FDM 13-35-1 Special Hydraulic Structures

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1.1 Introduction

Various structures are used for special hydraulic purposes. These structures can retard a flow rate, reduce the velocity, clean the water, stop the flow of water, or improve the flow of water through a structure. Descriptions of some commonly used structures follow.

1.2 Flow Control Gates

Flap gates and sluice gates are normally used as flood protection devices at the outlets of drainage structures to prevent floodwater from backing into the structure. The flow of a culvert normally is unimpeded during low flow conditions in a river. However, the water in the river closes the flap gate by exerting pressure against it when the river is flowing at flood stage. This prevents the floodwaters from backing through the culvert and flooding low-lying property upstream from the inlet. The flow rate contributed to a structure from its drainage area is usually small when there is high water in the river because of the lag in time of concentration of the river compared to the small culvert. The need for a pumping station for tributary floods may have to be considered, but the provision for pumping must be fully justified.

1.3 Debris Control Structures

When debris accumulates at the inlet of a highway drainage structure, the structure normally ceases performing its design functions, resulting in damage to the structure, to the highway, to adjacent property, and to the traveling public. A presentation on debris control structures can be found in the FHWA publication HEC #9, entitled "Debris Control Structures." The need for such a structure is normally evident by a field review of the drainage area and its debris problems. HEC #9 contains a discussion of the types of debris control structures, the classification of debris, and the field survey data required to determine the need for a debris control structure.

One of the essential design conditions for a debris control structure is to allow for planned maintenance rather than emergency maintenance during flood period. If the proposed schedule of planned maintenance is not followed, emergency maintenance again will become the normal operation, not the exception. A further discussion on the maintenance of debris control structures is given in H.E.C. #9, Chapter 7.

1.4 Detention Basin

The detention basin is not to be confused with the retention basin. The detention basin is used only for the purpose of increasing the time of concentration of water flow to any point of discharge. A detention basin, unlike a retention basin, does not hold water for infiltration into the subsoil but is self-draining and after a period of time will be completely free of water.

A special control may exist within a drainage area that will affect the flow rate through a structure. The greatest effect is caused when a storage area is immediately upstream from the proposed drainage structure. When a detention basin is placed immediately above a drainage structure, it accomplishes the same effect as flow rate control. As a result of the field review of the drainage area, it may be determined that it is not feasible to increase the flow rate downstream from the proposed highway crossing. This will require consideration of constructing an artificial upstream control, such as a detention basin.

The detention basin can be used only when there is enough land available to assure that adjacent land will not be flooded or damaged by the backup water. Areas that can be used for detention purposes are the interchanges and wide medians of divided highways. The design of a detention basin can be accomplished by utilizing FDM 13-10-10, "Hydrograph Developing, and Routing."

1.5 Temporary Sediment Structures

A temporary sediment structure consists of a basin constructed at a suitable location to trap and store sediment. The Soil Conservation Service classifies temporary sediment structures into the following two major types:

1. Sediment Trap: A small storage area formed by excavation and/or an embankment, with further classification according to outlet or inlet type. It is limited to drainage areas of five acres or less.
2. Sediment Basin: A dam created to temporarily impound water with or without an excavated storage area. It is limited to drainage areas of 150 acres or less.

Temporary sediment structures trap and retain sediment from erodible areas in order to protect properties and stream channels below the installation from excessive siltation. These structures trap and store sediment that is generated in spite of the use of temporary erosion control measures. See Chapter 10 of the FDM for further information on sediment traps and basins.

Formal design information may be obtained from a publication entitled "Standards and Specifications for Soil Erosion and Sediment Control in Developing Areas," U.S. Department of Agriculture, Soil Conservation Service, College Park, Maryland, July 1975. Also, additional general information may be obtained from "Model Drainage Manual 1991," AASHTO.

FDM 13-35-5 Energy Dissipaters

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5.1 Introduction

Energy dissipating devices are used where it is desirable to reduce the discharge velocity by inducing high-energy losses at the inlet or discharge ends of the structure. They are generally warranted when discharge velocities exceed 14 feet per second.

Energy losses may be induced at the inlet by a drop inlet type of culvert or at the outlet by formation of a hydraulic jump. Drop inlets are used where headroom is limited, and outlet dissipators are used where headroom is not critical. In addition, energy losses can be induced by stilling basins, impact basins, riprap basins, riprap blankets, stilling wells, tumbling flow in culverts, increased culvert resistance, etc.

The energy dissipater(s) that will work for a specific drainage structure may be determined with the aid of Attachment 5.1, which lists several types of dissipaters with their hydraulic limitations. For schematic depictions and design procedures of some of the dissipaters listed in Attachment 5.1, see HEC #14, Hydraulic Design of Energy Dissipaters for Culverts and Channels, Wisconsin Department of Transportation, Federal Highway Administration, July 2006. The Bridge Design Manual also contains procedures and sample problems for a drop inlet, drop outlet, and chute spillway. Moreover, design procedures and sample problems are given in this procedure for a riprap blanket and outlet expansion.

5.2 Riprap Blanket

Attachment 5.2 gives the recommended configuration of a riprap blanket, subject to tail waters. The maximum tail water condition is when the tail water is equal to or greater than half the culvert diameter, whereas the minimum tail water condition is when the tail water is less than half the culvert diameter. The average size of stone and configuration of a horizontal blanket of riprap at a culvert outlet required to control localized downstream scour can be estimated by the following relationships:

$$d_{50}/D_o = 0.020\ (D_o/TW)\ (Q/D_o^{5/2})^{4/3}$$

$$L_{sp}/D_o = 1.7\ (Q/D_o^{5/2}) + 8$$

Where:

D_o = diameter of width of culvert (feet)

d_{50} = diameter of average size stone (feet)

L_{sp} = length of stone protection (feet)

Q = discharge (cfs)

TW = tail water depth above invert of culvert (feet)

The width of stone protection W_{sp} can be estimated by the proportions shown in Attachment 5.2.

Example Problem

Given: Culvert Diameter = 6 feet

Tail Water Depth = 3.5 feet

Discharge = 425 cfs

Find: The average size of stone and configuration of a horizontal blanket of riprap to control erosion.

Solution:

1. Stone size:

$$d_{50}/D_o = 0.020\ (D_o/TW)\ (Q/D_o^{5/2})^{4/3}$$

$d_{50}/6 = 0.020\ (6/3.5)\ (425/6^{5/2})^{4/3}$

$d_{50} = 1.67$ feet

2.Length of stone protection:

$L_{sp}/D_o = 1.7\ (Q/D_o^{5/2}) + 8$

$L_{sp}/D_o = 1.7\ (425/6^{5/2}) + 8$

$L_{sp} = 97$ feet

3.Width of stone protection:

W_{sp} (max. TW) = $2\ (1.5\ D_o + 0.2\ L_{sp})$

$= 2\ 1.5\ (6) + 0.2\ (97)$

$= 57$ feet

5.3 Lined Channel Expansions

Channel expansions downstream of culvert outlets can also be lined with either sack revetment, cellular blocks, or rock riprap. Attachment 5.3 shows a practical configuration of the channel expansion geometry.

The required size of riprap, sack revetment, or cellular block can be determined by the following empirical formula:

d_{50}/D_o

or ù

T_s/D_o _ $= 0.016(D_o/TW)(Q/D_o^{5/2})^{4/3}$

or

T_B/D_o û

Where:

- T_s = thickness of sack revetment (feet)
- T_B = thickness of cellular block (feet)

The other terms are as defined for a riprap blanket.

The dimensions of the lined channel expansion can be determined by the proportions in Attachment 5.3.

Example Problem

Given: Culvert Diameter = 6 feet

Tail Water Depth = 3.5 feet

Discharge = 425 cfs

Find: The average size of stone and dimensions of a lined channel expansion.

Solution:

1.Stone size:

$d_{50}/D_o = 0.016\ (D_o/TW)\ (Q/D_o^{5/2})^{4/3}$

$d_{50}/6 = 0.016\ (6/3.5)\ 425/(6)^{5/2})^{4/3}$

$d_{50} = 1.34$ feet

2.Use Attachment 5.3 to determine the lined channel expansion dimensions. Refer to Attachment 5.4 for the final design dimensions of the lined channel expansion.

For further details on the design of riprap blankets, preformed scour holes, and lined channel expansions, the designer is referred to Miscellaneous Paper H-72-5, "Practical Guidance for Estimating and Controlling Erosion at Culvert Outlets," published by the U. S. Army Engineer Waterways Experiment Station in May 1972.

5.4 Oulet Expansion

At many culvert installations the designer can specify a maximum outlet velocity to minimize the possibility of scour and erosion at the outlet. These velocities may range from six to 10 fps, which is low enough that the scour at the outlet may be controlled by riprap or sod. Attachment 5.5 shows a typical outlet expansion design. As shown by this figure, the tail water must be at or above the crown of the pipe at design flow. This condition is fairly common in flat land drainage problems or in multi-pipe installations where smaller diameters are used because of limited headroom.

The design procedure to be outlined here was constructed from an American Concrete Pipe Association article published in Concrete Pipe News entitled "Culvert Velocity Reduction with an Outlet Expansion."

Procedure

Refer to Attachment 5.5 for a schematic diagram of the outlet expansion.

1. With the pipe flowing full under conditions of outlet control, the required pipe size is determined from the Continuity Equation, as follows:

   $D_2 = (4\ Q/pV_2)^{1/2}$

   Where:

   D_2 = pipe diameter (feet)

   Q = design discharge (cfs)

   V_2 = maximum allowable pipe velocity (fps)

2. This type of design produces a net head gain or a lowering of the pipe headwater, as given by the following formula:

   $hg = V_2\ (V_1 - V_2)/g$

   Where:

   hg = net head gain

   V_1 = velocity in initial pipe segment (fps)

   V_2 = velocity in expanded pipe segment (fps)

3. Determine the required length of the expanded pipe segment according to Attachment 5.6, Detail A. For a value of D_1/D_2 different than those listed, use Detail "B" of Attachment 5.6 to obtain a pro-rated value for L/D_L where L is the required length of the expanded pipe.

Example Problem

Given: Culvert Diameter = 6 feet

Tail Water Depth = 7 feet

Discharge = 400 cfs

Find: The diameter and length of the pipe expansion required to lower the discharge velocity to 10 fps.

Solution:

1. Expansion pipe diameter:

   $D_2 = (4\ Q/pV_2)^{1/2}$

   $D_2 = (4 \times 400/p \times 10)^{1/2} = 7.1$ feet

   Use D_2 = 7 feet = 84 inches

2. Determine head gain:

   $hg = V_2\ (V_1 - V_2)/g$

   $V_1 = Q/pr_1^2$

   $= 400\ cfs/p\ (3)^2$

   $= 14.2$ fps

   $V_2 = Q/pr_2^2 = 10.4$ fps

hg = 10.4 x (14.2 - 10.4)/32.2 = 1.23 feet

3. Expansion pipe length:

$D_1/D_2 = 6/7 = 0.857$

Use Attachment 5.6, Detail B, to obtain the length for 100 percent complete expansion.

$L/D_1 = 2.1$

$L = 2.1\ D_1 = 2.1\ (6) = 12.6$ feet

Use L = 14 feet.

5.5 Literature on Energy Dissipaters

Design of Small Dams, U.S. Bureau of Reclamation, lst Edition, 1961, Chapter VIII, "Spillways," Washington, D.C.

Rouse, Hunter, Engineering Hydraulics, John Wiley & Sons, New York, 1949.

Blaisdell, Fred W., and Donnelly, Charles A., Hydraulic Design of the Box Inlet Drop Spillway, U.S. Department of Agriculture, Soil Conservation Service, SCS-TP-106, July 1951.

Blaisdell, Fred W., and Donnelly, Charles A., Straight Drop Spillway Stilling Basin, University of Minnesota, St. Anthony Falls Hydraulic Laboratory, November 1954.

Handbook of Concrete Culvert Pipe Hydraulics, Portland Cement Association, 1964.

Technical Release No. 49, Criteria for the Hydraulic Design of Impact Basins Associated with Full Flow in Pipe Conduit, U.S. Department of Agriculture, Soil Conservation Service, March 1971.

LIST OF ATTACHMENTS

Attachment 5.1	Dissipater Limitations
Attachment 5.2	Recommended Configuration of Riprap Blanket Subject to Maximum and Minimum Tail Waters
Attachment 5.3	Culver Outlet Erosion Protection, Lined Channel Expansions
Attachment 5.4	Example Problem, Lined Channel Expansion Design
Attachment 5.5	Typical Outlet Expansion Diagram
Attachment 5.6	Length Requirements for Expanded Pipes