VOLUME TWO

CHAPTER 11
CULVERTS

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Chapter 11
CULVERTS

11.1 INTRODUCTION

11.1.1 Policy

Culvert policy, design criteria, design features, and related design are discussed in Volume One, Chapter 11 "Culverts." The hydraulics engineer should have determined the appropriate design frequencies; performed hydrologic analysis using Table 11-1 of Volume One, Chapter 11 "Culverts"; performed a tailwater channel analysis using the procedures of Volume Two, Chapter 10 "Channels"; and have the preliminary roadway geometrics before using the design procedures in this chapter.

11.1.2 Overview

This chapter provides the following:

- hydraulic design practices and methods, Section 11.2,
- design procedure, Section 11.3,
- design example, Section 11.4,
- documentation, Section 11.5,
- storage routing overview, Section 11.6,
- tapered inlet overview, Section 11.7,
- broken-back culvert overview, Section 11.8,
- fish passage overview, Section 11.9, and
- design aids for circular and box shapes, Section 11.10.

This chapter is based on FHWA Hydraulic Design Series No. 5 (HDS-5), *Hydraulic Design of Highway Culverts (7)*. The AASHTO *Highway Drainage Guidelines*, Chapter 4 *(1)*, provides an overview of highway culverts.

11.1.3 Culvert Definition

A culvert is defined as the following:

- A structure that can be 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 (bridge) designed hydraulically as a culvert is addressed in this chapter, regardless of its span length.

11.1.4 Concepts

The following concepts are important in culvert design:

1. Critical Depth. In channels with regular cross section, critical depth is the depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry, there is only one critical depth.
2. Crown. The crown is the inside top of the culvert.
3. Flow Type. USGS *(8)* has established seven culvert flow types that assist in determining the flow conditions at a particular culvert site. Diagrams of these flow types are provided in Section 11.2.
4. Free Outlet. Free outlet happens when tailwater depth is 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.
5. Improved Inlet. An improved inlet has an entrance geometry that decreases the flow contraction at the inlet and thus increases the capacity of the culvert. These inlets are referred to as either side- or slope-tapered. The side-tapered inlet has a face wider than the culvert. The slope-tapered inlet has both a larger face and increased flow-line slope at the entrance. Beveled edges at the culvert face may also improve the hydraulic capacity of a culvert for both conventional and improved inlets.
6. Invert. The invert is the flow line of the culvert (inside bottom).
7. Normal Depth. Normal depth occurs in a channel or culvert when the slope of the water surface and channel bottom is the same and the water depth remains constant. The discharge and velocity are constant throughout the reach. Normal flow will exist in a culvert operating on a constant slope provided that the culvert is sufficiently long.
8. Slope. The measurement of inclination of a pipe, representing the difference in elevation of the inlet and outlet inverts along the centerline of the pipe. A steep slope occurs where the normal depth is less than the critical depth. A mild slope occurs where the normal depth is greater than the critical depth.
9. Submerged. A submerged outlet occurs where the tailwater elevation is higher than the crown of the culvert. A submerged inlet occurs where the headwater is greater than 1.2D, where D is the culvert diameter or barrel height.

11.1.5 Symbols

To provide consistency within this chapter, the symbols given in Table 11-1 will be used. These symbols were selected because they are consistent with HDS-5 *(7)*.

Table 11-1. Symbols, Definitions, and Units

Symbol	Definition	Units
A	Area of cross section of flow	ft^2
B	Barrel width	in. or ft
B_f	Width of face section of a tapered inlet	ft
C_d	Coefficient of discharge for flow over an embankment	—
D	Culvert diameter or barrel height	in. or ft
d	Depth of flow	ft
d_c	Critical depth of flow	ft
d_n	Normal depth	ft
g	Acceleration due to gravity	ft/s^2
H	Headloss, 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_j	Headloss at junction	ft
H_g	Headloss at grate	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; f = face, t = throat)	ft
HW_a	Headwater allowable	ft
HW_i	Headwater depth above inlet invert	ft
HW_o	Headwater depth above the outlet invert	ft
HW_{oi}	Outlet control headwater	ft
HW_{ov}	Height of road above inlet invert	ft
HW_r	Upstream depth, measured above the roadway crest	ft
k_e	Entrance loss coefficient	—
L	Length	ft
n	Manning's roughness coefficient	—
P	Wetted perimeter	ft
Q	Rate of discharge	ft^3/s
Q_d	Design discharge	ft^3/s
Q_o	Overtopping flow	ft^3/s
Q_r	Routed (reduced) peak flow	ft^3/s
R	Hydraulic radius (A/P)	ft
S	Slope of culvert	ft/ft

Symbol	Definition	Units
S_o	Slope of streambed	ft/ft
TW	Tailwater depth above outlet 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

11.2 HYDRAULIC DESIGN

11.2.1 General

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

- analyzing non-uniform 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.

Most of the above complications are addressed in the software HY-8 (see Volume Two, Chapter 5 "Software"). The following discussion provides the basic equations that are used by HY-8 and other culvert analysis software.

11.2.2 Standard Practice

HDS-5 *(7)* is the standard practice for the hydraulic design of culverts. The hydraulics engineer has the option of performing an analysis using the equations outlined in this chapter, using the nomographs in Section 11.10, or using software that is consistent with the equations provided in HDS-5 (see Volume Two, Chapter 5 "Software").

The following standard practices apply to culverts:

- All culverts should be hydraulically designed.
- The overtopping flood selected should be consistent with the class of highway and appropriate for the risk at the site (see Volume One, Chapter 11 "Culverts").

- Survey information should include topographic features, channel characteristics, aquatic life, high-water information, existing structures, and other related site-specific information. Refer to Volume Two, Chapter 3 “Data Collection.”
- Culvert location in both plan and profile should be investigated to minimize the potential for sediment buildup in culvert barrels.
- The cost savings of multiple uses (utilities, stock and wildlife passage, land access, and fish passage) should be weighed against the advantages of separate facilities.
- Culverts should be designed to accommodate debris, or appropriate provisions should be made for debris maintenance.
- Material selection should include consideration of service life that includes abrasion and corrosion.
- Culverts should be located and designed to present a minimum hazard to traffic and people.
- The detail of documentation for each culvert site should be appropriate for the risk and importance of the structure. Design data and calculations should be assembled in an orderly fashion and retained for future reference as provided for in Volume Two, Chapter 4 “Documentation.”
- Where practical, some means should be provided for personnel and equipment access to facilitate maintenance.

11.2.2.1 Design Discharge

Culverts will be designed for a constant discharge that will normally be the peak discharge. This will yield a conservatively sized structure where temporary storage is available but not used. The storage can be assessed using the procedures in Section 11.6.

11.2.2.2 Control Section

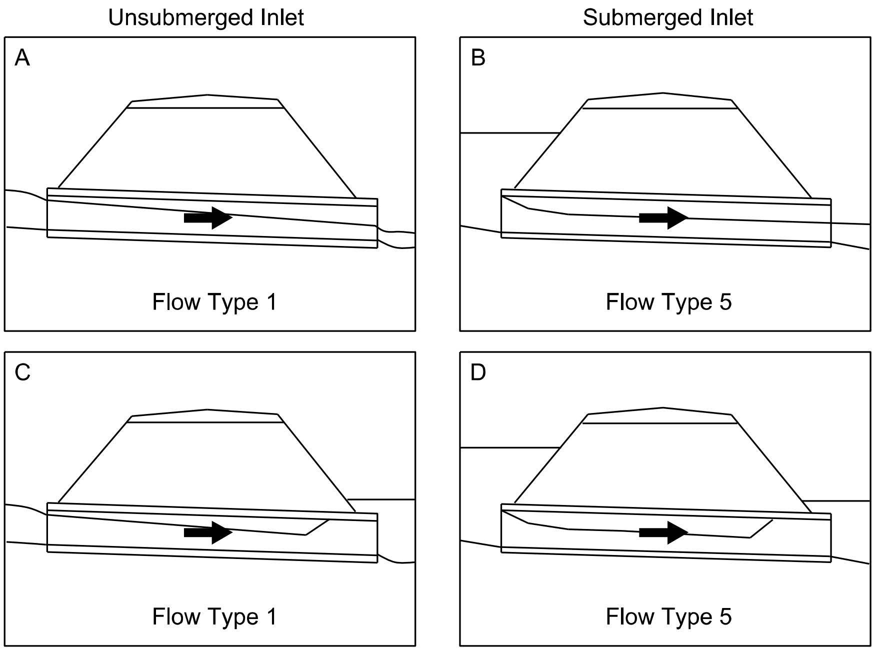
The control section is the location where there is a unique relationship between the flow rate and the upstream water surface elevation. Inlet control is governed by the inlet geometry. Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics, and the tailwater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

11.2.2.3 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.

11.2.3 Inlet Control

Figure 11-1 illustrates the types of inlet control flow. The USGS flow type *(8)* depends on the submergence of the inlet and outlet ends of the culvert. In all of these examples, the control section is at the inlet end of the culvert. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.



Source: HDS-5 *(7)*

Figure 11-1. Types of Inlet Control

11.2.3.1 Factors Influencing Inlet Control

Since the control is at the upstream end, only the headwater and the inlet factors affect the culvert performance:

- Headwater depth is measured from the 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, but for tapered inlets (Section 11.7) the face area is enlarged, and the control section is at the throat.
- Inlet configuration describes the entrance type. Some typical inlet 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; however, it may be enlarged as in the case of a tapered inlet. Typical shapes are rectangular, circular, and elliptical. Whenever the inlet face is a different size or shape than the culvert barrel, the possibility of an additional control section within the barrel exists.

- Barrel slope influences inlet control performance, but the effect is small. Inlet control nomographs assume a slope of 2 percent for the slope correction term (0.5S for most inlet types). This results in lowering the headwater required by 0.01D. In the computer program HY-8, the actual slope is used as a variable in the calculation.

11.2.3.2 Hydraulics

Inlet control performance is defined by the three regions of flow shown in Figure 11-2: unsubmerged, transition, and submerged. For low headwater conditions, as shown in Figure 11-1A and Figure 11-1C, the entrance of the culvert operates as a weir. A weir is an unsubmerged 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 or measurements are then used to develop equations for unsubmerged inlet control flow. HDS-5, Appendix A *(7)* contains the equations which were developed from the National Bureau of Standards (NBS) and other model test data.

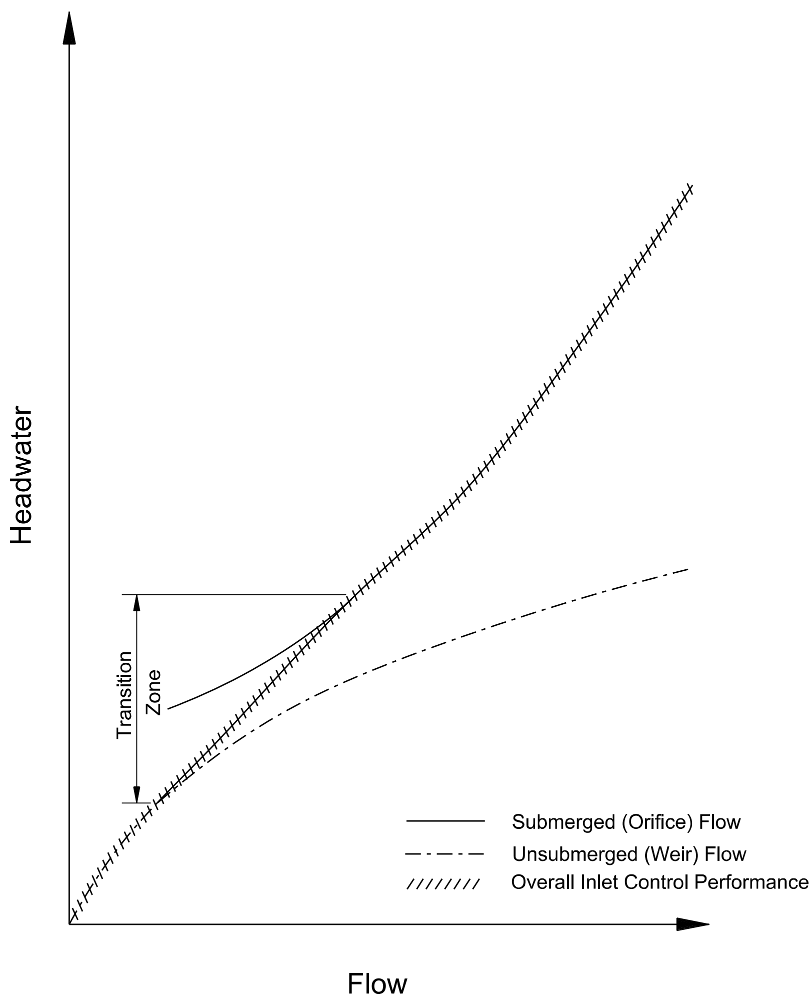


Figure 11-2. Inlet Control Curves

For headwaters submerging the culvert entrance, as shown in Figure 11-1B and Figure 11-1D, the entrance of 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 (see HDS-5 *(7)*).

The flow transition zone between the low headwater (weir control) and the high headwater (orifice control) flow conditions 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, as shown in Figure 11-2.

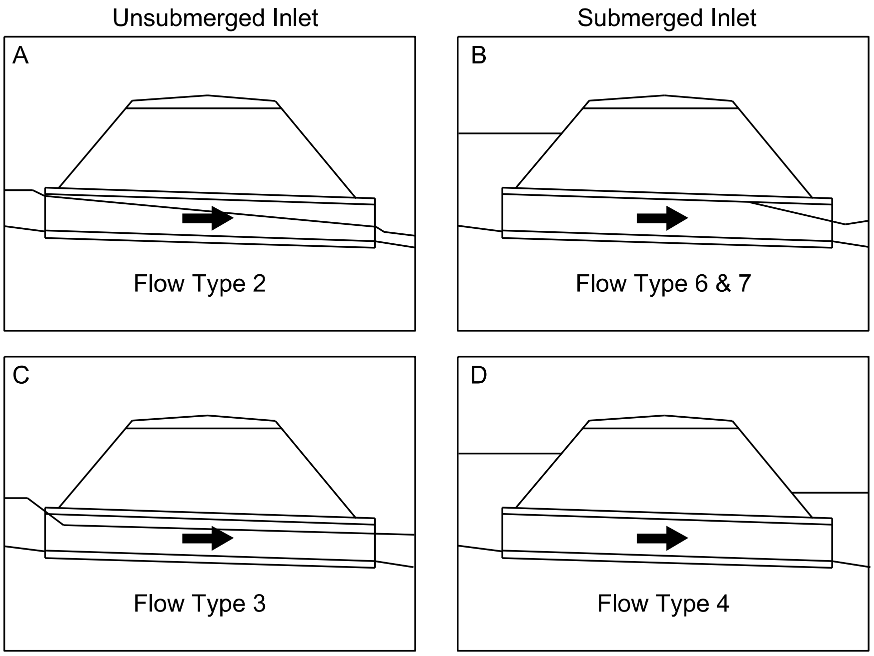
The inlet control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs and for developing equations used in software. The original equations for computer software were generally 5^{th} order polynomial curve-fitted equations that were developed to be as accurate as the nomograph solution (plus or minus 10 percent) within the headwater range of 0.5D to 3.0D. These equations are still being used in HY-8, but have been supplemented with a weir equation from 0.0D to 0.5D and an orifice equation above 3.0D.

11.2.3.3 Inlet Depression

Inlet depression is created by constructing the entrance inlet below the streambed. The amount of inlet depression is defined as the depth from the natural streambed at the face to the inlet invert. The inlet control equations or nomographs provide the depth of headwater above the inlet invert required to convey a given discharge through the inlet. This relationship remains constant regardless of the elevation of the inlet invert. If the entrance end of the culvert is constructed below the streambed, more head can be exerted on the inlet for the same headwater elevation.

11.2.4 Outlet Control

Figure 11-3 illustrates the types of outlet control flow. The USGS flow type *(8)* depends on the submergence of the inlet and outlet ends of the culvert. In all cases, the control section is at the outlet end of the culvert or further downstream. For the partly full flow situations, the flow in the barrel is subcritical.



Source: HDS-5 *(7)*

Figure 11-3. Types of Outlet Control

11.2.4.1 Factors Influencing Outlet Control

Since the control is at the downstream end, the headwater is influenced by all of the culvert factors. The inlet factors influencing the performance of a culvert in inlet control also influence culverts in outlet control (see Section 11.2.4). In addition, the barrel characteristics (roughness, area, shape, length, and slope) and the tailwater elevation affect culvert performance in outlet control:

- Barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete, corrugated metal, and plastic. The roughness is represented by a hydraulic resistance coefficient such as the Manning's *n* value. Additional discussion on the sources and derivations of the Manning's *n* values are contained in HDS-5 *(7)*, Appendix B. Typical Manning's *n* values used for designing culverts are $n = 0.012$ for smooth walled culverts and $n = 0.024$ for rough culverts (corrugated).
- Barrel area is a function of the culvert dimensions. A larger barrel area will convey more flow.
- Barrel shape is a function of culvert type and material. Based on the location of the center of gravity for a given area, a box is the most efficient shape, then the arch shape, followed by the circular shape.
- Barrel length is the total culvert length from the entrance to the exit 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 is the actual slope of the culvert barrel. The barrel slope is often the same as the natural stream slope. However, when the culvert inlet is raised or lowered, the barrel slope is different from the stream slope. The slope is not a factor in calculating the barrel losses for USGS Flow Types 4, 6, and 7 but is a factor in calculating USGS Flow Types 2 and 3 when a water surface profile is calculated.
- Tailwater elevation 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.

11.2.4.2 Hydraulics (Full Barrel Flow)

Full flow in the culvert barrel, as depicted in Figure 11-3D, is the best flow type for describing the hand computation of outlet control hydraulics. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool. The total energy (H_L) required to pass the flow through the culvert barrel is made up of the entrance loss (H_e), the friction losses through the barrel (H_f), and the exit loss (H_v). Other losses, including bend losses (H_b), losses at junctions (H_j), and losses at grates (H_g) should be included as appropriate. These other losses are discussed in Chapter 5 of HDS-5.

$$H_L = H_e + H_f + H_o + H_b + H_j + H_g \qquad (11\text{-}1)$$

where
H_L = total energy losses, ft
H_e = entrance headloss, ft
H_f = friction headloss, ft
H_o = exit headloss, ft
H_b = bend headloss, ft
H_j = headloss at junction, ft
H_g = headloss at grate, ft

The barrel velocity is calculated as follows:

$$V = Q / A \qquad (11\text{-}2)$$

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

The velocity head is:

$$H_v = \frac{V^2}{2g} \qquad (11\text{-}3)$$

where

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

The entrance loss is a function of the velocity head in the barrel and can be expressed as a coefficient times the velocity head:

$$H_e = k_e \left(\frac{V^2}{2g} \right) \tag{11-4a}$$

where

k_e = entrance loss coefficient (see Table 11-3)

The friction loss in the barrel is also a function of the velocity head. Based on the Manning equation, the friction loss is:

$$H_f = \left[\frac{\left(29n^2 L\right)}{R^{1.33}} \right] \left[\frac{V^2}{2g} \right] \tag{11-4b}$$

where

n = Manning's roughness coefficient for a culvert with uniform material on the full perimeter (for composite roughness (n_c) (see Table 11-2)

L = length of the culvert barrel, ft

A = cross-sectional area of the barrel, ft^2

R = hydraulic radius of the full culvert barrel = A/P, ft

P = wetted perimeter of the barrel, ft

V = velocity in the barrel, ft/s

The exit loss is a function of the change in velocity at the outlet of the culvert barrel. For a sudden expansion such as an endwall, the exit loss is:

$$H_o = 1.0 \left[\left(\frac{V^2}{2g} \right) - \left(\frac{V_d^2}{2g} \right) \right] \tag{11-4c}$$

where

V_d = channel velocity downstream of the culvert, ft/s

Equation 11-4c may overestimate exit losses, and a multiplier of less than 1.0 can be used (see HEC-14 *(5)*) for a transition loss. The downstream velocity is usually neglected, in which case the exit loss is equal to the full flow velocity head in the barrel, as shown in Equation 11-4d.

$$H_o = H_v = \frac{V^2}{2g} \tag{11-4d}$$

Equation 11-4d is the standard option in HY-8. If the hydraulics engineer chooses the Utah State University (USU) Method (which is the alternate in HY-8), the following equation will be used:

$$H_o = \frac{(V - V_d)^2}{2g} \qquad (11\text{-}4e)$$

Inserting the above relationships for entrance loss, friction loss, and exit loss (Equation 11-4d) into Equation 11-1, the following equation for barrel losses (H) is obtained:

$$H = \left[1 + k_e + \left(\frac{29n^2L}{R^{1.33}}\right)\right]\left[\frac{V^2}{2g}\right] \qquad (11\text{-}5)$$

11.2.4.3 Energy Grade Line

Figure 11-4 depicts the energy grade line and the hydraulic grade line for full flow in a culvert barrel. The energy grade line represents the total energy at any point along the culvert barrel. The headwater depth, HW_o, is the depth from the inlet invert to the energy 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 straight lines separated by the velocity head except in the vicinity of the inlet where the flow passes through a contraction. The headwater and tailwater conditions as well as the entrance, friction, and exit losses are also shown in Figure 11-4. Equating the total energy at Sections 1 and 2, upstream and downstream of the culvert barrel in Figure 11-4, the following relationship results:

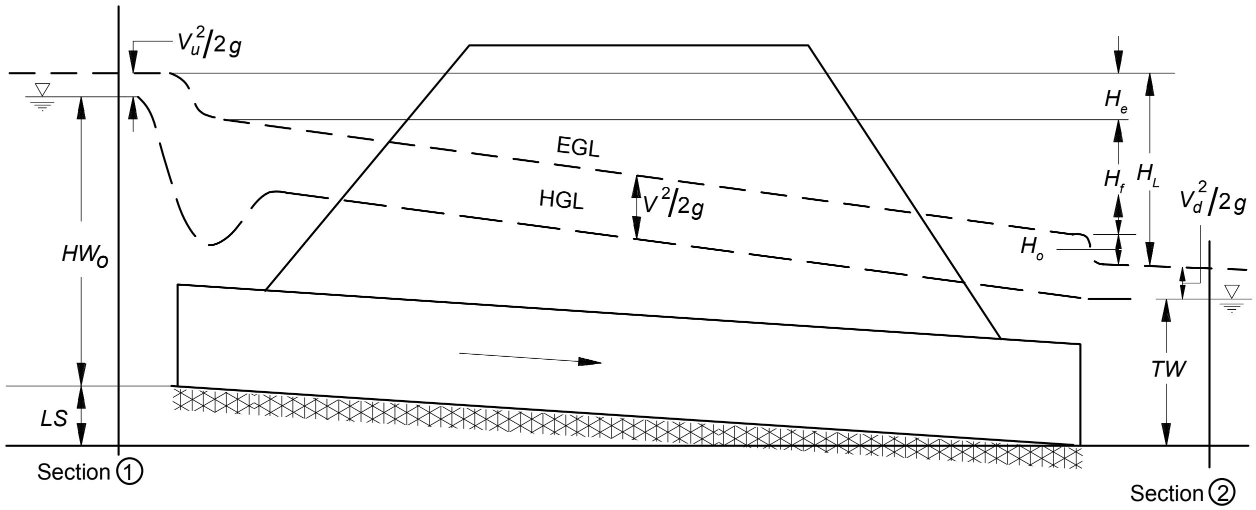
$$HW_o + LS + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_L \qquad (11\text{-}6a)$$

where
HW_o = headwater depth above the outlet invert, ft
LS = drop through the culvert, 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 11-1)

Note: The total available upstream headwater (HW_o) includes the depth of the upstream water above the inlet invert and the approach velocity head. In most instances, the approach velocity is low and the approach velocity head is neglected. However, it can be considered to be a part of the available headwater and used to convey the flow through the culvert.

Likewise, the velocity downstream of the culvert (V_d) is usually neglected. When both approach and downstream velocities are neglected, Equation 11-6a becomes:

$$HW_o = TW + H_L - LS \qquad (11\text{-}6b)$$



Source: HDS-5 *(7)*

Figure 11-4. Full Flow Energy and Hydraulic Grade Lines

11.2.4.4 HDS-5 Nomographs (Full Flow)

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

- $TW \geq D$, Flow Type 4 (see Figure 11-3D); or
- $d_c \geq D$, Flow Type 6 (see Figure 11-3B).

V_u is small and its velocity head can be considered to be a part of the available headwater (HW_o) used to convey the flow through the culvert. V_d is small and its velocity head can be neglected. Equation 11-6b is used with the outlet control nomographs to determine outlet control headwater (HW_o).

11.2.4.5 HDS-5 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 $^1/_2$ 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 is 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:

$$HW = h_o + H - S_o L \qquad (11\text{-}6c)$$

where

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

11.2.5 Outlet Velocity

Culvert outlet velocities should 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 Volume Two, Chapter 12 "Energy Dissipators").

11.2.5.1 Inlet Control

The velocity is calculated from Equation 11-2 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 depth may be obtained by hand computation or by software (e.g., FHWA Hydraulic Toolbox).

11.2.5.2 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.

11.2.6 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 flow will be similar to flow over a broad-crested weir. Flow coefficients for flow overtopping roadway embankments are found in Figure 11-31 (Chart 60B):

$$Q_o = C_d \, L \, HW_r^{1.5} \qquad (11\text{-}7)$$

where
Q_o = overtopping flow rate, ft^3/s

C_d = overtopping discharge coefficient (weir coefficient) = k_t $C_{r\ in\ which}$
k_t = submergence coefficient from Figure 11-31
C_r = discharge coefficient from Figure 11-31
L = length of the roadway crest, ft
HW_r = the upstream depth, measured above the roadway crest, ft

11.2.6.1 Roadway Crest Length

The length is difficult to determine where the crest is defined by a roadway sag vertical curve:

1. Recommend subdividing into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are added together to determine the total flow.
2. 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 (area/length) of the upstream pool above the roadway.

11.2.6.2 Total Flow

Total flow is calculated for a given upstream water surface elevation using Equation 11-9:

- 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.

11.2.7 Performance Curves

Performance curves are plots of flow rate versus headwater depth or elevation, velocity, or outlet scour. The culvert performance curve consists of the controlling portions of the individual performance curves for each of the following control sections (see Figure 11-5):

- The inlet performance curve is developed using the inlet control nomographs.
- The outlet performance curve is developed using Equations 11-1 through 11-7, the outlet control nomographs, or backwater calculations.
- The roadway performance curve is developed using Equation 11-9.

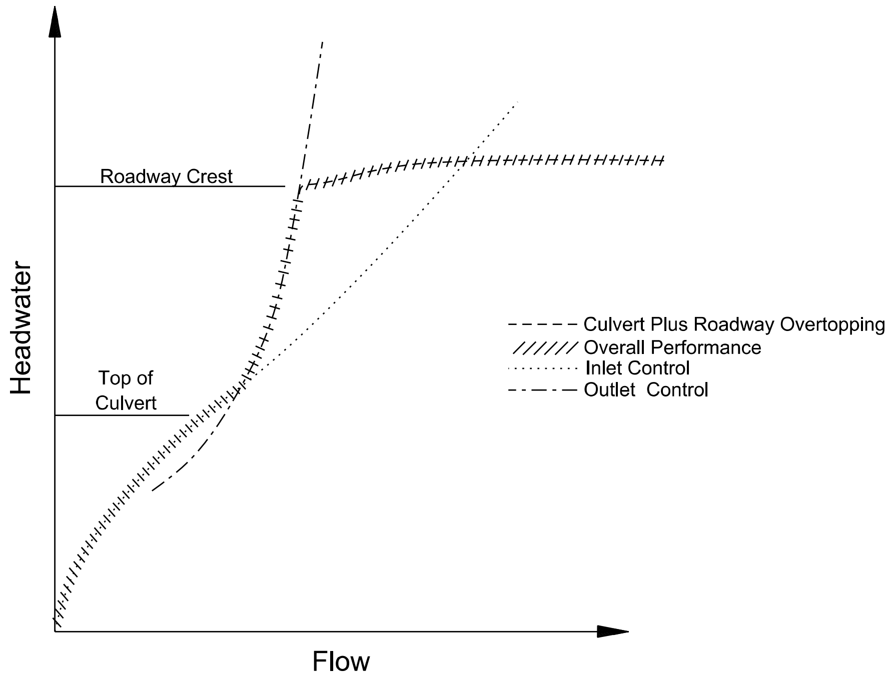


Figure 11-5. Overall Performance Curve

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

Step 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 should be calculated.

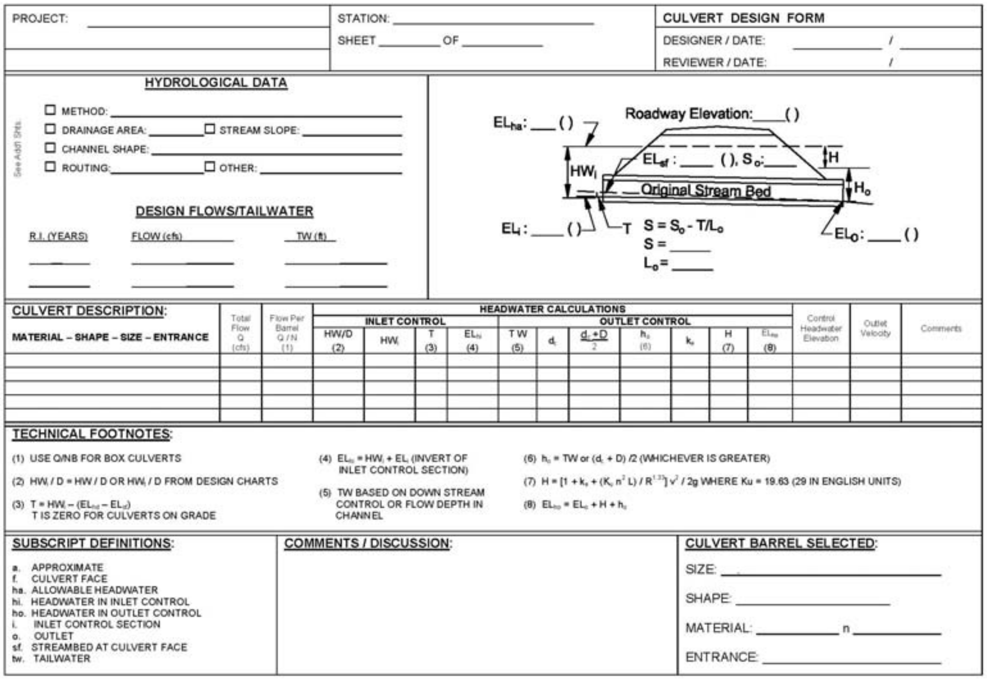
Step 2 Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.

Step 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 11-7 to calculate flow rates across the roadway.

Step 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 11-5.

11.2.8 Culvert Design Form

The Culvert Design Form, shown in Figure 11-6, has been formulated to guide the user through the design process. A full size form is provided as Figure 11-32. Summary blocks are provided at the top of the form for the project description and the designer's identification. Summaries of hydrologic data are also included. At the top right is a small sketch of a culvert with blanks for inserting important dimensions and elevations.



PROJECT: ______

STATION: ______

SHEET ______ OF ______

CULVERT DESIGN FORM

DESIGNER / DATE: ______ / ______

REVIEWER / DATE: ______ / ______

HYDROLOGICAL DATA

See Add'l Shts.

☐ METHOD: ______

☐ DRAINAGE AREA: ______ ☐ STREAM SLOPE: ______

☐ CHANNEL SHAPE: ______

☐ ROUTING: ______ ☐ OTHER: ______

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)

CULVERT DESCRIPTION: MATERIAL – SHAPE – SIZE – ENTRANCE	Total Flow Q (cfs)	Flow Per Barrel Q / N (1)	HEADWATER CALCULATIONS – INLET CONTROL: HW/D (2)	HW_i	T (3)	EL_{hi} (4)	OUTLET CONTROL: TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	Control Headwater Elevation	Outlet Velocity	Comments

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i / D = HW / D$ OR HW_i / D FROM DESIGN CHARTS

(3) $T = HW_i - (EL_{hd} - EL_{sf})$
T IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL

(6) h_o = TW or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $H = [1 + k_e + (K_u n^2 L) / R^{1.33}] v^2 / 2g$ WHERE Ku = 19.63 (29 IN ENGLISH UNITS)

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
ha. ALLOWABLE HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

CULVERT BARREL SELECTED:

SIZE: ______

SHAPE: ______

MATERIAL: ______ n ______

ENTRANCE: ______

Figure 11-6. Culvert Design Form

11.3 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 the Volume Two, Chapter 14 "Storage Facilities" and Section 11.6. The hydraulics engineer should be familiar with all the equations in Section 11.2 before using these procedures. Following the design method without an understanding of culvert hydraulics can result in an inadequate, unsafe, or costly structure.

The Culvert Design Form (see Figure 11-6) is provided 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.

- See Volume Two, Chapter 3 "Data Collection"—The minimum data are
    - USGS, site, and location maps;
    - roadway embankment cross section;
    - stream cross sections;
    - roadway profile;

   - photographs;
   - field visit (sediment, debris); and
   - design data at nearby structures.

- 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.

- Environmental constraints (see Volume Two, Chapter 2 "Permits and Certifications") including
   - commitments contained in review documents,
   - aquatic organism passage, and
   - wildlife passage.

- Design criteria
   - review Volume One, Chapter 11 "Culverts" for applicable criteria, and
   - prepare risk assessment or analysis.

Step 2 Determine hydrology.

- See Volume Two, Chapter 9 "Hydrology."
- Minimum data are drainage area map and a discharge-frequency plot.

Step 3 Design downstream channel.

- See Volume Two, Chapter 10 "Channels."
- Minimum data are cross section of channel and the rating curve for channel.

Step 4 Summarize data on Culvert Design Form.

- See Figure 11-6.
- Data from Steps 1–3.

Step 5 Select design alternative.

- See Volume One, Chapter 11 "Culverts," Design Criteria.
- Choose culvert material, shape, size, and entrance type.

Step 6 Select design discharge (Q_d).

- See Volume One, Chapter 11 "Culverts," Design Criteria.

- Determine flood frequency from design criteria.
- Determine Q from discharge-frequency plot (Step 2).
- Divide Q by the number of barrels.

Step 7 Determine inlet control headwater depth (HW_i).

Use the inlet control nomograph.

Note: A plastic sheet with a matte finish can be used to mark on so that the nomographs can be preserved. Since headwater depth is above the invert, T should be considered if there is a depression at the inlet.

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 straightedge.
- 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 the Culvert Design Form.

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_o).

a) Calculate the tailwater depth (TW) using the design flow rate and normal depth (single section) or using a water surface profile.

b) Calculate critical depth (d_c):

Locate flow rate and read d_c.

d_c cannot exceed D.

If $d_c > 0.9D$, consult *Handbook of Hydraulics (2)* for a more accurate d_c, if needed, because curves are truncated where they converge.

c) Calculate $(d_c + D)/2$.

d) Determine (h_o):

h_o = the larger of TW or $(d_c + D)/2$.

e) Determine (k_e):

Entrance loss coefficient from Table 11-3.

f) Determine losses through the culvert barrel (H):

- Use nomograph or Equation 11-5 or 11-6 if outside range.
- Locate appropriate k_e scale.
- Locate culvert length (L) or (L_1):
  - use (L) if Manning's n matches the n value of the culvert, and
  - use (L_1) to adjust for a different culvert n value:

$$L_1 = L(n_1 / n)^2 \qquad (11\text{-}8)$$

where

L_1 = adjusted culvert length, ft
L = actual culvert length, ft
n_1 = desired Manning n value
n = Manning n value on chart

- Mark point on turning line:
  - use a straightedge, and
  - connect size with the length.

- Read (H):
  - use a straight edge,
  - connect Q and turning point, and
  - Read (H) on Head Loss scale.

g) Calculate outlet control headwater (HW_{oi}):

- Use Equation 11-6; if V_u and V_d are neglected:

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

- Use Equations 11-1, 11-4c and 11-6a to include V_u and V_d.
- If HW_o is less than 1.2D and control is outlet control, the barrel may flow partly full:
  - If the headwater depth falls below 0.75D, the approximate nomograph method should not be used and the approximate method of using the greater of tailwater or (d_c + D)/2 may not be applicable.
  - Backwater calculations should be used to determine the headwater.

Step 9 Determine controlling headwater (HW_c).

- Compare HW_i and HW_o; use the higher.
- $HW_c = HW_i$, if $HW_i > HW_o$
- Where practicable, some means shall be provided for personnel and equipment access to facilitate maintenance.

- Culverts shall be regularly inspected and maintained.

Step 10 Compute discharge over the roadway (Q_o).

a) Calculate depth above the roadway (HW_r):

- $HW_r = HW_c - HW_{ov}$.
- HW_{ov} = height of road above inlet invert.

b) If $HW_r \leq 0$, $Q_o = 0$

If $HW_r > 0$, determine C_d from Figure 11-31 (Chart 60B).

c) Determine length of roadway crest (L).

d) Calculate Q_o using Equation 11-7:

$$Q_o = C_d L HW_r^{1.5}$$

Step 11 Compute total discharge (Q_t).

$$Q_t = Q_d + Q_o \quad (11\text{-}9)$$

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 the 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_o = overtopping flow):

- Q_{100}, if $Q_o \leq Q_{100.}$
- Q_{500}, if $Q_o > Q_{100.}$
- Q_{max} = largest flood that can be estimated, if no overtopping is possible

Step 15 Consider the following options:

- tapered inlets if culvert is in inlet control and has limited available headwater (see Section 11.7);
- flow routing if a large upstream headwater pool exists (see Section 11.6);
- energy dissipators if V_o is larger than the normal V in the downstream channel (see Volume Two, Chapter 12 "Energy Dissipators");
- debris control storage for sites with sediment concerns (e.g., alluvial fans) or with other debris concerns (see HEC-9 *(4)* and Volume Two, Chapter 20 "Erosion and Sediment Control");
- fish passage or aquatic organism passage (see Section 11.9); and
- broken-back culverts (see Section 11.8).

Step 16 Documentation.

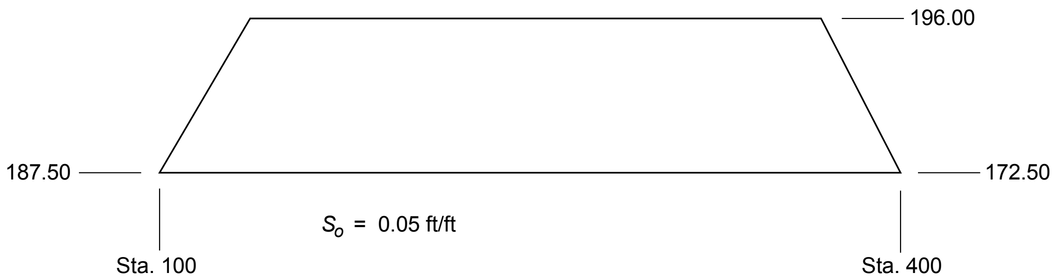
- See Volume Two, Chapter 4 "Documentation;"
- See Section 11.5; and
- Prepare report and file with background information.

11.4 DESIGN EXAMPLE USING NOMOGRAPHS

The following example problem follows the design procedure steps described in Section 11.3:

Step 1 Assemble site data and project file.

- Site survey project file contains
    - USGS, site, and location maps;
    - roadway profile; and
    - embankment cross section.



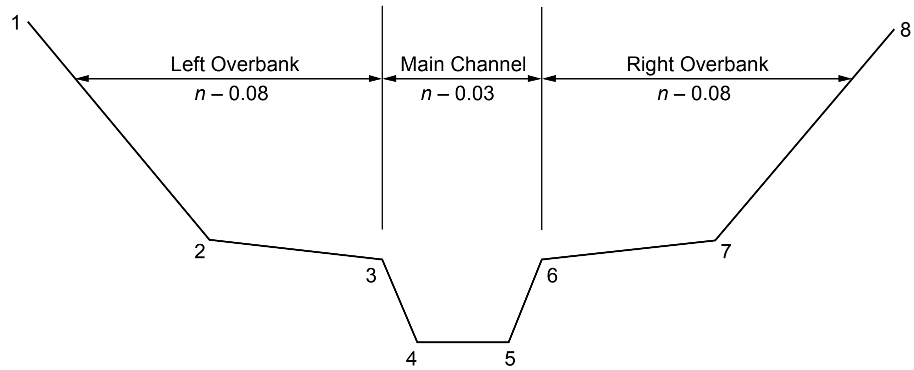
- Site visit notes indicate:
  - no sediment or debris problems, and
  - no nearby structures.
- Studies by other agencies—none.
- Environmental risk assessment shows:
  - no buildings near floodplain,
  - no sensitive floodplain values,
  - no FEMA involvement, and
  - convenient detours exist.
- Design criteria:
  - 50-yr frequency for design, and
  - 100-yr frequency for check.

Step 2 Determine hydrology.

USGS regression equations yield

- $Q_{50} = 400\ \text{ft}^3/\text{s}$
- $Q_{100} = 500\ \text{ft}^3/\text{s}$

Step 3 Design downstream channel, cross section of channel (Slope = 0.05 ft/ft).



Point	Station, ft	Elevation, ft
1	12	180.0
2	22	175.0
3	32	174.5
4	34	172.5
5	39	172.5
6	41	174.5
7	51	175.0
8	61	180.0

The rating curve for the channel calculated by normal depth yields:

Q (ft³/s)	TW (ft)	V (ft/s)
100	1.4	11.1
200	2.1	13.7
300	2.5	16.0
400	2.8	17.5
500	3.1	18.8

Step 4 Summarize data on design form.

See Figure 11-6.

Step 5 Select design alternative.

Shape—box Size—7 ft × 6 ft ($B \times D$)

Material—concrete Entrance—beveled

Step 6 Select design discharge.

$Q_d = Q_{50} = 400$ ft³/s

Step 7 Determine inlet control headwater depth (HW_i).

Use inlet control nomographs—Figure 11-25 (Chart 10B):

a) $D = 6$ ft

b) $Q = Q_d$/number of barrels

$Q = 400/1 = 400 \text{ft}^3/\text{s}$

$Q/NB = 400/7 = 57$

c) $HW/D = 1.33$ for $^3/_4$ in. chamfer

$HW/D = 1.27$ for 45° bevel

d) $HW_i = (HW/D)D = (1.27)6 = 7.6$ ft (neglect the approach velocity)

Step 8 Determine outlet control headwater depth at inlet (HW_o).

a) $TW = 2.8$ ft for $Q_{50} = 400 \text{ ft}^3/\text{s}$ (from tailwater rating curve, step 3)

b) $d_c = 4.7$ ft from Figure 11-29 (Chart 14B)

c) $(d_c + D)/2 = (4.7 + 6)/2 = 5.4$ ft

d) h_o = the larger of TW or $(d_c + D)/2$

$h_o = (d_c + D)/2 = 5.4$ ft

e) $k_e = 0.2$ from Table 11-3

f) Determine (H) from Figure 11-30 (Chart 15B):

- k_e scale = 0.2
- culvert length (L) = 300 ft
- $n = 0.012$ (same as on chart)
- area = 42 ft^2
- $H = 2.8$ ft

g) $HW_o = H + h_o - S_oL = 2.8 + 5.4 - (0.05)300 = -6.8$ ft

Because HW_o is less than 1.2D, the barrel will not flow full at the design discharge, which is the conservative assumption used for hand or nomograph solutions. The assumption is extremely conservative in this case because a negative HW_o indicates that the required HW is below the streambed. A computer solution shows that Flow Type 5 (see Figure 11-1) is present in the barrel at the design discharge.

Step 9 Determine controlling headwater (HW_c).

a) $HW_c = HW_i = 7.6 \text{ ft} > HW_{oi} = -6.8$ ft

b) The culvert is in inlet control.

Step 10 Compute discharge over roadway (Q_o).

a) Calculate depth above the roadway:

$HW_{ov} = 196 - 187.5 = 8.5$

$HW_r = HW_c - HW_{ov} = 7.6 - 8.5 = -0.9$ ft

b) If $HW_r \leq 0$, $Q_r = 0$

Step 11 Compute total discharge (Q_t).

$$Q_t = Q_d + Q_o = 400 \text{ ft}^3/\text{s} + 0 = 400 \text{ ft}^3/\text{s}$$

Step 12 Calculate outlet depth (d_n) and velocity (V_o).

Inlet Control

a) Calculate normal depth (d_n):

Q	=	$(1.486/n)A\,R^{2/3}\,S^{1/2} = 400$ ft^3/s
400	=	$(123.8)(7)(d_n)[7(d_n)/(7 + 2d_n)]^{2/3}(0.05)^{0.5}$
14.4	=	$(7)(d_n)[7(d_n)/(7 + 2\,d_n)]^{2/3}$
try d_n	=	2.0 ft, 16.5 > 14.4
use d_n	=	1.8 ft, 14.1 ≈ 14.4

b) $A = (1.8)7 = 12.6$ ft^2

c) $V_o = Q/A = 400/12.6 = 31.7$ ft/s

Step 13 Review results.

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

- barrel has (8.5 – 6) = 2.5 ft of cover,
- L = 300 ft is OK, since inlet control,
- headwalls and wingwalls fit site,
- allowable headwater (8.5 ft) > 7.6 ft is OK, and
- overtopping flood frequency >50-yr.

Step 14 Plot performance curve.

Use Q_{100} for the upper limit. Steps 6 through 12 should be repeated for each discharge used to plot the performance curve. These computations are provided on the Culvert Design Form that follows this example (see Figure 11-7).

Step 15 Special considerations.

Consider the following options:

- Tapered Inlets. Culvert is in inlet control and has limited available headwater.
- Flood Routing. Because a small upstream headwater pool exists, flood routing is not feasible.
- Broken-Back Culvert. No break in slope is needed.
- Energy Dissipation. Because V_o = 31.7 ft/s > 18.0 ft/s in the downstream channel, review options in Volume Two, Chapter 11 “Energy Dissipators.”
- Debris Control. The site has no sediment or other debris problems.
- Fish Passage. The stream is not a fishery and does not have other aquatic organism concerns.

Step 16 Documentation.

Report prepared and background filed.

PROJECT: Example Problem

STATION: 9+00

SHEET 1 OF 1

CULVERT DESIGN FORM

DESIGNER / DATE: plt / 12/1/2011

REVIEWER / DATE: tn / 12/1/2011

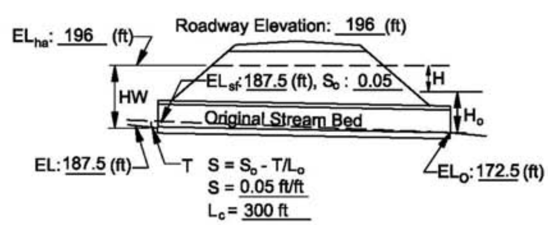
HYDROLOGICAL DATA

See Add'l Shts.

- ☐ METHOD: USGS
- ☐ DRAINAGE AREA: ☐ STREAM SLOPE: .05 ft/ft
- ☐ CHANNEL SHAPE: irregular cross section
- ☐ ROUTING: ☐ OTHER:

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50	400	2.8
100	500	3.1



CULVERT DESCRIPTION: MATERIAL – SHAPE – SIZE – ENTRANCE	Total Flow Q (cfs)	Flow Per Barrel Q / N (1)	HEADWATER CALCULATIONS: INLET CONTROL: HW/D (2)	HW_i	T (3)	EL_{hi} (4)	OUTLET CONTROL: TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	Control Headwater Elevation	Outlet Velocity	Comments
RCB – 7 ft x 6 ft – Bevel	400	57	1.27	7.6	0	195.1	2.8	4.7	5.4	5.4	0.2	2.8	180.7	195.1	32	195.1 < 196 ok
	500	72	1.56	9.4	0	196.9	3.1	5.4	5.7	5.7	0.2	4.3	182.2	196.9	34	196 calc Q_c
Performance Curve	100	14	0.46	2.8	0	190.3										
	200	29	0.78	4.7	0	192.2										
	300	43	1.01	6.1	0	193.6										

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) HW_i / D = HW / D OR HW_i / D FROM DESIGN CHARTS

(3) $T = HW_i - (EL_{hd} - EL_{sf})$
T IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL

(6) h_o = TW or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $H = [1 + k_e + (K_u n^2 L) / R^{1.33}] v^2 / 2g$ WHERE Ku = 19.63 (29 IN ENGLISH UNITS)

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
ha. ALLOWABLE HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

Assume 500 ft^3/s in culvert (196.9 – 196) = 0.9 ft
$Q_r = C_D L (HW_r)^{1.5} = 3.03(200)(0.9)^{1.5}$ = 520 ft^3/s
Q_T = 500 + 520 = 1020 ft^3/s

CULVERT BARREL SELECTED:

SIZE: 7 ft x 6 ft

SHAPE: RCB

MATERIAL: n 0.012

ENTRANCE: Bevel

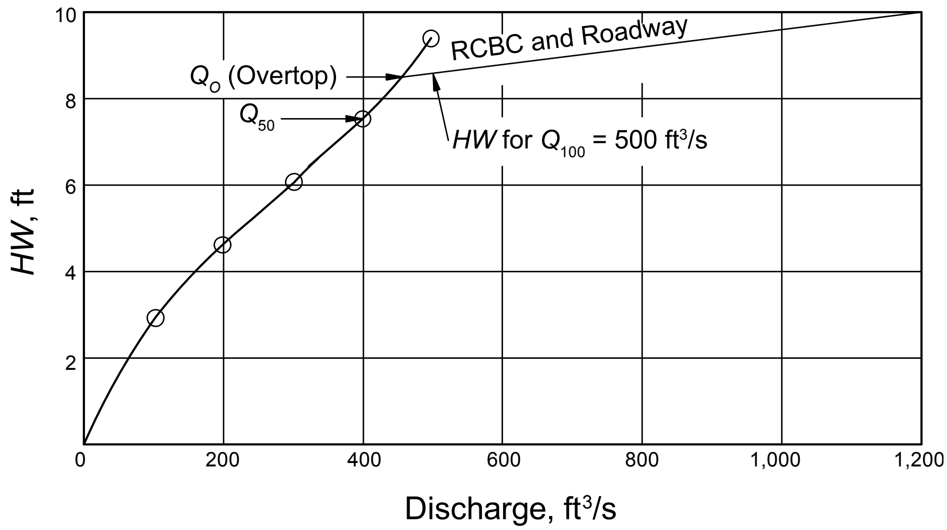


Figure 11-7. Culvert Design Form and Performance Curve for Design Example

11.4.1 HY-8 Solution

The hand solution shown above can be duplicated using HY-8:

- Enter Site Data shown in Step 1. For tailwater, enter irregular channel in Step 3.
- Enter Culvert Type and Size from Step 5, select straight. For Inlet Edge, select bevel edge 1V:1H. For Inlet Depression, select no.
- Analyze Crossing brings up Crossing Summary Table that shows 30.8 ft^3/s overtopping at 500 ft^3/s.
- Select Culvert Summary Table which shows that at 400 ft^3/s inlet control governs: HW_i = 7.49 ft and El_{hi} = 194.89 ft ≈ 195.1 ft of the nomograph solution for bevel edges.

11.5 DOCUMENTATION

A Hydraulic Design Report should be prepared for major and unusual culverts.

11.5.1 Draft Hydraulic Design Report

In addition to the items discussed in Volume Two, Chapter 4 "Documentation," the report should include the following, as appropriate:

a) Site-Specific Hydraulic Performance Criteria (see Volume One, Chapter 11 "Culverts")

b) Risk Assessment (see Volume One, Chapter 17 "Bridges")

   - Floodplain land use
   - Environmentally sensitive areas (e.g., fisheries, wetlands)

c) Stream Stability Assessment (see Volume Two, Chapter 16 “Stream Stability”)

- Level I qualitative analysis
- Geomorphic factors and hydraulic factors that affect stream stability
- Identification of existing bed or bank instability

d) Hydrologic Computations

- Discharges for specified frequencies
- Discharge and frequency for historical flood that complements the high-water marks used for calibration

e) Hydraulic Computations

- Computational method
- Computer model selection (see Volume Two, Chapter 5 “Software”)
- Hydraulic performance for existing conditions
- Hydraulic performance of proposed designs
- Scour computations, if appropriate (see Volume Two, Chapter 17 “Bridges”)

11.5.2 Final Hydraulic Design Report

In addition to the items already included in the Draft Hydraulic Design Report, the Final Hydraulic Design Report should include the following, as appropriate:

- Risk analysis documentation, if applicable (see Volume Two, Chapter 17 “Bridges”).
- Countermeasure design details (see Volume Two, Chapter 18 “Channel and Stream Bank Stabilization”).
- Scour computations, countermeasures, monitoring plan, or instrumentation, if applicable (see Volume Two, Chapter 17 “Bridges”).

11.6 STORAGE ROUTING

11.6.1 Introduction

Significant storage capacity behind a highway embankment can attenuate a flood hydrograph. Because of the reduction of the peak discharge associated with this attenuation, the required capacity of the culvert, and its size, can be reduced. This section outlines how to complete hydrologic routing. Detailed information on routing is provided in HEC-22 *(3)* and in HDS-5 *(7)*. While the calculation is not difficult and is readily completed with the FHWA Hydraulic Toolbox, most culvert designs do not consider attenuation upstream of the embankment, but rather consider it part of the safety factor in the design (see HDS-5, Chapter 5 *(7))*.

11.6.2 Design Procedure

Flood routing through a culvert is easily accomplished with the FHWA Hydraulic Toolbox or other software (see Volume Two, Chapter 5 “Software”). The design procedure is the same as for reservoir routing (see Volume Two, Chapter 14 “Storage Facilities”):

- The site data, including storage data and roadway geometry, are obtained (see Volume Two, Chapter 3 “Data Collection”).
- The hydrology analysis should include estimating a hydrograph (see Volume Two, Chapter 9 “Hydrology”).
- A trial culvert size is estimated and the hydrograph is routed.

Before attempting to design a culvert to take advantage of storage, the designer should review the culvert storage routing design process included in HDS-5, Chapter 5 and *Design Guideline 4 (7)*.

11.7 TAPERED INLETS

11.7.1 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 throat depression 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.

11.7.2 Side-Tapered Inlets

The side-tapered inlet has an enlarged face section with the transition to the culvert barrel accomplished by tapering the side walls (Figure 11-8). 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 percent (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 11-8, 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.

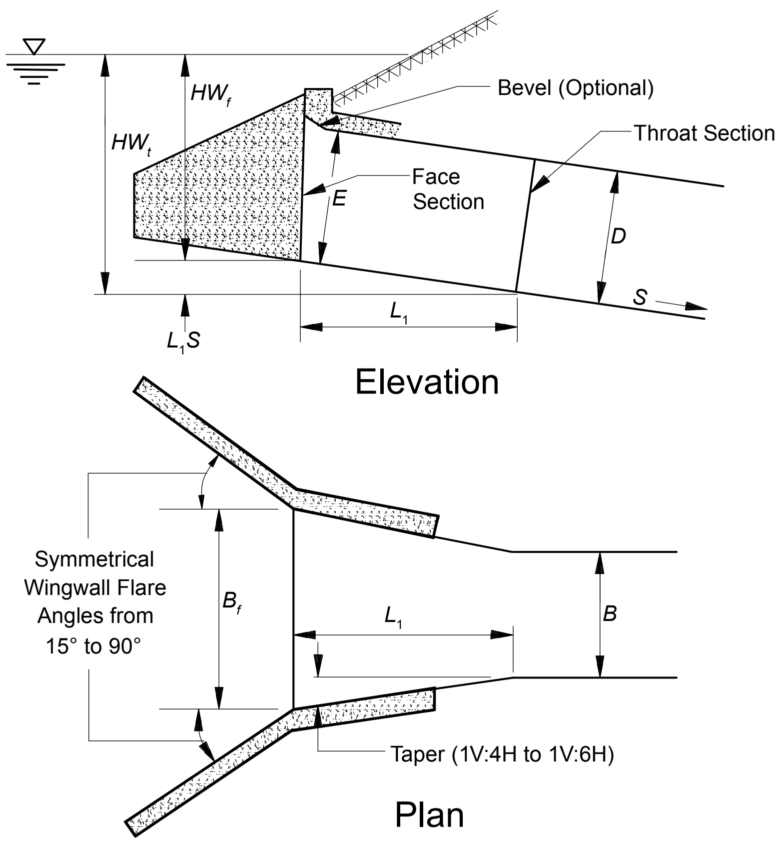


Figure 11-8. Side-Tapered Inlet

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 11-9 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 ensure 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.

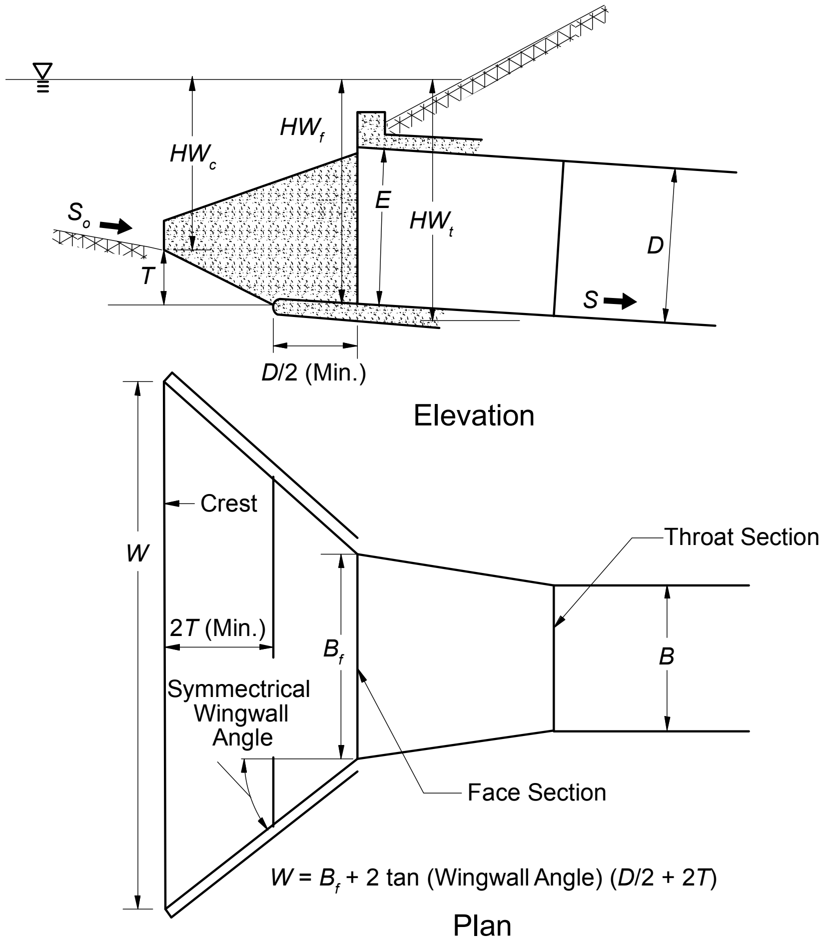


Figure 11-9. Side-Tapered Inlet with Upstream Depression Contained between Wingwalls

11.7.3 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 11-10). In addition, a vertical depression is incorporated into the inlet between the face and throat sections. This depression 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 HDS-5 *(7)*. 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.

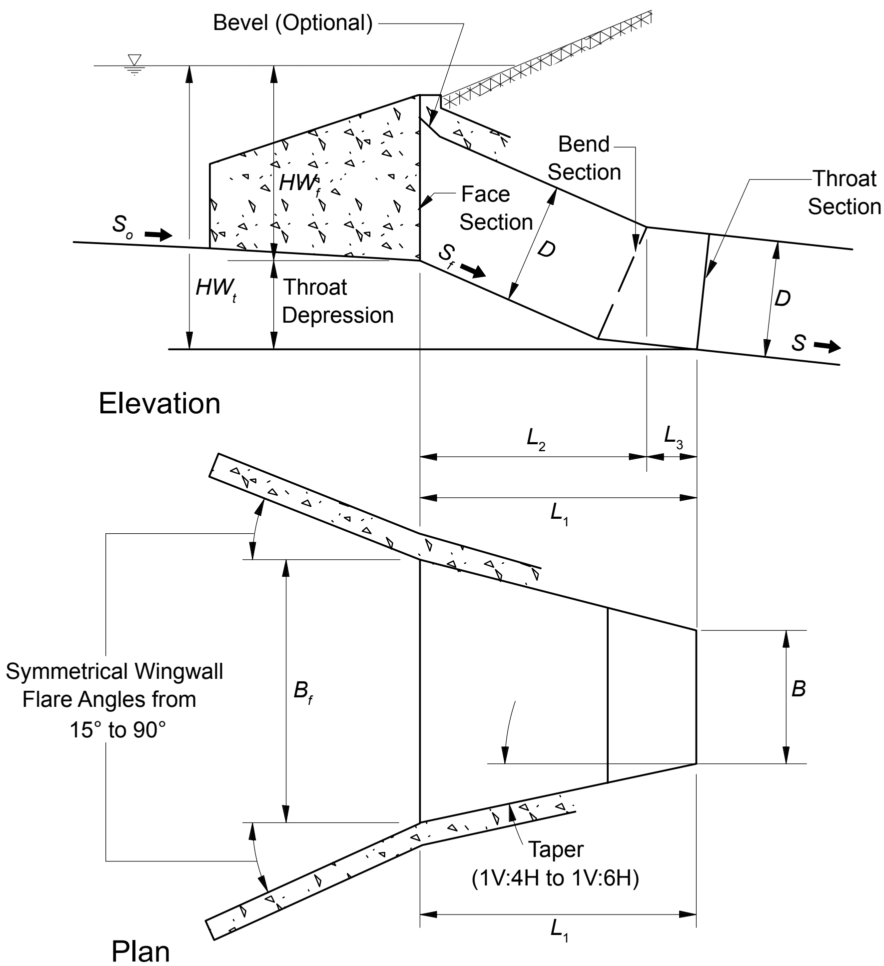


Figure 11-10. Slope-Tapered Inlet with Vertical Face

The slope-tapered inlet combines an efficient throat section with additional head on the throat. The face section does not benefit from the depression 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 11-10.

The slope-tapered inlet is the most complex inlet improvement recommended in this chapter. 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.

11.7.4 Hydraulic Design

11.7.4.1 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 11-11).

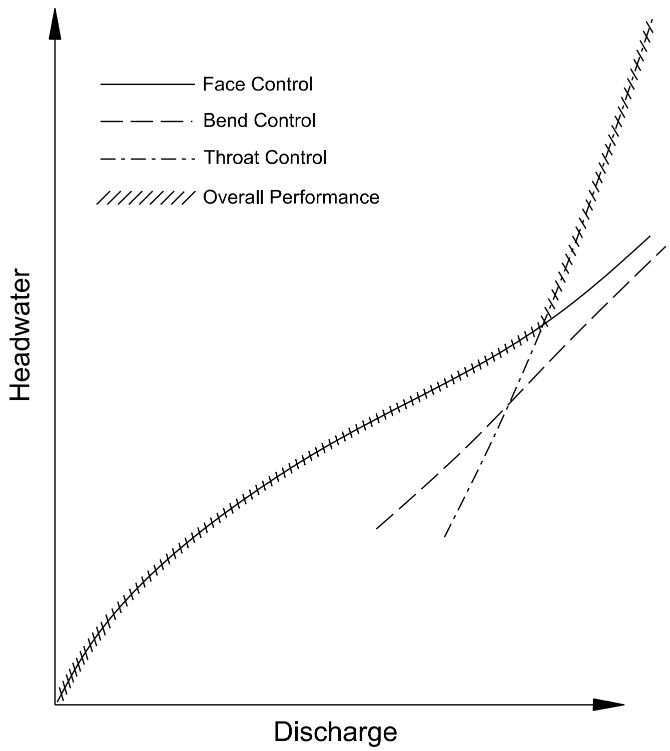


Figure 11-11. Inlet Control Performance Curves (Schematic)

11.7.4.2 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.

11.7.4.3 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 HDS-5 *(7)* are followed. However, the bend will contribute to the inlet losses that are included in the inlet loss coefficient, k_e.

11.7.4.4 Outlet Control

When a culvert with a tapered inlet performs in outlet control, the hydraulics are the same as described in Section 11.2 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.

11.7.5 Design Methods

Tapered inlet design begins with the selection of the culvert barrel size, shape, and material. 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 hydraulics engineer 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.

11.7.6 Performance Curves

Performance curves illustrate 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 11-12, 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.

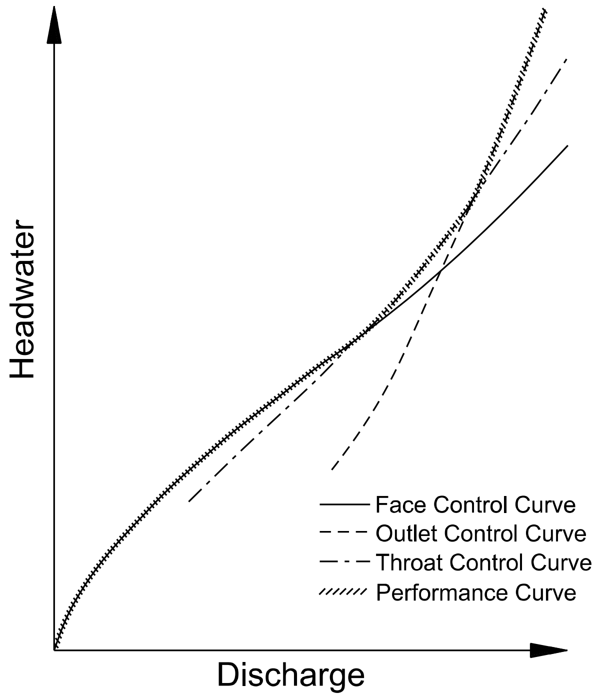


Figure 11-12. Culvert Performance Curve (Schematic)

11.8 BROKEN-BACK CULVERTS

11.8.1 Introduction

An alternative to installing a steeply sloped culvert is to break the slope into a steeper portion near the inlet followed by a horizontal runout section. This configuration is referred to as a broken-back culvert. Broken-back culverts can be considered an internal (integrated) energy dissipater if designed so that a hydraulic jump occurs in the runout section to dissipate energy (see HEC-14 *(5)*).

11.8.2 Guidelines

The broken-back configuration is one potential mechanism for creating a hydraulic jump. Two types are depicted in Figures 11-13 and 11-14. When used appropriately, a broken-back culvert configuration can influence and contain a hydraulic jump. However, there must be sufficient tailwater and there should be sufficient friction and length in Unit 3 (see Figures 11-13 and 11-14) of the culvert. In ordinary circumstances for broken-back culverts, the designer should employ one or more devices, such as roughness baffles, to create a tailwater that is high enough to force a hydraulic jump.

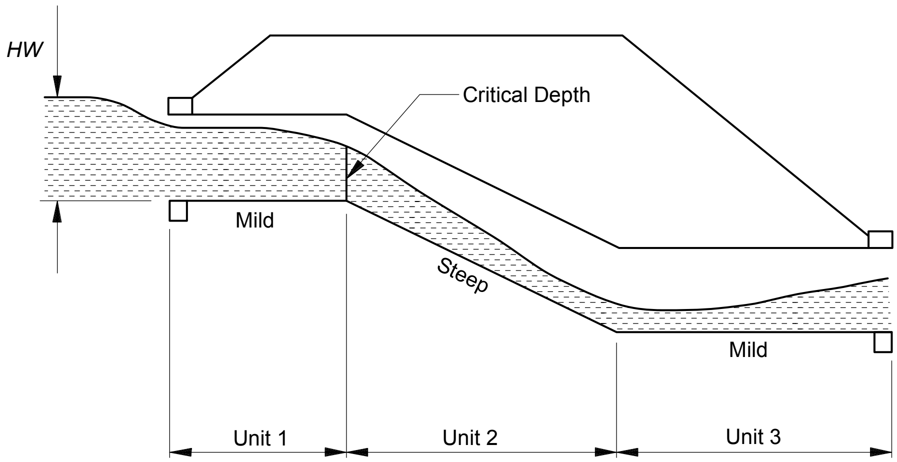


Figure 11-13. Three-Unit Broken-Back Culvert

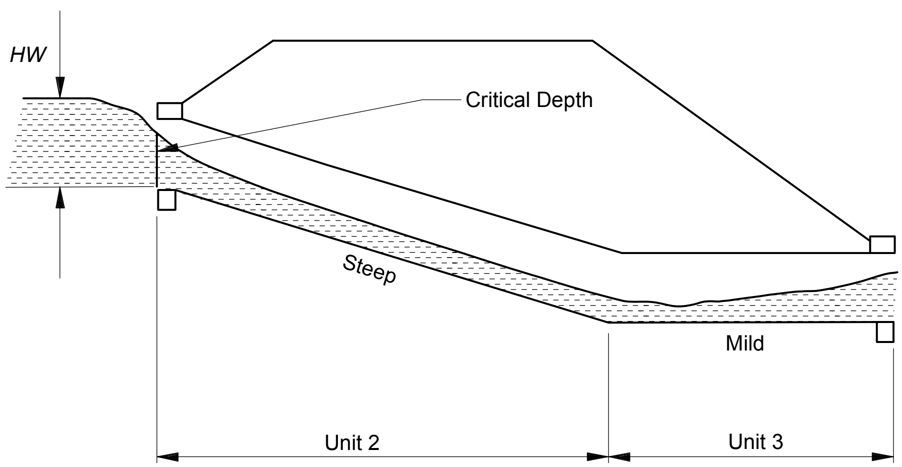


Figure 11-14. Two-Unit Broken-Back Culvert

11.8.3 Design Procedure

The design of a broken-back culvert is not difficult, but provisions must be made so that the primary intent of reducing velocity at the outlet is realized. The hydraulics of circular and rectangular culverts can be determined using the FHWA HY-8 software or the Broken-back Culvert Analysis Program (BCAP) software from the Nebraska Department of Roads. The design of associated energy dissipators is contained in HEC-14, Chapter 7 *(5)*.

11.9 AQUATIC ORGANISM PASSAGE

Simulating the natural stream bottom conditions in a culvert is the most desirable design option to accommodate aquatic organisms or to provide for the transport of large bed material. Open bottom culverts, such as arches, have obvious advantages if adequate foundation support exists for the culvert. Oversized embedded culverts have the advantage of a natural bottom while overcoming the problem of poor foundation material. The process of sizing an embedded culvert is provided in HEC-26 *(6)*.

Baffles can also be constructed in the bottom of culverts to facilitate fish passage (Figure 11-15). The hydraulic design of culverts with baffles is accomplished by modifying the friction resistance of the barrel in outlet control to account for the resistance of the bed material or the resistance imposed by the baffles if no bed material is retained. HEC-14, Section 7.2, Increased Resistance *(5)* provides equations and procedures for estimating the hydraulic loss due to regularly spaced, horizontal baffles. A pair of horizontal baffles that are angled either upstream or downstream should be treated as a single perpendicular baffle when applying the equations and slots should be ignored. The highest composite *n* value is then used in the outlet control calculations. The increased resistance equations are also available in HY-8 in the energy dissipator option. For inlet control, the reduced area of the entrance due to the baffles is used.

Source: left—HDG *(1)*, right—USFS FishXing Case Study

Figure 11-15. Embedded Culvert with Baffles

11.10 DESIGN AIDS

This section presents several tables, figures, and forms required for the hydraulic design of culverts. These include:

1. Manning's *n* values that have been determined in the laboratory are provided in Table 11-2 with the recommended design *n* value. Culvert materials are either treated as smooth or a corrugated. In this way, alternative materials can be substituted for a given structure.
2. Entrance loss coefficients (k_e) are provided in Table 11-3.
3. The following culvert nomographs for circular and rectangular shapes are included; see HDS-5 *(7)* for other culvert nomographs:
   - Figure 11-16 Headwater Depth for Concrete Pipe Culverts with Inlet Control;
   - Figure 11-17 Headwater Depth for C. M. Pipe Culverts with Inlet Control;
   - Figure 11-18 Headwater Depth for Circular Pipe Culverts with Beveled Ring Inlet Control;
   - Figure 11-19 Critical Depth (Circular Pipe);

- Figure 11-20 Head for Concrete Pipe Culverts Flowing Full (n = 0.012);
- Figure 11-21 Head for Standard C. M. Pipe Culverts Flowing Full (n = 0.024);
- Figure 11-22 Head for Structural Plate Corrugated Metal Pipe Culverts Flowing Full (n = 0.0328 to 0.0302);
- Figure 11-23 Headwater Depth for Box Culverts with Inlet Control;
- Figure 11-24 Headwater Depth for Inlet Control, Rectangular Box Culverts, Flared Wingwalls 18° to 33.7° and 45° with Beveled Edge at Top of Inlet;
- Figure 11-25 Headwater Depth for Inlet Control, Rectangular Box Culverts, 90° Headwall, Chamfered or Beveled Inlet Edges;
- Figure 11-26 Headwater Depth for Inlet Control, Single Barrel Box Culverts, Skewed Headwalls, Chamfered or Beveled Inlet Edges;
- Figure 11-27 Headwater Depth for Inlet Control, Rectangular Box Culverts, Flared Wingwalls, Normal and Skewed Inlet Edges, 3/4-in. Chamfer at Top of Opening;
- Figure 11-28 Headwater Depth for Inlet Control, Rectangular Box Culverts, Offset Flared Wingwalls and Beveled Edge at Top of Inlet;
- Figure 11-29 Critical Depth (Rectangular Section);
- Figure 11-30 Head for Concrete Box Culverts Flowing Full (n = 0.012); and
- Figure 11-31 Discharge Coefficients for Roadway Overtopping.

4. The following design forms are presented for hand calculations for the hydraulic design of culverts:

   - Figure 11-32 Culvert Design Form, which is the standard form used for culverts. The procedure in Section 11.3 is based on this form, and
   - Figure 11-33 Design Form for Side/Slope-Tapered Inlet.

Table 11-2. Manning's *n* Values for Culverts

Type of Conduit	Wall Description	Manning's *n* Laboratory[a]	Design Value
Concrete Pipe	Smooth	0.010–0.011	0.012
Concrete Boxes	Smooth	0.012–0.015	0.012
Spiral Rib Metal Pipe	Smooth walls	0.012–0.013	0.012
Corrugated Metal Pipe, Pipe-Arch and Box	$2^2/_3$ in. × $^1/_2$ in. Annular	0.022–0.027	0.024
	$2^2/_3$ in. × $^1/_2$ in. Helical	0.011–0.023	0.024
	6 in. × 1 in. Helical	0.022–0.025	0.024
	5 in. × 1 in.	0.025–0.026	0.024
	3 in. × 1 in.	0.027–0.028	0.024
	6 in. × 2 in. Structural Plate	0.033–0.035	0.035
	9 in. × $2^1/_2$ in. Structural Plate	0.033–0.037	0.035
Corrugated Polyethylene	Smooth	0.009–0.015	0.012
Corrugated Polyethylene	Corrugated	0.018–0.025	0.024
Polyvinyl Chloride (PVC)	Smooth	0.009–0.011	0.012

[a] *Source*: HDS-5 *(7)*

Table 11-3. Entrance Loss Coefficients (Outlet Control, Full or Partly Full)

$$H_e = k_e \left[\frac{v^2}{2g}\right]$$

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

Source: HDS-5 *(7)*

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

CHART 1B

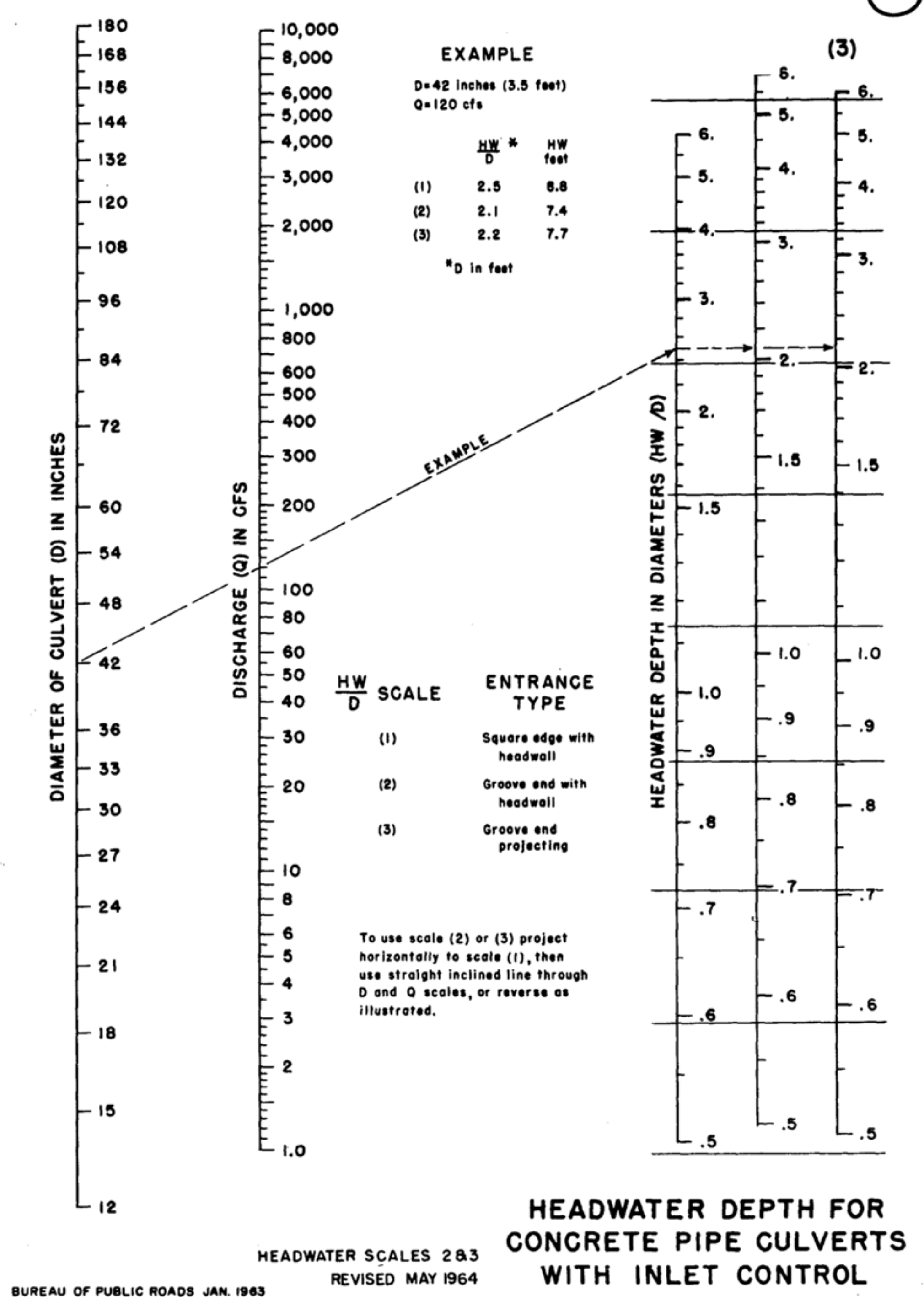


Figure 11-16. Headwater Depth for Concrete Pipe Culverts with Inlet Control

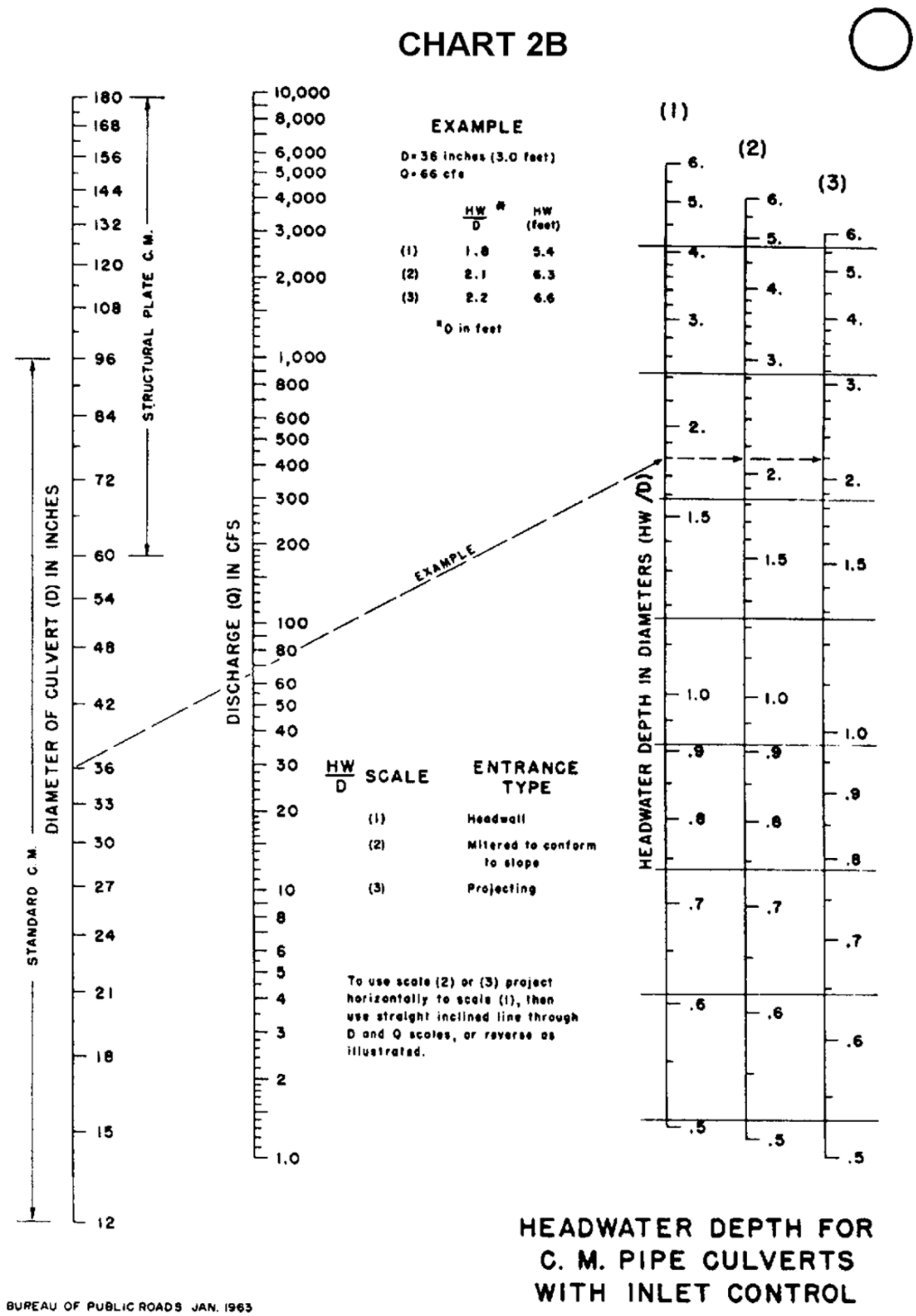


Figure 11-17. Headwater Depth for C. M. Pipe Culverts with Inlet Control

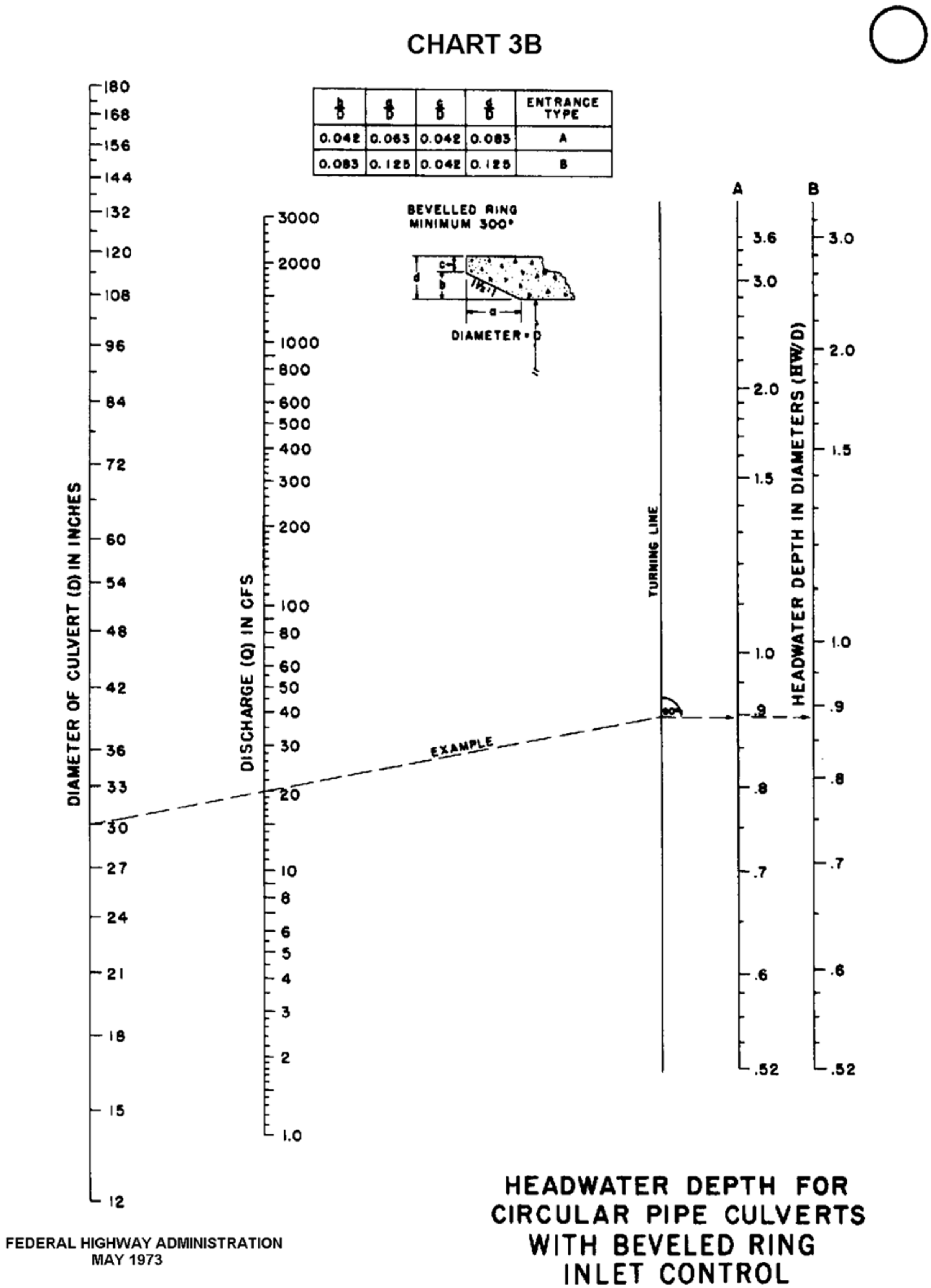


Figure 11-18. Headwater Depth for Circular Pipe Culverts with Beveled Ring Inlet Control

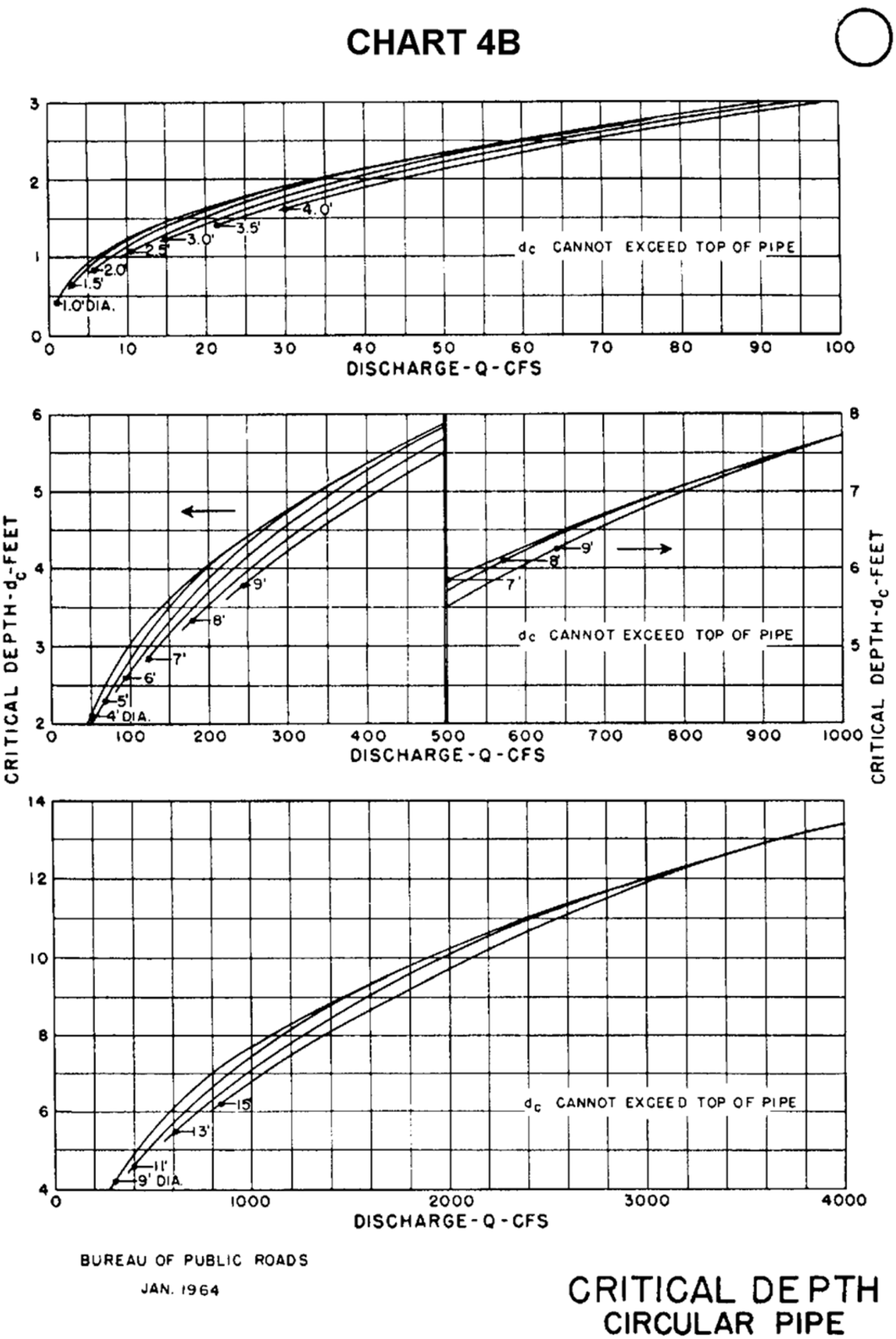


Figure 11-19. Critical Depth (Circular Pipe)

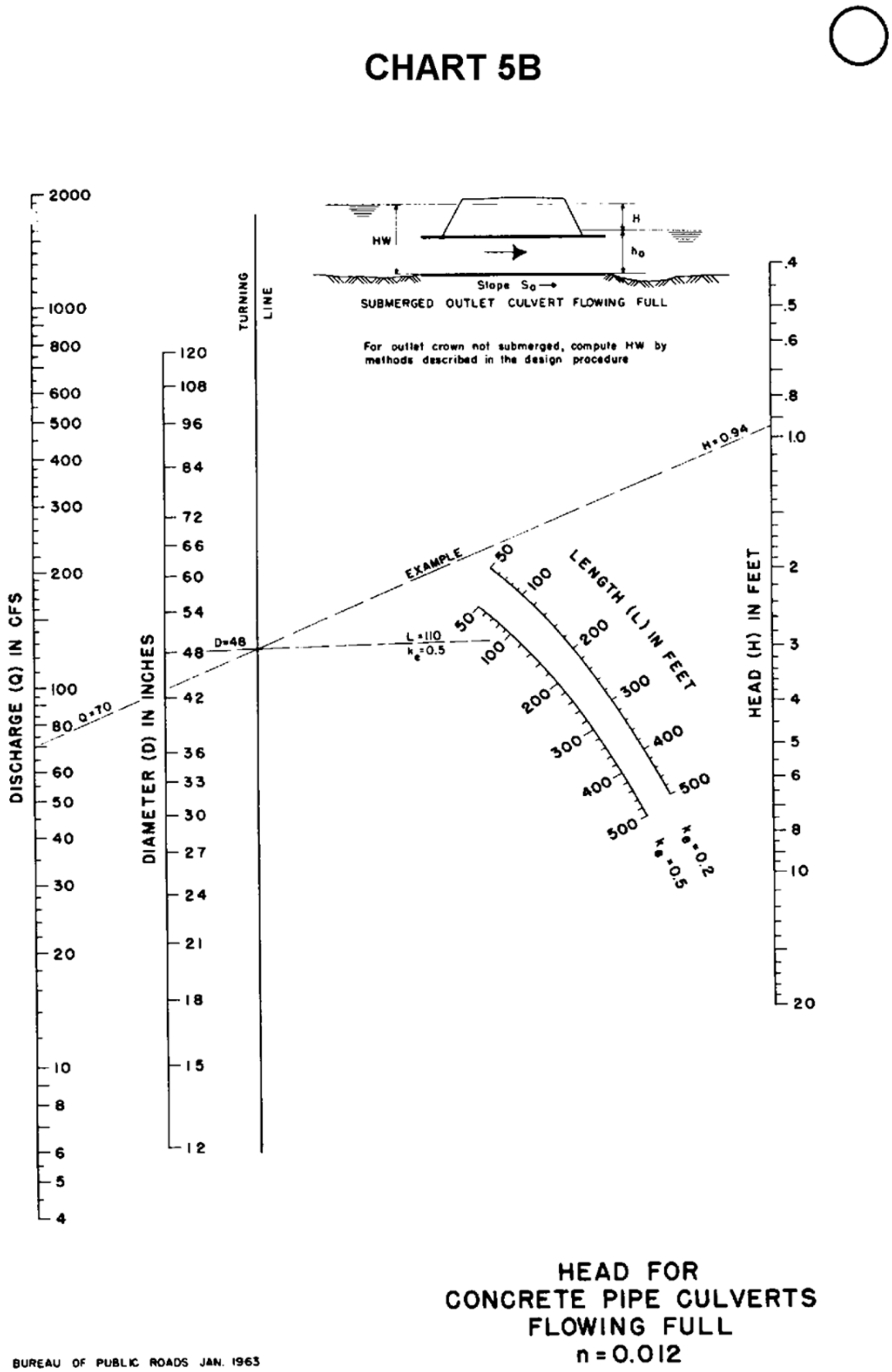


Figure 11-20. Head for Concrete Pipe Culverts Flowing Full (n = 0.012)

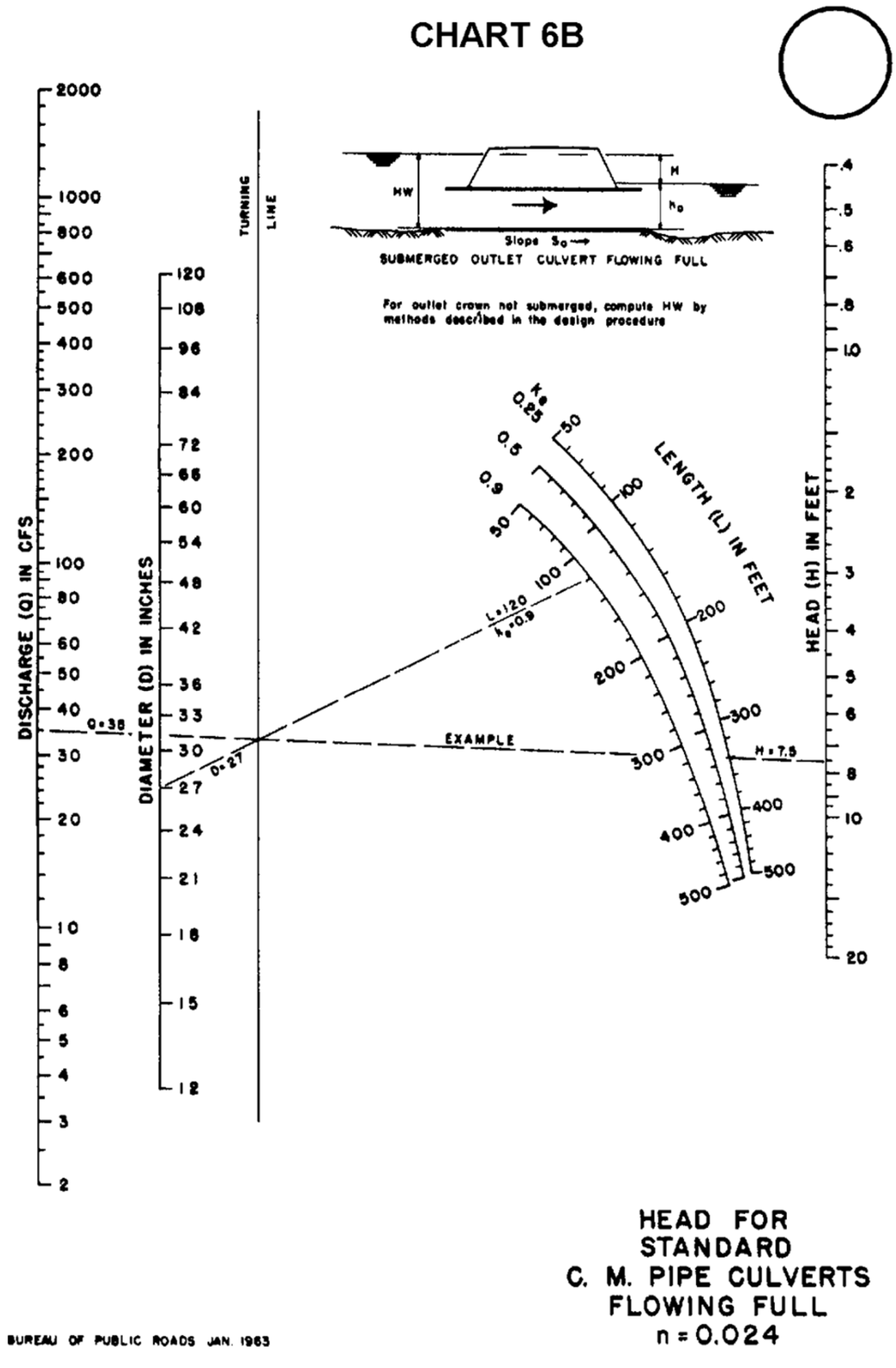


Figure 11-21. Head for Standard C. M. Pipe Culverts Flowing Full (n = 0.024)

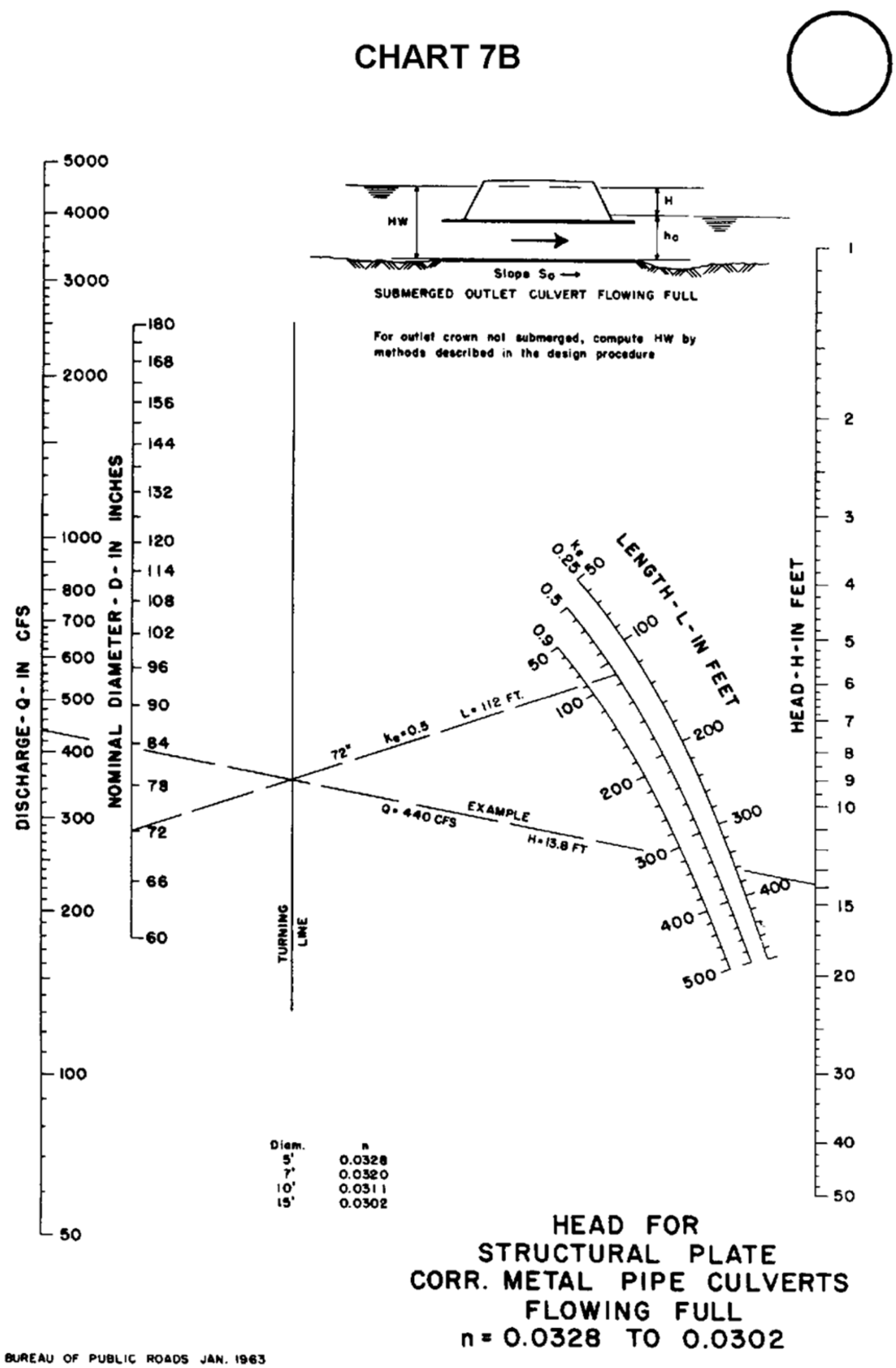


Figure 11-22. Head for Structural Plate Corrugated Metal Pipe Culverts Flowing Full (n = 0.0328 to 0.0302)

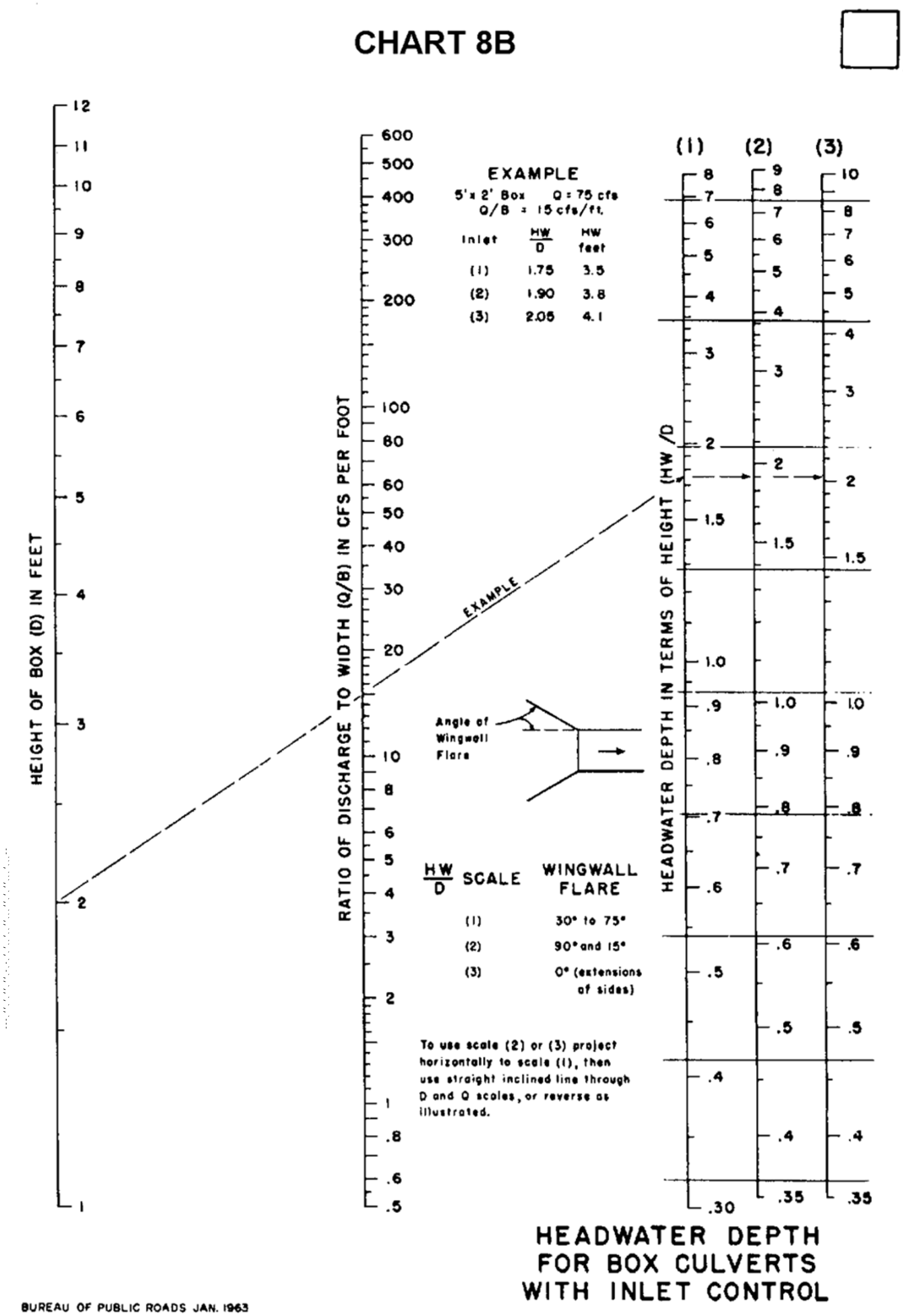


Figure 11-23. Headwater Depth for Box Culverts with Inlet Control

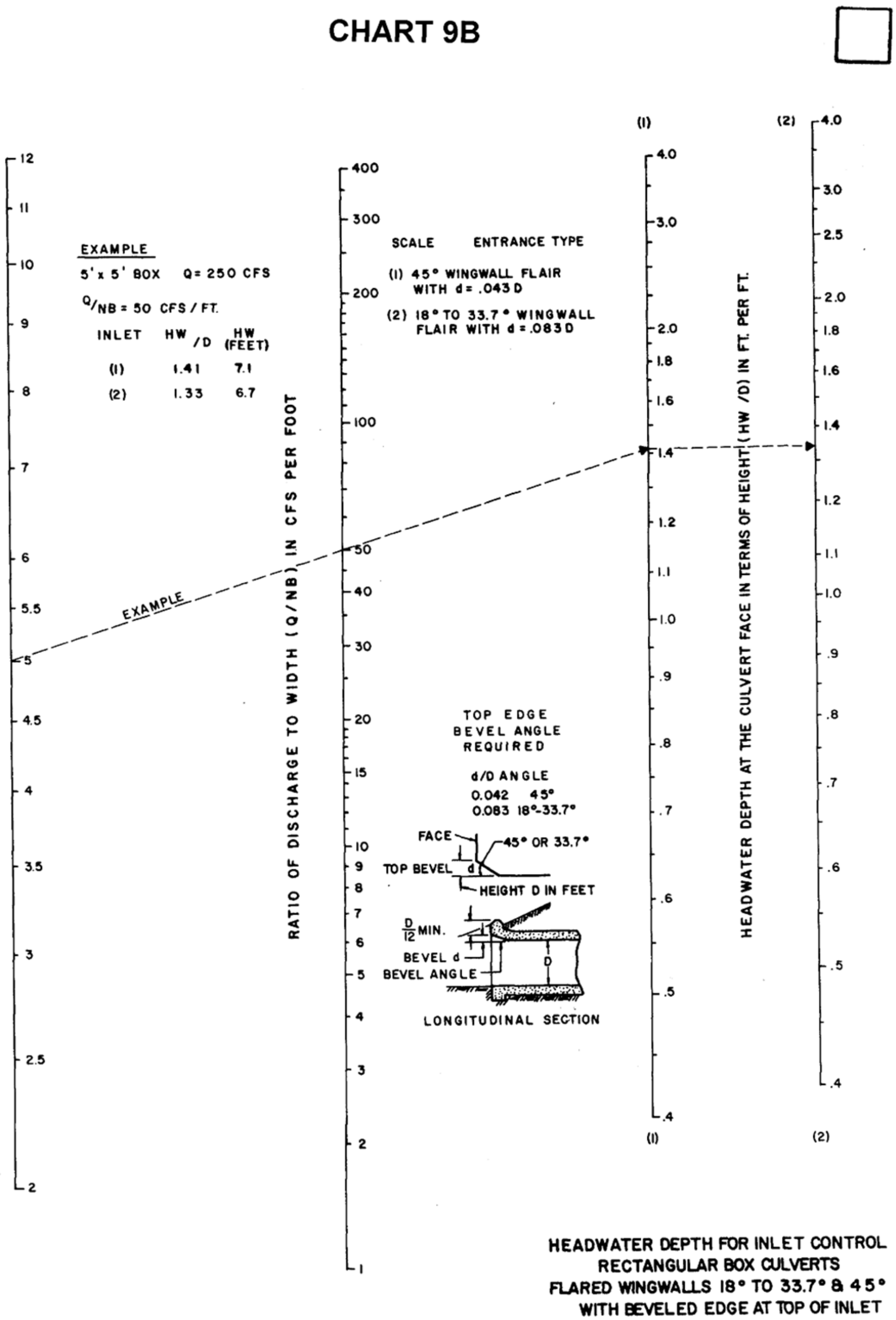


Figure 11-24. Headwater Depth for Inlet Control, Rectangular Box Culverts, Flared Wingwalls 18° to 33.7°, and 45° with Beveled Edge at Top of Inlet

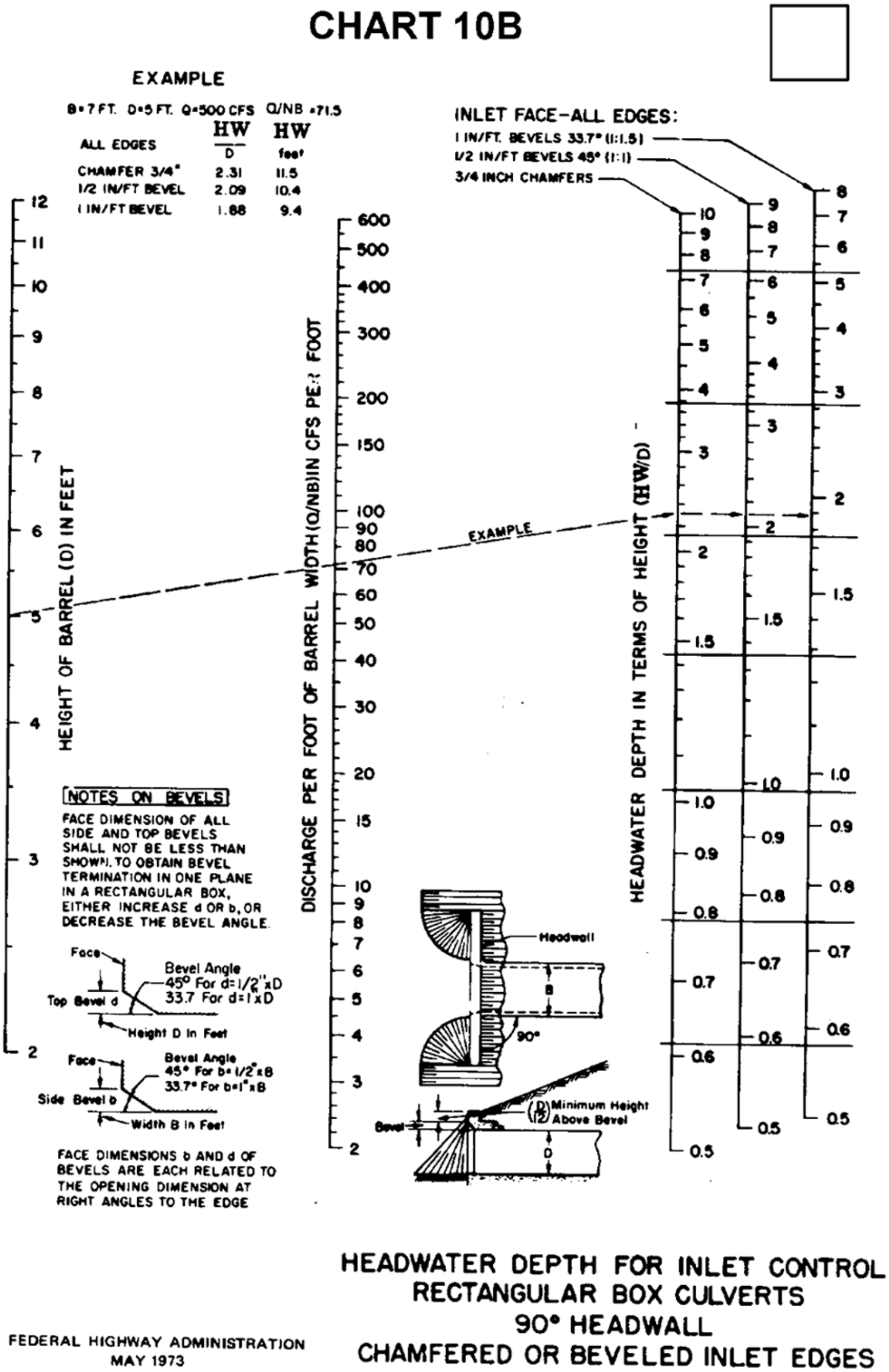


Figure 11-25. Headwater Depth for Inlet Control, Rectangular Box Culverts, 90° Headwall, Chamfered or Beveled Inlet Edges

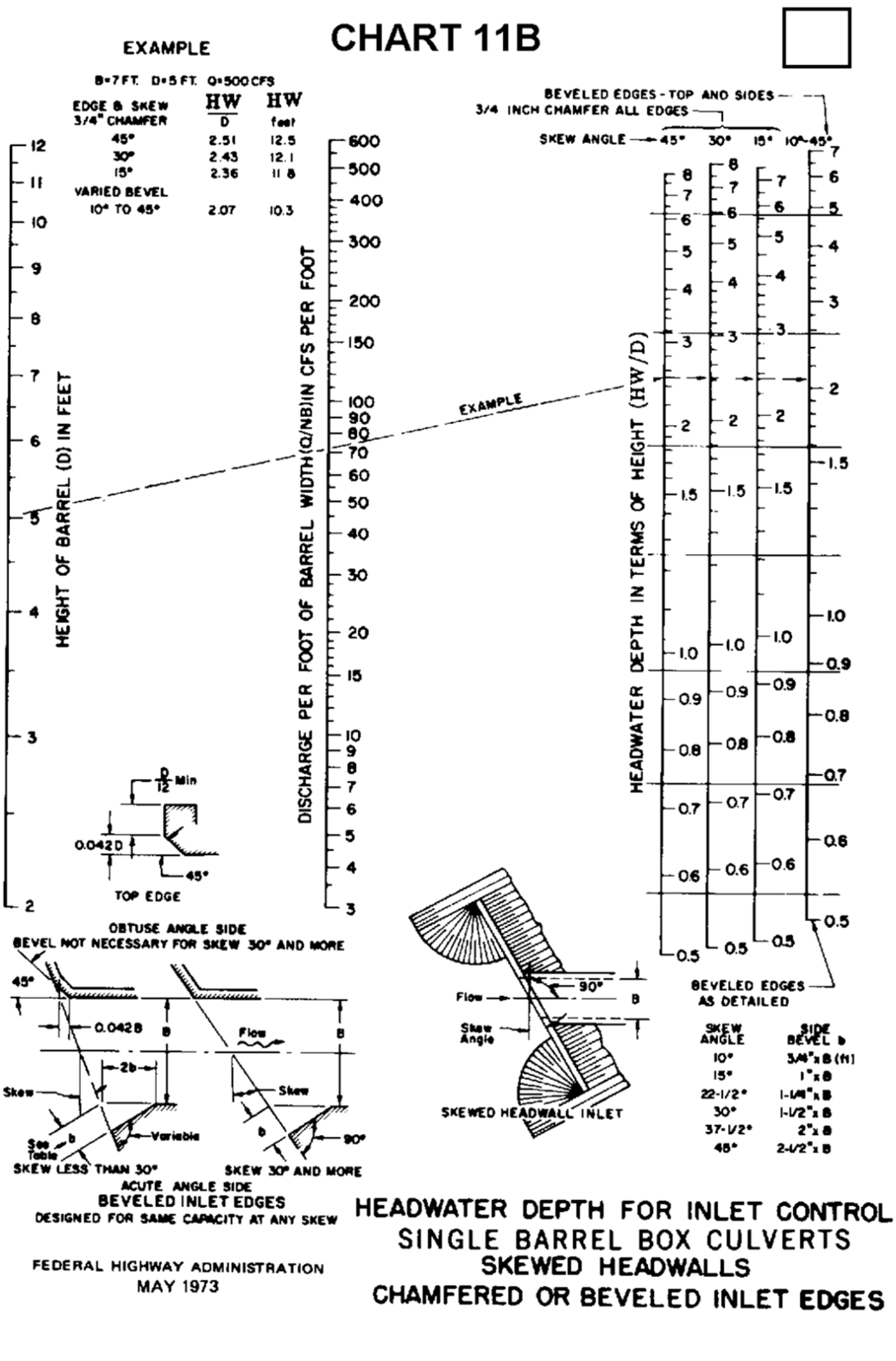


Figure 11-26. Headwater Depth for Inlet Control, Single Barrel Box Culverts, Skewed Headwalls, Chamfered or Beveled Inlet Edges

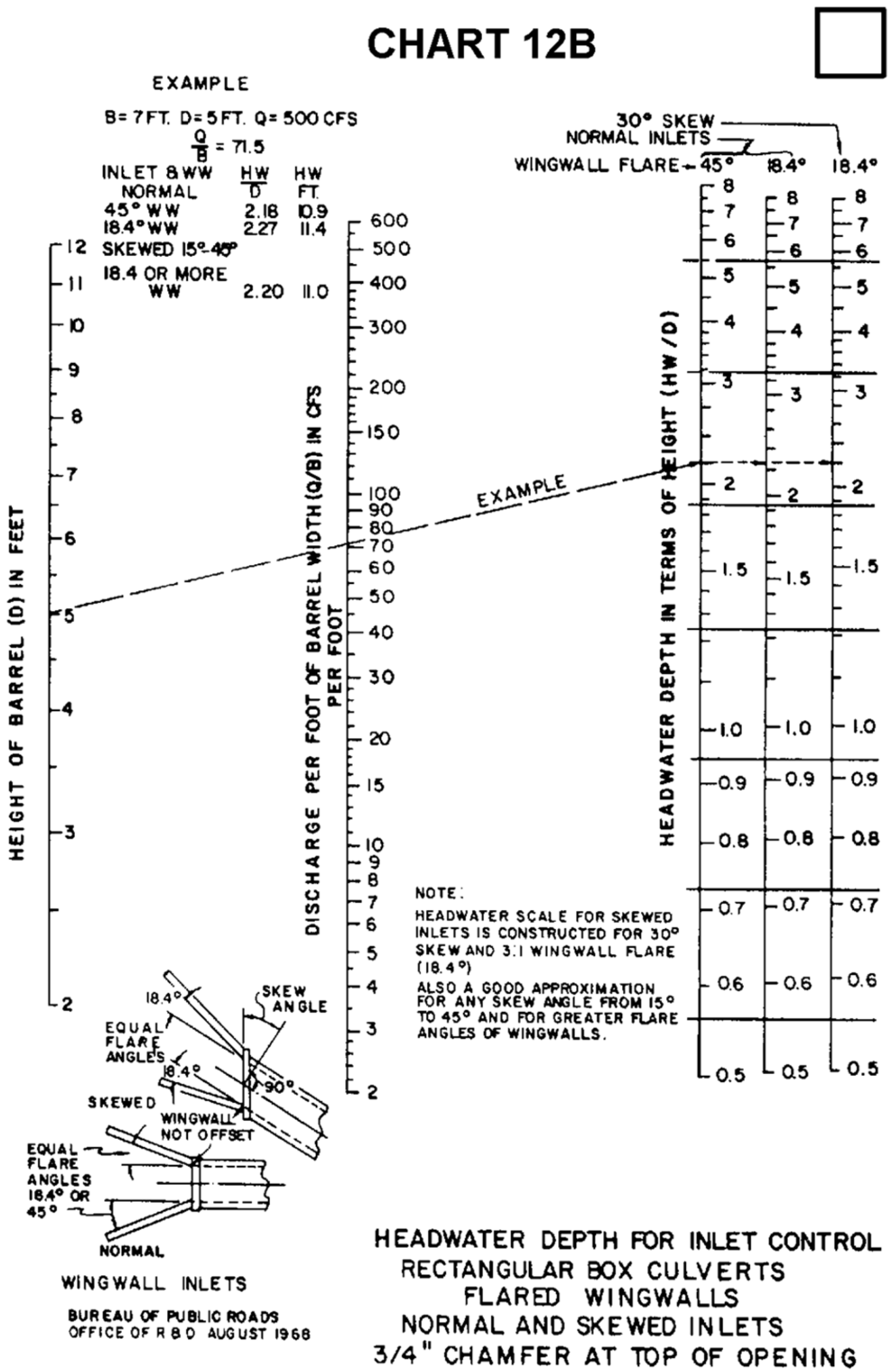


Figure 11-27. Headwater Depth for Inlet Control, Rectangular Box Culverts, Flared Wingwalls, Normal and Skewed Inlet Edges, ¾″ Chamfer at Top of Opening

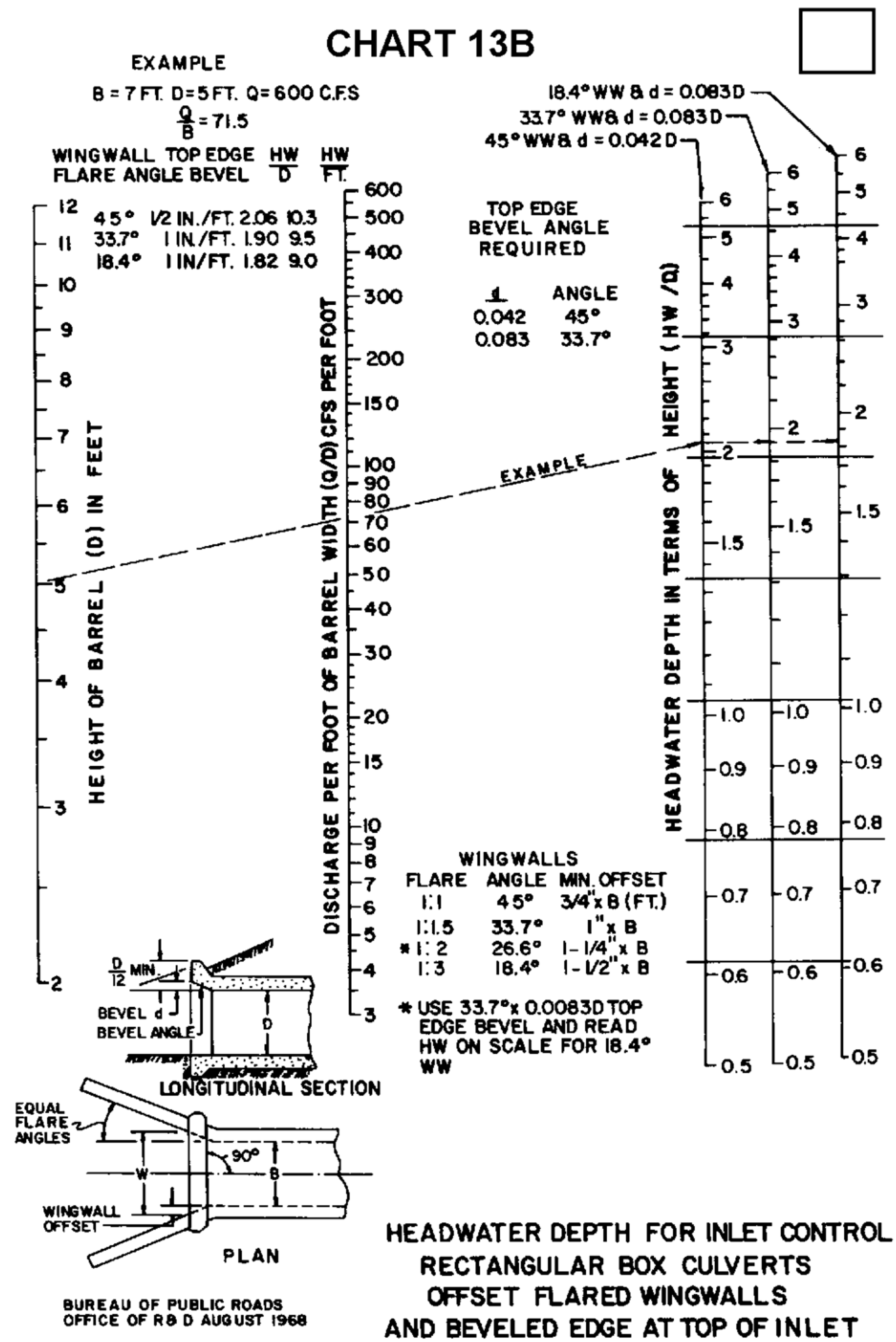


Figure 11-28. Headwater Depth for Inlet Control, Rectangular Box Culverts, Offset Flared Wingwalls, and Beveled Edge at Top of Inlet

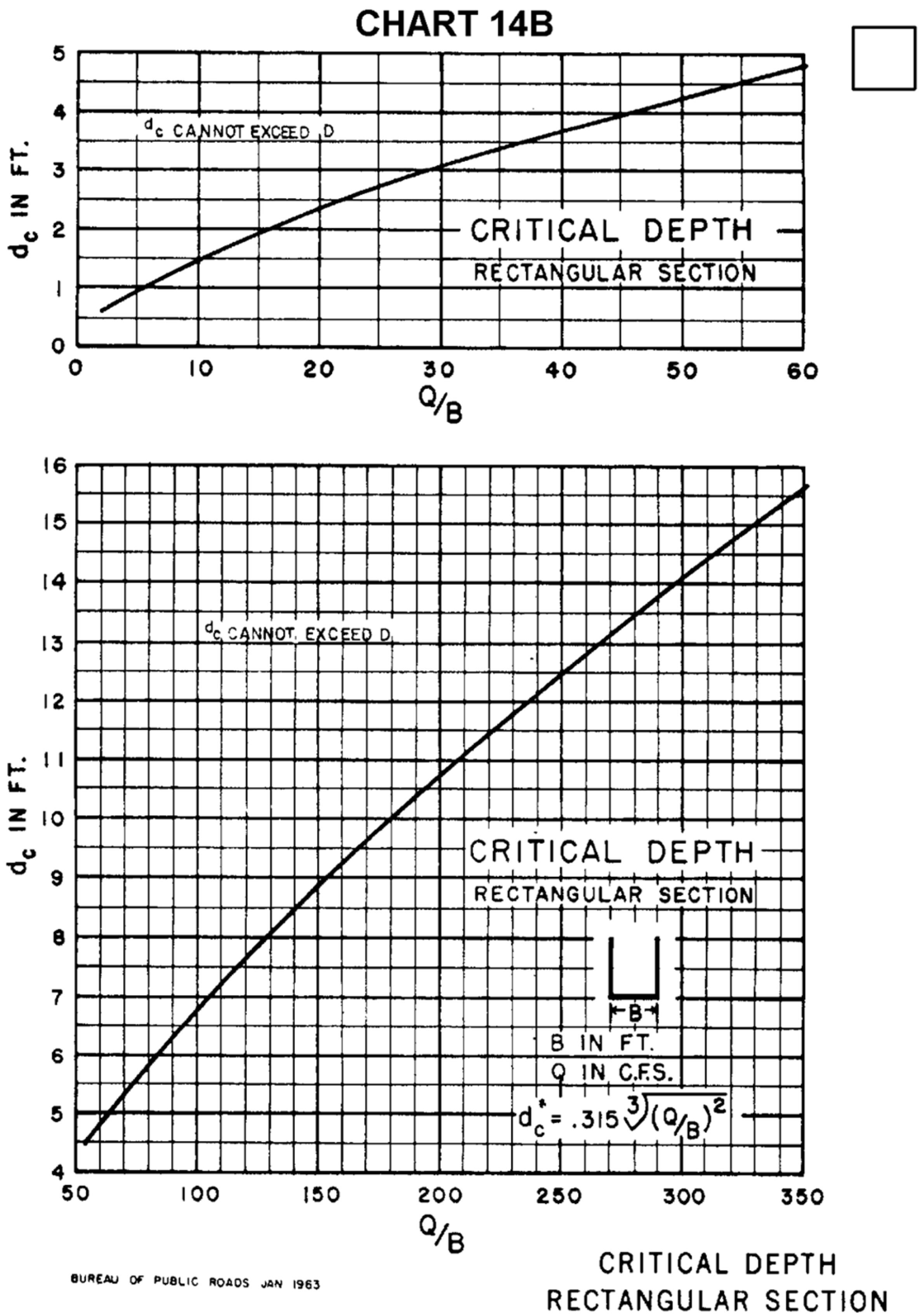


Figure 11-29. Critical Depth (Rectangular Section)

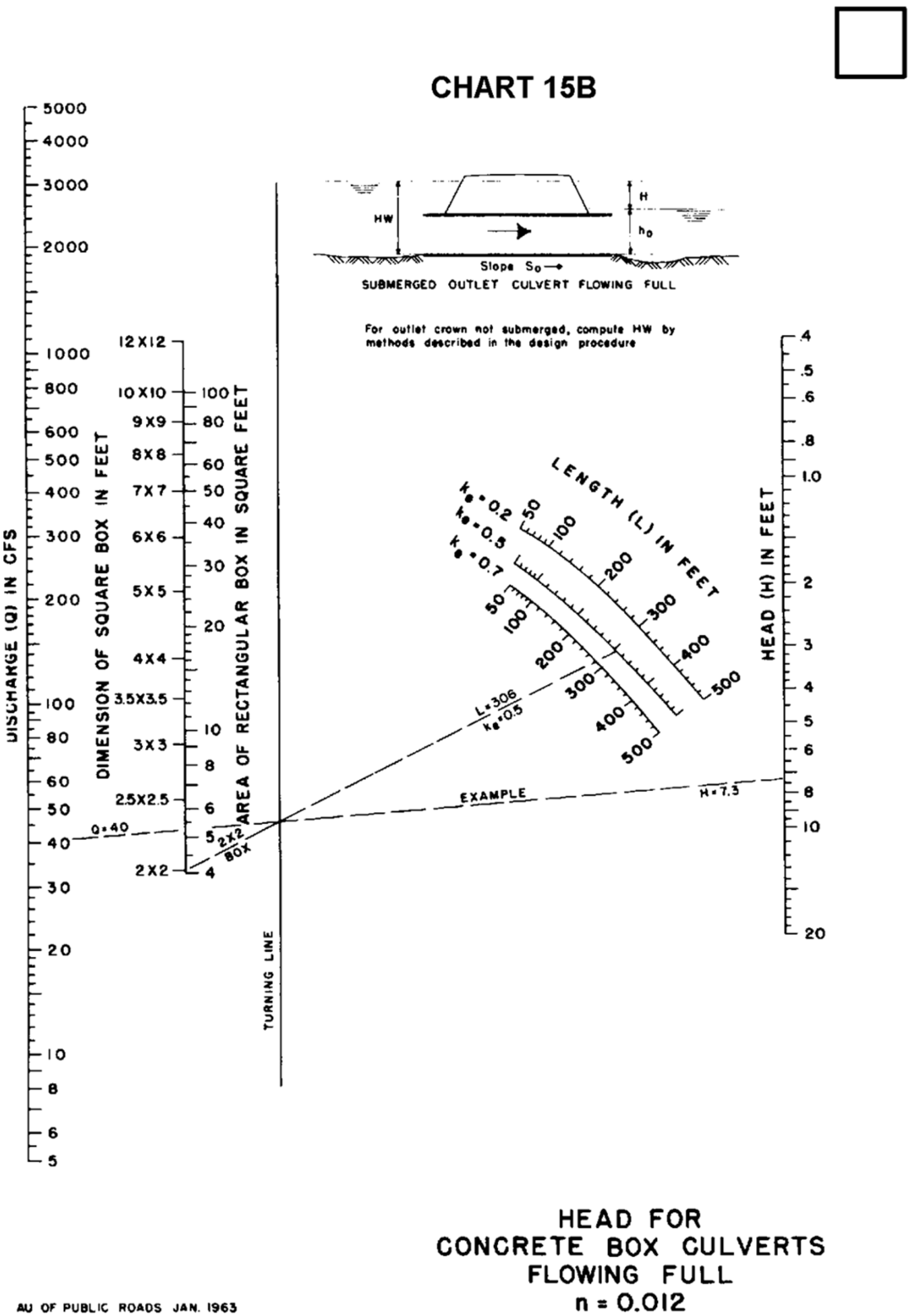
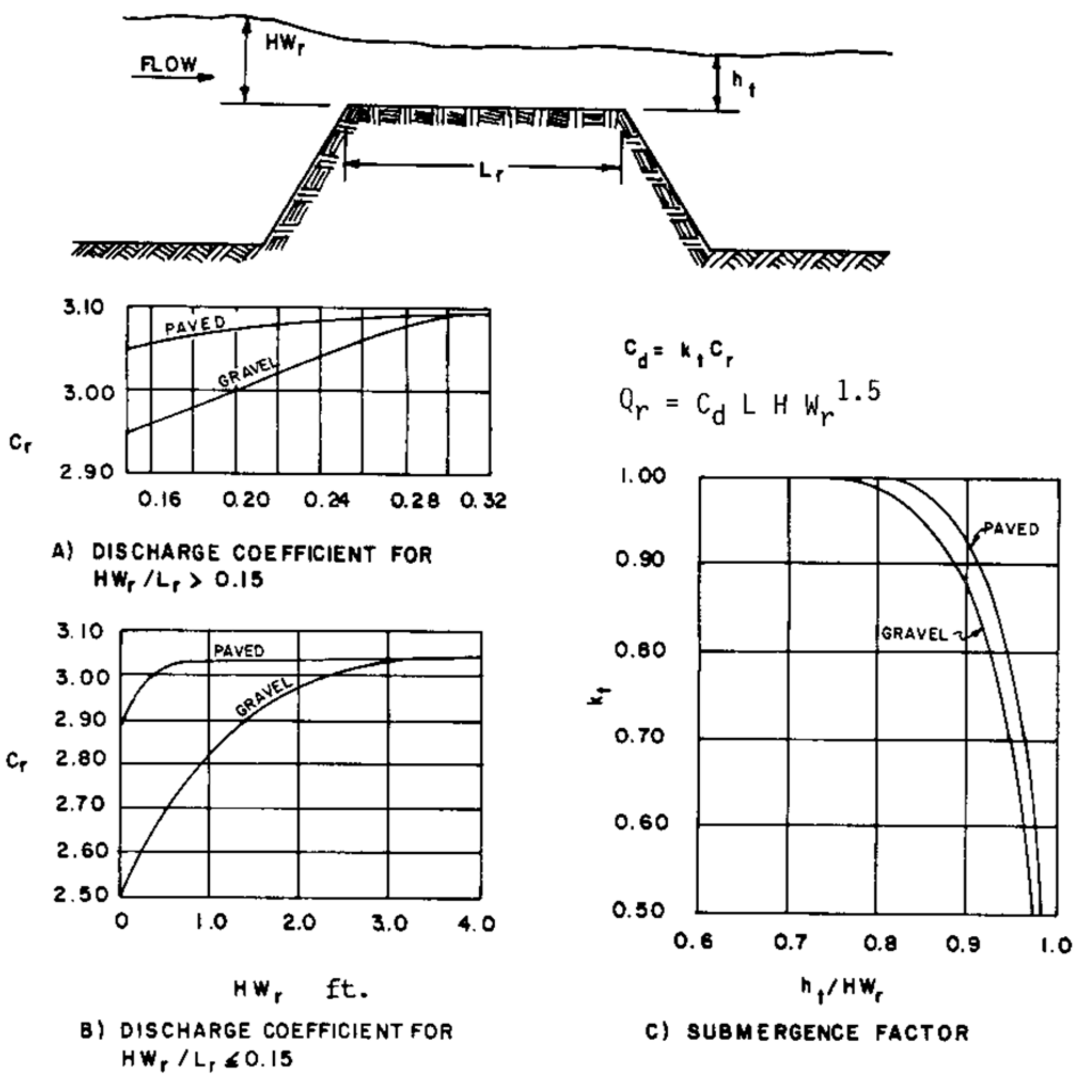


Figure 11-30. Head for Concrete Box Culverts Flowing Full (n = 0.012)

CHART 60B



English Discharge Coefficients for Roadway Overtopping

Figure 11-31. Discharge Coefficients for Roadway Overtopping

Figure 11-32. Culvert Design Form

PROJECT: ____________	STATION: ____________ SHEET ______ OF ______	CULVERT DESIGN FORM DESIGNER / DATE: ______ / ______ REVIEWER / DATE: ______ / ______

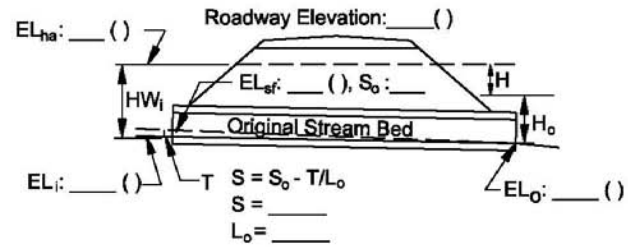
HYDROLOGICAL DATA

See Add'l Shts.

- ☐ METHOD: ____________
- ☐ DRAINAGE AREA: ________ ☐ STREAM SLOPE: ________
- ☐ CHANNEL SHAPE: ____________
- ☐ ROUTING: ________ ☐ OTHER: ________

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)



CULVERT DESCRIPTION: MATERIAL – SHAPE – SIZE – ENTRANCE	Total Flow Q (cfs)	Flow Per Barrel Q / N (1)	HEADWATER CALCULATIONS: INLET CONTROL HW/D (2)	HW_i	T (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c + D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	Control Headwater Elevation	Outlet Velocity	Comments

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) HW_i / D = HW / D OR HW_i / D FROM DESIGN CHARTS

(3) $T = HW_i - (EL_{hd} - EL_{sf})$
T IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL

(6) h_o = TW or $(d_c + D)/2$ (WHICHEVER IS GREATER)

(7) $H = [1 + k_e + (K_u n^2 L) / R^{1.33}] v^2 / 2g$ WHERE Ku = 19.63 (29 IN ENGLISH UNITS)

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

- a. APPROXIMATE
- f. CULVERT FACE
- ha. ALLOWABLE HEADWATER
- hi. HEADWATER IN INLET CONTROL
- ho. HEADWATER IN OUTLET CONTROL
- i. INLET CONTROL SECTION
- o. OUTLET
- sf. STREAMBED AT CULVERT FACE
- tw. TAILWATER

COMMENTS / DISCUSSION:

CULVERT BARREL SELECTED:

SIZE: ____________

SHAPE: ____________

MATERIAL: ________ n ________

ENTRANCE: ____________

Figure 11-33. Design Form for Side/Slope-Tapered Inlet

PROJECT: ____________	STATION: ____________	**TAPERED INLET DESIGN FORM**
	SHEET ______ OF ______	DESIGNER / DATE: ______ / ______
		REVIEWER / DATE: ______ / ______

DESIGN DATA:

Q ____ = ______ ( ); EL_{hi} __________ ( )

EL. THROAT INVERT __________ ( )

EL. STREAM BED AT FACE ________ ( )

T ______ TAPER ______ : 1 (4 : 1 TO 6 : 1)

STREAM SLOPE, S_o = ________ ( ) / ( )

SLOPE OF BARREL, S = ______ ( ) / ( )

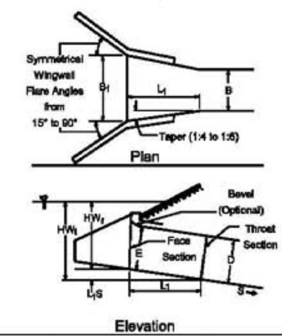
S_D ______ : 1 (2 : 1 TO 3 : 1)

BARREL SHAPE AND MATERIAL: ______________

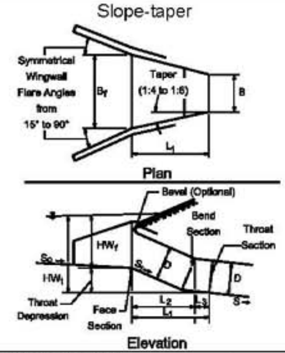
N = __________, B = ___________, D = _________

INLET EDGE DESCRIPTION ______________

Side-taper



Slope-taper



COMMENTS

									SLOPE-TAPERED ONLY						SIDE-TAPERED w/ depression		
Q ( )	EL_{hi} ( )	EL. Throat Invert	EL. Face Invert (1)	HW_f (2)	$\frac{HW_f}{E}$ (3)	$\frac{Q}{B_f}$ (4)	MIN. B_f (5)	Selected B_f	MIN. L_3 (6)	L_2 (7)	Check L_2 (8)	Adj. L_3 (9)	Adj. Taper (10)	L_1 (11)	EL. Crest Inv.	HW_c (12)	MIN. W (13)

(1) SIDE-TAPERED : EL. FACE INVERT = EL. THROAT INVERT + 1 FT (0.3 M APPROX.)
SLOPE-TAPERED : EL. FACE INVERT = EL. STREAM BED AT FACE

(2) $HW_f = EL_{hi}$ - EL. FACE INVERT

(3) 1.1 D ≥ E ≥ D; E = D FOR BOX CULVERTS

(4) FROM DESIGN CHARTS

(5) MIN. $B_f = Q / (Q / B_f)$

(6) MIN. L_3 = 0.5 NB

(7) L_2 = (EL. FACE INVERT- EL. THROAT INVERT) S_D

(8) CHECK $L_2 = \left[\frac{B_f - NB}{2}\right] \cdot \text{TAPER} - L_3$

(9) If (8)>(7), ADJ. $L_3 = \left[\frac{B_f - NB}{2}\right]$. TAPER - L_2

(10) If (7) >(8), ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2}\right]$

(11) SIDE-TAPERED : $L = \left[\frac{B_f - NB}{2}\right] \cdot \text{TAPER}$
SLOPE-TAPERED : $L_1 = L_2 + L_3$

(12) $HW_c = EL_{hi}$ - EL. CREST INVERT

(13) MIN. $W = K_u\, Q / HW_c^{1.5}$ Where K_u = 0.35 (0.64 SI)

SELECTED DESIGN

B_f ____________

L_1 ____________

L_2 ____________

L_3 ____________

BEVELS ANGLE ________

b = _____ ( ); d = _________ ( )

TAPER _________ : 1

S_D = _________ : 1

11.11 REFERENCES

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