Chapter 6 ENERGY DISSIPATOR

6.1 INTRODUCTION

The failure or damage of many culverts and detention basin outlet structures can be traced to unchecked erosion. Erosive forces which are at work in the natural drainage network are often exacerbated by the construction of a highway or by other urban development. Interception and concentration of overland flow and constriction of natural waterways may result in increased erosion potential. To protect the culvert and adjacent areas, it is sometimes necessary to employ an energy dissipator.

Throughout the selection and design process, the designer should keep in mind that the primary objective is to protect the highway structure and adjacent area from excessive damage due to erosion. One way to help accomplish this objective is to return the flow to the downstream channel in a condition which approximates the natural flow regime. This also implies guarding against over design or employing dissipation devices which reduce flow conditions substantially below the natural or normal channel conditions.

This chapter provides design procedures which are based on FHWA Hydraulic Engineering Circular Number 14 (HEC-14) *Hydraulic Design of Energy Dissipators for Culverts and Channels*, September 1983, revised in 1995.

6.1.1 Definition

An energy dissipator is any device designed to protect downstream areas from erosion by reducing the velocity of flow to acceptable limits. In this chapter, the terms internal and external are used to indicate the location of the dissipator in relationship to the culvert. An external dissipator is located outside of the culvert and an internal dissipator is located within the culvert barrel.

6.1.2 Concept Definitions

Brink Depth	Depth of flow at the outlet of a pipe.
Equivalent Depth (d_E)	Equivalent depth is an artificial depth which is calculated for culverts which are not rectangular so that a reasonable Fr can be determined.
External Dissipator	An external dissipator is located outside of the culvert.
Froude Number (Fr)	The Froude number is a flow parameter.
Internal Dissipator	An internal dissipator is located within the culvert barrel.
Mean Riprap Diameter (d_{50})	Average rock diameter of armament material. The d_{50} is frequently used to specify the size of the rock.

6.2 DESIGN CRITERIA

Following sections include criteria for application of various energy dissipators. Detailed information is provided for the most widely used energy dissipators in later sections. Additional information on energy dissipators including procedures and sample calculations are provided in HEC-14 (FHWA, 1995).

6.2.1 Natural Scour Holes

Erosion occurring at the end downstream end of a hydraulic structure will sometimes form a natural scour hole which will dissipate energy and reduce velocity. Design procedures and equations are available for both cohesive and cohesionless materials. Investigations indicate that the scour hole geometry varies with tailwater conditions with the maximum scour geometry occurring at tailwater depths less than half the culvert height and that the maximum depth of scour (h_s) occurs at a location approximately 0.4 L_s downstream of the culvert outlet where L_s is the length of scour.

Natural scour holes may be considered where:

- undermining of the culvert outlet will not occur or it is practicable to be checked by a cutoff wall,
- the expected scour hole will not cause costly property damage, and
- there is no nuisance effect.

See HEC-14 (FHWA, 1995) for further information on natural scour holes.

6.2.2 Riprap Apron

For major culverts riprap must be designed individually for each site. For minor culverts (equivalent diameter ≤ 48"), the riprap apron detailed in Standard Plates 3133 and 3134 will generally be adequate. For outlet velocities less than or equal to 6 fps, check shear stress to determine if vegetation will be adequate. If vegetation is used consider temporary erosion control during and immediately following construction until vegetation becomes established. Use the following guidelines:

Outlet Velocity, V_o	Riprap Specifications	Filter Specifications
$0 < V_o \leq 6$ fps	Riprap or stable vegetation	
$6 < V_o \leq 8$ fps	12" Class II riprap	6" granular or geotextile filter
$8 < V_o \leq 10$ fps	18" Class III riprap	9" granular or geotextile filter
$10 < V_o \leq 12$ fps	24" Class IV riprap	12" granular or geotextile filter

6.2.3 Internal Ring Dissipator

There are two types of internal ring dissipator available. Internal ring dissipator are used where:

- the culvert shape is round,
- a scour hole at the culvert outlet is unacceptable,
- the right-of way is limited,
- debris is not a problem, and
- riprap apron is not adequate.

See Section 6.4 for design procedures for the use of internal ring dissipators.

<u>Increased Resistance</u>

This type utilizes roughness elements to increase resistance inside the pipe near the culvert outlet. See Standard Plate 5010 for detail of elements.

- Use for slopes less than 4%.
- Use for culvert flowing partially full with inlet control.
- Can force full flow near the culvert outlet without creating additional headwater.
- Five roughness rings at culvert outlet are necessary.
- Diameter of outlet may be the same or larger than the diameter of the culvert.

<u>Tumbling Flow</u>

This type utilizes the same rings as the above dissipator but can handle higher velocities.

- Use with slopes greater than 4% but less than 25%.
- Five roughness rings at culvert outlet are necessary.
- The diameter of pipe where rings are located is larger than diameter of culvert.
- Standard reinforced concrete pipe (RCP) increasers are recommended to increase pipe size.
- Outlet velocity is approximately critical velocity.

6.2.4 Increased Resistance Box Culverts

The primary method to increase resistance in box culverts has been to place roughness elements on the flowline of the box culvert. The spacing and height of the elements are variable. They can be used independently or in conjunction with a drop weir placed at the inlet to reduce the slope of the culvert. The methodology presented in HEC-14 (FHWA, 1995) is sufficiently broad to allow the roughness elements to be placed on the bottom only or to extend up the side and across the top. The result would be a design similar to the ring dissipator for round pipes.

- Slope should not exceed 6 %.
- Roughness elements should be sharp edge with the element height (h) not exceeding 10% of the flow depth.
- Using element spacing (L) of 10 times element height (h) maximizes the Manning's n value. (L/h) = 10
- The first element, h_1, should be 2 times the height of other elements.
- The minimum number of rows is 5.
- A gap of 2 ± inches in the center of the element is recommended to assist the passing of sediment.

See HEC-14 (FHWA, 1995) for further information regarding increased resistance box culverts.

6.2.5 Riprap Basins

Riprap basins are preformed scour holes that are lined with riprap. The design is based on a study sponsored by the Wyoming Highway Department and conducted by Colorado State University. Consideration may be given to utilizing articulated concrete as an alternate to riprap if conditions are appropriate. Manufacturers recommendations should be consulted when comparing the size of articulated concrete to a riprap d_{50}.

- The basin is preshaped and lined with riprap.
- The depth (h_s), length (L_s), and width (W_s) of the scour hole are related to the characteristic size of riprap (d_{50}), discharge (Q), brink depth (y_o), and tailwater depth (TW).
- When (TW/y_o) is less than 0.75 and h_s/d_{50} is greater than 2.0, the scour hole operates very efficiently as an energy dissipator.
- When TW/y_o is greater than 0.75, the scour hole is shallower and longer, thus riprap may be required at the channel downstream of the rock lined basin.

See Section 6.5 for design procedures on the use of riprap basins.

6.2.6 Impact Dissipator

The use of the impact type energy dissipator (USBR Type VI) has largely been replaced by the use of the internal ring dissipator at Mn/DOT. However, use of the impact dissipator can be considered for severe conditions with discharges up to 400 cfs and outlet velocities up to 50 ft/sec.

- An impact basin has greater capacity for dissipating energy than the natural hydraulic jump.
- Tailwater is not necessary, but a moderate depth will improve performance.
- Riprap should be placed downstream of the basin for a length of at least four conduit widths.
- This dissipator is not recommended at locations where debris or ice buildup may cause substantial clogging.

See HEC-14 (FHWA, 1995) for further information on impact dissipators.

6.2.7 Stilling Basins

St. Anthony Falls (SAF) Basin and USBR Type II, III, and IV stilling basin types are presented in HEC-14 (FHWA, 1995). Stilling Basins are used where:

- the outlet scour hole is not acceptable,
- debris is present, and
- the culvert outlet velocity (V_o) is high, Fr > 3.

See HEC-14 (FHWA, 1995) for further information regarding stilling basins.

6.3 ENERGY DISSIPATOR ANALYSIS

An exact theoretical analysis of flow at culvert outlets is extremely complex and generally not attempted because the following data would be required:

- analyzing non-uniform and rapidly varying flow,
- applying energy and momentum balance,
- determining where a hydraulic jump will occur,
- applying the results of hydraulic model studies, and
- consideration of temporary upstream storage effects.

The design procedures presented in this Chapter are based on model studies that were done to calibrate the equations and charts for scour hole estimating and energy dissipator design. HEC-14 (FHWA, 1995) is the base reference and contains full explanation of all the equations and procedures used in this Chapter.

6.3.1 Design Parameters

The dissipator type selected for a site must be appropriate to the location. Selection of dissipator type is made in accordance with the criteria for each dissipator as detailed in Section 6.2. In order to determine the type of energy dissipator which is the most appropriate for a given site, some design information is necessary. Much of this information should already be available from the culvert design. The following information will be necessary.

Flood Frequency

The flood frequency used in the design of the energy dissipator device should be the same flood frequency as the culvert design. In general, this will be:

- 50 year discharge rate (Q_{50}) for minor culverts
- the lesser of overtopping discharge rate (Q_{OT}) or 100 year discharge rate (Q_{100}) for major culverts.

Tailwater Depth

The hydraulic conditions downstream should be evaluated to determine a tailwater depth and the maximum velocity for a range of discharges. For calculating maximum outlet velocity, a low tailwater is usually the most critical whereas for calculating the HW elevation, a high tailwater may be the most critical.

- Open channels - Use methods provided in the Channel Chapter.
- Pond or small body of water - Since the water surface will be rising during the runoff event, it's conservative to assume low tailwater, which will maximize the outlet velocity.
- Lake or large body of water - Use normal or controlled lake level elevation.
- A joint probability analysis comparing drainage areas of the culvert and the receiving water may be desirable in some cases. See the discussion on joint probabilities analysis in the Storm Drain Chapter.

Outlet Velocity

It is necessary to calculate the culvert outlet velocity in order to determine the need for erosion protection at the culvert exit. The flow depth and Froude number may also be required if erosion protection is needed. For a discussion on how to compute outlet velocities for inlet and outlet control, see the Culvert Chapter.

6.3.2 Culvert Outlet Conditions

The outlet flow conditions are established during the culvert design. These parameters may require a closer analysis for energy dissipator design.

Outlet Depth (d_o)

For culverts with supercritical flow, normal depth at the outlet is appropriate unless culvert length (L) < 50 d_o, then a water surface profile should be calculated. For culverts with subcritical flow, the brink depth should be used instead of critical depth at locations with low tailwater. Figures 6.8 and 6.9 are curves for determining outlet depth for subcritical flow conditions.

Area (A_o)

The cross sectional area of flow at the culvert outlet should be calculated based on (d_o).

Outlet Velocity (V_o)
The culvert outlet velocity should be calculated as follows:

$$V_o = \frac{Q}{A_o} \tag{6.1}$$

Where: Q = discharge (cfs)
A_o = area of flow at the outlet (ft^2)

Equivalent Depth (d_E)
Equivalent depth is an artificial depth which is calculated for culverts which are not rectangular so that a reasonable Fr can be determined.

$$d_E = \left(\frac{A_o}{2}\right)^{0.5} \tag{6.2}$$

Where: A_o = area of flow at the outlet (ft^2)

Froude Number (Fr)
The Froude number is a flow parameter that has traditionally been used to design energy dissipators and is calculated using:

$$Fr = \frac{V_o}{(gd_o)^{0.5}} \tag{6.3}$$

Where: g = acceleration due to gravity (32.2 ft/s^2)
d_o = d_E for rectangular shape (ft)

6.3.3 Erosion Assessment

In determining whether energy dissipation is necessary, it may be helpful to estimate the potential erosion at a culvert outlet. An assessment could then be made to determine if the scour hole is acceptable. Estimating scour at culvert outlets is difficult because of the many complex factors affecting erosion. These factors include discharge, culvert size and shape, soil type, duration of flow, culvert height above the bed, culvert slope, tailwater depth and vegetative cover. In addition, the magnitude of the total erosion can consist of local scour and/or channel degradation. Maintenance history, site reconnaissance, and data on soils, flows, and flow duration provide the best estimate of the potential erosion hazard at a culvert outlet. Analytical methods to estimate erosion at culvert outlets in both cohesive and non-cohesive soils are available in HEC-14 (FHWA, 1995).

6.4 INTERNAL RING DISSIPATORS

There are two types of design for ring dissipators which can be used to reduce the velocity in round reinforced concrete pipe. The first is the increased resistance type and the second is the tumbling flow type. Basic information and a design procedure will be given for each type. The derivation of the methodology can be found in HEC-14 (FHWA, 1995).

6.4.1 Increased Resistance Round Pipes

The methodology described in this section involves using roughness elements to increase resistance and induce velocity reductions. Increasing resistance may cause a culvert to change from partial flow to full flow in the roughened zone. Velocity reduction is accomplished by increasing the wetted surfaces as well as by increasing drag and turbulence by the use of roughness elements. The details shown on Standard Plate No. 5010 can be used to provide the resistance on 24" to 84" diameter pipes.

If the requirement is for outlet velocities between critical and normal velocity, designing increased resistance into the barrel is a viable alternative. The most obvious situation for application of increased barrel resistance is a culvert flowing partially full with inlet control. The objective is to force full flow near the culvert outlet without creating additional headwater.

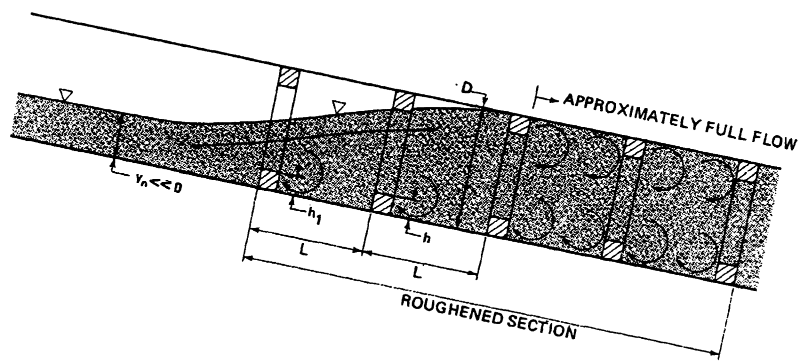


Figure 6.1 Conceptual Sketch of Roughness Elements to Increase Resistance Source: HEC-14 (FHWA, 1983)

The following criteria should be followed:

- Use on culverts with slopes less than 4% operating under inlet control.
- Use five rows of roughness elements.
- The height of each element should be 5% to 10% of the diameter.
- The diameter of the outlet may be the same or larger than the diameter of the culvert.
- Doubling the height of the first ring (Type 2 Table on Standard Plate No. 5010) is effective in triggering full flow in the roughened zone.

Studies of pertinent rough pipe flow data (Morris, 1963) have concluded that there are three flow regimes and each has a different resistance relationship. The three regimes are quasi-smooth flow, hyperturbulent flow, and isolated roughness flow. Quasi-smooth flow occurs only when roughness elements are spaced very close ($L/h \leq 2$) and is not important for this discussion. Hyperturbulent flow occurs when roughness elements are sufficiently close so each element is in the wake of the previous element and rough surface vortices are the primary source of the overall friction drag. Isolated roughness flow occurs when roughness spacing is large and overall resistance is due to drag on the culvert surface plus form drag on the roughness elements. Equations to solve for Manning's n for the two flow regimes are as follows:

Isolated Roughness Flow

$$n_{IR} = n\left(\frac{D_i}{D}\right)^{1/6}\left[1 + 67.2C_D\left(\frac{L_r}{P}\right)\left(\frac{h}{L}\right)\right]^{1/2} \qquad (6.4)$$

Where:
- n_{IR} = overall Manning's n for isolated roughness flow
- n = Manning's n for the culvert surface without roughness rings
- D = nominal diameter of culvert (ft)
- h = height of roughness rings (ft)
- D_i = inside diameter of roughness rings (ft) = D - 2h
- C_D = drag coefficient, which has a constant value of 1.9 for sharp edge rectangular roughness shapes
- L = spacing between roughness elements (ft)
- L_r/P = ratio of total peripheral length of roughness elements to total wetted perimeter

Hyperturbulent Flow

$$n_{HT} = \frac{0.0736 D_i^{1/6}}{\left(1.75 - 2\log_{10}\frac{L}{r_i}\right)} \quad (6.5)$$

Where: n_{HT} = Manning's n for hyperturbulent flow
h = height of roughness rings (ft)
D_i = inside diameter of roughness rings (ft) = D - 2h
L = spacing between roughness elements (ft)
r_i = pipe radius based on inside diameter of roughness rings (ft)

Step 1 Compute $n/D^{1/6}$, where "n" is Manning's coefficient for smooth culvert and D is the diameter in feet.

Step 2 Select L/D_i in the range 0.5 to 1.5. Try to use standard laying length of pipe for L and Standard Plate 5010 for D_i which is the inside diameter of the ring. This will not be possible for minor culverts as the L will be less than the normal laying length. Special design laying lengths will be necessary.
Compute inside ring diameter, D_i = D - 2h

Step 3 Select h/D_i in the range 0.05 to 0.10. Use sharp edged roughness rings.

Step 4 Determine the flow regime from Figure 6.5. The flow regime will be "isolated roughness" (I.R.), if the point defined by the L/D_i and h_i/D_i ratios is above the $n/D^{1/6}$ value. If the point is below, the flow is "hyperturbulent" (H.T.). Isolated roughness is the most common for large culverts.

Step 5 Determine the rough pipe resistance ($n_r = n_{IR}$ or n_{HT})
A. For isolated roughness flow obtain (n_{IR}/n) from Figure 6.6 or from Equation 6.4.
If gaps are to be left in the roughness rings so that L_r/P is much less than 1.0, Equation 6.4 must be used because Figure 6.6 is based on L_r/P = 1.0.
B. For hyperturbulent flow obtain $n_r = n_{HT}$ from Figure 6.2 or from Equation 6.5.

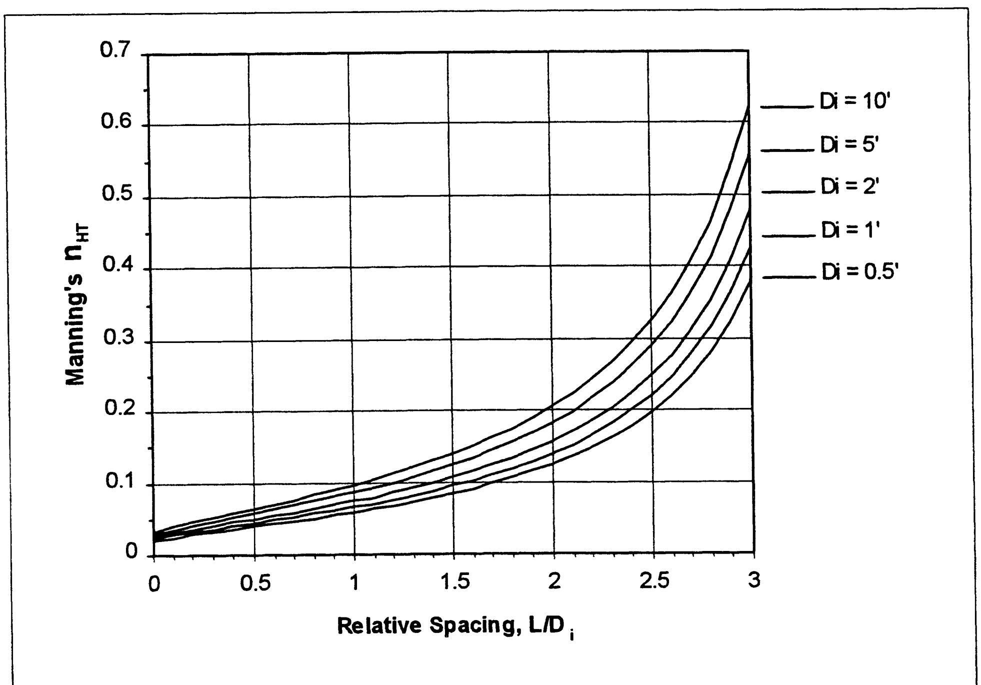


Figure 6.2 Resistance Curves for Hyperturbulent Flow

Step 6 Compute full flow characteristics based on D and n:

$$Q_{FULL} = \left(\frac{0.46}{n_r}\right) D_i^{8/3} S_o^{1/2} \qquad V_{FULL} = \left(\frac{0.59}{n_r}\right) D_i^{2/3} S_o^{1/2} \qquad (6.6)$$

Where: Q = discharge (cfs)
V = velocity (fps)
n_r = rough pipe resistance
D_i = inside diameter of roughness rings (ft)
S_o = slope of pipe (ft/ft)

Step 7 Determine outlet velocities:

A. If Q_{FULL} = Design Q,
$V_{OUTLET} = V_{FULL}$

B. If Q_{FULL} is less than Design Q, the culvert is likely to flow full and result in increased headwater requirements. In this case, a complete hydraulic analysis of the culvert is necessary to compute the outlet velocity which will be greater than V_{FULL} from Step 6. To avoid this situation, use an oversize diameter, D and D_i, for the roughened section of the culvert and repeat steps 1 through 6 above.

C. If Q_{FULL} is greater than Design Q, use Figure 6.4 to compute the velocity.

Step 8 Evaluate acceptability of outlet velocity and repeat design steps if necessary. Acceptable outlet velocity is a site determination that must be made by the designer. It is anticipated that the use of roughness rings may not eliminate the need for riprap but complement or minimize the use of riprap protection. If the outlet velocity is not acceptable, the recommended order of consideration is:

A. If Q_{DESIGN} is less than Q_{FULL}, increase h/D_i to approach full flow. A solution can usually be attained with one iteration by approximating the resistance from $n = [0.59D_i^{2\backslash 3}\ S_o^{1/2}]/V_{DESIRED}/1.15$ and using an estimated value of D_i slightly greater than expected. With n_r known, selecting a corresponding h/D_i from Figure 6.2 or Figure 6.6 is relatively straightforward.

B. If V_{FULL} is still too high, increase D for the roughened section to make possible higher values of h/D_i and correspondingly higher values of n_r; i.e., use an oversized culvert with diameter, D, to allow for the new D_i, in the rough section and repeat Steps 1 through 7 above.

C. Use a tumbling flow design as described in Section 6.4.2.

D. Use another type of dissipator either in lieu of or in addition to the roughness rings.

Step 9 Determine the size and spacing of roughness rings.

A. Prepare summary of the parameters.

Where: $D_i = D - 2h$ inside diameter of roughness rings (ft)
$h = (h/D_i)D_i$ height of roughness rings (ft)
$L = (L/D_i)D_i$ spacing between roughness elements (ft)
$h_1 = 2h$ height of first roughness ring (ft)
$D = D_i + 2h$ nominal diameter of culvert barrel (ft)

B. Use five roughness rings including the oversized first ring. If an oversized diameter is used, provide an approach length of one diameter before the first ring.

6.4.2 Tumbling Flow Circular Pipes

Tumbling flow in circular culverts can be attained by inserting circular rings inside the barrel, Figure 6.3. This concept is very similar to the Increased Resistance concept described previously; the primary difference being that it can be used for culverts on slopes between 4% and 25%. The variables that determine whether or not tumbling flow will occur are roughness height (h), spacing (L), slope (S_o), discharge (Q), and the diameter (D_1). Practical design limits can be assigned to h/D_1 and L/D_1 to further simplify the functional relationship. Based on qualitative laboratory observations, tumbling flow is easiest to maintain when:

- L/D_1 is between 1.5 and 2.5 — $L/D_1 \approx 2.0$ (Tolerance ± 25%)
- h/D_1 is between 0.10 and 0.15 — $h/D_1 \approx 0.125$ (Tolerance ± 20%)
- slope is between 4% and 25% — $4\% < S_o < 25\%$

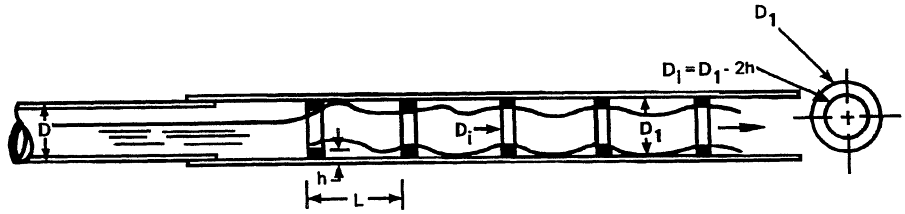


Figure 6.3 Definition Sketch For Tumbling Flow in Culverts
Source: HEC-14 (FHWA, 1983)

The basic design relationship for tumbling flow in steep circular culverts is:

$$0.21 < \frac{Q}{\left(gD_1^5\right)^{1/2}} < 0.32 \qquad \text{and} \qquad 1.6\left(\frac{Q^2}{g}\right)^{0.2} < D_1 < 1.9\left(\frac{Q^2}{g}\right)^{0.2} \qquad (6.7)$$

Where: Q = discharge (cfs)
g = acceleration due to gravity (32.2 ft/sec^2)
D_1 = pipe diameter (ft)

Five roughness rings (Standard Plate No. 5010) at the outlet end of the culvert are sufficient to establish tumbling flow. The diameter computed from Equation 6.7 is for the roughened section only, and will not necessarily be the same as the rest of the culvert. If a larger diameter is necessary for the roughened section, precast increasers may be used to transition from the culvert diameter to the larger roughened diameter. A length of at least one diameter of the larger pipe should be placed upstream of the first ring.

The outlet velocity for tumbling flow is approximately critical velocity. It can be computed by determining the critical depth (d_c) for the inside diameter of the roughness rings. Chart 4 in Appendix C can be used to determine critical depth using D_i. Figure 6.4 can be used to determine the critical area (A_c). Outlet velocity can be computed from Equation 6.1, substituting V_c for V_o and A_c for A_o.

Step 1 Check culvert control. If inlet control governs, tumbling flow may be a good choice for dissipating energy.

Step 2 Determine the diameter (D_1), of the roughened section of pipe to sustain tumbling flow using Equation 6.7.

Step 3 Compute h and L from:
$h/D_1 = 0.125 \pm 20\%$
$L/D_1 = 2.0 \pm 25\%$

Step 4 Compute the internal diameter of the roughness rings
$D_i = D_1 - 2h$

Step 5 Determine the critical depth (y_c), from Chart 4 in Appendix C using design discharge for Q and D_i for diameter.

Step 6 Compute y_c/D_i

Step 7 Determine A_c from Table 6.1. Setting $d = y_c$ and $A = A_c$, use the known (d/D) to determine (A/D^2).

Step 8 Compute the outlet velocity
$V_o \approx V_c = Q/A_c$

Step 9 Evaluate acceptability of outlet velocity, and document results.

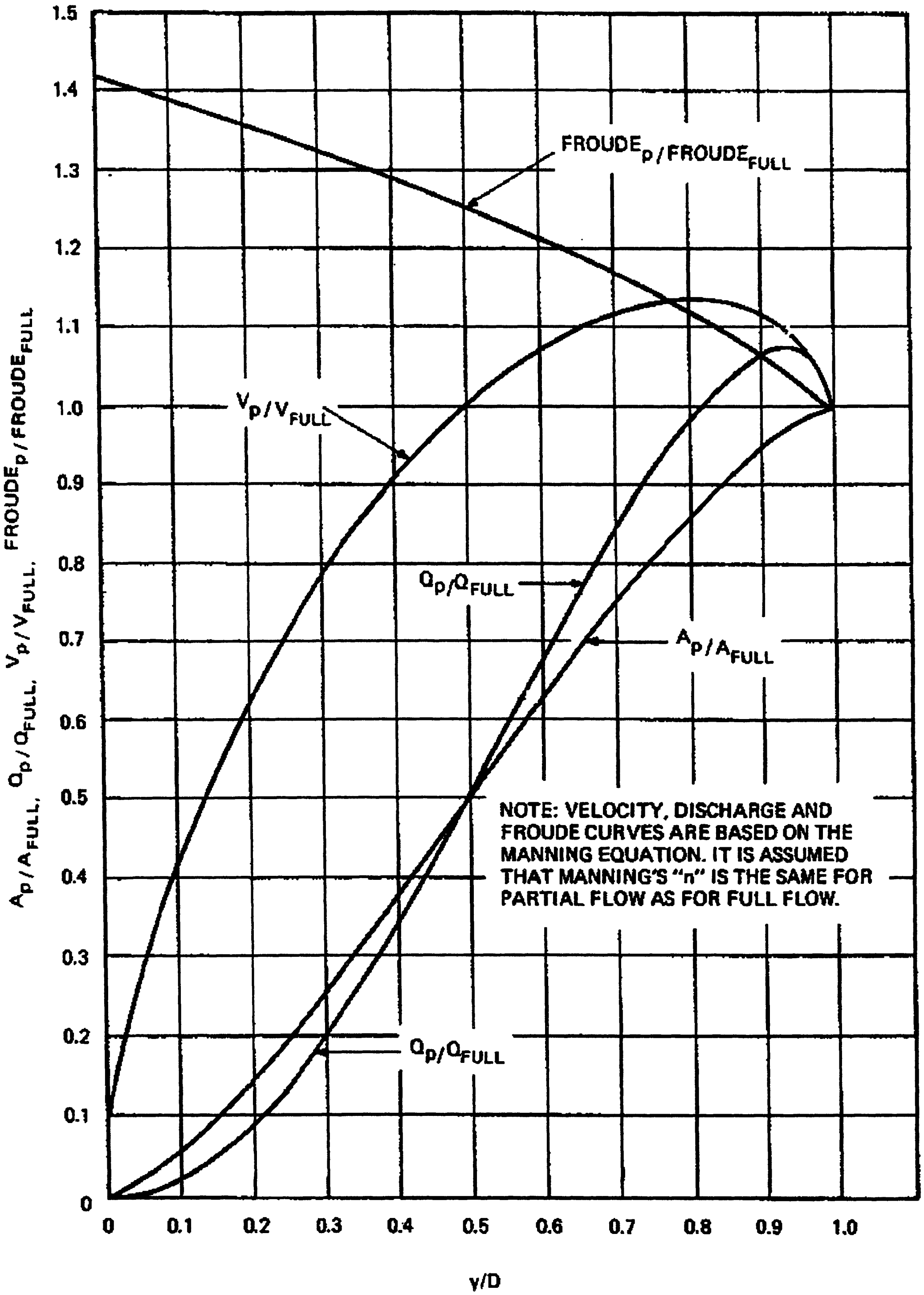


Figure 6.4 Hydraulic Elements Diagram for Circular Culverts Flowing Part Full
Source: HEC-14, Figure VII-C-3 (FHWA, 1983)

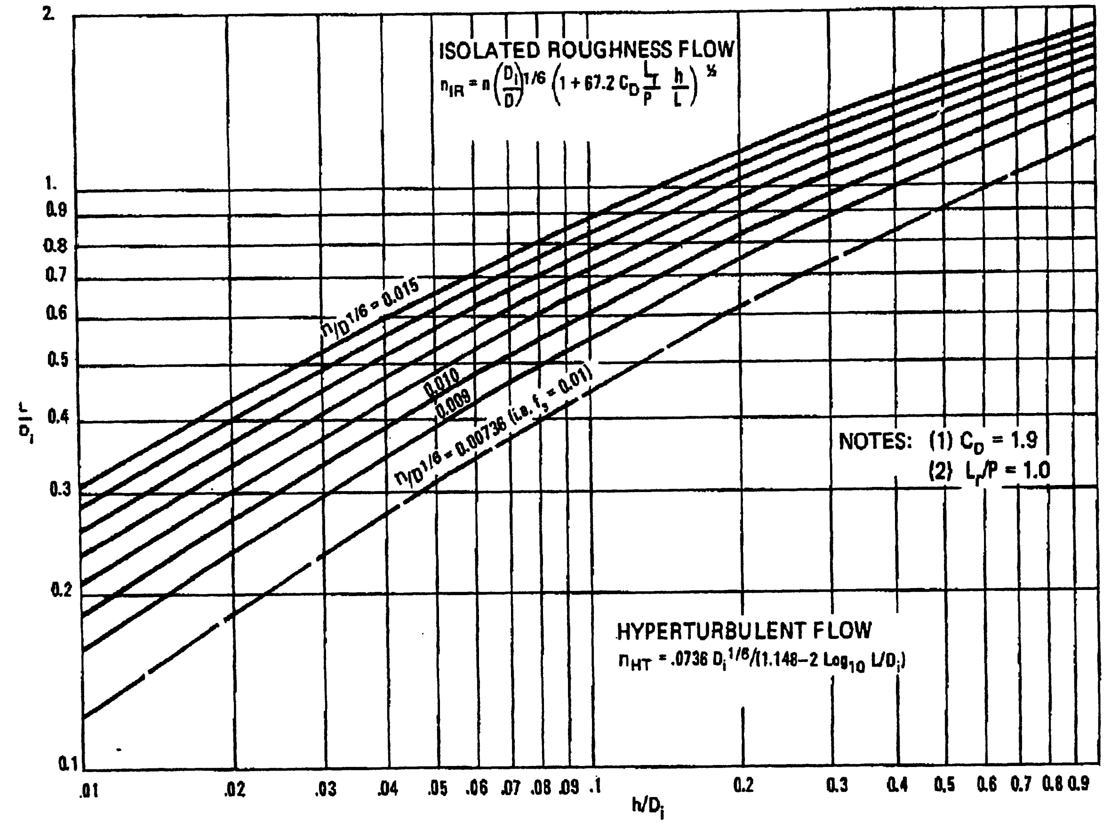


Figure 6.5 Flow Regime Boundary Curves
Source: HEC-14, Figure VII-C-6 (FHWA, 1983)

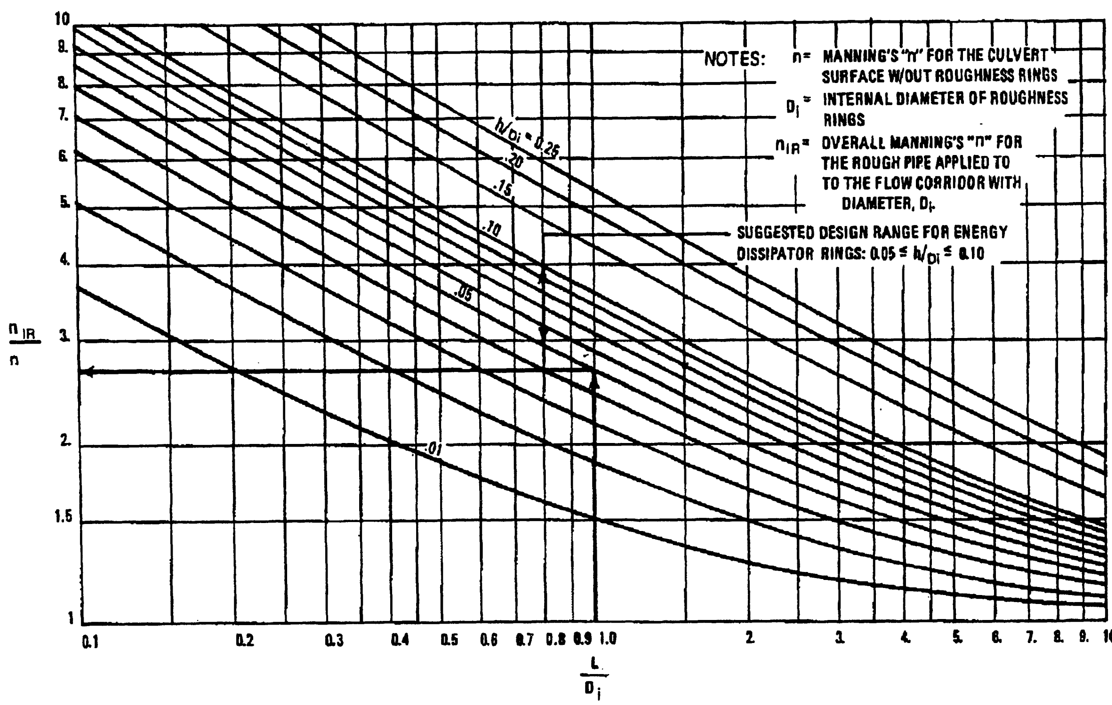


Figure 6.6 Relative Resistance Curves for Isolated Roughness Flow
Source: HEC-14, Figure VII-C-4 (FHWA, 1983)

Table 6.1 Uniform Flow in Circular Sections Flowing Partly Full

$\frac{d}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{Q_N}{D^{8/3}S^{1/2}}$	$\frac{Q_N}{d^{8/3}S^{1/2}}$	$\frac{d}{D}$	$\frac{A}{D^2}$	$\frac{R}{D}$	$\frac{Q_N}{D^{8/3}S^{1/2}}$	$\frac{Q_N}{d^{8/3}S^{1/2}}$
0.01	0.0013	0.0066	0.00007	15.04	0.51	0.4027	0.2531	0.239	1.442
0.02	0.0037	0.0132	0.00031	10.57	0.52	0.4127	0.2562	0.247	1.415
0.03	0.0069	0.0197	0.00074	8.56	0.53	0.4227	0.2592	0.255	1.388
0.04	0.0105	0.0262	0.00138	7.38	0.54	0.4327	0.2621	0.263	1.362
0.05	0.0147	0.0325	0.00222	6.55	0.55	0.4426	0.2649	0.271	1.336
.0.06	0.0192	0.0389	0.00328	5.95	0.56	0.4586	0.2676	0.279	1.311
.0.07	0.0242	0.0451	0.00455	5.47	0.57	0.4625	0.2703	0.287	1.286
0.08	0.0294	0.0513	0.00604	5.09	0.58	0.4724	0.2728	0.295	1.262
0.09	0.0350	0.0575	0.00775	4.79	0.59	0.4822	0.2753	0.303	1.238
0.10	0.0409	0.0635	0.00967	4.49	0.60	0.4920	0.2776	0.311	1.215
0.11	0.0470	0.0695	0.01181	4.25	0.61	0.5018	0.2799	0.319	1.192
0.12	0.0534	0.0755	0.01417	4.04	0.62	0.5115	0.2821	0.327	1.170
0.13	0.0600	0.0813	0.01674	3.86	0.63	0.5212	0.2842	0.335	1.148
0.14	0.0668	0.0871	0.01952	3.69	0.64	0.5308	0.2862	0.343	1.126
0.15	0.0739	0.0929	0.0929	3.54	0.65	0.5404	0.2882	0.350	1.105
0.16	0.0811	0.0985	0.0985	3.41	0.66	0.5499	0.2900	0.358	1.084
0.17	0.0885	0.1042	0.1024	3.28	0.67	0.5594	0.2917	0.366	1.064
0.18	0.0961	0.1097	0.1097	3.17	0.68	0.5687	0.2933	0.373	1.044
0.19	0.1039	0.1152	0.1152	3.06	0.69	0.5780	0.2948	0.380	1.024
0.20	0.1118	.01206	0.1206	2.96	0.70	0.5872	0.2962	0.388	1.004
0.21	0.1199	0.1259	0.1259	2.87	0.71	0.5964	0.2975	0.395	0.985
0.22	0.1281	0.1312	0.1612	2.79	0.72	0.6054	0.2987	0.402	0.965
0.23	0.1365	0.1364	0.1364	2.71	0.73	0.6143	0.2998	0.409	0.947
0.24	0.1449	0.1416	0.1416	2.63	0.74	0.6231	0.3008	0.416	0.928
0.25	0.1535	0.1466	0.1466	2.56	0.75	0.6319	0.3017	0.422	0.910
0.26	0.1623	0.1516	0.1516	2.49	0.76	0.6405	0.3024	0.429	0.891
0.27	0.1711	0.1566	0.1566	2.42	0.77	0.6489	0.3031	0.435	0.873
0.28	0.1800	0.1614	0.1614	2.36	0.78	0.6573	0.3036	0.441	0.856
0.29	0.1890	0.1662	0.1662	2.30	0.79	0.6655	0.3039	0.447	0.838
0.30	0.1982	0.1709	0.1709	2.25	0.80	0.6736	0.3042	0.453	0.821
0.31	0.2074	0.1756	0.1759	2.20	0.81	0.6815	0.3043	0.458	0.804
0.32	0.2167	0.11802	0.1802	2.14	0.82	0.6893	0.3043	0.463	0.787
0.33	0.2260	0.1847	0.1847	2.09	0.83	0.6969	0.3041	1.468	0.770
0.34	0.2355	0.1891	0.1891	2.05	0.84	0.7043	0.3038	1.473	0.753
0.35	0.2450	0.1935	0.1935	2.00	0.85	0.7115	0.3033	1.477	0.736
0.36	0.2546	0.1978	0.1978	1.958	0.86	0.7186	0.3026	0.481	0.720
0.37	0.2642	0.2020	0.2020	1.915	0.87	0.7254	0.3018	0.485	0.703
0.38	0.2739	0.2062	0.2062	1.875	0.88	0.7320	0.3007	0.488	0.687
0.39	0.2836	0.2102	0.2102	1.835	0.89	0.7384	0.2995	0.491	0.670
0.40	0.2934	.02142	0.2142	1.797	0.90	0.7445	0.2980	0.494	0.654
0.41	0.3032	0.2182	0.2182	1.760	0.91	0.7504	0.2963	0.496	0.637
0.42	0.3130	0.2220	0.2220	1.724	0.92	0.7560	0.2944	0.497	0.621
0.43	0.3229	0.2258	0.2258	1.689	0.93	0.7612	0.2921	0.498	0.604
0.44	0.3328	0.2295	0.2295	1.655	0.94	0.7662	0.2895	0.498	0.588
0.45	0.3428	0.2331	0.2331	1.622	0.95	0.7707	0.2865	0.498	0.571
0.46	0.3527	0.2366	0.2366	1.590	0.96	0.7749	0.2829	0.498	0.553
0.47	0.3627	0.2401	0.2401	1.559	0.97	0.7785	0.2778	0.496	0.535
0.48	0.3727	0.2435	0.2435	1.530	0.98	0.7817	0.2735	0.494	0.517
0.49	0.3827	0.2468	0.2468	1.500	0.99	0.7841	0.2666	0.483	0.496
0.50	0.3927	0.2500	0.232	1.471	1.00	0.7854	0.2500	0.463	0.463

d = depth of flow A = area of flow Q = discharge in cfs by Manning's formula N = Manning's coefficient
D = diameter of pipe R = hydraulic radius S = slope of the channel bottom and of the water surface SOURCE: HEC-14 (FHWA, 1983)

6.5 RIPRAP BASIN

The riprap basin should be considered for energy dissipation for those locations where the standard riprap apron or other energy dissipators are inadequate. The riprap basin design is based on laboratory data obtained from full scale prototype installations. Following are the principal features of the basin :

- The basin is preshaped and lined with riprap of median size, d_{50} (ft).
- Constructing the floor at a depth of h_S below the invert, where h_S (ft) is the approximate depth of scour that would occur in a thick pad of riprap of size located at the outfall of the culvert if subjected to the design discharge.
- Size d_{50} so that $2 < h_S/d_{50} < 4$.
- Size the length of the dissipating pool to be $10(h_S)$ or $3(W_o)$ whichever is larger for a single barrel.
- Size the overall length of the basin is $15(h_S)$ or $4(W_o)$, whichever is larger.
- Angular rock results were approximately the same as the results of rounded material.
- Layout details are shown on Figure 6.11.

<u>High Tailwater</u> ($TW/d_o > 0.75$)

- The high velocity core of water emerging from the culvert retains its jet like character as it passes through the basin.
- The scour hole is not as deep as with low tailwater and is generally longer.
- Riprap may be required for the channel downstream of the rock-lined basin.

6.5.1 Riprap Basin Design Procedures

The following variable definitions are for use with the riprap basin design procedures.

Where: d_{50} = median diameter size of riprap (ft)
y_o = brink depth, also referred to as d_o (ft)
V_o = velocity at brink (fps)
y_E = equivalent depth at the brink (ft)
Fr_o = Froude number at brink
D = height of box culvert (ft)
A_o = Wetted area associated with y_o (ft^2)
Q = Discharge rate (cfs)
h_S = scour hole depth (ft)
L_S = length of the dissipating pool (ft)
W_o = pipe diameter, box barrel width, or arch span of culvert (ft)
L_B = length of basin (ft)
d_B = critical depth at basin exit (ft)
V_B = Basin exit velocity (fps)

Step 1 **Determine Input Flow Properties**

Estimate flow properties at the brink of the culvert. (y_o, V_o, Fr_o)

A. For mild slopes (subcritical flow conditions) Figures 6.8 and 6.9 can be utilized to find the brink depth (y_o) for rectangular and round culverts. V_o is obtained by dividing Q by A_o (continuity equation)

B. For steep slopes assume normal depth at the brink. Velocity is calculated using Manning's equation.

C. Compute the brink Froude number, $Fr_o = V_o/(gy_e)^{0.5}$ using the equivalent depth at the brink, $y_E = (A/2)^{0.5}$.

Step 2 **Check tailwater (TW)**

Determine if $TW/y_o \leq 0.75$. If $TW/y_o > 0.75$, follow high tailwater design procedures outlined below.

Step 3 **Determine riprap size (d_{50})**

A. Use Figure 6.10.

B. Select d_{50}/y_e. Start with d_{50} values that are locally available and correspond with existing Mn/DOT riprap specifications (class II, class III, class IV).

C. Obtain h_S/y_e using Froude number (Fr) and Figure 6.10.

D. Check if $2 < h_S/d_{50} < 4$ and repeat until a d_{50} is found within the range.

Step 4 **Size Basin**

A. Size basin as shown in Figure 6.11.

B. Determine length of the dissipating pool, L_S. $L_S = 10h_S$ or $3W_o$ whichever is larger.

C. Determine length of basin, L_B. $L_B = 15h_S$ or $4W_o$ whichever is larger.

D. Thickness of riprap:
Approach $= 3d_{50}$ or $1.5\ d_{max}$
Remainder $= 2d_{50}$ or $1.5\ d_{max}$

Step 5 **Determine Basin Exit Velocity (V_B)**

A. Basin exit depth, d_B = critical depth at basin exit.

B. Basin exit velocity, $V_B = Q/(W_B.d_B)$.

C. Compare V_B with the average normal flow velocity in the natural channel, V_d.

Step 6 **High Tailwater Design**

A. Design a basin for low tailwater conditions, Steps 1-5.

B. Compute equivalent circular diameter D_E for brink area from: $A = \pi D_E^2/4 = d_o(W_o)$

C. Estimate centerline velocity at a series of downstream cross sections using Figure 6.12.

D. Size riprap using HEC-11 *Design of Riprap Revetment* (FHWA, 1989) or the Channel Chapter.

Step 7 **Design Filter**

Unless the streambed material is sufficiently well graded use a filter under the riprap. Follow Mn/DOT Specifications.

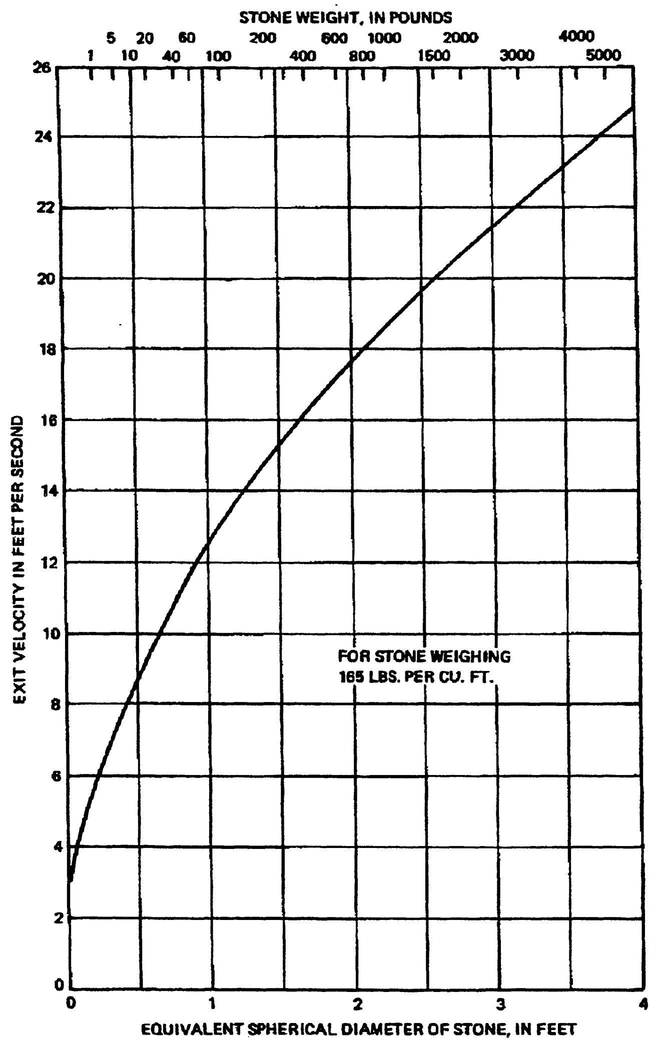


Figure 6.7 Riprap Size Versus Exit Velocity
Source: HEC-14 (FHWA, 1983)

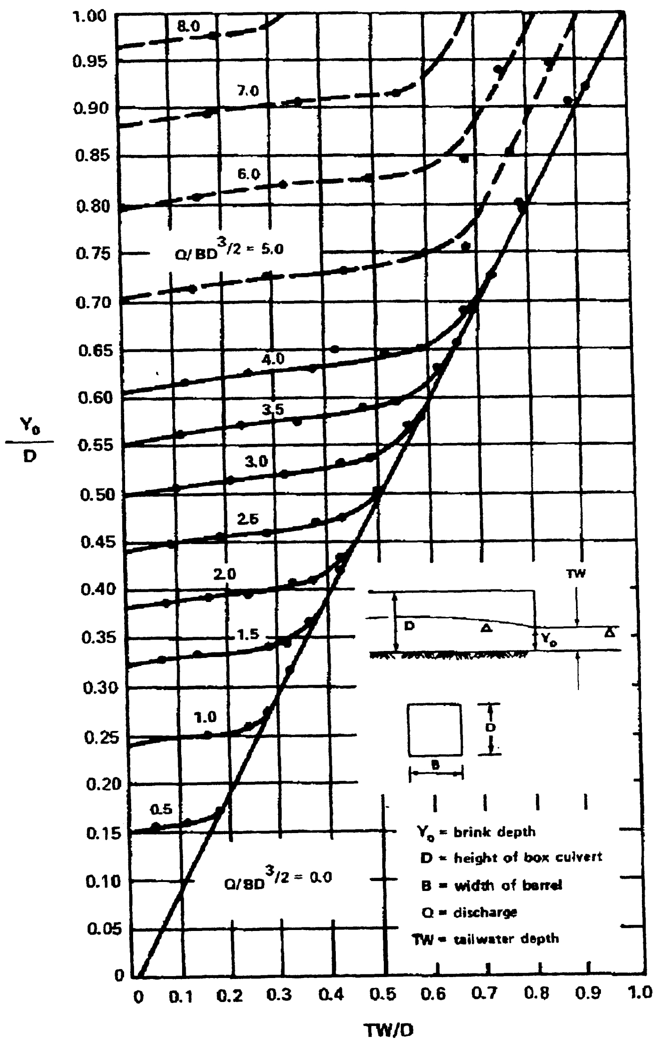


Figure 6.8 Dimensionless Rating Curves for Rectangular Culvert Outlets
Source: HEC-14, Figure III-9 (FHWA, 1983)

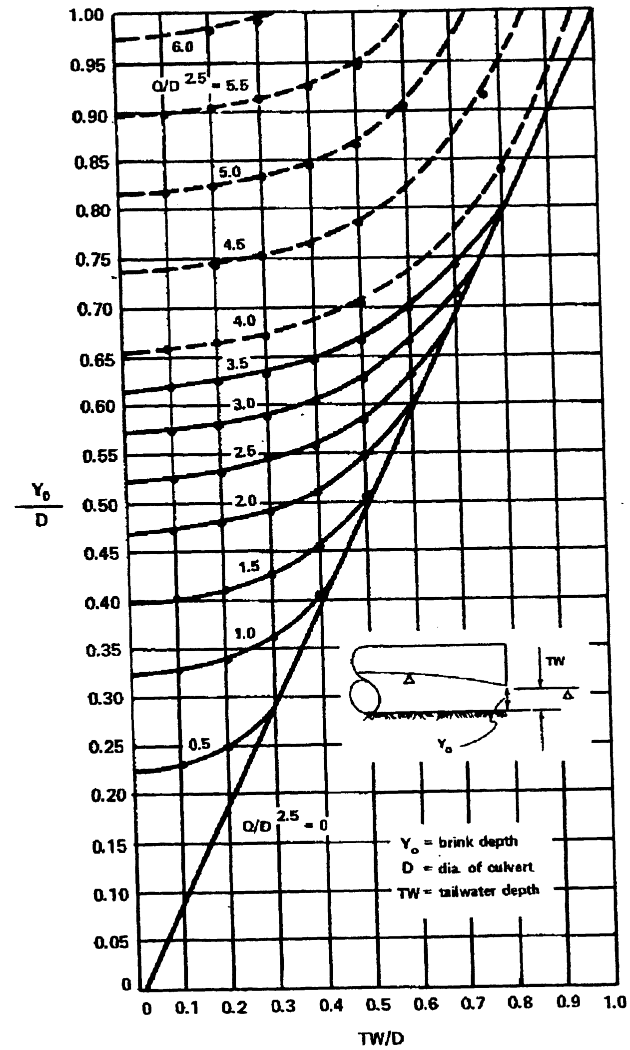


Figure 6.9 Dimensionless Rating Curves for Circular Culvert Outlets
Source: HEC-14, Figure III-10 (FHWA, 1983)

Figures 6.8 and 6.9 are dimensionless rating curves which indicate the effect on brink depth of tailwater for culverts on mild or horizontal slopes. Use these figures to determine the brink depth for culvert outlets. For circular culverts of known geometry (D = diameter), tailwater (TW), and Discharge (Q); compute $\frac{TW}{D}$ and $\frac{Q}{D^{5/2}}$. Use Figure 6.9 to look up $\frac{Y_o}{D}$, then compute Y_o. For rectangular culverts of known geometry (B = barrel width and D = box height), tailwater (TW), and Discharge (Q); compute $\frac{TW}{D}$ and $\frac{Q}{BD^{3/2}}$. Use Figure 6.8 to look up $\frac{Y_o}{D}$, then compute Y_o.

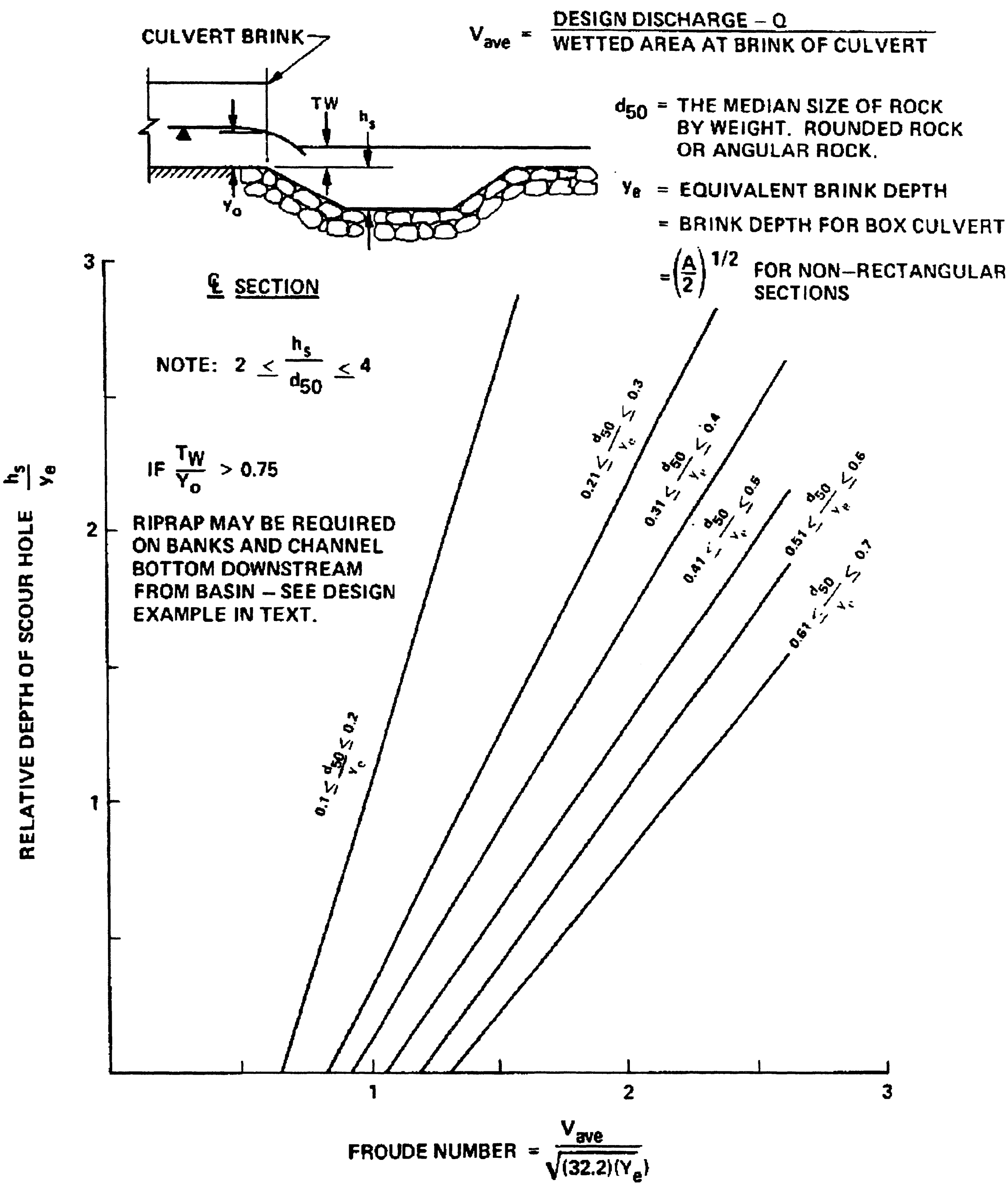
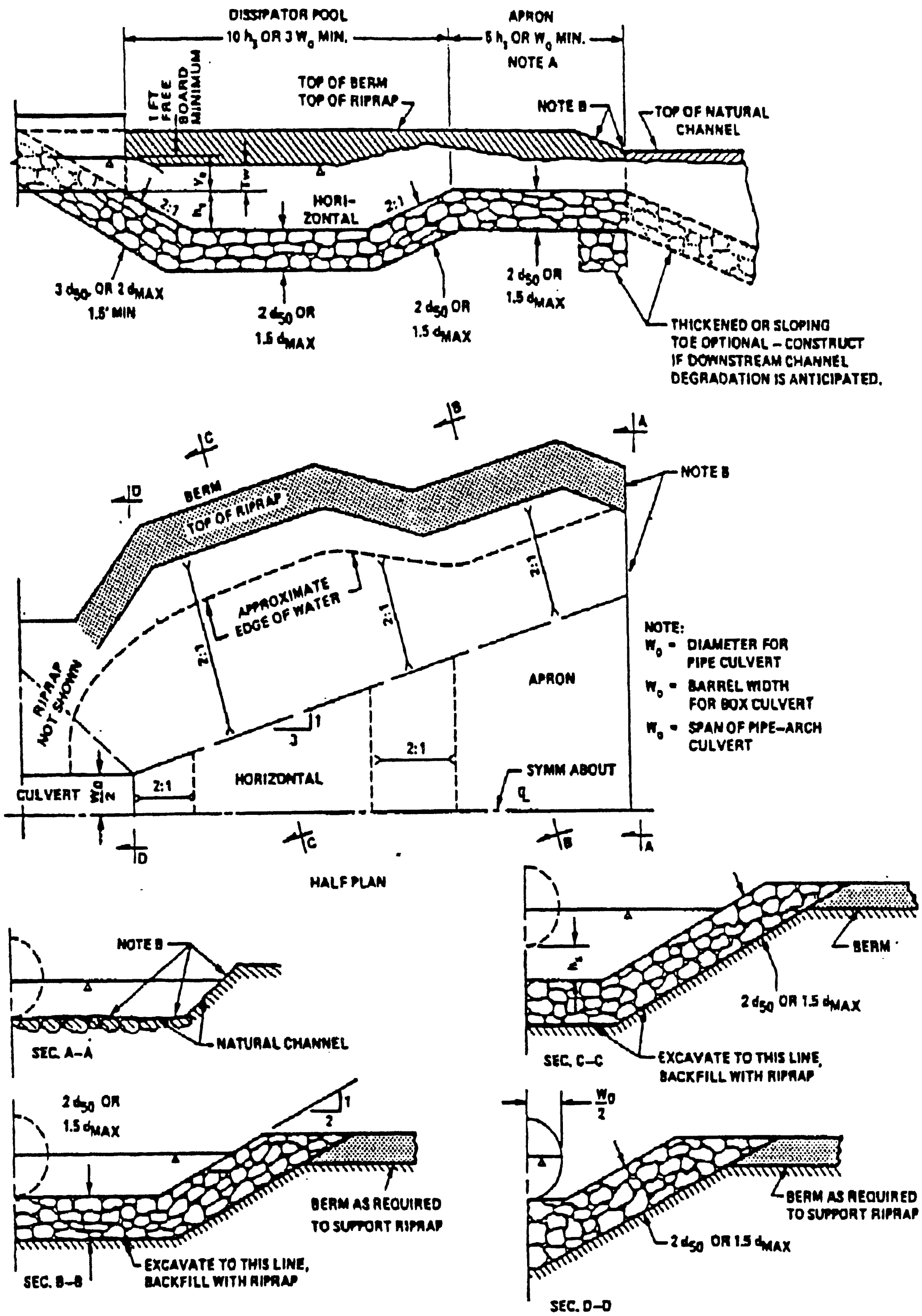


Figure 6.10 Riprapped Basin Depth of Scour
Source: HEC-14, Figure XI-2 (FHWA, 1983)



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_{des}/(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 6.11 Details of Riprapped Energy Dissipator
Source: HEC-14, Figure XI-1 (FHWA, 1983)

Figure 6.12 gives the distribution of centerline velocity for flow from submerged outlets to be used for predicting channel velocities downstream from culvert outlet where high tailwater prevails. Velocities from this figure are used with Figure 6.7 for sizing riprap.

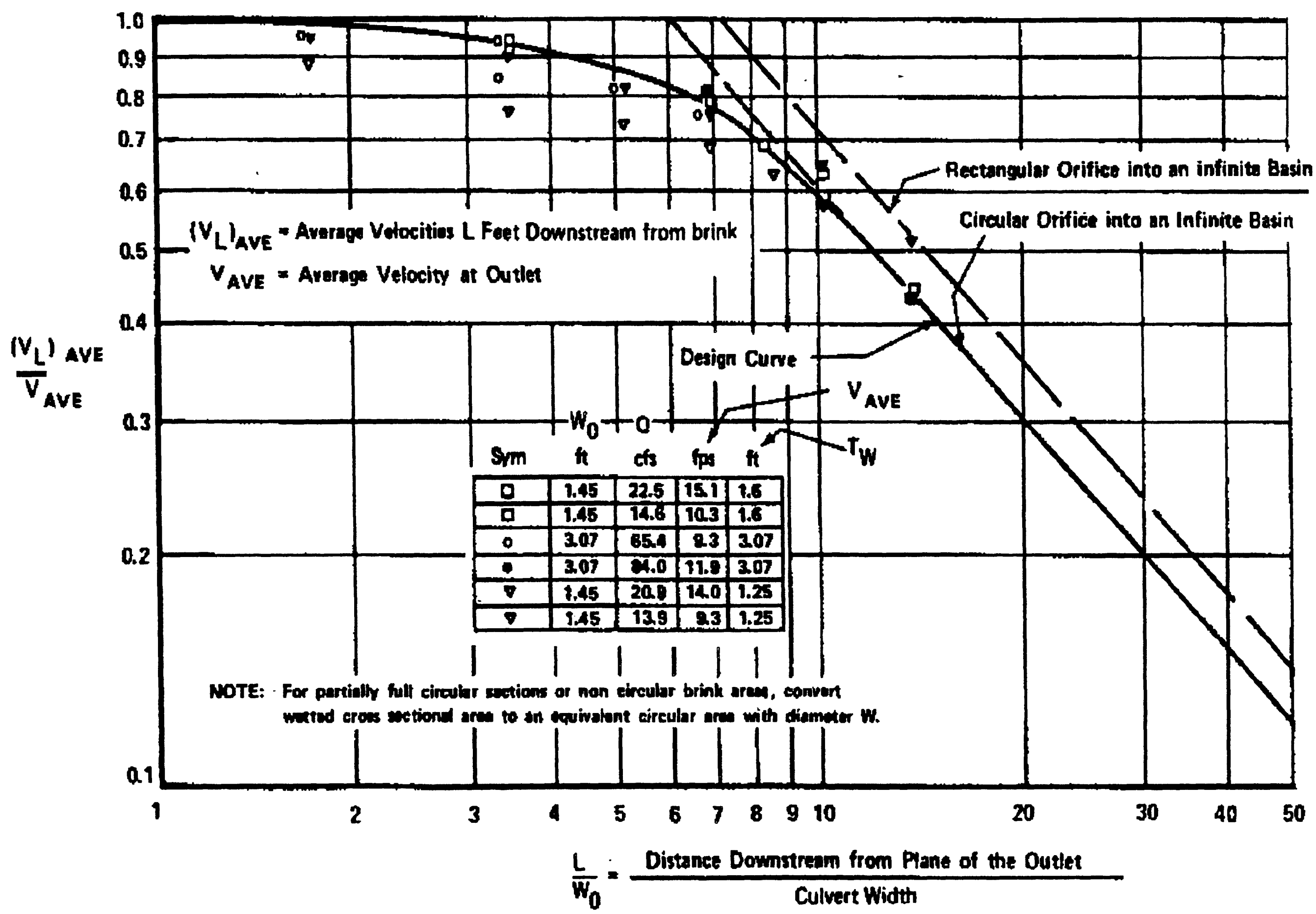


Figure 6.12 Velocity Distribution for High Tailwater
Source: HEC-14, Figure XI-3 (FHWA, 1983)

6.6 REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), 1991. *Model Drainage Manual.* ISBN I-56051-010-2.

Federal Highway Administration (FHWA), 1971. *Debris Control Structures,* Hydraulic Engineering Circular No. 9 (HEC-9), U.S. Department of Transportation., Washington, D.C..

Federal Highway Administration (FHWA), 1989. *Design of Riprap Revetment.* Hydraulic Engineering Circular No. 11 (HEC-11) U.S. Department of Transportation.

Federal Highway Administration (FHWA), 1983. *Hydraulic Design of Energy Dissipators for Culverts and Channels.* Hydraulic Engineering Circular No. 14 (HEC-14) U.S. Department of Transportation. FHWA-EPD-86-110.

A. Ginsburg, *HY8 - Culvert Analysis Microcomputer Program, Applications Guide*, FHWA-EPD-87-101, and software available from McTrans Center, 512 Weil Hall, University of Florida, Gainsville, Florida 32611, (904) 392-0378.

Morris, H. M., 1963. *Applied Hydraulics in Engineering.* The Ronald Press Company, New York, New York.

G.K. Young, J.S. Krolak, 1987. *HYDRAIN - Integrated Drainage Design Computer System*, Volumes 1-6, FHWA-RD-88-120, FHWA.