

## **Chapter 6 - Culverts**

A culvert is a single run of storm drain pipe that conveys water or stormwater under a road, railway, embankment, sidewalk, or other obstruction. A culvert typically connects two open channels, but they may connect an open channel to a storm drain.

Proper culvert design must consider many factors including:

- Design Flow
- Inlet conditions (flow approach conditions, allowable headwater, culvert inlet configuration)
- Culvert conditions (material roughness, pipe slope, and length)
- Tailwater depth
- Buoyancy potential
- Environmental considerations and effects on aquatic life
- Design loads and service life of the pipe material

Refer to the VDOT Drainage Manual, for a more through discussion of these items.

For the design of stormwater inlets and storm drains, see Chapter 7.

### **6.1 References**

Except where more stringent requirements are presented in this Design Manual, culverts shall comply with VDOT requirements. The primary design reference is the VDOT Drainage Manual. Other appropriate references include:

- VDOT Standards
- VDOT Specifications
- VA E&SC Handbook
- VDOT Instructional and Informational Memorandum IIM-ID-121.15, Allowable Pipe Criteria for Culverts and Storm Sewers
- FHWA Hydraulic Design of Highway Culverts HDS No. 5, Pub. No. FHWA-NHI-01-020, Current Edition, as amended
- FHWA Debris Control Structures Evaluation and Countermeasures HEC No. 9, Pub. No. FHWA-IF-04-016, Current Edition, as amended

## 6.2 Design Methodology and Criteria

### 6.2.1 Computation Methods

Manual computations use design equations and nomographs. Results are documented on VDOT's Design Form LD-269. Form LD-269 is included in Appendix 6A.

There are a number of computer programs available to design culverts. Any of these computer programs will be acceptable if their methodologies are based on the same equations and nomographs accepted by VDOT, and if they provide the same documentation of inputs, assumptions, and output as are contained on VDOT's Design Form LD-269.

### 6.2.2 Hydrology

#### A. Design Flow Methodology

See Chapter 4 for methodology used to determine design flows. Generally culverts shall be designed based on the peak flow (steady state), ignoring the effects of temporary upstream storage.

#### B. Obstruction Allowance

An obstruction allowance shall be applied in critical areas where excessive backwater may result in property damage or be a potential safety hazard.

After using the appropriate design methodology to calculate the peak stormwater flow for a given frequency, an obstruction allowance will be added to the peak flow to establish the design flow rate through the culvert. The minimum obstruction allowance factor is intended to account for normal culvert obstructions, which may lower the actual capacity of the culvert once constructed, and is based on the size of the culvert pipe in accordance with the following tabulation:

<u>Culvert Size</u>	<u>Minimum Obstruction Allowance Factor</u>
18" and less	25%
21"-24"	20%
30"	15%
36" and greater	10%

### 6.2.3 Culvert Hydraulics

#### A. Design Flow

The design flow shall be the peak flow from the following frequency storm event, plus the appropriate obstruction allowance:

<u>Roadway</u>	<u>Storm Frequency</u>
Primary & Arterial	25-year
Secondary & Other	10-year

These frequencies are minimum values. Designing for less frequent storms may be required where there is potential damage to structures, loss of human life, injury, or heavy financial loss in the event of flooding.

Compliance with the National Flood Insurance Program (NFIP) is necessary for all locations where construction will encroach on a 100-year frequency flood plain.

In addition, the 100-year peak flow (without the addition of the obstruction allowance) shall be routed through all culverts, determining the headwater depth behind the culvert with road overtopping, to ensure that buildings and other structures are not flooded and that adjacent roadways and adjacent properties do not suffer significantly increased damage during the 100-year storm event. Storage impacts of water behind the culvert may be considered in the calculation, but is not required.

#### B. Allowable Headwater

The allowable headwater is the depth of water that can be ponded at the upstream end of the culvert during the design condition, as measured from the culvert inlet invert.

The allowable headwater depth shall be limited by the following conditions:

- Headwater does not cause upstream property damage;
- Headwater does not increase the 100-year flood elevation, as mapped by NFIP;
- During a design storm event, the water surface shall be a minimum of 18 inches below the shoulder of the road at the point where the culvert crosses

under, or the low point of the road grade where the water would overtop the road;

- Headwater depth shall not exceed 1.5 times the diameter or height of the culvert barrel;
- Headwater depth shall not be such that stormwater flows to other ditches or terrain, which permits the flow to divert around the culvert.
- The maximum overtopping depths during an 100-year storm event for various street classifications are as follows:

<u>Classification</u>	<u>Max. Depth at Crown</u>	<u>Max. Velocity</u>
Local	1 ft*	6 fps
Collector	1 ft*	6 fps
Arterial	No Overflow	No Overflow
Highway	No Overflow	No Overflow

\* Street overflow during a 100-year storm will not be allowed if the street is the only means of access for 40 or more residences. A variance to this requirement may be granted if the applicant shows that the connecting roads will be experiencing substantial overtopping during a 100-year storm and that there is no benefit to enforcing this requirement.

- In most instances, the roadway overtopping may be treated as a broad crested weir.

**C. Tailwater Conditions**

Tailwater is the water into which a culvert outfall discharges. Culvert design shall be based on tailwater conditions that could reasonably be anticipated during the design condition.

- If an upstream culvert outlet is located near a downstream culvert inlet, the headwater elevation of the downstream culvert may establish the design tailwater depth at the upstream culvert.
- If the culvert discharges into a lake, pond, stream, or other body of water, the maximum water elevation of the body of water during the design storm may establish the design tailwater elevation at the upstream culvert.

#### D. Inlet and Outlet Control

Culvert hydraulic design shall consider both inlet and outlet control conditions. For a culvert operating with inlet control, the flow capacity is governed by the inlet geometry. For an outlet control culvert, the inlet geometry, barrel characteristics and tailwater elevation all impact the flow capacity.

Minimum culvert performance is determined by analyzing both inlet and outlet control for a given flow and using the highest resulting headwater.

##### (i) Inlet Control

The following factors are considered when calculating inlet control headwater:

- Inlet Area – cross sectional area of the culvert entrance face
- Inlet Edge – projecting, mitered, headwall, or beveled edges are common
- Inlet Shape – rectangular, circular, elliptical, or arch are common

The nomograph for inlet control for circular concrete, corrugated metal and corrugated HDPE culvert pipe is included in Appendix 6A. Nomographs for calculating headwater and flow capacity for other pipe geometries are contained in the VDOT Drainage Manual.

##### (ii) Outlet Control

The following factors are considered when calculating outlet control headwater:

- Manning's Roughness (n) – based on barrel material, for recommended n values, see the table in Appendix 6A.
- Barrel Area – cross section perpendicular to the flow
- Barrel Length
- Barrel Slope

- Tailwater Elevation

Outlet control affects the hydraulic grade line of the flow through the culvert. To calculate the hydraulic grade, reference the equations for velocity, velocity head, entrance losses, friction losses, and exit losses contained in the VDOT Drainage Manual.

The nomograph for outlet control on circular concrete and corrugated metal pipe is included in Appendix 6A. For additional nomographs, cross sections, and pipe materials, see the VDOT Drainage Manual.

### **E. Culvert Velocity**

Outlet velocity must be checked to assure that excessive erosion and scour problems will not occur. MS 19 from the VA E&SC Handbook requires that discharges be made to an adequate channel.

Culvert outlet protection shall be provided in accordance with the standards and specifications for Outlet Protection and Riprap in the VA E&SC Handbook.

Culverts under roads shall be provided with end sections or endwalls in accordance with the outlet protection requirements of the VDOT Drainage Manual.

Where a special design is needed to reduce outlet velocity, it shall be designed in accordance with VDOT standards.

The minimum velocity in a culvert barrel must be adequate to prevent siltation at low flow rates. At a minimum this velocity shall be 3 feet per second for a 2-year storm event.

#### **6.2.4 Structural Design**

All culverts shall be designed to withstand a HS-20 highway loading, unless it crosses under a railroad, in which case the culvert shall be designed for railroad loads. The structural design shall consider the depth of cover, trench width and condition, bedding type, backfill material, and compaction.

#### **6.2.5 Materials**

Culverts, both public and private, shall be constructed of materials as follows:

- Culverts in the VDOT right-of-way shall be VDOT approved materials in accordance with VDOT IIM-LD-121.15 and VDOT Standard PC-1. Minimum depths of cover are shown in the PC-1 details.
- Public culverts not in the VDOT right-of-way shall be:
  - Reinforced concrete pipe (RCP) Class III minimum or greater as required by loading conditions/cover or box.
  - Aluminized corrugated metal pipe (CMP), is allowed for private systems only for sizes 36-inch diameter or smaller. Minimum gage thickness for CMP culverts shall be 16 gage for 30-inch diameter and smaller. Minimum gage thickness for 36-inch diameter CMP culverts shall be 14 gage. Trench design for CMP culverts shall meet ASTM or AASHTO standards.
  - Special CMP culverts including diameters greater than 36-inch, elliptical, and arch designs will be considered on a case-by-case basis by the County of Roanoke for use as culvert pipe material in private storm drain systems.
- Private culverts not in the VDOT right-of-way may be:
  - Reinforced concrete pipe (RCP) Class III minimum or greater as required by loading conditions/cover or box.
  - Aluminized corrugated metal pipe (CMP), for sizes 36-inch diameter or smaller. Minimum gage thickness for CMP culverts shall be 16 gage for 30-inch diameter and smaller. Minimum gage thickness for 36-inch diameter CMP culverts shall be 14 gage. Trench design for CMP culverts shall meet ASTM or AASHTO standards.
  - Special CMP culverts including diameters greater than 36-inch, elliptical, and arch designs will be considered on a case-by-case basis
  - Corrugated high-density polyethylene (HDPE) with an integrally formed smooth interior is allowed for sizes 48-inch diameter or smaller. HDPE culvert pipe minimum cover must be in accordance with the County of Roanoke Inspection Specifications for HDPE Pipe contained in Chapter 7-B-11.

### 6.2.6 Culvert Sizes

The minimum culvert size shall be 18-inch diameter, except that culverts under private entrance roads or driveways may be 15-inch diameter if it meets all design flow conditions.

Culverts shall meet all cover conditions required. Where the site conditions preclude the use of a single culvert barrel to meet the design flow conditions, multiple barrel culverts are acceptable.

The maximum length of a culvert shall be 300 feet. A culvert longer than 300 feet shall have manholes or junction boxes and shall fall under the requirements of Chapter 7.

### 6.2.7 End Conditions

End sections and headwalls shall normally be required on inlets and outlets, as described below.

#### A. Prefabricated End Sections

Prefabricated end sections, or flared end sections, provide for a better flow path, improving the design flow and headwater conditions.

Prefabricated end sections shall be provided for culverts 18-inch to 36-inch diameter, except:

- No end section is required for 15-inch or 18-inch diameter driveway culverts.
- Where culvert alignment exceeds 20 feet in vertical elevation change or culvert slope exceeds a 2:1 slope, a standard concrete headwall shall be provided instead of a prefabricated end section.
- Where a concrete headwall is provided.

#### B. Concrete Headwalls and Structures

Precast concrete headwalls shall be provided at all culvert inlets and outlets, unless other end conditions are allowed, as stated above. Precast concrete headwalls shall meet the requirements of the VDOT Standards and VDOT Specifications.



Wingwalls may be required in conjunction with headwalls. Culvert pipes 48" or larger in diameter shall have concrete wingwalls. Wingwalls are generally used where the culvert is skewed to the normal channel flow or where the side slopes of the channel or roadway are unstable. Wingwalls shall meet the requirements of the VDOT Standards and VDOT Specifications. Wing walls shall be set at an angle between 30 degrees and 60 degrees from the headwall.

Concrete aprons may be used at the entrance or the exit of culvert. Aprons are typically used where high velocities or headwater conditions may cause erosion upstream or downstream of the culvert. An apron shall not protrude above the normal stream bed elevation.

Special design concrete slab end treatment, per VDOT Standards, may be used as a concrete end section.

### **6.2.8 Multiple Barrel Culverts**

Multiple barrel culverts shall be allowed where single culverts cannot handle the design flow while meeting the required cover or headwater condition requirements. The design of multiple barrels should avoid the need for excessive widening of the upstream or downstream receiving channels.

The minimum spacing between culverts in a multiple barrel culvert design shall be that required to provide adequate lateral support and allow proper compaction of bedding material under the pipe haunches.

### **6.2.9 Culvert Skew**

Where possible, culverts shall be installed parallel to the flow path. The maximum allowable skew shall be 45 degrees as measured from the line perpendicular to the roadway centerline.

### **6.2.10 Buoyancy**

Verify that culvert pipe, end sections, and concrete end wall structures will not fail under hydrostatic uplift conditions.

Buoyancy force consists of the weight of water displaced by the pipe and fill material that is over the pipe (below the headwater depth). The force resisting buoyancy includes the weight of the pipe, weight of the water within the pipe, and the weight of fill material over the pipe.

Buoyancy is more likely to be a problem where:

- Lightweight pipe is used
- Pipe is on a steep slope (usually inlet control with the pipe flowing partially full)
- There is little weight on the end of the pipe (flat embankment slopes, minimum cover, and/or no endwalls)
- High headwater depths ( $HW/D > 1.0$ )

Suitable cover, footings, or anchor blocks may be required to ensure the culvert's integrity during design conditions.

#### **6.2.11 Debris and Trash Racks**

In general, trash racks or debris deflectors shall not be used where other site modifications may be made to prevent excessive trash or debris from entering the culvert. However, they may be required at specific locations, by the County of Roanoke, where large amounts of storm debris may be anticipated.

### **6.3 Installation**

All culvert pipe, headwalls, end sections, outlets, and other peripheral structures shall be installed in accordance with VDOT requirements and the manufacturer's recommendations. The characteristics of the trench, bedding, and pipe material all impact the structural strength of the pipe system. The installed culvert conditions shall comply with the design assumptions and calculations.

HDPE pipe installation shall comply with the County of Roanoke's Inspection Specifications for HDPE Pipe. A copy of this installation guide is provided in Chapter 7.

#### **6.3.1 Bedding Material**

Bedding material and installation shall comply with the requirements of the VDOT Specifications.

#### **6.3.2 Backfill**

Backfill shall be suitable material and shall be placed and compacted in accordance with VDOT Specifications.

A minimum of 12" backfill shall be placed over the top of a HDPE or CMP culvert prior to placing pavement or other surface treatment.

#### **6.4 Environmental Considerations and Fishery Protection**

Where compatible with good hydraulic engineering, a culvert shall be located in “dry” conditions. Where this is not possible, the culvert shall be located to minimize impacts to streams or wetlands.

When a culvert is set in a perennial stream the invert of the culvert shall be set below the normal flow line of the stream as required in the VDOT Drainage Manual. The grade of the culvert shall not exceed the grade of the natural stream in the area.

Where construction requires other environmental permits, the applicant shall be responsible for obtaining all necessary environmental permits and complying with their requirements.

#### **6.5 Maintenance Requirements**

The permittee is responsible for maintenance of culverts until construction is complete, including final clean up and site stabilization, to the satisfaction of the County of Roanoke. After the completion of construction, the property owner or responsible party is responsible for maintenance of all culverts not located in public easements.

No one shall modify culverts in any way that impairs or restricts flow. The property owner shall periodically remove silt and sediment from the pipe and prune vegetation around the pipe entrance to avoid restricting flow capacity and shall correct erosion damage as necessary. All removed silt and sediment shall be properly disposed of away from storm drainage pipes and open channels and shall be properly stabilized with vegetation.

**APPENDIX 6A****AIDS FOR STORMWATER CULVERT DESIGN  
FROM CHAPTER 8, VDOT DRAINAGE MANUAL**

Appendix 8B-1, Culvert Design Form LD-269

Appendix 8C-1, Nomograph for Inlet Control for Circular Concrete Pipe

Appendix 8C-2, Nomograph for Inlet Control for Corrugated Metal Pipe

Nomograph for Inlet Control for Corrugated HDPE Pipe

*Note: This table is not from the VDOT Drainage Manual.*

Appendix 8C-4, Nomograph for Critical Depth, Circular Pipe

Appendix 8C-5, Nomograph for Outlet Control for Circular Concrete Pipe

Appendix 8C-6, Nomograph for Outlet Control for Corrugated Metal Pipe

Appendix 8D-1, Recommended Manning's n-Values

*Note: This table has been modified from VDOT's standard to include additional pipe materials.*

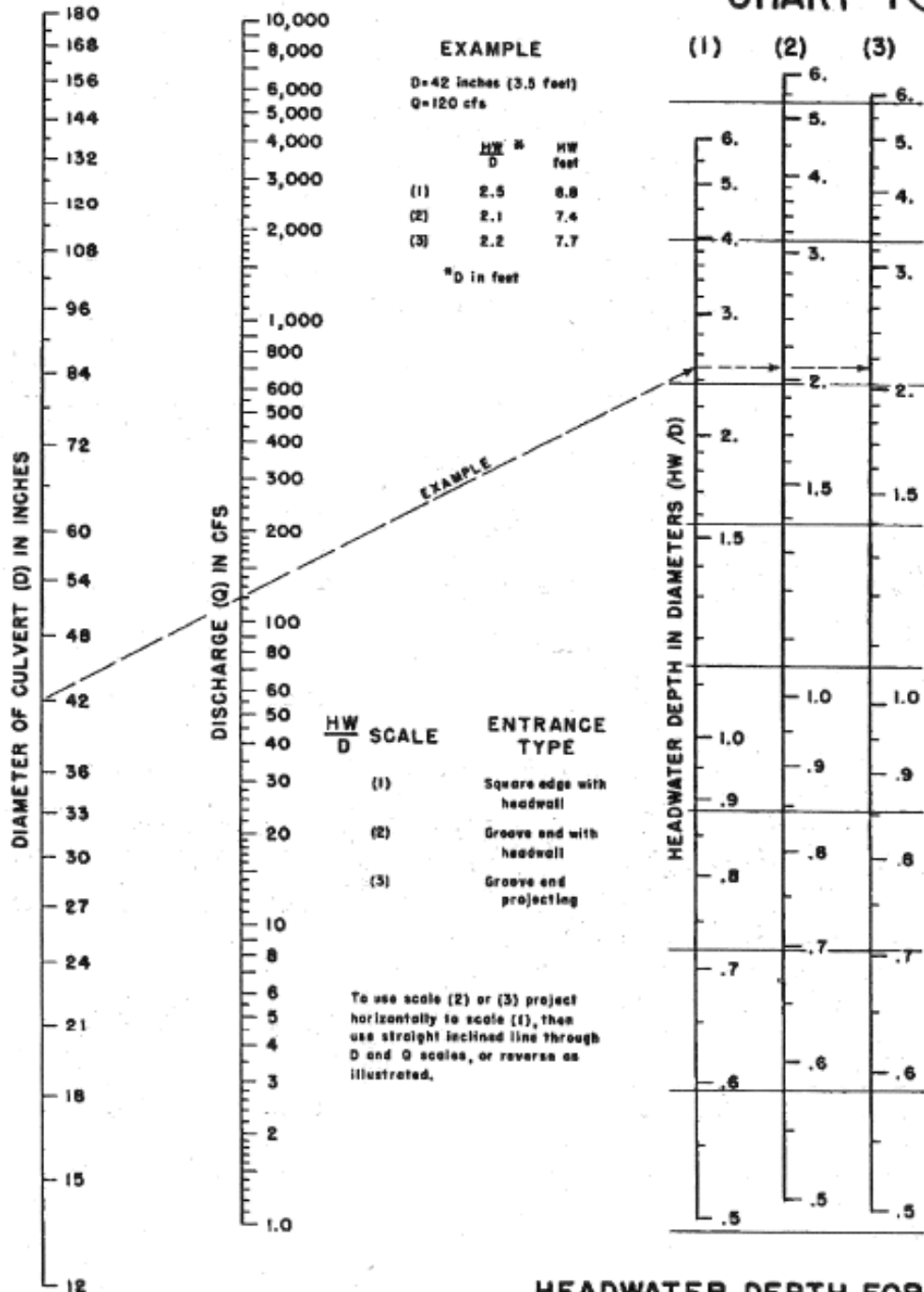
Appendix 8D-2, Entrance Loss Coefficients ( $K_e$ ), Outlet Control, Full or Partly Full

CULVERT DESIGN FORM (VDOT LD-269)

LD-269 Rev. 3-83 Project _____	Plan Sheet No. _____ Designer _____ Date _____ Rev. Date _____	Sheet _____ of _____
STATION: _____		
HYDROLOGICAL DATA: D.A. = _____ AC.	AHW Controls _____ 100 yr. Flood plain elev. _____ Design AHW depth elev. _____ Structures _____ elev. _____ TWelev. _____ freq. _____ _____ _____ _____	Shoulder elev. _____ CL elev. _____ Cover ft. _____ Skew _____ Inv. El. _____ Orig. Gr. Elev. _____ S <sub>0</sub> = _____ L = _____ Inv. El. _____ Orig. Gr. Elev. _____
DISCHARGES USED		
RISK ASSESSMENT		
ADT _____ Length _____		
Details Available _____ Overlapping Stage _____ Flood Plain Management _____ Criteria and Significant Impact _____		
Q = _____ CFS Q = _____ CFS Q = _____ CFS Q = _____ CFS Q = _____ CFS	HEADWATER COMPUTATIONS	
CULVERT TYPE & SIZE	Q/B	Q
H/W/D	HW	K <sub>s</sub>
d <sub>c</sub>	(d <sub>c</sub> + D)/2	h <sub>0</sub>
H	H	LS <sub>0</sub>
HW ELEV.	HW ELEV.	HW ELEV.
CONT.	OUTLET VELOCITY C.M.   Smooth	End Treat
COMMENTS		
SUMMARY & RECOMMENDATIONS:		
Design Flood Exceed. Prob. _____ Elev. _____ Overtop Flood Exceed. Prob. _____ Elev. _____ Base Flood 1% Exceed. Prob. _____ Elev. _____		

INLET CONTROL, CIRCULAR CONCRETE PIPE

CHART 1 



HEADWATER DEPTH FOR  
 CONCRETE PIPE CULVERTS  
 WITH INLET CONTROL

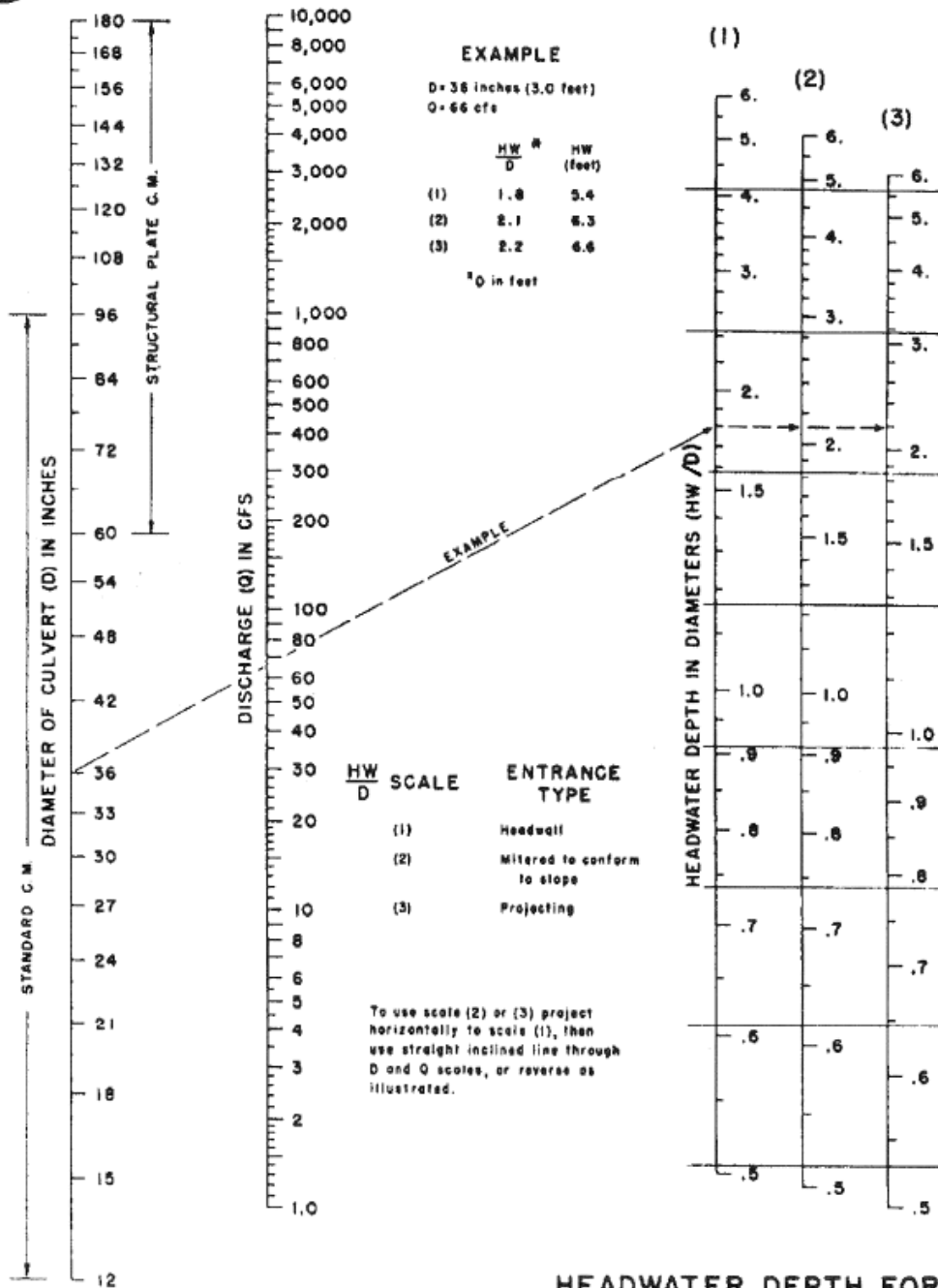
HEADWATER SCALES 2B3  
 REVISED MAY 1964

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INLET CONTROL, CIRCULAR CORRUGATED METAL PIPE



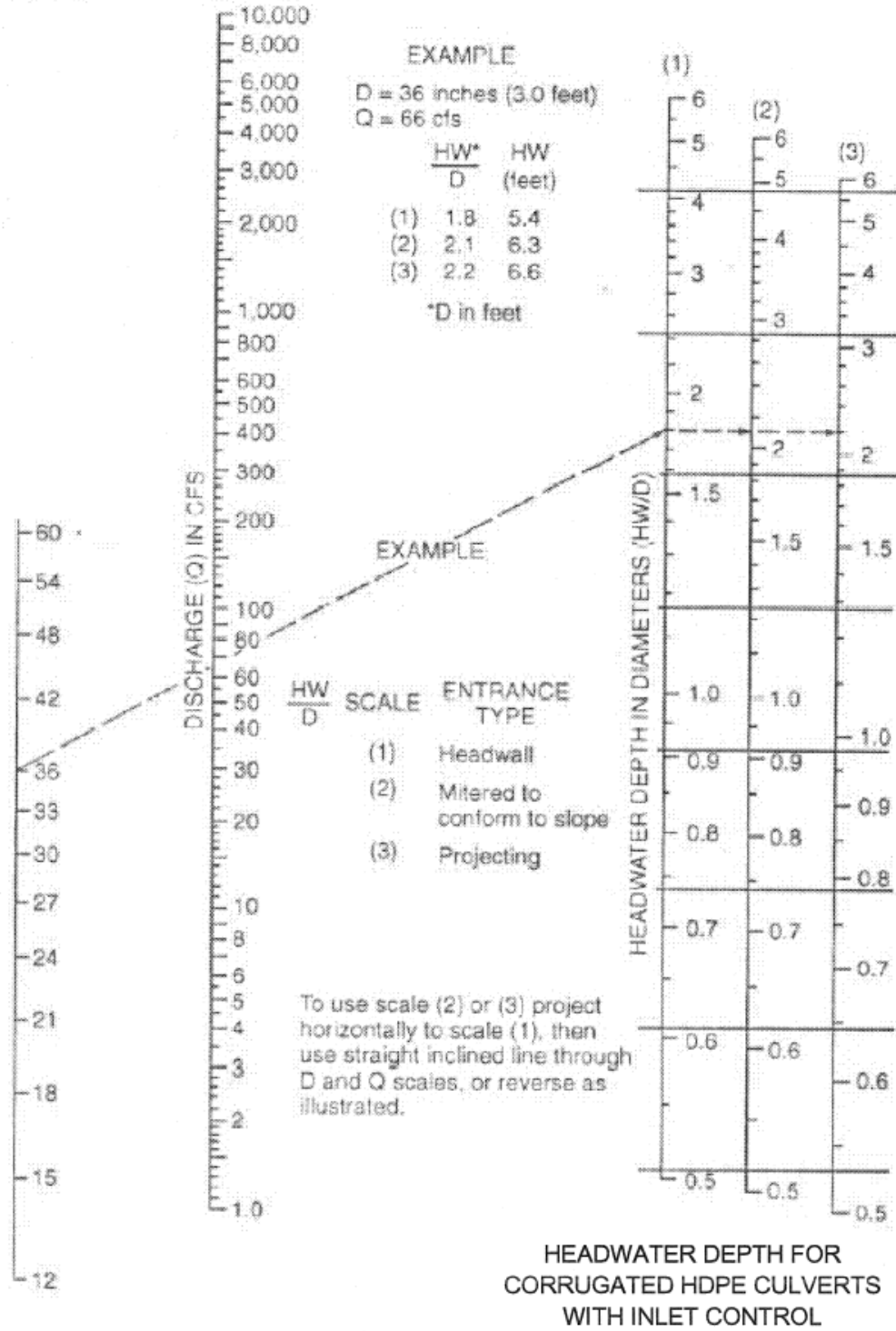
CHART 2



HEADWATER DEPTH FOR C. M. PIPE CULVERTS WITH INLET CONTROL

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### INLET CONTROL, CIRCULAR HDPE PIPE

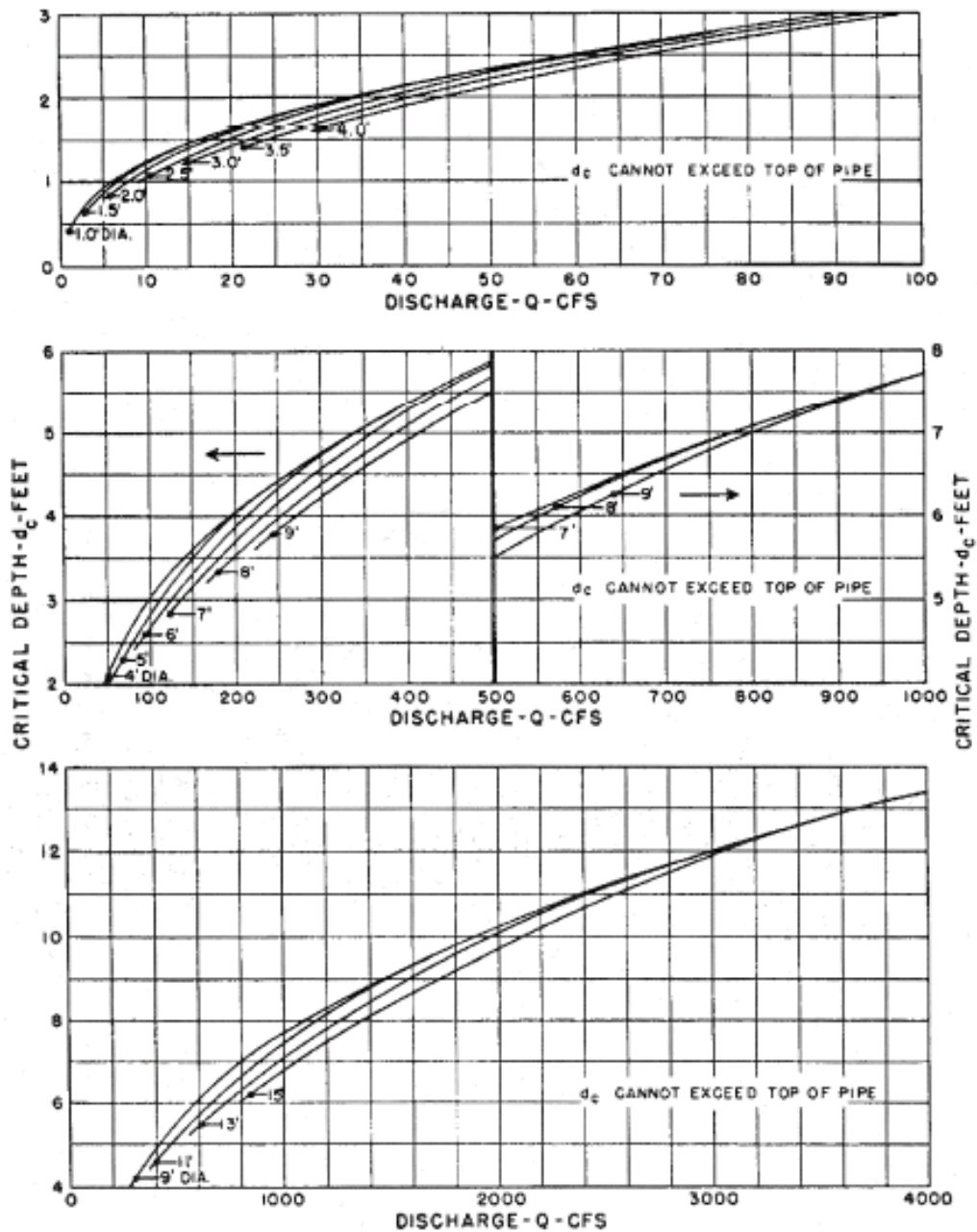




CRITICAL DEPTH, CIRCULAR PIPE



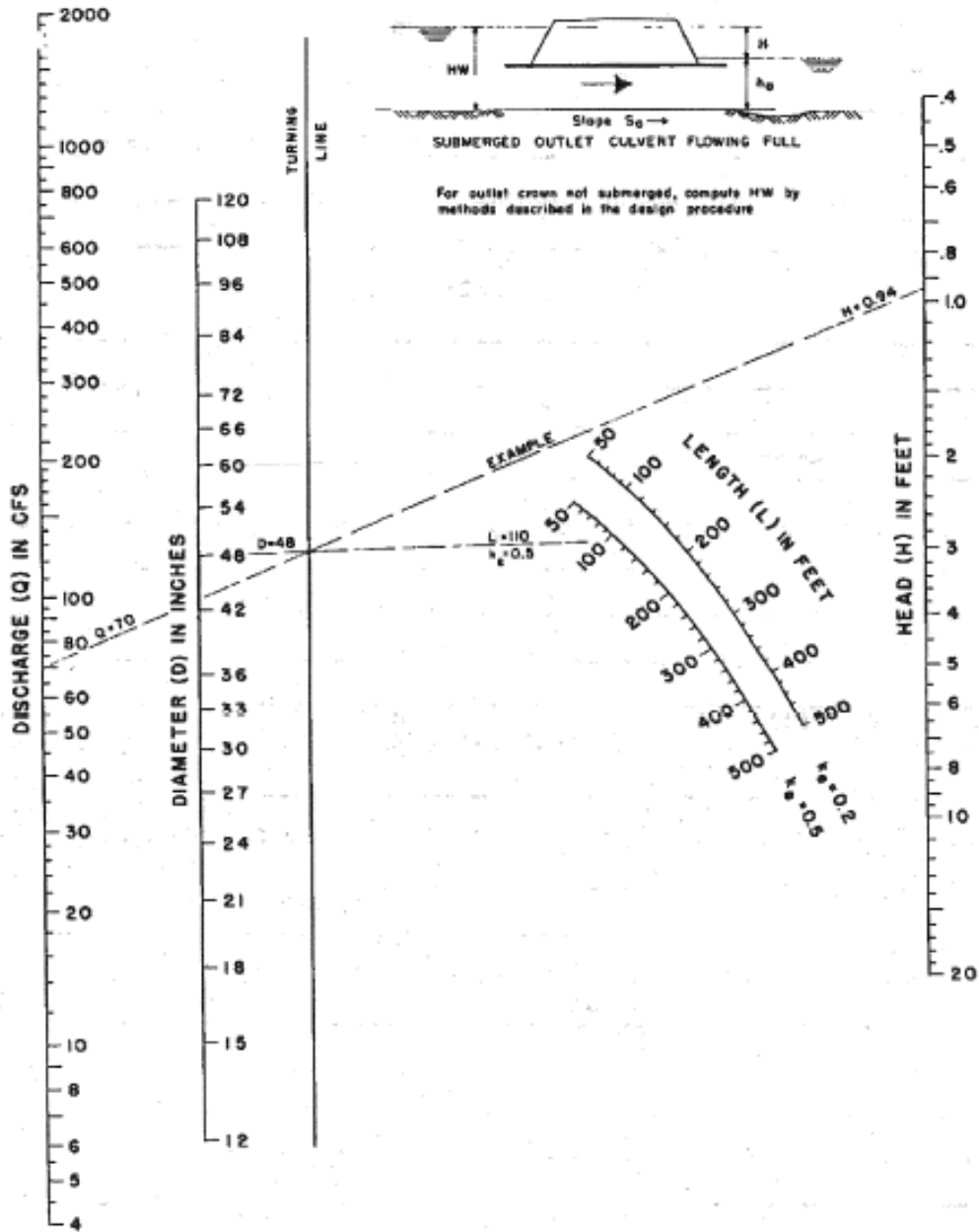
CHART 4



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CRITICAL DEPTH  
CIRCULAR PIPE

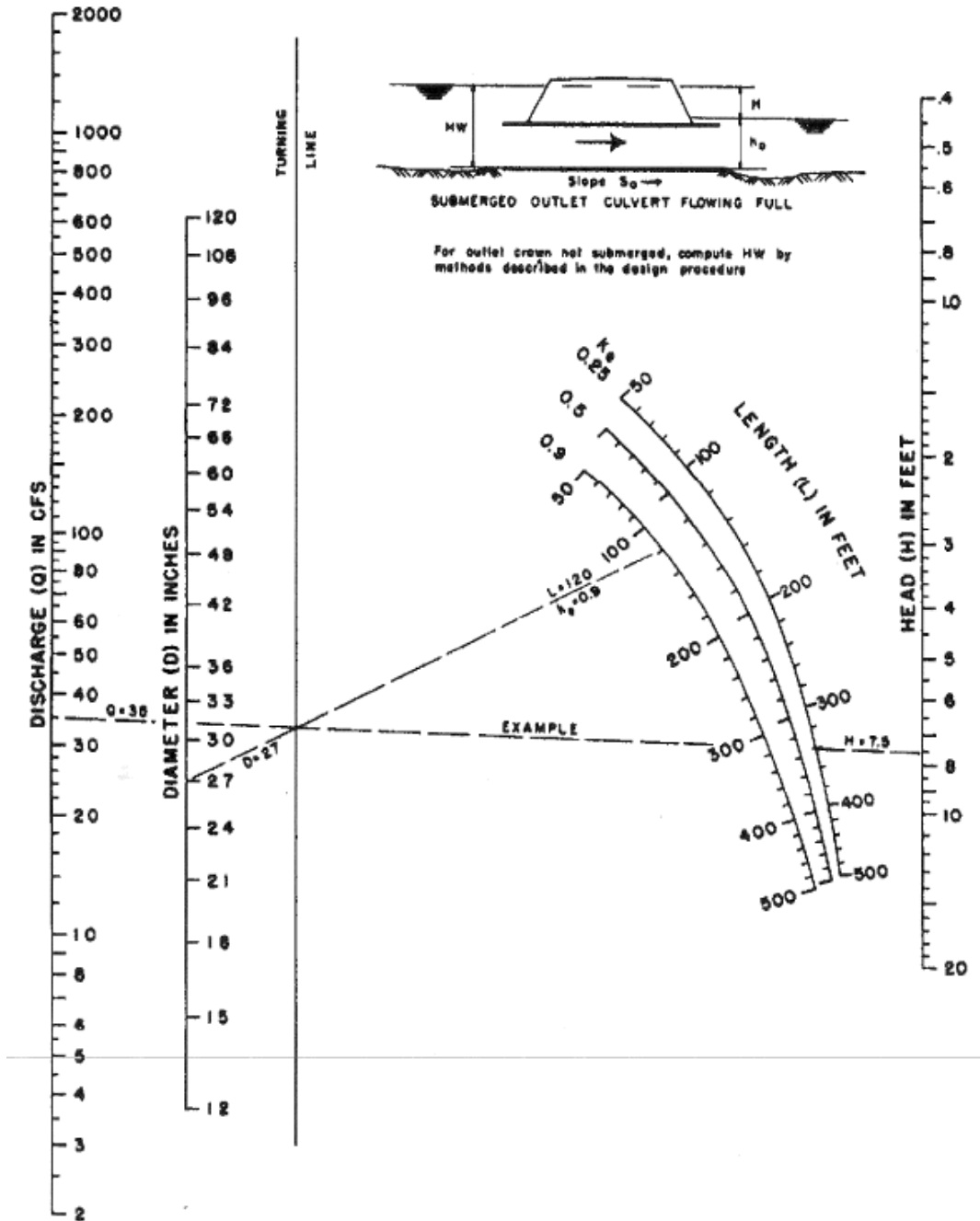
# OUTLET CONTROL, CIRCULAR CONCRETE PIPE



HEAD FOR  
CONCRETE PIPE CULVERTS  
FLOWING FULL  
 $n = 0.012$

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OUTLET CONTROL, CIRCULAR CORRUGATED METAL PIPE



HEAD FOR  
STANDARD  
C. M. PIPE CULVERTS  
FLOWING FULL  
n = 0.024

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## OUTLET CONTROL, CIRCULAR CONCRETE PIPE RECOMMENDED MANNING'S n-VALUES

Type of Conduit	Wall Description	Manning's n
Concrete Pipe	Smooth walls	0.010 - 0.013
Concrete Boxes	Smooth walls	0.012 - 0.015
Corrugated Metal Pipes and Boxes, Annular or Helical Pipe	2 2/3 by 1/2 inch corrugations	0.022 - 0.027
	6 by 1 inch corrugations	0.022 - 0.025
	5 by 1 inch corrugations	0.025 - 0.026
	3 by 1 inch corrugations	0.027 - 0.028
	6 by 2 inch structural plate	0.033 - 0.035
	9 by 2 1/2 inch structural plate	0.033 - 0.037
Corrugated Metal Pipe	2 2/3 by 1/2 inch corrugations	0.012 - 0.024
Spiral Rib Metal (Steel or Alum.)	Smooth walls	0.012-0.013
PVC	Smooth interior	0.010 - 0.012
Polyethylene (PE or HDPE)	Smooth interior	0.011 - 0.013
Corrugated PE or HDPE	Corrugated interior	0.022 - 0.026

Note 1: The values indicated in this table are recommended Manning's "n" design values. Actual field values may vary depending on the effects of abrasion, corrosion, deflection, and joint conditions. Concrete pipe with poor joints and deteriorated walls may have "n" values of 0.014 to 0.018. Corrugated metal with joint and wall problems may also have higher "n" values, and in addition, may experience shape changes which could adversely affect the general hydraulic characteristics of the culvert.

Note 2: For further information concerning Manning n values for selected conduits consult Hydraulic Design of Highway Culverts, Federal Highway Administration, HDS No. 5, page 163.

## ENTRANCE LOSS COEFFICIENTS ( $K_e$ ) OUTLET CONTROL, FULL OR PARTIALLY FULL

Type of Structure and Design of Entrance	Coefficient
Pipe, Concrete	
Mitered to conform to fill slope	0.7
End-section conforming to fill slope	0.5
Projecting from fill, square cut end	0.5
Headwall or headwall and wingwall	
Square-edge	0.5
Rounded (radius = 1/12 D)	0.2
Socket end of pipe (groove end)	0.2
Projecting from fill, socket end (groove end)	0.2
Beveled edges, 33.7° or 45° bevels	0.2
Side or slope-tapered inlet	0.2
Pipe, Corrugated Metal (or Corrugated HDPE)	
Projecting from fill (no headwall)	0.9
Mitered to conform to fill slope, paved or unpaved slope	0.7
Headwall or headwall and wingwall, square-edge	0.5
End section conforming and to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side or slope-tapered inlet	0.2
Box, Reinforced Concrete	
Wingwalls parallel (extension of sides), square edged at crown	0.7
Wingwalls at 10° to 25° or 30° to 75° to barrel, square edged on 3 edges	0.5
rounded on 3 edges to radius of 1/12 barrel	0.2
Wingwalls at 30° to 75° to barrel, crown edge rounded to radius 1/12 of barrel	0.2
Side or slope-tapered inlet	0.2

Note: End Section conforming to fill slope made of metal, concrete, or HDPE, are the sections commonly available from manufacturers. From limited hydraulic test they are equivalent in operation to a headwall in both inlet and outlet control. Some end sections incorporating a closed taper in their design have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.