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CHAPTER THIRTY-FOUR

ENERGY DISSIPATORS

34-1.0 INTRODUCTION

34-1.01 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 exacerbated by the construction of a highway or by other urban development. 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.

34-1.02 Definition

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

34-1.03 Purpose

This Chapter provides the following information.

1. 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; and

2. results of analysis using the HYDRAIN system and the HY8 software.

34-1.04 Symbols

See Figure 34-1A, Symbols, Definitions and Units.

34-2.0 DESIGN CRITERIA

34-2.01 Overview

34-2.01(01) Policy

Policy is a set of goals that establish a definite course of action or method of action and that are selected to guide and determine present and future decisions (see Section 28-4.0). Policy is implemented through design criteria for making decisions.

34-2.01(02) Design Criteria

Design criteria are the standards by which a policy is carried out or placed into action. They form the basis for the selection of the final design configuration. Listed below by categories are the design criteria which should be considered for all energy dissipator designs.

34-2.02 Dissipator Type Selection

The dissipator type selected for a site must be appropriate to the location. In this Chapter, the terms internal and external are used to indicate the location of the dissipator in relation to the culvert. An external dissipator is located outside of the culvert, and an internal dissipator is located within the culvert barrel. The following applies to type selection:

1. Internal Dissipators. Internal dissipators are used where:

    a. the scour hole at the culvert outlet is unacceptable,
    b. the right-of way is limited,
    c. debris is not a problem, and
    d. moderate velocity reduction is needed.

2. Natural Scour Holes. Natural scour holes are used where:

    a. undermining of the culvert outlet will not occur or it is practicable to be checked by a cutoff wall,

b. the expected scour hole will not cause costly property damage, and

c. there is no nuisance effect.

3. External Dissipators. External dissipators are used where:

a. the outlet scour hole is not acceptable, and
b. moderate amount of debris is present.

4. Stilling Basins. Stilling basins are used where:

a. the outlet scour hole is not acceptable, and
b. debris is present.

34-2.03 Design Limitations

The following applies.

1. Ice Buildup. If ice buildup is a factor, it shall be mitigated as follows:

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

2. Flood Frequency. The flood frequency used in the design of the energy dissipator device shall be the same flood frequency used for the culvert design.

3. Maximum Culvert Exit Velocity. The culvert exit velocity shall be less than 8 ft/s or shall be mitigated by using the following:

a. channel stabilization, and
b. energy dissipation.

4. Tailwater Relationship. The hydraulic conditions downstream shall be evaluated to determine a tailwater depth and the maximum velocity for the following:

a. open channels, and
b. lake, pond or large water body shall be evaluated using the high-water elevation that has the same frequency as the design flood for the culvert.

34-2.04 Design Options

34-2.04(01) Material Selection

The material selected for the dissipator should be based on a comparison of the total cost over the design life of alternate materials and should not be made using first cost as the only criteria. This comparison should consider replacement cost, the difficulty of construction and traffic delay.

34-2.04(02) Culvert Outlet Type

In choosing a dissipator, the selected culvert end treatment has the following implications.

1. Culvert ends which are projecting or mitered to the fill slope offer no outlet protection.

2. Headwalls provide embankment stability and erosion protection. They provide protection from buoyancy and reduce damage to the culvert.

3. Commercial end sections add little cost to the culvert and may require less maintenance, retard embankment erosion, and incur less damage from maintenance.

4. Aprons do not reduce outlet velocity but, if used, shall extend at least one culvert height downstream. They shall not protrude above the normal streambed elevation.

5. Wingwalls are used where the side slopes of the channel are unstable, where the culvert is skewed to the normal channel flow, to redirect outlet velocity or to retain fill.

34-2.04(03) Safety Considerations

Traffic should be protected from external energy dissipators by locating them outside the appropriate “clear zone” distance per Chapter Forty-nine.

34-2.05 Related Designs

34-2.05(01) Culvert

The culvert shall be designed independent of the dissipator design (see Chapter Thirty-one) with the exception of internal dissipators which may require an iterative solution. The culvert design shall be completed before the outlet protection is designed and shall include computation of outlet velocity.

34-2.05(02) Downstream Channel

The downstream channel protection shall be designed concurrently with dissipator design (see Chapter Thirty).

34-3.0 DESIGN PHILOSOPHY

34-3.01 Alternative Analysis

Choose alternatives which satisfy the following:

1. topography, and
2. design policies and criteria.

Analyze alternatives for the following:

1. environmental impact,
2. hydraulic efficiency, and
3. risk and cost.

The selected dissipator should meet the selected structural and hydraulic criteria and should be based on the following:

1. construction and maintenance costs,
2. risk of failure or property damage,
3. traffic safety,
4. environmental or aesthetic considerations,
5. political or nuisance considerations, and
6. land use requirements.

34-3.02 Design Methods

The designer must choose as follows:

1. to design for local scour or channel degradation;

2. to mitigate or monitor erosion problems;

3. to use drop structures, internal dissipators, scour holes, external dissipators or stilling basins; and

4. to use charts or computer software.

34-3.02(01) Types of Scour

The following apply.

1. Local Scour. Local scour is the result of high-velocity flow at the culvert outlet and extends only a limited distance downstream.

2. Channel Degradation. Channel degradation may proceed in a fairly uniform manner over a long length or may be evident in one or more abrupt drops (headcuts) progressing upstream with every runoff event.

34-3.02(02) Scour Hazard

The following apply.

1. Mitigated. The scour hazard shall be designed by providing protection at the culvert outlet as follows:

    a. Initial protection shall be sufficient to provide some assurance that extensive damage could not result from one design runoff event.

    b. Protection should be inspected after major storms to determine if protection must be increased or extended.

2. Monitored. The site should be inspected after major storm events to determine if protection is needed.

34-3.02(03) Dissipator Types

The following types are available.

1. Scour Holes. Details of the design of scour holes are as shown in Section 34-4.0.

2. Internal Dissipators. These include the following:

   a. tumbling flow, and
   b. increased resistance.

   This Chapter does not address the design of Internal Dissipators. The designer should refer to FHWA HEC 14 *Hydraulic Design of Energy Dissipators for Culverts and Channels*, September 1985, revised in 1995 and FHWA/OH-84/007 *Internal Energy Dissipators* if design details are needed.

3. External Dissipators. These include the following:

   a. USBR Type VI Impact (Section 34-9.0).
   b. Riprap (Section 34-8.0).
   c. CSU rigid boundary (see HEC 14).
   d. Contra Costa (see HEC 14).
   e. Hook (see HEC 14).
   f. Hydraulic jump (see HEC 14).

4. Stilling Basins. These include the following:

   a. Saint Anthony Falls (SAF) (Section 34-7.0).
   b. USBR Type II (see HEC 14).
   c. USBR Type III (see HEC 14).
   d. USBR Type IV (see HEC 14).

5. Drop Structures. See HEC 14.

34-3.02(04) Computational Methods

The following are available.

1. Charts. Charts are required for a manual solution. Charts required for the design of scour holes, riprap basin, USBR Type VI impact basin and SAF basin are included in this Chapter. Charts required for the design of other types of energy dissipators are found in HEC 14.

2. Computer Software. HY-8 (FHWA Culvert Analysis Software) Version 4.1 or greater contains an energy dissipator module which can be used to analyze most types of energy dissipators in HEC 14.

34-4.0 DESIGN EQUATIONS

34-4.01 General

An exact theoretical analysis of flow at culvert outlets is extremely complex because the following data is required.

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

34-4.02 Approach

The design procedures presented in this Chapter are based on the following.

1. Model studies were used to calibrate the equations and charts for scour hole estimating and energy dissipator design.

2. HEC 14 (revised version, 1995) is the base reference and contains a full explanation of all equations and procedures used in this Chapter with the exception of those discussed in Section 34-4.03.

34-4.03 Culvert Outlet Conditions

The culvert design establishes the outlet flow conditions. However, these parameters may require closer analysis for energy dissipator design.

1. Depth (ft), d_o. The normal depth assumption should be reviewed and a water surface profile calculated if $L < 50\ d_o$. The brink depth (see HEC 14 for curves) should be used for mild slopes and low tailwater, not critical depth.

2. Area (ft^2), A_o. The cross sectional area of flow at the culvert outlet should be calculated using (d_o).

3. Velocity (ft/s), V_o. The culvert outlet velocity should be calculated as follows:

   $V_o = Q/A_o$ (Equation 34-4.1)

   Where: Q = discharge, ft^3/s

4. Froude Number, Fr. The Froude number is a flow parameter that has traditionally been used to design energy dissipators and is calculated using the following formula.

   $Fr = V_o/[(g\ d_o)^{0.5}]$ (Equation 34-4.2)

   Where: g = acceleration of gravity, 32.2 ft/s^2

5. Equivalent Depth (ft), $d_E = (A_o/2)^{0.5}$. Equivalent depth is an artificial depth which is calculated for culverts which are not rectangular so that a reasonable Fr can be determined.

6. Discharge Intensity, DI_c. Discharge Intensity is a flow parameter similar to Fr which is used for circular culverts of diameter (D) which are flowing full.

   $DI_c = Q/(g^{0.5}D^{2.5})$ (Equation 34-4.3)

7. Discharge Intensity Modified, DI. Referring to Chapter V, HEC 14 (revised version, 1995), the Modified Discharge Intensity, DI, for all culvert shapes is as follows:

   $DI = Q/(g^{0.5}\ R_c^{\ 2.5})$ (Equation 34-4.4)

   Where: Q = discharge, ft^3/s

A_c = culvert area, ft^2
P_c = culvert perimeter, ft
R_c = (A_c/P_c)

$$\left[\frac{d_s}{R_c}, \frac{W_s}{R_c}, \frac{L_s}{R_c}\right] = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}\, R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta}$$

34-4.04 Scour Hole Estimation

Chapter V of HEC 14 (revised version, 1995) contains an estimating procedure for scour hole geometry based on soil, flow data and culvert geometry. This scour prediction procedure is intended to serve together with the maintenance history and site reconnaissance information for determining energy dissipator needs.

Only scour holes on cohesionless material will be discussed in this Chapter. For scour holes on cohesive soil, the designer can refer to Chapter V, HEC 14 for details.

The results of tests by the US Army Waterways Experiment Station, Vicksburg, Mississippi indicate that the scour hole geometry varies with the tailwater conditions. The maximum scour geometry occurs at tailwater depths less than half the culvert height. The maximum depth of scour, d_S, occurs at a location approximately $0.4L_S$ downstream of the culvert, where L_S is the length of the scour.

The following empirical equations defining the relationship between the culvert discharge intensity, time and the length, width, depth and volume of the scour hole are presented for the maximum or extreme scour case.

(Equation 34-4.5)

Where: d_S = maximum depth of scour hole, ft
L_S = length scour hole, ft
W_S = width of scour hole, ft

$$d_S,\ W_S,\ \text{or}\ L_S = (F_1)(F_2)(F_3)R_c \qquad \text{(Equation 34-4.6)}$$

Where:

$$F_1 = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)$$

$$F_2 = \left(\frac{Q}{\sqrt{g}\, R_c^{2.5}}\right)^{\beta} = (DI)^{\beta}$$

$$F_3 = \left(\frac{t}{316}\right)^{\theta}$$

Where: t = 30 minutes or the time of concentration, if longer

R_c = hydraulic radius of drainage structure flowing full

σ = material standard deviation (generally, $\sigma = 2.10$ for gravel and 1.87 for sand)

$\acute{\alpha}$, β, θ, C_S and C_h are coefficients as shown in Figure 34-4A, Coefficients (Scour Hole Estimation)

F_1 , F_2 and F_3 are factors to aid the computation, as shown in Step 7B, Figure 34-5A, Energy Dissipator Checklist. An editable version of this form may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/ .

34-5.0 DESIGN PROCEDURE

The following design procedures are intended to provide a convenient and organized method for designing energy dissipators manually. The designer should be familiar with all equations in Section 34-4.0 before using these procedures. In addition, application of the following design method without an understanding of hydraulics can result in an inadequate, unsafe or costly structure.

1. Step 1. Assemble Site Data And Project File.

    a. See culvert design file for site survey.
    b. Review Section 34-2.0 for applicable criteria.

2. Step 2. Determine Hydrology. See culvert design file.

3. Step 3. Select Design Q.

    a. See Section 34-2.03 "Design Limitations."
    b. See culvert design file.
    c. Select flood frequency.
    d. Determine Q from frequency plot (Step 2).

4. Step 4. Design Downstream Channel.

    a. See culvert design file.
    b. Determine channel slope, cross section, normal depth and velocity.
    c. Check bed and bank materials stability.

5. Step 5. Design Culvert. See culvert design file and obtain design discharge, outlet flow conditions (velocity and depth), culvert type (size, shape and roughness), culvert slope and performance curve.

6. Step 6. Summarize Data On Design Form.

   a. Use Figure 34-5A, Energy Dissipator Checklist.
   b. Enter data from Steps 1-5 into Figure 34-5A.

7. Step 7. Estimate Scour Hole Size.

   a. Enter input for scour equation on Figure 34-5A.
   b. Calculate d_S, W_S, L_S using Equations 34-4.5 or 34-4.6.

8. Step 8. Determine Need For Dissipator. An energy dissipator is needed if:

   a. the estimated scour hole dimensions, which exceed the allowable right-of-way, undermines the culvert cutoff wall or presents a safety or aesthetic problem;

   b. downstream property is threatened; or

   c. V_o is significantly greater than V_d.

9. Step 9. Select Design Alternative. See Section 34-2.04.

10. Step 10. Design Dissipators. Use the following design procedures and charts.

    a. Section 34-7.0 for the SAF.
    b. Section 34-8.0 for the Riprap.
    c. Section 34-9.0 for the USBR Type VI.

11. Step 11. Design Riprap Transition. Most dissipators require some protection adjacent to the basin exit. The length of protection can be judged based on the difference between V_o and V_d. The riprap should be designed using HEC 11.

12. Step 12. Review Results.

    a. If downstream channel conditions (velocity, depth and stability) are exceeded, either design riprap for channel (Step 4), or select another dissipator (Step 9).

    b. If preferred energy dissipator affects culvert hydraulics, return to Step 5 and calculate culvert performance.

c. If debris-control structures are required upstream, consult HEC 9.

d. If a check Q was used for the culvert design, assess the dissipator performance with this discharge.

13. Step 13. Documentation.

a. See Chapter Twenty-eight.
b. Include computations in culvert report or file.

34-6.0 DESIGN EXAMPLE

34-6.01 Design Example Steps

The following example problem uses the culvert data provided in Chapter Thirty-one.

1. Step 1. Assemble Site Data And Project File.

a. Site survey: The culvert project file contains USGS, site and location maps, roadway profile and embankment cross sections. Site visit notes indicate no sediment or debris problems and no nearby structures.

See Figure 34-6.1 for site data.

b. Studies by other agencies~ none.

c. Design criteria:

(1) 50-year frequency for design, and
(2) 100-year frequency for check.

2. Step 2. Determine Hydrology. USGS Regression equations yield the following:

a. $Q_{50} = 400\ ft^3/s$
b. $Q_{100} = 500\ ft^3/s$

3. Step 3. Select Design Q. Use $Q_{50} = 400\ ft^3/s$, as requested by the design criteria.

4. Step 4. Design Downstream Channel.

a. See Figure 34-6.2 for cross section of channel with slope = 0.05 ft/ft

Point	Station, ft	Elevation, ft
1	12.3	182.9
2	22.3	177.8
3	32.7	177.3
4	34.7	175.3
5	39.7	175.3
6	41.7	177.3
7	51.7	177.8
8	62.0	182.9

b. Rating curve for channel. Calculating normal depth yields:

Q (ft^3/s)	TW (ft)	V (ft/s)
100.0	1.43	11.33
200.0	2.10	14.00
300.0	2.57	16.20
400.0	2.87	17.83
500.0	3.13	19.13

c. At a V_{50} = 17.83 ft/s, the 3 in. gravel material which makes up the channel boundary is not stable and riprap is needed for a transition.

5. Step 5. Design Culvert. A 7 ft by 6 ft RCB with a beveled entrance on a slope of 0.05 ft/ft was the selected design. The FHWA HY8 program showed that this culvert is operating at inlet control and has the following properties.

Q (ft^3/s)	Hw_i (ft)	V_o (ft/s)
Q_{50} = 400.0	7.73	28.70
Q_{ot} = 460.0	8.63	29.60
Q_{100}= 500.0	8.73	29.67

6. Step 6. Summarize Data On Design Form. See Figure 34-5A.

7. Step 7. Size Scour Hole. The size of the scour hole is determined using Equations 34-4.5 and 34-4.6. For channel with gravel bed, the standard deviation of the material, σ, is 2.10. Figure 34-4A shows that the value of C_S =1.00 and C_h = 1.08. See Figure 34-6A, Energy Dissipator Checklist (Example), for a summary of the computation.

8. Step 8. Determine Need For Dissipator. The scour hole dimensions are excessive and, since V_o = 28.70 ft/s is much greater than V_d = 17.83 ft/s, an energy dissipator is needed.

9. Step 9. Select Design Alternative. See Section 34-2.04.

10. Step 10. Design Dissipators. The design of an SAF stilling basin is as shown in Section 34-7.0.

11. Step 11. Design Riprap Transition. Protection is required (see HEC 11).

12. Step 12. Review Results. The downstream channel conditions are matched by the dissipator.

13. Step 13. Documentation.

    a. See Chapter Twenty-eight.
    b. Include computations in the culvert report or file.

34-6.02 Computer Output

The scour hole geometry can also be computed by using the "Energy Dissipators" module of the FHWA microcomputer program HY-8, Culvert Analysis, Version 4.0 or later. A hardcopy of the module output is as shown as Figure 34-6B. The dimensions of the scour hole computed by the HY-8 program are reasonably close to the values calculated in the previous Section.

34-7.0 STILLING BASIN

34-7.01 Overview

The St. Anthony Falls (SAF) stilling basin uses a forced hydraulic jump to dissipate energy and:

1. is based on model studies conducted by the Natural Resources Conservation Service (NRCS) at the St. Anthony Falls (SAF) Hydraulic Laboratory of the University of Minnesota;

2. uses chute blocks, baffle blocks and an end sill to force the hydraulic jump and reduce jump length by about 80%; and

3. is recommended where Fr = 1.7 to 17.

34-7.02 Equations

1. Basin Width, W_B.

   a. for box culvert, $W_B = B$ = culvert width, ft
   b. for pipe, W_B = culvert diameter (D) ft, or

$$W_B = 1.769D\frac{Q}{g^{0.5}D^{2.5}} \qquad \text{(Equation 34-7.1)}$$

   which ever is larger.

   Where: Q = discharge, ft^3/s

2. Flare (z:1). Flare is optional. If used, it should be flatter than 2:1.

3. Basin Length, L_B.

$$d_j = 0.5d_1\left[\left(1+8Fr_1^2\right)^{0.5} - 1\right] \qquad \text{(Equation 34-7.2)}$$

Where: d_1 = initial depth of water, ft
d_j = sequent depth of jump, ft
Fr_1 = Froude number entering basin, $\neq$ Fr

$$L_B = \frac{4.5d_j}{Fr_1^{0.76}} \qquad \text{(Equation 34-7.3)}$$

4. Basin Floor. The basin floor should be depressed below the streambed enough to obtain the following depth (d_2) below the tailwater:

   a. For Fr_1 = 1.7 to 5.5

$$d_2 = d_j\left[1.1 - \left(\frac{Fr_1^2}{120}\right)\right] \qquad \text{(Equation 34-7.4)}$$

   b. For Fr_1 = 5.5 to 11

$d_2 = 0.85d_j$ (Equation 34-7.5)

c. For $Fr_1 = 11$ to 17

$$d_2 = d_j\left[1.1 - \left(\frac{Fr_1^2}{800}\right)\right] \quad \text{(Equation 34-7.6)}$$

5. Chute Blocks.

Height, $h_1 = d_1$
Width, W_1 = spacing, $W_1 = 0.75d_1$
Number of blocks = $N_c = W_B/2W_1$, rounded to a whole number
Adjusted $W_1 = W_2 = W_B/2N_c$
N_c includes the ½ block at each wall

6. Baffle Blocks.

Height, $h_3 = d_1$
Width, W_3 = spacing, $W_4 = 0.75d_1$
Basin width at baffle blocks, $W_{B2} = W_B + 2L_B/3z$
Number of blocks = $N_B = W_{B2}/2W_3$, rounded to a whole number
Adjusted $W_3 = W_4 = W_{B2}/2N_B$
Check total block width to ensure that 40% to 55% of W_{B2} is occupied by block
Staggered with chute blocks
Space at wall $\geq 0.38d_1$
Distance from chute blocks ($L_{1\text{-}3}$) = $L_B/3$

7. End Sill Height. $h_4 = 0.07d_j$

8. Sidewall Height. $d_2 + 0.33d_j$

9. Wingwall Flare. 45˚

34-7.03 Design Procedure

The design of a St. Anthony Falls (SAF) basin consists of several steps as follows:

1. Step 1. Select Basin Type.

a. Rectangular or flared.
b. Choose flare (if needed), z:1.
c. Determine basin width, W_B.

2. Step 2. Select Depression.

a. Choose the depth d_2 to depress below the streambed, B_d.
b. Assume $B_d = 0$ for first trial.

3. Step 3. Determine Input Flow.

a. d_1 and V_1, using energy equation.
b. Froude Number, Fr_1.

4. Step 4. Calculate Basin Dimensions.

a. d_j (Equation 34-7.2).
b. L_B (Equation 34-7.3).
c. d_2 (Equation 34-7.4, 34-7.5 or 34-7.6).
d. $L_S = (d_2 - TW)/S_S$
e. $L_T = (B_d)/S_T$ (see Figure 34-7A, St. Anthony Falls Basin Checklist). An editable version of this form may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/.
f. $L = L_T + L_B + L_S$ (see Figure 34-7A).

5. Step 5. Review Results.

a. If $d_2 \neq (B_d - LS_o + TW)$, return to Step 2.
b. If approximately equal, continue.

6. Step 6. Size Elements.

a. Chute blocks (h_1, W_1, W_2, N_c).
b. Baffle blocks (h_3, W_3, W_4, N_B, $L_{1\text{-}3}$).
c. End sill (h_4).
d. Side wall height ($h_5 = d_2 + 0.33d_j$).

34-7.04 Design Example

See Section 34-6.0 for input values. See Figure 34-7C, Energy Dissipator HY-8 Program Output, for completed computation form.

1. Step 1. Select Basin Type.

   a. Use rectangular
   b. No flare
   c. Basin width, $W_B = 7.00$ ft

2. Step 2. Select Depression. Trial 1 $B_d = 6.00$ ft, $S_S = S_t = 1$

3. Step 3. Determine Input Flow. Trial 1:

   a. Energy equation (culvert to basin):
      Culvert outlet = $B_d + d_o + V_o^2/2g = 6.00 + 1.87 + (28.9)^2/2(32.2) = 20.83\text{ft}$
      Basin floor = $0 + d_1 + V_1^2/2g$
      Solve: $20.83 = d_1 + V_1^2/2g$

d_1	V_1	$d_1+V_1^2/2g$
1.63	36.20	21.98 > 20.83
1.67	35.47	21.20 ≠ 20.83, Use

   b. $Fr_1 = 35.47/(1.67 \times 32.2)^{0.5} = 4.80$

4. Step 4. Calculate Basin Dimensions (Trial 1)

   a. $d_j = 10.50$ ft (Equation 11.8)
   b. $L_B = 14.33$ ft (Equation 11.9)
   c. $d_2 = 9.53$ ft (Equation 11.10)
   d. $L_S = (d_2 - TW)/S_S = (9.53 - 2.86)/1 = 6.67$ ft
   e $L_T = (B_d)/S_T = 6.00/1 = 6.00$ ft
   f $L = L_T + L_B + L_S = 6.00 + 14.33 + 6.67 = 27$ ft

5. Step 5. Review Results. Trial 1:

   a. If d_2 does not equal (B_d - LS_o + TW), then adjust drop.
      $9.53 \approx ((6.00 - 27.00(0.05) + 2.87)) = 7.52$ ft

   b. Add 9.53 – 7.52 = 2.01 more drop and return to Step 2.

6. Repeat Step 2. Select Depression. Trial 2: $B_d = 8.03$ ft, $S_S = S_T = 1$.

7. Repeat Step 3. Determine Input Flow. Trial 2:

a. Energy equation (culvert to basin):
Culvert outlet = $B_d + d_o + V_o^2/2g = 8.03 + 2.07 + (28.7)^2/2g = 22.89$ ft
Basin floor = $0 + d_1 + V_1^2/2g$
Solve: $22.89 = d_1 + V_1^2/2g$

d_1	V_1	$d_1 = V_1^2/2g$
1.60	36.93	22.78 ≈ 22.89, Use.

b. $Fr_1 = 36.93/(1.60 \times 32.2)^{0.5} = 5.11$

8. Repeat Step 4. Calculate Basin Dimensions. Trial 2:

a. $d_j = 10.53$ ft (Equation 34-7.2)
b. $L_B = 13.93$ ft (Equation 34-7.3)
c. $d_2 = 9.40$ ft (Equation 34-7.5)
d. $L_S = (d_2 - TW)/S_S = 6.53$ ft
e. $L_T = (B_d)/S_T = 8.03/1 = 8.03$ ft
f. $L = L_T + L_B + L_S = 8.03 + 13.93 + 6.53 = 28.5$ ft

9. Repeat Step 5. Review Results. Trial 2:

$d_2 = 9.40 \neq (8.03 - 28.5(0.05) + 2.87) = 9.47$ ft.
Is approximately equal; continue.

10. Step 6. Size Elements. Trial 2:

a. Chute blocks (h_1, W_1, W_2, N_c)
$h_1 = d_1 = 1.60$ ft
$W_1 = 0.75d_1 = 1.20$ ft
$N_c = W_B/2(W_1) = 7.00/2(1.2) = 2.92$; use 3
Adjusted $W_1 = 7.00/2(3) = 1.17$ ft $= W_2$
Use 2 full blocks, 3 spaces and a half of block at each wall.

b. Baffle blocks (h_3, W_3, W_4, N_B, $L_{1\text{-}3}$)
$h_3 = d_1 = 1.60$ ft
$W_3 = 0.75d_1 = 1.20$ ft
Use 3 blocks, as above $W_3 = W_4 = 1.17$ ft
$L_{1\text{-}3} = L_B/3 = 13.93/3 = 4.64$ ft

c. End sill (h_4) = $0.07d_j$ = 0.07(10.53) = 0.74 ft

d. Side wall height (h_5) = $d_2 + 0.33d_j$ = 9.40 + 0.33(10.53) = 12.88 ft

See Figure 34-7.1 for block design.

34-7.05 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module which is available in microcomputer program HY-8, Culvert Analysis. The output of the culvert and channel input data, and computed geometry using this module are shown as Figure 34-7B, St. Anthony Falls Basin (Example Problem).

34-8.0 RIPRAP BASIN

34-8.01 Overview

The riprap basin design is based on laboratory data obtained from full-scale prototypical installations. The following are the principal features of the basin.

1. Preshaping and lining with riprap of median size, d_{50}.

2. Constructing the floor at a depth of h_S below the invert, where h_S is the depth of scour that would occur in a pad of riprap of size d_{50}.

3. Sizing d_{50} so that $2 < h_S/d_{50} < 4$.

4. Sizing the length of the dissipating pool to be $10(h_S)$ or $3(W_o)$, whichever is larger for a single barrel. The overall length of the basin is $15(h_S)$ or $4(W_o)$, whichever is larger.

5. Angular rock results were approximately the same as the results of rounded material.

6. Layout details are shown on Figure 34-8A, Details of Riprap Basin Energy Dissipator.

For high tailwater ($TW/d_o > 0.75$), the following applies.

1. The high velocity core of water emerging from the culvert retains its jetlike character as it passes through the basin.

2. The scour hole is not as deep as with low tailwater and is generally longer.

3. Riprap may be required for the channel downstream of the rock-lined basin.

34-8.02 Design Procedure

An editable version of Figure 34-8C, Riprap Basin Design Checklist, may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/ .

1. Step 1. Determine Input Flow. d_o or d_E, V_o, Fr at the culvert outlet (d_E = the equivalent depth at the brink = $(A/2)^{0.5}$).

2. Step 2. Check TW. Determine if $TW/d_o \leq 0.75$.

3. Step 3. Determine d_{50}.

   a. Use Figure 34-8B, Riprap Basin Depth of Scour.
   b. Select d_{50}/d_E. Satisfactory results will be obtained if $0.25 < d_{50}/d_E < 0.45$.
   c. Obtain h_S/d_E using Froude number Fr and Figure 34-8B.
   d. Check if $2 < h_S/d_{50} < 4$ and repeat until a d_{50} is found within the range.

4. Step 4. Size Basin.

   a. As shown in Figure 34-8A, Details of Riprap Basin Energy Dissipator.

   b. Determine length of the dissipating pool, L_S.
      $L_S = 10h_S$ or $3W_o$ minimum.

   c. Determine length of basin, L_B.
      $L_B = 15h_S$ or $4W_o$ minimum.

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

5. Step 5. Determine 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.

6. 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 34-8D, Distribution of Centerline Velocity for Flow from Submerged Outlets.

   d. Size riprap using HEC 11 "Use of Riprap For Bank Protection."

7. Step 7. Design Filter. This is necessary unless the streambed material is sufficiently well graded. Follow instructions in Section 4.4, HEC 11.

34-8.03 Design Example (Low Tailwater)

Given: Box culvert: 8 ft by 6 ft
Design discharge $Q = 800\ ft^3/s$
Supercritical flow in culvert
Normal flow depth d_o = brink depth $d_E = 4.00$ ft
Tailwater depth, TW = 2.83 ft

1. Step 1. Determine Input Flow.

   $d_o = d_E$ for rectangular section
   $d_o = d_E = 4$ ft
   $V_o = Q/A = 800/(4)8 = 25$ ft/s
   $Fr = V/(g\ d_E)^{0.5} = 25/[(32.2)4]^{0.5} = 2.20 < 3.0$, O.K.

2. Step 2. Check TW.

   Determine if $TW/d_o \leq 0.75$
   $TW/d_E = 2.83/4.0 = 0.71$
   Therefore, $TW/d_E < 0.75$, O.K.

3. Step 3. Determine d_{50}.

   a. Use Figure 34-8B.

b. Select $d_{50}/d_E = 0.45$
$d_{50} = 0.45(4) = 1.8$ ft

c. Obtain h_S/d_E using Fr = 2.2 and line $0.41 \leq d_{50}/d_E \leq 0.5$
$h_S/d_E = 1.6$

d. Check if $2 < h_S/d_{50} < 4$:
$h_S = 4(1.6) = 6.4$ ft
$h_S/d_{50} = 6.4/1.8 = 3.55$ ft
$2 < 3.55 < 4$, O.K.

4. Step 4. Size Basin.

a. As shown in Figure 34-8A, Details of Riprap Basin Energy Dissipator.

b. Determine length of dissipating pool, L_S:
$L_S = 10h_S = 10(6.50) = 65.00$ ft
min. $= 3W_o = 3(8) = 24.00$ ft
Therefore, use $L_S = 65.00$ ft

c. Determine length of basin, L_B:
$L_B = 15h_S = 15(6.50) = 97.50$ ft
min. $= 4W_o = 4(8.00) = 32.00$ ft
Therefore, use $L_B = 97.50$ ft

d. Thickness of riprap:
Approach $= 3d_{50} = 3(1.83) = 5.49$ ft
Remainder $= 2d_{50} = 2(1.83) = 3.66$ ft

5. Step 5. Determine V_B.

a. d_B = critical depth at basin exit = 3.30 ft (assuming a rectangular cross section with width $W_B = 24$ ft)

b. $V_B = Q/(W_B d_B) = 800/(24)\ (3.30) = 10.10$ ft/s

c. $V_B = 10.10$ ft/s $< V_d = 18.3$ ft/s

34-8.04 Design Example (High Tailwater)

Given: Data on the channel and the culvert are the same as Example 34-8.03, except that the new tailwater depth, TW = 4.26 ft.
$TW/d_o = 4.20/4.00 = 1.06 > 0.75$
Downstream channel can tolerate only 7 ft/s.

1. Steps 1 through 5 are the same as in Example 34-8.03.

2. Step 6. High Tailwater Design.

   a. Design a basin for low tailwater conditions, Steps 1-5 as above:

   $d_{50} = 1.83$ ft, $h_S = 6.50$ ft
   $L_S = 65.00$ ft, $L_B = 97.50$ ft

   b. Compute equivalent circular diameter, D_E, for brink area from:

   $A = \pi D_E^2/4 = d_o(W_o) = 4(8) = 32.00 \text{ ft}^2$
   $D_E = [32.00(4)/\pi]^{0.5} = 6.5$ ft
   $V_o = 25.4$ ft/s

   c. Estimate centerline velocity at a series of downstream cross sections using Figure 34-8D, Distribution of Centerline Velocity for Flow from Submerged Outlets.

L/D_E [1]	L	V_L/V_o	V_L	d_{50} [2]
10	65.00	0.59	15.0	1.43
15 [3]	97.50	0.37	9.40	0.60
20	123.0	0.30	7.73	0.40
21	137.2	0.28	7.73	0.40

   [1] Use $W_o = D_E$ in Figure 34-8D.
   [2] from Figure 34-8E, Riprap Size Versus Exit Velocity (After HEC 14).
   [3] is on a logarithmic scale so interpolations must be logarithmically.

   d. Size riprap using HEC 11. The channel can be lined with the same size rock used for the basin. Protection must extend at least 135 ft downstream.

34-8.05 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module which is available in microcomputer program HY-8, Culvert Analysis. The output of the culvert and channel input data, and computed geometry using this module are shown as Figure 34-8G, Riprap Stilling Basin HY-8 Program Output.

34-9.0 IMPACT BASIN USBR TYPE VI

34-9.01 Overview

Figure 34-9A, USBR Type VI (Impact) Dissipator, was developed by the U.S. Bureau of Reclamation (USBR). The basin requirements are as follows:

1. is referred to as the USBR Type VI basin or hanging baffle,
2. is contained in a relatively small box-like structure,
3. requires no tailwater for successful performance,
4. may be used in open channels as well, and
5. is not recommended where debris or ice buildup may cause substantial clogging.

The following applies to the USBR Type VI basin.

1. Hanging Baffle. Energy dissipation is initiated by flow striking the vertical hanging baffle and being deflected upstream by the horizontal portion of the baffle and by the floor, creating horizontal eddies.

2. Notches in Baffle. Notches are provided to aid in cleaning the basin. The notches provide concentrated jets of water for cleaning. The basin is designed to carry the full discharge over the top of the baffle if the space beneath the baffle becomes completely clogged.

3. Equivalent Depth. This depth must be calculated for a pipe or irregular shaped conduit. The cross section flow area in the pipe is converted into an equivalent rectangular cross section in which the width is twice the depth of flow.

4. Limitations. Discharges up to 400 ft^3/s per barrel and velocities as high as 50 ft/s can be used without subjecting the structure to cavitation damage.

5. Tailwater. A moderate depth of tailwater will improve performance. For best performance, set the basin so that maximum tailwater does not exceed $h_3 + (h_2/2)$.

6. Slope. If the culvert slope is greater than 15º, a horizontal section of at least four culvert widths should be provided upstream.

7. End Treatment. An end sill with a low-flow drainage slot, 45º wingwalls, and a cutoff wall should be provided at the end of the basin.

8. Riprap. Riprap should be placed downstream of the basin for a length of at least four conduit widths.

34-9.02 Design Procedures

1. Step 1. Calculate Equivalent Depth, d_E.

   a. Rectangular section, $d_E = d_o = y_o$.
   b. Other sections, $d_E = (A/2)^{0.5}$.

2. Step 2. Determine Input Flow.

   a. Froude number, $Fr = V_o/(gd_E)^{0.5}$.
   b. Specific energy, $H_o = d_E + V_o^2/2g$.

3. Step 3. Determine Basin Width, W.

   a. Use Figure 34-9B, Design Curve for USBR Type VI Dissipator.
   b. Enter with Fr and read H_o/W.
   c. $W = H_o/(H_o/W)$.

4. Step 4. Size Basin.

   a. Use Figure 34-9C, Dimensions of USBR Type VI Basin, and W.
   b. Obtain the remaining dimensions.

5. Step 5. Energy Loss.

   a. Use Figure 34-9D, Energy Loss for USBR Type VI Dissipator.
   b. Enter with Fr and read H_L/H_o.
   c. $H_L = (H_L/H_o)H_o$.

6. Step 6. Exit Velocity (V_B).

   a. Exit energy (H_E) = $H_o - H_L$.
   b. $H_E = d_B + V_B^2/2g$.
   c. $V_B = (Q/W)/d_B$.

34-9.03 Design Example

An editable version of Figure 34-9E, Impact Basin Type VI Checklist, may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/ .

Given: $D = 48$ in. pipe, $S_o = 0.15$ ft/ft, $n = 0.015$
$Q = 300$ ft^3/s, $d_o = 2.3$ ft, $V_o = 40.00$ ft/s

1. Step 1. Calculate Equivalent Depth, d_E.
   Other sections, $d_E = (A/2)^{0.5}$
   $A = Q/V_o = 300/40.00 = 7.50$ ft^2
   $d_E = (7.50/2)^{0.5} = 1.94$ ft

2. Step 2. Determine Input Flow.

   a. Froude number, $Fr_o = V_o/(gd_E)^{0.5}$
      $Fr = 40.63/[32.2(1.94)]^{0.5} = 5.06$

   b. Specific energy, $H_o = d_E + V_o^2/2g$
      $H_o = 1.94 + (40.00)^2/(2)(32.2) = 26.78$ ft

3. Step 3. Determine Basin Width, W.

   a. Use Figure 34-9B, Design Curve for USBR Type VI Dissipator.
   b. Enter with $Fr = 5.06$ and read $H_o/W = 1.68$
   c. $W = H_o/(H_o/W) = 26.78/1.68 = 15.94$ ft ≈ 16 ft

4. Step 4. Size Basin.

   a. Use Figure 34-9C, Dimensions of USBR Type VI Basin, and W.
   b. Obtain the remaining dimensions.

5. Step 5. Energy Loss.

   a. Use Figure 34-9D, Energy Loss for USBR Type VI Dissipator.
   b. Enter with $Fr = 5.06$ and read $H_L/H_o = 0.67$
   c. $H_L = (H_L/H_o)H_o = 0.66(26.78) = 17.67$ ft

6. Step 6. Exit Velocity (V_B).

a. Exit energy (H_E) = H_o - H_L = 26.78 – 17.67 = 9.10 ft

b. $H_E = d_B + V_B^2/2g = 9.10$ ft

c. $V_B = (Q/W)/d_B = (300/16)/d_B = 18.75/d_B$

d_B	V_B	$d_B+V_B^2/2g = 9.10$
2.33 = d_c	8.33	3.41
1.00	19.4	6.84
0.67	29.2	13.9
0.87	22.4	8.66
0.90	21.6	8.14
0.83	23.3	9.25 ≈ 9.10, use

34-9.04 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module which is available in microcomputer program HY-8, Culvert Analysis. The output of the culvert and channel input data, and computed geometry using this module are shown as Figure 34-9G, USBR Type 6 Dissipator HY-8 Program Output.

34-10.0 REFERENCES

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