ENERGY DISSIPATION

Chapter Table of Contents

7.1 Symbols And Definitions

To provide consistency within this chapter as well as throughout this manual the following symbols will be used. These symbols were selected because of their wide use in many energy dissipation publications.

Table 7-1 Symbols And Definitions

Symbol	Definition	Units
A	Cross section area	sq ft
D	Height of box culvert	ft
d_{50}	Size of riprap	ft
d_w	Culvert width	ft
Fr	Froude Number	-
g	Acceleration of gravity	ft/s^2
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	$pounds/in^2$
t	Time of scour	min.
t_c	Critical tractive shear stress	$pounds/in^2$
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	ft^2
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 General Criteria

Energy Dissipators shall be employed whenever the velocity of flows leaving a stormwater management facility exceeds the erosion velocity of the downstream channel system.

7.2.2 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.

7.2.3 Recommended Dissipators

For many designs, the following outlet protection and energy dissipators provide sufficient protection at a reasonable cost.
- Riprap apron
- Riprap outlet basins
- Baffled outlets

This chapter will focus 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 the 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. 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.

Following is a discussion of applicable conditions for each outlet protection measure.

   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.
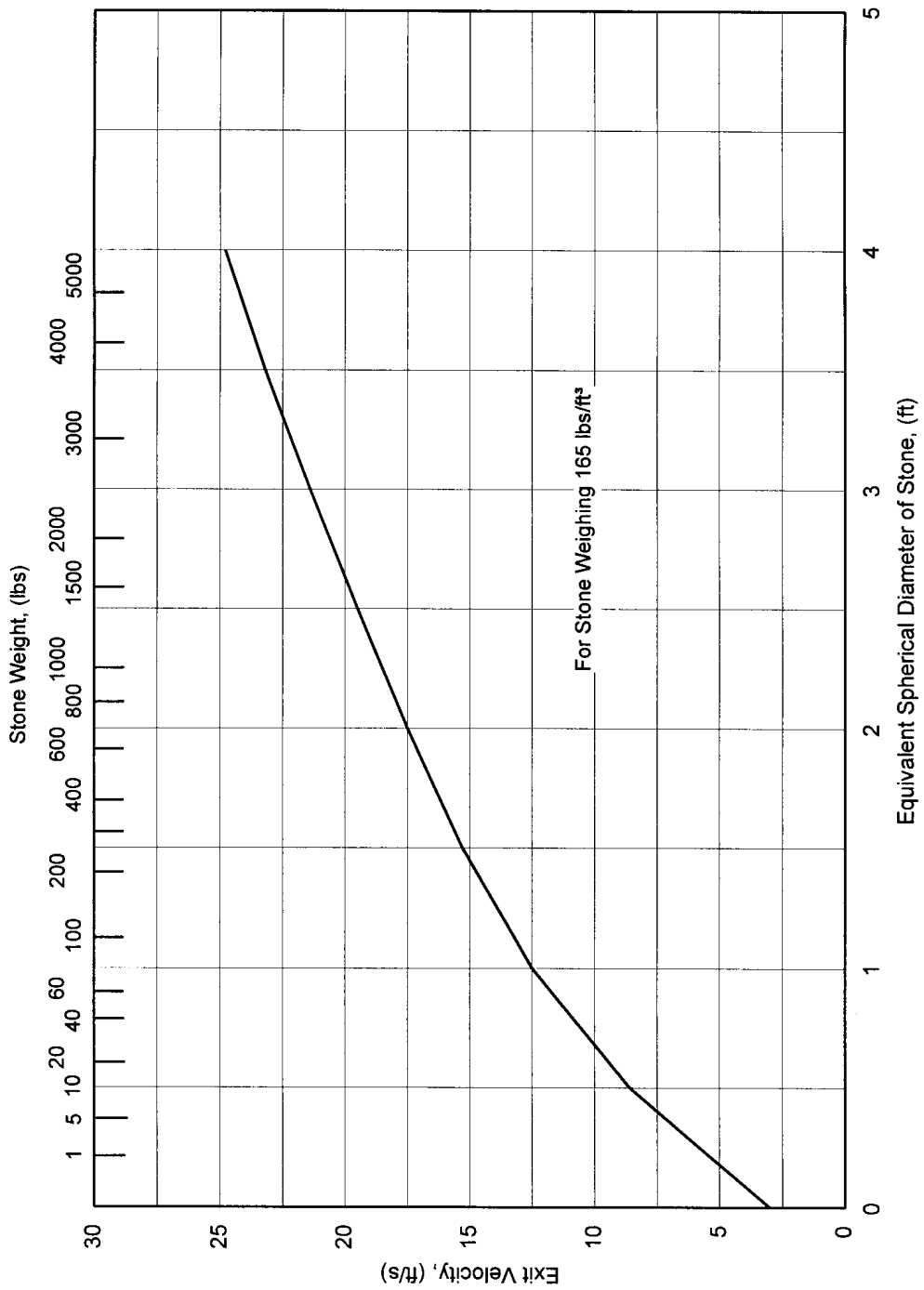
Figure 7-1   Riprap Size for Use Downstream of Energy Dissipator

b. <u>Riprap outlet basins</u> 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. <u>Baffled outlets</u> have been used with outlet velocities up to 50 feet per second. Practical application typically requires an outlet Froude number 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. If outlet protection is not provided, energy dissipation will occur through formation of a local scourhole. A cutoff wall will be needed at the discharge outlet to prevent structural undermining. The wall depth should be slightly greater than the computed scourhole depth, h_s. The scourhole should then be stabilized. If the scourhole is of such size that it will present maintenance, safety, or aesthetic problems, other outlet protection will be needed.

3. Evaluate the downstream channel stability and provide appropriate erosion protection if channel degradation is expected to occur.
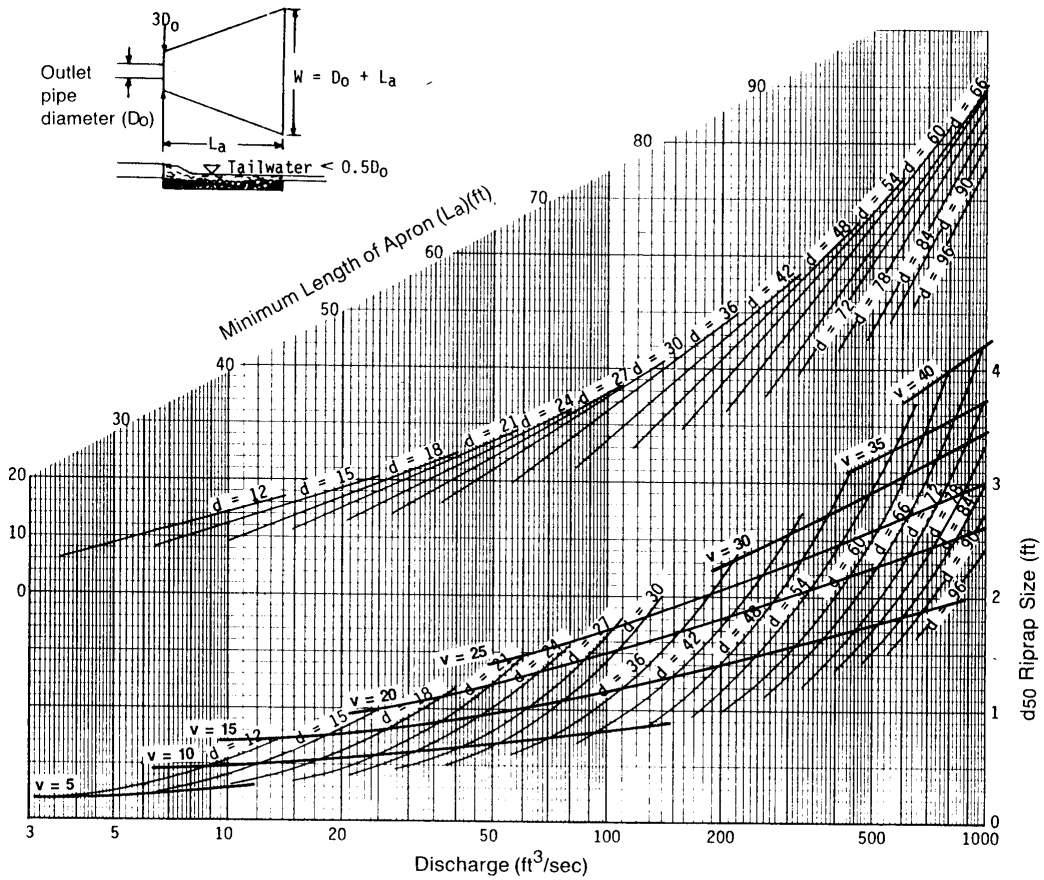
7.4 Riprap Aprons

7.4.1 Uses

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 Procedure

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:

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.

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.
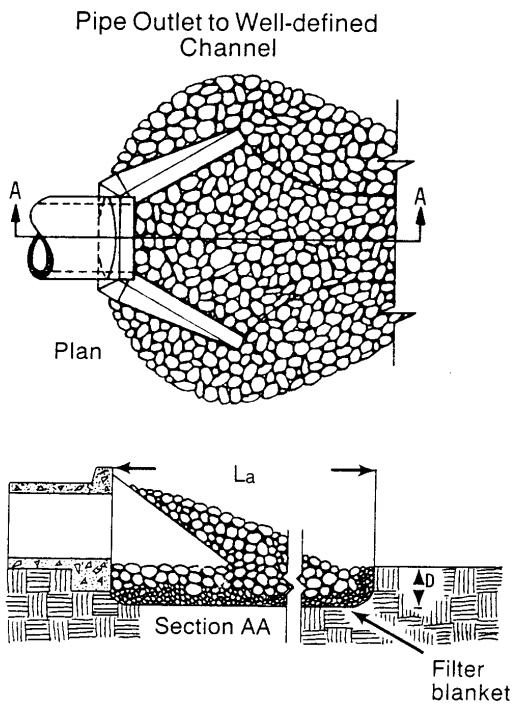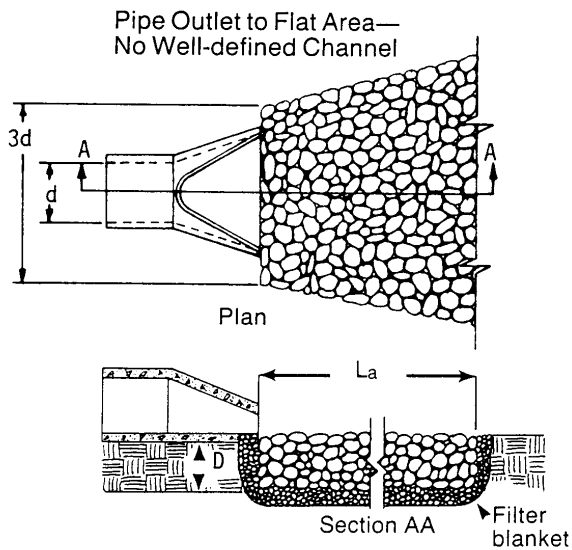
Figure 7-2 Design of Riprap Apron Under Minimum Tailwater Conditions
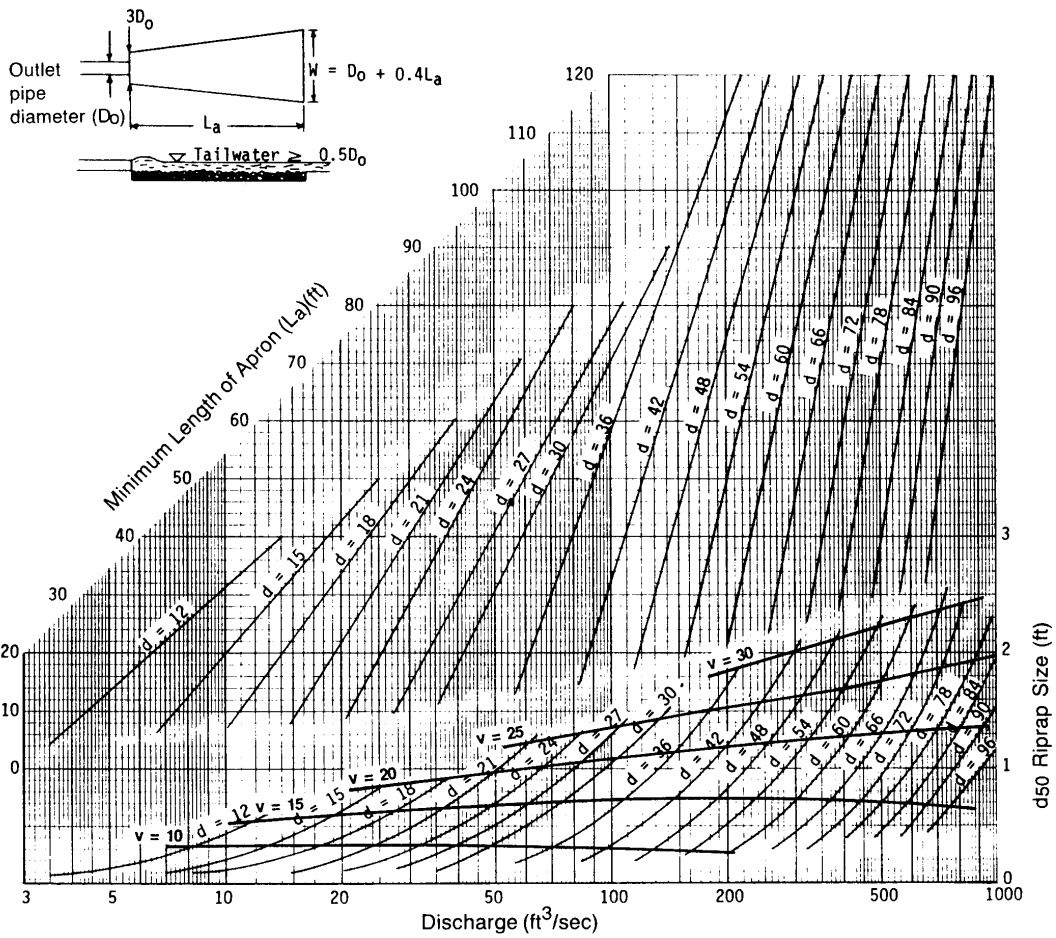
Curves may not be extrapolated.

Figure 7-3 Design of Riprap Apron Under Maximum Tailwater Conditions

Pipe Outlet to Flat Area—
No Well-defined Channel

Plan

Section AA

Filter blanket

Pipe Outlet to Well-defined Channel

Plan

Section AA

Filter blanket

Notes

1. L_a is the length of the riprap apron.

2. D = 1.5 times the maximum stone diameter but not less than 6".

3. In a well-defined channel extend the apron up the channel banks to an elevation of 6" above the maximum tailwater depth or to the top of the bank, whichever is less.

4. A filter blanket or filter fabric should be installed between the riprap and soil foundation.

Figure 7-4 Riprap Apron

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 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 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, L_a, using the scale on the left.

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.

7.4.3 Design Considerations

The following items should be considered during riprap apron design:

1. 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.

2. 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.)

3. 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.

4. 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.

5. 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.

6.   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.

7.4.4 Example Designs

Example 7-1. Riprap Apron Design for Minimum Tailwater Conditions

A flow of 280 cfs discharges from a 66-inch 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 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 7-2. 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 d_o = 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 foot. 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 Uses

One method to reduce the exit velocities from outlets is to install a riprap basin. A riprap outlet basin is a preshaped scourhole 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 chapter are shown on Figure 7-5. Principal features of the basin are:

1. The basin is preshaped and lined with riprap of median size (d_{50}).

2. 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.

3. 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.

1. Estimate the flow properties at the brink (outlet) of the culvert. Establish the outlet invert elevation such that $TW/y_o \leq 0.75$ for the design discharge.

2. For subcritical flow conditions (culvert set on mild or horizontal slope) utilize Figures 7-6 or 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.

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.

4. Size basin as shown in Figure 7-5.

5. Where allowable dissipator exit velocity is specified:

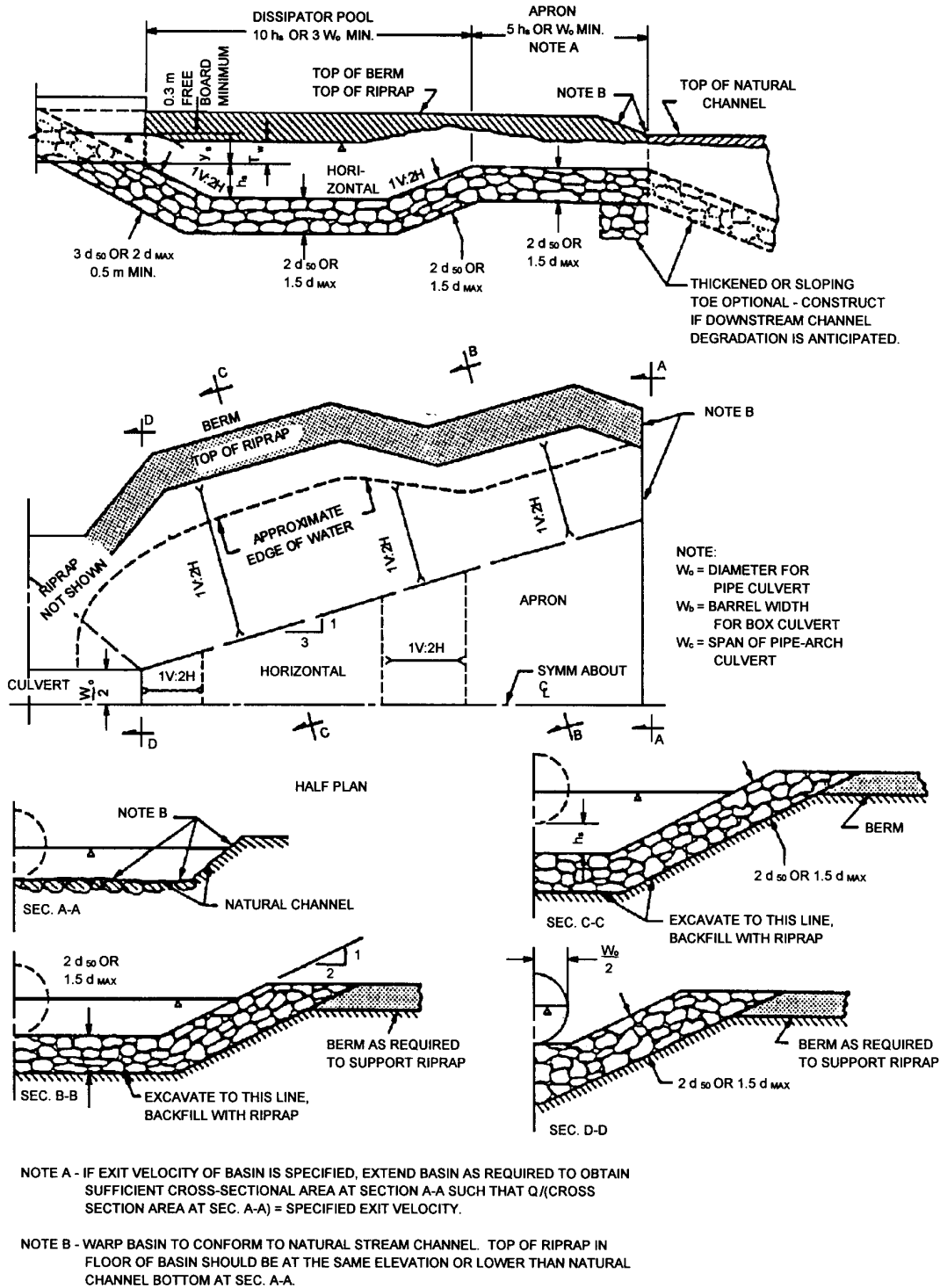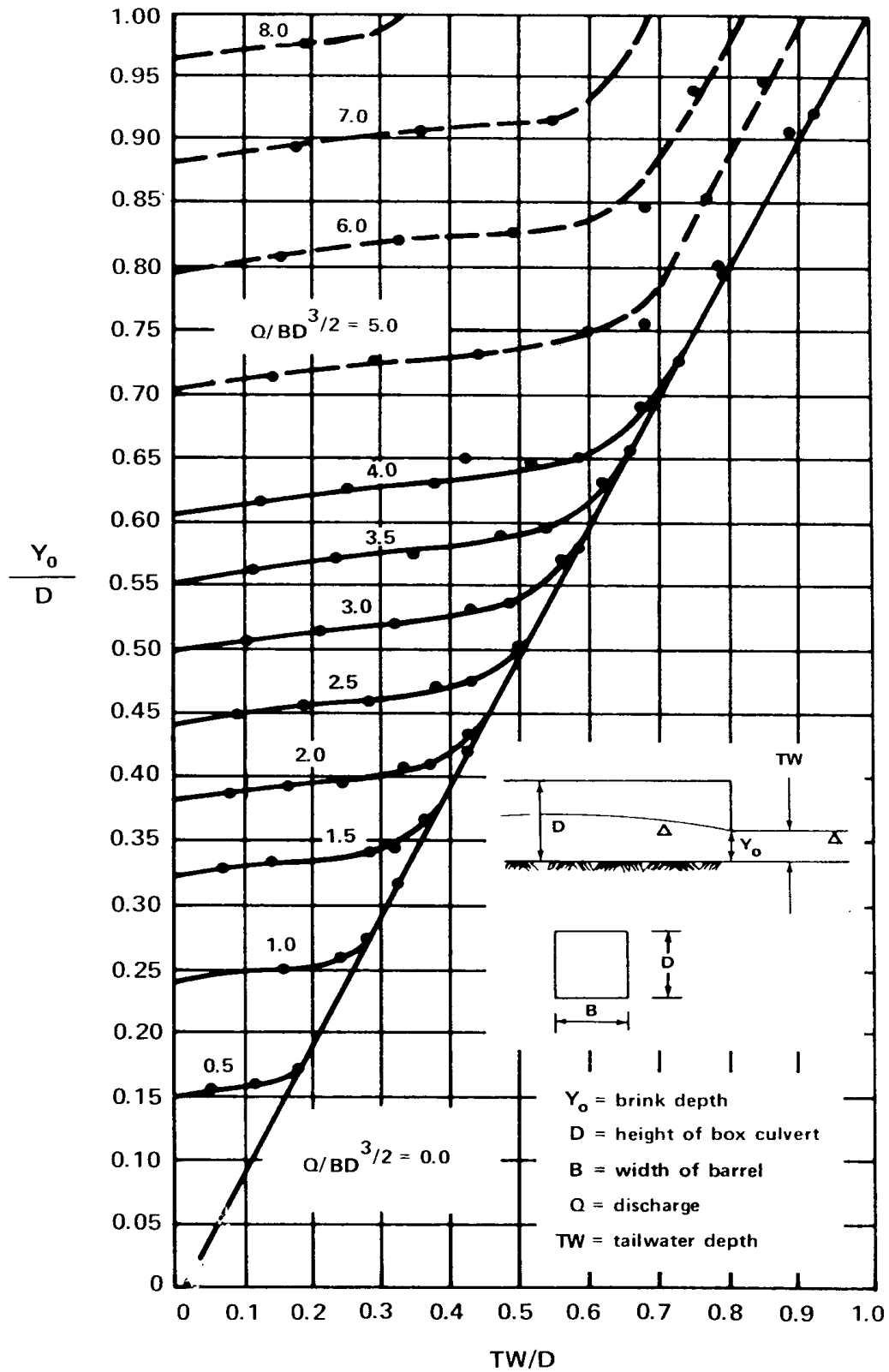   a. Determine the average normal flow depth in the natural channel for the design discharge.

DISSIPATOR POOL
10 h₀ OR 3 W₀ MIN.

APRON
5 h₀ OR W₀ MIN.
NOTE A

0.3 m FREE BOARD MINIMUM

TOP OF BERM
TOP OF RIPRAP

NOTE B

TOP OF NATURAL CHANNEL

HORIZONTAL
1V:2H
1V:2H

3 d₅₀ OR 2 d MAX
0.5 m MIN.

2 d₅₀ OR
1.5 d MAX

2 d₅₀ OR
1.5 d MAX

2 d₅₀ OR
1.5 d MAX

THICKENED OR SLOPING TOE OPTIONAL - CONSTRUCT IF DOWNSTREAM CHANNEL DEGRADATION IS ANTICIPATED.

BERM
TOP OF RIPRAP

NOTE B

RIPRAP NOT SHOWN

APPROXIMATE EDGE OF WATER

1V:2H
1V:2H
1V:2H

APRON

1V:2H

CULVERT
W₀/2

1V:2H

HORIZONTAL

1V:2H

SYMM ABOUT ℄

3 / 1

NOTE:
W₀ = DIAMETER FOR PIPE CULVERT
W_b = BARREL WIDTH FOR BOX CULVERT
W_c = SPAN OF PIPE-ARCH CULVERT

HALF PLAN

NOTE B

NATURAL CHANNEL

SEC. A-A

2 d₅₀ OR
1.5 d MAX

1 / 2

SEC. B-B

EXCAVATE TO THIS LINE, BACKFILL WITH RIPRAP

BERM AS REQUIRED TO SUPPORT RIPRAP

BERM

2 d₅₀ OR 1.5 d MAX

SEC. C-C

EXCAVATE TO THIS LINE, BACKFILL WITH RIPRAP

W₀/2

BERM AS REQUIRED TO SUPPORT RIPRAP

2 d₅₀ OR 1.5 d MAX

SEC. D-D

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

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

Source: USDOT, FHWA, HEC-14(1983)
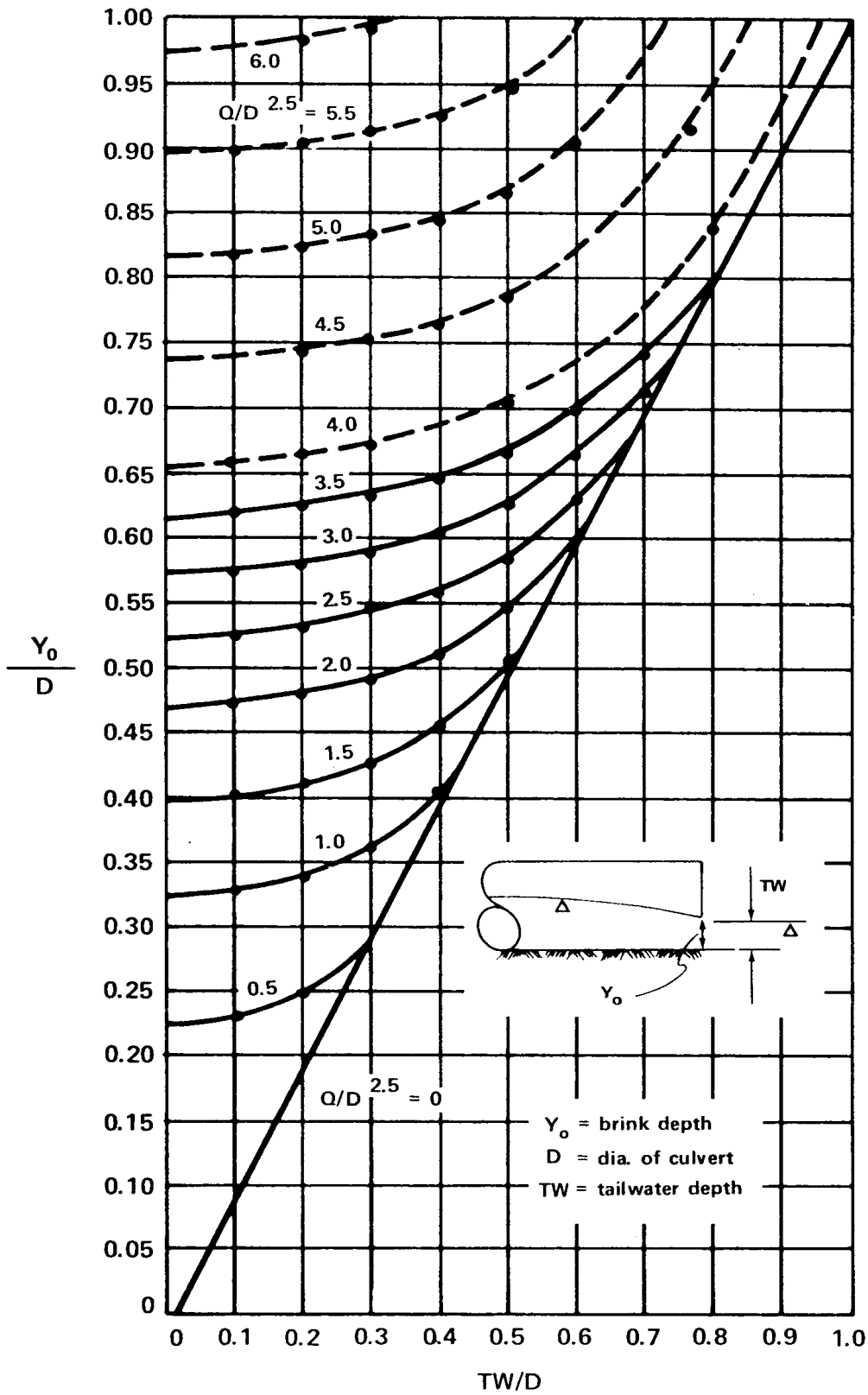
Figure 7-7   Dimensionless Rating Curve for the Outlets of Circular Culverts on Horizontal and Mild Slopes

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

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.

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.

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.

7.5.4 Design Considerations

Riprap basin design should include consideration of the following:

1. The dimensions of a scourhole in a basin constructed with angular rock can be approximately the same as the dimensions of a scourhole in a basin constructed of rounded material when rock size and other variables are similar.

2. 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 scourhole 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 scourhole, and flow is generally well dispersed as it leaves the basin.

3. The mound of material formed on the bed downstream of the scourhole contributes to the dissipation of energy and reduces the size of the scourhole; that is, if the mound from a stable scoured basin is removed and the basin is again subjected to design flow, the scourhole will enlarge.

4. 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 scourhole is much shallower and generally longer. Consequently, riprap may be required for the channel downstream of the rock-lined basin.

5. 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.

6.   See Standards in the in HEC No. 11 for details on riprap materials and use of filter fabric.

7.   Stability of the surface at the outlet of a basin should be considered using the methods for open channel flow as outlined in the Open Channel Hydraulics Chapter of this manual.

7.5.5 Example Designs

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

Example No. 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 1-5 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 = Fr = $V/(g \times y_e)^{0.5}$ (g = 32.3 ft/s^2)
        Fr = $25/(32.2 \times 4)^{0.5}$ = 2.20 < 2.5 O.K.

4. $TW/y_e = 2.8/4.0 = 0.7$ Therefore $TW/y_e < 0.75$ O.K.

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, $2 < h_s/d_{50} < 4$ O.K.

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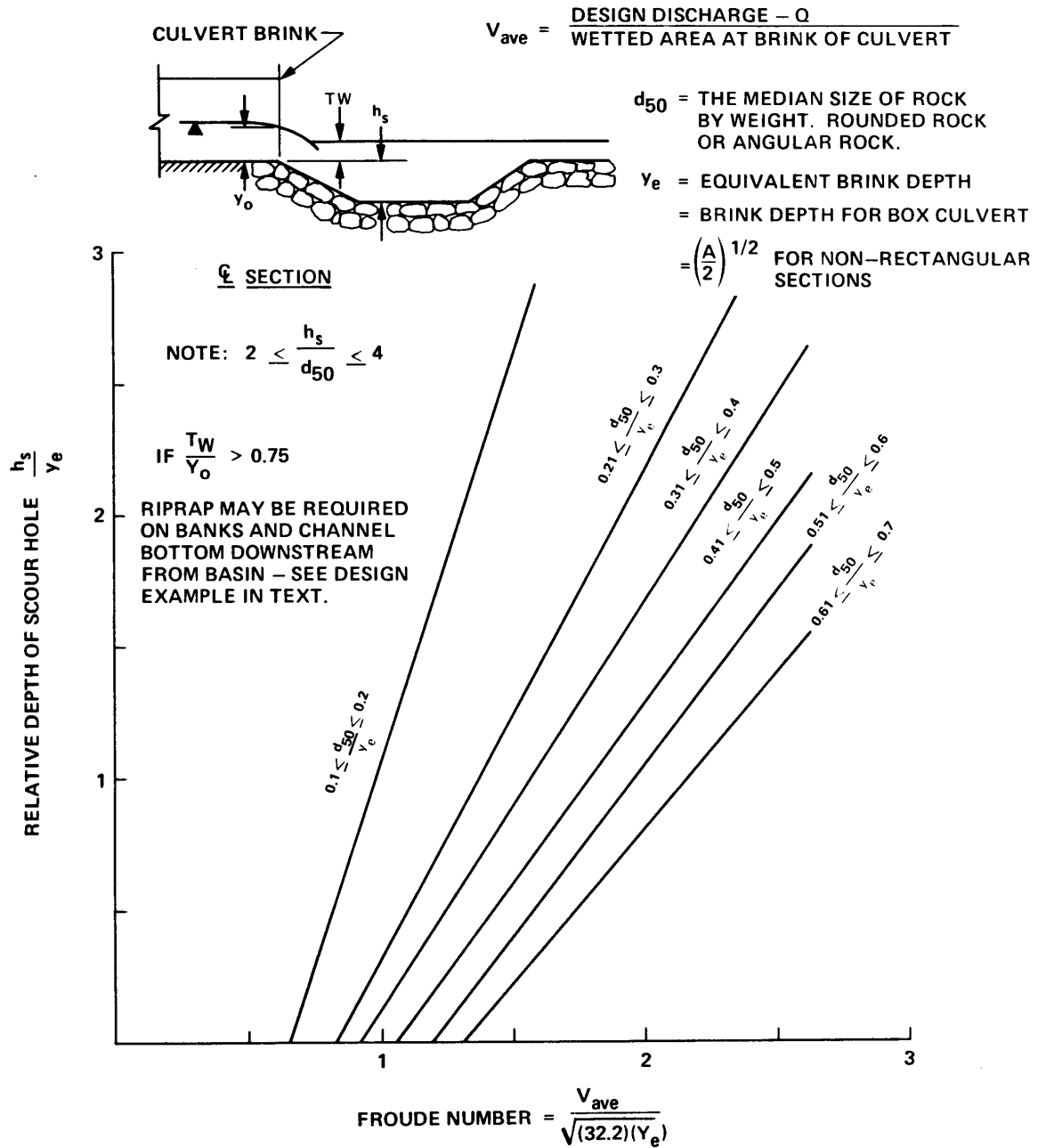
Figure 7-8 **Relative Depth of Scour Hole Versus Froude Number at Brink of Culvert with Relative Size of Riprap as a Third Variable**

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

The chart shows velocity distribution with axes:

Y-axis: $\dfrac{(V_L)_{AVE}}{V_{AVE}}$ (from 0.1 to 1.0)

$(V_L)_{AVE}$ = Average Velocities L Feet Downstream from Brink

V_{AVE} = Average Velocity at Outlet

Rectangular Orifice into an Infinite Basin

Circular Orifice into an Infinite Basin

Design Curve

V_{AVE}

T_W

Sym	W_o ft	Q cfs	fps	ft
□	1.45	22.5	15.1	1.6
□	1.45	14.6	10.3	1.6
○	3.07	65.4	9.3	3.07
○	3.07	84.0	11.9	3.07
▽	1.45	20.9	14.0	1.25
▽	1.45	13.9	9.3	1.25

NOTE: For partially full circular sections or non circular brink areas, convert wetted cross sectional areas to an equivalent circular area with diameter W.

X-axis: $\dfrac{L}{W_o} = \dfrac{\text{Distance Downstream from Plane of the Outlet}}{\text{Equivalent Circular Diameter}}$

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)

Example No. 2

Given: Same design data as example problem number 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.   Use the riprap basin designed in example 1 with: $d_{50} = 1.8$ ft, $h_s = 6.4$ ft, $L_s = 64$ ft, $L_B = 96$ ft.

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

       $A = 3.14 D_e^2/4 = y_o$ x $W_o = 4$ x $8 = 32$ ft^2
       $D_e = ((32$ x $4)/3.14)^{0.5} = 6.4$ ft
       $V_o = 25$ ft/s (From Example 1)

3.   Set up the following table:

				Rock Size
L/D_e	L	V_1/V_o	v_1	d_{50} (ft)
(Assume)	(Compute)	(Fig. 7-9)	ft/sec	(Fig. 7-1)
($D_e = W_o$)	ft			
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/W_o is on a logarithmic scale so interpolations must be 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 No. 3

Given: 6 ft diameter CMP
        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 7-7, $y_o/D = 0.45$
$Q/D^{2.5} = 135/6^{2.5} = 1.53$
$TW/D = 2.0/6 = 0.33$
$y_o = .45 \times 6 = 2.7$ 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 Culvert Chapter)
For $y_o/D = d/D = 0.45$
$A/D^2 = 0.3428$, therefore $A = 0.3428 \times 6^2 = 12.3$ ft^2
$V_o = Q/A = 135/12.3 = 11.0$ 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 = $Fr = V_o/(32.2 \times y_e)^{1/2} = 11/(32.2 \times 2.48)^{1/2} = 1.23 < 2.5$ O.K.

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 7-8, $h_s/y_e = 0.75$, therefore $h_s = 0.75 \times 2.48 = 1.86$ ft

      Uniform Flow in Circular Sections Flowing Partly Full (From Culvert Chapter)

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

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.

When using the design procedure outlined in this chapter, 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 $3 \times d_{50}$ thickness of riprap on the approach and the $2 \times d_{50}$ thickness
of riprap on the basin floor and the apron in the downstream portion of the basin, the damage
should be superficial.

7.6 Baffled Outlets

7.6.1 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 ft 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:

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, in cfs
v = Theoretical velocity, in ft/s = $2gh$
$A = Q/v$ = Flow area, in square ft
$d = A^{0.5}$ = Representative flow depth entering the basin, in ft (assumes square jet)
$Fr = v/(gd)^{0.5}$ = Froude number, dimensionless

2.   Calculate the minimum basin width, W, in ft, using the following equation, which is shown graphically in Figure 7-12:

$$W/d = 2.88Fr^{0.566} \text{ or } W = 2.88dFr^{0.566} \qquad\qquad (7.2)$$

Where: W = minimum basin width, in ft
         d = depth of incoming flow, in 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.

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).

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.

Figure 7-10 Riprap Basins

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

PLAN

$L = \frac{4}{3}(W)$

$f = \frac{1}{6}(W)$

$e = \frac{1}{12}(W)$

SEC. A-A

SECTION

Protection as required

5' Min.

Fillet

$H = \frac{3}{4}(W)$

$a = \frac{1}{2}(W)$

$b = \frac{3}{8}(W)$

$c = \frac{1}{2}(W)$

Rock diameter for protection $= \frac{1}{20}(W)$

Figure 7-11   Schematic of Baffled Outlet

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.

6. Calculate the outlet pipe diameter entering the basin assuming a velocity of 12 ft per second flowing full.

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.

8. If it is possible that both the upstream and downstream ends of the pipe will be submerged, provide an air vent of diameter 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
$v = (2gh)^{0.5} = [2(32.2 \text{ ft/sec}^2)(15 \text{ ft})]^{0.5} = 31.1 \text{ ft/s}$
This is less than 50 ft/s, so a baffled outlet is suitable.

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

3. Compute the flow depth using the area from Step 2.
$d = (A)^{0.5} = (4.8 \text{ ft}^2)^{0.5} = 2.12 \text{ ft}$

4. Compute the Froude number using the results from Steps 1 and 3.
$Fr = v/(gd)^{0.5} = 31.1 \text{ ft/sec}/[(32.2 \text{ ft/sec}^2)(2.12 \text{ ft})]^{0.5} = 3.8$

5. Determine the basin width using equation 7.3 with the Froude number from Step 4.
$W = 2.88 \text{ dFr}^{0.566} = 2.88 (2.12) (3.8)^{0.566} = 13.0 \text{ ft}$ (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 foot, 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 = 4.63 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.
      $(3.14d)^2/4 = Q/v$; $d = [(4Q)/3.14v)]^{0.5} = [(4(150\ cfs)/3.14(12\ ft/sec)]^{0.5} = 3.99$ ft
      Use 48-inch pipe. If a vent is required, it should be about 1/6 of the pipe diameter or 8 in.

References

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Searcy, James K. 1967. Use of Riprap for Bank Protection. Federal Highway Administration. Washington, D. C.

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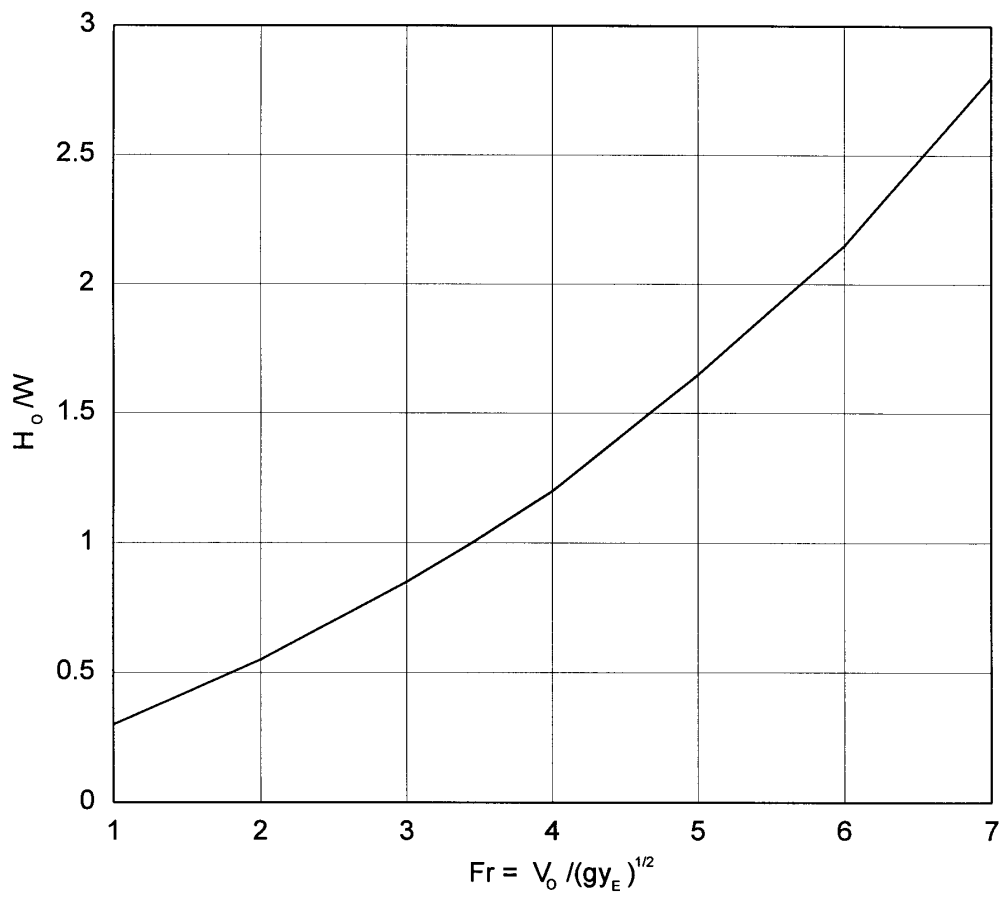
Figure 7-12 W/d vs. Froude Number for Baffled Outlet Basins
Source: U.S. Department of the Interior (1978)