11 Energy Dissipators

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11.1 Introduction

The failure or damage of many culverts, storm-drain outfalls, and detention-basin outlet structures can sometimes 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 result in an increased erosion potential. To protect the culvert and adjacent areas, it is sometimes necessary to employ outlet-protection measures. Depending on an outlet's hydraulic characteristics, outlet-protection measures can range from natural scour holes to structural energy dissipators.

Design guidance for energy dissipators is provided in FHWA's Hydraulic Engineering Circular Number 14 (HEC-14, 2006) "Hydraulic Design of Energy Dissipators for Culverts and Channels." This chapter provides an introduction to energy dissipators and summarizes key information from HEC-14. Designers should consult the current version of HEC-14 for detailed design procedures. The HEC-14 design methods have been automated in the FHWA HY-8 and Hydraulic Toolbox software referenced in Chapter 8 – Channels. Additional design guidance can be found in
Chapter 9 – Hydraulic Structures of Volume 2 of the Urban Drainage and Flood Control District (UDFCD) *Urban Storm Design Criteria Manual* (USDCM, 2016).

Photo 11.1 Culvert outlet failure on I 25 near milepoint 162.1, 9/6/2018

11.2 Design Criteria and Guidelines

11.2.1 Design Frequency

The design frequencies for hydraulic structures are provided in Table 7.2 of Chapter 7 – Hydrology. The design frequency for outlet protection and energy dissipator evaluation should equal the design frequency used for the structure design. In certain cases a lower design frequency can be used, but at minimum a 10-yr design frequency must be used in all cases. A lower design frequency may be justified if the following conditions are met:

- Low risk of failure of the crossing or impact to the State highway system;
- Substantial cost savings;
- Limited or no adverse effect on the downstream channel; and
- Limited or no adverse effect on downstream and upstream properties.

The designer must document the selection of the design frequency, the evaluation of risk, cost, and adverse impacts in the hydraulic report.

11.2.2 Selection of Outlet Protection Measures

The type of dissipator selected for a site must be appropriate for the location. 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.

As stated in HEC 14, energy dissipation at certain sites can be achieved by design of a flow transition, anticipating an acceptable scour hole, and/or allowing a confined hydraulic jump given sufficient tailwater. However, at many sites a more-involved energy-dissipator design may be required. Designs listed in HEC-14 may include:

- Internal Dissipators (Chapter 7)
- Stilling Basins (Chapter 8)
- Streambed Level Dissipators (Chapter 9)
- Riprap Basins and Aprons (Chapter 10)
- Drop Structures (Chapter 11)
- Stilling Wells (Chapter 12)

HEC-14 Table 1.1 provides a list of energy dissipators and their limitations that can be used to select from alternative energy dissipators for a site. General recommendations are provided in Table 11.1.

11.2.3 Design Philosophy

The designer should consider the culvert, energy dissipator, and channel-protection designs as an integrated system. Energy dissipators can change culvert performance and channel protection requirements. Some debris-control structures represent losses not normally considered in the culvert-design procedure. Velocity can be increased or decreased by changes in the culvert design. Downstream channel conditions (velocity, depth, and channel stability) are important considerations in energy dissipator design.

Table 11.1 Recommended Dissipator Type

Dissipator Type	Recommended When
Natural Scour Holes	Undermining of the culvert outlet will not occur, or it is practicable to be controlled by a cutoff wall; The expected scour hole will not cause property damage; and There is no nuisance effect.
Internal Dissipators	A scour hole at the culvert outlet is unacceptable; Right-of-way is limited; Debris is not a problem; and Moderate velocity reduction is needed.
External Dissipators	An outlet scour hole is not acceptable; Moderate amount of debris is present; and The culvert outlet velocity is moderate, the Froude number < 3
Stilling Basins	An outlet scour hole is not acceptable; Debris is present; and The culvert outlet velocity is high, the Froude number > 3

11.2.4 Alternative Analysis

The designer must evaluate and select alternatives that best satisfy site conditions, engineering criteria, design policies, and other considerations. The selected dissipator should meet required structural and hydraulic criteria, and the selection should be based on:

- Construction and maintenance costs;
- Risk of failure or property damage;
- Traffic safety;
- Environmental or aesthetic considerations;
- Political or nuisance considerations; and
- Land-use requirements.

11.2.5 Additional Design Considerations

Ice Buildup

If ice buildup is a factor, it must be mitigated by sizing the structure to not obstruct the winter low flow, and by using external dissipators.

Debris Control

Debris control must be designed using FHWA's Hydraulic Engineering Circular No. 9, (HEC-9, 2005) "Debris Control Structures." The designer must consider debris control where clean-out access is limited, or if the selected dissipator type cannot pass debris.

Maximum Culvert Exit Velocity

The culvert exit velocity must be consistent with the maximum velocity in the natural channel for stable channels. If the natural channel is unstable or degrading, channel-stabilization measures (see Bank Protection, Chapter 17) in conjunction with outlet energy dissipation may be required.

Tailwater Relationship

The hydraulic conditions downstream must be evaluated to determine tailwater depth and maximum velocity for a range of discharges. Open-channel hydraulics (see Chapter 8 – Channels) should be used for culverts with defined channels below the culvert. Lakes, ponds, or rivers must be evaluated using a water-surface elevation with the same frequency as the design flood for the culvert if events are known to occur concurrently (are statistically dependent). If statistically independent, evaluate the joint probability of flood magnitudes and use a likely combination.

Photo 11.2 USBR Type VI impact basin

Culvert Outlet Type

In choosing a dissipator, selection of a culvert end treatment must consider the following:

- Culvert ends that are projecting, or mitered to the fill slope, offer no outlet protection.
- Headwalls provide embankment stability and erosion protection. They also provide protection from buoyancy, and reduce damage to the culvert.
- Commercial end sections add little cost to the culvert, may require less maintenance, delay embankment erosion, and incur less damage from maintenance.

- Concrete aprons do not reduce outlet velocity. They delay outlet erosion undercutting of the culvert. The need for a concrete apron should be evaluated for all concrete box culverts and pipe culverts subject to erosion and in coordination with structural requirements. Refer to current CDOT M&S Standard Plans for culvert-apron details.
- 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.

Inspection and Monitoring

Scour hazards must be controlled by providing protection at the culvert outlet. Initial protection must be sufficient to prevent extensive damage resulting from one design-runoff event. Protection should be inspected after major storms to determine if it must be increased or extended.

11.3 Erosion Hazards

Erosion at culvert outlets is a common condition under low flow and high flow conditions. Determination of the local scour potential and channel erodibility should be standard procedure in the design of all highway culverts. Chapter 9 – Culverts provides procedures for determining culvert outlet velocity and shear stress, which will be the primary indicators of erosion potential.

11.3.1 Local Scour

Local scour is the result of high-velocity flow during high-flow events at the culvert outlet, and extends only a limited distance downstream as the velocity transitions to outlet-channel conditions.

11.3.2 Long-Term Channel Degradation

Culverts are generally constructed at crossings of small streams, many of which are eroding to reduce their slopes from daily flows or cyclical-flow events such as spring runoff. This long-term degradation may proceed in a fairly uniform manner over a long length of stream, and it is often exacerbated by severe runoff events. The upstream progression of degradation or erosion, referred to as headcutting, can be detected by location surveys or by periodic maintenance inspections following construction. Information regarding the degree of instability of the outlet channel is an essential part of the culvert site investigation. If substantial doubt exists as to the long-term stability of the channel, measures for protection should be included in the initial construction. FWHA Hydraulic Engineering Circular Number 20 (HEC-20, 2012), "Stream Stability at Highway Structures," provides procedures for evaluating horizontal and vertical channel stability.

11.4 DESIGN Procedure

Below is a summary of the design procedure recommended in HEC-14 for energy dissipators. The hydraulic engineer should treat the culvert, energy dissipator, and channel-protection designs as an integrated system. The following design procedure should be applied to one combination of culvert, energy dissipator, and channel protection at a time. The designer should consult HEC-14 for complete details.

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, channel-protection requirements (both upstream and downstream), and may include a debris-control structure. Much of the input data will be available for the energy-dissipator design phase from previous design efforts.

Culvert Data The culvert design should include:

- Type (e.g., RCB, RCP, CMP);
- Height, *D*;
- Width, *B*;
- Length, *L*;
- Roughness, *n*;
- Slope, S_o;
- Design discharge, Q_d;
- Tail water, 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 in Chapter 9 – Culverts. FHWA's Hydraulic Design Series 5, *Hydraulic Design of Highway Culverts,* provides design procedures for culverts.

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

Channel Data - The following channel data is necessary to determine *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*), expressed as 1V:ZH. FHWA's Hydraulic Design Series 4, *Introduction to Highway Hydraulics,* provides examples of how to compute normal depth in channels. The FHWA Hydraulic Toolbox software (see the Software section of Chapter 9 – Culverts) can be used to determine *TW* for uniform cross sections. The size and amount of bedload should be estimated. The size and amount of debris should be estimated using HEC-9.

Allowable Scour Estimate - The hydraulic engineer should determine in the field if the bed material at the planned exit of the culvert is erodible. If it is, the potential extent of scour (i.e., depth, h_s; width, W_s; and length, L_s) should be estimated using the equations found 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) may be limited by a rock ledge or vegetation.

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, buoyancy, shear, and other forces on the structure (see HEC-14, Chapter 2). If these are assessed as unstable, the depth of degradation or height of aggradation that will occur over the design life of the structure should be estimated.

Step 2 - Evaluate Velocities

Compute the culvert or chute-exit velocity (V_o) and compare it to the 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, 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, evaluate the use of energy dissipators (Step 4). The definitions of the terms *approximately equal*, *moderately higher*, and *substantially higher* are relative to site-specific concerns such as sensitivity of the site and the consequences of failure. However, as rough guidelines to be reevaluated on a site-specific basis, the ranges of less than 10 percent, between 10 percent and 30 percent, and greater than 30 percent 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, document the size of the expected-scour hole for maintenance and note the monitoring requirements. If the size of the scour hole is excessive, 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 listed in Table 11.1. Design one or more of the energy dissipators that substantially satisfies the design criteria. The dissipators fall into two general groups based on Fr:

- $Fr < 3$, most designs are in this group; or
- $Fr > 3$, 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 alternate designs.

Step 5 - Select Energy Dissipator

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

11.5 Recommended Design software

The recommended design software for estimating culvert scour and evaluating energy dissipators is shown in Table 11.2. Additional software for channel and culvert hydraulics is discussed in Chapters 8 and 9, respectively.

Table 11.2 Culvert Scour and Energy-Dissipator Design Software

Software Name	Features	Source
HY-8	HY-8 automates the design methods described in HDS No. 5, "Hydraulic Design of Highway Culverts," HEC No.14, "Hydraulic Design of Energy Dissipators for Culverts and Channels," and HEC No. 26, "Culvert Design for Aquatic Organism Passage."	FHWA website
FHWA Hydraulic Toolbox	The FHWA Hydraulic Toolbox Program is a stand-alone suite of calculators that performs routine hydrologic and hydraulic computations. The program allows a user to perform and save hydraulic calculations in one project file, analyze multiple scenarios, and create plots and reports of these analyses. The computations can be carried out in either English or SI units.	FHWA website

REFERENCES

1. Federal Highway Administration, "Debris Control Structures Evaluation and Countermeasures, Hydraulic Engineering Circular No. 9 (HEC-9), FHWA-IF-04-016, National Highway Institute, Arlington, VA, 2005.

2. 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, National Highway Institute, Arlington, VA, 2006.

3. Federal Highway Administration, "Stream Stability at Highway Structures," Hydraulic Engineering Circular No. 20 (HEC-20), Fourth Edition, FHWA-HIF-12-004, National Highway Institute, Arlington, VA, 2012.

4. Urban Drainage and Flood Control District, *Urban Storm Drainage Criteria Manual,* Volumes I and 2, Denver CO, 2016 and 2017.