CHAPTER 7

LIST OF FIGURES

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7.0 Energy Dissipation Design

7.1 Symbols and Definitions

To provide consistency within this section as well as throughout this Manual, the symbols listed in Table 7-1 will be used. These symbols were selected because of their wide use. In some cases, the same symbol is used in existing publications for more than one definition. Where this occurs in this section, the symbol will be defined where it occurs in the text or equations.

Table 7-1 Symbols and Definitions

Symbol	Definition	Units
A	Cross-sectional area	ft²
D	Height of box culvert	ft
d_{50}	Size of riprap	ft
d_w	Culvert width	ft
F_r	Froude Number	-
g	Acceleration of gravity	ft/s²
h_s	Depth of dissipator pool	ft
L	Length	ft
L_a	Riprap apron length	ft
L_B	Overall length of basin	ft
L_s	Length of dissipator pool	ft
PI	Plasticity index	-
Q	Rate of discharge	cfs
S_v	Saturated shear strength	lbs/in²
t	Time of scour	min.
t_c	Critical tractive shear stress	lbs/in²
TW	Tailwater depth	ft
V_L	Velocity L feet from brink	ft/s
V_o	Normal velocity at brink	ft/s
V_o	Outlet mean velocity	ft/s
V_s	Volume of dissipator pool	ft²
W_o	Diameter or width of culvert	ft
W_s	Width of dissipator pool	ft
y_e	Hydraulic depth at brink	ft
y_o	Normal flow depth at brink	ft

7.2 Design Criteria

7.2.1 Introduction

The outlets of pipes and lined channels are points of critical erosion potential. Stormwater that is transported through man-made conveyance systems at design capacity generally reaches a velocity that exceeds the capacity of the receiving channel or area to resist erosion. To prevent scour, wearing away by water, at stormwater outlets, protect the outlet structure and minimize the potential for downstream erosion, a flow transition structure is needed to absorb the initial impact of flow and reduce the speed of the flow to a non-erosive velocity.

Energy dissipators are engineered devices such as riprap aprons or concrete baffles placed at the outlet of stormwater conveyances for the purpose of reducing the velocity, energy and turbulence of the discharged flow.

7.2.2 General Criteria

- Erosion problems at culvert, pipe and engineered channel outlets are common. Determination of the flow conditions, scour potential, and channel erosion resistance shall be standard procedure for all designs.
- Energy dissipators shall be employed whenever the velocity of flows leaving a stormwater management facility exceeds the erosion velocity of the downstream area channel system.
- Energy dissipator designs will vary based on discharge specifics and tailwater conditions.
- Outlet structures should provide uniform redistribution or spreading of the flow without excessive separation and turbulence.

7.2.3 Erosion Hazards

Erosion problems at culverts or the outlet from detention basins are common. Determination of the flow conditions, scour potential, and channel erosion resistance, shall be standard procedure for all designs. The only safe procedure is to design on the basis that erosion at a culvert outlet and the downstream channel is to be expected.

Standard practice is to use the same headwall treatment at the culvert entrance and exit. It is important to recognize that the inlet is designed to improve culvert capacity or reduce headloss while the outlet structure should provide a smooth flow transition back to the natural channel or into an energy dissipator. Outlet structures should provide uniform redistribution or spreading of the flow without excessive separation and turbulence. Figure 7-1 on the next page provides the riprap size recommended for use downstream of energy dissipators.

7.2.4 Recommended Energy Dissipators

For many designs, the following outlet protection devices and energy dissipators provide sufficient protection at a reasonable cost:

- Riprap apron
- Riprap outlet basins
- Baffled outlets

This section focuses on the design on these measures. The reader is referred to the Federal Highway Administration Hydraulic Engineering Circular No. 14 entitled, Hydraulic Design of Energy Dissipators for Culverts and Channels, for the design procedures of other energy dissipators.

7.3 Design Procedure

(1) If outlet protection is required, choose an appropriate type. Suggested outlet protection facilities and applicable flow conditions (based on Froude number and dissipation velocity) are described below:

a. Riprap aprons may be used when the outlet Froude number (Fr) is less than or equal to 2.5. In general, riprap aprons prove economical for transitions from culverts to overland sheet flow at terminal outlets, but may also be used for transitions from culvert sections to stable channel sections. Stability of the surface at the termination of the apron should be considered.

b. Riprap outlet basins may also be used when the outlet Fr is less than or equal to 2.5. They are generally used for transitions from culverts to stable channels. Since riprap outlet basins function by creating a hydraulic jump to dissipate energy, performance is impacted by tailwater conditions.

c. Baffled outlets have been used with outlet velocities up to 50 feet per second. Practical application typically requires an outlet Fr between 1 and 9. Baffled outlets may be used at both terminal outlet and channel outlet transitions. They function by dissipating energy through impact and turbulence and are not significantly affected by tailwater conditions.

(2) When outlet protection facilities are selected, appropriate design flow conditions and site specific factors affecting erosion and scour potential, construction cost, and long-term durability should be considered.

(3) If outlet protection is not provided, energy dissipation will occur through formation of a local scour hole. If an immovable obstruction, such as a large boulder, restricts the area of flow in a stream channel. Water piles up against the upstream edge of the obstruction, causing an increase in velocity around the sides, accompanied by the development of vortexes which scour the bed. Scour holes may develop, and the scoured-out material may be deposited downstream as a gravel bar. If the obstruction is overtopped during high water an additional erosive force is introduced as water plunges over the downstream face, impinging on the bed like a jet. This force can greatly enlarge the scour hole below the obstacle. A cutoff wall will be needed at the discharge outlet to prevent structural undermining. The wall depth should be slightly greater than the computed scour hole depth, hs. The scour hole should then be stabilized. If the scour hole is of such size that it will present maintenance, safety, or aesthetic problems, other outlet protection will be needed.

(4) Evaluate the downstream channel stability and provide appropriate erosion protection if channel degradation is expected to occur. Figure 7-1 provides the riprap size recommended for use downstream of energy dissipators.

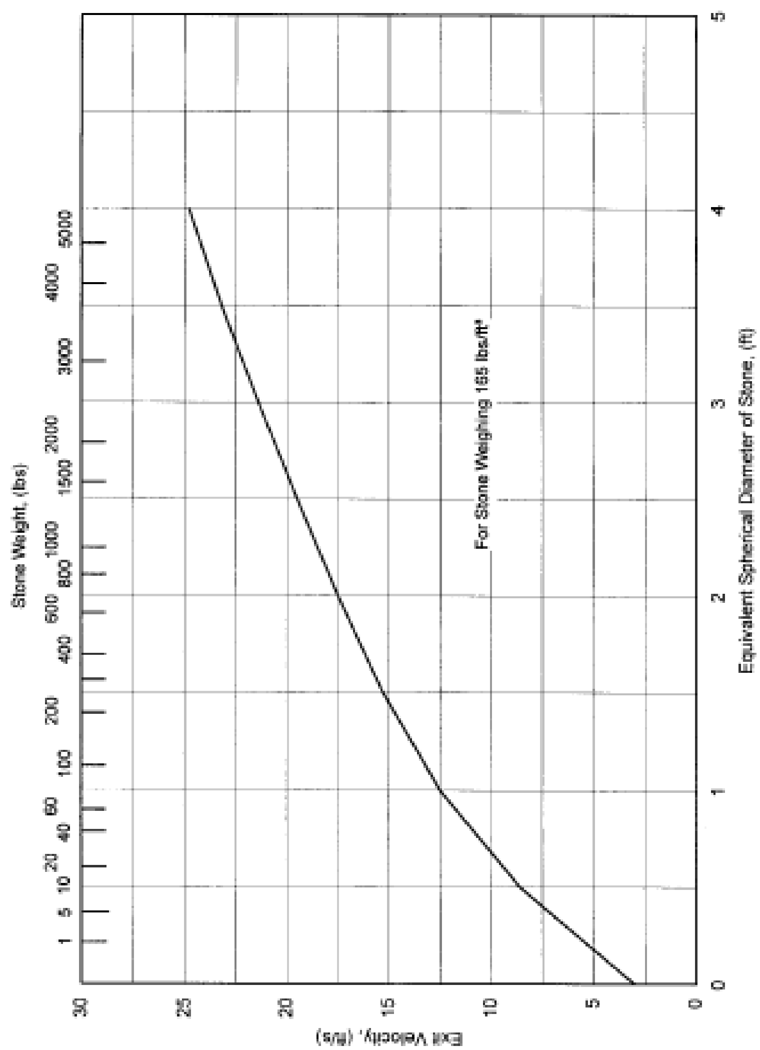


Figure 7-1 Riprap Size for Use Downstream of Energy Dissipator
(Source: Searcy, 1967)

7.4 *Riprap Aprons*

7.4.1 Description and Uses

A riprap-lined apron is a commonly used practice for energy dissipation because of its relatively low cost and ease of installation. A flat riprap apron can be used to prevent erosion at the transition from a pipe or box culvert outlet to a natural channel. Protection is provided primarily by having sufficient length and flare to dissipate energy by expanding the flow. Riprap aprons are appropriate when the culvert outlet Fr is less than or equal to 2.5.

7.4.2 Basin Features

7.4.3 Design Procedures

The procedure presented in this section is taken from USDA, SCS (1975). Two sets of curves, one for minimum and one for maximum tailwater conditions, are used to determine the apron size and the median riprap diameter, d_{50}. If tailwater conditions are unknown, or if both minimum and maximum conditions may occur, the apron should be designed to meet criteria for both. Although the design curves are based on round pipes flowing full, they can be used for partially full pipes and box culverts. The design procedure consists of the following steps:

(Step 1) If possible, determine tailwater conditions for the channel. If tailwater is less than one half the discharge flow depth (pipe diameter if flowing full), minimum tailwater conditions exist and the curves in Figure 7-2 apply. Otherwise, maximum tailwater conditions exist and the curves in Figure 7-3 should be used.

(Step 2) Determine the correct apron length and median riprap diameter, d_{50}, using the appropriate curves from Figures 7-2 and 7-3. If tailwater conditions are uncertain, find the values for both minimum and maximum conditions and size the apron as shown in Figure 7-4.

a. *For pipes flowing full:*

Use the depth of flow, d, which equals the pipe diameter, in feet, and design discharge, in cfs, to obtain the apron length, L_a, and median riprap diameter, d_{50}, from the appropriate curves.

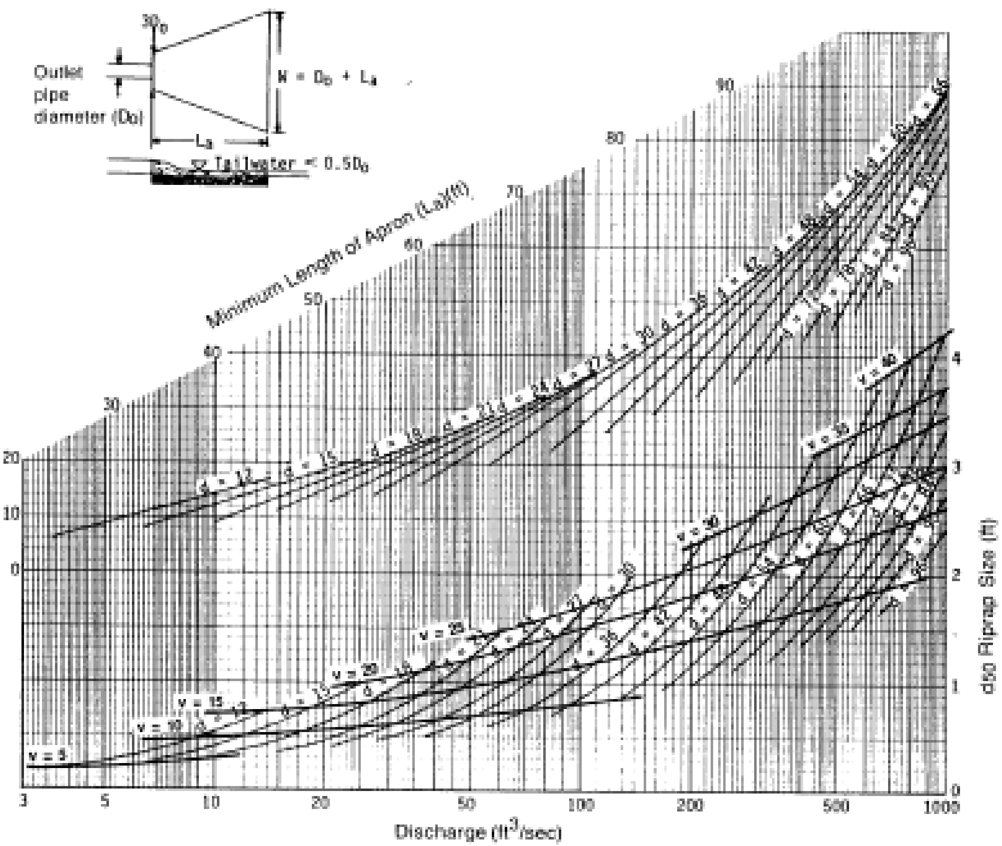
b. *For pipes flowing partially full:*

Use the depth of flow, d, in feet, and velocity, v, in ft/s. On the lower portion of the appropriate figure, find the intersection of the d and v curves, then find the riprap median diameter, d_{50}, from the scale on the right. From the lower d and v intersection point, move vertically to the upper curves until intersecting the curve for the correct flow depth, d. Find the minimum apron length, L_a, from the scale on the left.

c. *For box culverts:*

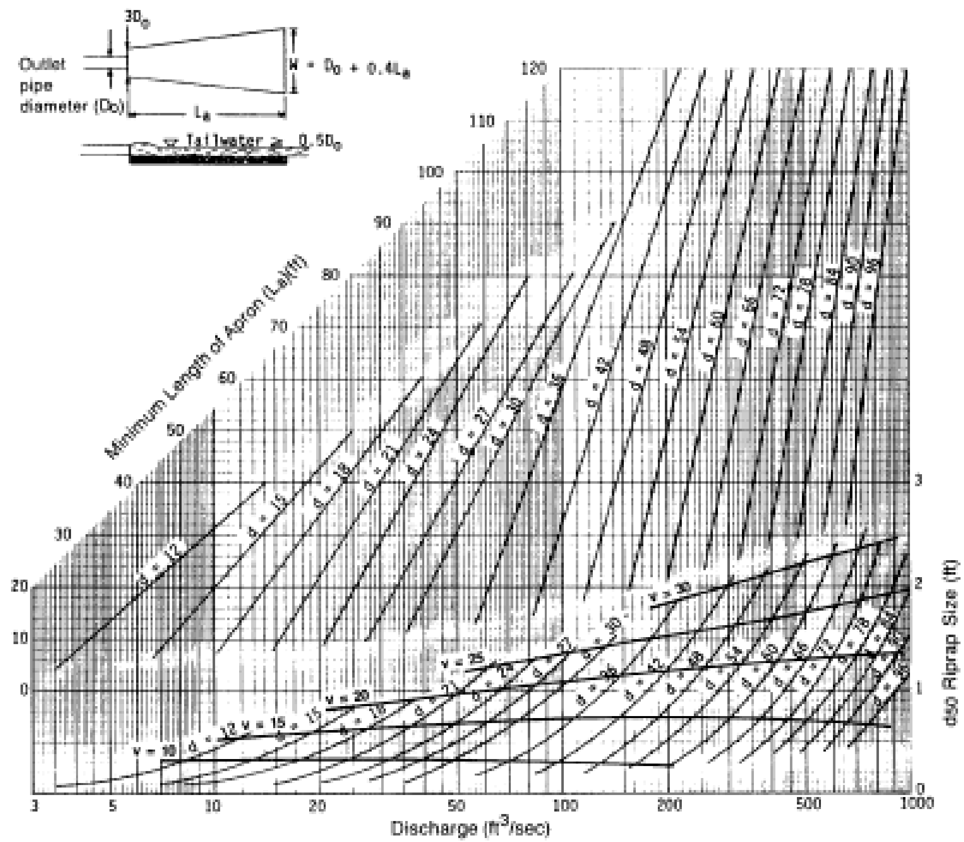
Use the depth of flow, d, in feet, and velocity, v, in feet/second. On the lower portion of the appropriate figure, find the intersection of the d and v curves, then find the riprap median diameter, d_{50}, from the scale on the right. From the lower d and v intersection point, move vertically to the upper curve until intersecting the curve equal to the flow depth, d. Find the minimum apron length, La, using the scale on the left.

(Step 3) If tailwater conditions are uncertain, the median riprap diameter should be the larger of the values for minimum and maximum conditions. The dimensions of the apron will be as shown in Figure 7-4. This will provide protection under either of the tailwater conditions.



Curves may not be extrapolated.

Figure 7-2 Design of Riprap Apron under Minimum Tailwater Conditions
(Source: USDA, SCS, 1975)



Curves may not be extrapolated.

Figure 7-3 Design of Riprap Apron under Maximum Tailwater Conditions
(Source: USDA, SCS, 1975)

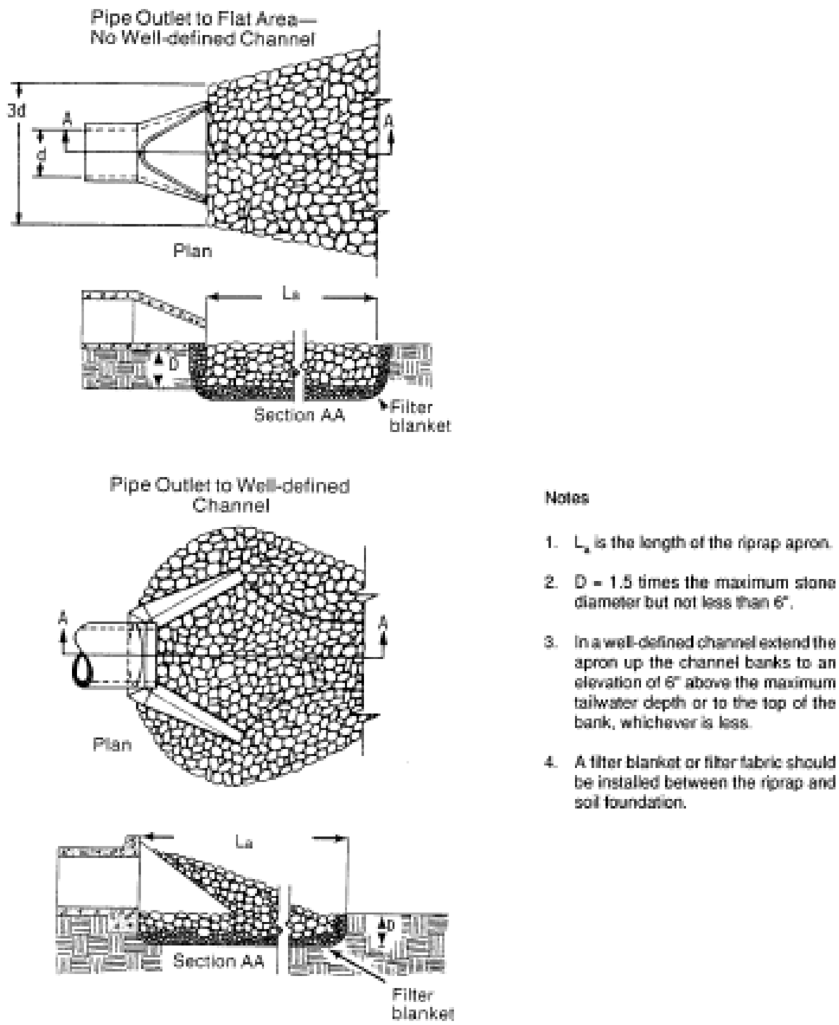


Figure 7-4 Riprap Apron

(Source: Manual for Erosion and Sediment Control in Georgia, 1996)

7.4.4 Design Considerations

The following items should be considered during riprap apron design:

- The maximum stone diameter should be 1.5 times the median riprap diameter. d_{max} = 1.5 x d_{50} , d_{50} = the median stone size in a well-graded riprap apron.

- The riprap thickness should be 1.5 times the maximum stone diameter or 6 inches, whichever is greater. Apron thickness = 1.5 x d_{max} (Apron thickness may be reduced to 1.5 x d_{50} when an appropriate filter fabric is used under the apron.)

- The apron width at the discharge outlet should be at least equal to the pipe diameter or culvert width, d_w. Riprap should extend up both sides of the apron and around the end of the pipe or culvert at the discharge outlet at a maximum slope of 2:1 and a height not less than the pipe diameter or culvert height, and should taper to the flat surface at the end of the apron.

- If there is a well-defined channel, the apron length should be extended as necessary so that the downstream apron width is equal to the channel width. The sidewalls of the channel should not be steeper than 2:1.

- If the ground slope downstream of the apron is steep, channel erosion may occur. The apron should be extended as necessary until the slope is gentle enough to prevent further erosion.

- The potential for vandalism should be considered if the rock is easy to carry. If vandalism is a possibility, the rock size must be increased or the rocks held in place using concrete or grout.

7.4.5 Example Designs

Example 1 Riprap Apron Design for Minimum Tailwater Conditions

A flow of 280 cfs discharges from a 66-in pipe with a tailwater of 2 ft above the pipe invert. Find the required design dimensions for a riprap apron.

(1) Minimum tailwater conditions = 0.5 d_o, d_o = 66 in = 5.5 ft; therefore, 0.5 d_o = 2.75 ft.

(2) Since TW = 2 ft, use Figure 7-2 for minimum tailwater conditions.

(3) By Figure 7-2, the apron length, L_a, and median stone size, d_{50}, are 38 ft and 1.2 ft, respectively.

(4) The downstream apron width equals the apron length plus the pipe diameter:

$$W = d + L_a = 5.5 + 38 = 43.5 \text{ ft}$$

(5) Maximum riprap diameter is 1.5 times the median stone size:
1.5 (d_{50}) = 1.5 (1.2) = 1.8 ft

(6) Riprap depth = 1.5 (d_{max}) = 1.5 (1.8) = 2.7 ft.

Example 2 Riprap Apron Design for Maximum Tailwater Conditions

A concrete box culvert 5.5 ft high and 10 ft wide conveys a flow of 600 cfs at a depth of 5.0 ft. Tailwater depth is 5.0 ft above the culvert outlet invert. Find the design dimensions for a riprap apron.

(1) Compute 0.5 do = 0.5 (5.0) = 2.5 ft.

(2) Since TW = 5.0 ft is greater than 2.5 ft, use Figure 7-3 for maximum tailwater conditions. v = Q/A = [600/(5) (10)] = 12 ft/s

(3) On Figure 7-3, at the intersection of the curve, d_o = 60 in and v = 12 ft/s, d_{50} = 0.4 ft. Reading up to the intersection with d = 60 in, find L_a = 40 ft.

(4) Apron width downstream = d_w + 0.4 L_a = 10 + 0.4 (40) = 26 ft.

(5) Maximum stone diameter = 1.5 d_{50} = 1.5 (0.4) = 0.6 ft.

(6) Riprap depth = 1.5 d_{max} = 1.5 (0.6) = 0.9 ft.

7.5 Riprap Basin Design

7.5.1 Description and Uses

Another method to reduce the exit velocities from stormwater outlets is through the use of a riprap basin. A riprap outlet basin is a pre-shaped scour hole lined with riprap that functions as an energy dissipator by forming a hydraulic jump.

7.5.2 Basin Features

General details of the basin recommended in this section are shown in Figure 7-5. Principal features of the basin are:

- The basin is pre-shaped and lined with riprap of median size (d_{50}).
- The floor of the riprap basin is constructed at an elevation of h_s below the culvert invert. The dimension h_s is the approximate depth of scour that would occur in a thick pad of riprap of size d_{50} if subjected to design discharge. The ratio of h_s to d_{50} of the material should be between 2 and 4.
- The length of the energy dissipating pool is 10 x h_s or 3 x W_o, whichever is larger. The overall length of the basin is 15 x h_s or 4 x W_o, whichever is larger.

7.5.3 Design Procedure

The following procedure should be used for the design of riprap basins.

(Step 1) Estimate the flow properties at the brink (outlet) of the culvert. Establish the outlet invert elevation such that TW/yo < 0.75 for the design discharge.

(Step 2) For subcritical flow conditions (culvert set on mild or horizontal slope) use Figure 7-6 or Figure 7-7 to obtain y_o/D, then obtain V_o by dividing Q by the wetted area associated with y_o. D is the height of a box culvert. If the culvert is on a steep slope, V_o will be the normal velocity obtained by using the Manning equation for appropriate slope, section, and discharge.

(Step 3) For channel protection, compute the Froude number for brink conditions with $y_e = (A/2)^{1.5}$. Select d_{50}/y_e appropriate for locally available riprap (usually the most satisfactory results will be obtained if $0.25 < d_{50}/y_e < 0.45$). Obtain h_s/y_e from Figure 7-8, and check to see that $2 < h_s/d_{50} < 4$. Recycle computations if h_s/d_{50} falls out of this range.

(Step 4) Size basin as shown in Figure 7-5.

(Step 5) Where allowable dissipator exit velocity is specified:

a. Determine the average normal flow depth in the natural channel for the design discharge.

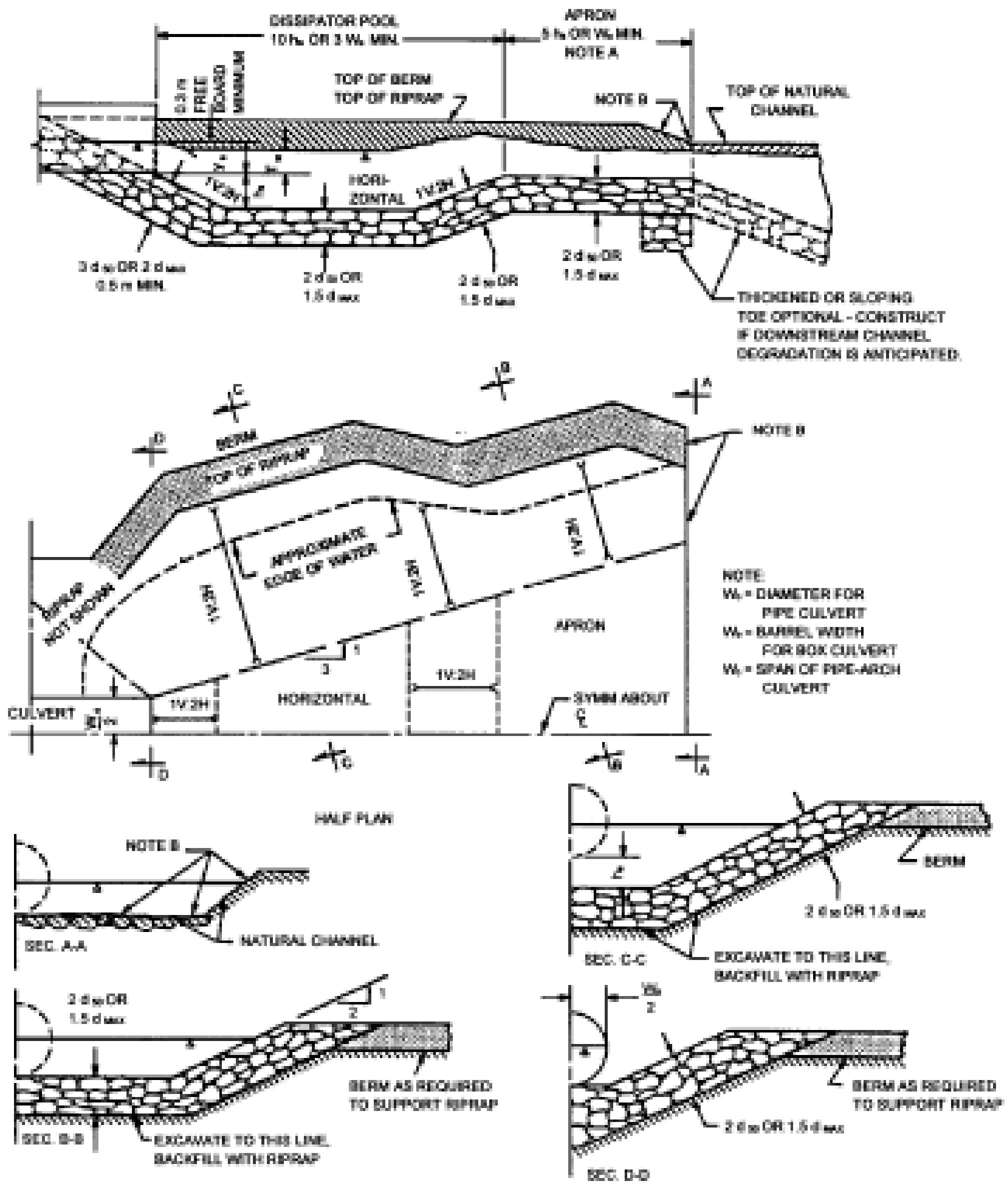
b. Extend the length of the energy basin (if necessary) so that the width of the energy basin at section A-A, Figure 7-5, times the average normal flow depth in the natural channel is approximately equal to the design discharge divided by the specified exit velocity.

(Step 6) In the exit region of the basin, the walls and apron of the basin should be warped (or transitioned) so that the cross section of the basin at the exit conforms to the cross section of the natural channel. Abrupt transition of surfaces should be avoided to minimize separation zones and resultant eddies.

(Step 7) If high tailwater is a possibility and erosion protection is necessary for the downstream channel, the following design procedure is suggested:

- Design a conventional basin for low tailwater conditions in accordance with the instructions above.
- Estimate centerline velocity at a series of downstream cross sections using the information shown in Figure 7-9.
- Shape downstream channel and size riprap using Figure 7-1 and the stream velocities obtained above.

Material, construction techniques, and design details for riprap should be in accordance with specifications in the Federal Highway publication HEC No. 11 entitled Use of Riprap for Bank Protection.



NOTE A - IF EXIT VELOCITY OF BASIN IS SPECIFIED, EXTEND BASIN AS REQUIRED TO OBTAIN SUFFICIENT CROSS-SECTIONAL AREA AT SECTION A-A SUCH THAT Q/(CROSS SECTION AREA AT SEC. A-A) = SPECIFIED EXIT VELOCITY.

NOTE B - WARP BASIN TO CONFORM TO NATURAL STREAM CHANNEL. TOP OF RIPRAP IN FLOOR OF BASIN SHOULD BE AT THE SAME ELEVATION OR LOWER THAN NATURAL CHANNEL BOTTOM AT SEC. A-A.

Figure 7-5 Details of Riprap Outlet Basin
(Source: Hec-14, 1983)

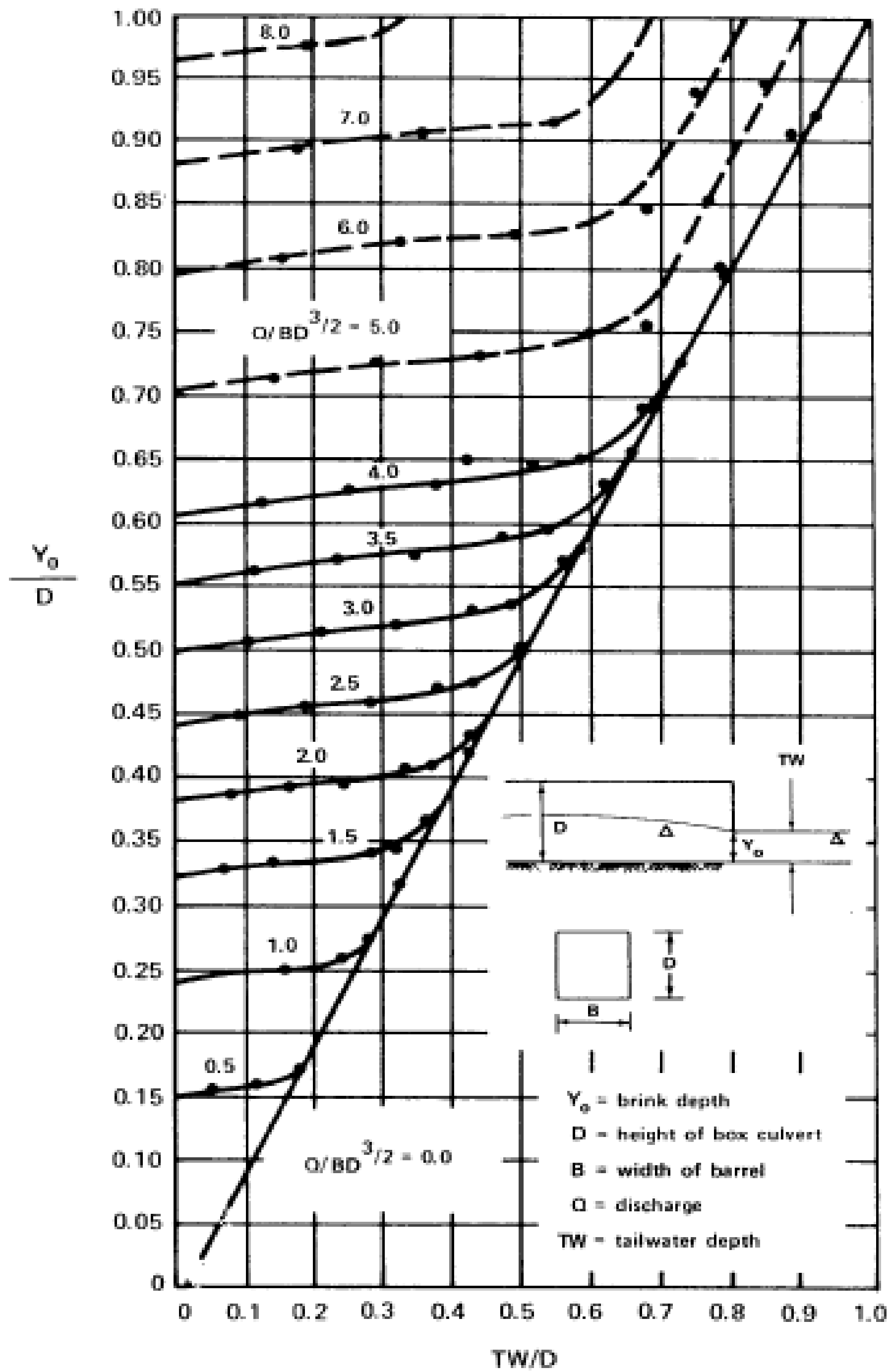


Figure 7-6 Dimensionless Rating Curves for the Outlets of Rectangular Culverts on Horizontal and Mild Slopes

(Source: USDOT, FHWA. HEC-14, 1983)

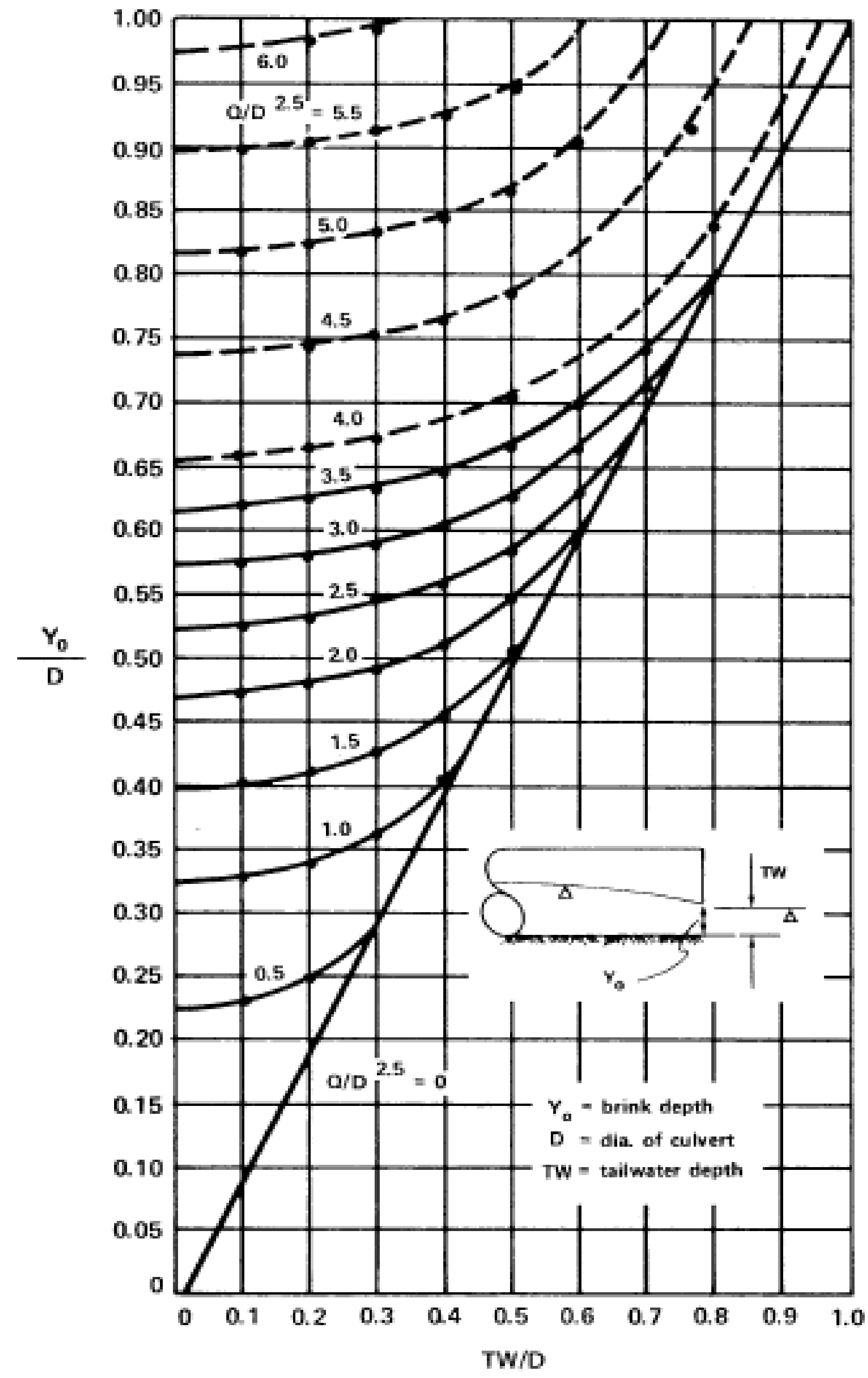


Figure 7-7 Dimensionless Rating Curves for the Outlets of Circular Culverts on Horizontal and Mild Slopes

(Source: USDOT, FHWA, HEC-14, 1983)

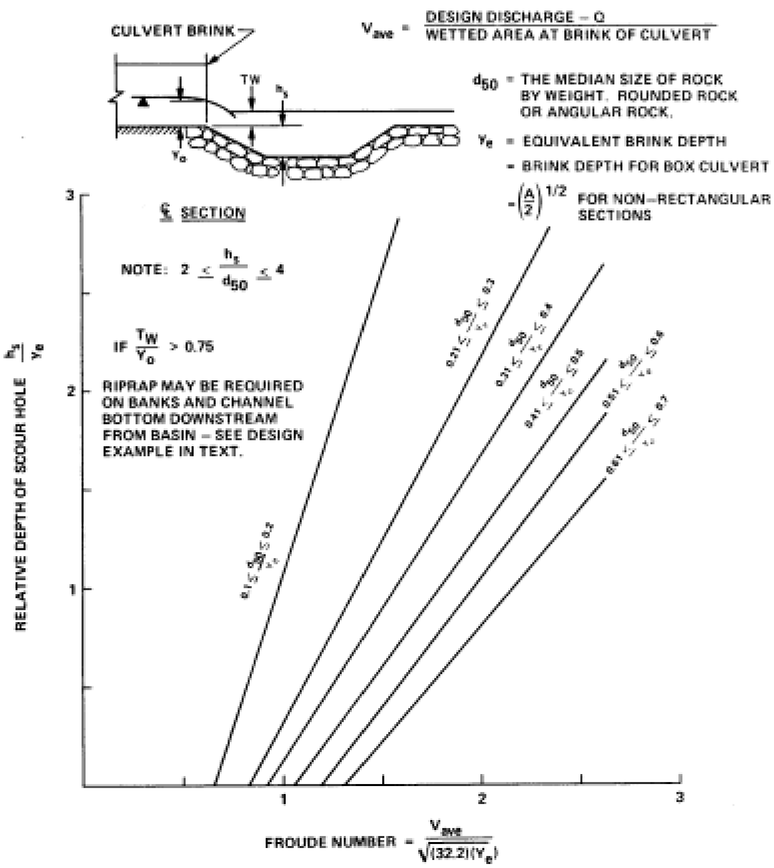


Figure 7-8 Relative Depth of Scour Hole versus Froude Number at Brink of Culvert with Relative Size of Riprap as a Third Variable

(Source: USDOT, FHWA, HEC-14, 1983)

7.5.4 Design Considerations

Riprap basin design should include consideration of the following:

- The dimensions of a scour hole in a basin constructed with angular rock can be approximately the same as the dimensions of a scour hole in a basin constructed of rounded material when rock size and other variables are similar.
- When the ratio of tailwater depth to brink depth, TW/y_o, is less than 0.75 and the ratio of scour depth to size of riprap, h_s/d_{50}, is greater than 2.0, the scour hole should function very efficiently as an energy dissipator. The concentrated flow at the culvert brink plunges into the hole, a jump forms against the downstream extremity of the scour hole, and flow is generally well dispersed leaving the basin.
- The mound of material formed on the bed downstream of the scour hole contributes to the dissipation of energy and reduces the size of the scour hole; that is, if the mound from a stable scoured basin is removed and the basin is again subjected to design flow, the scour hole will enlarge.

- For high tailwater basins (TW/y_o greater than 0.75), the high velocity core of water emerging from the culvert retains its jet-like character as it passes through the basin and diffuses similarly to a concentrated jet diffusing in a large body of water. As a result, the scour hole is much shallower and generally longer. Consequently, riprap may be required for the channel downstream of the rock-lined basin.
- It should be recognized that there is a potential for limited degradation to the floor of the dissipator pool for rare event discharges. With the protection afforded by the $2(d_{50})$ thickness of riprap, the heavy layer of riprap adjacent to the roadway prism, and the apron riprap in the downstream portion of the basin, such damage should be superficial.
- See Standards in the in FHWA HEC No. 11 for details on riprap materials and use of filter fabric.
- Stability of the surface at the outlet of a basin should be considered using the methods for open channel flow as outlined in Section 4.4, *Open Channel Design.*

7.5.5 Example Designs

Following are some example problems to illustrate the design procedures outlined.

Example 1

Given:	Box culvert - 8 ft by 6 ft	Design Discharge Q = 800 cfs
	Supercritical flow in culvert	Normal flow depth = brink depth
	Y_o = 4 ft	Tailwater depth TW = 2.8 ft

Find: Riprap basin dimensions for these conditions

Solution: Definition of terms in Steps 1 through 5 can be found in Figures 7-5 and 7-8.

(1) $y_o = y_e$ for rectangular section; therefore, with y_o given as 4 ft, y_e = 4 ft.

(2) $V_o = Q/A = 800/(4 \times 8) = 25$ ft/s

(3) Froude Number = $F_r = V/(g \times y_e)^{0.5}$ ($g = 32.3$ ft/s²)

$F_r = 25/(32.2 \times 4)^{0.5} = 2.20 < 2.5$ O.K.

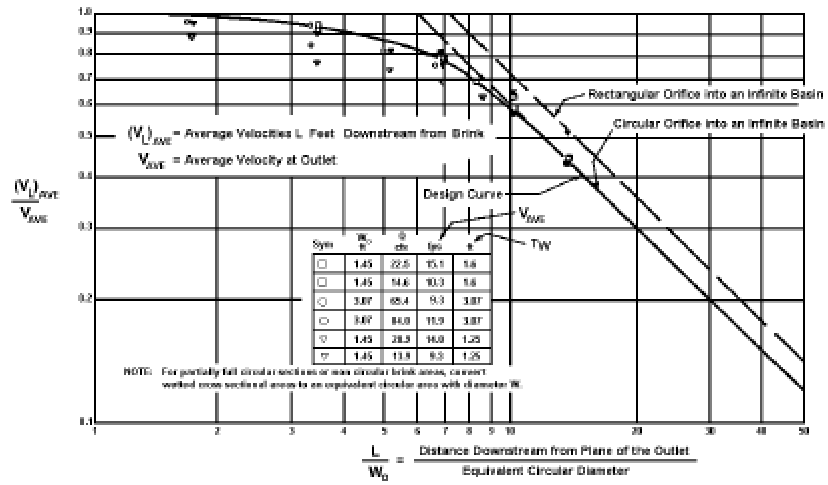


Figure 7-9 Distribution of Centerline Velocity for Flow from Submerged Outlets to Be Used for Predicting Channel Velocities Downstream from Culvert Outlet Where High Tailwater Prevails
(Source: USDOT, FHWA, HEC-14, 1983)

(4) $TW/y_e = 2.8/4.0 = 0.7$ Therefore, $TW/y_e < 0.75$ OK
(5) Try $d_{50}/y_e = 0.45$, $d_{50} = 0.45 \times 4 = 1.80$ ft
From Figure 7-8, $h_s/y_e = 1.6$, $h_s = 4 \times 1.6 = 6.4$ ft
$h_s/d_{50} = 6.4/1.8 = 3.6$ ft, $2 < h_s/d_{50} < 4$ OK
(6) $L_s = 10 \times h_s = 10 \times 6.4 = 64$ ft (L_s = length of energy dissipator pool)
L_s min $= 3 \times W_o = 3 \times 8 = 24$ ft; therefore, use $L_s = 64$ ft

$L_B = 15 \times h_s = 15 \times 6.4 = 96$ ft (L_B = overall length of riprap basin)
L_B min $= 4 \times W_o = 4 \times 8 = 32$ ft; therefore, use $L_B = 96$ ft
(7) Thickness of riprap: On the approach $= 3 \times d_{50} = 3 \times 1.8 = 5.4$ ft
Remainder $= 2 \times d_{50} = 2 \times 1.8 = 3.6$ ft
Other basin dimensions designed according to details shown in Figure 7-5.

Example 2

Given: Same design data as Example 1 except:
Tailwater depth TW = 4.2 ft
Downstream channel can tolerate only 7 ft/s discharge

Find: Riprap basin dimensions for these conditions

Solutions: Note -- High tailwater depth, $TW/y_o = 4.2/4 = 1.05 > 0.75$

(1) From Example 1: $d_{50} = 1.8$ ft, $h_s = 6.4$ ft, $L_s = 64$ ft, $L_B = 96$ ft.

(2) Design riprap for downstream channel. Use Figure 7-9 for estimating average velocity along the channel. Compute equivalent circular diameter D_e for brink area from:

$A = 3.14D_e^2/4 = y_o \times W_o = 4 \times 8 = 32 \text{ ft}^2$

$D_e = ((32 \times 4)/3.14)^{0.5} = 6.4 \text{ ft}$

$V_o = 25$ ft/s (From Example 1)

(3) Set up the following table:

L/De (Assume) ($D_e = W_o$)	**L (ft)** (Compute)	**V_L/V_o** (Fig. 7-9)	**v_1 (ft/s)**	**Rock Size d_{50} (ft)** (Fig. 7-1)
10	64	0.59	14.7	1.4
15*	96	0.37	9.0	0.6
20	128	0.30	7.5	0.4
21	135	0.28	7.0	0.4

*L/Wo is on a logarithmic scale so interpolations must be done logarithmically.

Riprap should be at least the size shown but can be larger. As a practical consideration, the channel can be lined with the same size rock used for the basin. Protection must extend at least 135 ft downstream from the culvert brink. Channel should be shaped and riprap should be installed in accordance with details shown in the HEC No. 11 publication.

Example 3

Given: 6-ft diameter CMC
Design discharge Q = 135 cfs
Slope channel $S_o = 0.004$
Manning's n = 0.024
Normal depth in pipe for Q = 135 cfs is 4.5 ft
Normal velocity is 5.9 ft/s
Flow is subcritical
Tailwater depth TW = 2.0 ft

Find: Riprap basin dimensions for these conditions.

Solution:

(1) Determine y_o and V_o

From Figure 4.5-7, $y_o/D = 0.45$

$Q/D^{2.5} = 135/6^{2.5} = 1.53$

$TW/D = 2.0/6 = 0.33$

$y_o = 0.45 \times 6 = 2.7$ ft
$TW/y_o = 2.0/2.7 = 0.74$ $TW/y_o < 0.75$ O.K.

Determine Brink Area (A) for $y_o/D = 0.45$

From Uniform Flow in Circular Sections Table (from Section 4.3)
For $y_o/D = d/D = 0.45$
$A/D^2 = 0.3428$; therefore, $A = 0.3428 \times 6^2 = 12.3$ ft²
$V_o = Q/A = 135/12.3 = 11.0$ ft/s

(2) For Froude number calculations at brink conditions,
$y_e = (A/2)^{1/2} = (12.3/2)^{1/2} = 2.48$ ft

(3) Froude number $= F_r = V_o/(32.2 \times y_e)^{1/2} = 11/(32.2 \times 2.48)^{1/2} = 1.23 < 2.5$ OK

(4) For most satisfactory results - $0.25 < d_{50}/y_e < 0.45$
Try $d_{50}/y_e = 0.25$
$d_{50} = 0.25 \times 2.48 = 0.62$ ft
From Figure 4.5-8, $h_s/y_e = 0.75$; therefore, $h_s = 0.75 \times 2.48 = 1.86$ ft

Uniform Flow in Circular Sections Flowing Partly Full (From Section 4.3)

Check: $h_s/d_{50} = 1.86/0.62 = 3$, $2 < h_s/d_{50} < 4$ OK

(5) $L_s = 10 \times h_s = 10 \times 1.86 = 18.6$ ft or $L_s = 3 \times W_o = 3 \times 6 = 18$ ft;
therefore, use $L_s = 18.6$ ft

$L_B = 15 \times h_s = 15 \times 1.86 = 27.9$ ft or $L_B = 4 \times W_o = 4 \times 6 = 24$ ft;
therefore, use $L_B = 27.9$ ft

$d_{50} = 0.62$ ft or use $d_{50} = 8$ in

Other basin dimensions should be designed in accordance with details shown on Figure 7-5. Figure 7-10 is provided as a convenient form to organize and present the results of riprap basin designs.

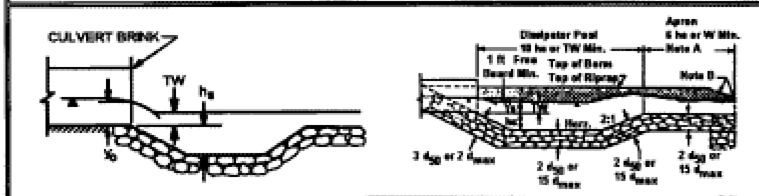
Note: When using the design procedure outlined in this section, it is recognized that there is some chance of limited degradation of the floor of the dissipator pool for rare event discharges. With the protection afforded by the 3 x d_{50} thickness of riprap on the approach and the 2 x d_{50} thickness of riprap on the basin floor and the apron in the downstream portion of the basin, the damage should be superficial.

RIPRAP BASIN

Project No. ______________________________

Designer ______________________________ Date ________

Reviewer ______________________________ Date ________



DESIGN VALUES	TRIAL 1	FINAL TRIAL
Equi. Depth, d_E		
D_{50}/d_E		
D_{50}		
Froude No., Fr		
h_B/d_E		
h_B		
h_B/D_{50}		
$2 < h_B/D_{50} < 4$		

BASIN DIMENSIONS		FEET	
Pool length is the larger of:	$10h_B$		
	$3W_o$		
Basin length is the larger of:	$15h_B$		
	$4W_o$		
Approach Thickness	$3D_{50}$		
Basin Thickness	$2D_{50}$		

TAILWATER CHECK	
Tailwater, TW	
Equivalent depth, d_E	
TW/d_E	
IF $TW/d_E > 0.75$, calculate riprap downstream	
$D_E=(4A_o/\pi)^{0.5}$	

DOWNSTREAM RIPRAP				
L/D_E	L	V_L/V_o	V_L	D_{50}

Figure 7-10 Riprap Basin Design Form
(Source: USDOT, FHWA, HEC-14, 1983)

7.6 Baffled Outlets

7.6.1 Description and Uses

The baffled outlet (also known as the Impact Basin - USBR Type VI) is a boxlike structure with a vertical hanging baffle and an end sill, as shown in Figure 7-11. Energy is dissipated primarily through the impact of the water striking the baffle and, to a lesser extent, through the resulting turbulence. This type of outlet protection has been used with outlet velocities up to 50 feet per second and with Froude numbers from 1 to 9. Tailwater depth is not required for adequate energy dissipation, but a tailwater will help smooth the outlet flow.

7.6.2 Design Procedure

The following design procedure is based on physical modeling studies summarized from the U.S. Department of Interior (1978). The dimensions of a baffled outlet as shown in Figure 7-11 should be calculated as follows:

(Step 1) Determine input parameters, including:

h = Energy head to be dissipated, in ft (can be approximated as the difference between channel invert elevations at the inlet and outlet)
Q = Design discharge (cfs)
v = Theoretical velocity (ft/s = 2gh)
$A = Q/v$ = Flow area (ft²)
$d = A^{1/2}$ = Representative flow depth entering the basin (ft) *assumes square jet*
$Fr = v/(gd)^{0.5}$ = Froude number, dimensionless

(Step 2) Calculate the minimum basin width, W, in ft, using the following equation.

$$W/d = 2.88Fr^{0.566} \text{ or } W = 2.88dFr^{0.556} \quad (7.1)$$

Where: W = minimum basin width (ft)
d = depth of incoming flow (ft)
$Fr = v/(gd)^{0.5}$ = Froude number, dimensionless

The limits of the W/d ratio are from 3 to 10, which corresponds to Froude numbers 1 and 9. If the basin is much wider than W, flow will pass under the baffle and energy dissipation will not be effective.

(Step 3) Calculate the other basin dimensions as shown in Figure 7-11, as a function of W. Construction drawings for selected widths are available from the U.S. Department of the Interior (1978).

(Step 4) Calculate required protection for the transition from the baffled outlet to the natural channel based on the outlet width. A riprap apron should be added of width W, length W (or a 5-foot minimum), and depth f (W/6). The side slopes should be 1.5:1, and median rock diameter should be at least W/20.

(Step 5) Calculate the baffled outlet invert elevation based on expected tailwater. The maximum distance between expected tailwater elevation and the invert should be b + f or some flow will go over the baffle with no energy dissipation. If the tailwater is known and fairly controlled, the baffled outlet invert should be a distance, b/2 + f, below the calculated tailwater elevation. If tailwater is uncontrolled, the baffled outlet invert should be a distance, f, below the downstream channel invert.

(Step 6) Calculate the outlet pipe diameter entering the basin assuming a velocity of 12 ft/s flowing full.

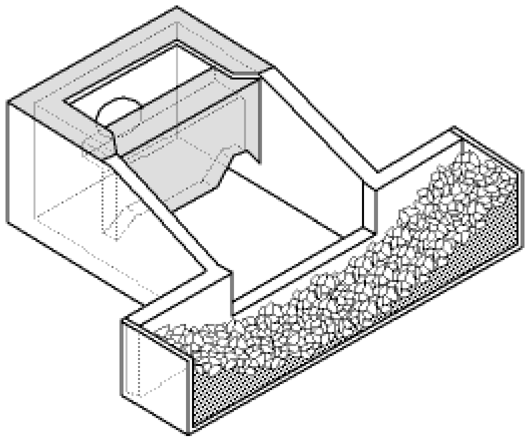


Figure 7-11 Isometric View of Baffled Outlet
(Source: Ohio Department of Natural Resources)

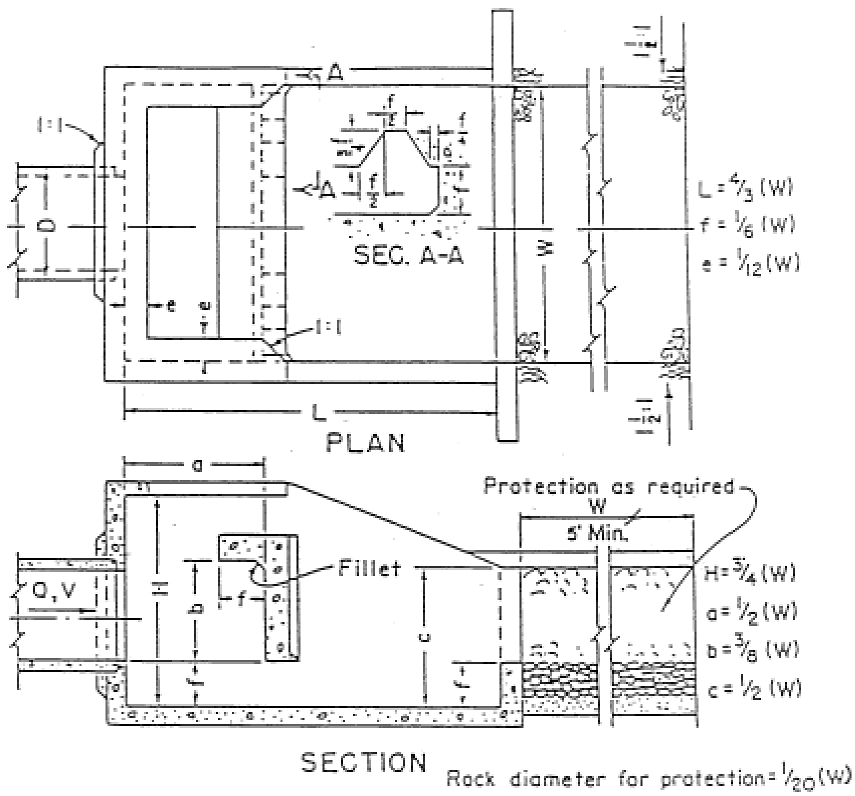


Figure 7-12 Schematic of Baffled Outlet
(Source: U.S. Dept. of the Interior, 1978)

(Step 7) If the entrance pipe slopes steeply downward, the outlet pipe should be turned horizontal for at least 3 ft before entering the baffled outlet.

(Step 8) If it is possible that both the upstream and downstream ends of the pipe will be submerged, provide an air vent approximately 1/6 the pipe diameter near the upstream end to prevent pressure fluctuations and possible surging flow conditions.

7.6.3 Example Design

A cross-drainage pipe structure has a design flow rate of 150 cfs, a head, h, of 15 ft from invert of pipe, and a tailwater depth, TW, of 3 ft above ground surface. Find the baffled outlet basin dimensions and inlet pipe requirements.

(1) Compute the theoretical velocity from
$v = (2gh)^{1/2} = [2(32.2\ \text{ft/sec}^2)(15\ \text{ft})]^{1/2} = 31.1$ ft/s
This is less than 50 ft/s, so a baffled outlet is suitable.

(2) Determine the flow area using the theoretical velocity as follows:
$A = Q/v = 150\ \text{cfs}/31.1\ \text{ft/sec} = 4.8\ \text{ft}^2$

(3) Compute the flow depth using the area from Step 2.
$d = (A)^{1/2} = (4.8\ \text{ft}^2)^{1/2} = 2.12$ ft

(4) Compute the Froude number using the results from Steps 1 and 3.
$Fr = v/(gd)^{1/2} = 31.1\ \text{ft/sec}/[(32.2\ \text{ft/sec}^2)(2.12\ \text{ft})]^{1/2} = 3.8$

(5) Determine the basin width using Equation 7.1 with the Froude number from Step 4.
$W = 2.88\ dFr^{0.556} = 2.88\ (2.12)\ (3.8)^{0.556} = 13.0$ ft (minimum)
Use 13 ft as the design width.

(6) Compute the remaining basin dimensions (as shown in Figure 7-11):
L = 4/3 (W) = 17.3 ft, use L = 17 ft, 4 in
f = 1/6 (W) = 2.17 ft, use f = 2 ft, 2 in
e = 1/12 (W) = 1.08 ft, use e = 1 ft, 1 in
H = 3/4 (W) = 9.75 ft, use H = 9 ft, 9 in
a = 1/2 (W) = 6.5 ft, use a = 6 ft, 6 in
b = 3/8 (W) = 4.88 ft, use b = 4 ft, 11 in
c = 1/2 (W) = 6.5 ft, use c = 6 ft, 6 in
Baffle opening dimensions would be calculated as shown in Figure 7-11.

(7) Basin invert should be at b/2 + f below tailwater, or
(4 ft, 11 in)/2 + 2 ft, 2 in = 4.73 ft
Use 4 ft 8 in; therefore, invert should be 2 ft, 8 in below ground surface.

(8) The riprap transition from the baffled outlet to the natural channel should be 13 ft long by 13 ft wide by 2 ft, 2 in deep (W x W x f). Median rock diameter should be of diameter W/20, or about 8 in.

(9) Inlet pipe diameter should be sized for an inlet velocity of about 12 ft/s.
$(3.14d)^2/4 = Q/v$; $d = [(4Q)/3.14v)]^{1/2} = [(4(150\ \text{cfs})/3.14(12\ \text{ft/sec})]^{1/2} = 3.99$ ft
Use 48-in pipe. If a vent is required, it should be about 1/6 of the pipe diameter or 8 in.

7.7 References

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