



CHAPTER 5 CULVERT HYDRAULICS



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Synopsis

Guidelines for selecting values of design variables such as the storm return period, headwater, tailwater, length, slope, velocity limitations, and construction material are briefly discussed. Nomographs are presented for performing culvert capacity calculations. The primary reference for information presented in this chapter is HDS-5 (USDOT, FHWA, 1985). Terminology is discussed in Volume 3.

5.1 Culvert Selection

The following factors should be considered when selecting a culvert:

1. Application
2. Shape and material
3. Size
4. End treatment
5. Control section

5.1.1 Application

For purposes of consistency, culvert applications are divided into two major categories: cross drains and side drains.

Cross Drain

A cross drain is a culvert placed transversely under roadway sections, with endwalls or some end treatment. Because cross drain installations are normally under pavement, they should have soiltight joints as a minimum to prevent soil migration. Leaking joints can cause uneven and differential settling of road surfaces or adjacent buildings.

Side Drain

This culvert is generally a pipe used longitudinally in roadway ditches under driveways or graded connections. Alignment joints rather than soiltight joints are generally adequate for side drains.



5.1.2 *Shape and Material*

Overall costs are a major factor in the selection of a culvert shape and material; other important factors are hydraulic capacity, load carrying capacity, allowable headwater, grade controls, and aesthetic considerations.

The two materials for culverts allowed within Right of Ways (or culverts that carry public water) are concrete and corrugated metal. Concrete pipe has a lower roughness coefficient (Manning's n value), although corrugated metal with a lining is comparable. To provide lower flow resistance, a lining should be expected to last for the service life of the culvert. Corrugated metal pipe (CMP) systems should be Aluminized Steel - Type 2, unless they are open-bottom culverts. All reinforced concrete pipes (RCP) with inverts less than 18 feet shall be Class III. Culverts are to be designed with upstream and downstream headwalls.

When the vertical distance from invert to roadway is limited, arch or elliptical culverts may be appropriate. When the rise of a culvert exceeds 4 feet, box culverts will generally offer cost advantages. Multiple pipe culverts are discouraged by MWS when other alternatives are available.

5.1.3 *Size*

Culverts should be sized using the nomographs presented in this chapter. Size reductions may be warranted after an evaluation of the effects of ponding and temporary storage. The minimum culvert pipe size shall be 15 inches.

5.1.4 *End Treatment*

The selection of end treatment facilities must be consistent with hydraulic requirements and give proper consideration to bank stability, safety, and costs. Entrance loss coefficients (k_e) for the standard inlet configurations are summarized in Table 5-1.

5.1.5 *Control Section*

The two basic types of culvert control sections are inlet and outlet control. The control section for inlet control is just inside the entrance. Critical depth occurs at or near this location and flow in the culvert is supercritical. The control section for outlet control is located at the barrel exit or downstream from the culvert. Either partially full subcritical flow or full pipe pressure flow conditions can occur. (See Volume 3 for additional information on culvert fundamentals.)

If inlet control exists, the culvert barrel is capable of carrying more flow than the inlet will accept, and a tapered inlet (see Section 5.3.4) can be used to increase capacity up to the outlet capacity. If outlet control exists, the culvert barrel would have to be increased to add capacity.



5.2 Design Criteria

The following parameters should be considered when culvert hydraulic calculations are performed:

1. Return period
2. Headwater
3. Tailwater
4. Length and slope
5. Velocity limitations

5.2.1 Return Period

The appropriate design storm return periods (from Section 6.5 of Volume 1) are summarized below:

Major facilities, including residential collector and commercial crossings	100 years
Minor facilities, including residential roads and crossings	10 years

In addition to the standard design flood, the culvert capacity should be checked for the base flood (Q_{100}), to ensure that access is consistent with the roadway classification. If ponding occurs at the entrance of the culvert, a reduction in the discharge may be appropriate. A reservoir routing procedure can be used to determine the discharge reduction attributable to storage.

5.2.2 Headwater

The allowable headwater elevation is determined from an evaluation of land use upstream of the culvert and the proposed or existing roadway elevation. The following criteria should be considered:

1. Non-damaging or permissible upstream flooding elevations (e.g., existing buildings or Flood Insurance Rate Map elevations) should be identified and headwater kept below them.
2. Headwater depth for the design discharge should not exceed a height greater than 1.5 feet below the edge of the shoulder of a road. In general, the maximum allowable headwater above the crown of a culvert should not exceed 5 feet.
3. Headwater depth for the design discharge should not cause water to rise above the top of approach channels adjacent to improved land or above the established flood plain easements.



4. Level pool backwater conditions should be evaluated upstream from the culvert to ensure that flooding of buildings does not occur for the 100-year, 24-hour design storm (see Section 6.5, Volume 1).

In general, the constraint that gives the lowest allowable headwater elevation should establish the basis for hydraulic calculations.

5.2.3 *Tailwater*

The hydraulic conditions downstream of the culvert site must be evaluated to determine a tailwater depth for the design discharge. If the culvert outlet is operating in a free fall condition (e.g., a cantilever pipe), the critical depth and equivalent hydraulic grade line should be determined using procedures from this chapter. For culverts that discharge to an open channel, the normal depth of flow in the channel must be evaluated using procedures presented in Chapter 3.

If an upstream culvert outlet is located near a downstream culvert inlet, the headwater elevation of the downstream culvert may establish the design tailwater depth for the upstream culvert. If the culvert discharges to a lake, pond, or other major waterbody, the expected high water elevation of the particular waterbody may establish the culvert tailwater.

5.2.4 *Length and Slope*

The length and slope of a culvert should be based on the channel bottom of the stream waterbody being conveyed, the geometry of the roadway embankment, and the skew angle of the culvert. In general, the culvert slope should be chosen to approximate existing topography.

5.2.5 *Velocity Limitations*

Both minimum and maximum velocities should be considered when designing a culvert. A minimum velocity of 2.5 feet per second when the culvert is flowing full is recommended to ensure a self-cleaning condition during partial depth flow. When velocities below this minimum are anticipated, the installation of a sediment trap upstream of the culvert should be considered.

The maximum velocity should be consistent with channel stability requirements at the culvert outlet. As outlet velocities increase, the need for channel stabilization at the culvert outlet increases. If velocities exceed permissible velocities for the outlet lining material (see Chapter 3), the installation of outlet protection may be appropriate. Channel stability information is presented in Chapter 3 and outlet protection is covered in Chapter 10.



5.3 Design Calculations

A flow chart for performing culvert design calculations is provided in Figure 5-1 (see discussion in Section 5.3.1). Worksheets for performing calculations are provided in Figures 5-2, 5-3, and 5-4 for standard culvert design, tapered inlet design, and mitered inlet design, respectively. Seven inlet control, seven outlet control, and six critical depth charts from HDS-5 (USDOT, FHWA, 1985) are provided in this chapter for performing culvert capacity calculations. The following culvert capacity charts are provided:

<u>Culvert Type</u>	<u>Inlet Control Fig. No.</u>	<u>Outlet Control Fig. No.</u>
Concrete Pipe	5-5	5-6
Corrugated Metal Pipe (CMP)	5-7	5-8
Structural Plate CMP	5-7	5-9
Concrete Box	5-10	5-11
Oval Concrete Pipe—Long Axis Horizontal	5-12	5-14
Oval Concrete Pipe—Long Axis Vertical	5-13	5-14
CMP Arch	5-15	5-16
Structural Plate CMP (18-inch Corner Radius)	5-15	5-17
Circular Pipe With Beveled Ring	5-18	5-6 or 5-8

Additional charts for corrugated metal box, arch, and long span culverts are available from HDS-5 (USDOT, FHWA, 1985).

5.3.1 General Procedure

The following general procedure, as represented schematically by the flow chart in Figure 5-1, is recommended to select a culvert size with the charts from HDS-5 (USDOT, FHWA, 1985):

1. Perform hydrologic calculations (see Chapter 2).
2. List the following design data (see suggested tabulation form, Figure 5-2):
 - a. Design discharge, Q , in cfs, with average return period (e.g., Q_{10}). When more than one barrel is used, show Q divided by the number of barrels. Note that MWS discourages the use of multiple barrel culverts when other alternatives are available.
 - b. Approximate length, L , of culvert, in feet.
 - c. Slope of culvert (if grade is given in percent, convert to slope in feet/foot).



- d. Allowable headwater depth, AHW, in feet; i.e., the vertical distance from the culvert invert (flow line) at the entrance to the water surface elevation permissible in the headwater pool or approach channel upstream from the culvert.
 - e. Mean and maximum flood velocities in natural stream (optional), in feet/second.
 - f. Type of culvert, including barrel material, barrel cross-sectional shape, and inlet configuration.
3. Determine a trial culvert size by choosing one of the following options:
- a. Arbitrary selection
 - b. An approximating equation such as:

$$A = \frac{Q}{v} \quad (5-1)$$

where:

A = Culvert area, in square feet

Q = Design discharge, in cfs

v = Average velocity, in feet/second

- c. Inlet control nomographs for the culvert type selected (see Section 5.3.2). A trial size is determined by assuming HW_i/D (e.g., $HW_i/D = 1.5$) and using the given Q.

If the trial size selected is larger than available standard culvert sizes or its use is prohibited by other physical limitations (such as limited embankment height), multiple culverts may be used by dividing the discharge equally between the number of barrels. It is also possible to consider raising the embankment height or using pipe arch and box culverts with width greater than twice the height.

4. Find inlet and outlet control headwater, HW, depths for the trial culvert size as follows:
- a. For inlet control, perform the following calculations:
 - (1) Use an appropriate inlet control chart as discussed in Section 5.3.2 and the trial size from Step 3, to find HW_i . Tailwater, TW, conditions are



neglected in this determination. HW_i is found by multiplying HW_i/D , obtained from the nomographs, by the height of culvert D .

- (2) If HW_i is greater or less than allowable (see Section 5.2.2 for design criteria), try another trial size until HW_i is acceptable for inlet control, before computing HW_o , for outlet control.
- (3) The headwater elevation for inlet control conditions is calculated as follows:

$$EL_{hi} = HW_i + EL_i \quad (5-2)$$

where:

EL_{hi} = Headwater elevation for inlet control, in feet

HW_i = Headwater depth, for inlet control, in feet

EL_i = Elevation of the culvert entrance, in feet

b. For outlet control, perform the following calculations:

- (1) Calculate H , the head loss across the culvert, using the proper outlet control nomograph from Figures 5-6 to 5-17 and procedures discussed in Section 5.3.3.
- (2) Approximate the depth of TW , in feet, above the invert at the outlet for the design flood condition in the outlet channel (see Section 5.2.3).
- (3) If the TW depth determined in Step (2) is equal to or greater than the top of the culvert at the outlet, set design tailwater, h_o , equal to TW and find the headwater depth for outlet control, HW_o , using the following equation:

$$HW_o = H + h_o - LS_o \quad (5-3)$$

where:

HW_o = Headwater depth for outlet control, in feet

H = Total head loss for outlet control from Step (1) above, in feet

h_o = Design tailwater, in feet



L = Barrel length, in feet

S_o = Barrel slope, in feet/foot

- (4) If the TW depth determined in Step (2) is less than the top of the culvert at the outlet, find the headwater depth for outlet control, HW_o, using Equation 5-3, except that h_o is the greater of the following two parameters:

$$d_e = \frac{d_c + D}{2} \quad (5-4)$$

or

TW

where:

d_e = Equivalent hydraulic depth at outlet, in feet

d_c = Critical depth, in feet (from Figures 5-19 through 5-24). Note: d_c cannot exceed D.

D = Height of culvert opening, in feet

TW = Downstream tailwater depth, in feet

Critical depth charts from HDS-5 (USDOT, FHWA, 1985) are presented in Figures 5-19 through 5-24 for the following culvert types;

<u>Culvert Type</u>	<u>Critical Depth Fig. No.</u>
Rectangular	5-19
Circular	5-20
Oval—Long Axis Vertical	5-21
Oval—Long Axis Horizontal	5-22
Standard CMP Arch	5-23
Structural Plate CMP Arch	5-24

Note: Headwater depth determined for this condition becomes increasingly less accurate as the headwater computed by this method falls below the value:



$$HW_o \leq D + (1 + k_e) \frac{v^2}{2g} \quad (5-5)$$

where:

HW_o = Headwater depth for outlet control, in feet

D = Height of culvert opening, in feet

k_e = Entrance loss coefficient

v = Average velocity of flow, in feet/second

g = Acceleration due to gravity, 32.2 feet/second²

- (5) The headwater elevation for outlet control is calculated as follows:

$$EL_{ho} = EL_o + H + h_o \quad (5-6)$$

where:

EL_{ho} = Headwater elevation for outlet control, in feet

EL_o = Elevation of the culvert outlet, in feet

H = Total head loss for outlet control (see Step (1) above), in feet

h_o = Design tailwater, in feet

5. Compare the headwater values found in Step 4a (inlet control) and Step 4b (outlet control). The higher headwater governs and indicates the type of flow control under the given conditions for the trial size and inlet configuration selected.
6. If outlet control governs and the HW_o is higher than the acceptable AHW, select a larger trial size and find HW_o as instructed under Step 4b. (Inlet control does not need to be checked, since the smaller size should be satisfactory for this control as determined under Step 4a.).
7. If desired, select an alternate culvert type or shape and determine size by repeating the above steps.



8. If the culvert operates under inlet control, a tapered inlet can be designed following the procedure in Section 5.3.4.
9. If roadway overtopping occurs, capacity calculations can be performed following the procedure in Section 5.3.5.
10. If storage routing is considered important, procedures in Chapter 8 should be followed.
11. Compute outlet velocities for the culvert size and types to be considered in selection:
 - a. If outlet control governs in Step 5, calculate the outlet velocity using Equation 5-1. The depth of flow at the outlet section is selected using the following criteria:

$$TW \leq d_c, d_o = d_c$$

$$D > TW > d_c, d_o = TW$$

$$TW > D, d_o = D$$

where:

TW = Tailwater depth, in feet (see Section 5.3.3)

d_c = Critical depth (see Figures 5-19 through 5-24), in feet

d_o = Depth at outlet, in feet

D = Culvert height, in feet

- b. If inlet control governs in Step 5, the depth of flow at the outlet section is assumed to be equal to the normal depth, d_n , which should be calculated using Manning's Equation (see Chapter 3).
12. Determine whether channel protection should be considered (see Chapter 3).
13. Record final selection of culvert with size, type, required headwater, outlet velocity, channel protection, and economic justification.

5.3.2 Inlet Control

Inlet control charts from HDS-5 (USDOT, FHWA, 1985) are presented in the following figures:



<u>Culvert Type</u>	<u>Inlet Control Figure No.</u>
Circular Concrete Pipe	5-5
Circular CMP	5-7
Concrete Box	5-10
Oval Concrete Pipe—Long Axis Horizontal	5-12
Oval Concrete Pipe—Long Axis Vertical	5-13
CMP Arch	5-15
Circular Pipe with Beveled Ring	5-18

The following three types of inlet calculations can be performed using these figures:

1. To determine the headwater, HW , given Q and size for selected culvert type and inlet configuration:
 - a. Use a straightedge to connect the culvert diameter or height, D , scale and the discharge, Q , scale, or Q/B for box culverts. Note the point of intersection of the straightedge on the HW_i/D scale marked (1).
 - b. If the HW_i/D scale marked (1) represents the inlet configuration used, read HW_i/D on this scale. When either of the other two inlet configurations listed on the nomograph is used, extend the point of intersection obtained in Step 1b horizontally to scale (2) or (3) and read HW_i/D .
 - c. Compute HW_i by multiplying HW_i/D by D .

Note: Approach velocity is assumed to be zero by this procedure. If the approach velocity is considered significant, HW_i can be decreased by subtracting the velocity head.
2. To determine Q per barrel, given HW_i and size for selected culvert type and inlet configuration:
 - a. Compute HW_i/D or given conditions.
 - b. Locate HW_i/D on scale for appropriate inlet configuration. If scale (2) or (3) is used, extend the HW_i/D point horizontally to scale (1).
 - c. Use a straightedge to connect the point on HW_i/D scale (1) obtained above with the culvert size on the far left scale. Read Q or Q/B at the intersection of this line with the middle discharge scale.



- d. If Q/B is read in Step 2c, multiply by B (span of box culvert) to find Q .
- 3. To determine culvert size, given Q , AHW , and type of culvert with desired inlet configuration:
 - a. Using a trial size, compute HW_i/D .
 - b. Locate HW_i/D on the scale for the appropriate inlet configuration. If scale (2) or (3) is used, extend the HW_i/D point horizontally to scale (1).
 - c. Use a straightedge to connect the point on HW_i/D scale (1) obtained above with the given discharge on the middle scale. Read diameter, height, or size of culvert required at the intersection of this line with the culvert size scale on the far left.
 - d. If D is not as originally assumed, repeat procedure with a new D .

5.3.3 *Outlet Control*

Outlet control charts from HDS-5 (USDOT, FHWA, 1985) are presented in the following figures:

<u>Culvert Type</u>	<u>Outlet Control Figure No.</u>
Circular Concrete Pipe	5-6
Circular CMP	5-8
Structural Plate CMP	5-9
Concrete Box	5-11
Oval Concrete Pipe—Long Axis Horizontal or Vertical	5-14
CMP Arch	5-16
Structural Plate CMP Arch with 18-inch Corner Radius	5-17

The following steps outline the use of these figures:

- 1. To determine H for a given culvert and Q :
 - a. Locate the appropriate nomograph for the type of culvert selected. Find k_e for the inlet configuration using data from Table 5-1.
 - b. Begin nomograph solution by locating the proper starting point on the length scale:
 - (1) If the n value of the nomograph corresponds to that of the culvert being used, select the proper length curve for an assigned k_e value and locate the starting point at the given culvert length. If a curve is not shown for the



selected k_e , see (2) below. If the n value for the culvert selected differs from that of the nomograph chart, see (3) below.

- (2) For the n value of the nomograph and a k_e intermediate between the scales given, connect the given length on adjacent scales by a straight line and select a point on this line spaced between the two scales in proportion to the k_e value.
- (3) For a different roughness coefficient, n_1 , than that of the chart n , use the length scales shown with an adjusted length, L_1 , calculated as:

$$L_1 = L \left(\frac{n_1}{n} \right)^2 \quad (5-7)$$

(See Step 2 for n values)

- c. Use a straightedge to connect the point on the length scale to the size of the culvert barrel and mark the point of crossing on the turning line. See Step 3 for size considerations for a rectangular box culvert.
- d. Pivot the straightedge on this point on the turning line and connect with the given discharge rate. For multiple barrels, divide Q by the number of barrels before using the nomograph. Note that MWS discourages the use of multiple barrel culverts when other alternatives are available. Read head in feet on the H scale located on the far right. For values beyond the limit of the printed scales, find H by solving the equation:

$$H = \left[1 + k_e + \frac{29n^2L}{R^{1.33}} \right] \frac{v^2}{2g} \quad (5-8)$$

where:

H = Total head loss, or the elevation difference between HW_o and h_o , in feet

HW_o = Headwater depth for outlet control, in feet

h_o = Design tailwater, in feet (see Section 5.3.1, Step 4)

k_e = Entrance loss coefficient (see Table 5-1)

n = Manning's roughness coefficient



L = Barrel length, in feet

R = Hydraulic radius of the culvert, in feet

v = Average velocity of flow, in feet/second

g = Acceleration due to gravity, 32.2 feet/second²

2. Values of n , which are the basis for the nomographs from HDS-5 (USDOT, FHWA, 1985), are presented on each nomograph.
3. To use the box culvert nomograph (Figure 5-11) for full flow for other than the configurations shown:
 - a. Compute cross-sectional area of the rectangular box.
 - b. Use a straightedge to connect the proper point (see Step 1) on the length scale to the barrel area and mark the point on the turning line. Note that the area scale on the nomograph is calculated for barrel cross sections with span B twice the height D ; its close correspondence with the area of square boxes ensures that it may be used for all sections intermediate between square and $B = 2D$ or $B = 1/2D$. For other box proportions, use Equation 5-8 for more accurate results.

5.3.4 Tapered Inlets

Tapered inlet nomographs from HDS-5 (USDOT, FHWA, 1985) are presented in the following figures:

<u>Culvert Type</u>	<u>Tapered Inlet Figure No.</u>
Throat Control—Side-Tapered Pipes	5-25
Face Control—Side-Tapered Pipes	5-26
Throat Control—Tapered Box	5-27
Face Control—Side-Tapered Box	5-28
Face Control—Slope-Tapered Box	5-29

Detail drawings for typical tapered inlet configurations are presented in Figures 5-30 through 5-35.

The following steps outline the design process for culverts with tapered inlets. Steps 1 and 2 are the same for all culverts, with and without tapered inlets.



1. Estimate the culvert barrel size to begin calculations (see Step 3 of Section 5.3.1).
2. Complete the culvert design form in Figure 5-2. These calculations yield the required fall at the culvert entrance. For the inlet control calculations, the appropriate inlet control nomograph is used for the tapered inlet throat. The required fall is upstream of the inlet face section for side-tapered inlets and is between the face section and throat section for slope-tapered inlets. The culvert design form should be completed for all barrels of interest. Plot outlet control performance curves for the barrels of interest and inlet control performance curves for the faces of culverts with nonenlarged inlets and for the throats of tapered inlets.
3. Use the tapered inlet design form in Figure 5-3 for selecting the type of tapered inlet to be used and determining its dimensions. If a slope-tapered inlet with mitered face is selected, use the special design form shown in Figure 5-4. A separate form is provided for the mitered inlet because of its dimensional complexity.

To use the tapered inlet design form (Figure 5-3) or the design form for a slope-tapered inlet with mitered face (Figure 5-4), perform the following steps:

- a. Fill in the required design data on the top of the form:
 - (1) Flow, Q , is the selected design flow rate from the culvert design form, Figure 5-2.
 - (2) EL_{hi} is the inlet control headwater elevation.
 - (3) The elevation of the throat invert, EL_t , is the inlet invert elevation, EL_i , from Figure 5-2.
 - (4) The elevation of the streambed at the face, EL_{sf} , the stream slope, S_o , and the slope of the barrel, S , are from Figure 5-2. (For the slope-tapered inlet with mitered face, estimate the elevation of the streambed at the crest. This point is located upstream of the face section.)
 - (5) The fall is the difference between the streambed elevation at the face and the throat invert elevation.
 - (6) Select a side taper between 4:1 and 6:1. For slope-tapered inlets, select a fall slope, S_f , between 2:1 and 3:1. The side taper may be modified during the calculations.



- (7) Enter the barrel shape and material, the size, and the inlet edge configuration from Figure 5-2. Note that for tapered inlets, the inlet edge configuration is designated the "tapered inlet throat."
- b. Calculate the face width:
 - (1) Enter the flow rate, the inlet control headwater elevation, EL_{hi} , and the throat invert elevation on the design forms. (For the slope-tapered inlet with mitered face, the face section is downstream of the crest. Calculate the vertical difference between the streambed at the crest and the face invert, y . y includes part of the total inlet fall.)
 - (2) Perform the calculations resulting in the face width, B . Face control design nomographs are presented in Figures 5-26, 5-28, and 5-29.
- c. Calculate tapered inlet dimensions. If the fall is less than $D/4$ ($D/2$ for a slope-tapered inlet with a mitered face), a side-tapered inlet must be used. Otherwise, either a side-tapered inlet with a depression upstream of the face or a slope-tapered inlet may be used.
 - (1) For a slope-tapered inlet with a vertical face, calculate L_2 , L_3 , and the taper. (For the slope-tapered inlet with a mitered face, calculate the horizontal distance between the crest and the face section invert L_4 . These dimensions are shown on the small sketches in the top center of the forms.)
 - (2) Calculate the overall tapered inlet length, L_1 .
 - (3) For a side-tapered inlet, check that the fall between the face section and the throat section is 1 foot or less. If not, return to Step 3b with a revised face invert elevation.
- d. For a side-tapered inlet with fall upstream of the face or for a slope-tapered inlet with a mitered face, calculate the minimum crest width and check it against the proposed crest width. To obtain the necessary crest length for a depressed side-tapered inlet, it may be necessary to increase the flare angle of the wingwalls for the type of depression shown in Figure 5-31, or to increase the length of crest on the sump for the design shown in Figure 5-32. For a slope-tapered inlet with a mitered face, reduce the taper to increase crest width. Note that the taper must be greater than 4:1.
- e. Using a sketch based on the derived dimensions and a sketch of the roadway section to the same scale, check that the culvert design fits the site. Adjust inlet



- dimensions as necessary, but do not reduce them below the minimum dimensions on the design form.
- f. Using additional flow rate values and the appropriate nomographs, calculate a performance curve for the selected face section. Do not adjust inlet dimensions at this step in the design process. Plot the face control performance curve on the same sheet as the throat control and the outlet control performance curves.
 - g. If the design is satisfactory, enter the dimensions at the lower right of the design form. Otherwise, calculate another alternative design by returning to Step 3a.
4. The following dimensional limitations must be observed when designing tapered inlets using the design charts:
- a. Side-tapered inlets:
 - (1) $4:1 \leq \text{taper} \leq 6:1$.
 - (2) Wingwall flare angle range from 15 to 26 degrees with top edge beveled or from 26 to 90 degrees with or without bevels (Figure 5-35).
 - (3) If a fall is used upstream of the face, extend the barrel invert slope upstream from the face a distance of $D/2$ before sloping upward more steeply. The maximum vertical slope of the apron is 2 (horizontal) : 1 (vertical) .
 - (4) $D \leq E \leq 1.1D$.
 - b. Slope-tapered inlets:
 - (1) $4:1 \leq \text{taper} \leq 6:1$.

Tapers greater than 6:1 may be used, but performance will be underestimated.
 - (2) $3:1 \geq S_f \geq 2:1$.

If $S_f > 3:1$, use side-tapered design.
 - (3) Minimum $L_3 = 0.5B$.
 - (4) $D/4 \leq \text{fall} \leq 1.5D$.



- i. For fall < D/4, use side-tapered design.
- ii. For fall < D/2, do not use the slope-tapered inlet with mitered face.
- iii. For fall > 1.5D, estimate friction losses between the face and the throat by using the following equation and adding the additional losses to HW:

$$H_1 = \left(\frac{29n^2 L_1}{R^{1.33}} \right) \frac{Q^2}{2gA^2} \quad (5-9)$$

where:

H_1 = Friction head loss in the tapered inlet, in feet

n = Manning's n for the tapered inlet material

L_1 = Length of the tapered inlet, in feet

R = Average hydraulic radius of the tapered inlet = $(A_f + A_t)/(P_f + P_t)$, in feet

Q = Flow rate, in cfs

g = Acceleration due to gravity, 32.2 feet/second²

A = Average cross-sectional area of the tapered inlet = $(A_f + A_t)/2$, in square feet

- (5) Wingwall flare angles range from 15 to 26 degrees with top edge beveled or from 26 to 90 degrees with or without bevels (Figure 5-35).
5. This section supplements the general design procedures described above with information specifically related to rectangular box culverts. The design charts for throat and face control for tapered box inlets are Figures 5-27, 5-28, and 5-29. There is a single throat control nomograph (Figure 5-27) for side- or slope-tapered rectangular inlets.
- a. For determining the required face width, Figure 5-28 is used for side-tapered inlets and Figure 5-29 is used for slope-tapered inlets. Each nomograph has two scales, and each scale refers to a specific inlet edge condition. The edge conditions are depicted in Figure 5-35. Both the inlet edge condition and the wingwall flare angle affect the performance of the face section for box culverts.



Scale 1 on the design nomographs refers to the less favorable edge conditions, defined as follows:

- (1) Wingwall flares of 15 to 26 degrees and a 1:1 top edge bevel, or
- (2) Wingwall flares of 26 to 90 degrees and square edges (no bevels) . A 90-degree wingwall flare is a straight headwall.

Scale 2 applies to the more favorable edge conditions, defined as follows:

- (1) Wingwall flares of 26 to 45 degrees with 1:1 top edge bevel, or
- (2) Wingwall flares of 45 to 90 degrees with a 1:1 bevel on the side and top edges.

Note that undesirable design features, such as wingwall flare angles less than 15 degrees or 26 degrees without a top bevel, are not covered by the charts. Although the large 33.7-degree bevels can be used, the smaller 45-degree bevels are preferred because of structural considerations.

- b. When designing side- or slope-tapered inlets for box culverts with double barrels, the required face width is the total clear width of the face. The thickness of the center wall must be added to this clear width to obtain the total face width. Design procedures for tapered inlets on box culverts with more than two barrels are not available.

5.3.5 Roadway Overtopping

The overall performance curve for roadway overtopping 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 should be calculated (see Sections 5.3.2 and 5.3.3).
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 equivalent upstream water surface depth above the roadway (crest of weir) for each selected flow rate. Use these water surface depths and the following equation to calculate flow rates across the roadway:



$$Q_o = C_d L HW_r^{1.5} \quad (5-10)$$

where:

Q_o = Overtopping flow rate, in cfs

$C_d = K_t C_r$ = Discharge coefficient

K_t = Submergence factor (from Figure 5-36)

C_r = Unsubmerged discharge coefficient (from Figure 5-36)

L = Length of roadway crest, in feet

HW_r = Upstream depth, measured from the roadway crest to the water surface upstream of the weir drawdown, in feet

4. Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve.

5.3.6 Example Problems

The following example problems demonstrate the procedure required to design culverts as presented in Section 5.3.1 and shown schematically in Figure 5-1. The example problems use the design forms shown in Figures 5-2 and 5-3, as well as appropriate nomographs.

Example 5-1. Circular Pipe Culvert

A culvert at a new roadway crossing must be designed to pass the 10-year flood. Hydrologic analysis indicates a peak flow rate of 200 cfs. The following information is known:

Invert elevation at culvert inlet = 100 feet

Natural streambed slope = 1% = 0.01 foot/foot

Tailwater for 10-year flood = 3.5 feet

Approximate culvert length = 200 feet

Roadway shoulder elevation = 110 feet

Required freeboard at shoulder = 2 feet



No fall at inlet face

Design a circular pipe culvert for this site. Consider a corrugated metal pipe with standard 2-2/3-by 1/2-inch corrugations with beveled concrete inlet edges. Also consider a concrete pipe with a groove end and 45-degree headwalls.

1. Record the known data on a copy of the culvert design form shown in Figure 5-2. The completed design form for this example problem is shown in Figure 5-37. The design headwater elevation is 108 feet (shoulder elevation minus the required freeboard). The outlet elevation is 98 feet (inlet elevation minus the length of the culvert times the bed slope). Other terms were given above.
2. Make the first trial calculation by assuming a circular corrugated metal pipe with a diameter of 72 inches. Because there is only one culvert barrel, the design flow rate of 200 cfs is written in the columns titled "Total Flow" and "Flow per Barrel."
3. Inlet Control Calculations: Find HW_i , the headwater that will occur if the inlet controls flow, using the nomograph in Figure 5-18. Multiply the diameter times the HW_i / D value to find the inlet headwater depth, HW_i , which is added to the inlet elevation to obtain EL_{hi} , the headwater elevation under inlet control conditions.
4. Outlet Control Calculations: The tailwater value was given as 3.5 feet. The critical depth, d_c , is obtained from Figure 5-20 for circular pipes. The equivalent hydraulic depth at the outlet, d_e , is calculated using Equation 5-4. The design tailwater, h_o , is determined to be the given tailwater value, TW , or d_e , whichever is greater. The entrance loss coefficient, k_e is found in Table 5-1. The head loss across the culvert, H , is found from the nomograph shown in Figure 5-8 for CMP. The headwater elevation under conditions of outlet control is obtained by adding the head loss and estimated depth to the inlet elevation:

$$EL_{ho} = EL_o + H + h_o.$$

5. Compare the headwater elevations EL_{hi} (inlet control) and EL_{ho} (outlet control) to determine which is greater and which type of control exists. For this example, the first iteration capacity is based on inlet control and the headwater elevation is 105.8 feet. Since a headwater of 108 feet is allowed, a smaller pipe can be used.
6. Determine the outlet velocity according to the procedure discussed in Section 5.3.1, Step 11. Because the flow in this first iteration is controlled at the inlet, the following steps are performed:



- a. Calculate the normal depth for the culvert using Manning's Equation. For circular pipes, the solution is shown graphically in Figure 3-7. The normal depth for the 6-foot diameter culvert is 4.32 feet.
 - b. Calculate the area of flow at the outlet section of the culvert based on the normal depth. For this iteration, the area of flow (depth = 4.32 feet) is 21.8 square feet.
 - c. Determine the outlet velocity from Equation 5-1: $v = Q/A = 9.2$ feet per second for this iteration.
7. Results of the second iteration (see Figure 5-37) show that the outlet controls with a headwater elevation of 108.6 feet. Since this is above the design headwater, the size is unacceptable. The outlet velocity was found to be 11.8 feet per second.

The conclusion at this point is that a 72-inch CMP will be required.

8. Assuming a diameter of 5 feet, perform the concrete pipe calculations as described above. The HW_i/D ratio for inlet control is determined from Figure 5-5, and the head loss for outlet control, H , is obtained from Figure 5-6. Results indicate that the inlet controls with a headwater elevation of 106.8 feet. The outlet velocity was found to be 11.8 feet per second.
9. Because the control headwater elevation is 1.2 feet below the design headwater, a smaller diameter pipe can be considered. A 4.5-foot diameter is assumed and the computations are repeated.
10. Results for the 4.5-foot concrete pipe show that the control headwater elevation is 108 feet for inlet control. The design headwater is not exceeded so the pipe is acceptable. The outlet velocity of 15.2 feet per second is high and protective measures will be necessary (see Chapter 10).

Example 5-2. Concrete Box Culvert

A culvert at a new roadway crossing will be designed to carry the 100-year flow rate of 300 cfs. The following information is known:

Maximum design headwater = $EL_{hd} = 110.0$ feet, based on adjacent structures

Roadway shoulder elevation = 113.5 feet

Elevation of streambed at culvert face = $EL_{sf} = 100$ feet

Natural stream slope = $S_o = 0.02$ foot/foot



Tailwater depth = $TW = 4$ feet

Approximate culvert length = $L = 200$ feet

Design a reinforced concrete box culvert for this installation. Consider both square edges and 45-degree beveled edges in a 90-degree headwall. The inlet is to be set at the existing channel elevation (no fall).

1. Assume a box size of 6 feet by 5 feet. The total flow rate and the flow rate per foot width per barrel (only for box culverts, see equation [1] in the Technical Footnotes) are written into the first and second columns, respectively, of the form presented in Figure 5-2. Data and results for this problem are recorded in Figure 5-38.
2. Determine the HW_i/D ratio for inlet control from Figure 5-10 for box culverts. The headwater for inlet control is 7.9 feet, giving an elevation of 107.9 feet.
3. Determine the critical depth of 4.25 feet from Figure 5-19. The entrance loss coefficient, k_e , is found in Table 5-1.
4. Determine the head loss for outlet control, H , from Figure 5-11. The resulting elevation is 103.2 feet.
5. The inlet conditions will create a higher headwater elevation and control flow through the culvert at an elevation of 107.9 feet. For this trial, the normal depth is 2.37 feet, which gives a flow area of 14.2 square feet and an outlet velocity of 21.1 feet per second.
6. Because the control headwater elevation is 2.1 feet below the maximum allowable headwater, it may be possible to use a smaller culvert size. A 5-foot by 5-foot box is assumed and Steps 1 through 5 are repeated for this new size.
7. Results reported in Figure 5-38 show that a 5-foot by 5-foot box with a headwater elevation of 109.6 feet is adequate. The normal depth is 2.8 feet and the outlet velocity is 21.2 feet per second.
8. Examine the effect of incorporating 45-degree bevels into the design. Repeat the computations as before. The result is that the inlet control headwater elevation is 108.6 feet, or 1 foot below the design without bevels. The normal depth and outlet velocity do not change. Both designs are acceptable, but the bevels provide more flow capacity.

Example 5-3. Box Culvert with Roadway Overtopping



An existing 7-foot by 7-foot concrete box culvert was designed for a 100-year flood of 600 cfs and a design headwater elevation of 114 feet. Upstream development has increased the 100-year runoff to 1,000 cfs. It is expected that the roadway will be overtopped. The gravel roadway profile can be approximated as a broad-crested weir 200 feet long, 40 feet wide, and with a mean elevation of 116 feet. Other site information is given below:

Inlet invert elevation = 110 feet

Existing culvert slope = 0.05 foot/foot

Existing culvert length = 200 feet

Entrance conditions = Square edges

For flow, in cfs, of 400, tailwater =	2.6 feet
600	3.1
800	3.8
1,000	4.1
1,200	4.5

Prepare a performance curve for this installation, including any roadway overtopping up to a total flow rate of 1,000 cfs.

1. Apply the methods presented in Section 5.3.5 along with culvert capacity methods from Examples 5-1 and 5-2. Data and results for this problem are shown in Figures 5-39 and 5-40.
2. Record the culvert description and the flow rates ranging from 400 to 1,000 cfs. The culvert flows are divided by the number of culverts ($N = 1$) and the width of each barrel ($B = 7$ feet) and recorded in the second column of the culvert form (Figure 5-2).
3. Perform the design computations as for Example 5-2. Figure 5-10 is used to obtain the HW_i/D ratios for inlet control. Figure 5-19 is used to obtain the critical depths, and Figure 5-11 is used to obtain the head loss for outlet control.
4. Record the maximum elevation of the inlet control or outlet control headwater for each flow rate in the control headwater elevation column in Figure 5-39. No outlet velocity computations are needed for the performance curve, but results are provided.
5. The performance curve shown in Figure 5-40 consists of three components: the culvert flow, the weir flow, and the combined or total flow. The culvert flow curve is defined by the flow rates written in column 1 (Q) of the design form and the resulting control headwater elevations. The weir flow is the amount of flow that will overtop the roadway



and is based on the control headwater elevations. The flow rate over the roadway is calculated from the weir equation (Equation 5-10) where, for this problem, C_d , is found from Figure 5-36 and HW_r = control headwater elevation - weir elevation (116 feet). The total flow is the sum of the culvert flows and weir flows at a specific elevation.

Example 5-4. Box Culvert with Side-Tapered Inlet

The culvert analyzed in Example 5-3 is reexamined for the possible addition of a side-tapered inlet to assure the new 100-year flood of 1,000 cfs can be passed without exceeding the design headwater elevation of 114 feet. The known information is the same as given in Example 5-3. Design a side-tapered inlet that will pass the 100-year flood without exceeding the design headwater of 114 feet. The inlet will be constructed upstream of the existing culvert. The elevation of the throat invert will be 100 feet. Begin the design by assuming a face invert elevation of 101 feet. Prepare face control, throat control, and outlet control performance curves for the new inlet.

1. The method for designing tapered inlet is described in Section 5.3.4. The procedure requires the use of the culvert design form in Figure 5-2 and the tapered inlet design form in Figure 5-3. The completed forms and performance curves for this example problem are shown in Figures 5-41 and 5-42.
2. First determine if a side-tapered inlet will pass the 100-year flood of 1,000 cfs without exceeding the design headwater elevation. Complete the culvert design form for the given culvert with a side-tapered inlet. Fill in the known elevations, pipe description, and flow rates at the appropriate section. Obtain the HW_i/D ratio from Figure 5-27. Other items in the headwater calculations are the same as in Example 5-3. The head loss across the culvert, H_c , is found in Figure 5-11.
3. Results for the headwater computations show that the culvert with a side-tapered inlet will pass the 100-year flood within the design headwater elevation.
4. To create the performance curves, other flow rates are used to calculate the resulting inlet (throat) and outlet control headwater elevations, as reported in Figure 5-41.
5. Design the required side-tapered inlet using the tapered inlet design form in Figure 5-3. The known information is first written into the appropriate sections. The computations for the inlet table are performed as follows:

Q is known = 1,000 cfs

EL_{hi} is known = 114 feet

EL throat invert is known = 100 feet



EL face invert is assumed = 101 feet

HW_f : See equation (2) below data in Figure 5-42

HW_f/E : See equation (3) below data in Figure 5-42, E = height of inlet, E = 7 feet

Q/F_f : Obtained from Figure 5-28

Min. B_f : See equation (5) below data in Figure 5-42

Selected B_f : Rounded up to nearest whole foot

L_1 : See equation (11) below data in Figure 5-42

The computations result in a side-tapered inlet with a width of 12 feet and a length of 10 feet.

6. Obtain the performance curve data for face control from the tapered inlet design form in Figure 5-3 by working the calculations from Step 5 in reverse. The procedure is as follows:
 - a. Choose the flow rate, Q, and divide by the designed inlet width, B_f . Place the new value in the Q/F_f column.
 - b. Determine the HW_f/E value from Figure 5-28 and calculate HW_f .
 - c. Find the design elevation of the face invert from the following equation:
$$EL \text{ Face Invert} = (L_1) (S_o)$$
 - d. Find the headwater elevation under face control conditions by adding HW to the elevation of the face invert.
7. Create the performance curves by graphing the following parameters:

Face Control: Flow rate, Q, vs. EL_{hi} from tapered inlet design form

Throat Control Flow rate, Q, vs. EL_{hi} from culvert design form

Outlet Control Flow rate, Q, vs. EL_{ho} from culvert design form



Table 5-1
 CULVERT ENTRANCE LOSS COEFFICIENTS

<u>Type of Structure and Design of Entrance</u>	<u>Entrance Coefficient, k_e</u>
<u>Pipe, Concrete</u>	
Projecting from fill, socket end (groove-end)	0.2
Projecting from fill, sq. cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe (groove-end)	0.2
Square-edge	0.5
Rounded (radius = 1/12D)	0.2
Mitered to conform to fill slope	0.7
End-section conforming to fill slope ^a	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side- or slope-tapered inlet	0.2
<u>Pipe or Pipe Arch, Corrugated Metal</u>	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls square-edge	0.5
Mitered to conform to fill slope, paved or unpaved slope	0.7
End-section conforming to fill slope ^a	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side- or slope-tapered inlet	0.2
<u>Box, Reinforced Concrete</u>	
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	
Square-edged at crown	0.4
Crown edge rounded to radius of 1/12 barrel dimension, or beveled top edge	0.2
Wingwall at 10° to 25° to barrel	
Square-edged at crown	0.5
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Side- or slope-tapered inlet	0.2

^a“End section conforming to fill slope,” made of either metal or concrete, is the section commonly available from manufacturers. From limited hydraulic tests, the sections are equivalent in operation to a headwall in both inlet and outlet control. End sections that incorporate a closed taper in their design have a superior hydraulic performance.

Reference: USDOT, FHWA, HDS-5 (1985).

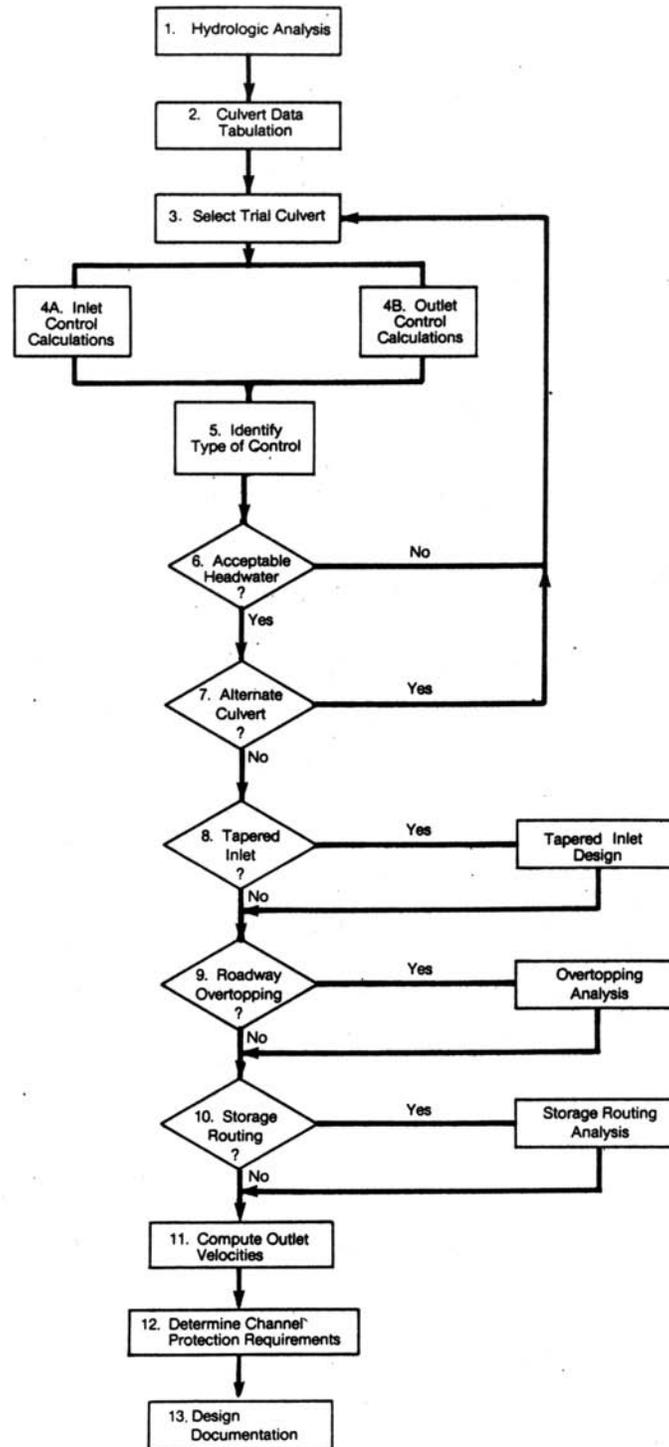
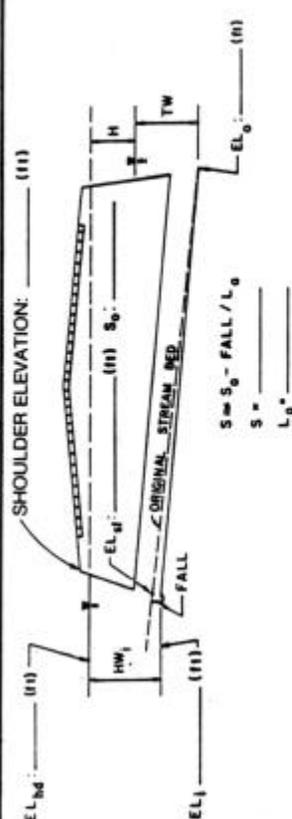


Figure 5-1
Culvert Design Flow Chart
Volume No. 2
Chapter 5 - 28



PROJECT : _____ STATION : _____ SHEET _____ OF _____	CULVERT DESIGN FORM DESIGNER / DATE : _____ / _____ REVIEWER / DATE : _____ / _____	SHOULDER ELEVATION: (11)  <p> EL_{hd} (11) EL_{ot} (11) HW_1 EL_{in} (14) EL_1 (11) EL_{out} (10) EL_0 (11) </p> <p> $S = S_0 - FALL / L_0$ $S =$ _____ $L_0 =$ _____ </p>																																																																													
HYDROLOGICAL DATA <input type="checkbox"/> METHOD : _____ <input type="checkbox"/> DRAINAGE AREA : _____ <input type="checkbox"/> CHANNEL SHAPE : _____ <input type="checkbox"/> ROUTING : _____ <input type="checkbox"/> OTHER : _____ SEE ADD'L SHTS _____ DESIGN FLOWS/TAIWATER R. I. (YEARS) _____ FLOW (cfs) _____ TW (ft) _____		HEADWATER CALCULATIONS <table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">INLET CONTROL</th> <th colspan="3">OUTLET CONTROL</th> <th rowspan="2">CONTROL HEADWATER ELEVATION</th> <th rowspan="2">OUTLET VELOCITY</th> <th rowspan="2">COMMENTS</th> </tr> <tr> <th>HW₁/D (2)</th> <th>HW₁ (3)</th> <th>EL_{in} (4)</th> <th>FALL (5)</th> <th>EL_{no} (6)</th> </tr> </thead> <tbody> <tr> <td> </td> </tr> <tr> <td> </td> </tr> <tr> <td> </td> </tr> <tr> <td> </td> </tr> <tr> <td> </td> </tr> <tr> <td> </td> </tr> <tr> <td> </td> </tr> <tr> <td> </td> </tr> </tbody> </table>	INLET CONTROL		OUTLET CONTROL			CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS	HW ₁ /D (2)	HW ₁ (3)	EL _{in} (4)	FALL (5)	EL _{no} (6)																																																																
INLET CONTROL			OUTLET CONTROL			CONTROL HEADWATER ELEVATION	OUTLET VELOCITY				COMMENTS																																																																				
HW ₁ /D (2)	HW ₁ (3)	EL _{in} (4)	FALL (5)	EL _{no} (6)																																																																											
CULVERT DESCRIPTION : MATERIAL - SHAPE - SIZE - ENTRANCE TOTAL FLOW PER BARREL Q (cfs) (1) _____ Q/N (cfs) (1) _____		TECHNICAL FOOTNOTES : (1) USE Q/NB FOR BOX CULVERTS (2) $HW_1/D = HW_1/D$ OR HW_1/D FROM DESIGN CHARTS (3) $FALL = HW_1 - (EL_{hd} - EL_{ot})$; FALL IS ZERO FOR CULVERTS ON GRADE (4) $EL_{in} = HW_1 + EL_1$ (INVERT OF INLET CONTROL SECTION) (5) $HW_1/D = HW_1/D$ OR HW_1/D FROM DESIGN CHARTS CONTROL OR FLOW DEPTH IN CHANNEL (6) $EL_{no} = TW$ OR $(4c^2 + D/2)$ (WHICHEVER IS GREATER) (7) $H = \left[1 + k_a \cdot (29n^2 L) / R^{1.33} \right] V^2 / 2g$ (8) $EL_{no} = EL_0 + H + h_0$																																																																													
SUBSCRIPT DEFINITIONS : A APPROXIMATE F CULVERT FACE N4 DESIGN HEADWATER N1 HEADWATER IN INLET CONTROL N0 HEADWATER IN OUTLET CONTROL I INLET CONTROL SECTION O OUTLET S STREAMBED AT CULVERT FACE TW TAILWATER			COMMENTS / DISCUSSION : _____ CULVERT BARREL SELECTED : SIZE : _____ SHAPE : _____ MATERIAL : _____ ENTRANCE : _____																																																																												

Reference: USDOT, FHWA, HDS-5 (1965).

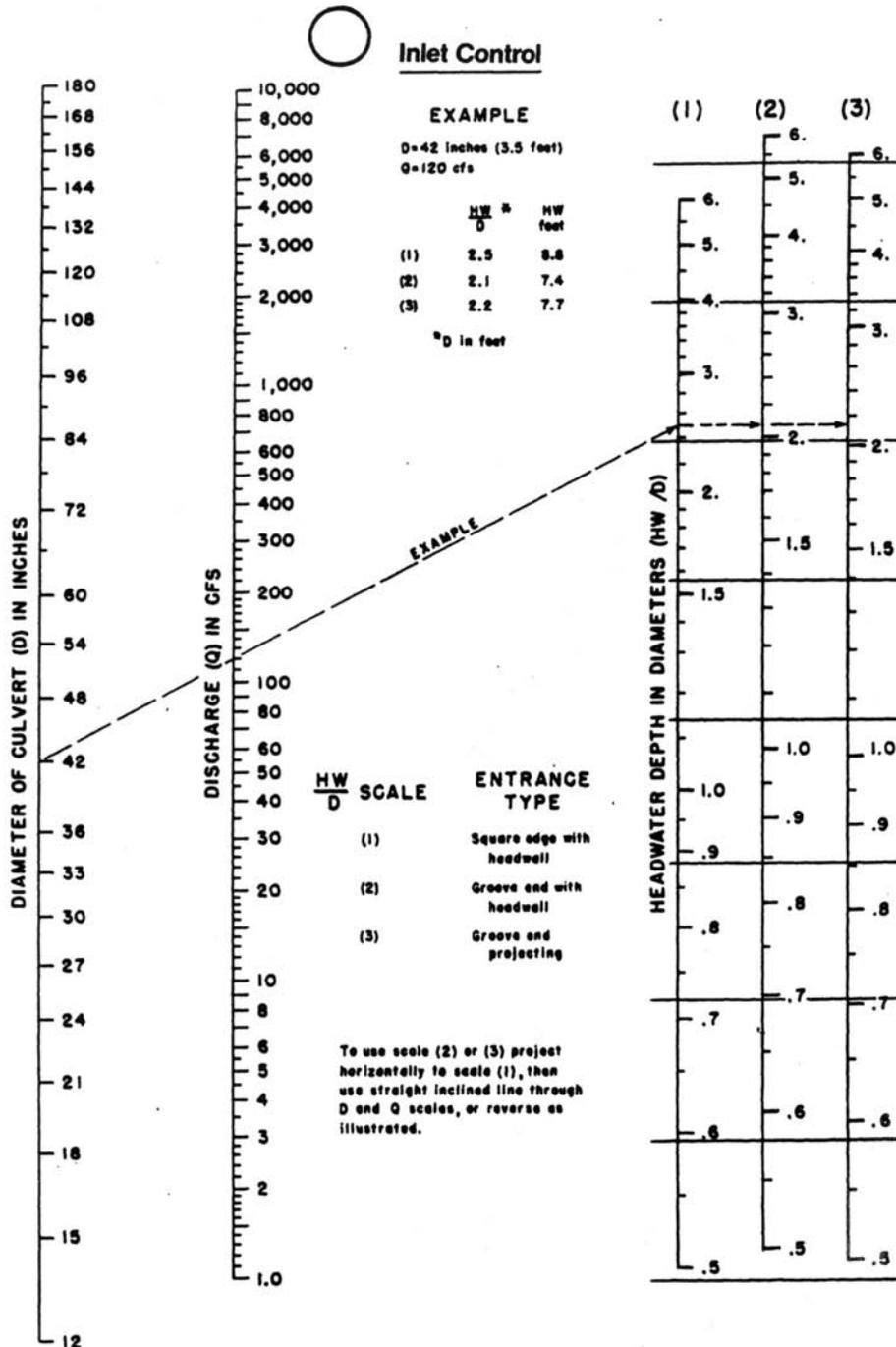
Figure 5-2
Culvert Design Form



PROJECT :		STATION : _____ OF _____ SHEET _____ OF _____		MITERED INLET DESIGN FORM											
DESIGN DATA : N _____ ; B _____ ; D _____ ; Q _____ cfs ; EL _{IN} _____ ft EL. THROAT INVERT _____ ft EL. STREAM BED AT CREST _____ ft FALL _____ ft ; TAPER _____ : (4:1 TO 6:1) STREAM SLOPE , S ₀ _____ ft/ft ; BARREL SLOPE , S ₁ _____ ft/ft SLOPE OF THE EMBANKMENT S ₂ _____ : (2:1 TO 3:1) BARREL SHAPE AND MATERIAL : _____ INLET EDGE DESCRIPTION : _____		DESIGNER / DATE : _____ REVIEWER / DATE : _____		COMMENTS											
Q (cfs)	EL. THROAT INVERT (1)	EL. FACE INVERT (2)	HW _f / E (4)	HW _f / E (5)	MIN. B _f (6)	MIN. SELECTED B _f (7)	L ₃ (8)	L ₄ (9)	L ₂ (10)	CHECK L ₂ (11)	ADJ. L ₃ (12)	ADJ. TAPER L ₁ (13)	EL. CREST INV. (14)	MIN. W (15)	W (16)
<p>(1) $y = \frac{(S_2 - S_1) - 1}{(S_2 + S_1)(S_f + 1)0.5} \cdot 0$</p> <p>(2) EL. FACE INVERT = EL. STREAM BED AT CREST - y</p> <p>(3) $HW_f = EL_{th} - EL. FACE INVERT$</p> <p>(4) I.D. & Z.D.</p> <p>(5) FROM DESIGN CHARTS</p> <p>(6) MIN. $B_f = Q / (1.0 / B_f)$</p> <p>(7) MIN. $L_3 = 0.5 NB$</p> <p>(8) $L_4 = S_f y + D / S_f$</p> <p>(9) $L_2 = (EL. CREST INVERT - EL. THROAT INVERT) S_1 - L_4$</p> <p>*** IF L₂ IS NEGATIVE DO NOT USE THIS INLET</p> <p>(10) CHECK $L_2 = \frac{B_f - NB}{2}$ TAPER - L₃</p> <p>(11) IF (10)>0, ADJ. $L_3 = \frac{B_f - NB}{2}$ TAPER - L₂</p> <p>(12) IF (9)>0, ADJ. TAPER = $(L_2 + L_3) / \left[\frac{B_f - NB}{2} \right]$</p> <p>(13) $L_1 = L_2 + L_3 + L_4$</p> <p>(14) $HW_c = EL_{th} - EL. CREST INVERT$</p> <p>(15) MIN $W = 0.35 Q / (HW_c)^{1.5}$</p> <p>(16) $W = NB + 2 \left[\frac{L_1}{TAPER} \right]$</p> <p>IF W < MIN W, ADJUST TAPER</p>															
<p>SELECTED DESIGN</p> <p>B_f _____</p> <p>L₁ _____</p> <p>L₂ _____</p> <p>L₃ _____</p> <p>L₄ _____</p> <p>BEVELS ANGLE _____</p> <p>b = _____ m ; d = _____ in</p> <p>TAPER _____ : 1</p> <p>S_f _____</p>															

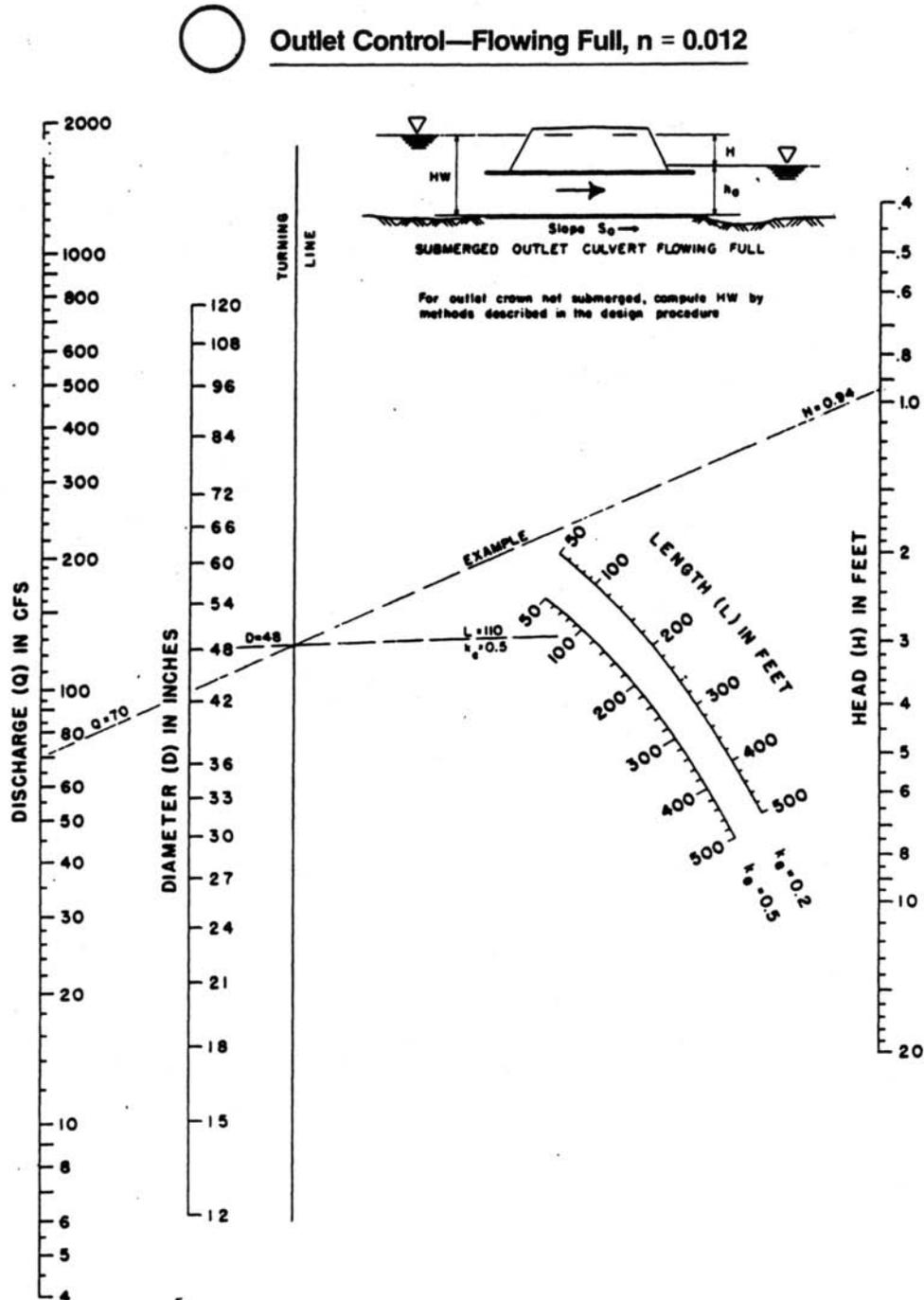
Reference: USDOT, FHWA, HDS-5 (1965).

Figure 5-4
Mitered Inlet Design Form



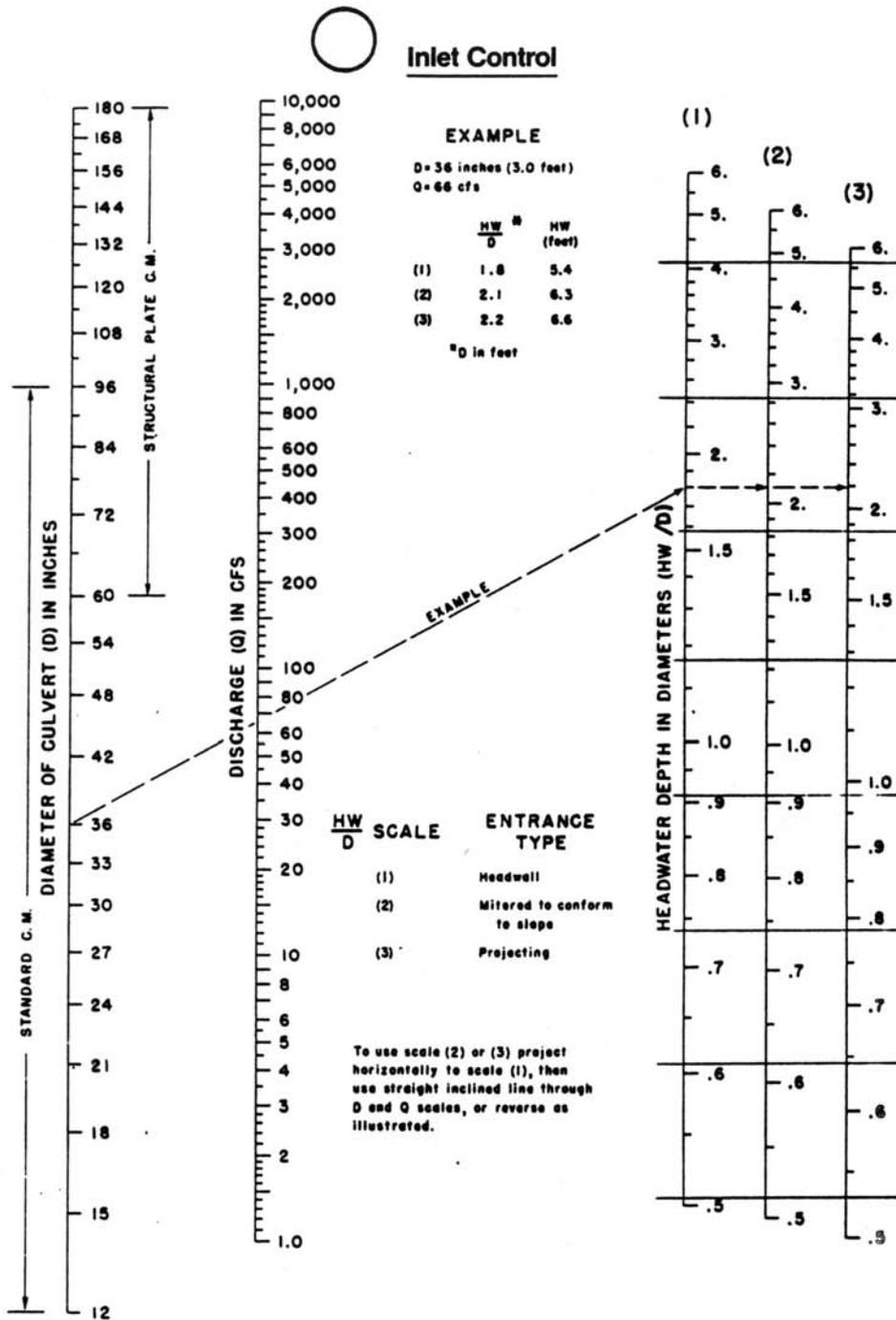
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-5
 Inlet Control Chart for Circular Concrete Pipe Culverts



Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-6
 Outlet Control Chart for Circular Concrete
 Pipe Culverts Flowing Full

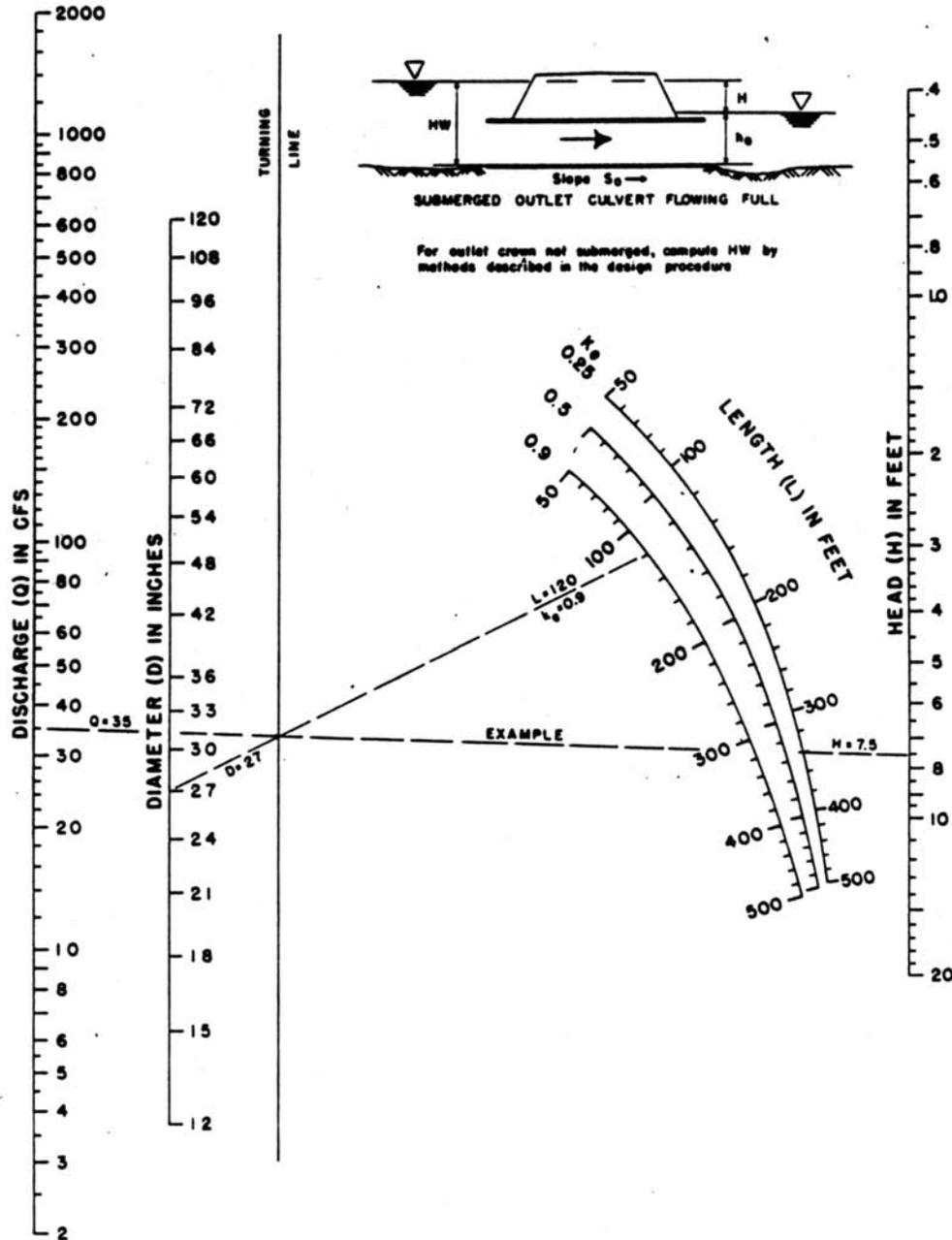


Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-7
 Inlet Control Chart for Circular CMP Culverts



Outlet Control—Flowing Full, $n = 0.024$

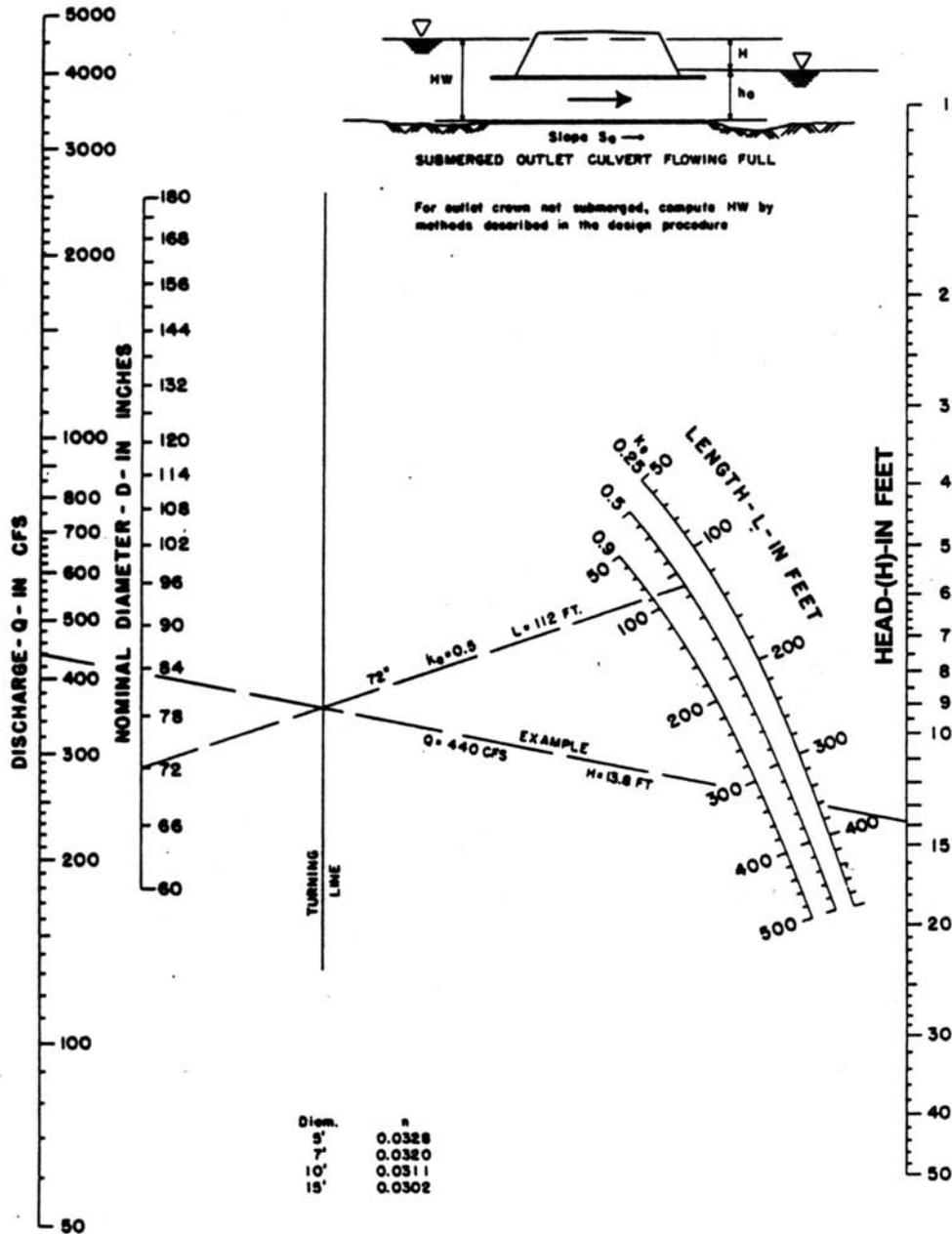


Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-8
 Outlet Control Chart for Circular CMP Culverts Flowing Full

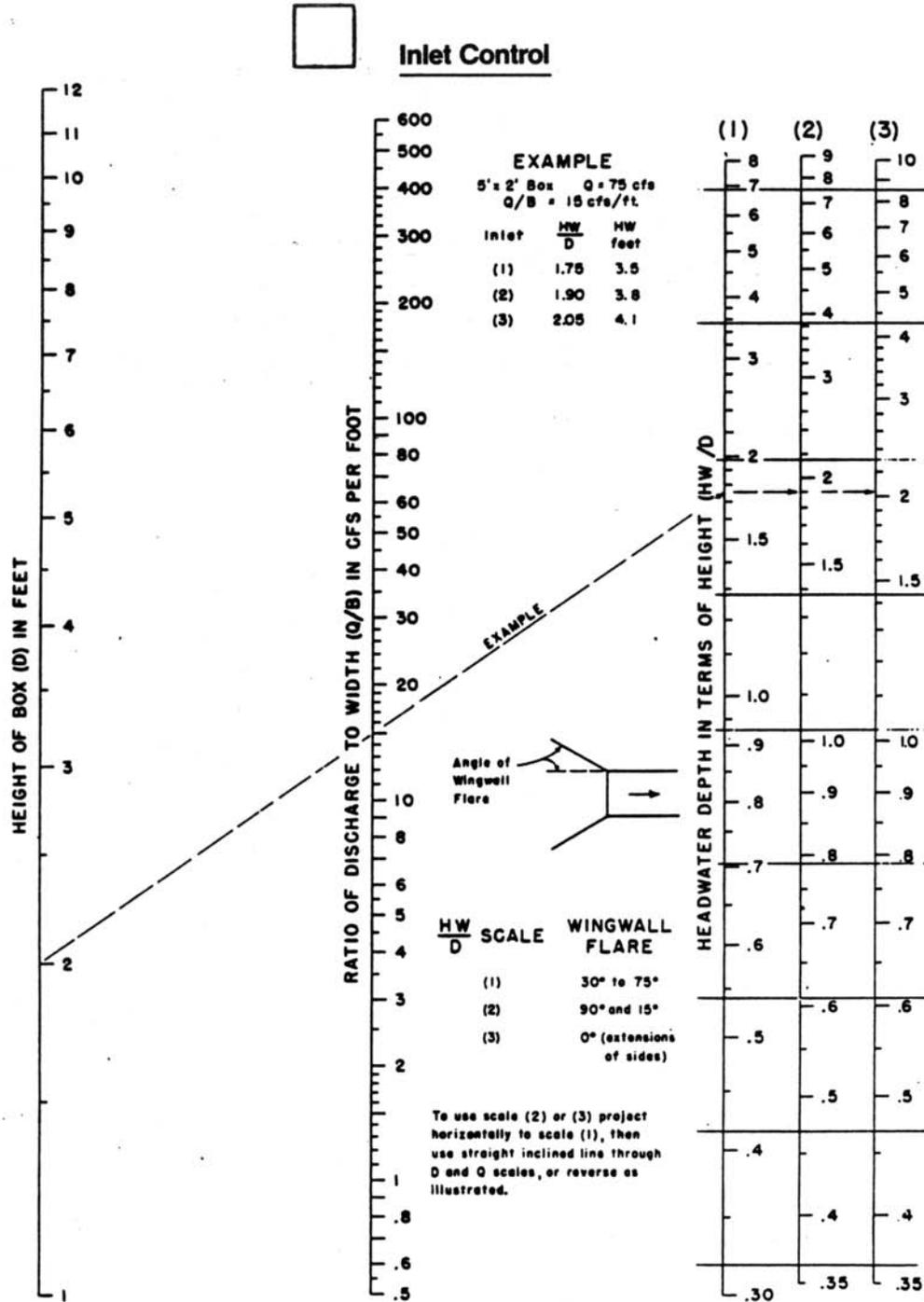


Outlet Control—Flowing Full, $n = 0.0328$ to 0.0302



Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-9
 Outlet Control Chart for Structural Plate
 CMP Culverts Flowing Full

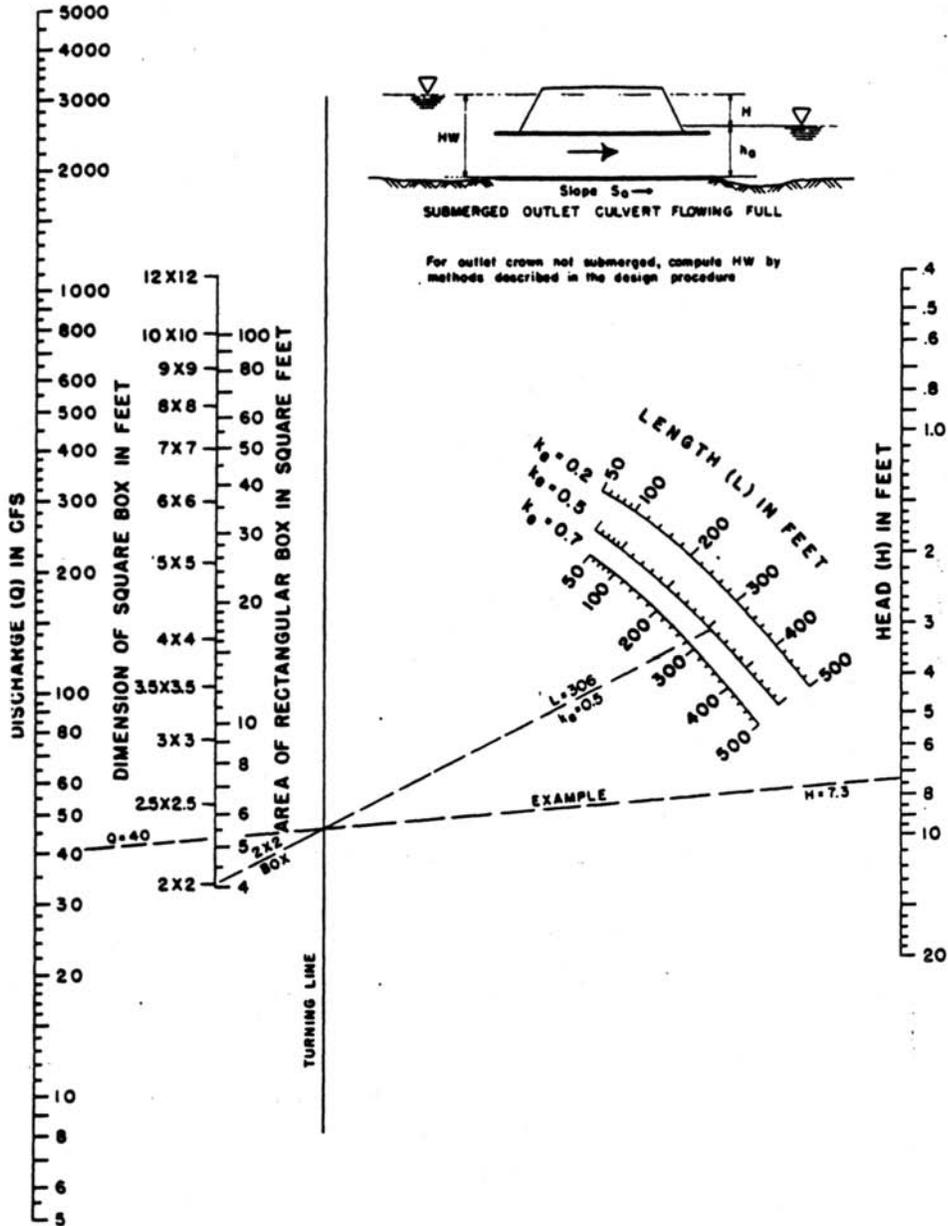


Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-10
 Inlet Control Chart for Concrete Box Culverts

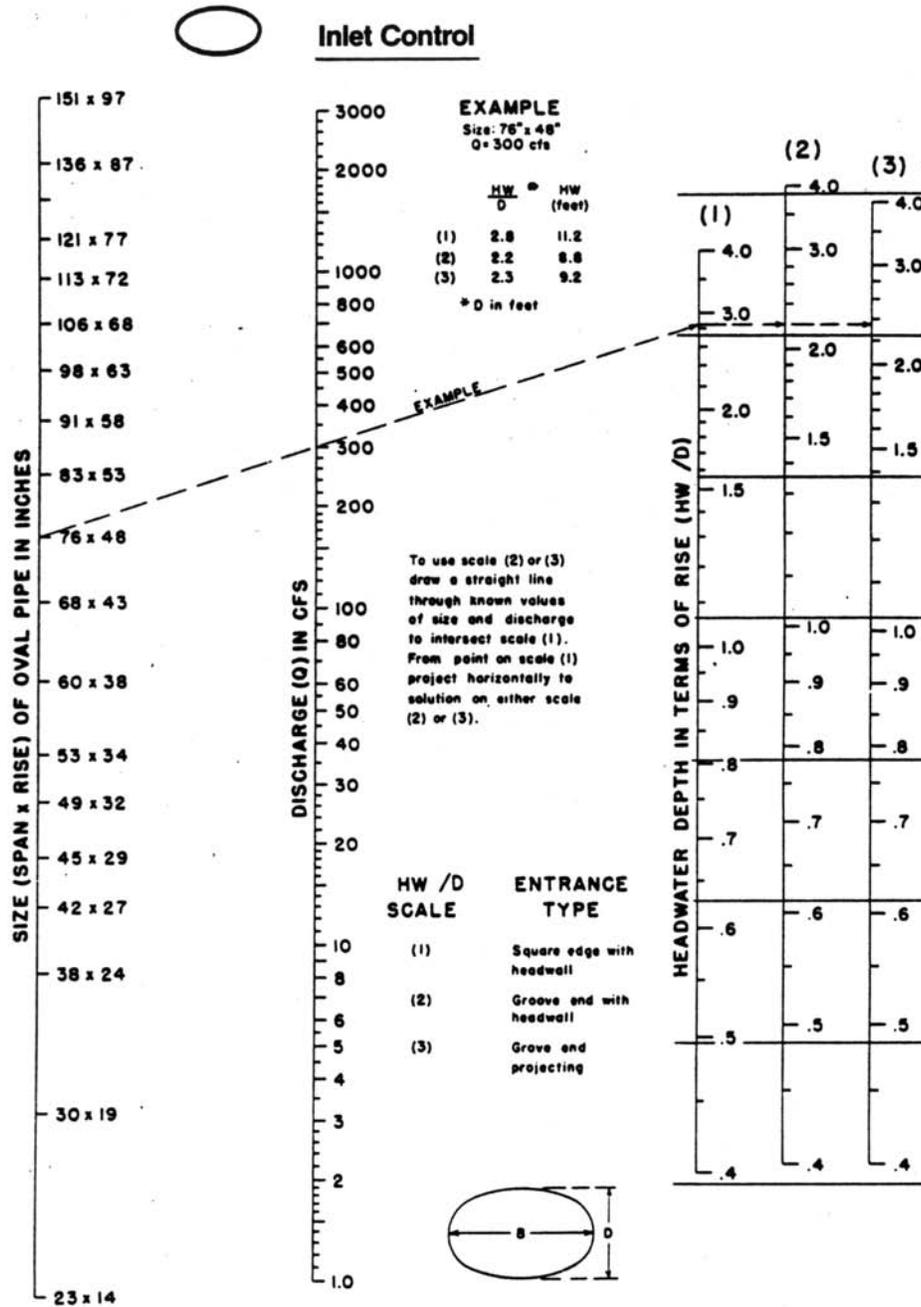


Outlet Control—Flowing Full, $n = 0.012$



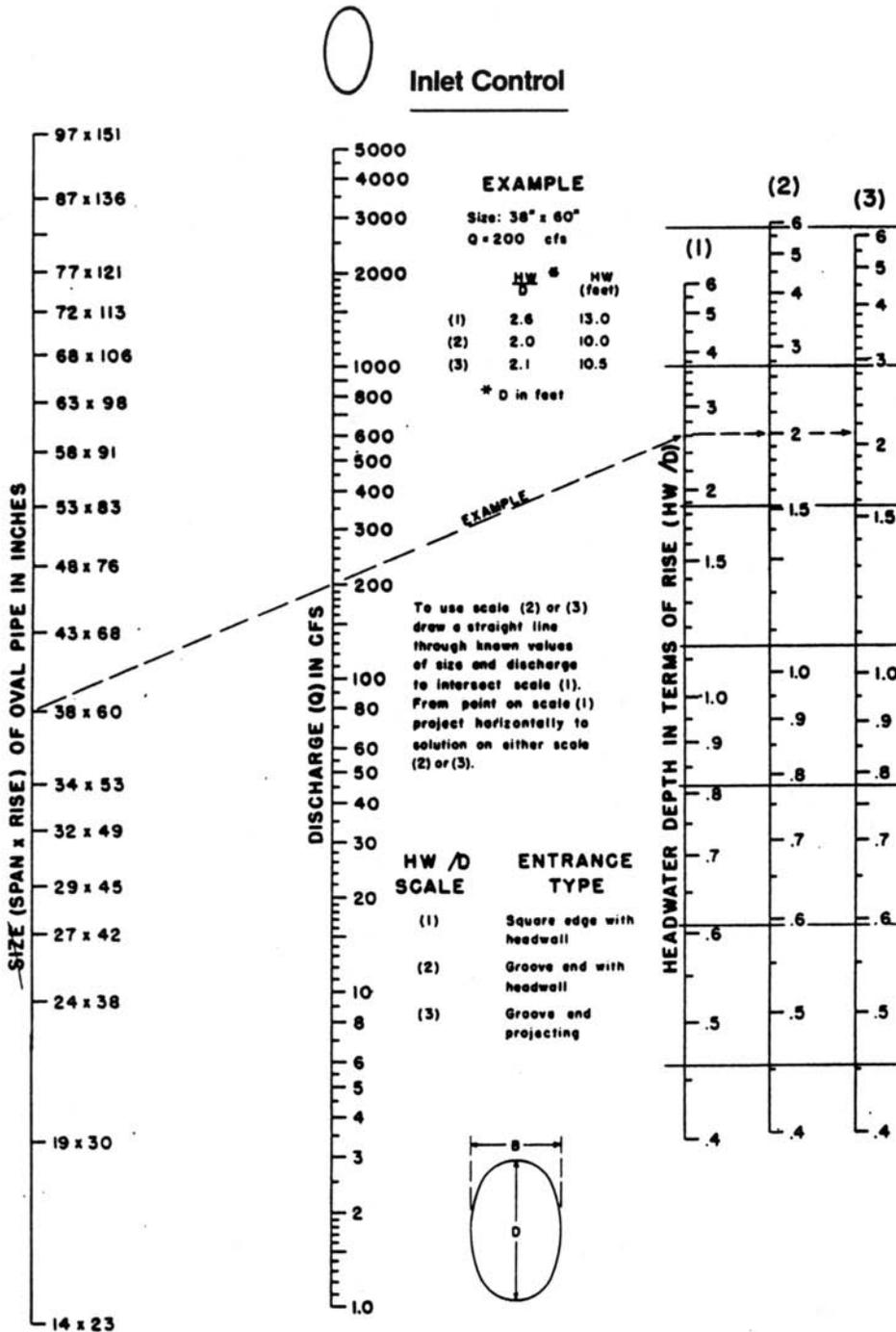
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-11
 Outlet Control Chart for Concrete Box Culverts Flowing Full



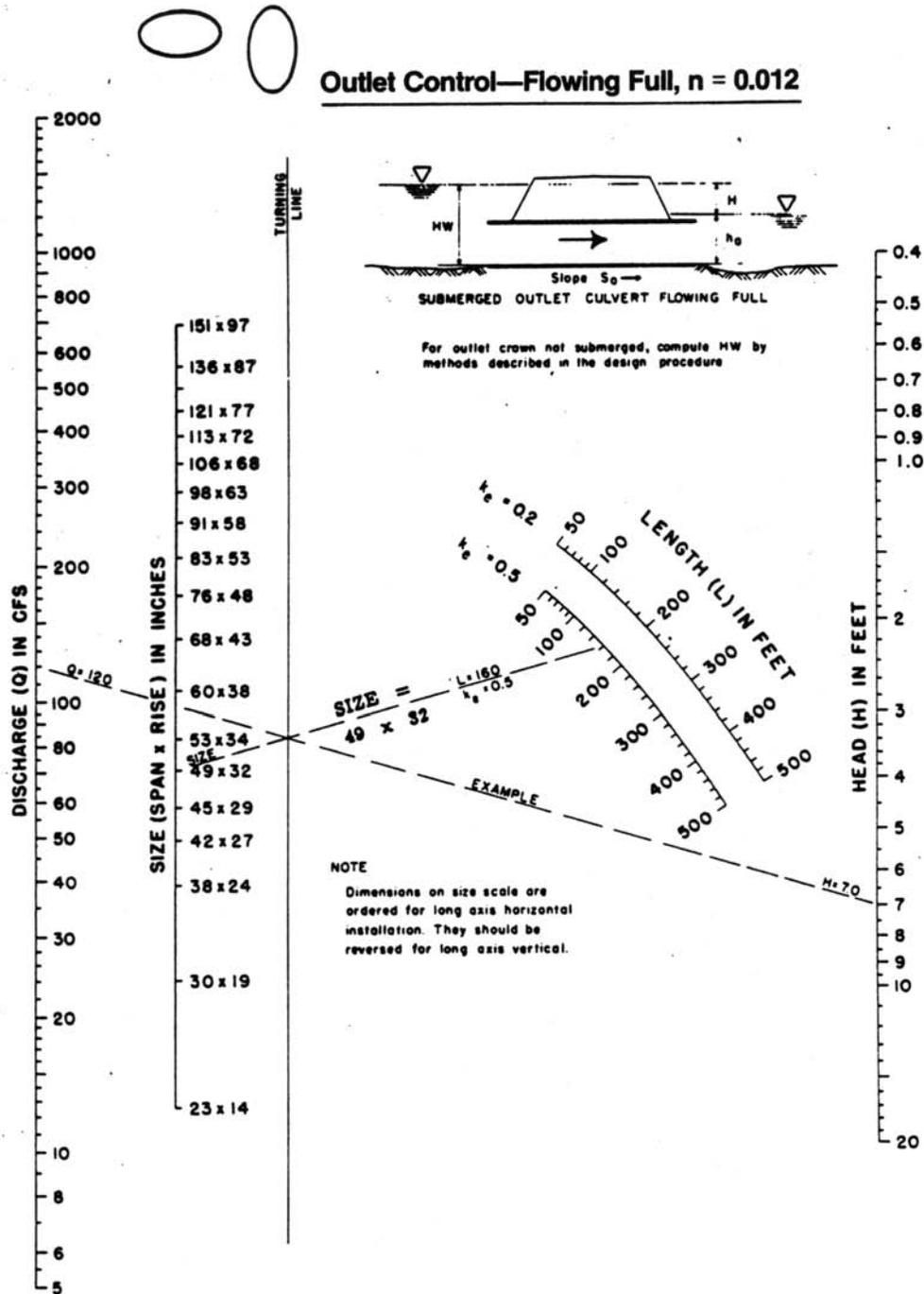
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-12
 Inlet Control Chart for Oval Concrete Pipe Culverts –
 Long Axis Horizontal



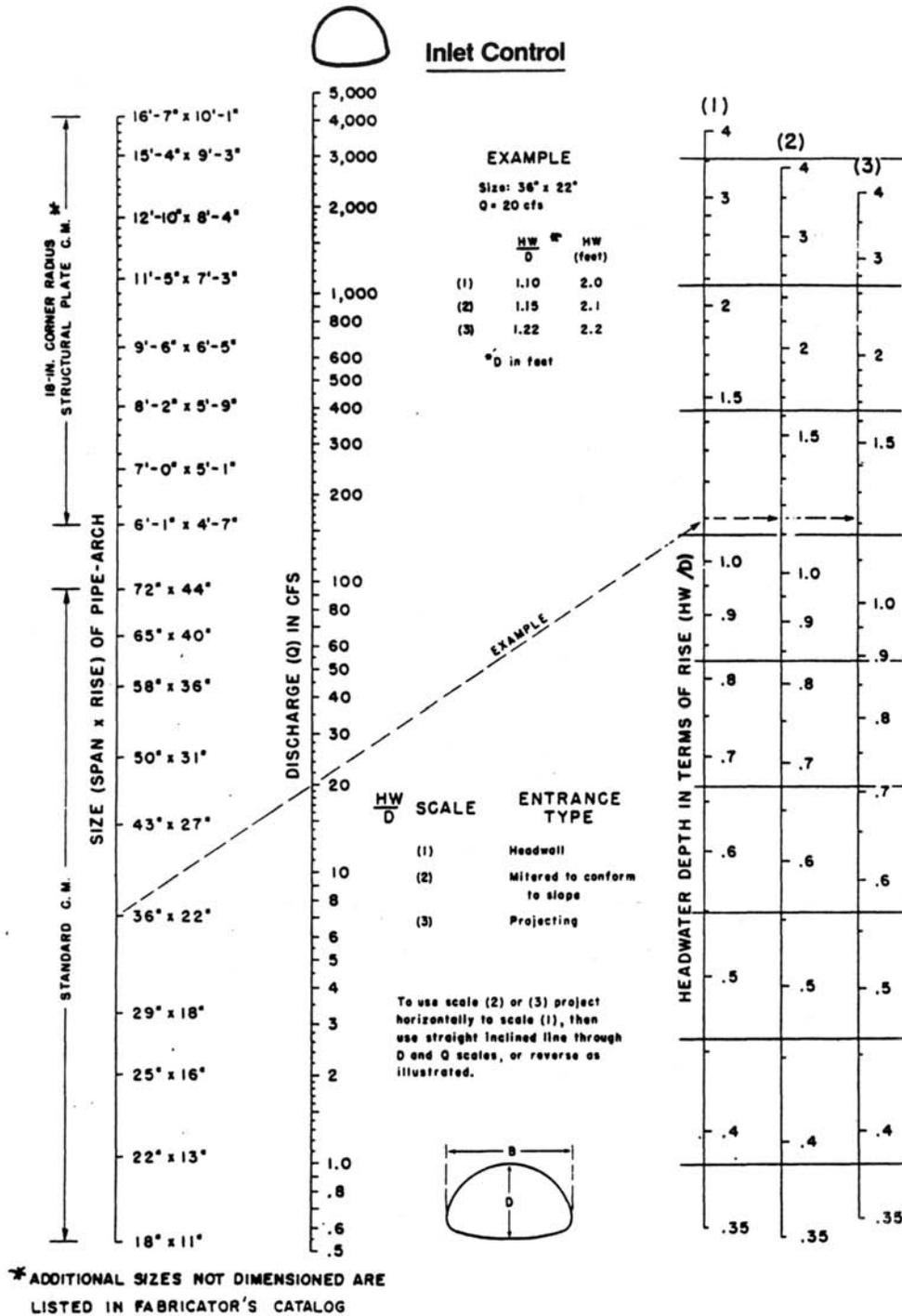
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-13
 Inlet Control Chart for Oval Concrete Pipe Culverts –
 Long Axis Vertical



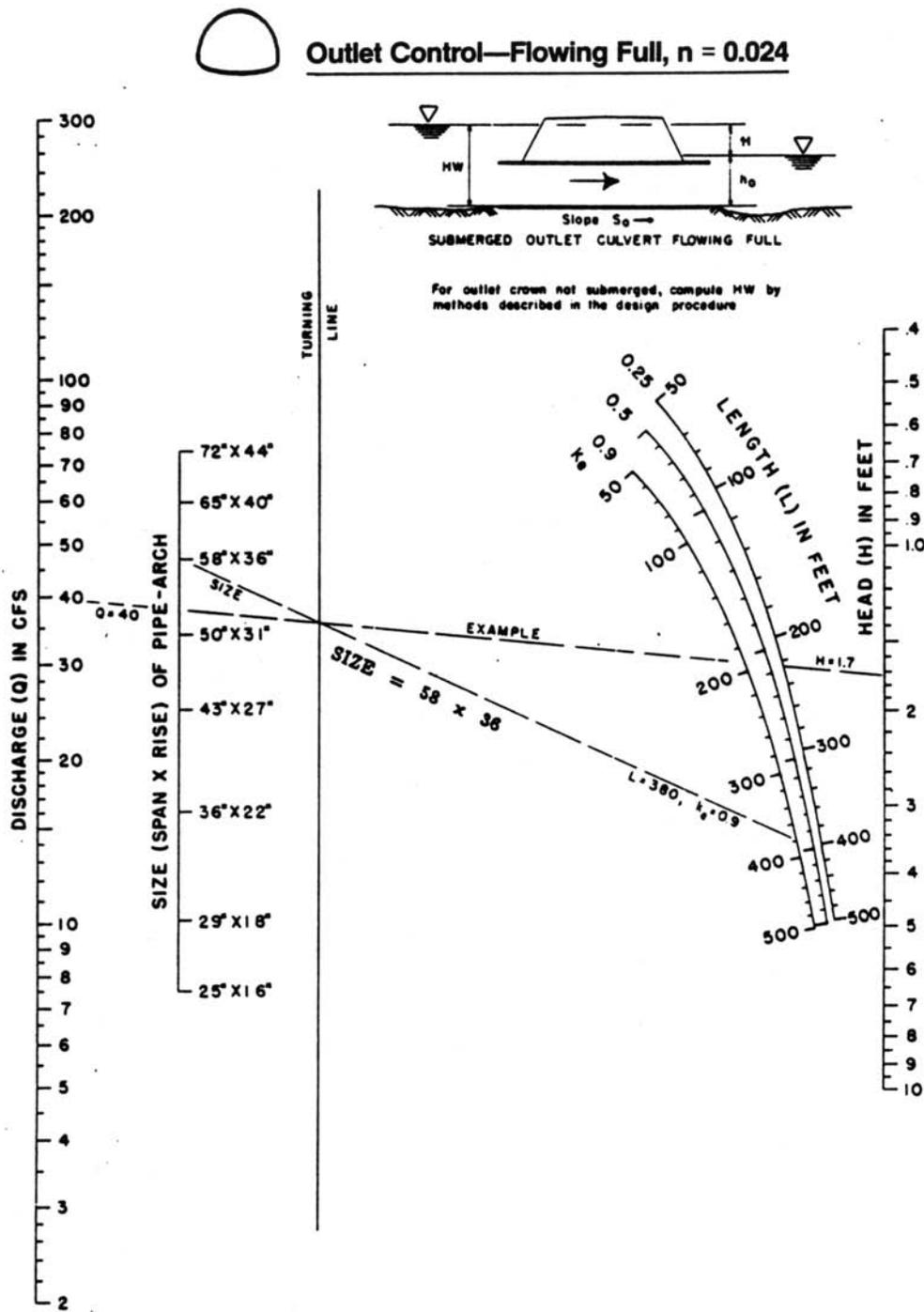
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-14
 Outlet Control Chart for Oval Concrete Pipe Culverts Flowing Full –
 Long Axis Horizontal or Vertical



Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-15
 Inlet Control Chart for CMP Arch Culverts

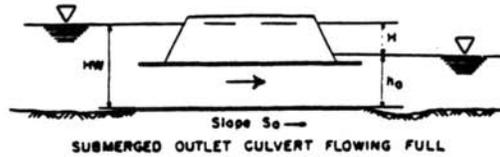


Reference: USDOT, FHWA, HDS-5 (1985).

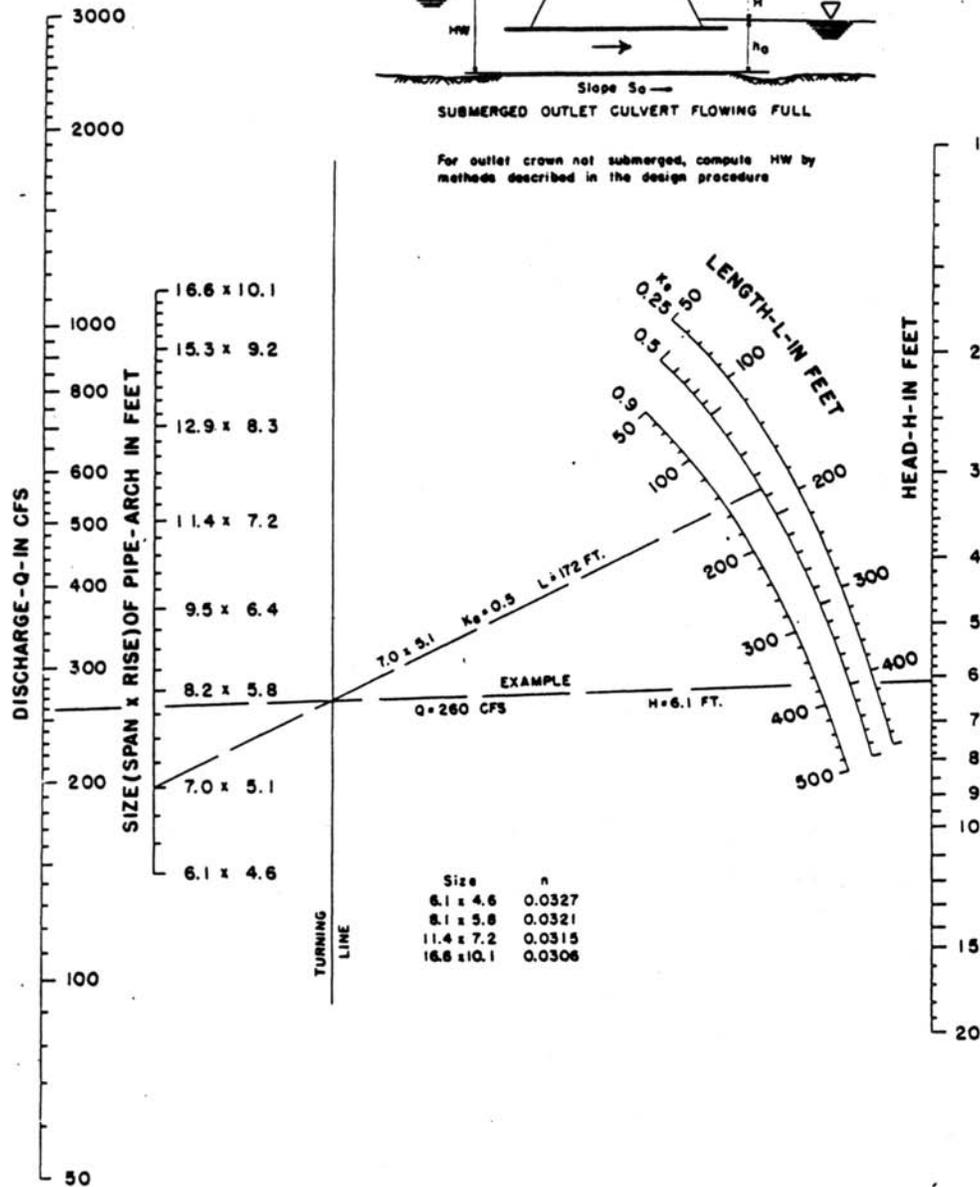
Figure 5-16
 Outlet Control Chart for CMP Arch Culverts Flowing Full



Outlet Control—Flowing Full, $n = 0.0327$ to 0.0306

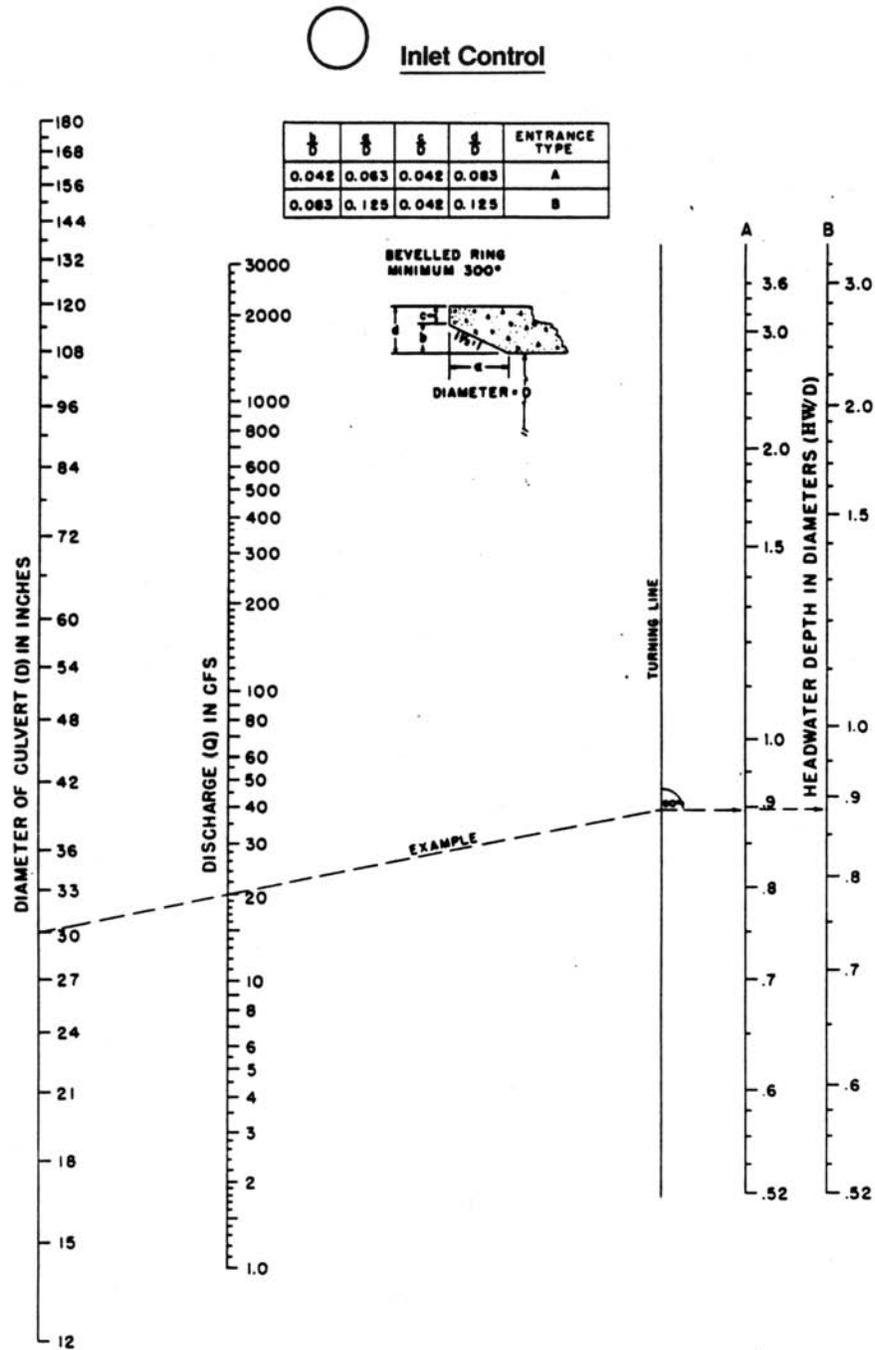


For outlet crown not submerged, compute HW by methods described in the design procedure



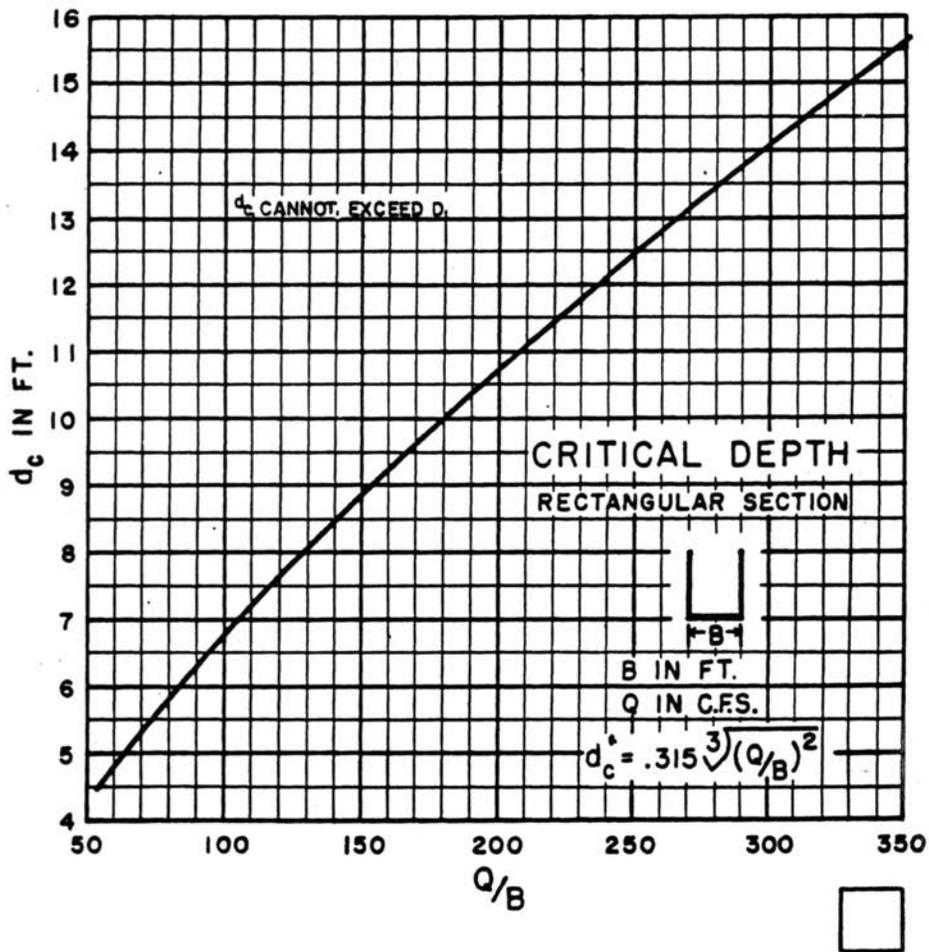
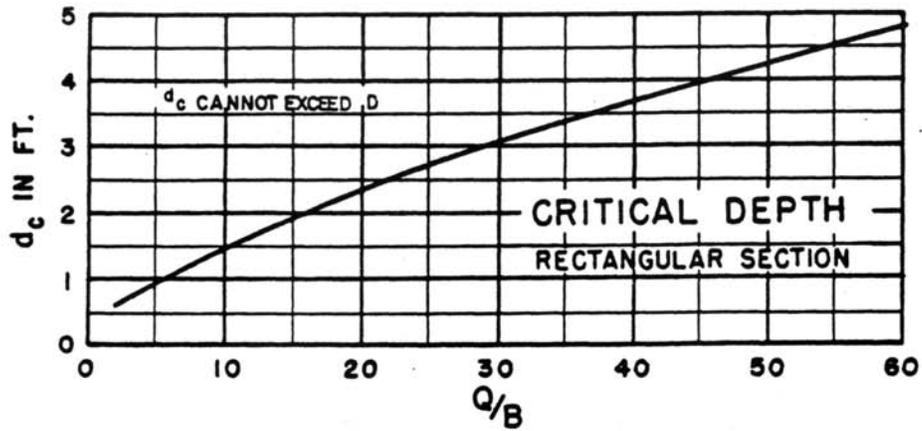
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-17
 Outlet Control Chart for Structural Plate CMP Arch Culverts
 (18-inch Corner Radius Flowing Full)



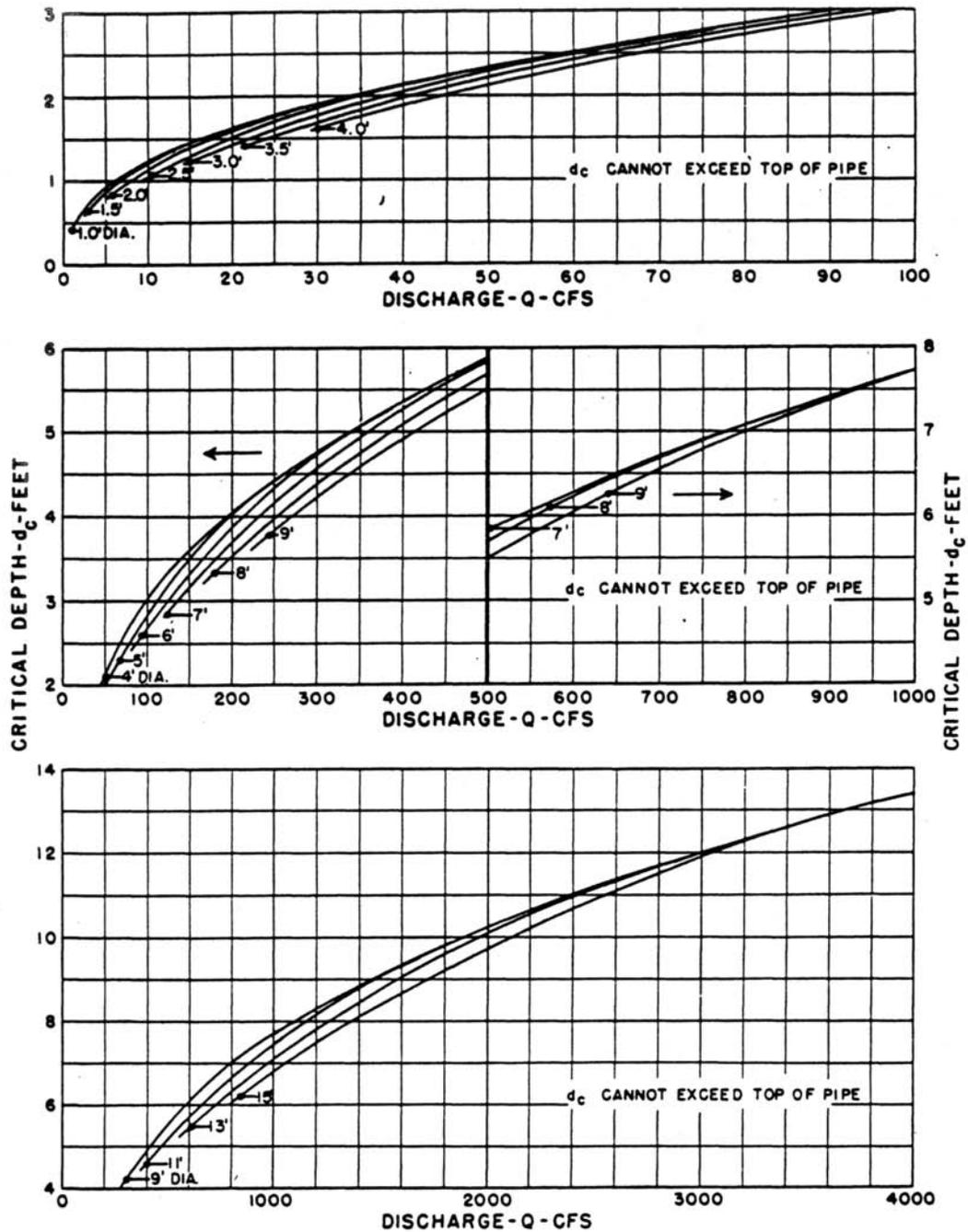
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-18
 Inlet Control Chart for Circular Pipe
 Culverts with Beveled Ring



Reference: USDOT, FHWA, HDS-5 (1985).

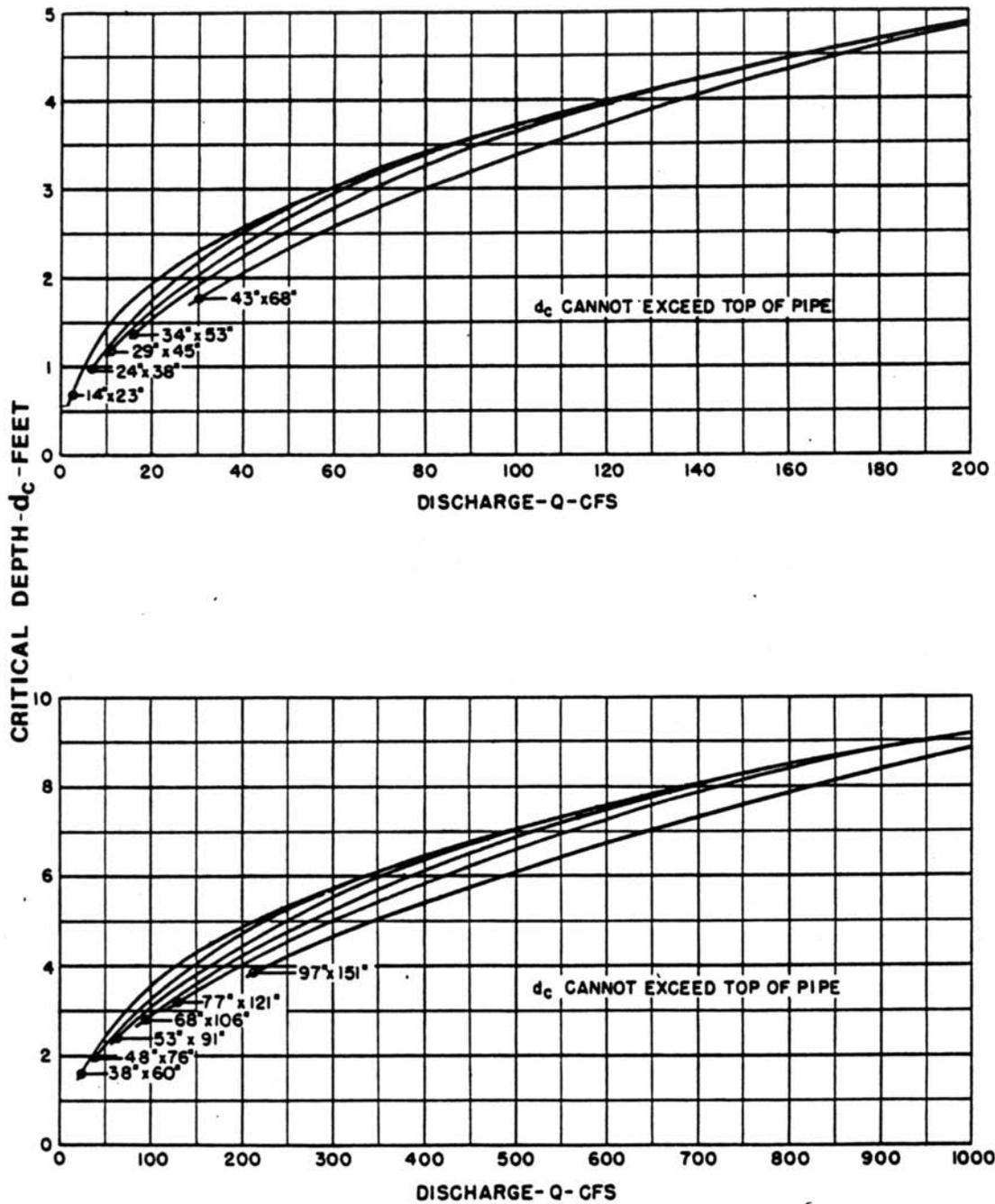
Figure 5-19
 Critical Depth Chart for Rectangular Sections



Reference: USDOT, FHWA, HDS-5 (1985).



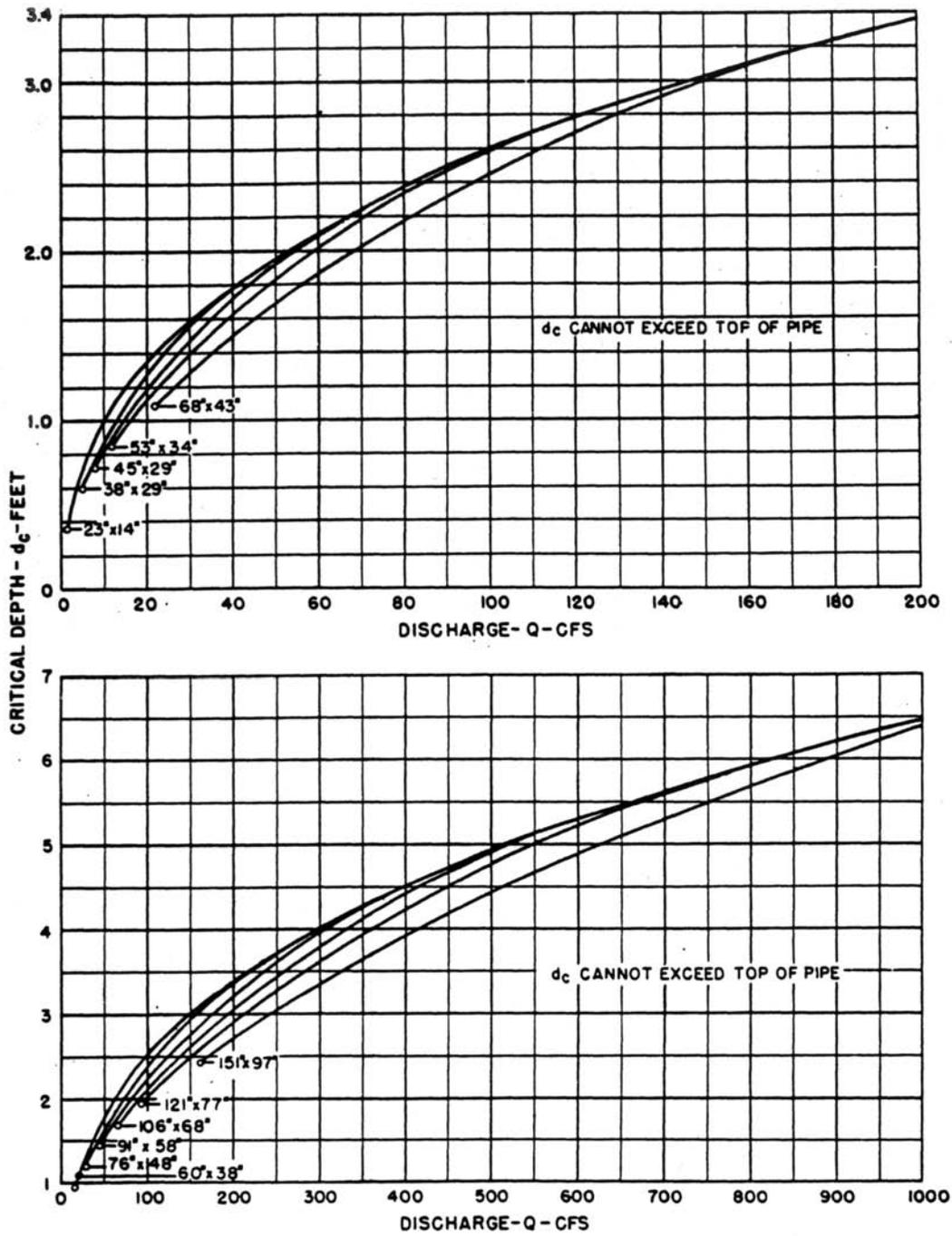
Figure 5-20
Critical Depth Chart for Circular Pipe



Reference: USDOT, FHWA, HDS-5 (1985).

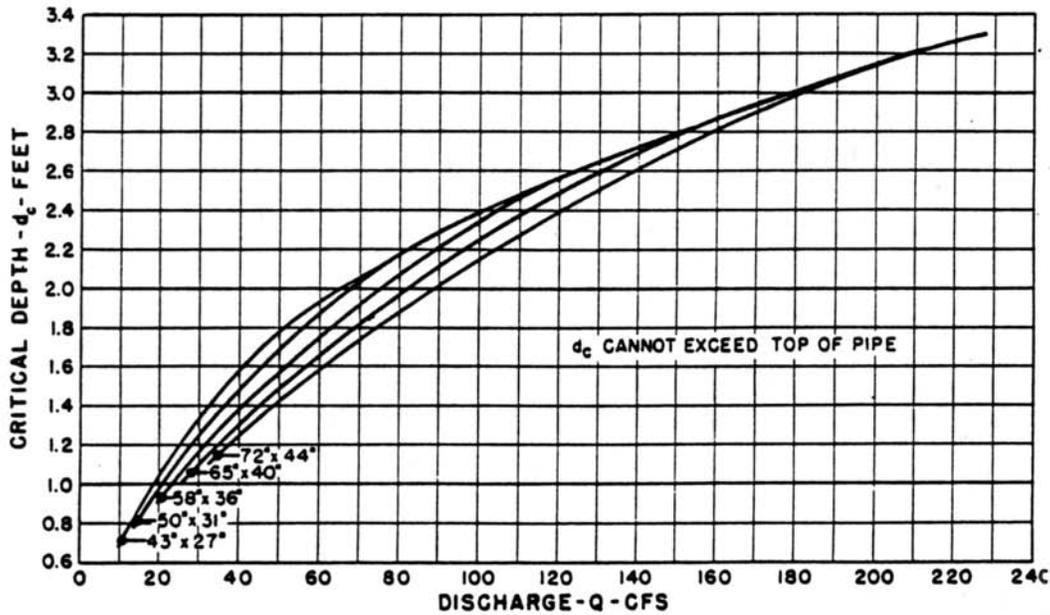
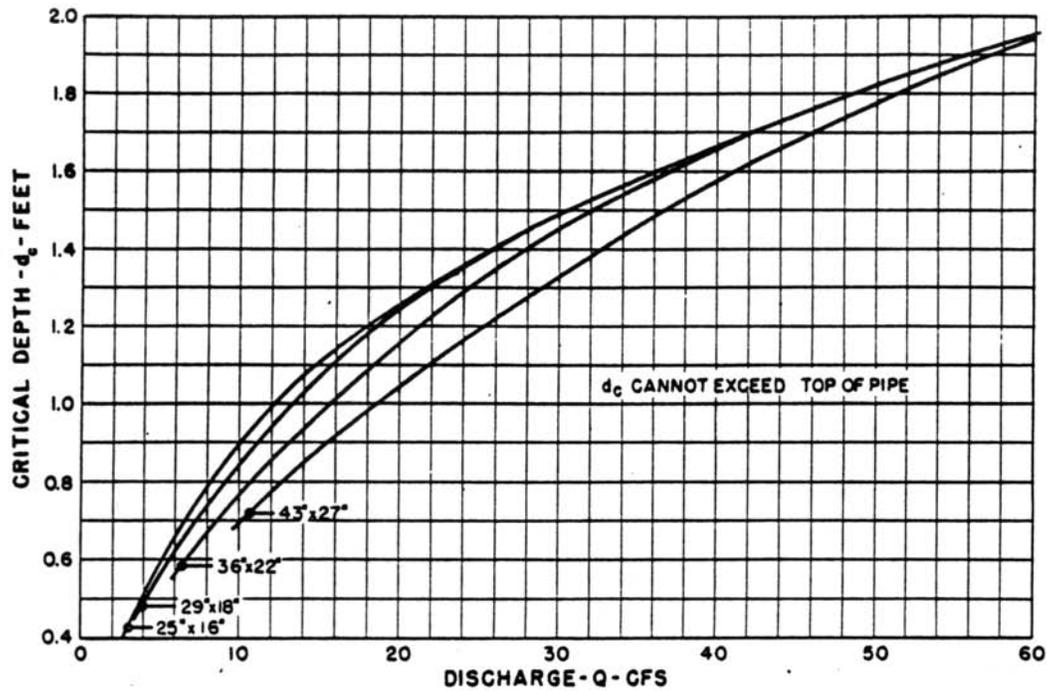
Figure 5-21
Critical Depth Chart for Oval Concrete Pipe –
Long Axis Vertical





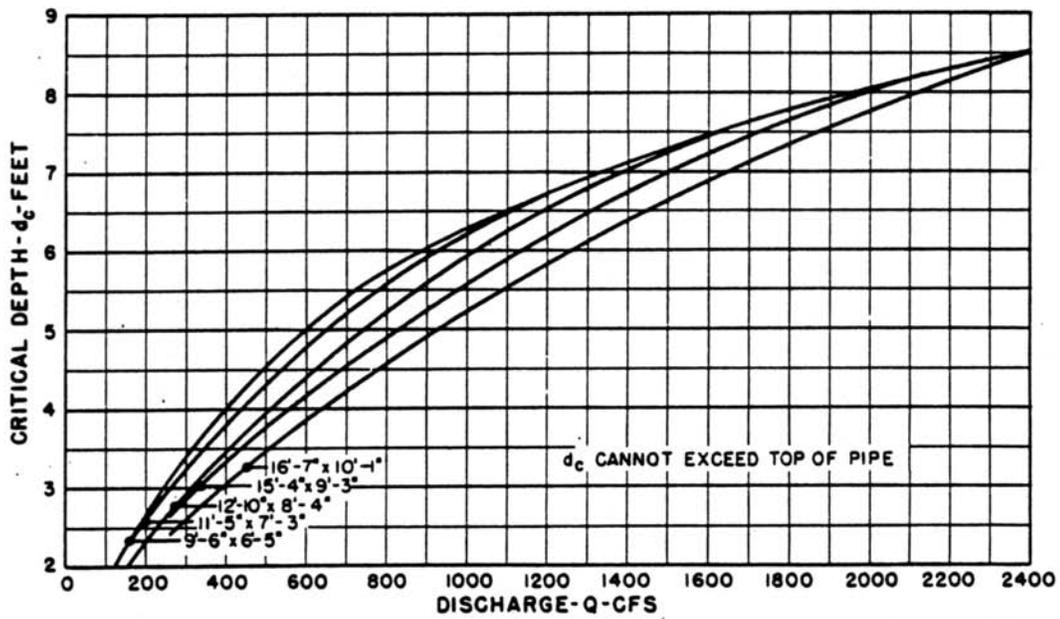
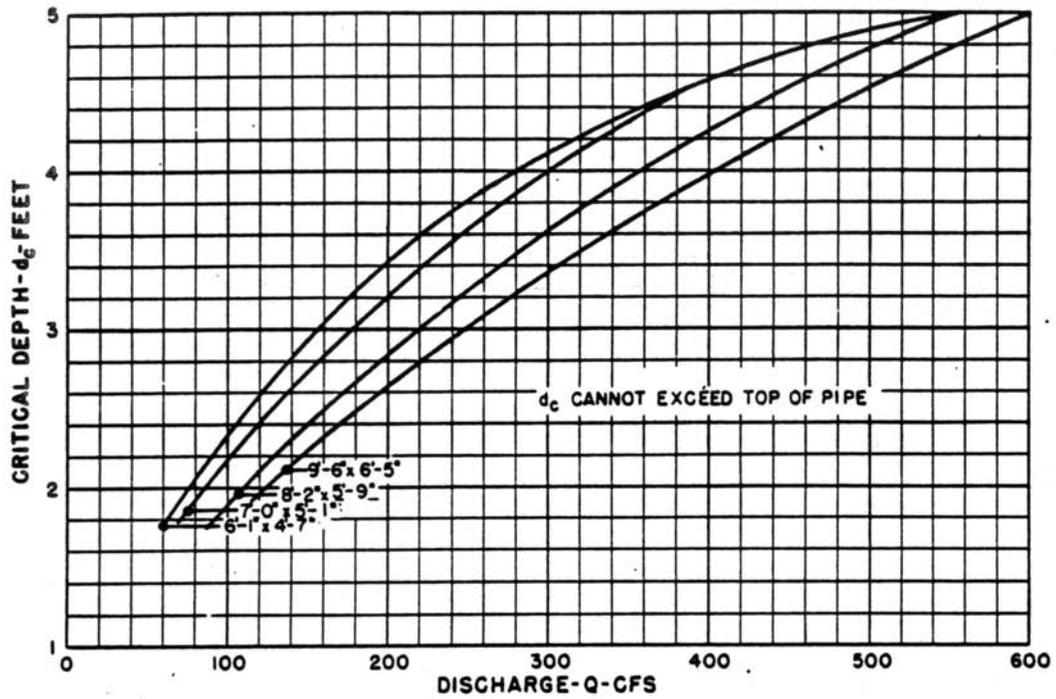
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-22
Critical Depth Chart for Oval Concrete Pipe –
Long Axis Horizontal



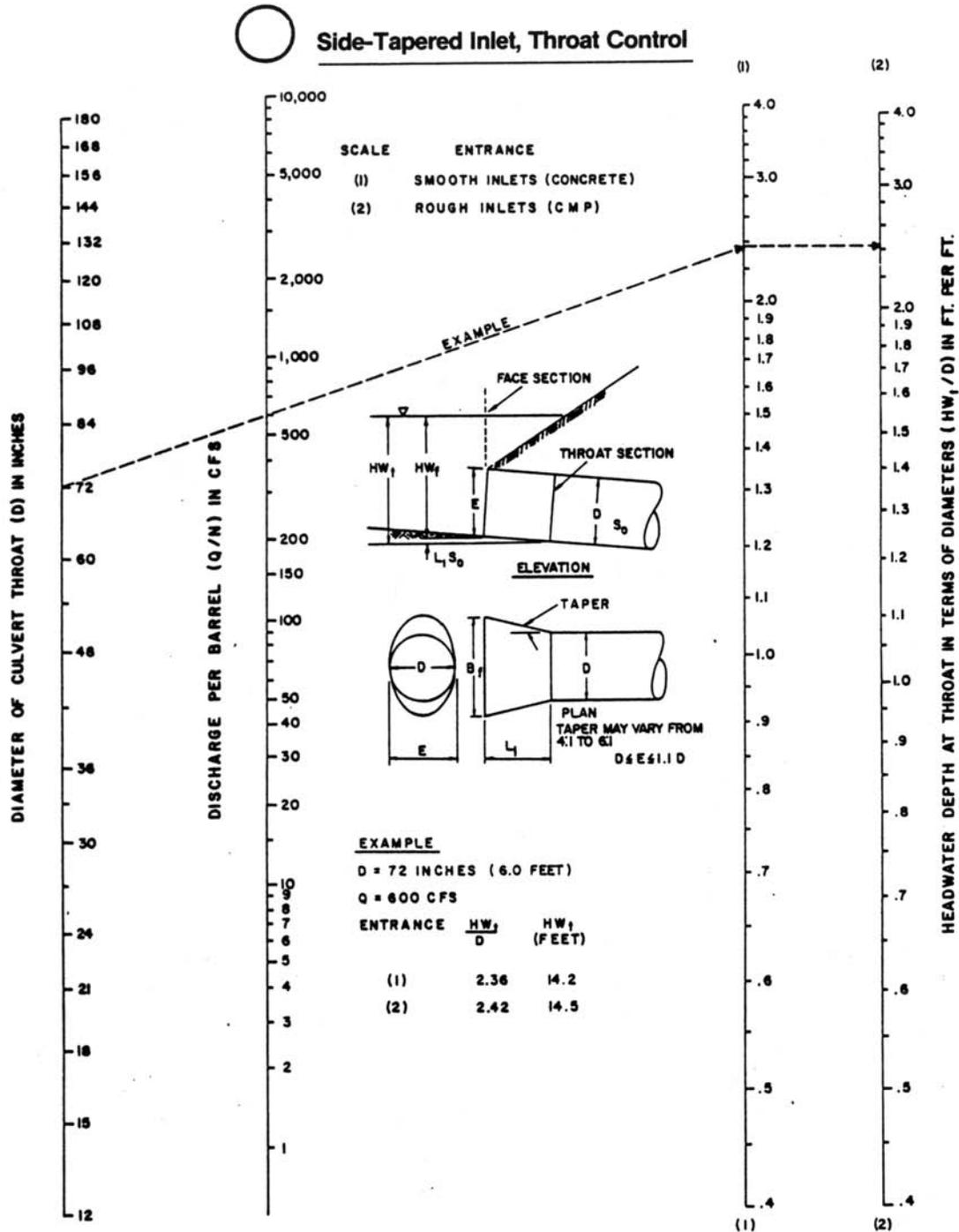
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-23
Critical Depth Chart for Standard CMP Arch



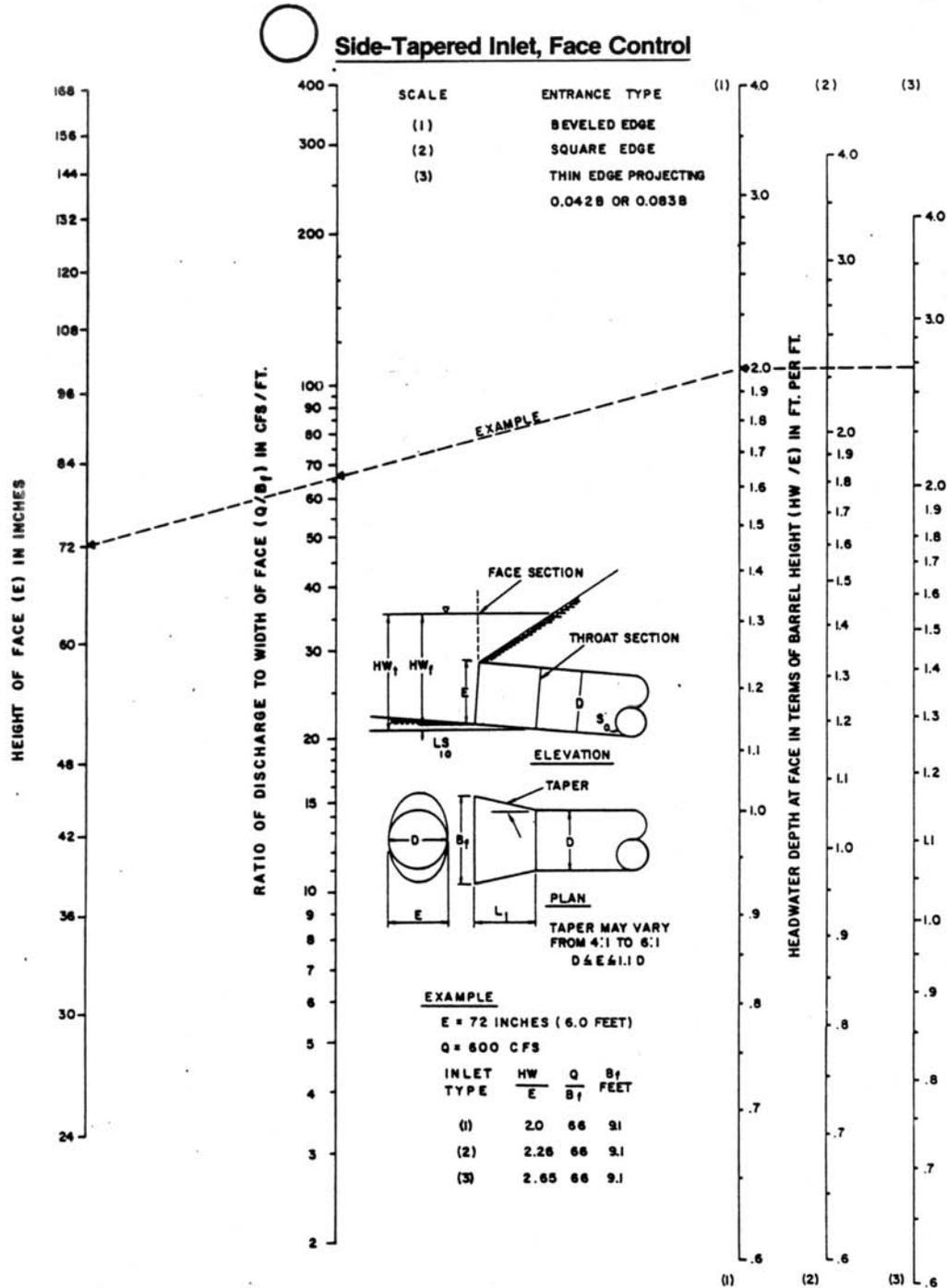
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-24
Critical Depth Chart for Structural Plate CMP Arch



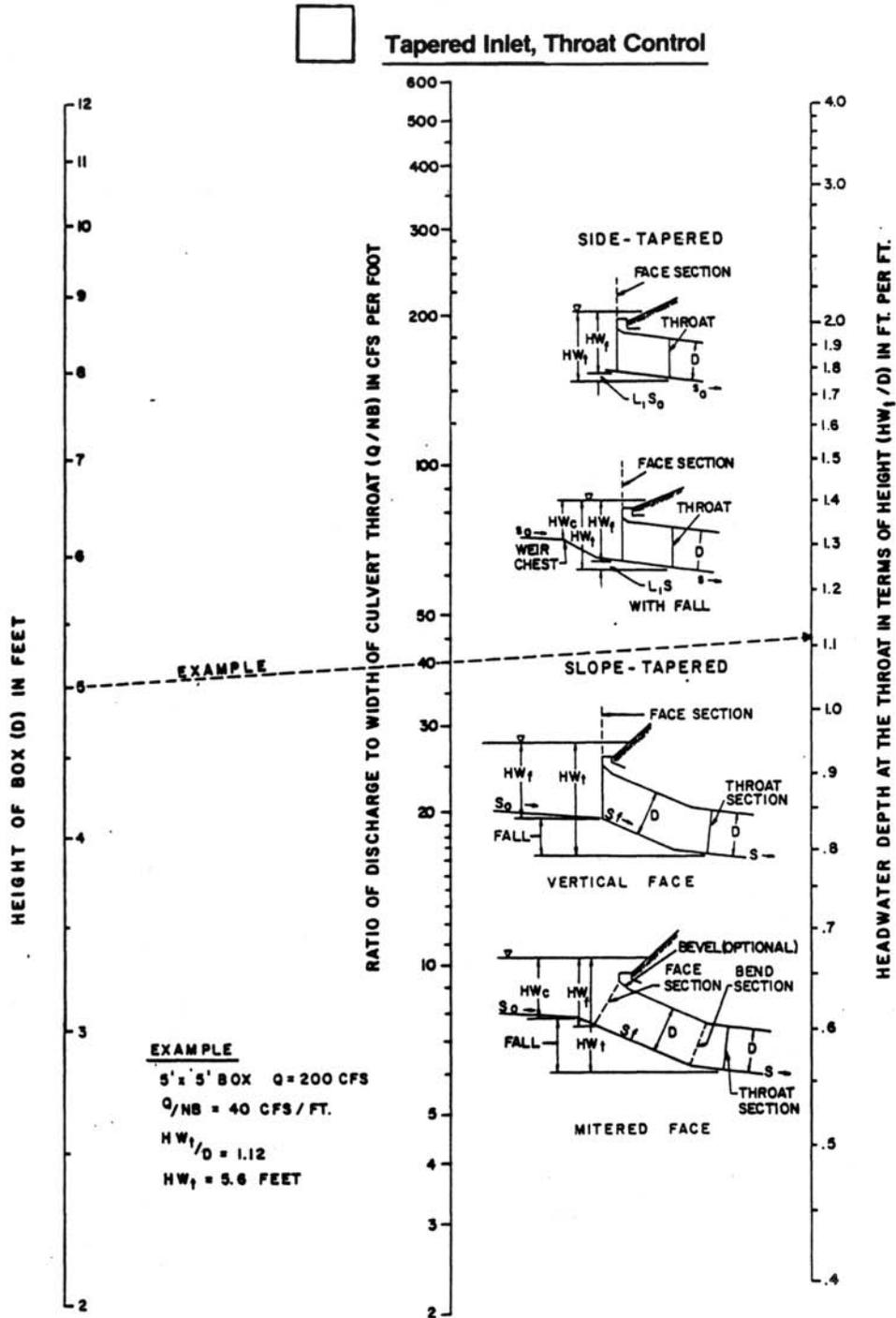
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-25
 Throat Control Chart for Side-Tapered Inlets to Pipe Culvert
 (Circular Section Only)



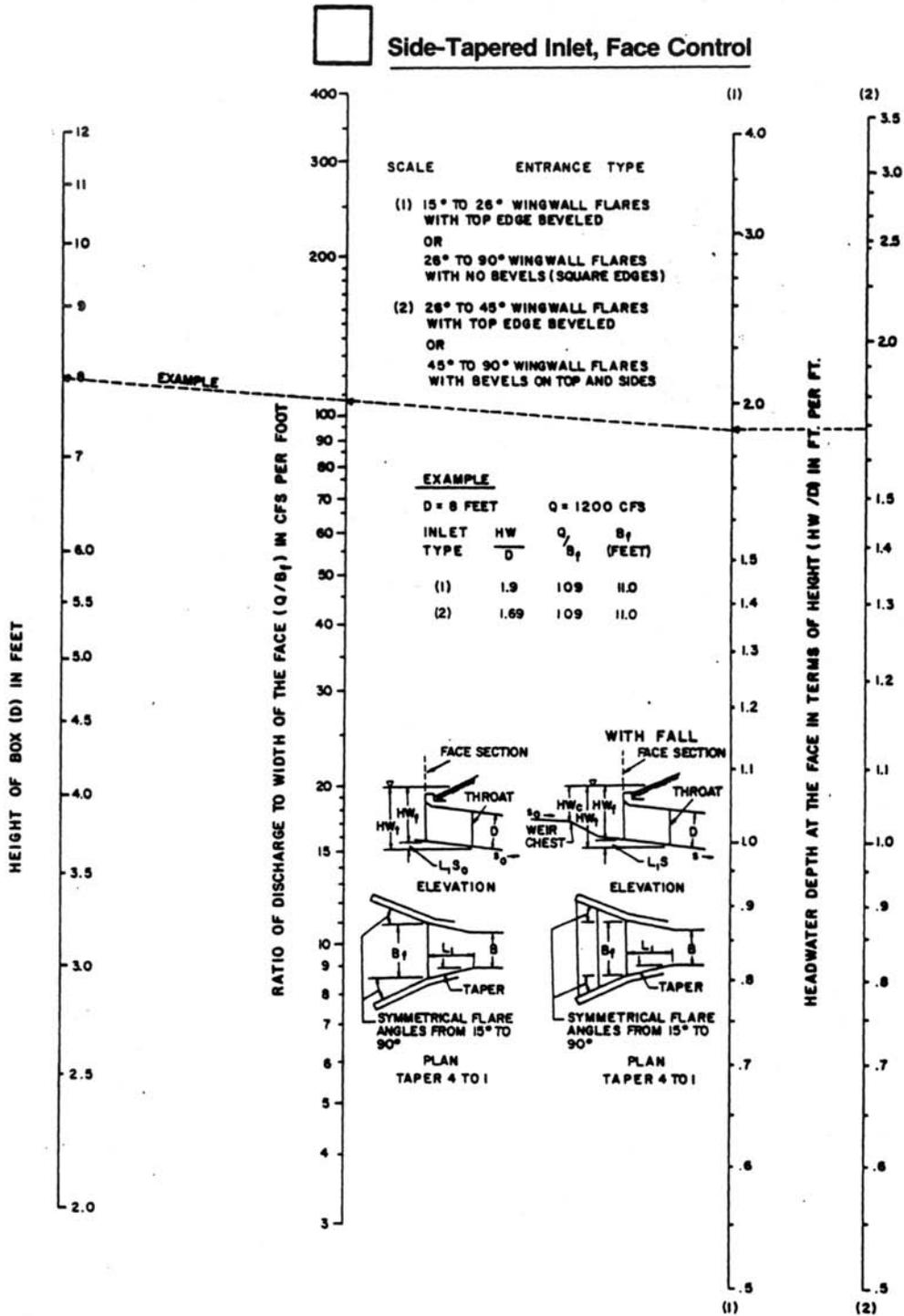
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-26
 Face Control Chart for Side-Tapered Inlets to Pipe Culvert
 (Non-Rectangular Sections Only)



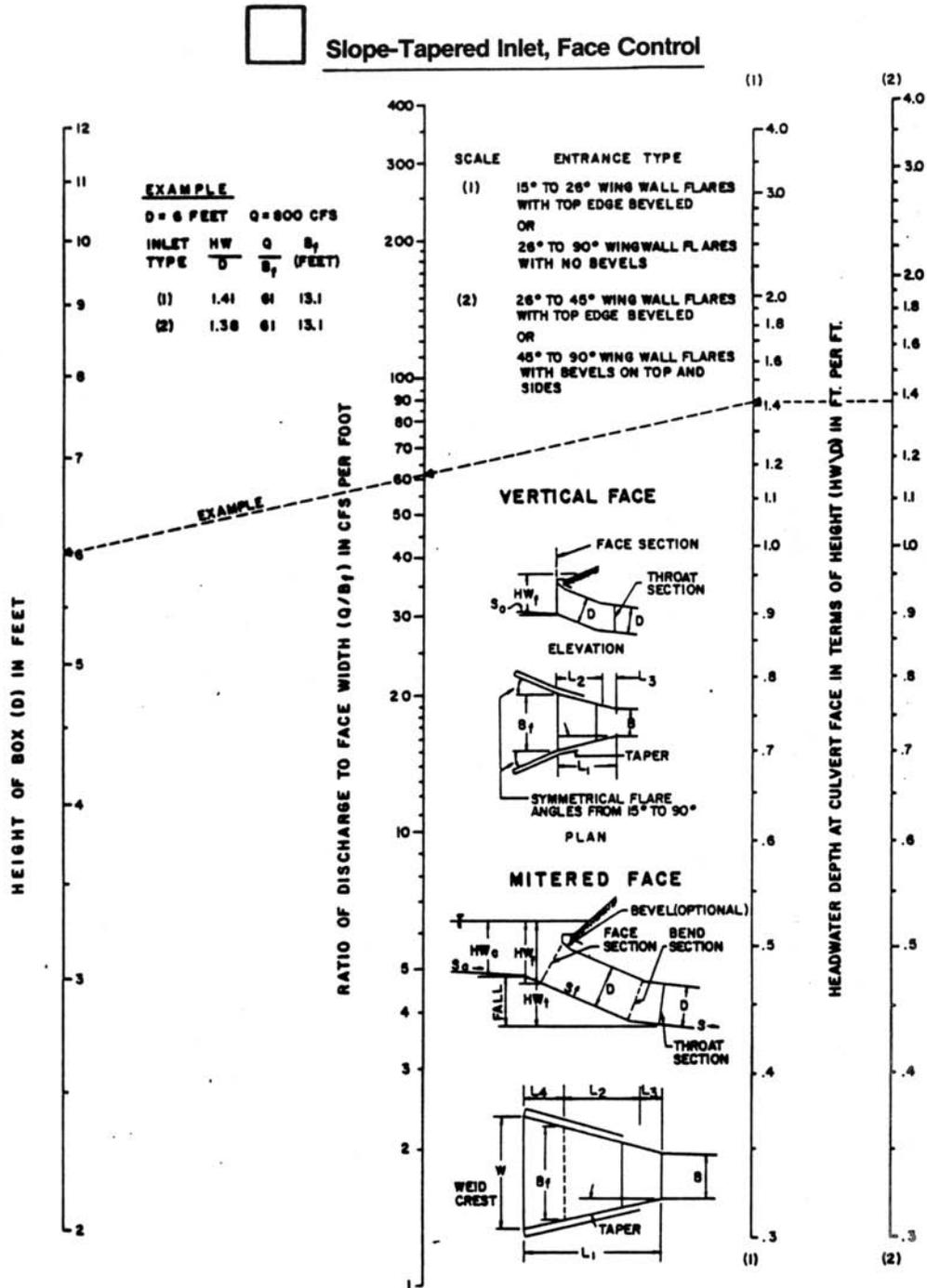
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-27
 Throat Control Chart for Box Culverts with Tapered Inlets



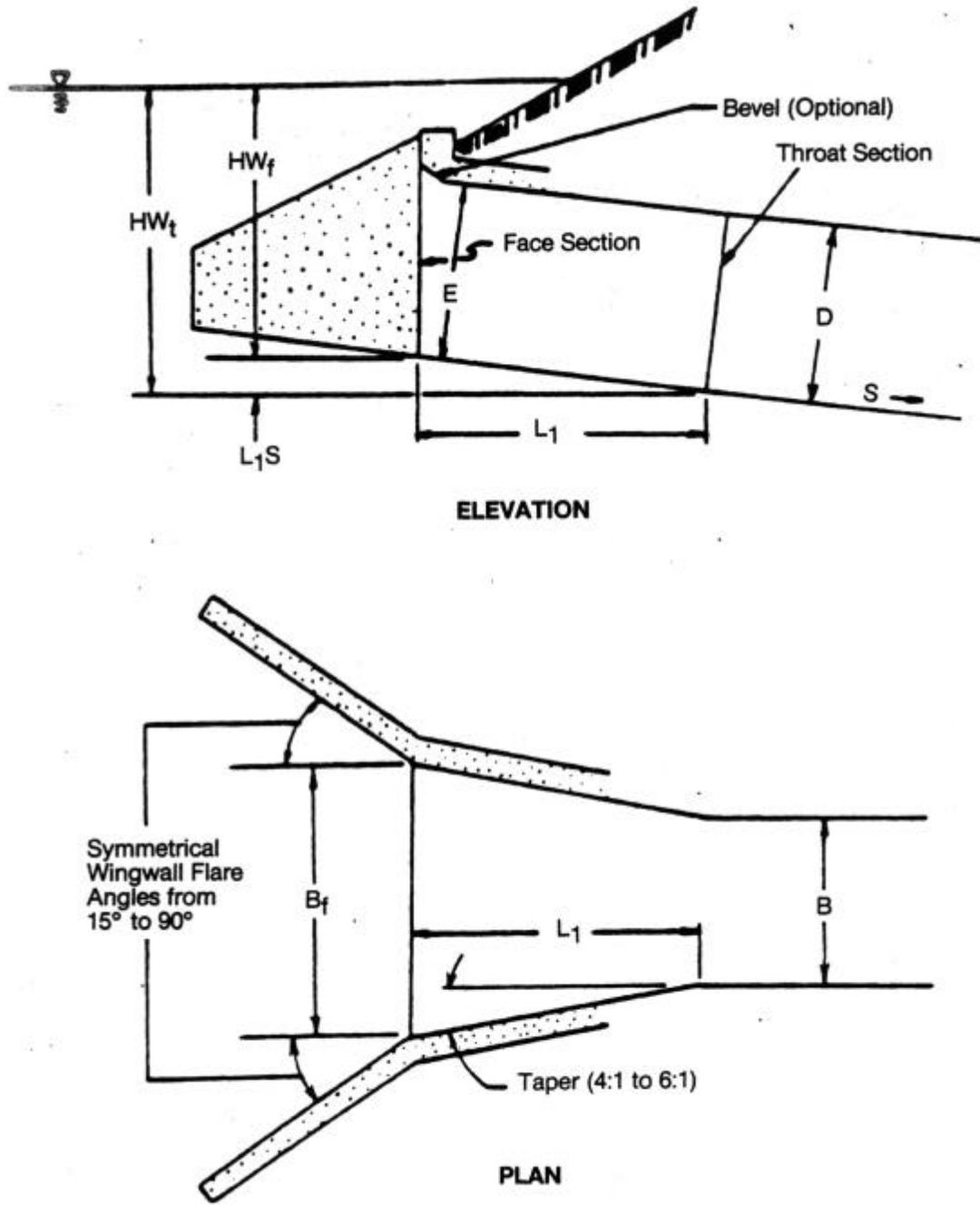
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-28
 Face Control Chart for Box Culverts with Side-Tapered Inlets



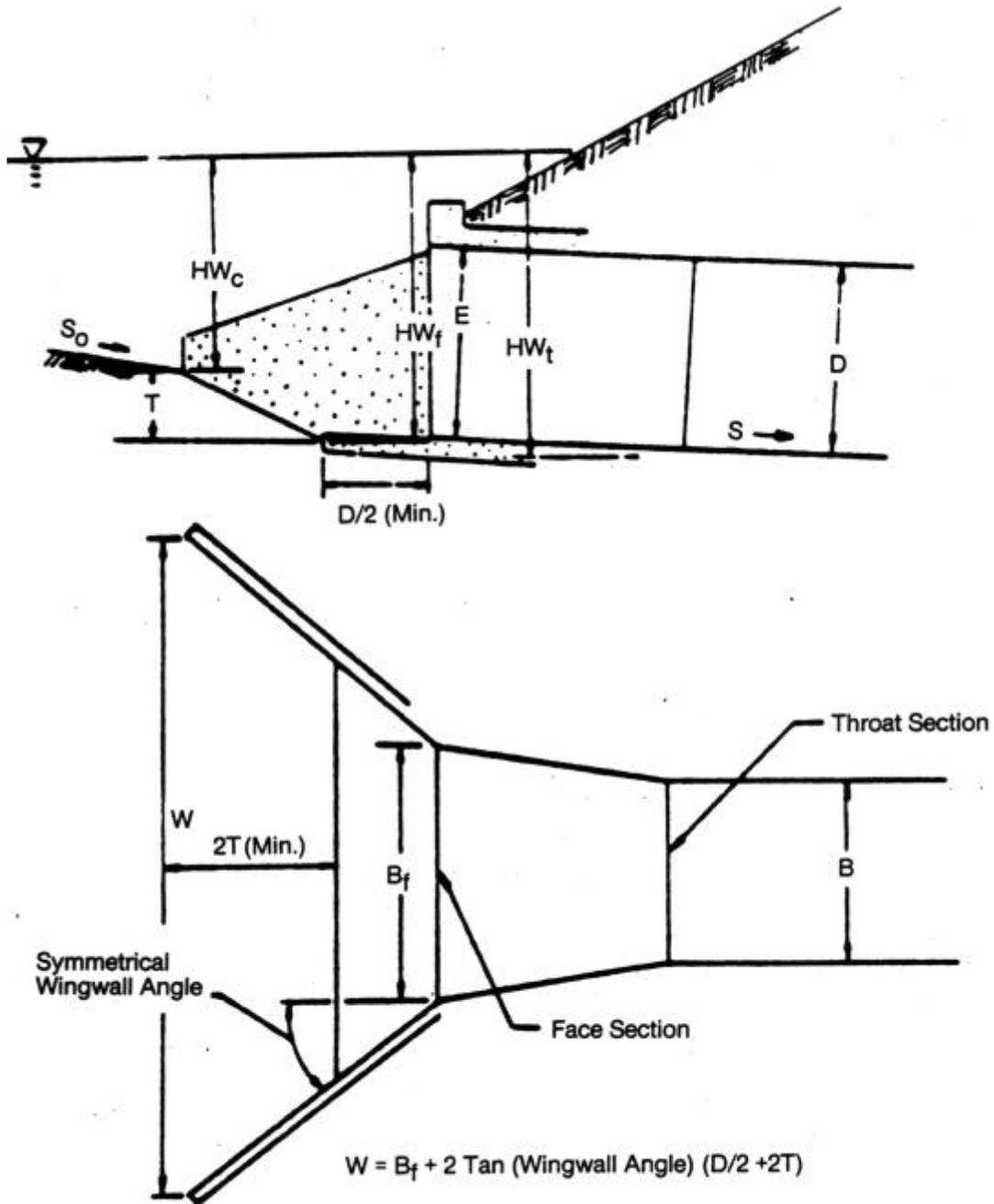
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-29
 Face Control Chart for Box Culverts with Slope-Tapered Inlets



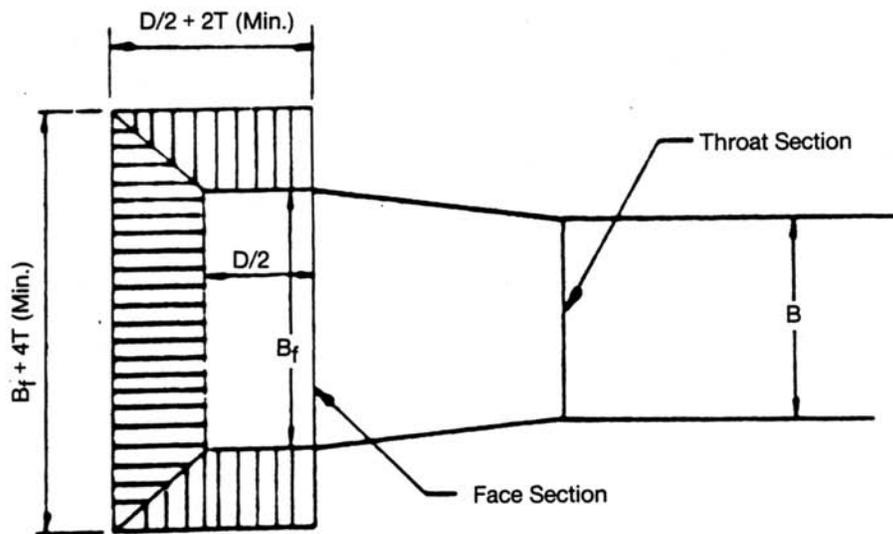
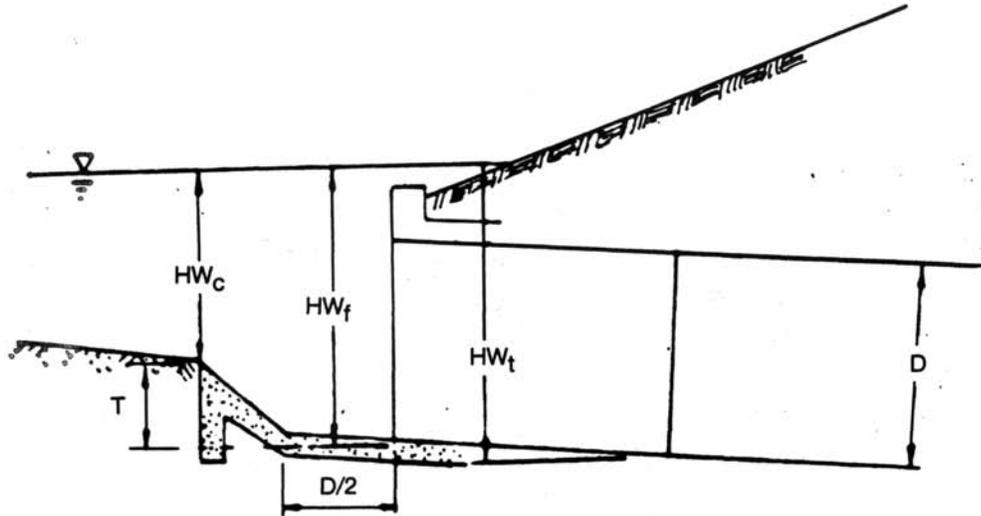
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-30
Typical Side-Tapered Inlet Details



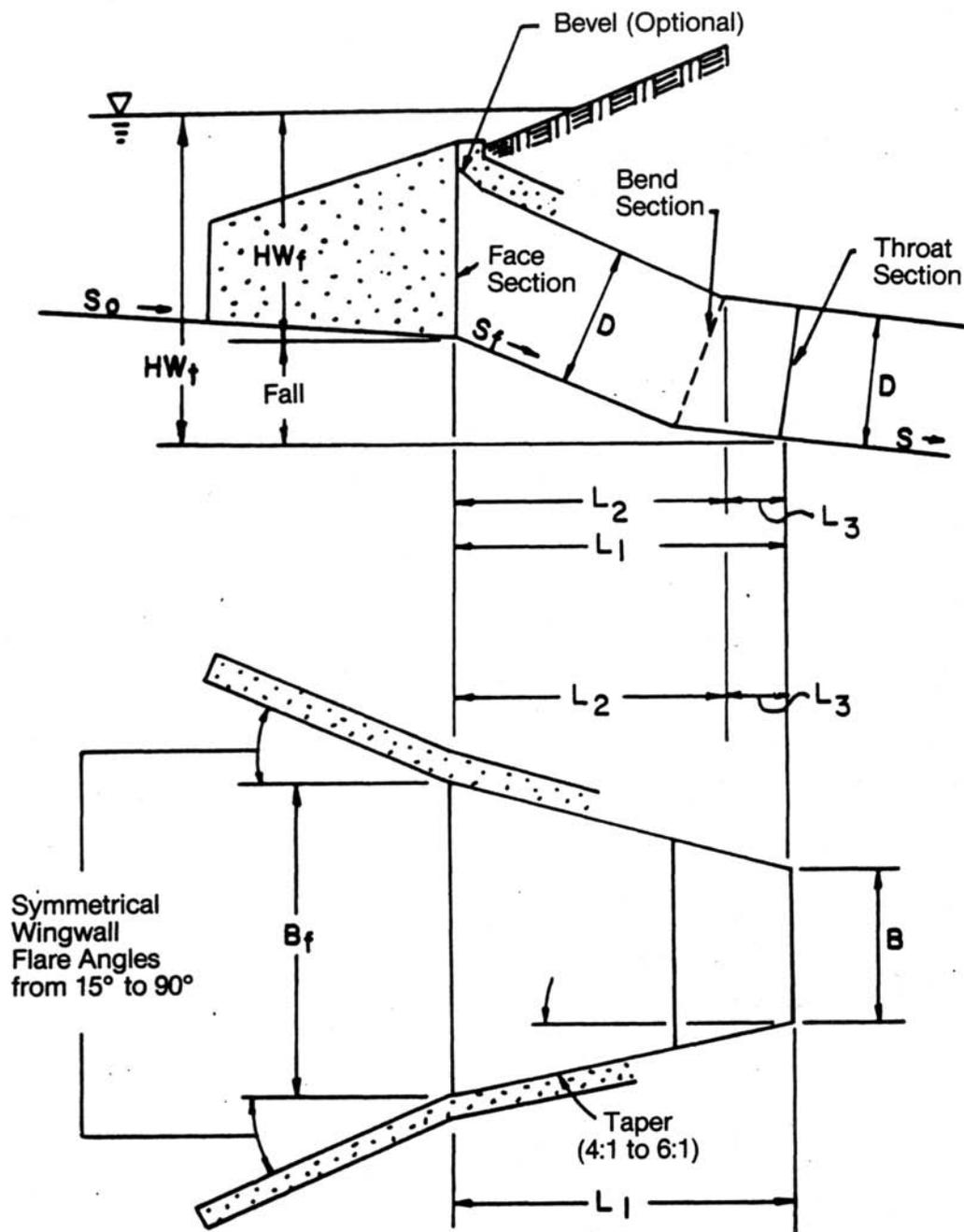
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-31
Side-Tapered Inlet with Upstream
Depression Contained between Wingwalls



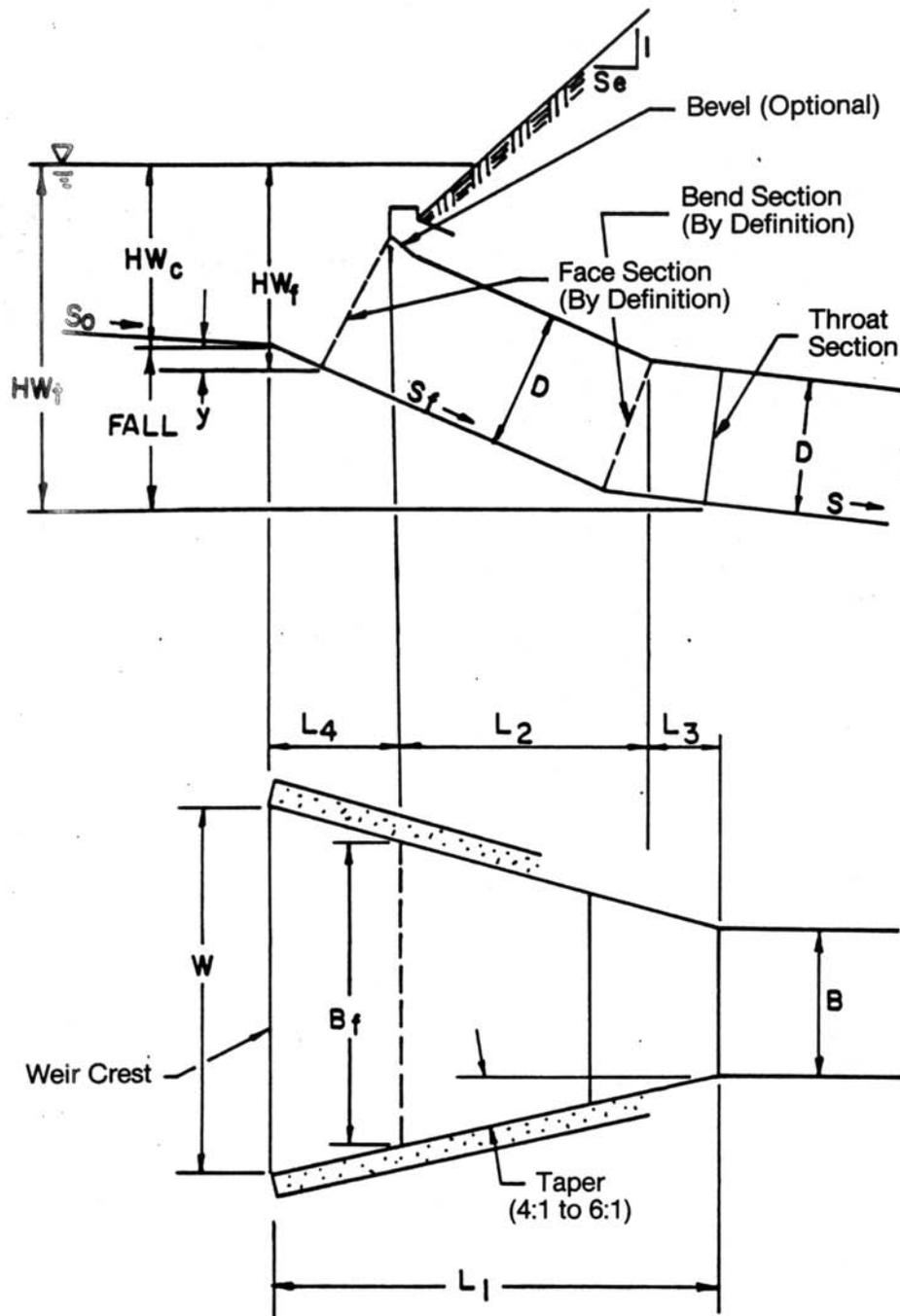
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-32
Side-Tapered Inlet with Upstream Sump



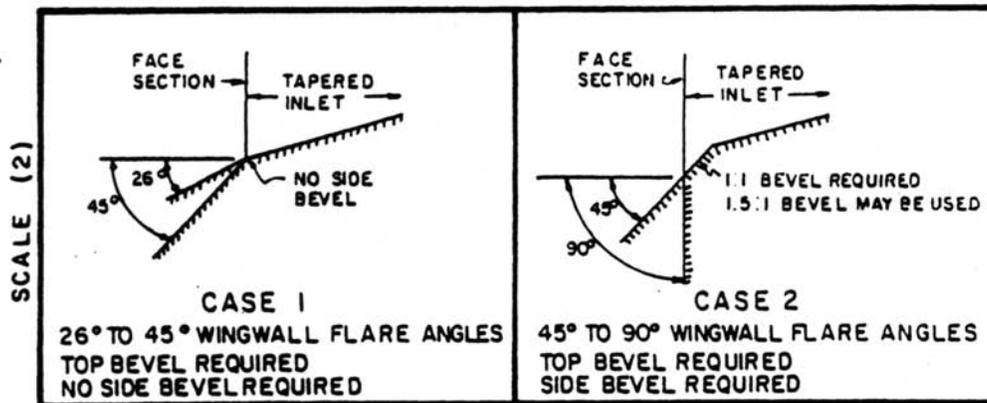
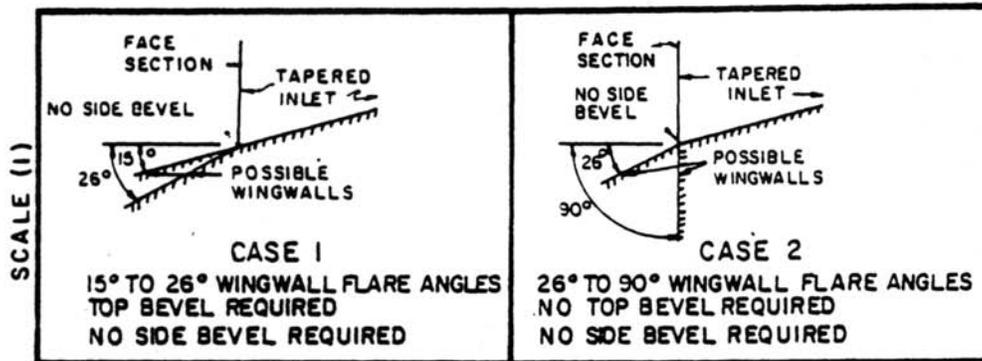
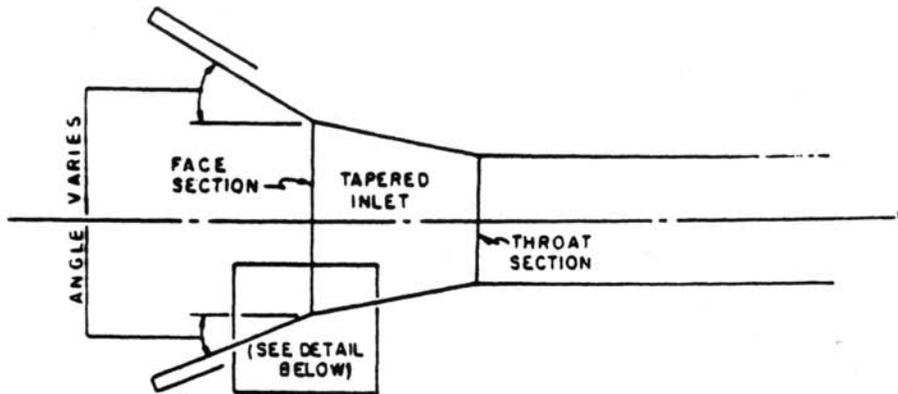
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-33
Slope-Tapered Inlet with Vertical Face



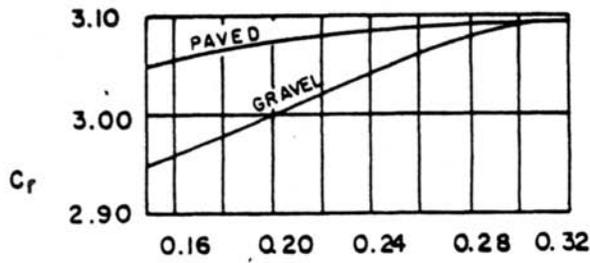
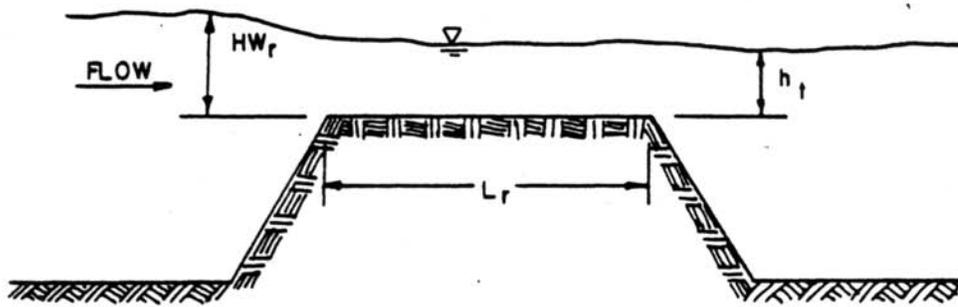
Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-34
Slope-Tapered Inlet with Mitered Face

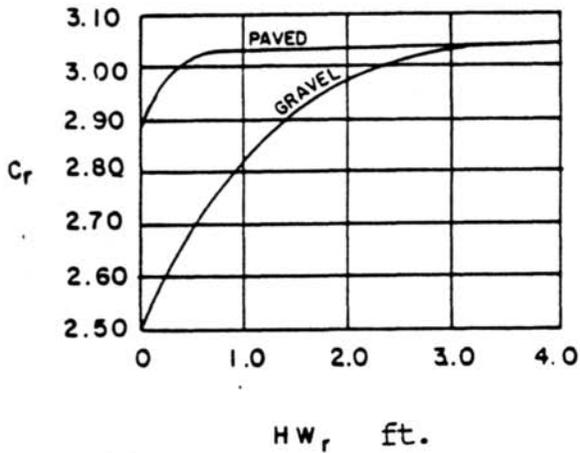


Reference: USDOT, FHWA, HDS-5 (1985).

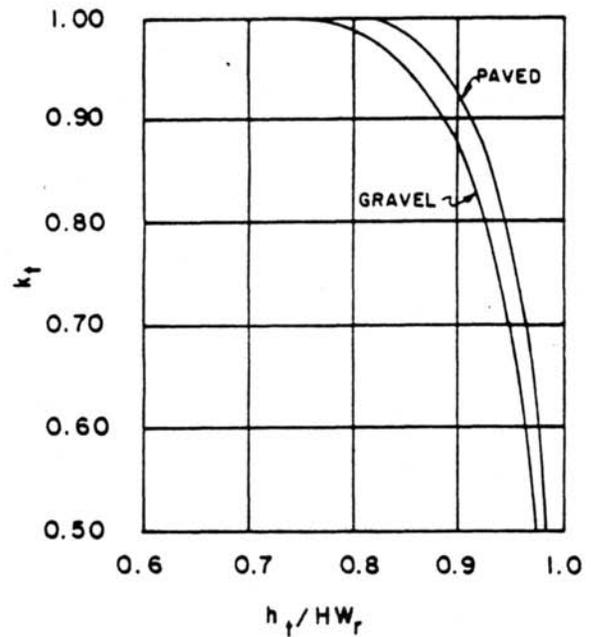
Figure 5-35
 Inlet Edge Conditions, Face Section, Rectangular Tapered Inlets



A) DISCHARGE COEFFICIENT FOR $HW_r/L_r > 0.15$



B) DISCHARGE COEFFICIENT FOR $HW_r/L_r \leq 0.15$



C) SUBMERGENCE FACTOR

Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-36
 Discharge Coefficients for Roadway Overtopping



PROJECT : EXAMPLE 5-1 CHAPTER 5, SECTION 5.3.6	STATION : 1 + 00 SHEET 1 OF 1	CULVERT DESIGN FORM DESIGNER / DATE : VCA / 6/21 REVIEWER / DATE : JES / 6/21	<p style="font-size: small;">SHOULDER ELEVATION: 110.0 (ft) EL_M: 108.0 (ft) EL₁: 100.0 (ft) EL₂: 100.0 (ft) EL₀: 98.0 (ft) S = S₀ - FALL / L₀ S = 0.01 L₀ = 200 (ft)</p>																																														
HYDROLOGICAL DATA <input type="checkbox"/> METHOD: RATIONAL <input type="checkbox"/> DRAINAGE AREA: 125 AC <input type="checkbox"/> STREAM SLOPE: 1.0% <input type="checkbox"/> CHANNEL SHAPE: TRAPEZOIDAL <input type="checkbox"/> ROUTING: N/A <input type="checkbox"/> OTHER:		DESIGN FLOWS/TAILWATER R. I. (YEARS) FLOW (cfs) TW (ft) 10 200 3.5																																															
CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE C.M.P. - Circ-72 in-45° Bevel Headwall C.M.P. - Circ-60 in-45° Bevel Headwall Concrete-Circ-60 in-Groove End, 45° Headwall Concrete-Circ-54 in-Groove End, 45° Headwall		<table border="1" style="width:100%; border-collapse: collapse; font-size: x-small;"> <thead> <tr> <th rowspan="2">TOTAL FLOW Q (cfs)</th> <th colspan="3">INLET CONTROL</th> <th colspan="3">OUTLET CONTROL</th> <th rowspan="2">COMMENTS</th> </tr> <tr> <th>HW/D (2)</th> <th>EL_{N1} (4)</th> <th>TW (5)</th> <th>d_c (6)</th> <th>h₀ (8)</th> <th>H (7)</th> </tr> </thead> <tbody> <tr> <td>200</td> <td>0.97</td> <td>105.8</td> <td>3.5</td> <td>3.8</td> <td>4.9</td> <td>0.2</td> <td>2.5</td> </tr> <tr> <td>200</td> <td>1.42</td> <td>107.0</td> <td>3.5</td> <td>4.1</td> <td>4.6</td> <td>0.2</td> <td>6.0</td> </tr> <tr> <td>200</td> <td>1.36</td> <td>106.8</td> <td>3.5</td> <td>4.1</td> <td>4.6</td> <td>0.2</td> <td>3.0</td> </tr> <tr> <td>200</td> <td>1.78</td> <td>108.0</td> <td>3.5</td> <td>3.9</td> <td>4.2</td> <td>0.2</td> <td>4.8</td> </tr> </tbody> </table>		TOTAL FLOW Q (cfs)	INLET CONTROL			OUTLET CONTROL			COMMENTS	HW/D (2)	EL _{N1} (4)	TW (5)	d _c (6)	h ₀ (8)	H (7)	200	0.97	105.8	3.5	3.8	4.9	0.2	2.5	200	1.42	107.0	3.5	4.1	4.6	0.2	6.0	200	1.36	106.8	3.5	4.1	4.6	0.2	3.0	200	1.78	108.0	3.5	3.9	4.2	0.2	4.8
TOTAL FLOW Q (cfs)	INLET CONTROL				OUTLET CONTROL			COMMENTS																																									
	HW/D (2)	EL _{N1} (4)	TW (5)	d _c (6)	h ₀ (8)	H (7)																																											
200	0.97	105.8	3.5	3.8	4.9	0.2	2.5																																										
200	1.42	107.0	3.5	4.1	4.6	0.2	6.0																																										
200	1.36	106.8	3.5	4.1	4.6	0.2	3.0																																										
200	1.78	108.0	3.5	3.9	4.2	0.2	4.8																																										
TECHNICAL FOOTNOTES: (1) USE Q/NB FOR BOX CULVERTS (2) HW ₁ /D • HW /D OR HW ₁ /D FROM DESIGN CHARTS (3) FALL • HW ₁ - (EL _{N1} - EL ₀), FALL IS ZERO FOR CULVERTS ON GRADE		(4) EL _{N1} • HW ₁ • EL ₁ (INVERT OF INLET CONTROL SECTION) (5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL. (6) h ₀ • TW OR (d _c • D/2) (WHICHEVER IS GREATER) (7) H = [1 + h ₀ • (29 • h ₀ ² L) / R ¹³³] ² / 2g (8) EL _{N0} • EL ₀ • H • h ₀																																															
SUBSCRIPT DEFINITIONS: 0. APPROXIMATE 1. CULVERT HEADWATER 2. HEADWATER IN INLET CONTROL 3. HEADWATER IN OUTLET CONTROL 4. INLET CONTROL SECTION 5. OUTLET CONTROL SECTION 6. STREAMBED AT CULVERT FACE 7. TAILWATER		COMMENTS / DISCUSSION: HIGH OUTLET VELOCITY: OUTLET EROSION PROTECTION OR LARGER CONDUIT MAY BE NECESSARY																																															
CULVERT DEFINITIONS: SIZE: 54 IN. SHAPE: CIRCULAR MATERIAL: CONCRETE n _{0.012 ENTRANCE: GROOVE END, 45° HEADWORKS}		CULVERT BARREL SELECTED: SIZE: 54 IN. SHAPE: CIRCULAR MATERIAL: CONCRETE n _{0.012 ENTRANCE: GROOVE END, 45° HEADWORKS}																																															

Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-37
Culvert Design Form Data for Example 5-1



PROJECT : EXAMPLE 5-2 CHAPTER 5, SECTION 5.3.6		STATION : 2 + 50 SHEET 1 OF 1		CULVERT DESIGN FORM DESIGNER / DATE : VCA / 6/21 REVIEWER / DATE : JES / 6/21																																																						
HYDROLOGICAL DATA <input type="checkbox"/> METHOD : SCS <input type="checkbox"/> DRAINAGE AREA : 200 AC <input type="checkbox"/> STREAM SLOPE : 2.0% <input type="checkbox"/> CHANNEL SHAPE : TRAPEZOIDAL <input type="checkbox"/> ROUTING : N/A <input type="checkbox"/> OTHER :		SHOULDER ELEVATION : 113.5 (ft)																																																								
DESIGN FLOWS/TAIWATER R. I. (YEARS) : 100 FLOW (cfs) : 300 TW (ft) : 4.0		$S = S_0 - \text{FALL} / L_0$ $S = 0.02$ $L_0 = 250$ (ft)																																																								
CULVERT DESCRIPTION : MATERIAL - SHAPE - SIZE - ENTRANCE.		TOTAL FLOW PER CHANNEL Q (cfs)		HEADWATER CALCULATIONS																																																						
				<table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">INLET CONTROL</th> <th colspan="3">OUTLET CONTROL</th> <th rowspan="2">CONTROL</th> <th rowspan="2">HEADWATER ELEVATION</th> <th rowspan="2">OUTLET VELOCITY</th> <th rowspan="2">COMMENTS</th> </tr> <tr> <th>HW_i/D (2)</th> <th>HW_i (1)</th> <th>FALL (3)</th> <th>EL_{hi} (4)</th> <th>TW (5)</th> <th>d_c (6)</th> <th>h₀ (7)</th> <th>H (8)</th> </tr> </thead> <tbody> <tr> <td>1.57</td> <td>7.9</td> <td>0</td> <td>107.9</td> <td>4.0</td> <td>4.25</td> <td>4.6</td> <td>3.6</td> <td>103.2</td> <td>107.9</td> <td>21.1</td> <td>Try Smaller Box</td> </tr> <tr> <td>1.91</td> <td>9.6</td> <td>0</td> <td>109.6</td> <td>4.0</td> <td>4.8</td> <td>4.9</td> <td>5.2</td> <td>105.1</td> <td>109.6</td> <td>21.2</td> <td>Check Bevels</td> </tr> <tr> <td>1.71</td> <td>8.6</td> <td>0</td> <td>108.6</td> <td>4.0</td> <td>4.8</td> <td>4.9</td> <td>4.6</td> <td>104.5</td> <td>108.6</td> <td>21.2</td> <td>Okay Inlet Control</td> </tr> </tbody> </table>		INLET CONTROL		OUTLET CONTROL			CONTROL	HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS	HW _i /D (2)	HW _i (1)	FALL (3)	EL _{hi} (4)	TW (5)	d _c (6)	h ₀ (7)	H (8)	1.57	7.9	0	107.9	4.0	4.25	4.6	3.6	103.2	107.9	21.1	Try Smaller Box	1.91	9.6	0	109.6	4.0	4.8	4.9	5.2	105.1	109.6	21.2	Check Bevels	1.71	8.6	0	108.6	4.0	4.8	4.9	4.6	104.5	108.6	21.2	Okay Inlet Control
INLET CONTROL		OUTLET CONTROL			CONTROL	HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS																																																		
HW _i /D (2)	HW _i (1)	FALL (3)	EL _{hi} (4)	TW (5)					d _c (6)	h ₀ (7)	H (8)																																															
1.57	7.9	0	107.9	4.0	4.25	4.6	3.6	103.2	107.9	21.1	Try Smaller Box																																															
1.91	9.6	0	109.6	4.0	4.8	4.9	5.2	105.1	109.6	21.2	Check Bevels																																															
1.71	8.6	0	108.6	4.0	4.8	4.9	4.6	104.5	108.6	21.2	Okay Inlet Control																																															
TECHNICAL FOOTNOTES: (1) USE Q/NB FOR BOX CULVERTS (2) HW _i /D = HW _i /D OR HW _i /D FROM DESIGN CHARTS (3) FALL = HW _i - (EL _{hd} - EL _{ft}); FALL IS ZERO FOR CULVERTS ON GRADE		(4) EL _{hd} = HW _i + EL _i (INVERT OF INLET CONTROL SECTION) (5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL. (6) h ₀ = TW OR (d _c + D/2) (WHICHEVER IS GREATER) (7) H = [1 + h ₀ + (29m ² L) / R ^{1.33}] v ² / 2g (8) EL _{ho} = EL ₀ + H + h ₀																																																								
SUBSCRIPT DEFINITIONS : 0 APPROXIMATE F CULVERT FACE N _F DESIGN HEADWATER N _i HEADWATER IN INLET CONTROL SECTION N _o HEADWATER IN OUTLET CONTROL SECTION o OUTLET st STREAMBED AT CULVERT FACE TW TAILWATER		COMMENTS / DISCUSSION : 5' x 5' BOX WILL WORK WITH OR WITHOUT BEVELS. BEVELS PROVIDE ADDITIONAL FLOW CAPACITY. HIGH OUTLET VELOCITIES EXIST.																																																								
		CULVERT BARREL SELECTED : SIZE : 5 FT. x 5 FT. SHAPE : RECTANGULAR MATERIAL : CONCRETE n : 0.012 ENTRANCE : 90° HEADWALL																																																								

Reference: USDOT, FHWA, HDS-5 (1985).

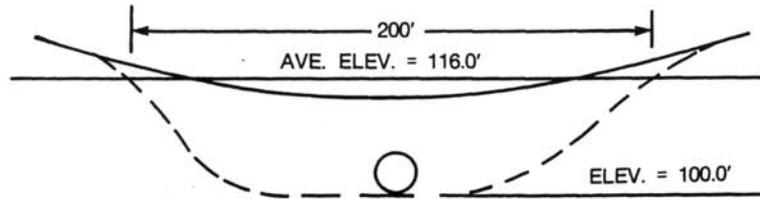
Figure 5-38
Culvert Design Form
Data for Example 5-2



<p>PROJECT : EXAMPLE 5-3 CHAPTER 5, SECTION 5.3.6</p>	<p>STATION : 4 + 00 SHEET 2 OF 3</p>	<p>CULVERT DESIGN FORM DESIGNER / DATE : VCA / 6/21 REVIEWER / DATE : JES / 6/21</p>	<p>HYDROLOGICAL DATA <input type="checkbox"/> METHOD: SCS <input type="checkbox"/> DRAINAGE AREA: 400 AC. <input type="checkbox"/> STREAM SLOPE: 5.0% <input type="checkbox"/> CHANNEL SHAPE: TRAPEZOIDAL <input type="checkbox"/> ROUTING: N/A <input type="checkbox"/> OTHER: _____</p> <p>DESIGN FLOWS/TAIWATER R.I. (YEARS) _____ TW (IN) _____ 100 (OLD) 600 3.1 100 (NEW) 1000 4.1</p>																																																																				
<p>CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE</p> <p>Conc.-Box-7'x7'-Square Edge</p>			<p>SHOULDER ELEVATION: 116.5 (ft) EL_M: 114.0 (ft) EL_I: 100.0 (ft) EL_O: 90.0 (ft) S = S₀ - FALL / L₀ S = 0.05 L₀ = 200 (ft)</p>																																																																				
<p>HEADWATER CALCULATIONS</p> <table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th rowspan="2">TOTAL FLOW PER BARREL Q (c.f.s.)</th> <th colspan="3">INLET CONTROL</th> <th colspan="3">OUTLET CONTROL</th> <th rowspan="2">CONTROL ELEVATION</th> <th rowspan="2">OUTLET VELOCITY</th> <th rowspan="2">COMMENTS</th> </tr> <tr> <th>HW_I/D (2)</th> <th>HW_I (3)</th> <th>FALL (4)</th> <th>TW (5)</th> <th>h₀ (6)</th> <th>h₀ (7)</th> <th>EL_{hd} (8)</th> </tr> </thead> <tbody> <tr> <td>850</td> <td>2.55</td> <td>17.9</td> <td>0</td> <td>117.9</td> <td>3.9</td> <td>≥ 7.0</td> <td>7.0</td> <td>0.5</td> <td>106.0</td> <td>117.9</td> <td>38.7</td> <td>—</td> </tr> <tr> <td>900</td> <td>2.72</td> <td>19.0</td> <td>0</td> <td>119.0</td> <td>4.0</td> <td>≥ 7.0</td> <td>7.0</td> <td>0.5</td> <td>107.3</td> <td>119.0</td> <td>39.3</td> <td>—</td> </tr> <tr> <td>950</td> <td>2.96</td> <td>20.7</td> <td>0</td> <td>120.7</td> <td>4.0</td> <td>≥ 7.0</td> <td>7.0</td> <td>0.5</td> <td>108.4</td> <td>120.7</td> <td>39.9</td> <td>—</td> </tr> <tr> <td>1000</td> <td>3.21</td> <td>22.5</td> <td>0</td> <td>122.5</td> <td>4.1</td> <td>≥ 7.0</td> <td>7.0</td> <td>0.5</td> <td>109.8</td> <td>122.5</td> <td>40.4</td> <td>—</td> </tr> </tbody> </table>			TOTAL FLOW PER BARREL Q (c.f.s.)	INLET CONTROL			OUTLET CONTROL			CONTROL ELEVATION	OUTLET VELOCITY	COMMENTS	HW _I /D (2)	HW _I (3)	FALL (4)	TW (5)	h ₀ (6)	h ₀ (7)	EL _{hd} (8)	850	2.55	17.9	0	117.9	3.9	≥ 7.0	7.0	0.5	106.0	117.9	38.7	—	900	2.72	19.0	0	119.0	4.0	≥ 7.0	7.0	0.5	107.3	119.0	39.3	—	950	2.96	20.7	0	120.7	4.0	≥ 7.0	7.0	0.5	108.4	120.7	39.9	—	1000	3.21	22.5	0	122.5	4.1	≥ 7.0	7.0	0.5	109.8	122.5	40.4	—
TOTAL FLOW PER BARREL Q (c.f.s.)	INLET CONTROL			OUTLET CONTROL			CONTROL ELEVATION	OUTLET VELOCITY	COMMENTS																																																														
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<p>TECHNICAL FOOTNOTES: (1) USE Q/NB FOR BOX CULVERTS (2) HW_I/D = HW / D OR HW_I/D FROM DESIGN CHARTS (3) FALL = HW_I - (EL_{hd} - EL_{sp}), FALL IS ZERO FOR CULVERTS ON GRADE</p>			<p>(4) EL_M = HW_I, EL_I (INVERT OF INLET CONTROL SECTION) (5) TW BASED ON DOWNSTREAM CONTROL OR FLOW DEPTH IN CHANNEL. (6) h₀ = TW or (d_c + D/2) (WHICHEVER IS GREATER) (7) H = [1 + h₀ + (29n²L) / R^{1.33}] V² / 2g (8) EL_{hd} = EL_O + H + h₀</p>																																																																				
<p>SUBSCRIPT DEFINITIONS: A APPROXIMATE F CULVERT FACE M DESIGN HEADWATER N HEADWATER IN INLET CONTROL O HEADWATER IN OUTLET CONTROL I INLET CONTROL SECTION O OUTLET CONTROL SECTION S STREAMBED AT CULVERT FACE M TAILWATER</p>			<p>COMMENTS / DISCUSSION: NEW Q=100 RESULTS IN ROADWAY OVERTOPPING OF ABOUT 2.0' (SEE FIGURE 5-40).</p> <p>CULVERT BARREL SELECTED: SIZE: 7 FT. X 7 FT. SHAPE: RECTANGULAR MATERIAL: CONCRETE R 0.012 ENTRANCE: SQ. EDGE W/HEADWALL</p>																																																																				

Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-39
Culvert Design Form
Data for Example 5-3



Culvert Flow (cfs)	EL _h (ft)	HW _r (ft)	C _d	Q _o Weir Flow (cfs)	Q Total Flow (cfs)
400	108.1	-	-	-	400
450	108.9	-	-	-	450
500	109.7	-	-	-	500
550	110.6	-	-	-	550
600	111.6	-	-	-	600
650	112.6	-	-	-	650
700	113.7	-	-	-	700
750	115.0	-	-	-	750
800	116.5	0.5	2.70	191	991
850	117.9	1.9	2.97	1,556	2,406
900	119.0	3.0	3.03	3,150	4,049
950	120.7	4.7	3.03	6,175	7,125
1000	122.5	6.5	3.03	10,043	11,043

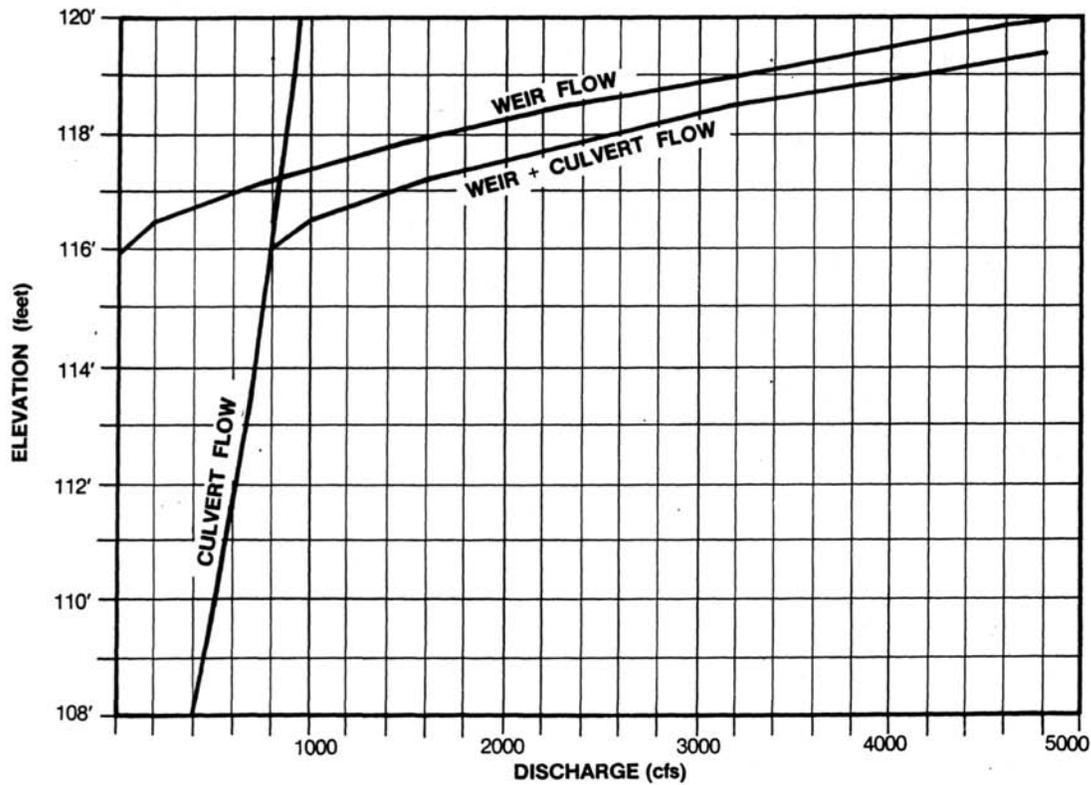


Figure 5-40
 Roadway Overtopping Data for Example 5-3



PROJECT : **EXAMPLE 5-4**
CHAPTER 5, SECTION 5.3.6

STATION : **4 + 00**
SHEET **1** OF **3**

CULVERT DESIGN FORM
DESIGNER / DATE : **VCA / 6/22**
REVIEWER / DATE : **JES / 6/22**

SHOULDER ELEVATION: **116.0 (11)**

EL_{hd} **114.0 (11)**
EL_{st} **100.0 (11)**
EL_o **90.0 (11)**
S = S_o - FALL / L_o
S = **0.05**
L_o = **200 (ft)**

HYDROLOGICAL DATA
METHOD: SCS
DRAINAGE AREA: **400 AC** STREAM SLOPE: **5.0%**
CHANNEL SHAPE: **TRAPEZOIDAL**
ROUTING: N/A OTHER

DESIGN FLOWS/TAIWATER
R. I. (YEARS) **100** FLOW (cfs) **1000** TW (ft) **4.1**

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/N (1)	INLET CONTROL			OUTLET CONTROL			CONTROL ELEVATION	OUTLET VELOCITY	COMMENTS					
			HW ₁ (2)	TW (5)	EL _{h1} (4)	FALL (3)	d _c (6)	h _o (9)				EL _{no} (8)	H (7)			
Conc.-Box-7'x7'-Tapered Inlet	1000	142.9	2.0	14.0	0	114.0	4.1	≥7	7.0	7.0	0.2	10.6	107.6	114.0	40.4	Meets El.hd
Conc.-Box-7'x7'-Tapered Inlet	800	114.3	1.61	11.3	0	111.3	3.8	≥7	7.0	7.0	0.2	6.7	103.7	111.3	38.1	Throat Outlet
Conc.-Box-7'x7'-Tapered Inlet	900	128.6	1.84	12.9	0	112.9	4.0	≥7	7.0	7.0	0.2	8.4	105.4	112.9	39.3	Control Performance
Conc.-Box-7'x7'-Tapered Inlet	1100	157.1	2.22	15.5	0	115.5	4.3	≥7	7.0	7.0	0.2	12.7	109.7	115.5	41.3	Data

HEADWATER CALCULATIONS

TECHNICAL FOOTNOTES:
 (1) USE Q/NB FOR BOX CULVERTS
 (2) HW₁/D = HW / D OR HW₁/D FROM DESIGN CHARTS
 (3) FALL = HW₁ - (EL_{hd} - EL_{st}); FALL IS ZERO FOR CULVERTS ON GRADE
 (4) EL_{h1} = HW₁; EL_{h1} (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 + h_o (29n² L) / R^{1.35}] V² / 2g
 (8) EL_{no} = EL_o + H + h_o

SUBSCRIPT DEFINITIONS:
 0 APPROXIMATE
 1 CULVERT FACE
 2 DESIGN HEADWATER
 3 HEADWATER IN INLET CONTROL
 4 HEADWATER IN OUTLET CONTROL
 5 INLET CONTROL SECTION
 6 OUTLET
 7 STREAMBED AT CULVERT FACE
 8 TAILWATER

COMMENTS / DISCUSSION:
 SIDE-TAPERED INLET WILL PASS NEW DESIGN FLOW (1000 cfs) IF ATTACHED TO EXISTING BARREL.

CULVERT BARREL SELECTED:
 SIZE: **7' x 7'**
 SHAPE: **RECTANGULAR**
 MATERIAL: **CONCRETE n 0.012**
 ENTRANCE: **TAPERED INLET**

Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-41
Culvert Design Form
Data for Example 5-4



PROJECT : <u>EXAMPLE 5-4</u> CHAPTER 5, SECTION 5.3.6		STATION : <u>4 + 00</u> SHEET <u>2</u> OF <u>3</u>		TAPERED INLET DESIGN FORM DESIGNER / DATE: <u>VSA / 6/22</u> REVIEWER / DATE: <u>JS / 6/22</u>										
DESIGN DATA: Q <u>100</u> cfs ; EL _N <u>114.0</u> ft EL. THROAT INVERT <u>100.0</u> ft EL. STREAM BED AT FACE <u>100.0</u> ft FALL <u>0</u> ft TAPER <u>4</u> : 1 (4:1 TO 6:1) STREAM SLOPE, S ₀ = <u>0.05</u> ft/ft SLOPE OF BARREL, S = <u>0.05</u> ft/ft S ₁ : 1 (2:1 TO 3:1) <u>BOX-CONCRETE</u> BARREL SHAPE AND MATERIAL : <u>BOX-CONCRETE</u> N = <u>1</u> , B = <u>7.0'</u> , D = <u>7.0'</u> INLET EDGE DESCRIPTION _____				COMMENTS										
Q (cfs)	EL _N THROAT INVERT (1)	EL. FACE INVERT (2)	HW _f E (3)	HW _f E (3)	Q B _f (4)	MIN. B _f (5)	SIDE - TAPERED			SLOPE - TAPERED			EL. CREST INV. (12)	MIN. W (13)
							SELECTED B _f	L ₃ (6)	L ₂ (7)	CHECK L ₂ (8)	ADJ. L ₃ (9)	ADJ. TAPER (10)		
1000	114.0	101.0	13.0	1.86	86	11.6	12					10		
1000	113.0	100.5	12.5	1.79	83	←	12							
800	110.7	100.0	10.2	1.45	67	←	12							
900	111.8	100.0	11.3	1.62	75	←	12							
1100	114.4	100.0	13.9	1.99	92	←	12							
Performance Curve Data														
(1) SIDE - TAPERED : EL. FACE INVERT = EL. THROAT INVERT + I _t (APPROX.) SLOPE - TAPERED : EL. FACE INVERT = EL. STREAM BED AT FACE (2) HW _f = EL _N - EL. FACE INVERT (3) I _t = 2 E Z D : E = HEIGHT OF INLET (4) FROM DESIGN CHARTS : FIG 5-25-5-28 (5) MIN. B _f = Q / (Q / B _f) (6) MIN. L ₃ = 0.5 MB (7) L ₂ = (EL. FACE INVERT - EL. THROAT INVERT) S ₁ (8) CHECK L ₂ = $\left[\frac{B_f - MB}{2} \right]$ · TAPER - L ₃ (9) IF (8) > (7), ADJ. L ₃ = $\left[\frac{B_f - MB}{2} \right]$ · TAPER - L ₂ (10) IF (7) > (8), ADJ. TAPER = (L ₂ · L ₃) / $\left[\frac{B_f - MB}{2} \right]$ (11) SIDE - TAPERED : L = $\left[\frac{B_f - MB}{2} \right]$ · TAPER SLOPE - TAPERED : L ₁ = L ₂ + L ₃ (12) HW _C = EL _N - EL. CREST INVERT (13) MIN. W = 0.35 Q / HW _C *Actual Invert = EL _t + L ₁ S = 100 + (10)(.05) = 100.5 ft														
SELECTED DESIGN B _f <u>12.0</u> L ₁ <u>10.0</u> L ₂ <u>—</u> L ₃ <u>—</u> BEVELS ANGLE <u>0</u> ° b = <u>0</u> in.; d = <u>0</u> in TAPER <u>4</u> : 1 S _f = <u>0</u> : 1														

Reference: USDOT, FHWA, HDS-5 (1985).

Figure 5-42
Tapered Inlet Design Form
Data for Example 5-4

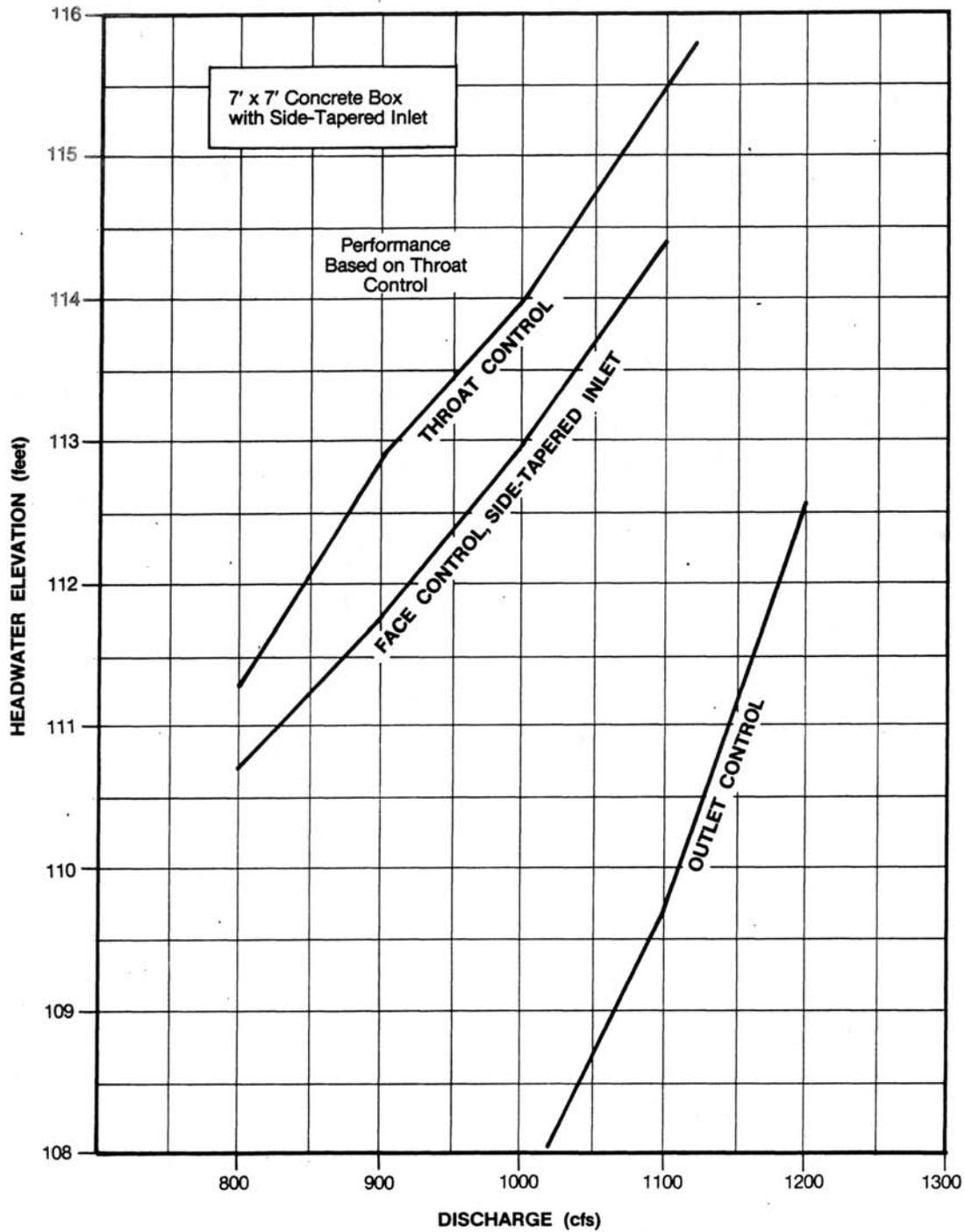


Figure 5-43
Results for Example 5-4