Chapter 11

ENERGY DISSIPATORS

ODOT ROADWAY DRAINAGE MANUAL

November 2014

Chapter 11
ENERGY DISSIPATORS

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11.1 INTRODUCTION

11.1.1 Overview

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 increased by the construction of a highway or by urban development. The interception and concentration of overland flow and constriction of natural waterways inevitably results in an increased erosion potential. To protect the culvert and adjacent areas, it is sometimes necessary to employ an energy dissipator, which is discussed in this chapter. Roadside channel protection measures are found in Chapter 8 “Channels.” Stream channel revetment and countermeasures are found in Chapter 14 “Bank Protection.”

11.1.2 Definition

Energy dissipators are devices designed to protect downstream areas from erosion by reducing the velocity of flow to acceptable limits.

11.1.3 Guidelines

This chapter is based on Chapter 12 Energy Dissipators of the AASHTO *Drainage Manual* (1) and HEC-14 *Hydraulic Design of Energy Dissipators for Culverts and Channels* (2), The AASHTO *Drainage Manual* provided recommended policy and criteria. HEC-14 provides in-depth design information for analyzing energy dissipation problems at culvert outlets and in open channels. HEC-14 includes procedures for designing dissipators that are both internal and external to the culvert and that are located on or below the streambed.

HEC-14 should be used when designing energy dissipators. This chapter provides a brief overview of energy dissipators and references HEC-14 for detailed design. The HEC-14 design methods have been automated in the FHWA software HY-8. See Chapter 16 “Hydraulic Software.”

11.2 TYPE SELECTION

11.2.1 General

The dissipator type selected for a site must be appropriate to the location. Figure 11.2-A provides guidelines for each dissipator type and the table can be used to determine the alternative types to consider. The types in Figure 11.2-A can be designed by using either HEC-14 (2) or FHWA HY-8 software (see Chapter 16 “Hydraulic Software”).

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.

HEC-14 Chapter	Dissipator Type	Froude Number(1) (Fr)	Allowable Debris(2)			Tailwater (TW)
			Silt/ Sand	Boulders	Floating	
4	Flow transitions	N/A	H	H	H	Desirable
5	Scour hole	N/A	H	H	H	Desirable
6	Hydraulic jump	> 1	H	H	H	Required
7	Tumbling flow(3)	> 1	M	L	L	Not needed
7	Increased resistance(4)	N/A	M	L	L	Not needed
7	USBR Type IX baffled apron	< 1	M	L	L	Not needed
7	Broken-back culvert(4)	> 1	M	L	L	Desirable
7	Outlet weir	2–7	M	L	M	Not needed
7	Outlet drop/weir	3.5–6	M	L	M	Not needed
8	USBR Type III stilling basin	4.5–17	M	L	M	Required
8	USBR Type IV stilling basin	2.5–4.5	M	L	M	Required
8	SAF stilling basin	1.7–17	M	L	M	Required
9	CSU rigid boundary basin	< 3	M	L	M	Not needed
9	Contra Costa basin	< 3	H	M	M	< 0.5D
9	Hook basin	1.8–3	H	M	M	Not needed
9	USBR Type VI impact basin(5)	N/A	M	L	L	Desirable
10	Riprap basin	< 3	H	H	H	Not needed
10	Riprap apron	N/A	H	H	H	Not needed
11	Straight drop structure(6)	< 1	H	L	M	Required
11	Box inlet drop structure(7)	< 1	H	L	M	Required
12	USACE stilling well	N/A	M	L	N	Desirable

(1) At release point from culvert or channel
(2) Debris notes: N = None, L = Low, M = Moderate, H = Heavy
(3) Internal: Bed slope must be in the range of 4% < So < 25%
(4) Internal: Check headwater for outlet control
(5) Discharge, Q < 400 cfs and Velocity, V < 50 fps
(6) Drop < 15 ft
(7) Drop < 12 ft

N/A = not applicable

Source: HEC-14 (2)*, see Section 3.1.4 for acronym definitions*

Figure 11.2-A — ENERGY DISSIPATORS AND LIMITATIONS

11.2.2 ODOT Practice

This section provides ODOT practice for internal and external dissipators.

Internal dissipators commonly used are precast energy dissipator rings for circular culverts and broken back culverts for both box and circulars culverts.

External dissipators (e.g., riprap aprons or basins, drop structure, SAF basin) may be used alone or in combination with internal dissipators. Gabion aprons (rock and wire baskets) are primarily used at the outlets of pipe culverts. Riprap and concrete aprons are commonly used at box culvert outlets. See HEC-14 (2). Where a riprap apron is not adequate, the riprap basin is preferred for $Fr \leq 3$. For $Fr > 3$, the SAF basin is preferred.

11.2.3 Guidelines

The following general guidelines, with a reference to the applicable Chapter in HEC-14, can be used to limit the number of alternative types of dissipators to consider:

1. Internal Dissipators (HEC-14, Chapter 7). Internal dissipators are used where:
   - the estimated outlet scour hole is not acceptable,
   - the right-of-way is limited,
   - debris is not a problem, and
   - moderate velocity reduction is needed.

2. Natural Scour Holes (HEC-14, Chapter 5). Natural scour holes are used where undermining of the culvert outlet will not occur or it is practical to be checked by a cutoff wall, and:
   - the estimated scour hole will not cause costly property damage, or
   - create a public nuisance.

3. External Dissipators (HEC-14, Chapters 9, 10 and 11). External dissipators (e.g., Section 11.5 Riprap Energy Dissipator) are used where:
   - the estimated outlet scour hole is not acceptable,
   - a moderate amount of debris is present, and
   - the culvert outlet velocity (V_o) is moderate ($Fr \leq 3$).

4. Stilling Basins (HEC-14, Chapter 8). Stilling basins are designed using Section 11.6 where:
   - the estimated outlet scour hole is not acceptable,
   - debris is present, and
   - the culvert outlet velocity (V_o) is high ($Fr > 3$).

5. Drop Structures (HEC-14, Chapter 11). Drop structures are designed using Section 11.7 where:

- the downstream channel is degrading, or
- channel headcutting is present.

11.3 DESIGN CONSIDERATIONS

The energy dissipator types selected for design should be evaluated considering the following factors.

11.3.1 Ice Buildup

If ice buildup is a factor, consider mitigating by:

- sizing the structure to not obstruct the winter low flow, and
- using external dissipators.

11.3.2 Debris Control

If debris is an issue, consider mitigating by:

- using a dissipator type that can pass debris (see Figure 11.2-A), or
- installing a countermeasure upstream of the culvert, as described in HEC-9 (3).

11.3.3 Flood Frequency

The flood frequency used in the design of the energy dissipator device should be the same flood frequency used for the culvert design (see Chapter 9 “Culverts”).

11.3.4 Culvert Exit Velocity

The culvert exit velocity should be consistent with the maximum velocity in the natural channel or should be mitigated by using:

- channel protection (see Chapter 8 “Channels” and Chapter 14 “Bank Protection”), and
- energy dissipation.

11.3.5 Tailwater Relationship

The hydraulic conditions downstream should be evaluated to determine a tailwater depth and the maximum velocity for a range of discharges:

- Open channels (see Chapter 8 “Channels”).
- Lakes, ponds or large water bodies should be evaluated using Figure 11.3-A.

Drainage Area Ratio	10-Year Design		100-Year Design	
	Main Stream	Tributary	Main Stream	Tributary
10,000 to 1	1 10	10 1	2 100	100 2
1000 to 1	2 10	10 2	10 100	100 10
100 to 1	5 10	10 5	25 100	100 25
10 to 1	10 10	10 10	50 100	100 50
1 to 1	10 10	10 10	100 100	100 100

Source: HDG, Chapter 9 (4)

Figure 11.3-A — EXAMPLE OF JOINT PROBABILITY ANALYSIS FOR STREAMS NEAR VIRGINIA BEACH, VA (early 1970s)

11.3.6 Cost

The type selected for the energy dissipator should be based on a comparison of the total cost over the design life of alternative types and should not be made using first cost as the only criteria. This comparison should consider maintenance costs, replacement costs, traffic delay costs and the difficulty of construction.

11.3.7 Weep Holes

Weep holes are openings left in such things as impermeable walls, revetments, aprons, linings or foundations to relieve the water pressure and permit drainage. If weep holes are used to relieve uplift pressure, they should be designed in a manner similar to underdrain systems. The location of weep holes should be selected carefully to avoid causing an icing hazard.

11.4 GENERAL DESIGN PROCEDURE

The design procedure, illustrated in Figure 11.4-A, presents the recommended design steps. The hydraulics designer should treat the culvert, energy dissipator and channel protection designs as an integrated system. The hydraulics designer should apply the following design procedure to one combination of culvert, energy dissipator and channel protection at a time. The symbols used in the design procedure are taken from HEC-14 (2). The HEC-14 list of symbols should be consulted for units. While the design steps were established assuming a hand solution using HEC-14, they also provide a roadmap for using HY-8.

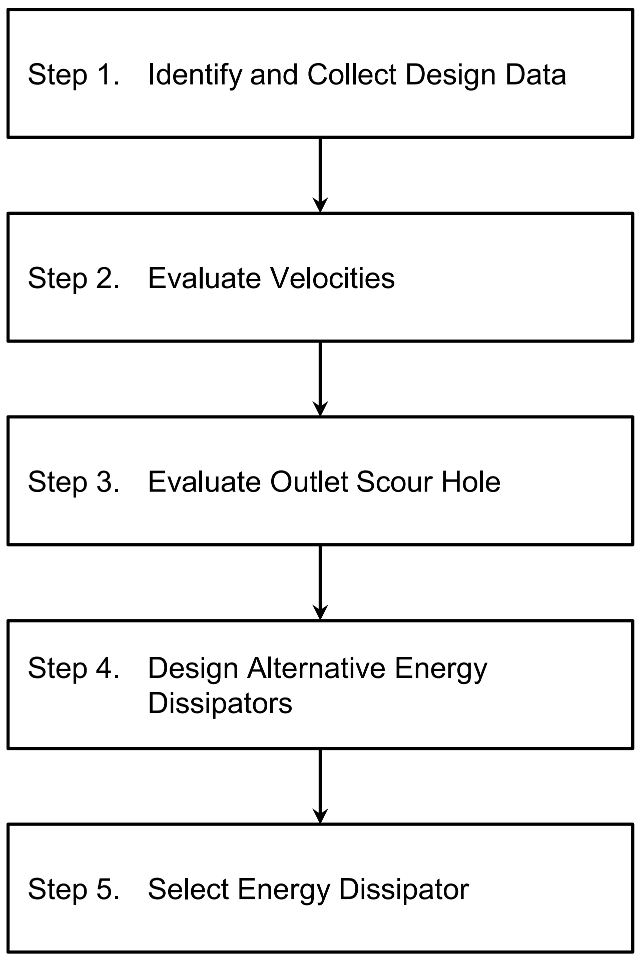


Figure 11.4-A — ENERGY DISSIPATOR DESIGN PROCEDURE

Step 1. Identify and collect design data.

Energy dissipators should be considered part of a larger design system, which includes a culvert or a chute and channel protection requirements (both upstream and downstream) and may include a debris-control structure. Much of the input data will be available to the energy dissipator design phase from previous design efforts.

- Culvert Data. The culvert design should provide:

  - type (e.g., RCB, RCP, CMP);
  - height, D;
  - width, B;
  - length, L;
  - roughness, n;
  - slope, S_o;
  - design discharge, Q_d;
  - tailwater, TW;
  - type of control (inlet or outlet);
  - outlet depth, y_o;
  - outlet velocity, V_o; and
  - outlet Froude number, Fr_o.

  Culvert outlet velocity (V_o) is discussed in Chapter 3 of HEC-14 and Chapter 9 "Culverts."

- Transition Data. Flow transitions are discussed in Chapter 4 of HEC-14. For most culvert designs, the hydraulics designer must determine the flow depth (y) and velocity (V) at the exit of standard wingwall/apron combinations.

- Channel Data. The following channel data is used to determine the TW for the culvert design:

  - design discharge, Q_d;
  - slope, S_o;
  - cross section geometry;
  - bank and bed roughness, n;
  - normal depth, y_n = TW; and
  - normal velocity, V_n.

  If the cross section is a trapezoid, it is defined by the bottom width (B) and side slope (Z), which is expressed as 1V:ZH. HDS-4 (5) provides examples of how to compute normal depth in channels. The FHWA Hydraulic Toolbox (see Chapter 16 "Hydraulic Software") can be used to determine TW for uniform cross sections. The size and amount of debris should be estimated using HEC-9 (3). The size and amount of bedload should be estimated.

- Allowable Scour Estimate. In the field, the hydraulics designer should determine if the bed material at the planned exit of the culvert is erodible. If yes, the potential extent of scour (i.e., depth, h_s; width, W_s; and length, L_s) should be estimated using the equations in HEC-14, Chapter 5 or HY-8. These estimates should be based on the physical limits to scour at the site. For example, the length (L_s) can be limited by a rock ledge or vegetation. The following soil parameters in the vicinity of planned culvert outlets should be provided. For non-cohesive soil, a grain size distribution including D_{16} and

D_{84} is needed. For cohesive soil, the values needed are saturated shear strength (S_v) and plasticity index (PI).

- Stability Assessment. The channel, culvert and related structures should be evaluated for stability considering potential erosion plus buoyancy, shear and other forces on the structure (see HEC-14, Chapter 2 or HEC-20 (6)). If these are assessed as unstable, estimate the depth of degradation or height of aggradation, which will occur over the design life of the structure.

Step 2. Evaluate velocities.

Compute culvert or chute exit velocity (V_o) and compare with downstream channel velocity (V_n).

- If the exit velocity and flow depth approximate the natural flow condition in the downstream channel, the culvert design is acceptable.
- If the velocity is moderately higher, the hydraulics designer can evaluate reducing velocity within the barrel or chute (see HEC-14, Chapter 3) or reducing the velocity with a scour hole (Step 3). Another option is to modify the culvert or chute (channel) design so that the outlet conditions are mitigated.
- If the velocity is substantially higher or the scour hole from Step 3 is unacceptable, or both; the hydraulics designer should evaluate the use of energy dissipators (Step 4). The definition of the terms “approximately equal,” “moderately higher” and “substantially higher” is relative to site-specific concerns such as sensitivity of the site and the consequences of failure. However, as rough guidelines, which should be re-evaluated on a site-specific basis, the ranges of less than 10%, between 10% and 30% and greater than 30% may be used.

Step 3. Evaluate outlet scour hole.

Compute the outlet scour hole dimensions using the procedures in HEC-14, Chapter 5 or HY-8.

- If the size of the scour hole is acceptable, the hydraulics designer should document the size of the expected scour hole for maintenance and note the monitoring requirements.
- If the size of the scour hole is excessive, the hydraulics designer should evaluate energy dissipators (Step 4).

Step 4. Design alternative energy dissipators.

Compare the design data identified in Step 1 to the attributes of the various energy dissipators in Figure 11.2-A. Design one or more of the energy dissipators that substantially satisfies the design criteria. The dissipators fall into two general groups based on the Froude number, Fr:

Fr ≤ 3: Most designs are in this group.

Fr > 3: These include tumbling flow, USBR Type III stilling basin, USBR Type IV stilling basin, SAF stilling basin and USBR Type VI impact basin.

Debris, tailwater channel conditions, site conditions and cost must also be considered in selecting alternative designs.

Step 5. Select energy dissipator.

Compare the design alternatives and select the dissipator that has the best combination of cost and velocity reduction. Each situation is unique, and engineering judgment will always be necessary. The hydraulics designer should document the alternatives considered.

Chapter 1 of HEC-14 contains examples that are intended to provide an overview of the design process. Pertinent chapters of HEC-14 should be consulted for design details for specific dissipators. HY-8 software can be used to quickly compare the design details of alternative energy dissipator types; see Chapter 16 “Hydraulic Software.”

11.5 RIPRAP ENERGY DISSIPATOR

Riprap is a material that has long been used to protect against the forces of water. The material can be pit-run (as provided by the supplier) or specified (standard or special). ODOT has standard specifications for a number of classes (sizes or gradations) of riprap. Suppliers maintain an inventory of frequently used classes. Special gradations of riprap are produced on-demand and are therefore more expensive than both pit-run and standard classes. This section provides a design procedure for the riprap energy dissipator. The riprap for this basin is a specified gradation. The design procedure for the riprap energy dissipator basin is based on HEC-14, Chapter 10 (2). The recommended riprap basin layout is shown in Figures 11.5-A and 11.5-B.

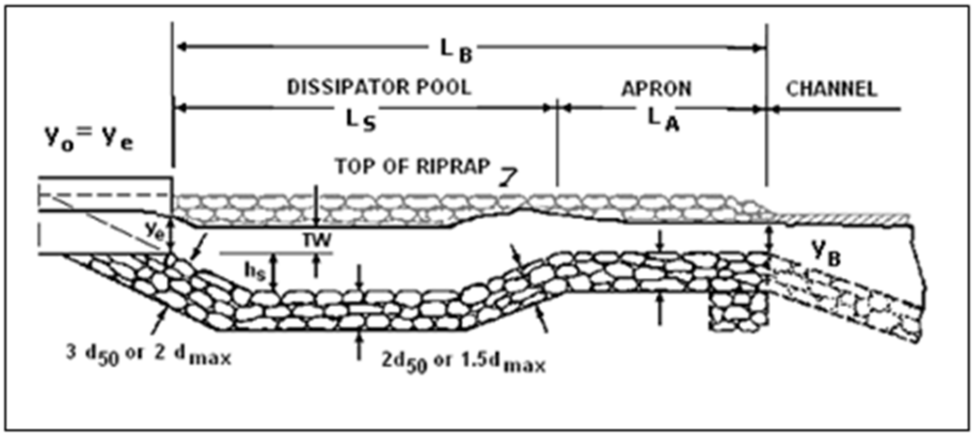


Figure 11.5-A — PROFILE OF RIPRAP ENERGY DISSIPATOR

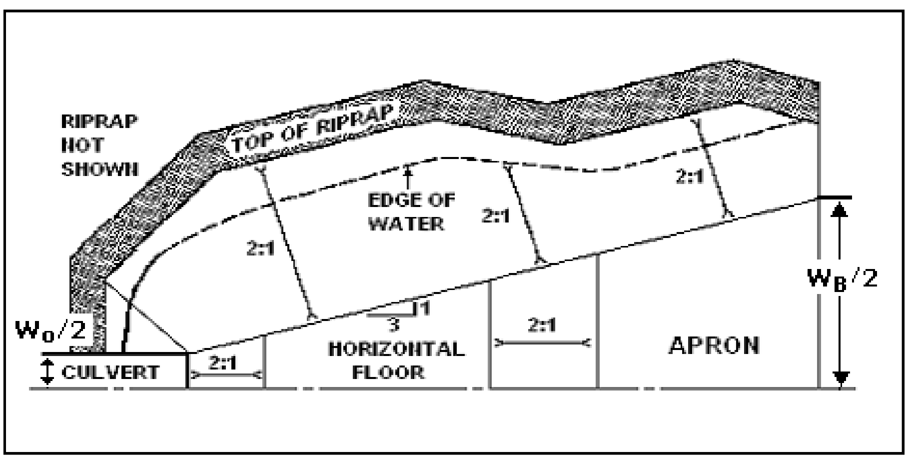


Figure 11.5-B — HALF PLAN OF RIPRAP ENERGY DISSIPATOR

The dissipator includes the following features:

- The basin is pre-shaped and lined with riprap that is at least $2D_{50}$ thick.

- The riprap floor is constructed at the approximate depth of scour, h_s, that would occur in a thick pad of riprap. The h_s/D_{50} of the material should be greater than 2.
- The length of the energy dissipating pool, L_s, is $10(h_s)$ or no less than $3W_o$; the length of the apron, L_A, is $5h_s$, but no less than W_o. The overall length of the basin is $15(h_s)$, but no less than $4W_o$.
- A riprap cutoff wall or sloping apron can be constructed if downstream channel degradation is anticipated as shown in Figure 11.5-A.

11.5.1 Design Equations

An envelope design relationship in the form of Equation 11.5(1) and Equation 11.5(2) was developed. These equations provide a design envelope for the experimental data equivalent to the design figure provided in the previous edition of HEC-14 (2). Equations 11.5(1) and 11.5(2), however, improve the fit to the experimental data reducing the root mean-square (RMS) error from 1.24 to 0.83.

$$\frac{h_s}{y_e} = 0.86\left(\frac{D_{50}}{y_e}\right)^{-0.55}\left(\frac{V_o}{\sqrt{gy_e}}\right) - C_o \qquad \text{Equation 11.5(1)}$$

Where:

h_s	=	dissipator pool depth, ft
y_e	=	equivalent brink (outlet) depth, ft
D_{50}	=	median rock size by weight, ft
C_o	=	tailwater parameter

The tailwater parameter, C_o, for envelope relationship is defined as:

$$\begin{aligned} C_o &= 1.4 && TW/y_e < 0.75 \\ C_o &= 4.0(TW/y_e) - 1.6 && 0.75 < TW/y_e < 1.0 \\ C_o &= 2.4 && 1.0 < TW/y_e \end{aligned} \qquad \text{Equation 11.5(2)}$$

A best fit design relationship that minimizes the RMS error when applied to the experimental data was also developed. Equation 11.5(1) still applies, but the description of the tailwater parameter, C_o, is defined in Equation 11.5(3) The best fit relationship for Equations 11.5(1) and 11.5(3) exhibits a RMS error on the experimental data of 0.56.

The tailwater parameter, C_o, for best fit relationship is defined as:

$$\begin{aligned} C_o &= 2.0 && TW/y_e < 0.75 \\ C_o &= 4.0(TW/y_e) - 1.0 && 0.75 < TW/y_e < 1.0 \\ C_o &= 3.0 && 1.0 < TW/y_e \end{aligned} \qquad \text{Equation 11.5(3)}$$

Use of the envelope design relationship (Equations 11.5(1) and 11.5(2)) is recommended when the consequences of failure at or near the design flow are severe. Use of the best fit design relationship (Equations 11.5(1) and 11.5(3)) is recommended when basin failure may easily be addressed as part of routine maintenance. Intermediate risk levels can be adopted by the use of intermediate values of C_o. The above equations are available in HY-8. The hydraulics designer chooses either envelope or best fit relationship.

11.5.2 Design Procedure

The design procedure for a riprap basin is as follows:

Step 1. Compute the culvert outlet velocity, V_o, and depth, y_o.

For subcritical flow (culvert on mild or horizontal slope), use HEC-14 (2) Figure 3.3 or Figure 3.4 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 or diameter of a circular culvert.

For supercritical flow (culvert on a steep slope), V_o will be the normal velocity obtained by using the Manning's Equation for appropriate slope, section and discharge.

Compute the Froude number, Fr, for brink conditions using brink depth for box culverts ($y_e = y_o$) and equivalent depth ($y_e = (A/2)^{1/2}$) for non-rectangular sections.

Step 2. Select D_{50} appropriate for locally available riprap. Determine C_o from Equation 11.5(2) or 11.5(3) and obtain h_s/y_e from Equation 11.5(1). Check to see that $h_s/D_{50} \geq 2$ and $D_{50}/y_e \geq 0.1$. If h_s/D_{50} or D_{50}/y_e is out of this range, try a different riprap size. (Basins sized where h_s/D_{50} is greater than, but close to, 2 are often the most economical choice.)

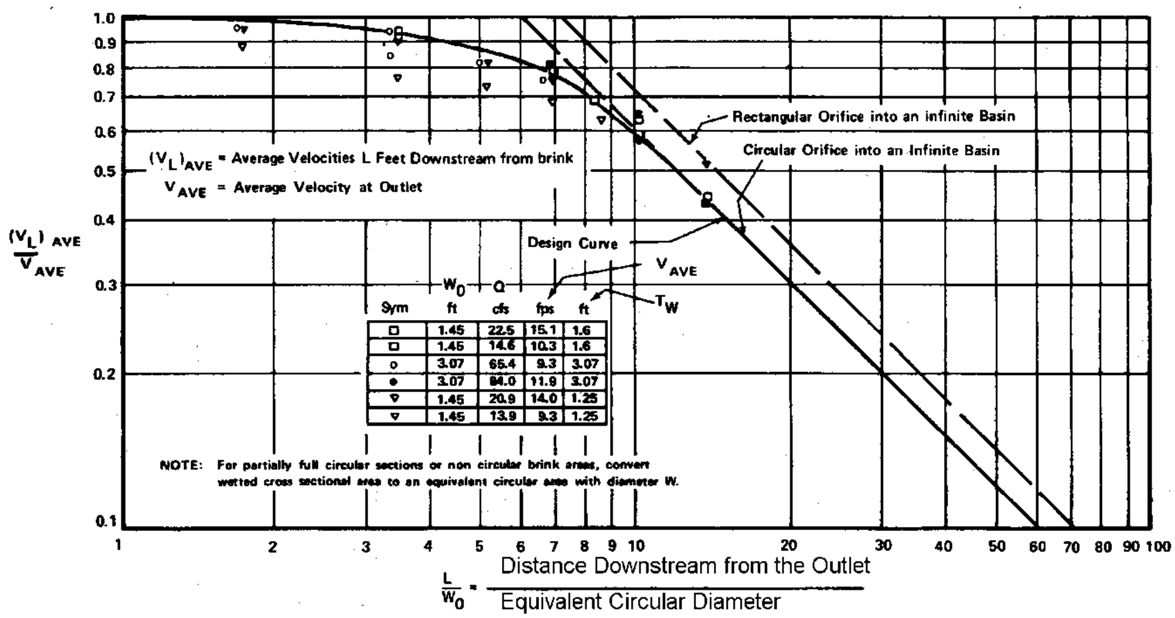
Step 3. Determine the length of the dissipation pool (scour hole), L_s, total basin length, L_B, and basin width at the basin exit, W_B, as shown in Figures 11.5-A and 11.5-B. The walls and apron of the basin should be warped (or transitioned) so that the cross section of the basin at the exit conforms to the cross section of the natural channel. Abrupt transition of surfaces should be avoided to minimize separation zones and resultant eddies.

Step 4. Determine the basin exit depth, $y_B = y_c$, and exit velocity, $V_B = V_c$ and compare with the allowable exit velocity, V_{allow}. The allowable exit velocity may be taken as the estimated normal velocity in the tailwater channel or a velocity specified based on stability criteria, whichever is larger. Critical depth at the basin exit may be determined iteratively using:

$Q^2/g = (A_c)^3/T_c = [y_c(W_B + zy_c)]^3/ (W_B + 2zy_c)$ by trial and success to determine y_B.
$V_c = Q/A_c$
z = basin side slope, z:1 (H:V)

If $V_c \leq V_{allow}$, the basin dimensions developed in Step 3 are acceptable. However, it may be possible to reduce the size of the dissipator pool and/or the apron with a larger riprap size. It may also be possible to maintain the dissipator pool, but reduce the flare on the apron to reduce the exit width to better fit the downstream channel. Steps 2 through 4 are repeated to evaluate alternative dissipator designs.

Step 5. Assess need for additional riprap downstream of the dissipator exit. If $TW/y_o \leq 0.75$, no additional riprap is needed. With high tailwater ($TW/y_o \geq 0.75$); estimate centerline velocity at a series of downstream cross sections using Figure 11.5-C to determine the size and extent of additional protection. The riprap design details should be in accordance with ODOT specifications.



Sym	W_0 ft	Q cfs	V_{AVE} fps	T_W 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

Figure 11.5-C — DISTRIBUTION OF CENTERLINE VELOCITY FOR FLOW FROM SUBMERGED OUTLETS

11.5.3 Design Example (RCB on a Steep Slope)

Determine riprap basin dimensions using the envelope design (Equations 11.5(1) and 11.5(2)) for an 8 ft by 6 ft reinforced concrete box (RCB) culvert that is in inlet control with supercritical flow in the culvert. Allowable exit velocity from the riprap basin, V_{allow}, is 7 fps. Riprap is available with a D_{50} of 1.67, 1.83 and 2.5 ft. Consider two tailwater conditions: 1) TW = 2.8 ft and 2) TW = 4.2 ft. Given:

Q = 800 cfs
y_o = 4 ft (normal flow depth) = brink depth

Step 1. Compute the culvert outlet velocity, V_o, depth, y_o, and Froude number for brink conditions. For supercritical flow (culvert on a steep slope), V_o will be V_n.

$y_o = y_e = 4$ ft
$V_o = Q/A = 800/ [4 (8)] = 25$ fps
$Fr = V_o / (32.2y_e)^{1/2} = 25/ [32.2(4)]^{1/2} = 2.2$

Step 2. Select a trial D_{50} and obtain h_s/y_e from Equation 11.5(1). Check to see that $h_s/D_{50} \geq 2$ and $D_{50}/y_e \geq 0.1$.

Try $D_{50} = 1.83$ ft; $D_{50}/y_e = 1.83/4 = 0.46$ (≥ 0.1 OK)

Two tailwater elevations are given; use the lowest to determine the basin size that will serve the tailwater range, that is, TW = 2.8 ft.

$TW/y_e = 2.8/4 = 0.7$, which is less than 0.75. From Equation 11.5(2), $C_o = 1.4$

From Equation 11.5(1):

$$\frac{h_s}{y_e} = 0.86\left(\frac{D_{50}}{y_e}\right)^{-0.55}\left(\frac{V_o}{\sqrt{gy_e}}\right) - C_o = 0.86(0.46)^{-0.55}(2.2) - 1.4 = 1.50$$

$h_S = (h_S / y_e)y_e = 1.50\ (4) = 6.0$ ft
$h_S/D_{50} = 6.0/1.83 = 3.3$ and $h_S/D_{50} \geq 2$ is satisfied

Step 3. Size the basin as shown in Figures 11.5-A and 11.5-B.

$L_S = 10h_S = 10(6.0) = 60$ ft
L_S min $= 3W_o = 3(8) = 24$ ft, use $L_S = 60$ ft
$L_B = 15h_S = 15(6.0) = 90$ ft
L_B min $= 4W_o = 4(8) = 32$ ft, use $L_B = 90$ ft
$W_B = W_o + 2(L_B/3) = 8 + 2(90/3) = 68$ ft

Step 4. Determine the basin exit depth, $y_B = y_c$, and exit velocity, $V_B = V_c$.

$Q^2/g = (A_c)^3/T_c = [y_c(W_B + zy_c)]^3/ (W_B + 2zy_c)$
$800^2/32.2 = 19{,}876 = [y_c(68 + 2y_c)]^3/ (68 + 4y_c)$
By trial and success, $y_c = 1.60$ ft, $T_c = 74.4$ ft, $A_c = 113.9$ ft^2
$V_B = V_c = Q/A_c = 800/113.9 = 7.0$ fps (acceptable)

The initial trial of riprap ($D_{50} = 1.83$ ft) results in a 90 ft basin that satisfies all design requirements. Try the next larger riprap size to test if a smaller basin is feasible by repeating steps 2 through 4.

Step 2 (2nd iteration). Select riprap size and compute basin depth.

Try $D_{50} = 2.5$ ft; $D_{50}/y_e = 2.5/4 = 0.63$ (≥ 0.1 OK)

From Equation 11.5(1):

$$\frac{h_s}{y_e} = 0.86\left(\frac{D_{50}}{y_e}\right)^{-0.55}\left(\frac{V_o}{\sqrt{gy_e}}\right) - C_o = 0.86(0.63)^{-0.55}(2.2) - 1.4 = 1.04$$

$h_S = (h_S / y_e) y_e = 1.04\ (4) = 4.2$ ft

$h_S/D_{50} = 4.2/2.5 = 1.7$ and $h_S/D_{50} \geq 2$ is not satisfied. Although not available, try a riprap size that will yield h_S/D_{50} close to, but greater than, 2. (A basin sized for smaller riprap may be lined with larger riprap.) Repeat Step 2.

Step 2 (3rd iteration). Select riprap size and compute basin depth.

Try $D_{50} = 2.3$ ft; $D_{50}/y_e = 2.3/4 = 0.58$ (≥ 0.1 OK)

From Equation 11.5(1):

$$\frac{h_s}{y_e} = 0.86\left(\frac{D_{50}}{y_e}\right)^{-0.55}\left(\frac{V_o}{\sqrt{gy_e}}\right) - C_o = 0.86(0.58)^{-0.55}(2.2) - 1.4 = 1.15$$

$h_S = (h_S / y_e) y_e = 1.15\ (4) = 4.6$ ft
$h_S/D_{50} = 4.6/2.3 = 2.0$ and $h_S/D_{50} \geq 2$ is satisfied.

Step 3 (3rd iteration). Size the basin as shown in Figures 11.5-A and 11.5-B.

$L_S = 10h_S = 10(4.6) = 46$ ft
L_S min $= 3W_o = 3(8) = 24$ ft, use $L_S = 46$ ft
$L_B = 15h_S = 15(4.6) = 69$ ft
L_B min $= 4W_o = 4(8) = 32$ ft, use $L_B = 69$ ft
$W_B = W_o + 2(L_B/3) = 8 + 2(69/3) = 54$ ft

However, because the trial D_{50} is not available, the next larger riprap size ($D_{50} = 2.5$ ft) would be used to line a basin with the given dimensions.

Step 4 (3rd iteration). Determine the basin exit depth, $y_B = y_c$, and exit velocity, $V_B = V_c$.

$Q^2/g = (A_c)^3/T_c = [y_c(W_B + zy_c)]^3/ (W_B + 2zy_c)$
$800^2/32.2 = 19{,}876 = [y_c(54 + 2y_c)]^3/ (54 + 4y_c)$
By trial and success, $y_c = 1.85$ ft, $T_c = 61.4$ ft, $A_c = 106.9$ ft^2

$V_B = V_c = Q/A_c = 800/106.9 = 7.5$ fps (not acceptable). If the apron were extended (with a continued flare) such that the total basin length was 90 ft, the velocity would be reduced to the allowable level.

Two feasible options have been identified. First, a 6-ft-deep, 60-ft-long pool with a 30-ft-apron using $D_{50} = 1.83$ ft. Second, a 4.6-ft-deep, 46-ft-long pool with a 44-ft-apron using $D_{50} = 2.5$ ft. Because the overall length is the same, the first option is likely to be more economical.

Step 5: For the design discharge, determine if $TW/y_o \leq 0.75$.

For the first tailwater condition, $TW/y_o = 2.8/4.0 = 0.70$, which satisfies $TW/y_o \leq 0.75$. No additional riprap needed downstream.

For the second tailwater condition, $TW/y_o = 4.2/4.0 = 1.05$, which does not satisfy $TW/y_o \leq 0.75$. To determine required riprap, estimate centerline velocity at a series of downstream cross sections using Figure 9.5-C.

Compute equivalent circular diameter, D_e, for brink area:

$A = \pi D_e^2 /4 = (y_o)(W_o) = (4)(8) = 32 \text{ ft}^2$

$D_e = [32(4)/ \pi]^{1/2} = 6.4 \text{ ft}$

The computations are summarized below:

L/D_e	L (ft)	V_L/V_o (Figure 9.5-C)	V_L (ft/s)	Rock Size, D_{50} (ft)
10	64	0.59	14.7	1.42
15	96	0.42	10.5	0.72
20	128	0.30	7.5	0.37
21	135	0.28	7.0	0.32

The calculations above continue until $V_L \leq V_{allow}$. Riprap should be at least the size shown. 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, which is 45 ft beyond the basin exit. Riprap should be installed in accordance with details shown in Chapter 8 "Channels."

11.5.4 Design Example (RCB on a Steep Slope) using HY-8 Version 7.3

The Section 11.5.3 example can also be solved with HY-8. The first step is to duplicate the outlet conditions (y_o = 4 ft and TW = 2.8 ft) shown above by creating appropriate site conditions for the 8 ft × 6 ft RCB:

- Tailwater Data - rectangular channel with 16.5 ft bottom width, 0.02 ft/ft slope and invert elevation of 90
- Roadway Data - crest length of 100 ft, crest elevation of 120 ft, paved roadway, top width of 40 ft
- Culvert Data - RCB 8 × 6, no embedment, straight, square edge, no depression
- Site Data - Inlet (station 100, elevation 100), outlet (station 525, elevation 90), 1 barrel

The above site conditions give a y_o = 3.99 ft and V_o = 25.03 fps for 800 cfs. Select energy dissipator option, select at top design external dissipator and below culvert data select streambed level structures, riprap basin and envelope curve:

- If the D_{50} = 1.83 ft and D_{max} = 2 ft is selected, the basin dimensions from HY-8 are similar to those shown in Step 3 above and V_c is about 7 fps.
- If the D_{50} = 2.5 ft is selected, HY-8 indicates that it is too high and replaces it with the maximum size needed of D_{50} = 2.0 ft. The dimensions are slightly smaller than the basin for D_{50} = 1.83 ft

11.6 STILLING BASIN DESIGN

Stilling basins are external energy dissipators placed at the outlet of a culvert, chute or rundown. These basins are characterized by some combination of chute blocks, baffle blocks and sills designed to trigger a hydraulic jump in combination with a required tailwater condition. With the required tailwater, velocity leaving a properly designed stilling basin is equal to the velocity in the receiving channel. While various stilling basin designs are available in HEC-14 (2), ODOT practice is to use the St. Anthony Falls (SAF) stilling basin, which can operate over a range of approach flow Froude numbers from 1.7 to 17.

11.6.1 Expansion and Depression for Stilling Basins

The higher the Froude number at the entrance to a basin, the more efficient the hydraulic jump and the shorter the resulting basin. To increase the Froude number as the water flows from the culvert to the basin, an expansion and depression is used as is shown in Figure 11.6-A. The expansion and depression converts depth, or potential energy, into kinetic energy by allowing the flow to expand, drop or both. The result is that the depth decreases and the velocity and Froude number increase.

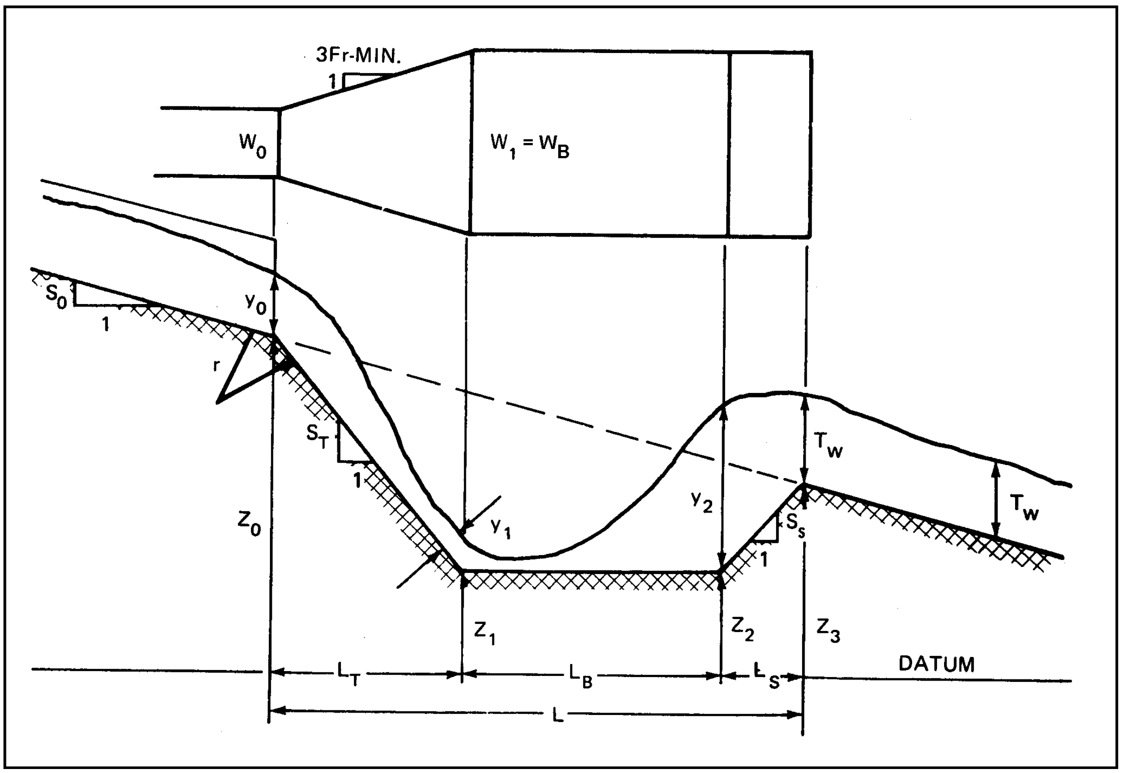


Figure 11.6-A — DEFINITION SKETCH FOR STILLING BASIN

The Froude number used to determine jump efficiency and to evaluate the suitability of alternative stilling basins is defined in Equation 11.6(1).

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}}$$ Equation 11.6(1)

Where:

Fr_1	=	Froude number at the entrance to the basin
V_1	=	velocity entering the basin, fps
y_1	=	depth entering the basin, ft
g	=	acceleration due to gravity, ft/s^2

To solve for the velocity and depth entering the basin, the energy balance is written from the culvert outlet to the basin floor (Section 1). Substituting $Q/(y_1W_B)$ for V_1 and solving for Q results in:

$$Q = y_1W_B\left[2g(z_o - z_1 + y_o - y_1) + V_o^2\right]^{1/2}$$ Equation 11.6(2)

Where:

W_B	=	width of the basin, ft
V_o	=	culvert outlet velocity, fps
y_1	=	depth entering the basin, ft
y_o	=	culvert outlet depth, ft
z_1	=	ground elevation at the basin entrance, ft
z_o	=	ground elevation at the culvert outlet, ft

Equation 11.6(2) has three unknowns: y_1, W_B and z_1. The depth y_1 can be determined by trial and error if W_B and z_1 are assumed. W_B should be limited to the width that a jet would flare naturally in the slope distance L.

$$W_B \le W_o + \frac{2L_T\sqrt{S_T^2 + 1}}{3Fr_o}$$ Equation 11.6(3)

Where:

L_T	=	length of transition from culvert outlet to basin, ft
S_T	=	slope of the transition, ft/ft
Fr_o	=	outlet Froude number

Since the flow is supercritical, the trial y_1 value should start near zero and increase until the design Q is reached. This depth, y_1, is used to find the sequent (conjugate) depth, y_2, using the hydraulic jump equation:

$$y_2 = \frac{Cy_1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right)$$ Equation 11.6(4)

Where:

y_2	=	conjugate depth, ft
y_1	=	depth approaching the jump, ft
C	=	ratio of tailwater to conjugate depth, TW/y_2
Fr_1	=	approach Froude number

For a free hydraulic jump, C = 1.0. Section 11.6.4 provides guidance on the value of C for the SAF basin. For the jump to occur, the value of $y_2 + z_2$ must be equal to or less than TW + z_3 as shown in Figure 11.6-A. If $z_2 + y_2$ is greater than z_3 + TW, the basin must be lowered and the trial and error process repeated until sufficient tailwater exists to force the jump.

In order to perform this check, z_3 and the basin lengths must be determined. The length of the transition is calculated from:

$$L_T = \frac{z_o - z_1}{S_T} \qquad \text{Equation 11.6(5)}$$

Where:

L_T	=	length of the transition from the culvert outlet to the bottom of the basin, ft
S_T	=	slope of the transition entering the basin, ft/ft

The length of the basin, L_B, depends on the type of basin, the entrance flow depth, y_1, and the entrance Froude number, Fr_1. Figure 11.6-B describes these relationships for the free hydraulic jump and several USBR stilling basins.

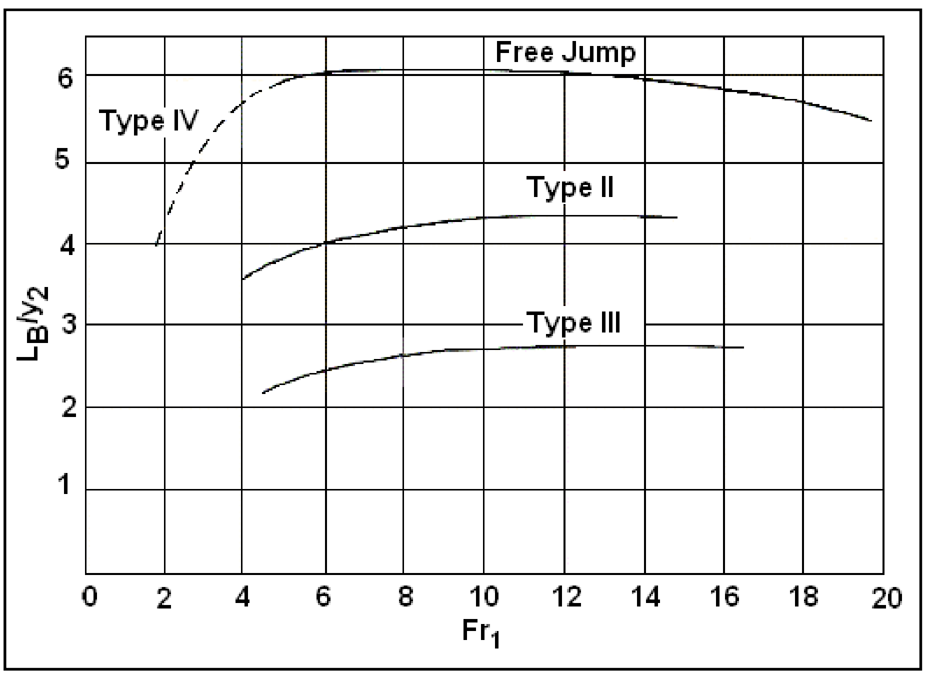


Figure 11.6-B — LENGTH OF HYDRAULIC JUMP ON A HORIZONTAL FLOOR

The length of the basin from the floor to the sill is calculated from:

$$L_S = \frac{L_T(S_T - S_o) - L_B S_o}{S_S + S_o} \qquad \text{Equation 11.6(6)}$$

Where:

L_S = length of the basin from the bottom of the basin to the basin exit (sill), ft
S_S = slope leaving the basin, ft/ft

The elevation at the entrance to the tailwater channel is then calculated from:

$$z_3 = L_S S_S + z_1 \qquad \text{Equation 11.6(7)}$$

Where:

z_3 = elevation of basin at basin exit (sill), ft

Figure 11.6-A also illustrates a radius of curvature between the culvert outlet and the transition to the stilling basin. If the transition slope is 0.5V:1H or steeper, use a circular curve at the transition with a radius defined by Equation 11.6(8). It is also advisable to use the same curved transition going from the transition slope to the stilling basin floor.

$$r = \frac{y}{e^{\frac{1.5}{Fr^2}} - 1} \qquad \text{Equation 11.6(8)}$$

Where:

r = radius of the curved transition, ft
F_r = Froude number
y = depth approaching the curvature, ft

For the curvature between the culvert outlet and the transition, the Froude number and depth are taken at the culvert outlet. For the curvature between the transition and the stilling basin floor, the Froude number and depth are taken as Fr_1 and y_1.

11.6.2 General Design Procedure

The design procedure for all stilling basins may be summarized in the following steps. Basin specific variations to these steps are discussed in the section on the SAF basin.

Step 1. Determine the velocity and depth at the culvert outlet. For the culvert outlet, calculate culvert brink depth, y_o, velocity, V_o and Fr_o. For subcritical flow, use HEC-14 (2), Figure 3.3 or Figure 3.4. For supercritical flow, use normal depth in the culvert for y_o.

Step 2. Determine the velocity and TW depth in the receiving channel downstream of the basin.

Step 3. Estimate the conjugate depth for the culvert outlet conditions using Equation 11.6(4) to determine if a basin is needed. Substitute y_o and Fr_o for y_1 and Fr_1, respectively. The value of C is dependent, in part, on the type of stilling basin to be designed. However, in this Step the occurrence of a free hydraulic jump without a basin is considered so a value of 1.0 is used. Compare y_2 and TW. If $y_2 < TW$, there is sufficient tailwater and a jump will form without a basin. The remaining steps are unnecessary.

Step 4. If Step 3 indicates a basin is needed ($y_2 > TW$), make a trial estimate of the basin bottom elevation, z_1, a basin width, W_B and slopes S_T and S_S. A slope of 0.5 (0.5V:1H) or 0.33 (0.33V:1H) is satisfactory for both S_T and S_S. Confirm that W_B is within acceptable limits using Equation 11.6(3). Determine the velocity and depth conditions entering the basin and calculate the Froude number. Select candidate basins based on this Froude number.

Step 5. Calculate the conjugate depth for the hydraulic conditions entering the basin using Equation 11.6(4) and determine the basin length and exit elevation. Basin length and exit elevation are computed using Equations 11.6(5), 11.6(6) and 11.6(7). Verify that sufficient tailwater exists to force the hydraulic jump. If the tailwater is insufficient go back to Step 4. If excess tailwater exists, the hydraulics designer may either go on to Step 6 or return to Step 4 and try a shallower (and smaller) basin.

Step 6. Determine the needed radius of curvature for the slope changes entering the basin using Equation 11.6(8).

Step 7. Size the basin elements for basin types other than a free hydraulic jump basin. The details for this process differ for each basin and are included in the individual basin sections.

11.6.3 Design Example: Stilling Basin with Free Hydraulic Jump

Find the dimensions for a stilling basin (see Figure 11.6-A) with a free hydraulic jump providing energy dissipation for a reinforced concrete box culvert. Given:

Q = 417 cfs

Culvert

B = 10.0 ft

D = 6 ft

n = 0.015

S_o = 0.065 ft/ft

z_o = 100 ft

Downstream channel (trapezoidal)

B = 10.2 ft

Z = 1V:2H

n = 0.030

Solution

Step 1. Determine the velocity and depth at the culvert outlet. By trial and error using Manning's Equation, the normal depth is calculated as:

V_o = 27.8 fps, y_o = 1.50 ft

$$Fr_o = \frac{V_o}{\sqrt{gy_o}} = \frac{27.8}{\sqrt{32.2(1.50)}} = 4.0$$

Because the Froude number is greater than 1.0, the normal depth is supercritical and the normal depth is taken as the brink depth.

Step 2. Determine the velocity and tailwater depth (TW) in the receiving channel. By trial and error using Manning's Equation:

V_n = 15.9 fps, y_n = TW = 1.88 ft

Step 3. Estimate the conjugate depth for the culvert outlet conditions using Equation 11.6(4). C = 1.0.

$$y_2 = \frac{Cy_o}{2}\left(\sqrt{1+8Fr_o^2}-1\right) = \frac{1.0(1.50)}{2}\left(\sqrt{1+8(4.0)^2}-1\right) = 7.8 \text{ ft}$$

Because y_2 (7.8 ft) > TW (1.88 ft) a jump will not form and a basin is needed.

Step 4. Because y_2 - TW = 8.55 – 1.88 = 6.67 ft, try $z_1 = z_o$ – 6.67 = 93.3 ft, use 93.

Also, choose W_B = 10.0 ft (no expansion from culvert to basin) and slopes S_T = 0.5 and S_S = 0.5. Check W_B using Equation 11.6(3), but first calculate the transition length from Equation 11.6(5).

$$L_T = \frac{z_o - z_1}{S_T} = \frac{100-93}{0.5} = 14 \text{ ft}$$

$$W_B \le W_o + \frac{2L_T\sqrt{S_T^2+1}}{3Fr_o} = 10.0 + \frac{2(14)\sqrt{(0.5)^2+1}}{3(4.0)} = 12.6 \text{ ft ; WB is OK}$$

By using Equation 11.6(2) or other appropriate method by trial and error, the velocity and depth conditions entering the basin are:

V_1 = 35.3 fps, y_1 = 1.18 ft

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}} = \frac{35.3}{\sqrt{32.2(1.18)}} = 5.7$$

Step 5. Calculate the conjugate depth for a free hydraulic jump (C=1) using Equation 11.6(4).

$$y_2 = \frac{Cy_1}{2}\left(\sqrt{1+8Fr_1^2}-1\right) = \frac{1.0(1.18)}{2}\left(\sqrt{1+8(5.7)^2}-1\right) = 8.94 \text{ ft}$$

From Figure 11.6-B basin length, L_B/y_2 = 6.1. Therefore, L_B = 6.1(8.94) = 54.5 ft.

The length of the basin from the floor to the sill is calculated from Equation 11.6(6):

$$L_S = \frac{L_T(S_T - S_o) - L_B S_o}{S_S + S_o} = \frac{14(0.5-0.065) - 54.5(0.065)}{0.5+0.065} = 4.5 \text{ ft}$$

The elevation at the entrance to the tailwater channel is from Equation 11.6(7):

$$z_3 = L_S S_S + z_1 = 4.5(0.5) + 93.0 = 95.25 \text{ ft}$$

Because $y_2 + z_2$ (8.94 + 93) > z_3 + TW (95.25 + 1.88), tailwater is not sufficient to force a jump in the basin. Go back to Step 4.

<u>Step 4 (2nd iteration)</u>. Try z_1 = 84.5 ft. Maintain W_B, S_T and S_S.

$$L_T = \frac{z_o - z_1}{S_T} = \frac{100-84.5}{0.5} = 31.0 \text{ ft}$$

By using Equation 11.6(2) or other appropriate method by trial and error, the velocity and depth conditions entering the basin are:

V_1 = 42.5 fps, y_1 = 0.98 ft

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}} = \frac{42.5}{\sqrt{32.2(0.98)}} = 7.6$$

<u>Step 5 (2nd Iteration)</u>. Calculate the conjugate depth for a free hydraulic jump (C=1) using Equation 11.6(4).

$$y_2 = \frac{Cy_1}{2}\left(\sqrt{1+8Fr_1^2}-1\right) = \frac{1.0(0.98)}{2}\left(\sqrt{1+8(7.6)^2}-1\right) = 10.07 \text{ ft}$$

From Figure 11.6-B basin length, L_B/y_2 = 6.1. Therefore, L_B = 6.1(10.07) = 61.4 ft.

The length of the basin from the floor to the sill is calculated from Equation 11.6(6):

$$L_S = \frac{L_T(S_T - S_o) - L_B S_o}{S_S + S_o} = \frac{31.0(0.5-0.065) - 61.4(0.065)}{0.5+0.065} = 16.8 \text{ ft}$$

The elevation at the entrance to the tailwater channel is from Equation 11.6(7):

$$z_3 = L_S S_S + z_1 = 16.8(0.5) + 84.5 = 92.90 \text{ ft}$$

Because $y_2 + z_2$ (10.1 + 84.5) < z_3 + TW (92.90 + 1.88), tailwater is sufficient to force a jump in the basin. Continue on to Step 6.

Step 6. For the slope change from the outlet to the transition, determine the needed radius of curvature using Equation 11.6(8) and the results from step 1.

$$\mathbf{r = \frac{y}{e^{\frac{1.5}{Fr^2}} - 1} = \frac{1.50}{e^{\frac{1.5}{(4.0)^2}} - 1} = 15.3\ ft}$$

Step 7. Size the basin elements. Because this is a free hydraulic jump basin, there are no additional elements and the design is complete. The basin is shown in the following sketch. Total basin length = 31.0 + 61.4 + 16.8 = 109.2 ft

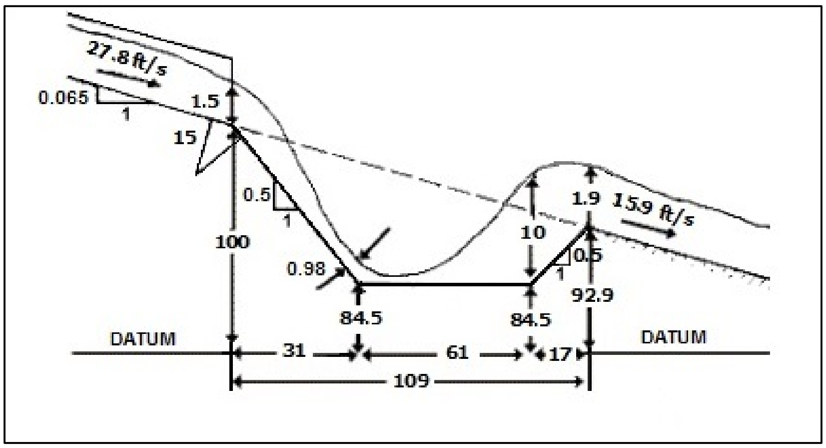


Figure 11.6-C — SKETCH FOR FREE HYDRAULIC JUMP STILLING BASIN DESIGN EXAMPLE

11.6.4 SAF Stilling Basin

The Saint Anthony Falls (SAF) stilling basin, shown in Figure 11.6-D from HEC-14 (2), provides chute blocks, baffle blocks and an end sill that allows the basin to be shorter than a free hydraulic jump basin. It is recommended for use at small structures such as spillways, outlet works and canals where the Froude number at the dissipator entrance is between 1.7 and 17. The reduction in basin length achieved through the use of appurtenances is about 80% of the free hydraulic jump length. The SAF stilling basin provides an economical method of dissipating energy and preventing stream bed erosion.

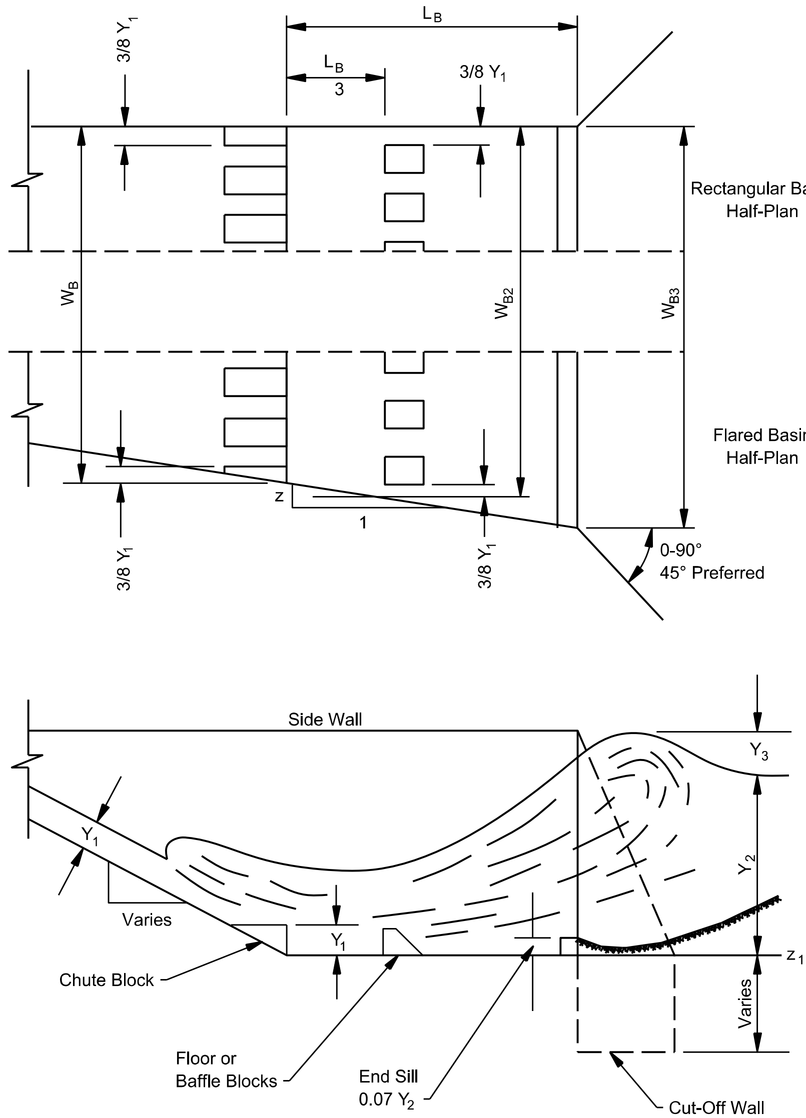


Figure 11.6-D — SAF STILLING BASIN

The general design procedure outlined in Section 11.6.2 applies to the SAF stilling basin. Steps 1 through 3 and Step 6 are applied without modification. As part of Step 4, the hydraulics designer selects a basin width, W_B. For box culverts, W_B must equal the culvert width, W_o. For circular culverts, the basin width is taken as the larger of the culvert diameter and the value calculated according to the following equation:

$$W_B = 1.7 D_o \left(\frac{Q}{g^{0.5} D_o^{2.5}} \right)$$ Equation 11.6(9)

Where:

W_B = basin width, ft

Q = design discharge, cfs
D_o = culvert diameter, ft

The basin can be flared to fit an existing channel as indicated on Figure 11.6-D. The sidewall flare dimension z should not be greater than 0.5, i.e., 0.5:1, 0.33:1 or flatter.

For Step 5, two adaptations to the general design procedure are made. First, for computing conjugate depth, C is a function of Froude number as given by the following set of equations. Depending on the Froude number, C ranges from 0.64 to 1.08 implying that the SAF basin may operate with less tailwater than the USBR basins, though tailwater is still required.

$$C = 1.1 - \frac{Fr_1^2}{120} \quad \text{when } 1.7 < Fr_1 < 5.5$$ Equation 11.6(10a)

$$C = 0.85 \quad \text{when } 5.5 < Fr_1 < 11$$ Equation 11.6(10b)

$$C = 1.0 - \frac{Fr_1^2}{800} \quad \text{when } 11 < Fr_1 < 17$$ Equation 11.6(10c)

The second adaptation is the determination of the basin length, L_B, using Equation 11.6(11).

$$L_B = \frac{4.5y_2}{CFr_1^{0.76}}$$ Equation 11.6(11)

For Step 7, sizing the basin elements (chute blocks, baffle blocks and an end sill), the following guidance is recommended. The height of the chute blocks, h_1, is set equal to y_1.

The number of chute blocks is determined by Equation 11.6(12) rounded to the nearest integer.

$$N_c = \frac{W_B}{1.5y_1}$$ Equation 11.6(12)

Where:

N_c = number of chute blocks

Block width and block spacing are determined by:

$$W_1 = W_2 = \frac{W_B}{2N_c}$$ Equation 11.6(13)

Where:

W_1 = block width, ft
W_2 = block spacing, ft

Equations 11.6(12) and 11.6(13) will provide N_c blocks and N_c spaces between those blocks. A half block is placed at the basin wall so there is no space at the wall.

The height, width and spacing of the baffle blocks are shown on Figure 11.6-D. The height of the baffles, h_3, is set equal to the entering flow depth, y_1.

The width and spacing of the baffle blocks must account for any basin flare. If the basin is flared as shown in Figure 11.6-D, the width of the basin at the baffle row is computed according to the following:

$$W_{B2} = W_B + \left(\frac{2zL_B}{3}\right) \qquad \text{Equation 11.6(14)}$$

Where:

W_{B2}	=	basin width at the baffle row, ft
L_B	=	basin length, ft
z	=	basin flare, z:1 as defined in Figure 11.6-D (z = 0.0 for no flare)

The top thickness of the baffle blocks should be set at $0.2h_3$ with the back slope of the block on a 1:1 slope. The number of baffle blocks is as follows:

$$N_B = \frac{W_{B2}}{1.5y_1} \qquad \text{Equation 11.6(15)}$$

Where:

N_B	=	number of baffle blocks (rounded to an integer)

Baffle width and spacing are determined by:

$$W_3 = W_4 = \frac{W_{B2}}{2N_B} \qquad \text{Equation 11.6(16)}$$

Where:

W_3	=	baffle width, ft
W_4	=	baffle spacing, ft

Equations 11.6(15) and 11.6(16) will provide N_B baffles and N_{B-1} spaces between those baffles. The remaining basin width is divided equally for spaces between the outside baffles and the basin sidewalls. No baffle block should be placed closer to the sidewall than $3y_1/8$. Verify that the percentage of W_{B2} obstructed by baffles is between 40% and 55%. The distance from the downstream face of the chute blocks to the upstream face of the baffle block should be $L_B/3$.

The height of the final basin element, the end sill, is given as:

$$h_4 = \frac{0.07y_2}{C} \qquad \text{Equation 11.6(17)}$$

Where:

h_4 = height of the end sill, ft

The fore slope of the end sill should be set at 0.5:1 (V:H). If the basin is flared the length of sill (width of the basin at the sill) is:

$$W_{B3} = W_B + 2zL_B \qquad \text{Equation 11.6(18)}$$

Where:

W_{B3} = basin width at the sill, ft
L_B = basin length, ft
z = basin flare, z:1 as defined in Figure 11.6-D (z = 0.0 for no flare)

Wingwalls should be equal in height and length to the stilling basin sidewalls. The top of the wingwall should have a 1H:1V slope. Flaring wingwalls are preferred to perpendicular or parallel wingwalls. The best overall conditions are obtained if the triangular wingwalls are located at an angle of 45° to the outlet centerline.

The stilling basin sidewalls may be parallel (rectangular stilling basin) or diverge as an extension of the transition sidewalls (flared stilling basin). The height of the sidewall above the floor of the basin is given by:

$$h_5 \geq y_2\left(1 + \frac{1}{3C}\right) \qquad \text{Equation 11.6(19)}$$

Where:

h_5 = height of the sidewall, ft

A cut-off wall should be used at the end of the stilling basin to prevent undermining. The depth of the cut-off wall must be greater than the maximum depth of anticipated erosion at the end of the stilling basin.

11.6.5 Design Example: SAF Stilling Basin

Design a SAF stilling basin with no flare for a reinforced concrete box culvert. Given:

Q = 417 cfs
Culvert
B = 10.0 ft
D = 6.0 ft
n = 0.015
S_o = 0.065 ft/ft
z_o = 100.0 ft
Downstream channel (trapezoidal)
B = 10.2 ft

Z	=	1V:2H
n	=	0.030

Solution

The culvert, design discharge and tailwater channel are the same as considered for the free hydraulic jump stilling basin addressed in the design example in Section 11.6.3. Steps 1 through 3 of the general design process are identical for this example so they are not repeated here. The tailwater depth from the previous design example is TW = 1.88 ft.

Step 4. Try z_1 = 91.40 ft. W_B = 10.0 ft (no flare), S_T = 0.5 ft/ft and S_S = 0.5 ft/ft. From Equation 11.6(5):

$$L_T = \frac{z_o - z_1}{S_T} = \frac{100.0 - 91.4}{0.5} = 17.2 \text{ ft}$$

By using Equation 11.6(2) or other appropriate method by trial and error, the velocity and depth conditions entering the basin are:

V_1 = 36.8 fps, y_1 = 1.13 ft

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}} = \frac{36.8}{\sqrt{32.2(1.13)}} = 6.1$$

Step 5. Calculate the conjugate depth in the basin using Equation 11.6(4). First estimate C using Equation 11.6(10). For the calculated Froude number, C = 0.85.

$$y_2 = \frac{Cy_1}{2}\left(\sqrt{1+8Fr_1^2} - 1\right) = \frac{0.85(1.13)}{2}\left(\sqrt{1+8(6.1)^2} - 1\right) = 7.85 \text{ ft}$$

From Equation 11.6(11) basin length is calculated:

$$L_B = \frac{4.5y_2}{CFr_1^{0.76}} = \frac{4.5(7.85)}{0.85(6.1)^{0.76}} = 10.5 \text{ ft}$$

The length of the basin from the floor to the sill is calculated from Equation 11.6(6):

$$L_S = \frac{L_T(S_T - S_o) - L_B S_o}{S_S + S_o} = \frac{17.2(0.5 - 0.065) - 10.5(0.065)}{0.5 + 0.065} = 12.0 \text{ ft}$$

The elevation at the entrance to the tailwater channel is from Equation 11.6(7):

$Z_3 = L_S S_S + Z_1$ = 12.0(0.5) + 91.40 = 97.40 ft

Because $y_2 + z_2$ (7.85 + 91.40) < z_3 + TW (97.40 + 1.88), tailwater is sufficient to force a jump in the basin. If tailwater had not been sufficient, repeat Step 4 with a lower assumption for z_1.

<u>Step 6</u>. Determine the needed radius of curvature for the slope changes entering the basin. See the design example Section 11.6.3 for this step. It is unchanged.

<u>Step 7</u>. Size the basin elements. For the SAF basin, the elements include the chute blocks, baffle blocks and an end sill.

For the chute blocks:

The height of the chute blocks, h_1=y_1=1.13 (round to 1.1 ft).

The number of chute blocks is determined by Equation 11.6(12):

$$N_c = \frac{W_B}{1.5y_1} = \frac{10.0}{1.5(1.13)} = 5.9 \approx 6$$

Block width and block spacing are determined by Equation 11.6(13):

$$W_1 = W_2 = \frac{W_B}{2N_c} = \frac{10.0}{2(6)} = 0.8 \text{ ft}$$

A half block is placed at each basin wall so there is no space at the wall.

For the baffle blocks:

The height of the baffles, h_3 = y_1 = 1.13 ft. (round to 1.1 ft)
The basin has no flare so the width in the basin is constant and equal to W_B.

The number of baffles blocks is from Equation 11.6(15):

$$N_B = \frac{W_{B2}}{1.5y_1} = \frac{10.0}{1.5(1.13)} = 5.9 \approx 6$$

Baffle width and spacing are determined from Equation 11.6(16). In this case, W_{B2}=W_B.

$$W_3 = W_4 = \frac{W_{B2}}{2N_B} = \frac{10.0}{2(6)} = 0.8 \text{ ft}$$

For this design, we have six baffles at 0.8 ft and 5 spaces between them at 0.8 ft. The remaining 1.2 ft is divided in half and provided as a space between the sidewall and the first baffle.

The total percentage blocked by baffles is 6(0.8)/10.0 = 48%, which falls within the acceptable range of between 40% and 55%.

The distance from the downstream face of the chute blocks to the upstream face of the baffle block equals L_B/3 = 10.5/3 = 3.5 ft.

For the sill:

The height of the end sill, is given in Equation 11.6(17):

$$h_4 = \frac{0.07y_2}{C} = \frac{0.07(7.85)}{0.85} = 0.6 \text{ ft}$$

Total basin length = 17.2 + 10.5 + 12.0 = 39.7 ft. The basin is shown in the following sketch.

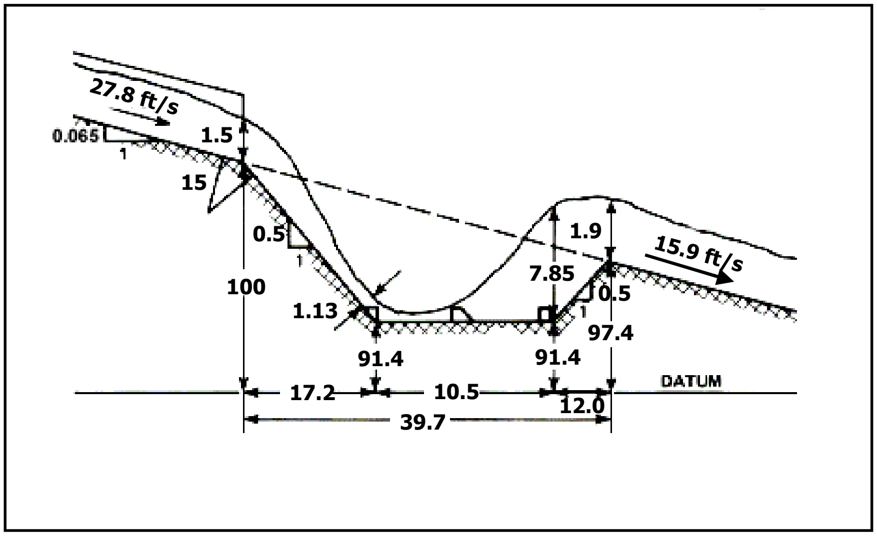


Figure 11.6-E — SKETCH FOR SAF STILLING BASIN DESIGN EXAMPLE

11.6.6 Design Example: SAF Stilling Basin using HY-8 Version 7.3

The Section 11.6.5 example can also be solved with HY-8. The first step is to duplicate the outlet conditions (y_o = 1.5 ft and V_o = 27.8 fps) shown above by creating appropriate site conditions for the 10 x 6 ft RCB:

- Tailwater Data – trapezoidal channel with 10.2 ft bottom width, 2:1 side slopes, 0.065 ft/ft channel slope, Mannings's n of 0.03 and invert elevation of 100 ft
- Roadway Data – constant roadway elevation, crest length of 300 ft, crest elevation of 160 ft, paved roadway, top width of 40 ft
- Culvert Data – RCB 10 x 6, n = 0.015, no embedment, straight, square edge, no depression
- Site Data – Inlet (station 0, elevation 138), outlet (station 595, elevation 100), 1 barrel

The above site conditions give a y_o = 1.5 ft and V_o = 27.83 fps for 417 cfs. Select energy dissipator option, select at top design external dissipator and below culvert data select stilling basin, SAF basin and rectangular shape to make basin the same width as culvert:

- y_1 = 1.132 ft, V_1 = 36.82 fps, y_2 = 7.89 ft, V_B = 15.884 fps
- Basin Length (L) is 39.8 ft, (L_T = 17.14 ft, L_B = 10.57 ft, L_S = 12.06 ft)

- Basin elevations: floor (z_1) = 91.48 ft and exit (z_3) = 97.46 ft
- Chute blocks: No. = 6, height (H_1) =1.13 ft and width (W_1) = 0.833 ft
- Baffle blocks: No. = 6, height (H_1) =1.13 ft and width (W_1) = 0.833 ft
- Baffle block location: 3.52 ft from chute blocks
- End sill: height (H_3) = 0.65 ft

11.7 DROP STRUCTURES

Drop structures are commonly used for flow control and energy dissipation. Changing the channel slope from steep to mild, by placing drop structures at intervals along the channel reach, changes a continuous steep slope into a series of gentle slopes and vertical drops. Instead of slowing down and transferring high erosion producing velocities into low non-erosive velocities, drop structures control the slope of the channel in such a way that the high, erosive velocities never develop. The kinetic energy or velocity gained by the water as it drops over the crest of each structure is dissipated by a specially designed apron or stilling basin.

The drop structures discussed here (see Figure 11.7-A) require an aerated nappe and are, in general, for subcritical flow in the upstream as well as downstream channel. The effect of upstream supercritical flow on drop structure design is discussed in a later section. The stilling basin protects the channel against erosion below the drop and dissipates energy. This is accomplished through the impact of the falling water on the floor, redirection of the flow and turbulence. The stilling basin used to dissipate the excess energy can vary from a simple concrete apron to an apron with flow obstructions such as baffle blocks, sills or abrupt rises. The length of the concrete apron required can be shortened by the addition of these appurtenances.

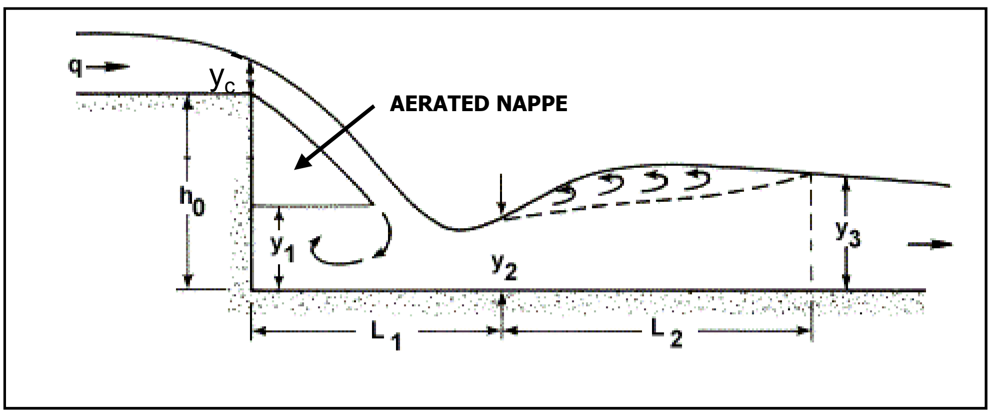


Figure 11.7-A — FLOW GEOMETRY OF A STRAIGHT DROP SILLWAY

The drop number gives a quantitative measure for drop:

$$N_d = \frac{q^2}{gh_o^3} \qquad \text{Equation 11.7(1)}$$

Where:

N_d	=	drop number
q	=	unit discharge, cfs/ft
g	=	acceleration due to gravity, 32.2 ft/s^2
h_o	=	drop height, ft

Another commonly used quantitative measure for drop is given by:

$$D_r = \frac{h_o}{y_c}$$ Equation 11.7(2)

Where:

D_r	=	relative drop
y_c	=	critical depth at the drop, ft
h_o	=	drop height, ft

Drop structures may be categorized based on either Equations 11.7(1) or 11.7(2). Drops for which N_d is greater than 1 or relative drop D_r is less than 1 are considered "low drop" structures. Two dissipators are discussed in HEC-14 (2); the straight drop structure and the box inlet drop structure. Neither of these is considered low drop structures. ODOT uses only the straight drop structure.

11.7.1 Straight Drop Structure

A straight drop structure is characterized by flow through a rectangular weir followed by a drop into a stilling basin. The stilling basin may be a flat apron or an apron with various baffles and sills depending on the site conditions. First, a simple stilling basin is considered followed by discussion of other features available to modify the drop structure performance.

The basic flow geometry of a straight drop structure is shown in Figure 11.7-A. The discharge passes through critical depth as it flows over the drop structure crest. The free-falling nappe reverses its curvature and turns smoothly into supercritical flow on the apron at the distance L_1 from the drop wall. The mean velocity at the distance L_1 is parallel to the apron; the depth y_2 is the smallest depth in the downstream channel and the pressure is nearly hydrostatic. The depth of supercritical flow in the downstream direction increases due to channel resistance and, at some point, will reach a depth sufficient for the formation of a hydraulic jump.

For a given drop height, h_o, and discharge, q, the sequent depth, y_3, in the downstream channel and the drop length, L_1, may be computed. The length of jump L_j, is discussed in Section 11.6. The drop number can be used to estimate the dimensions of a simple straight drop structure.

$$L_1 = 4.30 h_o N_d^{0.27}$$ Equation 11.7(3a)

$$y_1 = 1.0 h_o N_d^{0.22}$$ Equation 11.7(3b)

$$y_2 = 0.54 h_o N_d^{0.425}$$ Equation 11.7(3c)

$$y_3 = 1.66 h_o N_d^{0.27}$$ Equation 11.7(3d)

Where:

L_1 = drop length (the distance from the drop wall to the position of the depth y_2, ft
y_1 = pool depth under the nappe, ft
y_2 = depth of flow at the toe of the nappe or the beginning of the hydraulic jump, ft
y_3 = tailwater depth sequent to y_2, ft

By comparing the channel tailwater depth, TW, with the computed, y_3, one of the following cases will occur. The case will determine design modifications necessary to the structure.

1. <u>TW > y_3</u>. The hydraulic jump will be submerged and the basin length may need to be increased.

2. <u>TW = y_3</u>. The hydraulic jump begins at depth y_2, no supercritical flow exists on the apron and the distance L_1 is a minimum. In this case, the basin will function without additional design modifications.

3. <u>TW < y_3</u>. The hydraulic jump will recede downstream and the basin will not function.

For Case 3, when the tailwater depth is less than y_3, it is necessary to modify the basin to force the hydraulic jump to stay in the basin. Two alternatives to achieve this are to provide an apron:

- at the bed level with an end sill or baffles to trigger the jump in the basin, or

- depressed below the downstream bed level to effectively increase tailwater with an end sill.

The choice of design type and the design dimensions will depend, for a given unit discharge, q, on the drop height, h_o, and on the downstream depth, TW. The apron may be designed to extend to the end of the hydraulic jump. However, including an end sill allows the use of a shorter and more economical stilling basin.

The geometry of the undisturbed flow should be taken into consideration in the design of a straight drop structure. If the overfall crest length is less than the width of the approach channel, it is important that a transition be properly designed by shaping the approach channel to reduce the effect of end contractions. Otherwise, the contraction at the ends of the spillway notch may be so pronounced that the jet will land beyond the stilling basin and the concentration of high velocities at the center of the outlet may cause additional scour in the downstream channel.

11.7.2 <u>Straight Drop Structure Design Features</u>

A general design for a stilling basin at the toe of a drop structure was developed by the Agricultural Research Service, St. Anthony Falls Hydraulic Laboratory, University of Minnesota and is included in HEC-14 (2). The basin consists of a horizontal apron with blocks and sills to dissipate energy as shown in Figure 11.7-B. Tailwater also influences the amount of energy dissipated. The stilling basin length computed for the minimum tailwater level required for good performance may be inadequate at high tailwater levels. Scour of the downstream channel may occur if the nappe is supported sufficiently by high tailwater so that it lands beyond the end of the stilling basin. A method for computing the stilling basin length for all tailwater levels is presented.

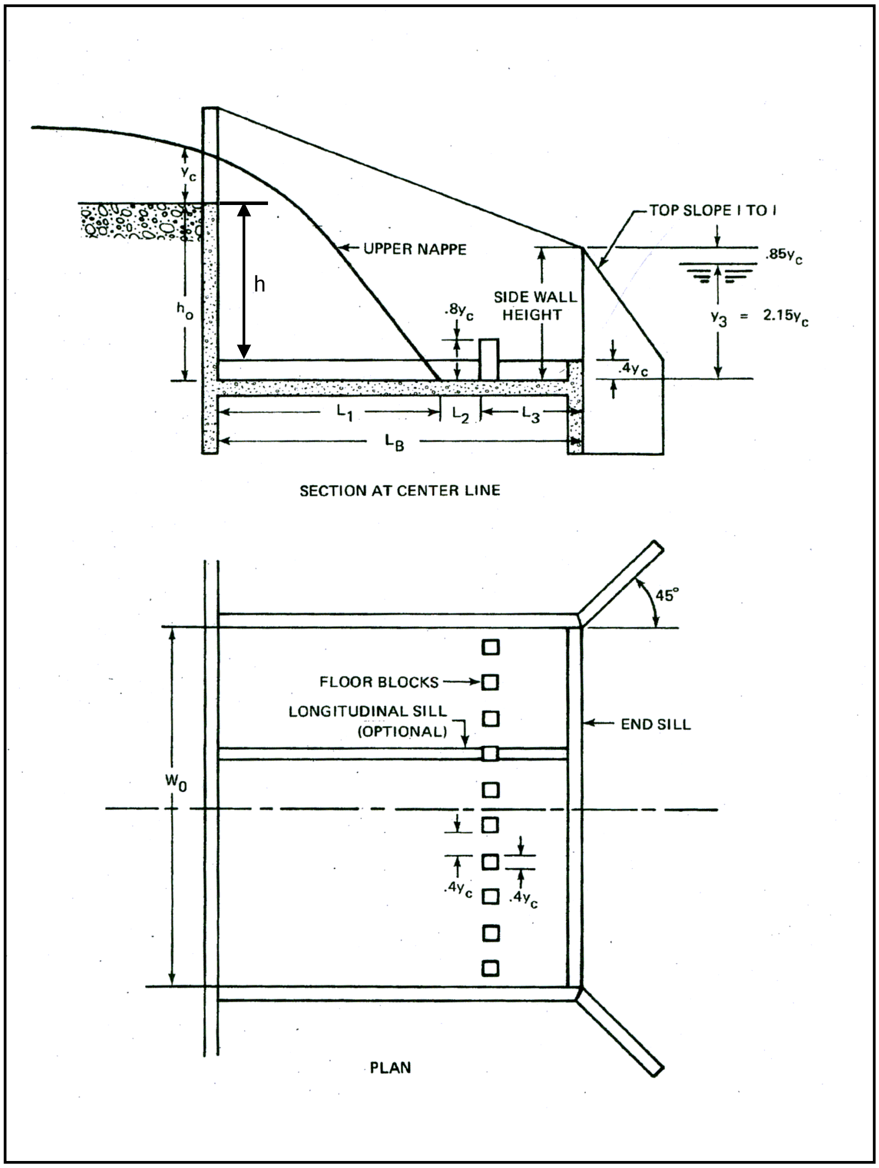


Figure 11.7-B — STRAIGHT DROP STRUCTURE

The recommended design is limited to the following conditions:

- Total drop, h_o, less than 15 ft with sufficient tailwater.
- Relative drop, h_o/y_c, between 1.0 and 15.
- Crest length, W_o, greater than $1.5y_c$.

The elements that must be considered in the design of this stilling basin include the length of basin, the position and size of floor blocks, the position and height of end sill, the position of the wingwalls and the approach channel geometry. Figure 11.7-B illustrates a straight drop structure that provides adequate protection from scour in the downstream channel.

Many of the design parameters for the straight drop structure are based on the critical depth. Critical depth in a rectangular channel or culvert is calculated from the unit discharge (discharge divided by culvert/chute width, B).

$$y_c = \left(\frac{q^2}{g}\right)^{1/3}$$ Equation 11.7(4)

Where:

y_c = critical depth, ft
q = unit discharge (Q/B), $ft^2/s/ft$

Critical flow for an open channel of any shape will occur when:

$$\frac{Q^2 T_c}{g A_c^3} = 1$$ Equation 11.7(5)

Where:

T_c = water surface width at critical flow condition, ft
A_c = flow area at critical flow condition, ft^2

As discussed earlier, the tailwater must neither be too high nor too low. Therefore, the following relationships must be achieved in the design. First, the tailwater depth above the floor of the stilling basin must be calculated from Equation 11.7(6).

$$y_3 = 2.15 y_c$$ Equation 11.7(6)

Where:

y_3 = tailwater depth above the floor of the stilling basin, ft

The tailwater also needs to be a distance below the crest to maintain the aerated nappe trajectory as given below. Using the crest as the reference point, this distance is a negative number.

$$h_2 = -(h - y_o)$$ Equation 11.7(7)

Where:

h_2 = vertical distance of the tailwater below the crest, ft
h = vertical drop between the approach and tailwater channels, ft

y_o = normal depth in the tailwater channel (equals normal depth in approach channel assuming same channel characteristics), ft

To achieve sufficient tailwater and to maintain adequate drop from the crest to the tailwater, it is sometimes necessary to depress the floor below the elevation of the tailwater channel. The total drop from the crest to the stilling basin floor is given by:

$$h_o = h_2 - y_3$$ Equation 11.7(8)

Where:

h_o = drop from crest to stilling basin floor, ft

The horizontal dimensions of the basin must also be established. From Figure 11.7-B, it can be seen that the total basin length is the sum of three components.

$$L_B = L_1 + L_2 + L_3$$ Equation 11.7(9)

Where:

L_B = stilling basin length, ft

L_1 = distance from the headwall to the point where the surface of the upper nappe strikes the stilling basin floor, ft

L_2 = distance from the point where the surface of the upper nappe strikes the stilling basin floor to the upstream face of the floor blocks, ft

L_3 = distance from the upstream face of the floor blocks to the end of the stilling basin, ft

L_1 is given by:

$$L_1 = \frac{L_f + L_s}{2}$$ Equation 11.7(10)

Where:

L_f = length given by Equation 11.7(11) ft
L_s = length given by Equation 11.7(12), ft

$$L_f = \left(-0.406 + \sqrt{3.195 - 4.368 \frac{h_o}{y_c}} \right) y_c$$ Equation 11.7(11)

$$L_s = \frac{\left(0.691 + 0.228\left(\frac{L_t}{y_c}\right)^2 - \left(\frac{h_o}{y_c}\right)\right)y_c}{0.185 + 0.456\left(\frac{L_t}{y_c}\right)} \quad \text{Equation 11.7(12)}$$

Where:

$$L_t = \left(-0.406 + \sqrt{3.195 - 4.368\frac{h_2}{y_c}}\right)y_c \quad \text{Equation 11.7(13)}$$

L_2 and L_3 are determined by:

$$L_2 = 0.8y_c \quad \text{Equation 11.7(14)}$$

$$L_3 \geq 1.75y_c \quad \text{Equation 11.7(15)}$$

In comparison with the simple straight drop structure discussed in Section 11.7.1, the addition of floor blocks and a sill, allows for a shorter basin as given by Equation 11.7(9). The floor blocks should be proportioned to have a height of $0.8y_c$ with a width and spacing of $0.4y_c$. The basin will perform acceptably if the width and spacing varies within plus or minus $0.15y_c$. The blocks should be square in plan and should occupy between 50% and 60% of the stilling basin width.

The end sill height should be $0.4y_c$. Longitudinal sills, as shown in Figure 11.7-B, are optional from a hydraulic perspective. If needed, they reinforce the basin structurally, but should pass through the blocks, not between them.

Final consideration is given to the configuration of the exit of the basin as well as the transition from the approach channel to the basin. With respect to the exit, the sidewall height at the basin exit should be above the tailwater elevation by $0.85y_c$. Wingwalls should be located at an angle of 45° with the outlet centerline and have a top slope of 1 to 1.

With respect to the approach channel, the crest of spillway should be at same elevation as the invert of the approach channel. The bottom width of the approach channel should be equal to the spillway notch length, W_o, at the headwall. Because of the acceleration as the flow approaches the crest, riprap or paving should be provided for a distance upstream from the headwall equal to $3y_c$.

11.7.3 Straight Drop Design Procedure

The design procedure for the straight drop structure may be summarized in the following steps.

Step 1. Estimate the elevation difference required between the approach and tailwater channel, h. This may be to address a drop at the outlet of a culvert resulting from erosion or headcutting or it may be to flatten a channel to a series of subcritical slopes and drops.

Step 2. Calculate normal flow conditions approaching the drop to verify subcritical conditions. If not subcritical, repeat Step 1.

Step 3. Calculate critical depth over the weir (usually rectangular) into the drop structure. Calculate the vertical dimensions of the stilling basin using Equations 11.7(6) through 11.7(8).

Step 4. Estimate the basin length using Equations 11.7(9) through 11.7(15).

Step 5. Design the basin floor blocks and end sill.

Step 6. Design the basin exit and entrance transitions.

11.7.4 Design Example: Straight Drop Structure

Find the dimensions for a straight drop structure with a rectangular weir used to reduce channel slope. Given:

Q = 250 cfs
h = 6.0 ft
W_o = 10.0 ft

Upstream and downstream channel (trapezoidal)

B = 10.0 ft
Z = 1V:3H
S_o = 0.002 ft/ft (after providing for drop)
n = 0.030

Solution

Step 1. Estimate the required approach and tailwater channel elevation difference, h. This is estimated and given above as 6.0 ft. This drop forces the slope of the upstream and downstream channel to 0.002 ft/ft, as given.

Step 2. Calculate normal flow conditions approaching the drop to verify subcritical conditions. By trial and error:

y_o = 3.36 ft, V_o = 3.71 fps, Fr_o = 0.36; therefore, flow is subcritical.
Proceed to Step 3.

Step 3. Calculate critical depth over the weir into the drop structure. Calculate the vertical dimensions of the stilling basin. Start by finding the critical depth over the weir using Equation 11.7(4) based on the unit discharge, q = Q/B = 250/10 = 25 cfs/ft.

$$y_c = \left(\frac{q^2}{g}\right)^{1/3} = \left(\frac{25^2}{32.2}\right)^{1/3} = 2.69 \text{ ft}$$

The required tailwater depth above the floor of the stilling basin is calculated from Equation 11.7(6).

$y_3 = 2.15y_c = 2.15(2.69) = 5.77$ ft

The distance from the crest down to the tailwater needs to be calculated using Equation 11.7(7). (The negative indicates the tailwater elevation is below the crest.)

$h_2 = -(h - y_o) = -(6.0 - 3.36) = -2.64$ ft

The total drop from the crest to the stilling basin floor is given by Equation 11.7(8):

$h_o = h_2 - y_3 = -2.64 - 5.77 = -8.41$ ft (round to –8.4)

Because the nominal drop, h, is 6.0 ft, the floor must be depressed by 2.4 ft

Step 4. Estimate the basin length. Use Equations 11.7(11), 11.7(12) and 11.7(13).

$$L_f = \left(-0.406 + \sqrt{3.195 - 4.368\frac{h_o}{y_c}}\right)y_c = \left(-0.406 + \sqrt{3.195 - 4.368\frac{-8.41}{2.69}}\right)2.69 = 9.94 \text{ ft}$$

$$L_t = \left(-0.406 + \sqrt{3.195 - 4.368\frac{h_2}{y_c}}\right)y_c = \left(-0.406 + \sqrt{3.195 - 4.368\frac{-2.64}{2.69}}\right)2.69 = 6.26 \text{ ft}$$

$$L_s = \frac{\left(0.691 + 0.228\left(\frac{L_t}{y_c}\right)^2 - \left(\frac{h_o}{y_c}\right)\right)y_c}{0.185 + 0.456\left(\frac{L_t}{y_c}\right)} = \frac{\left(0.691 + 0.228\left(\frac{6.26}{2.69}\right)^2 - \left(\frac{-8.41}{2.69}\right)\right)2.69}{0.185 + 0.456\left(\frac{6.26}{2.69}\right)} = 10.89 \text{ ft}$$

L_1 is given by Equation 11.7(10):

$$L_1 = \frac{L_f + L_s}{2} = \frac{9.94 + 10.89}{2} = 10.4 \text{ ft}$$

L_2 and L_3 are determined by Equations 11.7(14) and 11.7(15):

$L_2 = 0.8y_c = 0.8(2.69) = 2.2$ ft

$L_3 \geq 1.75y_c = 1.75(2.69) = 4.7$ ft

Total basin length required is given by Equation 11.7(9):

$$L_B = L_1 + L_2 + L_3 = 10.4 + 2.2 + 4.7 = 17.3 \text{ ft}$$

<u>Step 5</u>. Design the basin floor blocks and end sill.

Block height = $0.8y_c = 0.8(2.69) = 2.1$ ft
Block width = block spacing = $0.4y_c = 0.4(2.69) = 1.1$ ft
End sill height = $0.4y_c = 0.4(2.69) = 1.1$ ft

<u>Step 6</u>. Design the basin exit and entrance transitions.

Sidewall height above tailwater elevation = $0.85y_c = 0.85(2.69) = 2.3$ ft
Armour approach channel above headwall to length = $3y_c = 3(2.69) = 8.1$ ft

11.7.5 <u>Design Example: Straight Drop Structure Using HY-8 Version 7.3</u>

The Section 11.7.4 example can also be solved with HY-8. The first step is to duplicate the upstream and downstream channel conditions shown above by creating appropriate site conditions:

- Tailwater Data – trapezoidal channel with 10 ft bottom width, 3:1 side slopes, 0.002 ft/ft slope and invert elevation of 99.6 and n = 0.03
- Roadway Data – constant roadway elevation, crest length of 100 ft, crest elevation of 120 ft, paved roadway, top width of 50 ft
- Culvert Data - RCB 10 x 6, n = 0.011, no embedment, straight, 1:1 bevel, no depression
- Site Data - Inlet (station 0, elevation 100), outlet (station 200, elevation 99.6), 1 barrel

The above site conditions give $y_o = 3.36$ ft and $V_{TW} = 3.70$ fps for 250 cfs. Select energy dissipator option, select at top design external dissipator and below culvert data select drop structure and straight drop structure, input 6 ft drop height and 0.002 slope:

- $y_c = 2.687$ ft, $V_c = 9.3$ fps, $h_o = -8.416$ ft
- Basin Length (L_B) is 17.3 ft, ($L_1 = 10.4$ ft, $L_2 = 2.2$ ft, $L_3 = 4.7$ ft)
- Floor blocks: height = 2.15 ft and width = 1.075 ft
- End sill height = 1.1 ft
- Side wall height = 2.3 ft

11.8 CULVERT OUTLET RIPRAP DESIGN GUIDELINES

The most commonly used device for outlet protection, primarily for culverts 60 in or smaller, is a riprap apron. They are constructed of riprap or grouted riprap at a zero grade for a distance that is often related to the outlet pipe diameter. These aprons do not dissipate significant energy except through increased roughness for a short distance. However, they do serve to spread the flow helping to transition to the natural drainage way or to sheet flow where no natural drainage way exists. However, if they are too short or otherwise ineffective, they simply move the location of potential erosion downstream. The key design elements of the riprap apron are the riprap size as well as the length, width and depth of the apron.

Several relationships have been proposed for riprap sizing for culvert aprons and several of these are discussed in greater detail in HEC-14 (2), Chapter 10 and HEC-14, Appendix D.

ODOT standard practice to protect downstream from the culvert outflow velocity is to use the dimensions provided in Figure 11.8-A.

Outflow Vel. (fps)	Riprap D_{50} (ft)	Length of Riprap in ft		Riprap Thickness	Filter Thickness	Riprap Type
		For Pipe Culvert	For Box Culvert			
6 – 9	> 0.50	2.5 × Dia.	3 × Rise	12 in	0 in	Type 1 Plain
10 – 15	> 0.80	5 × Dia.	6 × Rise	18 in	0 in	Type 1 Plain
16 – 24	> 1.20	7.5 × Dia.	9 × Rise	24 in	6 in	Type 1 Plain
Over 24	> 1.50	10 × Dia.	12 × Rise	30 in	12 in	Type 4 Grouted

Figure 11.8-A — RIPRAP DESIGN GUIDELINES FOR CULVERT OUTLETS

11.9 REFERENCES

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