velocity can be found using the *Continuity* equation. Namely,

$$Q_{full} = \frac{1.49}{n} \cdot A_{full} \cdot \left(R_{full}\right)^{2/3} \cdot S_o^{1/2}$$

in which: Q_{full} = Pipe full discharge at its slope, in cubic feet per second; n = Manning's n for the pipe full depth; A_{full} = Cross-sectional area of the pipe, in square feet; S_o = Longitudinal slope of the pipe, in feet per foot; R = Hydraulic Radius for a pipe flowing full, in feet [$R_{full} = D/4$ for circular pipes,

$R_{full} = A_{full} / (2H + 2w)$ for rectangular pipes], where D = diameter of a circular conduit, H = height of a rectangular conduit, and w = width of a rectangular conduit, all in feet. Then,

$$V_{full} = Q_{full} / A_{full}$$

in which: V_{full} = Flow velocity in a pipe flowing full, in feet per second.

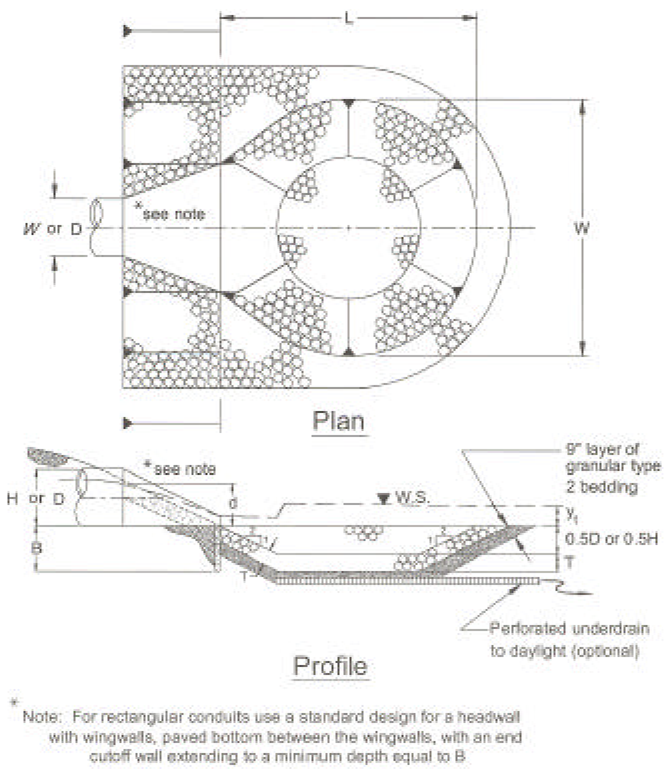

Figure 1. Low Tailwater Energy Dissipating Basin at Pipe Outlets.

The normal depth of flow and the velocity at that depth in a conduit can be found with the aid of Figure 2. Using the known design discharge, Q, and the calculated pipe-full discharge, Q_{full}, enter Figure 2 with the value of Q/Q_{full} and find d/D for a circular pipe or d/H for a rectangular pipe.

Compare this value of this d/D (or d/H) with that obtained from Figure 3 using the Froude parameter, namely,

$$Q / D^{2.5} \qquad \text{or} \qquad Q / (w \cdot H^{1.5})$$

Choose the smaller of the two d/D (or d/H) ratios to calculate the flow depth at the end of the pipe, namely,

$$d = D \cdot \left(d/D \right) \qquad \text{or} \qquad d = H \cdot \left(d/H \right)$$

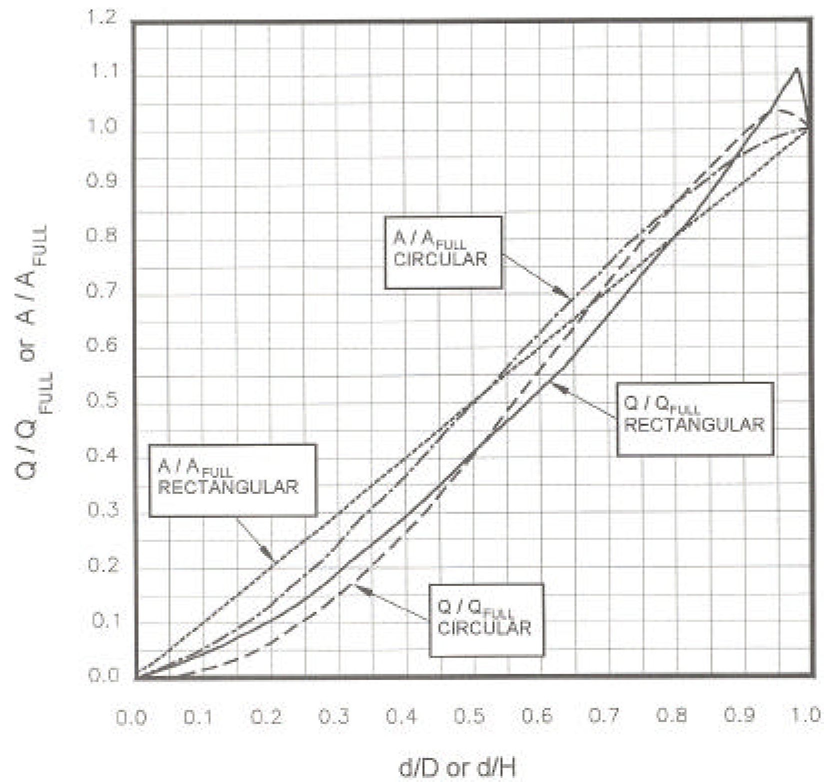

Figure 2. Discharge and Flow Area vs. Depth of Flow for Circular and Rectangular Pipes.

Again enter Figure 2 using the smaller *d/D* (or *d/H*) ratio to find the A/A_{full} ratio. Use this to calculate the area of flow at the end of the pipe, namely,

$$A = {A}/{A_{full}} \cdot A_{full}$$

in which : A = Area of the design flow in the end of the pipe, in square feet.

Finally,

$$V = {Q}/{A}$$

in which: V = Design flow velocity at the pipe outlet, in feet per second.

Finding the Appropriate Riprap Size

Use Figure 4 to find the size and type of the riprap to use in the scour protection basin downstream of the pipe outlet [i.e., HG (grouted H), H, M or L]. First, calculate the riprap sizing design parameter, P_d , namely,

$$P_d = \left(V^2 + g \cdot d\right)^{1/2}$$

in which: g = acceleration due to gravity, 32.2 feet per second per second.

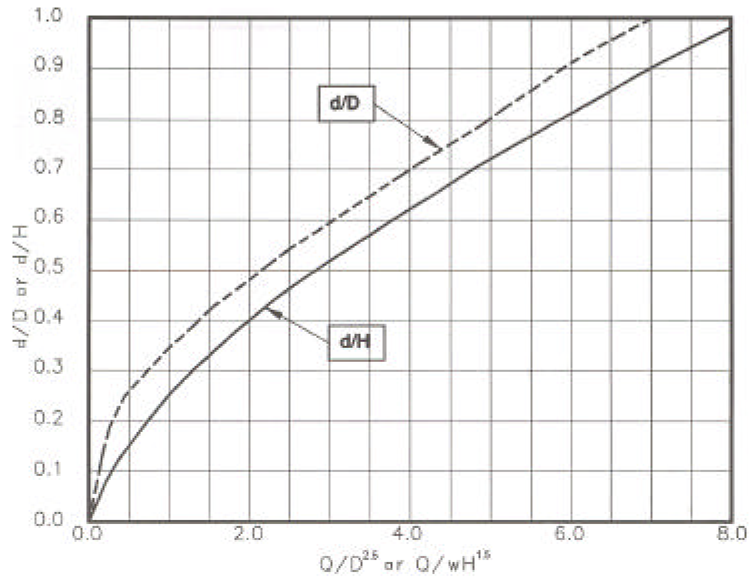

Figure 3. Brink Depth for Very Flat Longitudinal Sloped Circular and Rectangular Pipes

When the riprap sizing design parameter indicates conditions that place the design above the Type H riprap line in Figure 4, use HG, or larger, grouted rock. An alternative to a grouted or loose riprap basin is to use the standard Bureau of Reclamation Basin VI, a reinforced concrete impact structure, to dissipate the energy in the flow at the outlet of the pipe.

After the riprap size has been selected, the minimum thickness of the riprap layer, *T* in feet, in the basin is set at

$$T = 1.75 \cdot D_{50}$$

in which: D_{50} = the median size of the riprap (see Table 1).

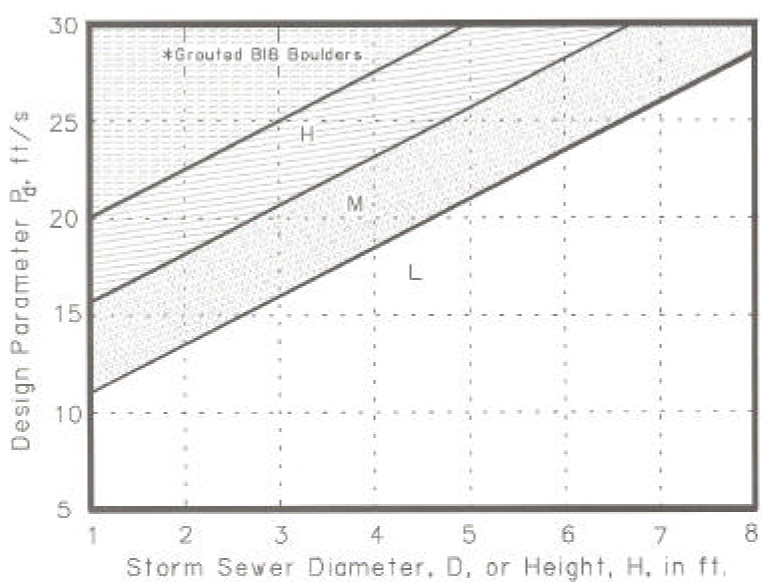

Figure 4. Riprap Size Selection Chart for the Basin at Pipe Outlet.

Table 1. Median (i.e., D_{50}) Size of Urban Drainage District's Riprap.

Riprap Type	D_{50} - Median Rock Size (Inches)
L	9
M	12
H	18

Finding the Basin Length

The minimum length of the basin, L in Figure 1, is defined as being the greater of the following lengths:

For circular pipe,

$$L = 4D \qquad \text{or} \qquad L = (D)^{1/2} \cdot \frac{V}{2}$$

For rectangular pipe,

$$L = 4H \qquad \text{or} \qquad L = (H)^{1/2} \cdot \frac{V}{2}$$

Finding the Basin Width

The minimum width, W, of the basin downstream of the pipe's flared end section is set at:

For circular pipes:

$$W = 4D$$

For rectangular pipe:

$$W = w + 4H$$

Other Design Requirements

- All slopes in the preshaped riprapped basin are 2H to 1V.
- Provide a structural concrete cutoff wall at the end of the flared end section that extends down to a depth of

$$B = \frac{D}{2} + T \qquad \text{or} \qquad B = \frac{H}{2} + T$$

- The riprap must be extended up the outlet embankment's slope to the mid-pipe level.

Examples

Example 1 - Circular pipe on a relatively flat slope.

Given: Design flow, Q = 90 cfs; Tailwater depth, y_t = 1.0 feet
Pipe: Diameter: D = 4.0 feet; Slope: S = 0.005 ft/ft
Manning's: n = 0.013

Step 1. Determine if method is applicable: $y_t < D/3$; namely, low tailwater.

Step 2. Calculate the capacity of the pipe flowing full:

Q_{full} = 102 cfs is found using the Manning's Equation.

Step 3. Using the Q/Q_{full} = 0.88 ratio, Figure 2 gives d/D = 0.82 for a cicular pipe.

Step 4. Calculate: $Q/D^{2.5}$ = 2.81. Use this in Figure 3 to find d/D = 0.57.

Step 5. Since the smaller of the two d/D ratios is 0.57, use it to find the calculate depth, d, at the outletand then in Figure 2 to find the ratio for A/A_{full} = 0.59.

$$d = (d/D) \cdot D = 0.57 \cdot 4.0 = 2.28 \text{ feet}$$

Step 6. Using the A/A_{full} =0.59 ratio, calculate flow area and velocity at the end of the pipe:

$$A = (A/A_{full}) \cdot A_{full} = (0.59) \cdot (\pi \cdot 2.0^2) = 7.41 \text{ square feet}$$

$$V = (Q/A) = (90) / (7.41) = 12.1 \text{ feet per second}$$

Step 7. Calculate the riprap sizing design parameter, P_d , and use it in Figure 4 find the appropriate riprap size:

$P_d = (12.1^2 + 32.2 \cdot 2.28)^{1/2} = 14.8$; Thus, **use Type L Riprap**

Step 8. Calculate the minimum thickness of the riprap layer for D_{50} = 9 inches:

$\boldsymbol{T} = 1.75 \cdot 9.0 = 15.75$ inches. **USE: $\boldsymbol{T}$ = 16 inches**.

Step 9. Find the width of the riprap basin:

$\boldsymbol{W} = 4 \cdot D = 4 \cdot 4 =$ **16 feet**

Step 10. Find the length of the basin, namely the greater of the following two lengths:

$\boldsymbol{L} = (d/D) \cdot H = 4 \cdot 4 =$ **16 feet** (Greater of the two: **use this value**.)

$L = (D^{1/2}) \cdot (V/2) = 4^{1/2} \cdot (12.1 / 2) = 12.1$ feet

<u>*Example 2 - Rectangular pipe on a fairly steep slope.*</u>

Given:	Design flow,	$Q = 300$ cfs;	Tailwater depth,	$y_t = 1.0$ feet
	Box: Height:	$H = 4.0$ feet;	Width:	$w = 5.0$ feet
	Slope:	$S = 0.05$ ft/ft;	Manning's:	$n = 0.013$

Step 1. Determine if method is applicable: $y_t < H/3$; namely, low tailwater.

Step 2. Calculate the capacity of the pipe flowing full:

$Q_{full} = 426$ cfs is found using the Manning's Equation.

Step 3. Using the $Q/Q_{full} = 0.70$ ratio, Figure 2 gives the ratio $d/H = 0.73$.

Step 4. Calculate $Q/wH^{1.5} = 7.50$ and use this in Figure 3 to find $d/H = 0.94$.

Step 5. Since the smaller of the two d/H ratios is 0.73, use it to find the depth, d, at the outlet and in Figure 2 to find the ratio for $A/A_{full} = 0.73$.

$d = 0.73 \cdot 4.0 = 2.92$ feet

Step 6. Also, using the 0.59 ratio, calculate the flow area and velocity at the end of the pipe:

$A = A/A_{full} \cdot A_{full} = (0.73) \cdot (4 \cdot 5) = 14.6$ square feet

$V = Q/A = (300) / (14.6) = 20.5$ feet per second

Step 7. Calculate the riprap sizing design parameter, P_d, and use Figure 4 find the appropriate riprap size:

$P_d = (20.5^2 + 32.2 \cdot 2.92)^{1/2} = 22.7;$ Thus, **use Type M Riprap**

Step 8. Calculate the <u>minimum</u> thickness of the riprap layer for $D_{50} = 12$ inches:

$\boldsymbol{T} = 1.75 \cdot 12.0 =$ **21 inches**.

Step 9. Find the width of the riprap basin:

$$\boldsymbol{W} = w + 4 \cdot H = 5 + 4 \cdot 4 = \mathbf{21\ feet}$$

Step 10. Find the length of the basin, namely the greater of the following two lengths:

$$L = 4 \cdot H = 16 \text{ feet}$$

$$\boldsymbol{L} = (H^{1/2}) \cdot (V/2) = 4^{1/2} \cdot (20.5 / 2) = \textbf{20.5 feet (use this length)}$$

References

The information on brink depth for mild slopes and size of riprap is taken from:
Stevens, M.A., (1969). *Scour In Riprap At Culvert Outlets.* Ph.D. dissertation, Civil Engineering Department, Colorado State University, Ft. Collins, Colorado.