Chapter 11

ENERGY DISSIPATORS

SOUTH DAKOTA DRAINAGE MANUAL

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Table of Contents

List of Figures

Chapter 11
ENERGY DISSIPATORS

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 and/or other countermeasures. For roadside drainage and channel revetment, see Chapter 9 “Roadside Channels” and Chapter 15 “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 HEC 14

HEC 14 *Hydraulic Design of Energy Dissipators for Culverts and Channels* (Reference (1)) 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.

SDDOT recommends that HEC 14 be used when designing energy dissipators with the exception of riprap aprons. Refer to Section 11.6 when designing riprap aprons. This Chapter provides a brief overview on energy dissipators and references HEC 14 for detailed design. With the exception of riprap aprons, the HEC 14 design methods have been automated in the FHWA software HY-8; see Chapter 18 “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 Figure 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 (Reference (1)) or HY-8; see Chapter 18 "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.

11.2.2 SDDOT Practices

SDDOT practice is to use external dissipators for box culverts and either external and/or internal dissipators for circular pipe. Internal dissipators commonly used by SDDOT are broken-back culverts and precast energy dissipator rings. Gabion aprons (rock and wire baskets) are primarily used at the outlets of pipe culverts. Riprap aprons are commonly used at box culvert outlets. See Section 11.6. Where a riprap apron is not adequate, the riprap basin is preferred for $Fr \leq 3$. For $Fr > 3$, the SAF basin is preferred.

The South Dakota *Standard Specifications for Roads and Bridges* allows for rock with a specific gravity of 2.48; therefore, some of the equations provided in HEC 14 must be adjusted.

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.

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 to 7	M	L	M	Not needed
7	Outlet drop/weir	3.5 to 6	M	L	M	Not needed
8	USBR Type III stilling basin	4.5 to 17	M	L	M	Required
8	USBR Type IV stilling basin	2.5 to 4.5	M	L	M	Required
8	SAF stilling basin	1.7 to 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 to 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[6]	N/A	H	H	H	Not needed
11	Straight drop structure[7]	< 1	H	L	M	Required
11	Box inlet drop structure[8]	< 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% < S_o < 25%
4 Internal: Check headwater for outlet control
5 Discharge, Q < 400 cfs and Velocity, V < 50 fps
6 See Section 11.6
7 Drop < 15 ft
8 Drop < 12 ft (HEC 14, Reference (1))

N/A = not applicable

Figure 11.2-A — ENERGY DISSIPATORS AND LIMITATIONS (Reference (1))

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
   - will not create a public nuisance.

3. External Dissipators (HEC 14, Chapters 9, 10 and 11). External dissipators 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 used 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 used 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.

11.3.1 Ice Buildup

If ice buildup is a factor, it can be mitigated by:

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

11.3.2 Debris Control

Debris control can be designed using HEC 9 (Reference (2)) and should be considered:

- where clean-out access is limited, and
- if the dissipator type selected cannot pass debris.

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. The use of a design flood of less magnitude may be permitted if justified by:

- low risk of failure of the crossing,
- substantial cost savings,
- limited or no adverse effect on the downstream channel, and
- limited or no adverse effect on downstream development.

The review flood frequency should also be evaluated. For most external dissipators, the review flood check will indicate that the dissipator will have a higher outlet velocity than the design flood. If this higher velocity causes concern, it should be mitigated. Internal dissipators and some external dissipators (e.g., hook, USBR Type VI) may cause the culvert to flow full for the review flood. If this is likely and if the higher headwater causes concern, a different dissipator should be evaluated.

11.3.4 Maximum 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 stabilization (see Chapter 9 "Roadside Channels" and Chapter 15 "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 9 "Roadside Channels" and Chapter 14 "Bridge Hydraulics").
- Lakes, ponds or large water bodies should be evaluated using the high-water elevation, which has the same frequency as the design flood for the culvert if events are known to occur concurrently (statistically dependent). If statistically independent, evaluate the joint probability of flood magnitudes and use a likely combination (worst-case scenario).

11.3.6 Cost

The type selected for the 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 neutral stress or pore 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.

11.4 DESIGN PROCEDURE

The energy dissipator design procedure, illustrated in Figure 11.4-A, presents the recommended design steps. The designer should treat the culvert, energy dissipator and channel protection designs as an integrated system. The 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 (Reference (1)). The HEC 14 List of Symbols should be consulted for units.

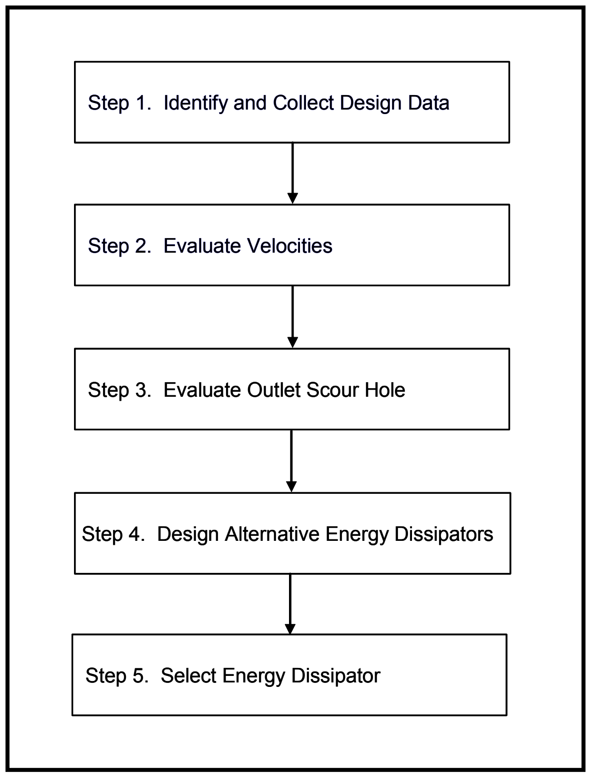

Figure 11.4-A — ENERGY DISSIPATOR DESIGN PROCEDURE

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:

a. Culvert Data. The culvert design should provide:

- type (e.g., RCBC, 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 10 "Culverts."

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

c. 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 ZH:1V. HDS 4 (Reference (3)) provides examples of how to compute normal depth in channels or use the FHWA Hydraulic Toolbox; see Chapter 18 "Hydraulic Software." The size and amount of debris should be estimated using HEC 9 (Reference (2)). The size and amount of bedload should be estimated.

d. Allowable Scour Estimate. In the field, the 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. 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).

e. 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). 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 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 such that the outlet conditions are mitigated. If the velocity is substantially higher and/or the scour hole from Step 3 is unacceptable, the 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. If the size of the scour hole is acceptable, the 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 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 Fr:

- $Fr \leq 3$: Most designs are in this group. SDDOT preferred practice is to use a riprap/gabion apron or riprap basin.

- $Fr > 3$: These include tumbling flow, USBR Type III stilling basin, USBR Type IV stilling basin, SAF stilling basin and USBR Type VI impact basin. SDDOT preferred practice is to use the SAF stilling 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 designer should document the alternatives considered.

11.5 DESIGN EXAMPLES

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 18 “Hydraulic Software.”

11.6 RIPRAP APRONS

11.6.1 Apron Use Independent of Other Energy Dissipators

SDDOT practice is to use riprap aprons at large pipe culvert and box culvert outlets where applicable. Figure 11.6-A provides an example schematic of a riprap apron at the outlet of a box culvert.

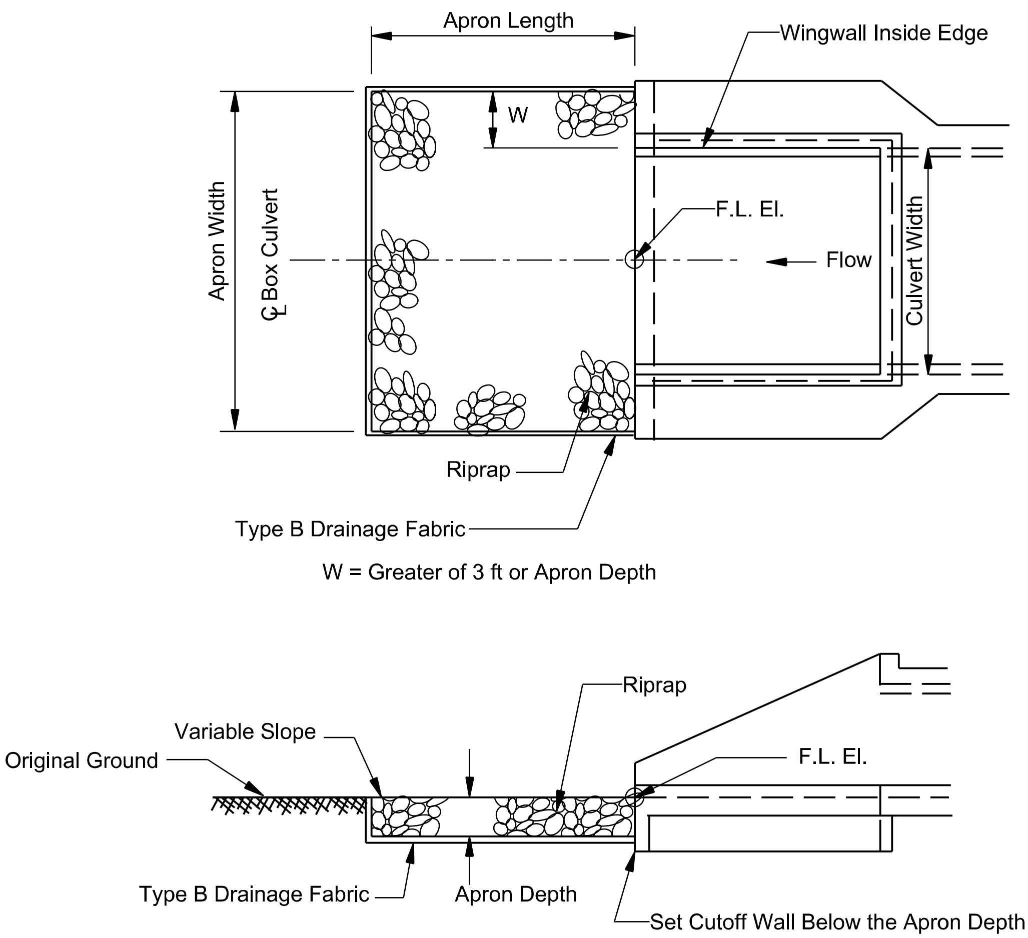

Figure 11.6-A — RIPRAP APRON AT BOX CULVERT OUTLET

Riprap aprons are constructed of riprap or grouted riprap at a zero grade for a distance that is often related to the culvert outlet velocity. 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 plus the length, width and depth of the apron.

Several relationships have been proposed for riprap sizing for culvert aprons (see HEC 14, Appendix D). The independent variables in these relationships include one or more of the following variables:

- outlet velocity (SDDOT uses review frequency velocity for apron design);
- rock specific gravity;
- pipe dimension (e.g., diameter);
- outlet Froude number; and
- tailwater.

The following equation (from the Urban Drainage and Flood Control District in Denver Colorado (UD&FCD, 2004) (Reference (1)) was developed for box culverts:

$$D_{50} = 0.014D\left(\frac{Q}{BD^{1.5}}\right)\left(\frac{D}{TW}\right) \qquad \text{(Equation 11.1)}$$

where:

D_{50} = riprap size, ft
Q = review frequency discharge, cfs
D = culvert rise (rectangular), ft
B = culvert span (rectangular), ft
TW = tailwater depth, ft

The following equation (from Fletcher and Grace, Reference (3)) was developed for circular culverts:

$$D_{50} = 0.2\,D\left(\frac{Q}{\sqrt{g}D^{2.5}}\right)^{4/3}\left(\frac{D}{TW}\right) \qquad \text{(Equation 11.2)}$$

where:

D_{50} = riprap size, ft
Q = review frequency discharge, cfs
D = culvert diameter (circular), ft

TW = tailwater depth, ft
g = acceleration due to gravity, 32.2 ft/sec^2

Tailwater depth for Equations 11.1 and 11.2 should be limited to between 0.4D and 1.0D. If the tailwater depth is unknown, use 0.4D.

When the flow is supercritical in the culvert, the culvert diameter or rise is adjusted as follows:

$$D' = \frac{D + y_n}{2} \qquad \text{(Equation 11.3)}$$

where:

D′ = adjusted culvert diameter or rise, ft
y_n = normal (supercritical) depth in the culvert, ft

Equations 11.1 and 11.2 assume that the rock specific gravity is 2.65. If the actual specific gravity differs significantly from this value, the D_{50} should be adjusted inversely to specific gravity. For instance, SDDOT uses a riprap specific gravity of 2.48; therefore, multiply the calculated D_{50} by (2.65/2.48) to obtain the corrected D_{50} particle size.

The designer should calculate D_{50} using Equation 11.1 or 11.2 and compare with available riprap classes. Figure 11.6-B provides the SDDOT standard riprap classes and ranges for apron depths. The class of riprap to be specified is that which has a D_{50} greater than or equal to the required size. For projects with several riprap aprons, it is often cost effective to use fewer riprap classes to simplify acquiring and installing the riprap at multiple locations. In this case, the designer must evaluate the tradeoffs between oversizing riprap at some locations to reduce the number of classes required on a project.

Riprap Class	D_{50} (ft)	D_{100} (ft)	Minimum Apron Depth, (ft)	Recommended Apron Depth* (ft)
A	0.95	1.30	1.5	2.25
B	1.30	1.80	2.0	2.75
C	1.80	2.25	2.5	3.50
D	2.25	2.85	3.0	4.50

**Recommended Apron Depth is based on HEC 14 calculations.*

Figure 11.6-B — SDDOT RIPRAP CLASSES AND APRON DEPTHS

V_o* (fps)	Apron Length (ft)
≤ 11	12
12	14
13	16
14	18
15	20
16	22
17	24
18	26

** V_o = culvert outlet velocity for review frequency.*

Figure 11.6-C — RECOMMENDED SDDOT APRON LENGTHS

The apron dimensions must also be specified. Figures 11.6-B and 11.6-C provide guidance on the apron depth and length. Apron depth ranges from $2.4D_{50}$ for the smallest riprap (Class A) to a limit of $2.0D_{50}$ for the larger riprap sizes (Classes C and D). Apron length is given as a function of the culvert outlet velocity. The apron width typically extends beyond the culvert opening on each side a distance equal to the greater of 3 ft or the apron riprap thickness. Additional width may be added for excessive outlet velocities. The riprap apron width should conform to the dimensions of the downstream channel. Type B drainage fabric should also be provided as described in HEC 11 (Reference (5)).

There are many other variables to consider that may affect the layout and dimensions of a riprap apron. These may include but are not limited to:

- size of the existing scour hole;
- sensitivity of the site (e.g., rural or urban setting, landowner directly upstream or downstream);
- velocity in the downstream natural channel;
- using rounded (field stone) or angular (quarried) riprap;
- the time of concentration for the drainage basin;
- the duration of flow;
- whether or not the culvert is skewed;

- if the culvert is used as a fish passage; and
- if the culvert is used as a cattle pass.

Over their service life, riprap aprons experience a wide variety of flow and tailwater conditions. In addition, the relations summarized in Figures 11.6-B and 11.6-C do not fully account for the many variables in culvert design. To ensure continued satisfactory operation, maintenance personnel should inspect them after major flood events. If repeated severe damage occurs, the location may be a candidate for extending the apron or another type of energy dissipator.

Example 11.6-1 (Box Culvert)

Design a riprap apron for the following 10 ft × 9 ft box culvert installation. Available riprap classes are provided in Figure 11.6-B. Given:

Q = 1,000 cfs
D = 9.0 ft
B = 10.0 ft
TW = 4.1 ft
V_o = 14.7 fps
y_n = 7.7 ft
y_c = 6.8 ft

Solution

Step 1 Calculate D_{50} from Equation 11.1

First, verify that tailwater is within range:

TW/D = 4.1/9 = 0.46. This is between 0.4D and 1.0D; therefore, use TW = 4.1 ft

Next, check to see if flow is supercritical:

$y_n > y_c$; therefore, flow is not supercritical; use D = 9 ft in Equation 11-1:

$$D_{50} = 0.014D\left(\frac{Q}{BD^{1.5}}\right)\left(\frac{D}{TW}\right) = 0.014(9)\left[\frac{1000}{(10)(9)^{1.5}}\right]\left(\frac{9}{4.1}\right) = 1.02\text{ ft}$$

Because SDDOT riprap specific gravity = 2.48, D_{50} is adjusted as follows:

$$D_{50} = \left(\frac{2.65}{2.48}\right)(1.02\text{ ft}) = 1.09\text{ ft}$$

Step 2 Determine Riprap Class

From Figure 11.6-B, riprap Class B (D_{50} = 1.30 ft) is recommended.

Step 3 Estimate Apron Dimensions

From Figure 11.6-B for Class B riprap: Apron Depth = 2.75 ft

From Figure 11.6-C for V_o = 14.7 fps: Apron Length = 20 ft

W (see Figure 11.6-A) = greater of 3 ft or apron depth. 3 ft > 2.75 ft; use 3 ft. Therefore:

Apron Width = B + (2 × W) = 10 ft + (2 × 3 ft) = 16 ft

Example 11.6-2 (Circular Culvert)

Design a riprap apron for the following 84-in circular pipe installation. Available riprap classes are provided in Figure 11.6-B. Given:

Q	=	275 cfs
D	=	7.0 ft
TW	=	2.3 ft
V_o	=	11.7 fps
y_n	=	4.1 ft
y_c	=	4.3 ft

Solution

Step 1 Calculate D_{50} from Equation 11.2

First, verify that tailwater is within range:

TW/D = 2.3/7 = 0.33. This is less than 0.4D; therefore, use
TW = 0.4D = 0.4(7) = 2.8 ft

Next, check to see if flow is supercritical:

$y_n < y_c$; therefore, flow is supercritical; therefore, use Equation 11.3 to obtain:

$$D' = \frac{D + y_n}{2} = \frac{(7 + 4.1)}{2} = 5.55 \text{ ft}$$

$$D_{50} = 0.2D \left(\frac{Q}{\sqrt{g}\,D^{2.5}}\right)^{\frac{4}{3}} \left(\frac{D}{TW}\right) = 0.2(5.55)\left[\frac{275}{\sqrt{32.2}\,(5.55^{2.5})}\right]^{\frac{4}{3}} \left(\frac{5.55}{2.8}\right) = 1.28 \text{ ft}$$

Because SDDOT riprap specific gravity = 2.48, D_{50} is adjusted as follows:

$$D_{50} = \left(\frac{2.65}{2.48}\right)(1.28 \text{ ft}) = 1.37 \text{ ft}$$

Step 2 Determine Riprap Class

From Figure 11.6-B, riprap Class C (D_{50} = 1.80 ft) is recommended.

Step 3 Estimate Apron Dimensions

From Figure 11.6-B for Class C riprap: Apron Depth = 3.5 ft

From Figure 11.6-C for V_o = 11.7 fps: Apron Length = 14 ft

W (see Figure 11.6-A) = greater of 3 ft or apron depth. 3 ft < 3.5 ft; use 3.5 ft. Therefore:

Apron Width = D + (2 × W) = 7 ft + (2 × 3.5 ft) = 14 ft

11.6.2 Apron Use with Other Energy Dissipators

Some energy dissipators provide exit conditions (i.e., velocity and depth) near critical. This flow condition rapidly adjusts to the downstream or natural channel regime; however, critical velocity may be sufficient to cause erosion problems requiring protection adjacent to the energy dissipator. Equation 11.4 provides the riprap size recommended for use downstream of energy dissipators. This relationship is from Searcy (Reference (6)) and is the same equation used in HEC 11 (Reference (5)) for riprap protection around bridge piers:

$$D_{50} = \frac{0.692}{S - 1}\left(\frac{V^2}{2g}\right) \qquad \text{(Equation 11.4)}$$

where:

D_{50} = median rock size, ft
V = velocity at the exit of the dissipator, ft/sec
S = riprap specific gravity

The length of protection can be judged based on the magnitude of the exit velocity compared with the natural channel velocity. The greater this difference, the longer will be the length required for the exit flow to adjust to the natural channel condition. A filter blanket should also be provided as described in HEC 11 (Reference (5)).

11.7 REFERENCES

(1) Federal Highway Administration, *Hydraulic Design of Energy Dissipators for Culverts and Channels*, Hydraulic Engineering Circular No. 14 (HEC 14), Third Edition, FHWA-NHI-06-086, 2006.

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(3) Fletcher, B. P. and Grace, J. L., *Practical Guidance for Estimating and Controlling Erosion at Culvert Outlets*, Misc. Paper H-72-5, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, 1972 (NTIS Product Number AD743461).

(4) Federal Highway Administration, *Use of Riprap for Bank Protection*, Hydraulic Engineering Circular No. 11 (HEC 11), pp. 43, 1967 (NTIS PB86-179793).

(5) Federal Highway Administration, *Design of Riprap Revetment*, Hydraulic Engineering Circular No. 11 (HEC 11), FHWA-IP-89-016, Washington, DC, 1989.

(6) Federal Highway Administration, *Introduction to Highway Hydraulics*, Hydraulic Design Series No. 4 (HDS 4), FHWA-NHI-08-090, 2008.