CHAPTER 9
CULVERTS

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9.1 INTRODUCTION

9.1.1 Definition

A culvert is any structure not classified as a bridge that provides an opening under a roadway, and other type of access or utility.

A culvert is defined as the following:

- A structure that is usually designed hydraulically to take advantage of submergence to increase hydraulic capacity.
- A structure used to convey surface runoff through embankments.
- A structure, as distinguished from bridges, that is usually covered with embankment and is composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert.
- A structure that is 20 feet or less in centerline span width between extreme ends of openings for multiple boxes. However, a structure designed hydraulically as a culvert is treated in this Chapter, regardless of its span.

The following discusses some of the basic concepts and definitions that are commonly used in the hydraulic design and installation of culvert.

Photo 9.1

Photo 9.2

Photo 9.3

Photo 9.4

9.1.2 Purpose of Use

A culvert is used primarily to convey water through embankments or other type of flow obstructions. It is also used as a passage for pedestrian, stock, wildlife, and fish as well as for land access and to carry utilities. This chapter focuses on drainage applications of culverts.

9.1.3 Concepts and Definitions

Following are discussions of concepts that are important in culvert design.

Backfill

The backfill is the material used to refill the trench after the pipe and the embedment have been placed.

Barrel Roughness

Barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete, plastic, and corrugated metal.

Barrel Area

Barrel area is the cross-sectional area perpendicular to the flow.

Barrel Length

Barrel length is the total culvert length from the entrance to the exit of the culvert.

Bedding

The bedding is the material placed at the bottom of the trench on which the pipe is laid.

Bottom of Pipe

Bottom of pipe is the point along the pipe vertical axis which is a wall thickness below the invert.

Control Section

The control section is the location where there is a unique relationship between the flow rate and the upstream water surface elevation.

Cover

The cover is the depth of backfill over the top of the pipe. Refer to the Colorado Department of Transportation (CDOT) M&S Standards for the minimum and maximum cover requirements.

Critical Flow

A state of flow where the specific energy is a minimum for a given discharge. Also, it is the state of flow where the velocity head is equal to one-half the hydraulic depth or where the ratio of inertial forces to gravity forces is equal to unity (Froude number equal to 1).

Critical Depth

Critical depth is the depth at the critical flow. For a given discharge and cross section geometry, there is only one critical depth. Critical depth charts for circular pipes and box culverts are included in Appendix A. For other shapes, refer to Hydraulic Design of Highway Culverts - Federal Highway Administration, Hydraulic Design Series No. 5 (FHWA HDS No. 5).

Critical Slope

A slope that sustains a given discharge at a uniform and critical depth.

Crown

The crown is the inside top of the culvert.

Embedment

The pipe embedment comprises the soil that is placed under and around the pipe immediately above the bedding to support the load on the pipe. It includes the haunch fill, the shoulder fill, and the initial cover.

Energy Grade Line

The energy grade line represents the total energy at any point along the culvert barrel. The total energy at any section is the sum of flow depth, velocity head ($V^2/2g$), and all energy losses.

Flexible Pipe

Flexible pipe is a structure that transmits the load on the pipe to the soils at the sides of the pipe. Examples of flexible pipes are plastic and thin-walled metal pipes.

Flowline

The flowline is the line running longitudinally with the channel connecting all the lowest points in a series of two or more channel cross sections.

Flow Type

The United States Geological Survey (USGS) has established seven culvert flow types which assist in determining the flow conditions at a particular culvert site. Diagrams of these flow types are provided below.

Foundation

The foundation is the in-place or borrow material beneath the bottom of pipe or layer of bedding material. The foundation material should be removed and replaced if unsuitable.

Free Outlet

A free outlet has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

Haunches

The haunches of the pipe are the outside areas between the springline and the bottom of pipe.

Headwater

The headwater is the depth of the upstream water surface measured from the flowline at the culvert entrance.

Hydraulic Grade Line

The hydraulic grade line represents the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel.

Improved Inlet

An improved inlet has an entrance geometry which decreases the flow constriction at the inlet and thus increases the capacity of culverts flowing under inlet control conditions.

Invert

The invert is the inside bottom of the culvert.

Normal Flow

Normal flow occurs in a channel reach when the discharge, velocity and depth of flow do not change throughout the reach. The water surface profile and channel bottom slope will be parallel. This type of flow can exist in a culvert operating on a steep slope provided the culvert is sufficiently long.

Normal Depth

Normal depth is the depth of water at a steady, uniform, constant velocity and flow at a given channel reach.

Rigid Pipe

Rigid pipe is a structure that transmits the backfill load on the pipe through the pipe walls to the foundation beneath the pipe. Examples of rigid pipes are reinforced concrete and thick-walled metal pipes.

Round Pipe and Corrugation Terminologies

Figure 9.1 shows the terminology commonly used in describing round pipe. Figure 9.2 depicts a profile of a corrugated pipe (3 in. x 1 in. corrugation) with terminology and sample dimensions.

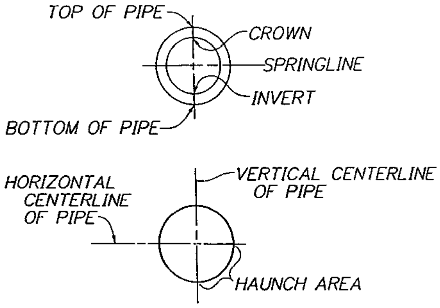


Figure 9.1 Terminology used in describing round pipes.

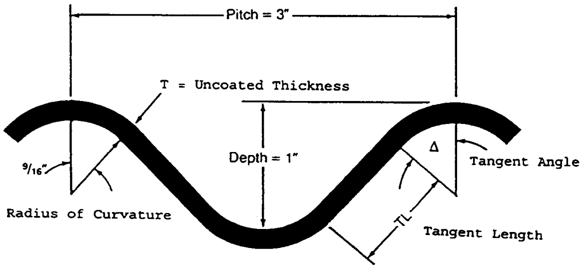


Figure 9.2 Profile of a corrugated pipe.

Slope

Steep slope occurs where the critical depth is greater than the normal depth. Mild slope occurs where critical depth is less than normal depth.

Spring-line

The springline is the horizontal line at the midpoint of the vertical axis of the pipe.

Subcritical Slope

A slope less than the critical slope which causes a slower flow of subcritical state for a given discharge.

Submerged Condition

A submerged outlet occurs where the tallwater elevation is higher than the crown of the culvert.
A submerged inlet occurs where the headwater is greater than 1.2 times the culvert diameter or barrel height.

Supercritical Slope

A slope greater than the critical slope which causes a faster flow of supercritical state for a given discharge.

Tailwater

The depth of water downstream of the culvert measured from the outlet flowline. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation.

Top of Pipe

Top of pipe is the point along the pipe vertical axis which is a wall thickness above the crown.

Trench

A trench is a cut or an excavation made in the ground for the placement of culvert and required bedding, embedment, backfill and cover materials.

Trench Terminology

Figure 9.3 shows the different terminologies commonly used in trenches.

9.1.4 <u>Symbols</u>

To provide consistency within this Chapter and throughout this *Manual*, the symbols given in Table 9.1 will be used. These symbols were selected because of their wide use in culvert publications.

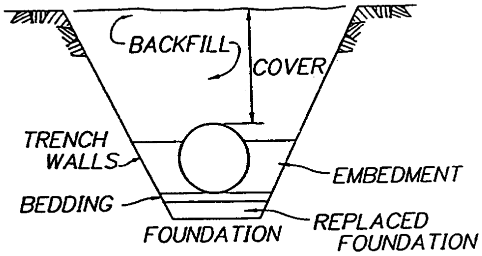


Figure 9.3 Trench terminology.

Table 9.1 Symbols and Definitions

Symbol	Definition	Units
A	Area of cross section of flow	ft^2
AHW	Allowable HW	ft
B	Barrel width	inches or ft
D	Culvert diameter or barrel height	inches or ft
d	Depth of flow	ft
d_c	Critical depth of flow	ft
g	Acceleration due to gravity	ft/s^2
H	Sum of $H_E + H_f + H_o$	ft
H_b	Bend headloss	ft
H_E	Entrance headloss	ft
H_f	Friction headloss	ft
H_L	Total energy losses	ft
H_o	Outlet or exit headloss	ft
H_v	Velocity head	ft
h_o	Hydraulic grade line height above outlet invert	ft
HW	Headwater depth (subscript indicates section)	ft
K_E	Entrance loss coefficient	-
L	Length of culvert	ft
n	Manning's roughness coefficient	-
P	Wetted perimeter	ft
Q	Rate of discharge	ft^3/s
R	Hydraulic radius (A/P)	ft
S	Slope of culvert	ft/ft
TW	Tailwater depth above invert of culvert	ft
V	Mean velocity of flow with barrel full	ft/s
V_d	Mean velocity in downstream channel	ft/s
V_o	Mean velocity of flow at culvert outlet	ft/s
V_u	Mean velocity in upstream channel	ft/s
γ	Unit weight of water	lb/ft^3
τ	Tractive force	lb/ft^2

9.1.5 Classification

Culverts can be classified according to their:

- Geometry;
- Construction material; and
- Type of flow control.

In the following sections, each classification and the factors used in the classification process are discussed.

9.1.6 Geometry

The geometric factors used in culvert classiciation are:

- The barrel shapes; and
- Inlet tpes.

Barrel Shapes

Numerous cross-sectional shapes are available. The most commonly used shapes include circular, rectangular, elliptical, pipe-arch, and arch. The shape selection is based on the cost of construction, the limitation on upstream water surface elevation, roadway embankment height, and hydraulic performance.

Inlet Types

A number of different inlet configurations are utilized on culvert barrels. These include both prefabricated and constructed-in-place installations. Commonly used inlet configurations include projecting culvert barrels, cast-in-place concrete headwalls, precast or prefabricated end sections, and culvert ends mitered to conform to the fill slope. Drawings of these inlet configurations are shown in Figure 9.4. Structural stability, aesthetics, erosion control, and fill retention are considerations in the selection of various inlet configurations.

Figure 9.4 Four Standard Inlet Types (Schematic)

The hydraulic capacity of a culvert may be improved by appropriate inlet selection. Since the natural channel is usually wider than the culvert barrel, the culvert inlet edge represents a flow contraction and may be the primary flow control. The provision of a more gradual flow transition will lessen the energy loss and thus create a more hydraulically efficient inlet condition. Beveled edges are therefore more efficient than square edges. Side-tapered and slope-tapered inlets, commonly referred to as improved inlets, further reduce the flow contraction losses.

Depressed inlets, such as slope-tapered inlets, increase the effective head on the flow control section, thereby further increasing the culvert efficiency. To design tapered inlets, refer to Hydraulic Design of Highway Culverts - FHWA Hydraulic Design Series No. 5 (FHWA HDS No. 5).

9.1.7 Culvert Construction Materials

The most common culvert materials are:

- Concrete (reinforced and non-reinforced);
- Corrugated aluminum;
- Corrugated steel;

- Plastic (corrugated or non-corrugated); and
- High density polyethylene (HDPE).

Culverts may also be lined with other materials to inhibit corrosion and abrasion, or to reduce hydraulic roughness. Refer to Section 603-Culverts and Sewers, Section 616-Siphons, Section 617-Culvert Pipe and Section 624-Corrosion Resistant Culverts, of the Standard Specifications for Road and Bridge Construction for various construction materials acceptable to the Colorado Department of Transportation.

Materials used in constructing culverts result in different structural and performance properties. These properties are:

- Durability;
- Structural strength;
- Hydraulic roughness;
- Embedment conditions;
- Abrasion and corrosion resistance; and
- Watertightness requirements.

Durability

Durability (service life) is defined by the number of years a pipe lasts until it becomes structurally or functionally unfit for the intended purpose. The estimated minimum service life under normal conditions for all types of culvert pipes listed in the Standard Specifications for Road and Bridge Construction shall be 50 years. This service life covers pipes used for highway drainage system including cross culverts, siphons and side drains.

Structural Strength

Structural design of the culvert barrel must provide adequate strength to resist the moments, thrusts, and shears determined through structural analysis. The prism load (dead load), dynamic load (traffic load), the type of pipe material and pavements (flexible or rigid), and the properties of in-situ soil, backfill, embedment, bedding, and foundation materials should be determined before an adequate structural analysis is performed. The designer should refer to the CDOT M & S Standards for the strength requirements of structures with standard sizes. The Bridge Engineer should be consulted if the proposed structure is not standard or if for any reason it requires special design. The structural requirements specified by the Bridge Engineer and those found in the CDOT M & S Standards should apply during and after construction period.

Hydraulic Roughness

The hydraulic roughness represents the hydraulic resistance to flow by culverts. The Manning equation is commonly used to calculate the barrel friction losses in culvert design. The hydraulic resistance coefficients for corrugated metal conduits are based on the size and shape of the corrugations, spacing of the corrugations, type of joints, bolt or rivet roughness, method of manufacture, size of conduit flow velocity and aging. For concrete pipe, the hydraulic resistance varies with the method of manufacture, field installation, quality of joints and aging. For concrete box culverts, the hydraulic resistance is based on the method of manufacture, quality of the formwork, installation or construction practices and aging. Typical ranges of recommended Manning's n values are given in Table 9.2.

Table 9.2 Recommended Manning's n Roughness 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 MetalPipes and Boxes	2-2/3 x 1/2 inch corrugations	0.022-0.027

Annular or Helical Pipe (n varies with barrel size) Refer to Figure 9.10	6 x 1 inch corrugations	0.025-0.026
	5 x 1 inch corrugations	0.025-0.026
	3 x I inch corrugations	0.027-0.028
	6 x 2 inch structural plate	0.033-0.035
	9 x 2-1/2 inch min structural plate	0.033-0.037
Spiral Rib Metal	Smooth walls	0.012-0.024

Notes:

1. The values indicated in this table are recommended Manning's n design values. Actual field values for older existing pipelines 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 pipe 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.
2. For further information concerning Manning's n values for selected conduits, consult FHWA HDS No. 5.

Embedment Conditions

For rigid pipe, the embedment distributes the load over the foundation. For flexible pipe, the embedment resists the deflection of the pipe due to load. The flat surface makes compaction difficult at the very bottom of large structures. Trenches should be wide enough to permit compacting the remainder of the embedment under the haunches of the structure. Refer to CDOT M&S Standards for structure excavation backfill limits, and fill height requirements (allowable minimum and maximum cover).

Abrasion and Corrosion Resistance

Abrasion is the erosion of culvert material primarily due to the natural movement of bedload in the stream. Effects of abrasion on the life of culverts in Colorado are poorly documented. In the past, only a few of the Department's culverts had required repair as a result of abrasion damage. This changed dramatically in the recent years due to aging of existing installations. When abrasion problems are expected, several options are available to the designers.

- Debris control structures, although require periodic maintenance, can be used to reduce or eliminate abrasive material inflow into culverts.
- A liner or bottom reinforcement utilizing additional abrasion resistant material is another option.
- Concrete or bituminous lining of the invert of corrugated metal pipes is a commonly employed method to minimize effects due to abrasion.
- Concrete culverts may require additional cover over the reinforcement bars or high strength concrete mixes to resist abrasion.
- 2 to 6 inches of high strength concrete placed over the reinforcing steel may be used to minimize abrasion of pipes.
- The use of metal or wooden planks attached to the culvert bottom normal to the flow will trap and hold bedload materials, thereby providing invert protection.
- Oversized culvert barrels which are partially buried accomplish the same purpose.

Method of predicting abrasion performance of metal pipes may be available from the manufacturer. If preliminary evaluation indicates that deterioration of pipe by abrasion is a good possibility, the designer may consult with the manufacturer to determine the required pipe thickness.

All available culvert materials are subject to deterioration when placed in certain corrosive environment. The required level of corrosion resistance (C.R.) is determined by the Region and Staff Materials Engineers using site soil, water tests, and visual observations of culverts in the area. The C.R. level shall be specified in the project plans. The contractor will then be allowed to select alternative culvert materials as specified in Section 624 - Corrosion Resistant Culverts, of the Standard Specifications for Road and Bridge Construction.

Watertightness Requirements

Watertightness pertains to the tightness of the fit of the installed pipes as to be impermeable to water. Piping caused by seepage along a culvert removes fill material to form a hollow similar to a pipe. Fine soil particles are washed out freely along the hollow and the erosion inside the fill may ultimately cause failure of the culvert or the embankment. Piping may also occur through open joints into the culvert barrel. Therefore, it is important that culvert joints be as watertight as practical. The designer must ensure that the proposed pipe system is sufficiently watertight to handle the hydrostatic pressure resulting from the design headwater. Headwalls, impervious materials at the upstream end of the culvert and anti-seep or cutoff collars decrease the probability of piping. Antiseep collars usually consist of bulkhead type plates or blocks around the entire perimeter of the culvert. They may be of metal or of reinforced concrete and, if practical, their dimensions should be sufficient to key into impervious material.

9.1.8 Types of Flow Control

Culvert classification based on the flow control type categorizes culverts into two basic groups:

1. Inlet control culverts; and
2. Outlet control culverts.

The basis for this classification is the location of the control section. The hydraulic capacity of a culvert depends upon a different combination of factors for each type of control.

An accurate theoretical analysis of culvert flow is extremely complex and will require the following:

- Analysis of nonuniform flow with regions of both gradually varying and rapidly varying flow;
- Determination of how the flow type changes as the flow rate and tailwater elevations change;
- Application of backwater and drawdown calculations, energy and momentum balance;
- Application of the results of hydraulic model studies; and
- Determination if hydraulic jump occurs and its location.

Inlet Control

Inlet control occurs when the culvert barrel is capable of conveying more flow than the inlet will accept. The control section of a culvert operating under inlet control is located just inside the entrance. Critical depth occurs at or near this location, and the flow region immediately downstream is supercritical. Figure 9.5 shows a typical inlet control flow condition. Hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity. The upstream water surface elevation and the inlet geometry represent the major flow controls. The inlet geometry includes the barrel shape, cross-sectional area, and the inlet edge. Majority of the existing culverts in Colorado's highways operate under inlet control.

Three regions of flow for inlet control are shown in the Figure 9.6. They are: i) unsubmerged; ii) transition; and iii) submerged. The equations used to develop the nomographs and to define inlet control conditions are presented in the FHWA publication HDS No. 5.

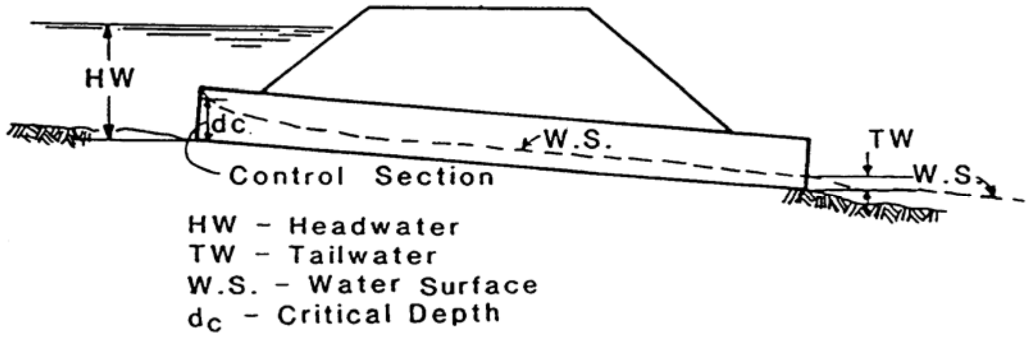


Figure 9.5 Typical inlet control flow condition.

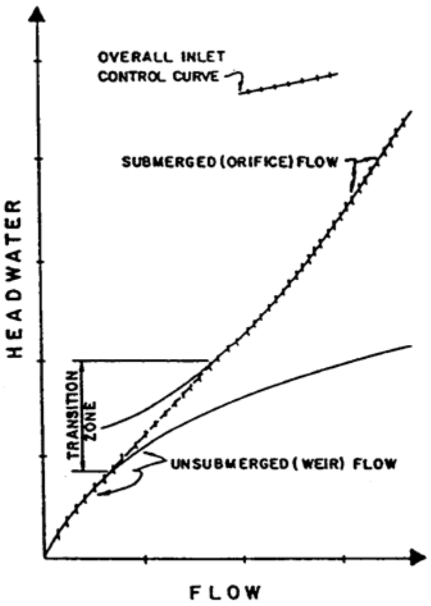


Figure 9.6 Unsubmerged, transition and submerged regions of flow.

For **unsubmerged** region of flow, headwater elevation is below the inlet crown and the entrance operates as a weir.

- A weir is a flow control section where the upstream water surface elevation can be predicted for a given flow rate.
- The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges.
- These tests are then used to develop equations. Appendix A of FHWA HDS No. 5 contains the equations which were developed from model test data.

For **submerged** region of flow, headwater elevation is above the inlet, the culvert operates as an orifice.

- An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section.
- The relationship between flow and headwater can be defined based on results from model tests.

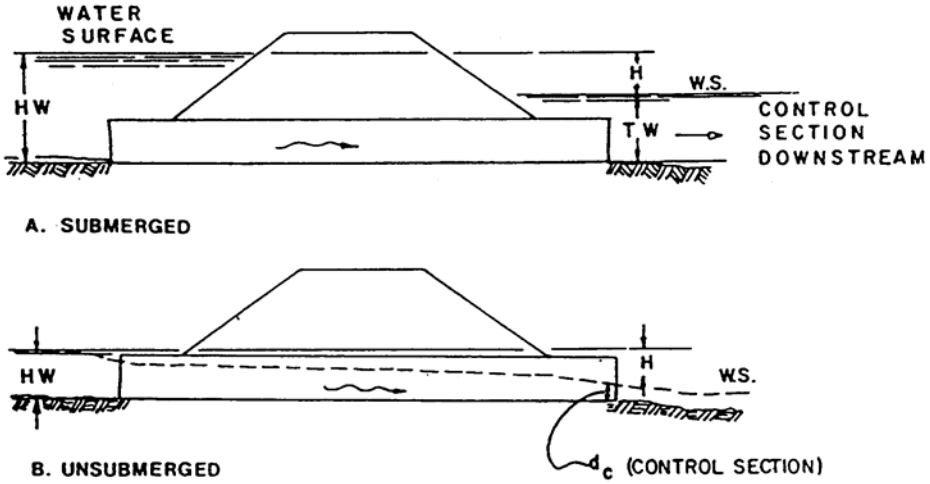
The **transition** zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and by connecting them with a line tangent to both curves.

Outlet Control

Outlet control flow occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept. The control section for outlet control flow in a culvert is located at the barrel exit or further downstream. The culvert may outfall into a pond, lake, gulch, creek, river, and other drainageways. In an outlet control condition, the water surface elevations or tailwater on these waterways are high enough to cause backwater to a distance upstream of the culvert inlet and therefore control the flow.

In culvert barrels operating under outlet control, either subcritical or pressure flow exists. Figure 9.7 shows typical outlet control flow conditions. Under outlet flow control conditions, all of the geometric and hydraulic characteristics of the culvert have a role in determining its capacity. These characteristics include all of the factors governing inlet control, the water surface elevation at the outlet (tailwater), the slope, length, and hydraulic roughness of the culvert barrel.

The various equations and graphical representations which define the flows in culverts operating in outlet control conditions are presented in FHWA HDS No. 5.



NOTES:

HW - HEADWATER
TW - TAILWATER
W.S. - WATER SURFACE
H - LOSSES

Figure 9.7 Typical outlet control flow conditions.

9.1.9 Roadway Overtopping

Roadway overtopping will begin when the headwater rises to the elevation of the roadway. The overtopping will usually occur at the low point of a sag vertical curve on the roadway.

The following equation is used to define the overtopping flow across the roadway. The equation is the same relationship used to define the flow over a broad crested weir. Flow coefficients for flow overtopping roadway embankments are given in Figure 9.8.

$$Q_r = C_d L (HW_r)^{1.5} \tag{9.1}$$

Where Q_r = overtopping flow rate, cfs; C_d = overtopping discharge coefficient (= k_t C_r); k_t = submergence coefficient; C_r = discharge coefficient; L = length of the roadway crest, ft; HW_r = the upstream depth, measured above the roadway crest, ft.

The crest length is difficult to determine when the crest is defined by a roadway sag vertical curve.

- Recommend subdividing into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are then added together to determine the total flow.

- The length can be represented by a single horizontal line (one segment). The length of the weir is the horizontal length of this segment. The depth is the average depth of the upstream pool above the roadway.

The total flow is calculated for a given upstream water surface elevation using the above overtopping equation.

- Roadway overflow plus culvert flow must equal total design flow.
- A trial and error process is necessary to determine the flow passing through the culvert and the amount flowing across the roadway.
- Performance curves for the culvert and the road overflow may be summed to yield an overall performance.

9.2 DESIGN CRITERIA

Listed below by categories are the design criteria that shall be considered for all culvert designs.

9.2.1 Site and Structure Selection Criteria

Culvert Location

The Region will normally submit field culvert reports specifying the culvert location with supporting survey and topography. The survey to be transmitted to the Hydraulics Unit shall be in accordance with the requirements of the Survey Manual.

Cross culverts shall be located as close to the natural drainage waterway as possible. The combining of flows from several channels into a common channel to use only one cross culvert is discouraged. However, if such concentration is necessary, care must be taken to avoid severe erosion or deposition of silt at the culvert outlet. The same applies to concentrating sheet flow from wide or undefined waterways. Flow should not be diverted to another watershed without an evaluation of the legal and physical consequences.

Figure 9.8 Flow coefficients for overtopping roadway.

Culvert Alignment

From the standpoint of hydraulic efficiency, durability and maintenance, abrupt changes in flow direction are undesirable. The maximum angle of bend at any point along a culvert horizontal or vertical alignment should be 22°30'. This angle of bend must be referenced to an alignment taken along the side of the culvert nearest to the center of curvature. Any angle of bend greater than this value should be divided into smaller angles and the miters spaced at a minimum interval of 1.2 times the total diameter or span of the culvert. As an alternative to mitering and if facility of construction dictates, the culvert can be curved using a minimum radius of curvature equal to 3 times the diameter or span. Similar to mitering, curving should be taken along the side of the culvert nearest to the center of the curvature.

Any abrupt change of direction at either end of a culvert will retard flow, may trap debris and cause scouring or silting. The ideal installation is to locate the culvert in the existing streambed. Though this is not always feasible, channel changes should be held to a minimum. The water should be intercepted by the cross culvert as near as possible to the point where the drainage channel first impinges on the highway template. If a channel change cannot be avoided, it should be made at the culvert outlet rather than at the inlet. In general, when a roadway crosses an irrigation ditch, the skew angle of the crossing cannot be changed in order to reduce the culvert length.

Structure Type Selection

Culverts are used:

- Where bridges are not hydraulically required;
- Where debris and ice are tolerable; and
- Where more economical than a bridge.

Bridges are used:

- Where culverts cannot be used;
- Where more economical than a culvert;
- To satisfy land-use requirements;
- To mitigate environmental harm caused by a culvert;
- To avoid floodway ((or irrigation canal)) encroachments; and
- To accommodate ice and large debris.

Length, Slope, and Flowline

The culvert length and slope shall be chosen to approximate existing topography, and to the degree practicable.

- The culvert invert shall be aligned with the flowline and the skew angle of the stream; and
- The culvert entrance shall match the geometry of the roadway embankment.

The **length** of the culvert is determined from the structure cross-section. The ends of culverts are positioned from the fill slope as shown in CDOT M&S Standards.

- Increase the culvert length to compensate for soil sloughing from steep high fills by projecting the culvert end out an additional 1 foot for each 10 feet of fill height.
- Increase the length as required on skewed culverts with ends perpendicular to the flow.
- These guidelines may be modified when safety, right-of-way or physical obstructions dictate.

To reduce sediment deposition within the culvert, the **slopes** should be selected to be steep enough to maintain or exceed natural channel velocities.

- Broken-back culvert slopes are discouraged.
- Abrupt slope changes may trap debris and make culvert cleaning difficult.
- However, in mountainous regions, a broken back slope may be necessary to avoid placing the outfall high on the fill.

In cases where streambed is aggrading, the culvert **flowline** may be raised accordingly. This reduces sedimentation in the barrel. However, due to the uncertainty of continued aggradation, it is advisable to increase the culvert height, leaving the flowline as is. Conditions causing aggradation may be natural or man-made downstream control.

- The designer should not select the culvert flowline until upstream and downstream channel flowline elevations are known.
- The ground lines of a structure cross section may not represent the channel bottom causing the designer to erroneously set the culvert flowline on the banks of the channel.
- The channel flowline may be determined from field survey data or a contour map. The field survey data shall include channel cross sections as prescribed in the Survey Manual.

Ice Buildup

Ice buildup shall be mitigated as necessary by:

- Assessing the flood damage potential resulting from a plugged culvert,
- Increasing the culvert height 1 ft above the total of the maximum observed ice buildup plus any winter flow depth; and
- Increasing the culvert width to encompass the observed channel's static ice width plus 10% where appropriate to prevent property damage.

Debris Control

Debris control shall be designed using Hydraulic Engineering Circular No. 9, "Debris-Control Structures" *(4)* and shall be considered:

- Where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris,
- For culverts located in mountainous or steep regions,
- For culverts that are under high fills, and
- Where clean-out access is limited. However, access must be available to clean out the debris-control device.

The designer should seek information concerning the type and the amount of debris to be expected during a major flow. Since it is nearly impossible to calculate the volume by visual observation of the basin, history from previous flows in the proximity of the site is most reliable. The designer may attempt to retain the debris upstream of the entrance or intentionally pass it through the culvert.

It is not feasible to retain small debris such as silt, small stones, brush, or trash upstream of a culvert. Generally, it is not even feasible to retain larger debris such as large boulders and trees. Debris control devices are often unsightly and expensive and they can require considerable maintenance after each flood occurrence. If the storage capacity of the debris trap is too small for a major storm, water may be diverted away from the culvert entrance causing more damage than naturally.

When the debris is passed through the culvert, the size of the culvert must be adequate to prevent much ponding at the entrance. If debris is to be retained upstream, a debris control structure is necessary.

The center web wall in a concrete box culvert can collect excessive debris. If excessive debris is expected, a single span culvert is favored. Cost comparisons should be made among the single span and larger double or triple cell concrete box culverts. The use of an upstream sloping web wall is effective in reducing plugging by floating debris. See Chapter 10 - Bridges for more information.

Excessive silt generally will not be deposited in a culvert provided the inlet and the outlet are on or above the flowline of the channel. Exceptions may occur if the culvert is so wide that the velocity in the culvert is less than the natural channel, or if the culvert constricts a supercritical channel.

9.2.2 <u>Design Limitations</u>

Allowable Headwater

The allowable headwater is the depth of water that can be ponded or tolerated at the upstream end of the culvert. The allowable headwater does not permit encroachment of water into adjacent roadway or inundation of upstream property. Both the surrounding features and flow limitations must be considered for each site before the allowable headwater is determined. The potential for future development must also be considered in determining the allowable headwater elevation.

The surrounding features which may control the allowable headwater include the following:

- Lowest elevation of the roadway subgrade adjacent to the ponding area;
- Flowline of the roadway ditch which passes water along the roadway to another drainage basin;
- Upstream property, such as buildings or farm crops, which will be damaged if inundated.

Flow limitation factors that can affect the allowable headwater values to be used include the following:

- The debris which could plug the structure;
- Excessive ponding which would allow too much silting; or
- High hydrostatic pressure which would cause seepage along the culvert backfill.

When the above factors are insignificant, the ratios of headwater depth to structure depth (HW/D) from the flowline given in Table 9.3 should be used as the maximum values in design. These values should be reduced to a ratio of 1.0 or less when the design flows are from snowmelt or in irrigation ditches.

Table 9.3 Maximum Headwater Depth to Structure Depth Ratios, HW/D.

Range of Diameter or Height or Rise, inches	**Maximum HW/D**
Less than 36 in.	2.0
36 in.to 60 in.	1.7
Larger than 60 in. but less than 84 in.	1.5
84 in. to less than 120 in.	1.2
120 in. or larger	1.0

For detention ponds, all the hydraulic design work should be performed by the Hydraulic Engineer. The use of HW/D ratios greater than those values given in Table 9-3 should be approved by the Hydraulic Engineer. Refer to Chapter 12 - Storage Facilities and the U.S. Bureau of Reclamation's, "Design of Small Dams," Second Edition, Rev. 1977 for additional information on the design of detention ponds.

Review Headwater

The review headwater is the flood depth that:

- Does not exceed a 1-ft increase over the existing 100-yr flood elevation in the National Flood Insurance Program mapped floodplains or in the vicinity of insurable buildings, and
- Has a level of inundation that is tolerable to upstream property and roadway for the review discharge.

Tailwater Relationship (Channel)

- Evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth for a range of discharges, which includes the review discharge (see Channel Chapter).
- Calculate backwater curves at sensitive locations or use a single cross section analysis. (Backwater curves yield the most accurate tailwater.)
- Use the critical depth and equivalent hydraulic grade line if the culvert outlet is operating with a free outfall.
- Use the headwater elevation of any nearby, downstream culvert if it is greater than the channel depth.

Tailwater Relationship (Confluence or Large-Water Body)

- Use the high-water elevation that has the same frequency as the design flood if events are known to occur concurrently (statistically dependent).
- If statistically independent, evaluate the joint probability of flood magnitudes, and use a likely combination resulting in the greater tailwater depth. Guidelines are provided in Table 13-7, Joint Probability Analysis.

Maximum Velocity

The maximum velocity at the culvert exit shall be consistent with the velocity in the natural channel or shall be mitigated with channel stabilization (See Chapter 8 - Channels), and energy dissipation (See Chapter 11 - Energy Dissipator). High velocities greater than 16 fps along with large discharges shall require concrete stilling basin or other types of appropriate energy dissipators. Energy dissipators shall be designed by the Hydraulic Engineer for in-house projects.

Minimum Velocity

The minimum velocity in the culvert barrel shall result in a tractive force ($\tau = \gamma dS$) greater than critical τ of the transported streambed material at low-flow rates.

- Use 3ft/s when streambed material size is not known.
- If clogging is probable, consider installation of a sediment trap or a size of culvert to facilitate cleaning.

Storage (Temporary or Permanent)

If storage is being assumed upstream of the culvert, consideration shall be given to:

- Limiting the total area of flooding,
- Limiting the average time that bankfull stage is exceeded for the design flood to 48 h in rural areas or 6 h in urban areas, and
- Ensuring that the storage area will remain available for the life of the culvert through the purchase of right-of-way or easement.

Flood Frequency

The flood frequency used to design or review the culvert shall be based on:

- The roadway classification;
- The level of risk associated with failure of the crossing, increasing backwater or redirection of the floodwaters;
- An economic assessment or analysis to justify the flood frequencies greater or lesser than the minimum flood frequencies listed below; and
- Location of FEMA-mapped floodplains.

The flood frequency used to design the culvert shall be based on criteria given in Chapter 7 - Hydrology. The minimum design frequencies for various types of roads, terrain, and flood magnitudes are listed in Table 7.2 of Chapter 7 - Hydrology. The frequencies in this table shall be used unless an economic analysis indicates otherwise. No through lanes of interstate highways shall be designed for less than a 50-year flood frequency.

9.2.3 <u>Design Features</u>

Culvert Sizes and Shape

Selection of culvert size and shape shall be based on engineering and economic criteria related to site conditions:

- The minimum diameters to be used for various types of applications are listed in Table 9-3.
- Land-use requirements (e.g., need for a cattle pass) can dictate a larger or different barrel geometry than required for hydraulic considerations.
- Use arch or oval shapes only if required by hydraulic limitations, site characteristics, structural criteria or environmental criteria.

A circular culvert is the most efficient shape because of its higher ratio of cross sectional area to the wetted perimeter relative to other shapes with identical cross-sectional areas. A narrow but high rectangular culvert is less expensive than a wide, low culvert of the same area. However, the wider culvert has several advantages that are very important. The wider culvert spreads the outlet flow more; the outlet flow is shallower and has slightly slower velocity, causing less outlet erosion damage. The lower culvert is necessary where clearance is minimal and headwater depths are limited.

Table 9.4 Minimum Culvert Diameters

Application	Minimum Diameter, Inches
Cross Culvert	36 in.
Side Drain	18 in.
Median Drain	18 in.
Storm Drain Trunk Line	18 in.
Connections	
Median drain to cross culvert	15 in.
Curb inlet to trunk line	15 in.
Irrigation crossing	18 in.

Broken-Back Culverts

A broken-back culvert, which combines two different slopes, may be necessary to accommodate a large differential of flow line elevation or may result from one or more extensions to an original straight profile culvert.

Multiple Barrels

Multiple-barrel culverts shall fit within the natural dominant channel with minor widening of the channel to avoid conveyance loss through sediment deposition in some of the barrels. They are to be avoided where:

- The approach flow is high velocity, particularly if supercritical. (these sites require either a single barrel or special inlet treatment to avoid adverse hydraulic jump effects.);
- Irrigation canals or ditches are present unless approved by the canal or ditch owner;
- Fish passage is required unless special treatment is provided to ensure adequate low flows (commonly one barrel is lowered);
- A high potential exists for debris problems (clogging of culvert inlet); or
- A meander bend is present immediately upstream.

Material Selection

The material selection shall consider replacement cost and difficulty of construction and traffic delay:

- The material selected shall be based on a comparison of the total cost of alternative materials over the design life of the structure, which is dependent upon the following:

- Durability (service life),
- Structural strength,
- Hydraulic roughness,
- Bedding conditions,
- Abrasion and corrosion resistance, and
- Water-tightness requirements.
- The selection shall not be made using first cost as the only criteria.

Culvert Skew

The culvert skew is the acute horizontal angle left or right (looking in the direction of increasing station) between the roadway centerline and the culvert centerline. The culvert skew shall not be less than 45 degrees without the approval of the Hydraulic Engineer.

End Treatment (Inlet or Outlet)

The culvert inlet type shall be selected from the following list based on the considerations given and the inlet coefficients. Refer to FHWA HDS No. 5 for recommended values of entrance loss coefficients. Considerations shall also be given to safety since some end treatments can be hazardous to errant vehicles. All culverts 48 inches in diameter and larger should have headwalls or slope paving on the inlet end.

<u>Projecting Inlets or Outlets</u>

- Extend beyond the roadway embankment and are susceptible to damage during roadway maintenance and from errant vehicles.
- Have low construction cost.
- Have poor hydraulic efficiency for thin materials.
- Are used predominantly with metal pipe.
- Shall include anchoring the inlet to strengthen the weak, leading edge for culverts 4 feet in diameter and larger.

<u>Mitered Inlets</u>

- Are hydraulically more efficient than thin-edge projecting.
- Shall be mitered to match the fill slope.
- Shall include anchoring the inlet to strengthen the weak, leading edge for culverts 4 feet in diameter and larger.

<u>Headwalls</u>

- A full headwall is required for culverts with 50 ft^2 of area, 96" and larger.
- A concrete type " S " headwall is required at the minimum on metal culverts 42" in diameter and larger operating under inlet control.
- The headwalls should be placed perpendicular to the culvert centerline for all culverts with span less than 7 ft.
- For wider spans, use the following steps to determine if headwall is to be placed perpendicular to the culvert or parallel to the roadway:
- Subtract the width of culvert (ft.) from the culvert skew (degrees).
- Use headwalls perpendicular to culvert if result is greater than 50.
- Use headwalls parallel to roadway if result is less than 50.

Headwalls with Bevels

- Increase the efficiency of metal pipe.
- Provide embankment stability and embankment erosion protection.
- Provide protection from buoyancy.
- Shorten the required structure length.
- Reduce maintenance damage.

Improved Inlets

- Shall be considered for culverts that will operate in inlet control.
- Can increase the hydraulic performance of the culvert, but may also add to the total culvert cost. Therefore, they should only be used if practicable.
- With a slope-taper, shall not be considered where fish passage is required.

Commercial End Sections

All cross culverts and side drains shall be installed with end sections unless other types of end treatments are proven more appropriate.

- Are available for both corrugated metal and concrete pipe.
- Retard embankment erosion and incur less damage from maintenance.
- May improve projecting metal-pipe entrances by increasing hydraulic efficiency, reducing the accident hazard and improving their appearance.
- Are hydraulically equal to a headwall, but can be equal to a beveled or side-tapered entrance if a flared, enclosed transition occurs before the barrel.

Wingwalls

- Are used to retain the roadway embankment to avoid a projecting culvert barrel.
- Are used where the side slopes of the channel are unstable.
- Are used where the culvert is skewed to the normal channel flow.
- Provide the best hydraulic efficiency if the flare angle is between 30° and 60°.
- Concrete wingwalls shall be used in all box culverts and pipes with full concrete headwalls.

The wingwall geometry is initially determined by a combination of six parameters identified in Figure 9.9. These six parameters include the following:

1. The distance in feet from the flowline to the crown (**H, B_a, or Rise** generally fixes the value of the height in feet of the upper end of the wingwall);
2. The skew angle of the culvert (θ);
3. The roadway fill slope (**Z**);
4. The height in feet of the lower end of the wingwall (**k**) which can be determined from the given equation below. The site topography should dictate the actual value of k that must be used.
5. The angle between the wingwall and a line parallel to the roadway (θ_a or θ_b);
6. The length of the wingwall (***l***) in feet.

A schematic drawing of the culvert layout should be shown in the plans, identifying k, θ, and *l* for each wingwall (m should also be shown if other than standard). The following guidelines should be used in selecting the values for the above six parameters in most situations. However, the designer must set the wings to conform to the culvert site even though the geometry differs from these guidelines.

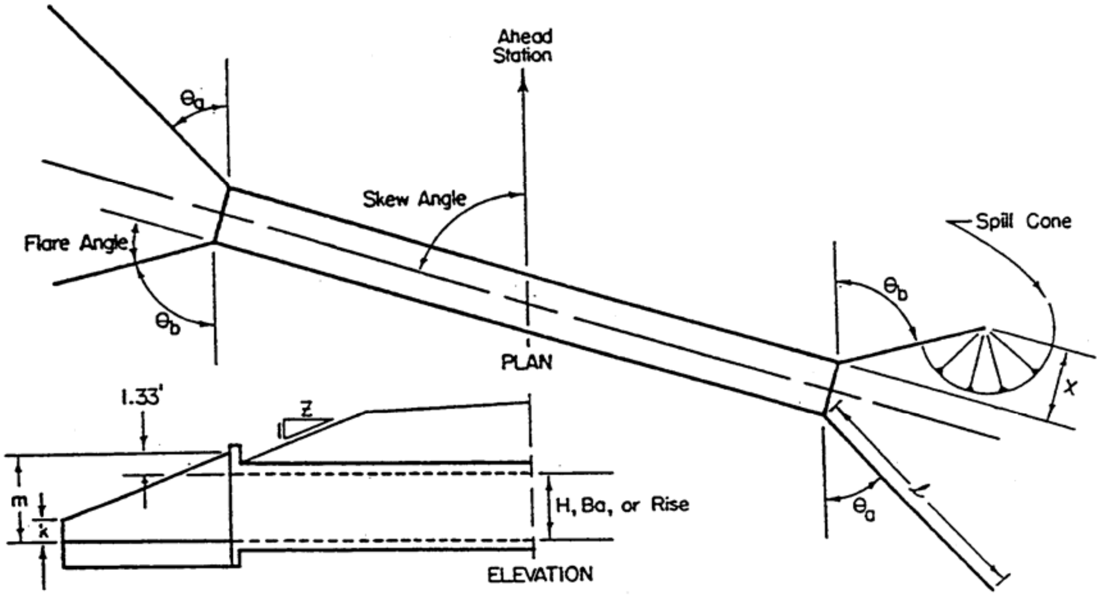


Figure 9.9 Layout of wingwalls.

- The value of **k** can be determined from the equation:

$$k = 1/2[H, Ba, \text{or Rise}] - 1 \qquad (9.2)$$

Values of k and θ must be chosen so that the spill cones do not obstruct the culvert inlet and outlet. Higher ends of wings may be used when the spill cone is not subject to erosion. The top of the wingwall should nearly match the final ground elevation. For irrigation structures, the k height should be above the design discharge water surface elevation.

- A wingwall **flare angle** of from 20 to 40 degrees normally provides a hydraulically efficient inlet condition for the culvert. Use of the recommended values for θ_a or θ_b given in Table 9.5 and k will generally effect a smooth flow transition from channel to culvert, and keep the spill cone out of the projected jet of flow.

Table 9.5 Recommended wingwall flare angles (θ_a or θ_b).

Skew Angle, θ (Degrees)	**θ_a (Degrees)**	**θ_b (Degrees)**
90	60	60
80	50	70
70	45	80
60	40	90
50	30	90
40	20	100
30	15	105
Less than 30	Consult the Hydraulic Engineer	

- The value of **m** can be calculated from the equation:

$$m = [H, Ba, \text{or Rise}] + 1.33 \qquad (9.3)$$

Special headwall designs may dictate some other values for m.

- The value of wingwall length, ***l*** can be obtained from the equation:

$$l = Z\,(m-k)\ /\ \sin\theta \qquad (9.4)$$

- The wingwall length is constrained by the selection of Z, m, k, and θ. Fill slopes flatter than 4:1 should be warped to 4:1 or steeper beyond the culvert headwall to reduce excessive wingwall length.

- Wingwall lengths should be rounded to the nearest foot for *l* less than 14 feet; to the nearest even foot for *l* greater than 14 feet but less than 30 feet; and to the nearest four-foot increment (30', 34', 38', etc.) for *l* equal to or greater than 30 feet.

- A plan showing site contours or spot elevations is often helpful when laying out the final wingwall geometry, especially when the wingwalls must conform to a distinct channel.

- Allow a spill cone slope of 1.5:1 or flatter at the wingwall ends to assure that the main flow jet, roughly defined by the culvert width, does not impinge on the spill cone.

- Culvert headwalls shall be perpendicular to the culvert centerline unless excessive cost or aesthetics favors a skewed headwall. A wide culvert with a small skew angle usually justifies the skewed headwall as discussed in the section for headwalls.

Aprons

- Shall be used to reduce scour from high headwater depths or from approach velocity in the channel.
- Shall extend at least one pipe diameter upstream.
- Shall not protrude above the normal streambed elevation.
- Concrete aprons shall be used at the outlet of culvert with wingwalls and at both inlet and outlet if culvert also serves as a stockpass.
- Concrete aprons should be considered at the outlet for scour protection.
- If scour damage is anticipated, a concrete apron should be placed between the wingwalls.
- Toe walls are required on all wingwalls except when a concrete apron is used. Toe walls are placed on the end of the apron as shown in the CDOT M & S Standards.

Cut-off Walls

- Are used to prevent piping along the culvert barrel and undermining at the culvert ends.
- Shall be used on all culverts with headwalls or slope paving.
- Shall be a minimum of 20 inches depth.

Safety Considerations

Traffic shall be protected from culvert ends as follows:

- Small culverts (30 inches in diameter or less) shall use an end section or slope paving.
- Culverts greater than 30 inches in diameter shall receive one of the following:

  - Be extended to the appropriate "clear zone" distance per Reference (2).
  - Safety treated with a grate if the consequences of clogging and causing a potential flooding hazard is less than the hazard of vehicles impacting an unprotected end. If a grate is used, the net area of the grate (excluding the bars) shall be 1.5 to 3.0 times the culvert entrance area.
  - Shielded with a traffic barrier if the culvert is very large, cannot be extended, has a channel that cannot be safely traversed by a vehicle, or has a significant flooding hazard with a grate.
- Periodically inspect each site to determine if safety problems exist for traffic or for the structural safety of the culvert and embankment.

Weep Holes

If weep holes are used to relieve uplift pressure in wingwalls and other types of wall structures, they shall be designed in a manner similar to underdrain systems.

Performance Curves

A performance curve is a plot of flow rate versus headwater depth or elevation, velocity, or outlet scour. The culvert performance curve is made up of the controlling portions of the individual performance curves for each of the following control sections (inlet, outlet, and roadway).

Performance curves can be developed for all culverts for evaluating the hydraulic capacity of a culvert for various headwaters, outlet velocities, and scour depths. These curves will display the consequence of high flow rates at the site and provide a basis for evaluating flood hazards.

Inlet Performance Curve

The inlet performance curve is developed using the inlet control nomographs (See design charts provided at the end of this chapter).

Outlet Performance Curve

The outlet performance curve is developed using the outlet control nomographs (See appropriate design chart at the end of this chapter), or backwater calculations.

Roadway Performance Curve

Performance curve is developed using the equation for roadway overtopping flow.

Overall Performance Curve

Overall performance curve is the sum of the flow through the culvert and the flow across the roadway and can be determined by performing the following steps.

1. Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters shall be calculated.

2. Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.

3. When the culvert headwater elevations exceed the roadway crest elevation, overtopping will begin. Calculate the upstream water surface depth above the roadway for each selected flow rate. Use these water surface depths and equation for roadway overtopping flow to calculate flow rates across the roadway.

4. Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve as shown in Figure 9.10.

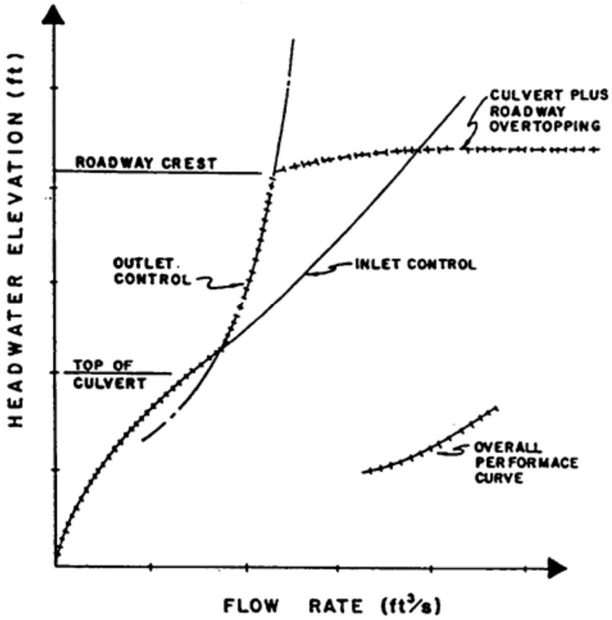


Figure 9.10 Overall performance curve.

9.2.4 Related Designs

Buoyancy Protection

Headwalls, endwalls, slope paving or other means of anchoring to provide buoyancy protection shall be considered for all flexible culverts. Buoyancy is more serious with steepness of the culvert slope (due to higher velocities and hydrodynamic forces), depth of the potential headwater (debris blockage may increase), inadequate fill height, large culvert skews, or mitered ends.

Fire Protection

Full concrete headwall shall be considered for any size of plastic culvert pipes if project site is located in areas where risk of fire is relatively high.

Outlet Protection and Erosion Control

Outlet treatment should be designed to restore natural flow conditions downstream. The outlet should be carefully scrutinized for conditions which can produce scour (See Chapter 11, Energy Dissipators). When detrimental scour is expected, protective measures should be utilized. The two common types of channel instability are **gully scour** or "headcutting" and **scour holes**. Gully scour occurs over a long reach. It is influenced insignificantly by the increased culvert velocity. Generally, it is a result of concentrated flow or natural conditions downstream which are independent of the culvert. Scour holes are caused by high outlet velocities and concentrated flows. Aside from aesthetics, scour holes are not necessarily detrimental unless structural damage due to undermining occurs. In fact, scour holes at culvert outlets provide efficient energy dissipators. As such, outlet protection for the selected culvert design flood shall only be provided where the outlet scour hole depth computations indicate:

- the scour hole will undermine the culvert outlet,

- the expected scour hole may cause costly property damage,
- The scour hole causes a nuisance effect (most common in urban areas),
- The scour hole blocks fish passage, or
- The scour hole will restrict land-use requirements.

Gully scour may be controlled by a series of check dams. These would probably be located outside of the right-of-way. Keeping the culvert outlet elevation low will avoid or reduce the undermining problem. However, lowering should be done only when beneficial and then with caution so as not to reduce the culvert's capacity. A deep toe wall, a buried rundown or a concrete apron will also protect the culvert's outlet. Scour holes can be controlled with riprap, gabions and plunge basins. Plunge basins are effective in reducing velocities as are natural scour holes.

Relief Opening

Where multiple use culverts or culverts serving as relief openings have their outlet set above the normal stream flow line, special precautions shall be required to avoid headcuts that would undermine the culvert outlet

Land-Use Culverts

Consideration shall be given to combining drainage culverts with other land-use requirements necessitating passage under a highway:

- During the selected design flood, the land use is temporarily forfeited but available during lesser floods;
- Two or more barrels are required with one situated to be dry during floods less than the selected design flood;
- The outlet of the higher land-use barrel may need protection from headcutting;
- Shall be sized to ensure it can serve its intended land frequency use function up to and including a 2-yr flood; and
- The height and width constraints shall satisfy the hydraulic or land-use requirements, whichever is larger.

Stock Passes

Economic justification should be determined for all proposed stock passes. Economic analyses should be performed for both cases with and without the proposed stock pass. The value of the parcel of land on either side of the highway should be included in the economic evaluation. The following data are required to determine if stock passes are economically justified or necessary as safety measures: the number of cattle or other livestock that would use the stock pass; the frequency of crossings by the stock; the use of stock pass for drainage; and the required size of drainage structure if the stock pass is not provided.

The proposed stock pass shall consist of either a standard box culvert with an opening of 6 feet wide and 7 feet high, an 84" culvert or a structural plate arch culvert 5'-10" x 7'-8". Approval of the Transportation Regional Director shall be required if other sizes of stock pass structures are used. 6 inches of earth fill material shall be placed in the invert of the round or arch culvert after installation. Stock passes that are not needed for drainage can be constructed away from the drainage site to insure the most economical installation with respect to length, cover, and excavation requirement.

If unusual conditions clearly indicate the need for a larger stock pass, full details concerning the proposed size of structures, local conditions, right-of-way considerations, comparative costs, and all other pertinent data shall be submitted to the Transportation Regional Director.

Pedestrian Walkways and Bikeways

The minimum design flood frequency for any stream crossing for pedestrian walkway and bikeway shall be 2 years. A design frequency of less than 2 years may be used if appropriate and the reasons are stated in the drainage report. In general, selection of the appropriate design flood frequency for pedestrian walkway and bike path should be justified by a cost benefit ratio analysis of all alternative designs.

Erosion and Sediment Control

Temporary measures shall be included in the construction plans. These measures include the use of the following: silt boxes, straw silt barriers, brush silt barriers, filter cloth, temporary silt fence and check dams. For more information, see the Erosion and Sediment Control Chapter.

Environmental Considerations And Fishery Protection

Care must be exercised in selecting the location of the culvert site to control erosion, sedimentation and debris. Select a site that will permit the culvert to be constructed and will limit the impact on the stream or wetlands. For more information, see Chapter 15 - Surface Water Environment.

Irrigation Facilities

Unless legally abandoned, an irrigation structure shall be required even if the irrigation canal or ditch is no longer used. The canal or ditch owner shall approve the use of multiple barrel culverts. In general, the inlet and outlet ends of the irrigation structure should extend to a maximum of 16.4 ft left and right outside the CDOT's right-of-way. In some locations, extensions longer than the maximum may be required. In both cases, construction easement should be obtained from the canal or ditch owner. Provision shall be made to accommodate any water escaping the ditch so as to avoid a flood hazard.

- Irrigation facilities shall be designed to accommodate the water right and intercepted runoff using the following criteria which give the largest culvert size:
- Constrain the headwater within the existing canal or ditch banks unless provision is made for overflow during high flows,
- Provide freeboard to pass expected debris,
- No increase in the velocity beyond what the unprotected ditch material or protection will sustain,
- Avoid a flood hazard from a canal or ditch failure,
- Provide a width capable of delivering the water and flood right at its existing operating depth, and
- Provide for known winter ice accumulation problems.

Detour Culvert Pipe Size

Temporary drainage structures like detour culvert pipes are normally required during construction to handle both traffic and stream flows. From the standpoint of adequate hydraulic design, the higher the design frequency used, the lower the risk of failure will be.

In general, the design flood for a temporary detour structure should be less than that of a permanent drainage structure. The designer should select the design flood frequency for the detour and at the same time keep the cost of the culvert pipes at a minimum. Refer to Table 7.2 of Chapter 7 - Hydrology to determine the design frequency to be used in sizing the detour culvert pipe. After the design flood is established using reasonable and acceptable hydrology methods, the design steps outlined in sizing permanent culvert structures may be followed to size the detour culvert pipe.

Since detour culvert pipes, in general, are temporary installations, they are placed without headwalls and sometimes without adequate cover. For this reason, installation procedure should ensure that failure of the detour pipe due to buoyancy forces is minimized.

A couple of good construction practices involving detour culvert pipes include locating the detour culvert pipe upstream of the proposed permanent structure site and constructing the drainage structure during low flow seasons.

9.3 MISCELLANEOUS GUIDELINES

9.3.1 Culvert Repair Practices

Maintenance of culverts may include major repairs of corrosion and abrasion damage. Techniques employed for metal culverts may include recoating; lining with concrete, cement grout, and plastics; plugging of leaks with expanding bands, grouting, and welding; and insertion of a smaller pipe. Concrete culverts may be repaired by relining with grout; removal and replacement of deteriorated concrete; with the insertion of clay or plastic liners; and by applying polymer coatings.

The increasing cost of replacing long culverts under high fills warrants an evaluation of all repair techniques currently available. A new technique is being employed in which a special extruded plastic profile is fed into a winding machine to form a tube that fits into the existing pipe. The Federal Highway Administration (FEEWA) has published a guide entitled "Culvert Repair Practices" to assist construction and maintenance personnel in repairing damaged culverts.

9.3.2 Alternative to Pipe-Arches

The use of round pipe with buried inverts is sometimes required because of environmental requirement and for various reasons. For example, pipe invert must be buried under native or borrow materials to improve passage of fish or livestock if culvert is used as a stockpass. Metal pipe invert may also be buried under concrete and other lining materials to reduce or eliminate the impact of heavy sediment loads that can cause abrasion and subsequent corrosion.

It is not always necessary to fill the invert up to the natural channel flowline as water will transport the sediment to do the backfilling. To use a round pipe with a buried invert, the size of the round pipe should be selected so that its capacity will be equivalent to that of the required unburied pipe-arch. Refer to FHWA publication entitled "Design of Depressed Invert Culverts," (Report No. FE[WA-AK-RD-87-23) for procedure to determine the required equivalent diameter of buried round pipe. The equivalent diameter is the diameter of a circle which has an area equal to the total area above the bed of a depressed invert culvert. Figure 9.11 and Table 9.6 provide a diagram of a buried round pipe and a comparison of the area of unburied metal arch pipes and that of a partially buried pipes respectively.

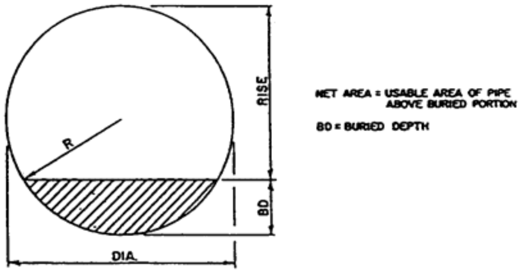


Figure 9.11 Usable area of buried round pipe.

Table 9.6(a) Pipe-arch area vs. round pipe area

PIPE-ARCH DATA

EQUIVALENT DIAMETER	**SPAN**	**RISE**	**AREA**
54"	65”	40"	14.3 ft^2
60"	72"	44 "	17.6 ft^2
66"	73"	55"	22.0 ft^2
72"	81 "	59"	26.0 ft^2
78"	87"	63 "	31.0 ft^2
84"	95"	67"	35.0 ft^2
90"	103 "	71 "	40. 0 ft^2
96"	112"	75"	46.0 ft^2
102"	117"	79"	52.0 ft^2
108"	128"	83"	58.0 ft^2
114"	137"	87"	64 .0 ft^2
120"	142"	91	71.0 ft^2

Table 9.6(b) Pipe-Arch Area vs. Round Pipe Area

BURIED ROUND PIPE DATA

DIAMETER	**RISE**	**BD**	**AREA**	**NET AREA**
60"	42"	18"	19.64 ft^2	14.7 ft^2
66"	46"	20"	23.76 ft^2	17.7 ft^2
72"	55"	17"	28.27 ft^2	23.2 ft^2
78"	59"	19"	33.18 ft^2	26.9 ft^2
84"	63”	21"	38.49 ft^2	31.0 ft^2
90"	67"	23"	44.18 ft^2	35.3 ft^2
96"	71”	25”	50.27 ft^2	39.9 ft^2
102"	77"	25”	56.75 ft^2	46.0 ft^2
108"	82"	26"	63.62 ft^2	51.8 ft^2
114"	86"	28"	70.88 ft2	57.4 ft^2
120"	90"	30"	78.54 ft^2	63.2 ft^2
126"	95”	31”	86.59 ft^2	70.0 ft^2

9.3.3 Jacking Welded Steel and Reinforced Concrete Pipe

In roadway, utility, and drainage projects, pipe jacking operation is commonly used to install piping system with minimal or no interruption to the vehicular traffic or any type of utility service. Design and construction guidelines are required to accomplish pipe jacking in a cost-effective manner. To achieve this purpose, guidelines in jacking welded steel and reinforced concrete pipe (RCP) are provided in Appendix B.

9.4 ALTERNATIVE ANALYSIS AND DESIGN METHODS

The design of a culvert system for a highway crossing of a floodplain involves using information from the following Chapters in this *Manual* (Policy, Documentation, Planning and Location, Hydrology, Channels, Energy Dissipators, Storm Drainage Systems, Surface Water Environment and Erosion and Sediment Control). Each of these should be consulted as appropriate. The discussion in this Section is focused on alternative analysis and design methods.

9.4.1 Alternative Analysis

Culvert alternatives shall be selected that satisfy:

- Topography; and
- Design policies and criteria.

Alternatives shall be analyzed for:

- Environmental impact,
- Hydraulic equivalency, and
- Risk and cost.

Select an alternative that best integrates engineering, economic and political considerations. The chosen culvert shall meet the selected structural and hydraulic criteria and shall 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.

9.4.2 Design Methods

The designer shall choose whether:

A. to use a culvert, storm drain or inverted siphon;
B. to assume a constant discharge or route a hydrograph; or
C. to use nomographs or computer software.

A. Structure Type

Culvert

- Is a covered structure with both ends open.
- Designed using procedures of HDS 5 *(8)*.

Storm Drain

Is a covered structure with either end in a manhole and is usually a part of a system of pipes.

- Explained in HEC 22 *(11)*.
- Designed using HYDRA software contained in HYDRAIN.

Inverted Siphon

- Is a covered structure that is sometimes termed a sag culvert with both ends open and operates at a low head. The invert profile dips below the approach and exit channels.
- Designed using procedures in U.S. Bureau of Reclamation, "Design of Small Canal Structures," Reference *(13)*.

B. Hydrology Methods

Constant Discharge

- Is assumed for most culvert designs.
- Is usually the peak discharge.
- Will yield a conservatively sized structure where temporary storage is available but not used.

Hydrograph and Routing

- Storage capacity behind a highway embankment attenuates a flood hydrograph and reduces the peak discharge.
- Significant storage will reduce the required culvert size.
- Is checked by routing the design hydrographs through the culvert site to determine the outflow hydrograph and stage (backwater) behind the culvert.
- Procedures are in in Chapter 12 - Storage Facilities and HDS 5, Section V *(8)*.

C. Computational Methods

Nomographs

- Require a trial-and-error solution, which is easy and provides reliable designs for many applications.
- Require additional computations for tailwater, outlet velocity, and roadway overtopping.
- may require additional computations for hydrographs and routing.
- Charts for circular and box shapes are included at the end of this Chapter. Other shapes and improved inlets are found in HDS 5.
- Electronic version of the nomographs are at http://www.fhwa.dot.gov/bridge/hydsoft.htm as HDS 5 Chart Calculator.

Computer Software

HYDRAIN is a microcomputer system which:

- Is recommended by AASHTO.
- Includes HY8.
- Has a fully documented users manual.

HY8 (FHWA Culvert Analysis Software):

- Is an interactive program written in Basic.
- Uses the theoretical basis for the nomographs.
- Can compute tailwater, improved inlets, roadway overtopping, hydrographs, routing and multiple independent barrels.
- Develops and plots tailwater rating curves.
- Develops and plots performance curves.
- Is documented in HYDRAIN Users Manual (7) and HY8 Applications Guide (6).

CDS (Wyoming Culvert Design System) *(14)*

- Is a batch operation program written in Fortran.
- Includes roadway overtopping capability.
- Plots performance curves for headwater, outlet velocity and outlet scour.
- Includes options for both design and analysis.
- Computes tailwater for any cross section shape with up to 10 subsections.
- Has extensive flood-routing capability.
- Is documented in the *Users Manual* for HYDRAIN *(7)*.

The CDS is available from:
Hydraulics Section
Wyoming Highway Department
Cheyenne, WY 82009

9.5 DESIGN EQUATIONS

9.5.1 General

An exact theoretical analysis of culvert flow is extremely complex because the following is required:

- Analyzing nonuniform flow with regions of both gradually varying and rapidly varying flow;
- Determining how the flow type changes as the flow rate and tailwater elevations change;
- Applying backwater and drawdown calculations, energy and momentum balance;
- Applying the results of hydraulic model studies; and
- Determining if hydraulic jumps occur and if they are inside or downstream of the culvert barrel.

9.5.2 Approach

The procedures in this Chapter use the following.

Control Section

- The control section is the location where there is a unique relationship between the flow rate and the upstream water surface elevation.
- Inlet control is governed by the inlet geometry.
- Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics and the tailwater or critical depth.

Minimum Performance

Minimum performance is assumed by analyzing both inlet and outlet control and using the highest headwater. The culvert may operate more efficiently at times (more flow for a given headwater level), but it will not operate at a lower level of performance than calculated.

9.5.3 Inlet Control

For inlet control, the control section is at the upstream end of the barrel (the inlet). The flow passes through critical depth near the inlet and becomes shallow, high-velocity (supercritical) flow in the culvert barrel. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

Headwater Factors

- Headwater depth is measured from the inlet invert of the inlet control section to the surface of the upstream pool.
- Inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area.
- Inlet edge configuration describes the entrance type. Some typical inlet edge configurations are thin-edge projecting, mitered, square edges in a headwall and beveled edge.
- Inlet shape is usually the same as the shape of the culvert barrel. Typical shapes are rectangular, circular, elliptical and arch. Check for an additional control section, if different than the barrel.

Hydraulics

Three regions of flow are shown in the Figure 9.12: unsubmerged, transition and submerged.

Unsubmerged

For headwater between the invert and the culvert height, the entrance operates as a weir:

- A weir is a flow control section where the upstream water surface elevation can be predicted for a given flow rate.
- The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges.
- These tests are then used to develop equations. Appendix A of HDS 5 *(8)* contains the equations that were developed from model test data; see Figure 9.13, Flow Type I.

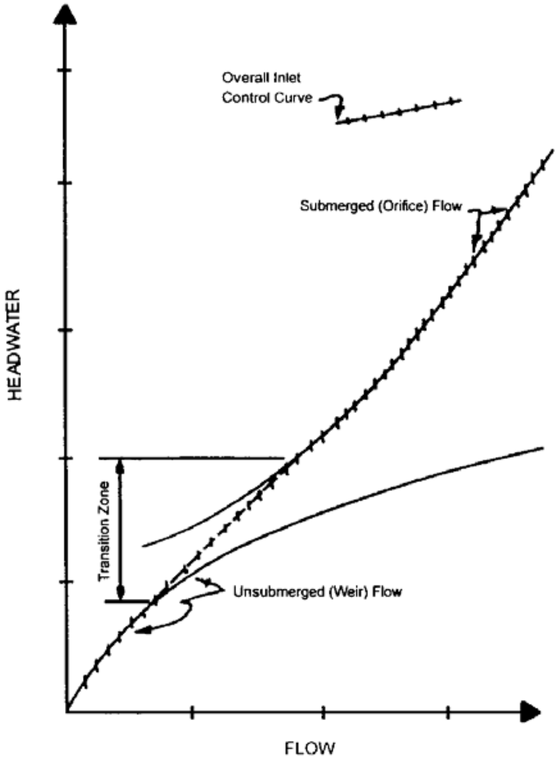


Figure 9.12 Unsubmerged, transition and submerged.

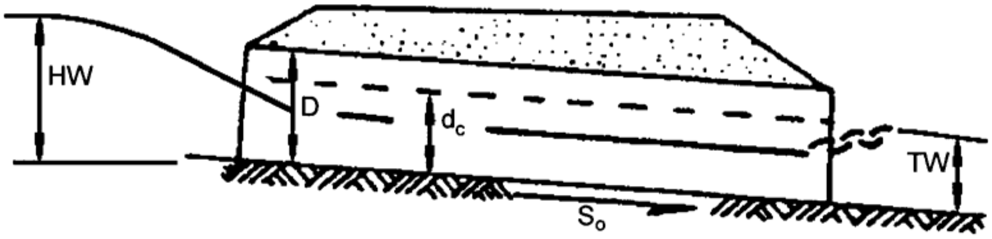


Figure 9.13 Flow Type I.

Submerged

For headwaters above the inlet, the culvert operates as an orifice:

- An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section.
- The relationship between flow and headwater can be defined based on results from model tests. Appendix A of HDS 5 *(8)* contains flow equations which were developed from model test data. See Figure 9.14, Flow Type V.

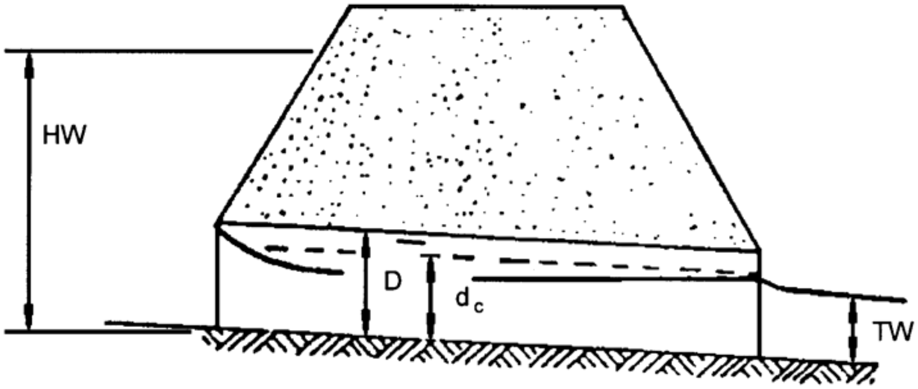


Figure 9.14 Flow Type V.

Transition Zone

The transition zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves.

Nomographs

The inlet control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs. Note that, in the inlet control nomographs, HW is measured to the total upstream energy grade line including the approach velocity head.

9.5.4 Outlet Control

Outlet control has depths and velocity that are subcritical. The control of the flow is at the downstream end of the culvert (the outlet). The tailwater depth is either assumed to be critical depth near the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the barrel factors. All of the inlet control factors also influence culverts in outlet control.

Barrel Roughness

Barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by a hydraulic resistance coefficient; i.e., the Manning n value. Typical Manning n values are presented in Table 9.2.

Barrel Area

Barrel area is measured perpendicular to the flow.

Barrel Length

Barrel length is the total culvert length from the entrance crown to the exit crown of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.

Barrel Slope

Barrel slope is the actual slope of the culvert barrel and is often the same as the natural stream slope. However, where the culvert inlet or outlet is raised or lowered, the barrel slope is different from the stream slope.

Tailwater Elevation

Tailwater is based on the downstream water surface elevation. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation.

Hydraulics

Full flow in the culvert barrel is assumed for the analysis of outlet control hydraulics. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool. Outlet control can occur as full, partial flow or a combination of both through the culvert:

1. <u>Losses</u>:

$$HL = HE + Hf + Hv + Hb + Hj + Hg \tag{9.5}$$

where:
H_L = total energy loss, ft
HE = entrance loss, ft
Hf = friction losses, ft
Hv = exit loss (velocity head), m (equivalent to Ho; see Equation 9.8d)
Hb = bend losses, ft (see HDS 5)
Hj = losses at junctions, ft (see HDS 5)
H_g = losses at grates, ft (see HDS 5)

2. <u>Velocity</u>:

$$V = Q/A \tag{9.6}$$

where:
V = average barrel velocity, ft/s
Q = flow rate, ft^3/s
A = cross sectional area of flow with the barrel full, ft^2

3. <u>Velocity head</u>:

$$H_v = V^2/2g \tag{9.7}$$

where:
g = acceleration due to gravity, 32.2 ft/s^2

4. <u>Entrance loss</u>:

$$H_E = K_E\,(V^2/2g) \tag{9.8a}$$

where:
K_E = entrance loss coefficient.

5. Friction loss:

$$H_f = [(29n^2L)/R^{1.33}]\ [V^2/2g] \qquad (9.8b)$$

where:
n = Manning's roughness coefficient
L = length of the culvert barrel, ft
R = hydraulic radius of the full culvert barrel = A/P, ft
P = wetted perimeter of the barrel, ft

6. Exit loss

(9.8c)

where: V_d = channel velocity downstream of the culvert, ft/s (usually neglected; see Equation 9.8d).

$$Ho = Hv = V2/2g \tag{9.8d}$$

7. Barrel losses:

$$H = H_E + H_o + H_f$$

$$H = [1 + Ke + (29n^2L/R^{1.33})]\,[V^2/2g] \tag{9.9}$$

Energy Grade Line

The energy grade line represents the total energy at any point along the culvert barrel. Equating the total energy at Sections 1 and 2, upstream and downstream of the culvert barrel in Figure 9.15, the following relationship results:

(9.10)

where:

HW_o = headwater depth above the outlet invert, ft
V_u = approach velocity, ft/s
TW = tailwater depth above the outlet invert, ft
V_d = downstream velocity, ft/s
H_L = sum of all losses (Equation 9.1)

Note that this Equation is only true if TW is higher than critical depth at the outlet.

Hydraulic Grade Line

The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel lines separated by the velocity head except at the inlet and the outlet.

Nomographs (Full Flow)

The nomographs were developed assuming that the culvert barrel is flowing full and:

- $TW \geq D$, Flow Type IV (see Figure 9.15); or
- $d_c \geq D$, Flow Type VI (see Figure 9.16)
- V_u is small and its velocity head can be considered to be a part of the available headwater (HW) used to convey the flow through the culvert.
- V_d is small and its velocity head can be neglected.

Equation (9.10) becomes:

$$HW = TW + H - S_oL \qquad (9.11)$$

where:

HW = depth from the inlet invert to the energy grade line, ft
H = the value read from the nomographs (Equation 9.5), ft
S_oL = drop from inlet to outlet invert, ft.

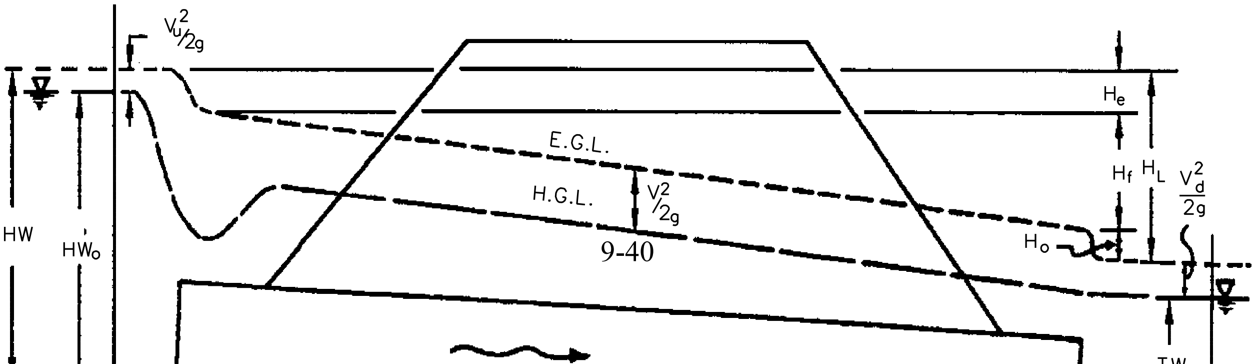


Figure 9.15 Flow Type IV.

Figure 9.16 Flow Type VI.

Nomographs (Partial Full Flow)

Equations (9.5) through (9.11) were developed for full barrel flow. The Equations also apply to the flow situations which are effectively full-flow conditions, if TW < d_c; see Figure 9.17.

Backwater calculations may be required that begin at the downstream water surface and proceed upstream. If the depth intersects the top of the barrel, a full flow extends from that point upstream to the culvert entrance.

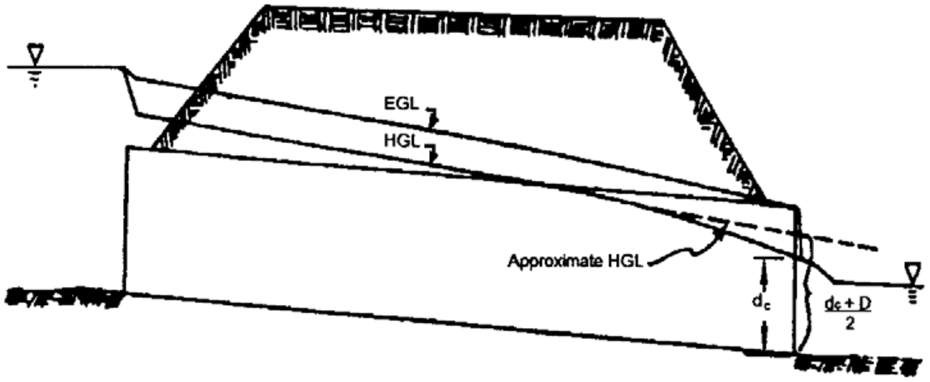


Figure 9.17 Flow Type VII.

Nomographs (Partial Full Flow) — Approximate Method

Based on numerous backwater calculations performed by the FHWA staff, it was found that the hydraulic grade line pierces the plane of the culvert outlet at a point approximately one-half of the way between critical depth and the top of the barrel, or $(d_c + D)/2$ above the outlet invert. The approximation should only be used if the barrel flows full for part of its length or the headwater is at least 0.75D. If neither of these conditions are met, a water surface profile should be used to establish the hydraulic grade line. TW should be used if higher than $(d_c + D)/2$. The following equation should be used:

$$HW = ho + H - SoL \qquad (9.12)$$

where: h_o = the larger of TW or $(d_c + D)/2$, ft

Adequate results are obtained down to a HW = 0.75D. For lower headwaters, backwater calculations are required.

(See Figure 9.18 if $TW < d_c$ and Figure 9.19 if $TW > d_c$)

9.5.5 Outlet Velocity

Culvert outlet velocities shall be calculated to determine the need for erosion protection at the culvert exit. Culverts usually result in outlet velocities that are higher than the natural stream velocities. These outlet velocities may require flow readjustment or energy dissipation to prevent downstream erosion. If outlet erosion protection is necessary, the flow depths and Froude number may also be needed (see Chapter 11, Energy Dissipators).

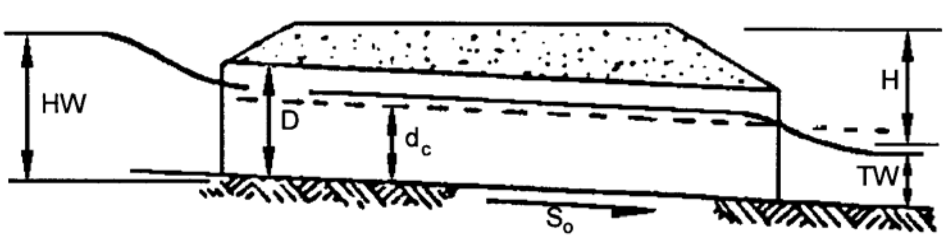


Figure 9.18 Flow Type II, $TW < d_c$.

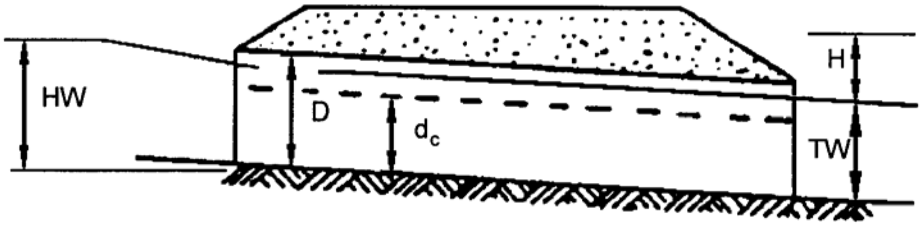


Figure 9.19 Flow Type III, TW > d_c.

Inlet Control

The velocity is calculated from Equation 9.10 after determining the outlet depth. Either of the following methods may be used to determine the outlet depth:

- Calculate the water surface profile through the culvert. Begin the computation at d_c at the entrance and proceed downstream to the exit. Determine at the exit the depth and flow area.
- Assume normal depth and velocity. This approximation may be used because the water surface profile converges towards normal depth if the culvert is of adequate length. This outlet velocity may be slightly higher than the actual velocity at the outlet. Normal depths may be obtained from design aids in publications (e.g., HDS 3 *(10)*, which is in US Customary units).

Outlet Control

The cross sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth or the height of the conduit:

- Critical depth is used where the tailwater is less than critical depth.
- Tailwater depth is used where tailwater is greater than critical depth but below the top of the barrel.
- The total barrel area is used where the tailwater exceeds the top of the barrel.

9.6 DESIGN PROCEDURE

The following design procedure provides a convenient and organized method for designing culverts for a constant discharge, considering inlet and outlet control. The procedure does not address the effect of storage which is discussed in Chapter 12 - Storage Facilities.

- The designer should be familiar with all the equations in Section 9.5 before using these procedures.
- Following the design method without an understanding of culvert hydraulics can result in an inadequate, unsafe or costly structure.
- The computation form has been provided in Appendix A to guide the user. It contains blocks for the project description, designer's identification, hydrologic data, culvert dimensions and elevations, trial culvert description, inlet and outlet control HW, culvert barrel selected and comments.

Step 1 Assemble Site Data And Project File

a. See Data Chapter — The minimum data are:
  - USGS, site and location maps;
  - Embankment cross section;
  - Roadway profile;
  - Photographs;
  - Field visit (sediment, debris); and
  - Design data at nearby structures.

b. Studies by other agencies including:
  - Small dams — NRCS, USACE, TVA, BLM;

- Canals — NRCS, USACE, TVA, USBR;
- Floodplain — NRCS, USACE, TVA, FEMA, USGS, NOAA; and
- Storm drain — local or private.

c. Environmental constraints including:
  - Commitments contained in review documents,
  - Fish migration, and
  - Wildlife passage.

d. Design criteria:
  - Review Section 9.3 for applicable criteria, and
  - Prepare risk assessment or analysis.

Step 2 Determine Hydrology

a. See Hydrology Chapter.
b. Minimum data are drainage area map and a discharge-frequency plot.

Step 3 Design Downstream Channel

a. See Channel Chapter.
b. Minimum data are cross section of channel and the rating curve for channel.

Step 4 Summarize Data On Design Form

Collect all data from the preceding steps and record on a single design form.

Step 5 Select Design Alternative

Choose culvert material, shape, size and entrance type.

Step 6 Select Design Discharge, Q_d

a. See Section 9.2.2 “Design Limitations.”
b. Determine flood frequency from criteria.
c. Determine Q from discharge-frequency plot (Step 2).
b. Divide Q by the number of barrels.

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use the inlet control nomographs or the inlet design equations found at the end of this . An example on how to use the chart is shown on each nomograph.

a. Locate the size or height on the scale.

b. Locate the discharge:

- For a circular shape, use discharge.
- For a box shape, use Q per foot of width.

c. Locate HW/D ratio:
  - Use a straight edge.
  - Extend a straight line from the culvert size through the flow rate.
  - Mark the first HW/D scale. Extend a horizontal line to the desired scale and read HW/D and note on Design Form in Appendix 9.E.

d. Calculate headwater depth (HW_i):
  - Multiply HW/D by D to obtain HW to energy grade line.
  - Neglecting the approach velocity, $HW_i = HW$.
  - Including the approach velocity, $HW_i = HW$ – approach velocity head.

Step 8 Determine Outlet Control Headwater Depth At Inlet (HW_{oi}):

Calculate the tailwater depth (TW) from the design flow rate, outlet channel geometry, roughness, and slope using uniform flow equations such as the Manning's formula. TW can also be obtained using water surface profile analysis. Calculate the critical depth (d_c) using appropriate charts at the end of this chapter. Calculate the value of (d_c + D)/2 and compare with the value of TW. D is the inside diameter or height of the culvert. Determine h_o = TW or (d_c+ D)/2 whichever is larger. Determine H which is the sum of the energy losses at the culvert entrance, barrel, and the outlet from the outlet control charts. An example on how to use the chart is shown on each nomograph. Calculate HW_{oi} from the equation:

$$HW_{oi} = H + h_o - S_o L$$

Where: H and h_o are as defined above, S_o and L are the slope and length of the culvert, respectively.

If HW_{oi} is less than 1.2 times the diameter or rise D and flow condition is an outlet control, the barrel maybe is flowing partly full and the approximate method of using the greater of tailwater or may not be applicable. If the headwater depth falls (d_c+ D)/2 below 0.75 times D, the approximate method should not be used. Backwater calculations should be used to check the result.

Step 9 Determine Controlling Headwater (HW_c)

Compare HWi and HWOj. If HWi is greater than HW,,i, the culvert is in inlet control. If HW.j is greater than HWj, the culvert is in outlet control. If HWj is equal to HWOj, the culvert is both in inlet and outlet control. Use the higher value as the controlling headwater.

Step 10 Compute Discharge Over The Roadway (Q_r)

Compute culvert discharge Q, discharge over the roadway, Q_r , and total discharge Q_t,by trial and error method or graphically by using performance curve.

The culvert discharge (Q) is the discharge corresponding to the non-overtopping elevation.

Determine the overtopping discharge, Q_r, from the equation:

$Q_r = C_d L (HW_r)^{1.5}$

$Q_r = 0$, if flow does not overtop the roadway. See section on roadway overtopping for the definition of the variables used in the equation.

a. Calculate depth above the roadway (HW_r):
    - $HW_r = HW_c - HW_{ov}$.
    - HW_{ov} = height of road above inlet invert.

b. If $HW_r \leq 0$, $Q_r = 0$
   If $HW_r > 0$, determine C_d from Figure 9.8.

c. Determine length of roadway crest (L).

d. Calculate Q_r using Equation:

$$Q_r = C_d L (HW_r)^{1.5} \tag{9.12}$$

Step 11 Compute Total Discharge (Q_t)

Determine the total discharge (Q_t) from the equation: $Q_t = Q + Q_r$

Repeat the calculation process until $Q_t \approx Q_d$. Refer to FHWA HDS No. 5 for procedure to construct performance curves.

Step 12 Calculate Outlet Velocity (V_o) And Depth (d_n)

If inlet control is the controlling headwater:

a. Calculate flow depth at culvert exit:
    - use normal depth (d_n), or
    - use water surface profile.

b. Calculate flow area (A).
c. Calculate exit velocity (V_o) = Q/A.

If outlet control is the controlling headwater:

a. Calculate flow depth at culvert exit:
    - use (d_c) if $d_c > TW$.
    - use (TW) if $d_c < TW < D$.
    - use (D) if $D < TW$.
b. Calculate flow area (A).
c. Calculate exit velocity (V_o) = Q/A.

Step 13 Review Results

Compare alternative design with constraints and assumptions. If any of the following are exceeded, repeat Steps 5 through 12:

- The barrel must have adequate cover,
- The length shall be close to the approximate length,
- The headwalls and wingwalls must fit site,
- The allowable headwater shall not be exceeded, and
- The allowable overtopping flood frequency shall not be exceeded.

Step 14 Plot Performance Curve

a. Repeat Steps 6 through 12 with a range of discharges.
b. Use the following upper limit for discharge:
  - Q_{100}, if $Q_o \leq Q_{100}$.
  - Q_{500}, if $Q_o > Q_{100}$.
  - Q_{max}, if no overtopping is possible
  - Q_{max} = largest flood that can be estimated.

Step 15 Related Designs

Consider the following options:

- Tapered inlets if culvert is in inlet control and has limited available headwater;
- Flow routing if a large upstream headwater pool exists;
- Energy dissipators if v_o is larger than the normal v in the downstream channel (see energy dissipator chapter);
- Sediment control storage for sites with sediment concerns (e.g., Alluvial fans) (see erosion and sediment control chapter);
- Fish passage; and/or
- Broken-back culverts.

Step 16 Documentation

- See Documentation Chapter.
- Prepare report and file with background information.

All plans for drainage culverts shall have the following information:

D.A. = acres
Q_d = cfs, Design
DHW (Elev.) = ft
AHW (Elev.) = ft
Q_{100} = cfs
Qr = cfs (O.T.) when appropriate.
HW (Elev.) = ft
OTHW (Elev.) = ft
QWR = cfs (water right, if applicable)

Where:

D.A. - drainage area of the contributing basin;
Q_ - the discharge associated with the frequency indicated by the subscript;
HW - the headwater elevation associated with the indicated discharge;

DHW - the design headwater elevation for the design discharge (not to inundate the roadway);
AHW - allowable headwater elevation. The maximum headwater which can be tolerated due to "nonhydraulic" features, (i.e., private buildings, roadway profile, flowline of ditches which would pass water into an adjacent basin);
O.T. - overtopping flood. The discharge at the moment water begins to overtop the roadway or flows into an adjacent basin;
OTHW - headwater elevation for the overtopping flood;
QWR - adjudicated water right

The above information is not required for culverts 24 in. or smaller and with design discharges less than 20 cfs. Only water right and stage (DHW) are required for irrigation structures. This information is to be placed with the structure note on the plan sheet or in a tabulation. On special design culverts, this information is to be placed on the layout sheet. The above information is also required for culverts to be extended unless pipe diameter is 24 in. or less. See Chapter 4 - Documentation for additional requirements.

9.7 FLOOD ROUTING FOR CULVERT DESIGN

9.7.1 Introduction

Flood routing through a culvert is a practice that evaluates the effect of temporary upstream ponding caused by the culvert's backwater. By not considering flood routing, it is possible that the findings from culvert analyses will be conservative. If the selected allowable headwater is considered acceptable without flood routing, then costly over design of both the culvert and outlet protection may result, depending on the amount of temporary storage involved.

These special considerations associated with culvert flood routing are discussed in the following subsections:

Culvert Replacement Applications — Normally, a smaller culvert may be used for the same headwater condition.

Environmental — Evaluating environmental concerns may be more realistic.

Flood Hazards — A routing culvert design may require less land for an upstream easement and assessments of potential flood hazards may be more realistic.

Sediment — Estimation of sediment accumulation is required.

Limitations — Temporary storage must be available.

Culvert Replacement Applications

Improved hydrologic methods or changed watershed conditions are factors that can cause an older, existing culvert to be inadequate. A culvert analysis that relies on findings that ignore any available temporary storage may be misleading. A flood routing analysis may show that what was thought to be an inadequate existing culvert is, in fact, adequate.

Often existing culverts require replacement due to corrosion or abrasion. This can be very costly, particularly where a high fill is involved. A less costly alternative is to place a smaller culvert inside the existing culvert. A flood routing analysis may, where there is sufficient storage, demonstrate that this is acceptable in that no increase in flood hazard results.

Environmental

With culvert flood routing, a more realistic assessment can be made where environmental concerns are important. The temporary time and extent of upstream ponding can be estimated. This allows environmental specialists to assess whether such ponding is beneficial or harmful to localized environmental features (e.g., fisheries, beaver ponds, wetlands, uplands).

Flood Hazards

Potential flood hazards increase upstream wherever a culvert increases the natural flood stage. Some of these hazards can conservatively be assessed without flood routing. However, some damages associated with culvert backwater are time dependent and thus require an estimate of depth versus duration of inundation. Some vegetation and commercial crops can tolerate longer periods of inundation than others and to greater depths. Such considerations become even more important when litigation is involved.

Sediment

Complex culvert sediment deposition ("silting") solutions require a sediment routing analysis. This practice requires a time-flood discharge relationship or hydrograph. This flood hydrograph must be coupled to a flood discharge-sediment discharge relationship to route the sediment through the culvert site.

Limitations

There are situations where culvert sizes and velocities obtained through flood routing will not differ significantly from those obtained by designing to the selected peak discharge and ignoring any temporary upstream storage. This occurs where:

- there is no significant temporary pond storage available (as in deep incised channels),
- The culvert must pass the design discharge with no increase in the natural channel's flood stage, and
- Runoff hydrographs last for long periods of time such as with snowmelt runoff (or irrigation flows).

9.7.2 Routing Equations

In addition to the previous Design Equations (Section 9.5), the following routing equations shall be used. The basic flood routing equation is:

$$I - O = \Delta S/\Delta t \text{, or} \tag{9.14}$$

$$2S_1/\Delta t - O_1 + I_1 + I_2 = 2S_2/\Delta t + O_2 \tag{9.15}$$

For a finite interval of time, Δt, Equation 9.14 can be expressed by:

$$\Delta S = Q_i\Delta t - Q_0\Delta t \tag{9.16}$$

From these equations:

$$(I_1 + I_2)/2 = \Delta S/\Delta t + O_1/2 + O_2/2 \tag{9.17}$$

where: ΔS = $S_2 - S_1$

S_1 = storage volume in the temporary pond at the beginning of the incremental time period Δt, ft^3

S2 = storage volume in the temporary pond at the end of the incremental time period Δt, ft^3

Δt = incremental routing time interval selected to subdivide hydrograph into finite time elements, s

I = average hydrograph inflow to the temporary pond during incremental time period Δt, ft^3/s

I1 = instantaneous inflow to the temporary pond at the beginning of the incremental time period Δt, ft^3/s

I2 = instantaneous inflow at the end of the time period Δt, ft^3/s

O = average outflow from the temporary pond during incremental time period Δt, ft^3/s

O_1 = instantaneous outflow at the beginning of the time period Δt, ft^3/s

O2 = instantaneous outflow at the end of the time period Δt, ft^3/s.

9.7.3 Design Procedure

The design procedure for flood routing through a culvert is the same as for reservoir routing. The site data and roadway geometry are obtained (Data Collection Chapter) and the hydrology analysis completed to include estimating a hydrograph (Hydrology Chapter). Once this essential information is available, the culvert can be designed.

Flood routing through a culvert can be time consuming. It is recommended that the HYDRAIN *(7)* system be used because it contains software that very quickly routes floods through a culvert to evaluate an existing culvert (review) or to select a culvert size that satisfies given criteria (design).

However, the designer should be familiar with the culvert flood-routing design process. This familiarization is necessary to:

- Recognize and test suspected software malfunctions,
- Circumvent any software limitations,
- Flood route manually where the software is limited, and
- Understand and credibly discuss culvert flood routing.

The Design Steps are outlined below.

Trial and Error

A multiple, trial-and-error procedure is required for culvert flood routing. In general:

- A trial culvert(s) is selected;
- A trial culvert discharge (outflow) for a particular inflow hydrograph time element is selected;
- Flood-routing computations are made with successive trial discharges until the flood-routing equation is satisfied;
- The hydraulic findings are compared to the selected site criteria; and
- If the selected site criteria are satisfied, then a trial discharge for the next time increment is selected and this procedure is repeated; if not, a new trial culvert is selected and the entire procedure is repeated.
- Note: the analysis is simplified if a multiple iteration is not necessary, if the culvert performance is in inlet control over the range of appropriate discharges or if the tailwater is below critical depth for outlet control over the range of discharges.

Design Steps

The design Steps are as follows:

Step 1 HYDROGRAPH. Plot the selected design and review hydrograph as computed using the practices from the Hydrology Chapter. Select a time interval, Δt, for use in the flood routing procedure and subdivide the hydrograph into these increments.

Step 2 DISCHARGE CURVE. Using the practices in the Channel Chapter, compute and plot a stage-discharge curve for the downstream channel.

Step 3 CULVERT PERFORMANCE CURVE. Compute and plot a culvert performance curve (headwater versus discharge) for the trial culvert(s). Where overtopping occurs, it is necessary that the upper end of this performance curve be adjusted to reflect this additional discharge. This additional discharge is computed using the weir equation as adjusted to reflect a roadway embankment and any downstream effects where a low roadway fill is involved. This performance curve is the spillway discharge curve commonly used in reservoir routing.

Step 4 STAGE-STORAGE CURVE. Compute and plot a stage-storage curve for the temporary upstream pond.

Step 5 INITIAL ROUTING STEP. Start with the first inflow hydrograph time increment:

- Determine the average hydrograph inflow and the volume discharge corresponding to the first selected time increment.
- Recognizing that, with an increasing headwater, the temporary pond storage will generally reduce this inflow, select a trial outflow (from the culvert) discharge that is less than the inflow discharge.
- With this smaller outflow discharge, estimate the headwater from the trial culvert(s) performance curve.
- Use this headwater to estimate the storage volume corresponding to this headwater from the upstream stage-storage curve.
- Compute the outflow volume corresponding to this selected outflow discharge and the previously selected time increment.
- Subtract this volume from the foregoing average inflow volume; this is the volume that would have to go into temporary upstream pond storage.
- Compare this volume with the volume corresponding to the previously estimated headwater. If they are the same (or nearly so), proceed to the next Step; if not, repeat this Step using a different trial outflow discharge.

Step 6a INCREASING HW. The procedure for subsequent routing Steps where the headwater is increasing is similar to the Initial Routing Step. The difference is in how storage is handled:

- Determine the average hydrograph inflow and volume discharge corresponding to the next selected time increment.
- Recognizing that, with an increasing headwater, the temporary pond storage will generally reduce this inflow, select a trial outflow (from the culvert) discharge that is less than the inflow discharge.
- With this smaller outflow discharge, estimate the headwater from the trial culvert(s) performance curve.
- Use this headwater to estimate the storage volume corresponding to this headwater from the upstream stage-storage curve.
- Compute the outflow volume corresponding to this selected outflow discharge and the previously selected time increment.
- Subtract this volume from the foregoing average inflow volume; this is the volume that would have to go into temporary upstream storage.
- Add this volume to the volume already in storage.
- Compare this total volume with the volume corresponding to the previously estimated headwater. If they are the same (or nearly so), proceed to the next Step. If not, repeat this Step using a different trial outflow discharge.

Step 6b DECREASING HW. The procedure is similar to the subsequent Routing Steps for an Increasing Headwater. The difference is (1) the selected trial culvert outflow discharge will be greater than the average inflow hydrograph discharge, and (2) the outflow volume is greater than the inflow volume so that the temporary pond storage volume will be decreasing:

- Determine the average hydrograph inflow and volume discharge corresponding to the next selected time increment.

- Recognizing that, with a decreasing headwater, the temporary pond storage will be decreasing, select a trial outflow (from the culvert) discharge that is larger than the inflow discharge.
- With this larger outflow discharge, estimate the headwater from the trial culvert(s) performance curve.
- Use this headwater to estimate the storage volume corresponding to this headwater from the upstream stage-storage curve.
- Compute the outflow volume corresponding to this selected outflow discharge and the previously selected time increment.
- Subtract this volume from the foregoing average inflow volume; this is the volume that would have to go into temporary upstream pond storage.
- Subtract this volume from the volume already in storage.
- Compare this total volume with the volume corresponding to the previously estimated headwater, If they are the same (or nearly so), proceed to the next Step; if not, repeat this Step using a different trial outflow discharge.

Step 7 CRITERIA CHECK. Following (or during) the foregoing routing Steps, compare the resulting headwater and outlet velocity, and temporary pond size and duration, with the corresponding criteria selected for the site. Should there be a violation of these criteria, return to Step 1 and select a larger trial culvert; a smaller trial culvert would be selected if there appeared to be a significant over design.

9.8 TAPERED INLETS

9.8.1 General

A tapered inlet is a flared culvert inlet with an enlarged face section and a hydraulically efficient throat section. A tapered inlet may have a depression, or FALL, incorporated into the inlet structure or located upstream of the inlet. The depression is used to exert more head on the throat section for a given headwater elevation. Therefore, tapered inlets improve culvert performance by providing a more efficient control section (the throat). Tapered inlets are not recommended for use on culverts flowing in outlet control because the simple beveled edge is of equal benefit.

- Design criteria and methods have been developed for two basic tapered inlet designs: the side-tapered inlet and the slope-tapered inlet.
- Tapered inlet design charts are available for rectangular-box culverts and circular-pipe culverts.

9.8.2 Side-Tapered

The side-tapered inlet has an enlarged face section with the transition to the culvert barrel accomplished by tapering the side walls (Figure 9.20). The face section is approximately the same height as the barrel height, and the inlet floor is an extension of the barrel floor. The inlet roof may slope upward slightly, provided that the face height does not exceed the barrel height by more than 10% (1.1D). The intersection of the tapered sidewalls and the barrel is defined as the throat section.

There are two possible control sections — the face and the throat. HW_f, shown in Figure 9.20, is the headwater depth measured from the face section invert, and HW_t is the headwater depth measured from the throat section invert. The throat of a side-tapered inlet is a very efficient control section. The flow contraction is nearly eliminated at the throat. In addition, the throat is always slightly lower than the face so that more head is exerted on the throat for a given headwater elevation.

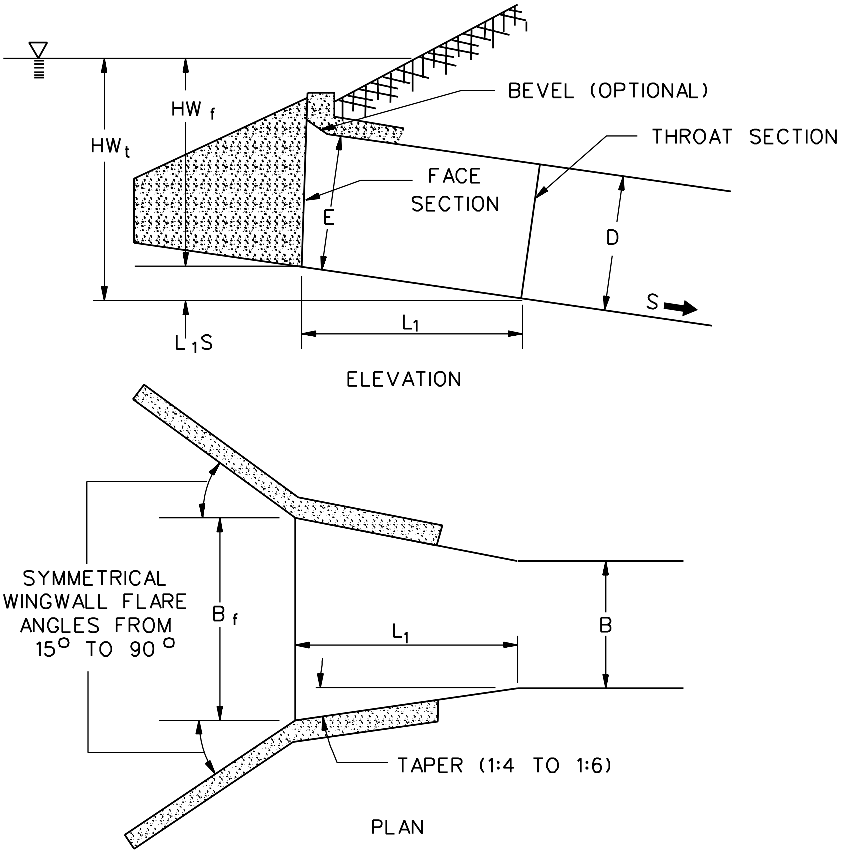


FIGURE 9-20 — Side-Tapered Inlet

The beneficial effect of depressing the throat section below the streambed can be increased by installing a depression upstream of the side-tapered inlet. Figure 9.21 depicts a side-tapered inlet with the depression contained between wingwalls. For this type of depression, the floor of the barrel should extend upstream from the face a minimum distance of D/2 before sloping upward more steeply. The length of the resultant upstream crest where the slope of the depression meets the streambed should be checked to assure that the crest will not control the flow at the design flow and headwater. If the crest length is too short, the crest may act as a weir-control section; the barrel is defined as the throat section.

9.8.3 Slope-Tapered Inlets

The slope-tapered inlet, like the side-tapered inlet, has an enlarged face section with tapered sidewalls meeting the culvert barrel walls at the throat section (Figure 9.22). In addition, a vertical FALL is incorporated into the inlet between the face and throat sections. This FALL concentrates more head on the throat section. At the location where the steeper slope of the inlet intersects the flatter slope of the barrel, a third section, designated the bend section, is formed.

A slope-tapered inlet has three possible control sections — the face, the bend and the throat. Of these, only the dimensions of the face and the throat section are determined by the design procedures of this *Manual*. The size of the bend section is established by locating it a minimum distance upstream from the throat so that it will not control the flow.

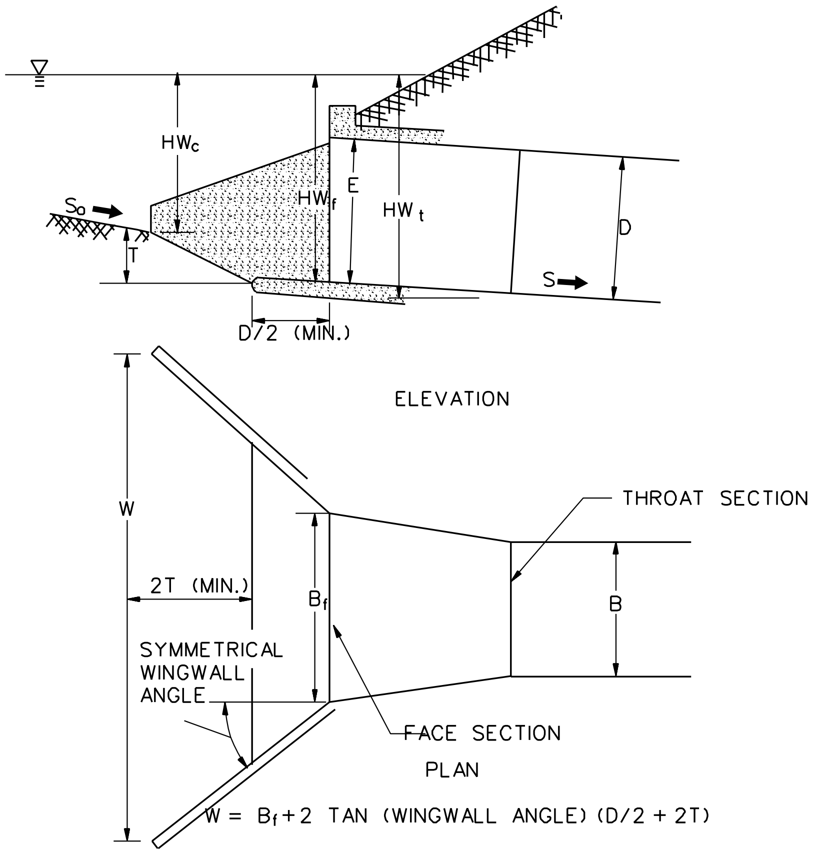


Figure 9.21 — Side-Tapered Inlet with Upstream Depression Contained Between Wingwalls

The slope-tapered inlet combines an efficient throat section with additional head on the throat. The face section does not benefit from the FALL between the face and throat; therefore, the face sections of these inlets are larger than the face sections of equivalent depressed side-tapered inlets. The required face size can be reduced by the use of bevels or other favorable edge configurations. The vertical face slope-tapered inlet design is shown in Figure 9.22.

The slope-tapered inlet is the most complex inlet improvement recommended in this *Manual*. Construction difficulties are inherent, but the benefits in increased performance can be significant. With proper design, a slope-tapered inlet passes more flow at a given headwater elevation than any other configuration. Slope-tapered inlets can be applied to both box culverts and circular-pipe culverts. For the latter application, a square-to-round transition is normally used to connect the rectangular, slope-tapered inlet to the circular pipe.

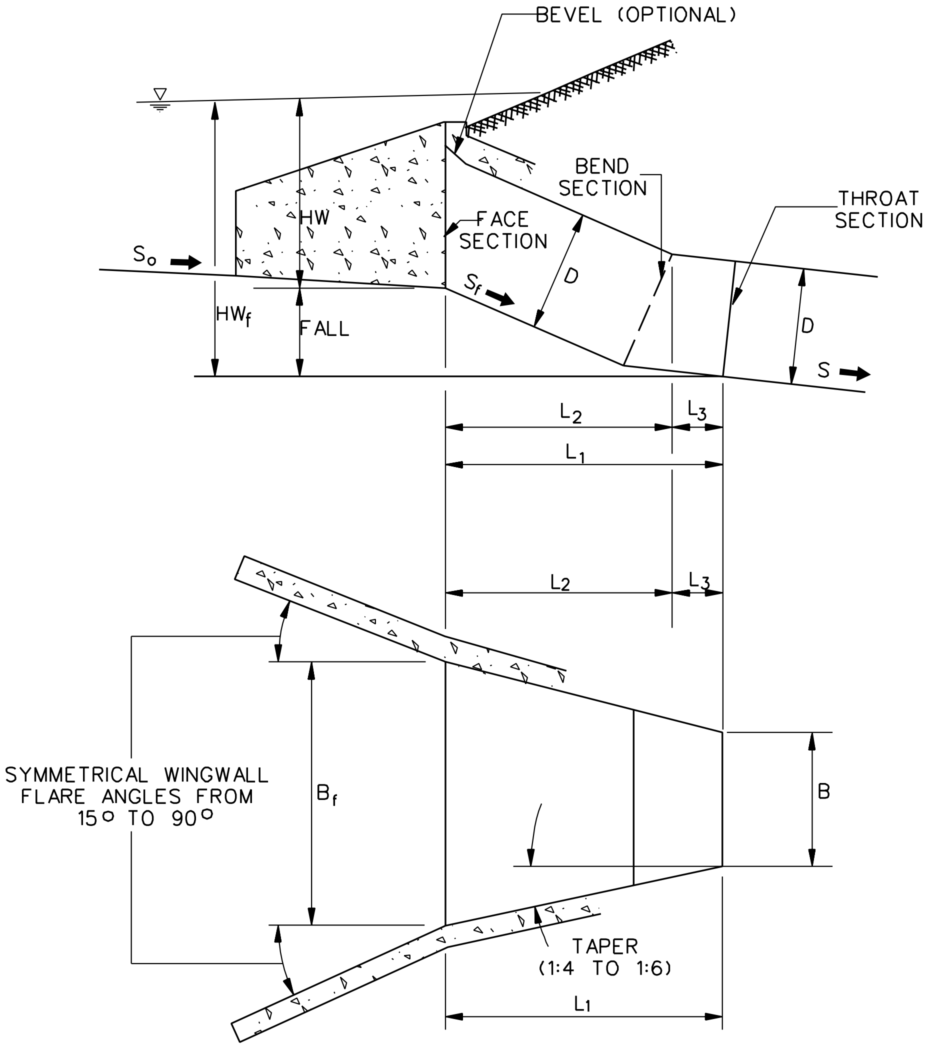


Figure 9.22 Slope-tapered inlet with vertical face.

9.8.4 Hydraulic Design

Inlet Control

Tapered inlets have several possible control sections including the face, the bend (for slope-tapered inlets) and the throat. In addition, a depressed side-tapered inlet has a possible control section at the crest upstream of the depression. Each of these inlet control sections has an individual performance curve. The headwater depth for each control section is referenced to the invert of the section. One method of determining the overall inlet control performance curve is to calculate performance curves for each potential control section, and then select the segment of each curve which defines the minimum overall culvert performance (Figure 9.23).

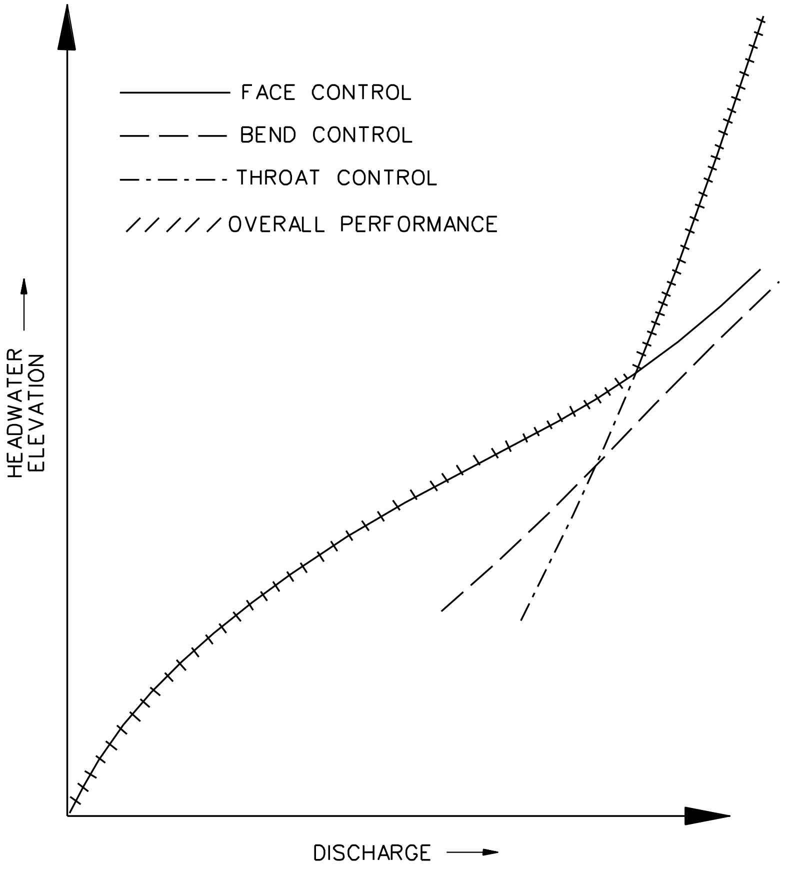


Figure 9.23 Inlet Control Performance Curves (Schematic)

Side-Tapered Inlet

The side-tapered inlet throat should be designed to be the primary control section for the design range of flows and headwaters. Because the throat is only slightly lower than the face, it is likely that the face section will function as a weir or an orifice with downstream submergence within the design range. At lower flow rates and headwaters, the face will usually control the flow.

Slope-Tapered Inlet

The slope-tapered inlet throat can be the primary control section with the face section submerged or unsubmerged. If the face is submerged, the face acts as an orifice with downstream submergence. If the face is unsubmerged, the face acts as a weir, with the flow plunging into the pool formed between the face and the throat. As previously noted, the bend section will not act as the control section if the dimensional criteria of this *Manual* are followed. However, the bend will contribute to the inlet losses that are included in the inlet loss coefficient, K_E.

Outlet Control

When a culvert with a tapered inlet performs in outlet control, the hydraulics are the same as described in Section 9.5 for all culverts. The tapered inlet entrance loss coefficient (K_E) is 0.2 for both side-tapered and slope-tapered inlets. This loss coefficient includes contraction and expansion losses at the face, increased friction losses between the face and the throat, and the minor expansion and contraction losses at the throat.

9.8.5 Design Methods

Tapered inlet design begins with the selection of the culvert barrel size, shape and material. These calculations are performed using the Culvert Design Form provided in the Appendix. The design procedure is similar to designing a culvert with other control sections (face and throat). The result will be one or more culvert designs, with and without tapered inlets, all of which meet the site design criteria. The designer must select the best design for the site under consideration.

In the design of tapered inlets, the goal is to maintain control at the efficient throat section in the design range of headwater and discharge. This is because the throat section has the same geometry as the barrel, and the barrel is the most costly part of the culvert. The inlet face is then sized large enough to pass the design flow without acting as a control section in the design discharge range. Some slight oversizing of the face is beneficial because the cost of constructing the tapered inlet is usually minor compared with the cost of the barrel.

Performance Curves

Performance curves are of utmost importance in understanding the operation of a culvert with a tapered inlet. Each potential control section (face, throat and outlet) has a performance curve, based on the assumption that the particular section controls the flow. Calculating and plotting the various performance curves results in a graph similar to Figure 9.24, containing the face control, throat control and outlet control curves. The overall culvert performance curve is represented by the hatched line. In the range of lower discharges, face control governs; in the intermediate range, throat control governs and, in the higher discharge range, outlet control governs. The crest and bend performance curves are not calculated because they do not govern in the design range.

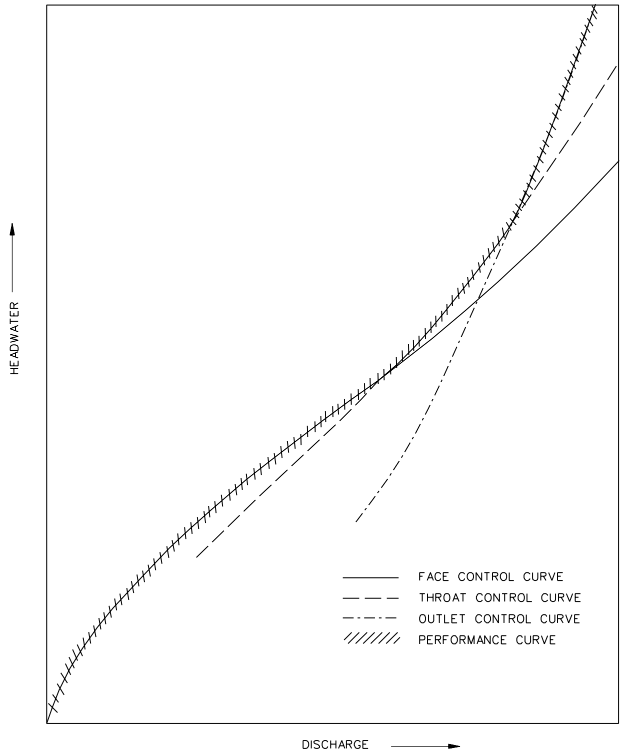


Figure 9.24 — Culvert Performance Curve (Schematic)

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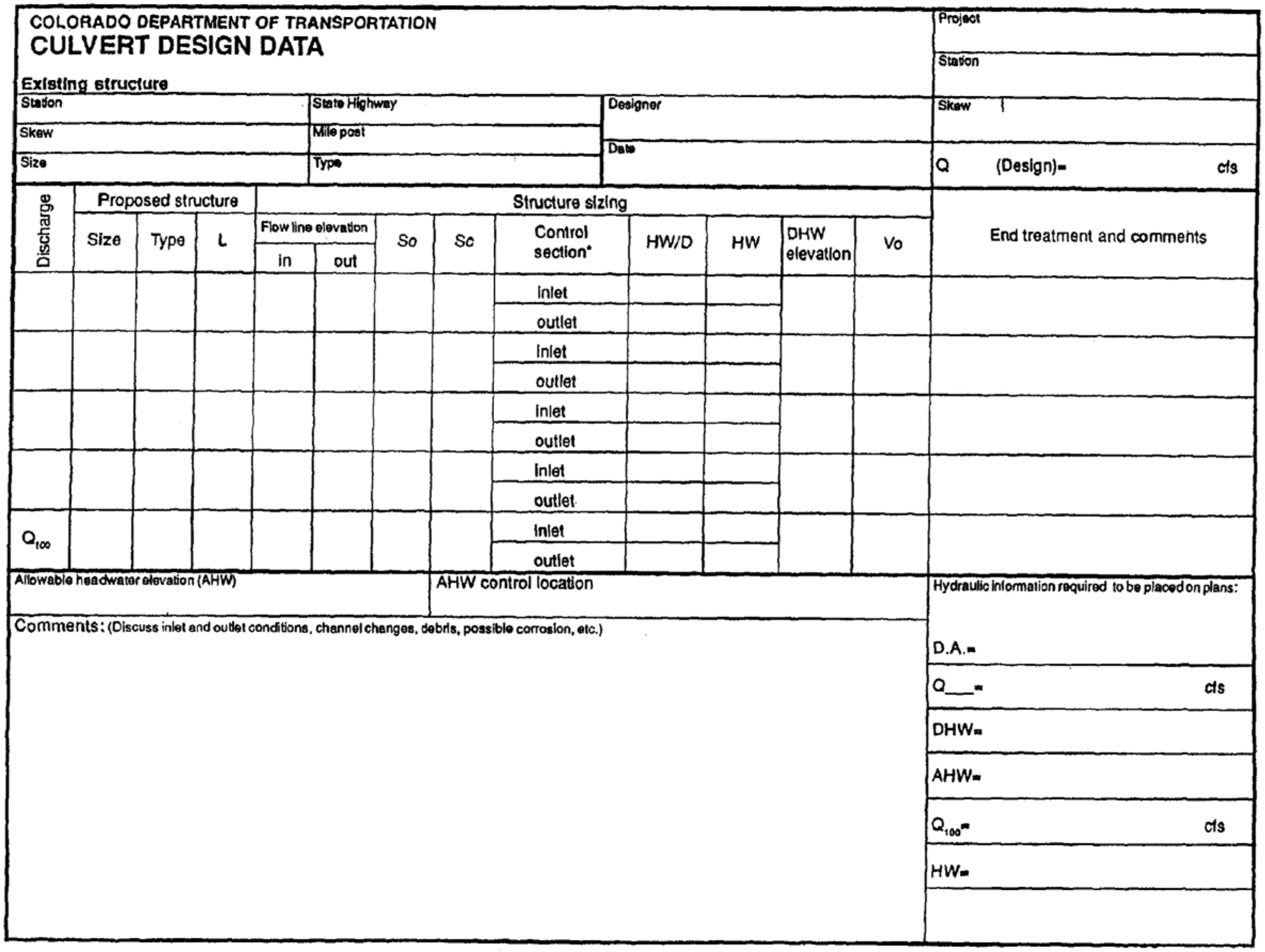
APPENDIX A – DESIGN CHARTS



COLORADO DEPARTMENT OF TRANSPORTATION

CULVERT DESIGN DATA

Project

Station

Existing structure

Station

State Highway

Designer

Skew

Mile post

Date

Size

Type

Skew

Q (Design)= cfs

Discharge	Proposed structure			Structure sizing									End treatment and comments
	Size	Type	L	Flow line elevation		So	Sc	Control section*	HW/D	HW	DHW elevation	Vo	
				in	out								
								inlet					
								outlet					
								inlet					
								outlet					
								inlet					
								outlet					
								inlet					
								outlet					
Q_{100}								inlet					
								outlet					

Allowable headwater elevation (AHW)

AHW control location

Comments: (Discuss inlet and outlet conditions, channel changes, debris, possible corrosion, etc.)

Hydraulic information required to be placed on plans:

D.A.=

Q___= cfs

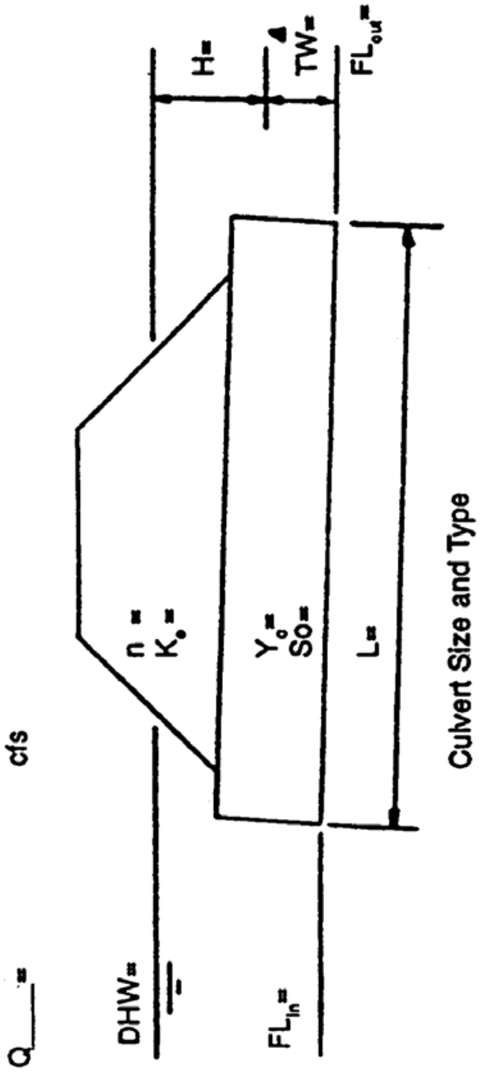
DHW=

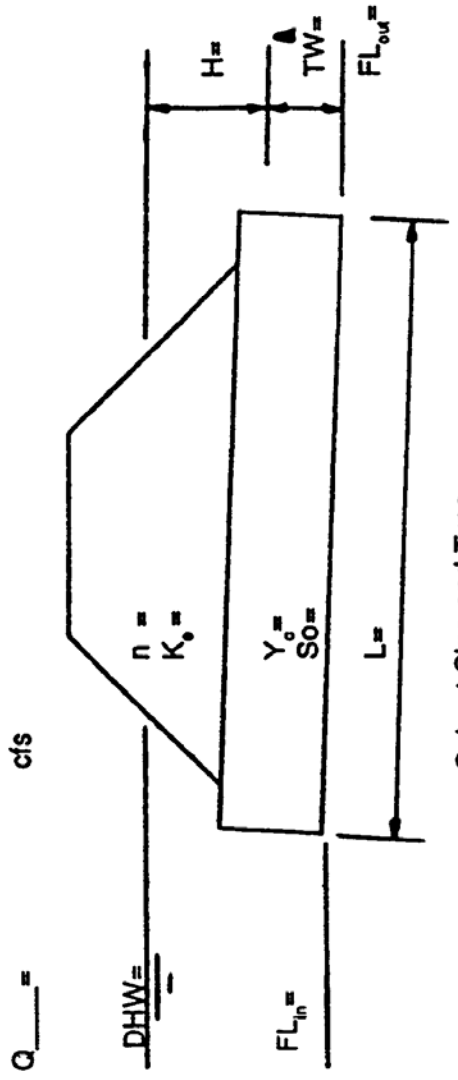
AHW=

Q_{100}= cfs

HW=

CDOT Culvert design data form





CDOT culvert design data form (outlet control headwater computations)

APPENDIX B
Jacking Welded Steel And Reinforced Concrete Pipe

Pipe Jacking and/or boring is done to install pipelines under roadways, railroads, runways, canals, etc., without interrupting surface traffic. The choice of jacking pipe by either boring out the inside of the pipe with rotary equipment or by mining out the material within the pipe, is the option of the contractor performing the installation. Jetting with water is not allowed.

The Colorado Department of Transportation (CDOT) bid system does not differentiate between mining and boring. All pipes placed without trenching are identified in the bid items as "(Jacked)".

A jacked pipe may be used as a carrier pipe or as a casing to protect a carrier pipe. Utilities such as electrical wiring, water, natural gas, petroleum products, and sewage are transmitted through the carrier pipe. The carrier pipe may be within a jacked casing pipe allowing the utility pipe to be removed, repaired and replaced from within the casing, without disruption to traffic. Storm drainage generally is run directly through the carrier pipe.

Jacked pipe generally is reinforced concrete pipe, precast concrete boxes, or welded steel pipe. Nine hundred-millimeter (36") diameter pipe is the smallest practical diameter for mining jacked concrete or steel pipe. The ability for workmen to maneuver within the jacked pipe is the controlling criteria for the diameter of jacked pipe. Concrete pipe as large as 132" diameter can be jacked. Precast concrete boxes may be jacked in sizes up to approximately 10 feet by 10 feet. Welded steel pipe may be bored in diameters up to 48". Small diameter pipe is generally smooth welded steel.

Pipe jacking requires sufficient surface area to provide an access pit. This pit is used to set up jacking equipment and to remove the earth excavated from the jacked pipe. All utilities must be located prior to commencing the jacking operation.

A safe working pit and safe working area near the pit is an essential part of jacked pipe installation. The beginning and the end of the casing pipe should extend at least to a point 1 ft away from the edge of the roadway for every 1 ft depth. Surface working areas must be adequate to enable the contractor to use a crane, trucks and backhoe. Storage area for the excavated earth from the pit and for the casing pipe should be available at the site.

The distance that a pipe can be jacked varies with the pipe size, pipe material, soil types, and alignment.

Welded Steel Pipe

Bare welded steel pipe is normally used for jacked casing pipe. A wall thickness of 0.25 inch for pipe diameters of 12 to 20 inches provides a collapse pressure of 80 psi or more, as well as providing handling rigidity. As sizes increase in diameter, the 80 psi collapse pressure can be used as a minimum "wall thickness/diameter guide". Evaluation of the 80 psi minimum collapse pressure must be made for special load conditions. Railroad crossing casing pipe usually requires heavier wall thickness for steel pipe and the wall thickness is specified by the railroad owner.

Wall Thickness-Welded Steel Pipe

Table B.1 containing values of wall thicknesses is based on the 80 psi collapse pressure. It can be used as a guide for minimum wall thickness.

Table B.1 Minimum Wall Thickness for Welded Steel Pipe

Pipe Outside Diameter (inches)	**Minimum Wall Thickness (inches) (For Highway Use)**
12 in.	0.250 in.
16 in.	0.312 in.
18 in.	0.312 in.
20 in.	0.312 in.
24 in.	0.344 in.
30 in.	0.375 in.
36 in.	0.438/0.500 in.
42 in.	0.500/0.538/0.625 in.
48 in.	0.625 in. or special design

Note:
Welded steel pipe is measured by outside diameter in sizes above 12in. Special conditions such as rocky ground or highly corrosive soils may require a heavier wall thickness.

Casing pipe is joined by field welding. (The Standard Specifications for Road and Bridge Construction requires a certified welder unless waived by Project Special Provision). When the casing pipe is bored, grouting the outside of the casing is not required, unless voids are created or present. When a casing pipe is jacked by mining out the material, voids are usually created and must be grouted to avoid settlement of the ground above. This can be done from the casing pipe interior, through 2-inch grout plugs spaced at given intervals throughout the casing. Grouting pressures to pump the soil-cement or sand, cement, and water slurry mix, normally need not exceed 20 psi to adequately fill all earth voids. The grouting or sand filling of the void between the outside of the jacking pipe and the overexcavation creates an almost perfect bedding condition and may be superior than normal trench bedding conditions.

Carrier pipe is installed after completion of the casing installation by threading through the casing. The carrier pipe is supported on wooden skids banded to the carrier pipe or with factory installed skid bands that have runners around the band to support the carrier. Steel casing pipe placed by boring or mining should be bare steel. The integrity of pipe coatings inside or outside of the pipe cannot be maintained with jacking operations and are impossible to replace or repair. Extra pipe thickness should be used to protect against corrosive environments.

Reinforced Concrete Pipe

Reinforced concrete pipe cannot be placed by boring due to the thick walls of the pipe. The material within the area to be occupied by the jacked pipe, including the walls, must be removed by hand mining.

Loading Criteria - Jacked Concrete Pipe

The class of reinforced concrete jacking pipe is determined from the the table of the height of fill as shown in CDOT Standard M-603-2.

Reinforced concrete pipe is subject to the axial forces of the jacking operations, dead load, and live load. The jacking forces must be evenly distributed around the periphery of the ends of the pipe with the use of a heavy rope wrap or plywood. The dead load on the jacked pipe is usually less than a trench installation (with a trench width equal to the bore) due to the cohesive force of the soil reducing overburden load.

Reinforced concrete jacking pipe is manufactured in all joint types, with a smooth outside surface of the pipe barrel. Although tongue and groove (T-G) or rubber and concrete (R-C) joints can be used as a jacking pipe, rubber and steel (R-S) joints are often used to increase the integrity of the joint under the severe installation conditions of the jacking operation.

Jacking Installation Procedures

The leading edge of reinforced concrete pipe is usually protected with a steel cutting guide or shoe to protect the pipe joint. Material is excavated in front of the lead pipe while an axial force is applied along the pipe centerline. A lubricant such as bentonite is applied to the outside of the pipe at the jacking pit or is pumped through the grout nipples as the jacking operation progresses. The jacking operation is often a continuous operation from beginning to completion. Alignment rails in the jacking pit can be set in concrete to assist in the control of the alignment and grade. Careful excavation at the lead pipe to prevent overexcavation, alignment of the guiderails in the jacking pit, and equal distribution of axial jacking load, all contribute to a good final pipe alignment and grade.

As the pipe is advanced, the jack ram is retracted and another section of pipe is set on the guide rails, joined to the preceding pipe, and the jacking pressure reapplied. The size and the number of jacks required and the size of the jacking abutment is a function of soil types encountered, size of pipe, and length of the jacked installation.

Excavated material is usually removed through the jacking pipe installation in carts or by a conveyor system. Once the installation is complete, soil cement, grout or sand is pumped through grout nipples into the void between the excavated bore and the outside of the pipe. Nipples are plugged after grouting.

Casing Pipe Size

The size of a jacked casing pipe is a function of the carrier pipe size. The size of the casing pipe is determined by the largest dimension of the carrier pipe. This is the outside diameter of the bell, flange or other joint detail. To this must be added the dimensions of any skids used to install the carrier pipe within the casing. The inside diameter of the casing pipe should be adequate to easily accommodate the largest diameter of the flange or bell allowing for 2 in. x 4 in. or 4 in. x 4 in. redwood skids which are banded to the carrier pipe to facilitate sliding it through the casing pipe.

The designer must allow ample room between the carrier and the casing pipe. A minimum of 1 inch of clearance between the casing and the skids must be allowed. A 6-inch difference between bell outside diameter (O.D.) and carrier pipe inside diameter (I.D.) is suggested. The dimensions of the carrier pipe joint details must be known before the casing pipe diameter can be determined. The designer should contact the utility or owner of the carrier pipe to determine the type of pipe and the dimensions of the joint details. It may be necessary to obtain manufacturer's catalogs of the exact pipe to obtain these details.

It is not uncommon for jacking contractors to oversize the casing pipe to compensate for unanticipated alignment problems.