NASHVILLE STORMWATER MANAGEMENT MANUAL

VOLUME 3—THEORY

CHAPTER 5
Culvert Hydraulics

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Chapter 5
CULVERT HYDRAULICS

SYNOPSIS

A culvert is a hydraulically short conduit that conveys stormwater through a roadway embankment or past some type of flow obstruction. Culverts generally do not form a part of the traveled roadway and have a span of 20 feet or less. Conversely, the opening between inside exterior walls of a bridge generally exceeds 20 feet and the bridge span, which generally rests on abutments, is part of the traveled roadway. Whereas bridges are usually designed to provide freeboard for design event conditions that can handle boat traffic, culverts are designed to flow full or have a submerged inlet during the design flood.

During a given storm event, a culvert may operate under inlet control, outlet control, or both. This chapter provides basic theoretical information on the different variables and equations that determine the culvert capacity for each type of control. A brief discussion of improved inlets concludes the chapter. The primary reference for the information presented is HDS-5 (USDOT, FHWA, 1985).

5.1 FUNDAMENTALS

Theoretical analysis of culvert hydraulics is extremely complex, because flow is usually nonuniform, with regions of both gradually varying and rapidly varying flow. Exact analyses might require backwater and drawdown calculations, the balancing of energy and momentum, and the use of physical models. In practice, the results of numerous physical tests and theoretical calculations performed for the Federal Highway Administration (USDOT, FHWA, HDS-5, 1985) are presented in the form of culvert capacity nomographs.

To apply these nomographs, common types of flow are classified and analyzed on the basis of a control section. A control section is a location where a unique relationship exists between the rate of flow and depth of flow or water surface elevation. The two basic types of control sections defined by research are termed inlet and outlet control.

Inlet control exists when the culvert barrel is capable of conveying more flow than the inlet will accept. The control section for this condition is located just inside the entrance. Critical depth occurs at or near this location and the flow in the culvert is supercritical. The entrance water surface elevation and inlet geometry (barrel shape, cross-sectional area, and inlet edge) are the variables influencing culvert performance.

Flow under inlet control may be described mathematically by either the weir formula or the orifice formula, depending on the headwater depth. A weir is an edge or surface over which water flows, while an orifice is an opening with a closed perimeter through which water flows. If the perimeter of an orifice is not closed, or if the opening flows only partially full, the orifice operates as a weir.

Outlet control occurs when the culvert barrel is not capable of conveying as much flow as the inlet will accept. The control section for this situation is located at the barrel exit or downstream from the culvert. Either partially full subcritical flow or full pipe pressure flow conditions can occur. In addition to the variables influencing inlet performance, the slope, length, and roughness of the culvert barrel and the water surface elevation at the outlet (tailwater) can affect outlet performance. The variables influencing culvert performance are summarized in Table 5-1.

For inlet control, the tailwater elevation has no influence on performance. For outlet control, the difference between headwater and tailwater elevation represents the energy that conveys the flow through the culvert.

In most situations, the hydraulic sizing of a culvert is a trial and error process. A trial culvert size is assumed and inlet and outlet performance are evaluated to determine if they will satisfy the conditions prevailing at the proposed location. A culvert system is selected by choosing an inlet structure; barrel material, shape, and size; and an outlet structure. The inlet and outlet structures are usually the same, to achieve a symmetrical installation. If the outlet velocity is high enough to cause erosion, protection or energy dissipation is required.

Table 5-1
VARIABLES INFLUENCING CULVERT PERFORMANCE

	Variable	Inlet Control	Outlet Control
1.	Headwater Elevation	X	X
2.	Inlet Area	X	X
3.	Inlet Edge Configuration	X	X
4.	Inlet Shape	X	X
5.	Barrel Roughness		X
6.	Barrel Area		X
7.	Barrel Shape		X
8.	Barrel Length		X
9.	Barrel Slope	a	X
10.	Tailwater Elevation		X

[a] Barrel slope has only a small effect on inlet control performance and is usually neglected.

5.2 INLET CONTROL

When a culvert is operating under inlet control, flow is supercritical and the barrel (outlet) has a greater hydraulic capacity than the inlet. For this reason, culvert capacity depends primarily on the inlet properties, with minimal effect from barrel properties. Although a steep slope may increase inlet capacity by a small amount, in practice this increase can be considered insignificant and should be neglected unless slope-tapered improvements are provided (see Section 5.6).

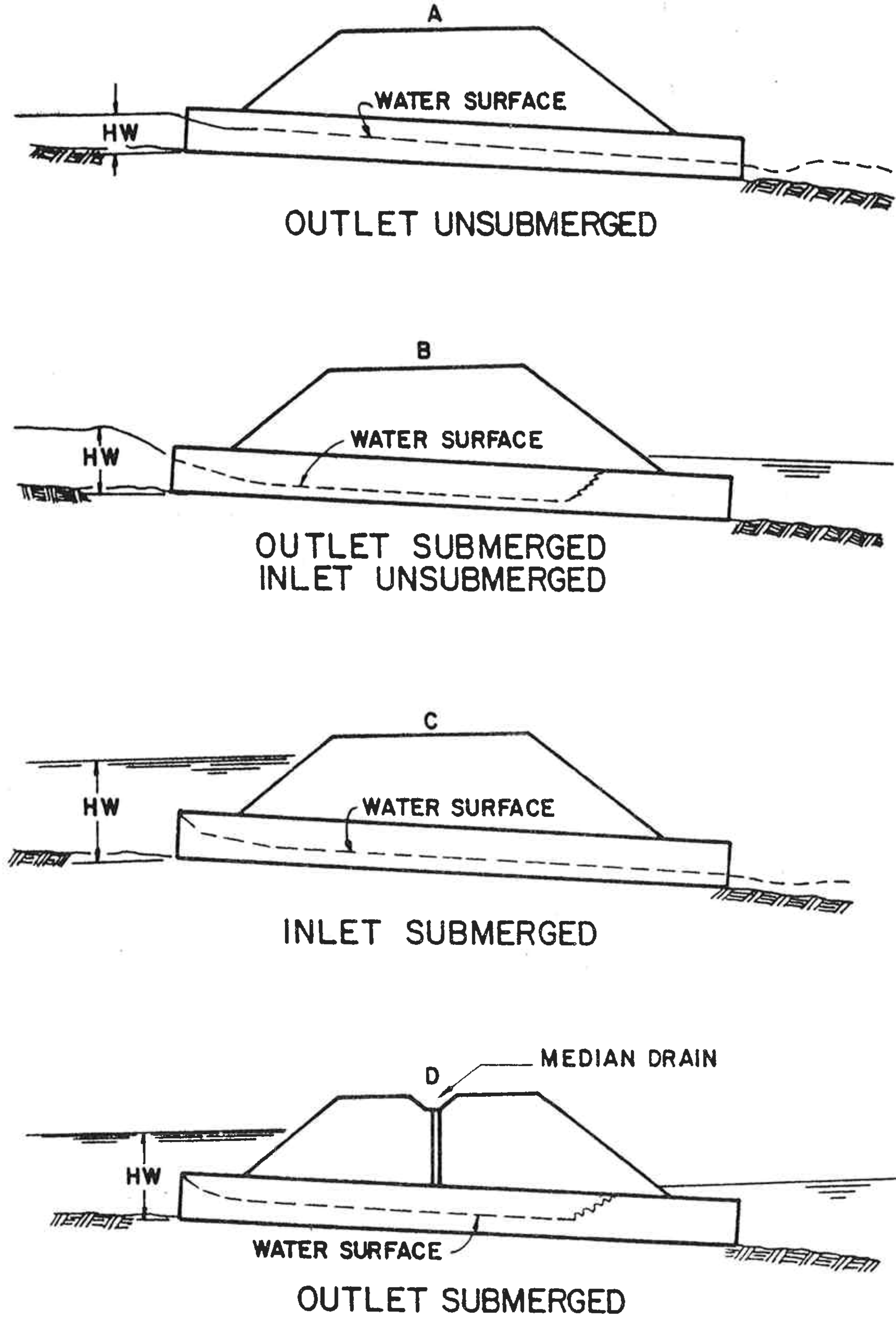
5.2.1 SUBMERGENCE CONFIGURATIONS

The four configurations of inlet control illustrated in Figure 5-1 present various combinations of submergence at the inlet and outlet ends of the culvert. When the depth of water approaching the culvert is less than the culvert height (Figure 5-1, Part A), the flow rate is governed by weir control. When the entrance is submerged and the control is at the inlet, the flow will be governed by orifice flow (Figure 5-1, Parts C and D).

If the culvert outlet is not submerged (Figure 5-1, Parts A and C), the barrel flows partially full over its length, and flow approaches normal depth at the outlet. As shown in Parts B and D of Figure 5-1, submergence of the outlet does not ensure outlet control. In both cases, a hydraulic jump forms in the barrel, allowing flow to pass from supercritical to subcritical conditions. If the configuration shown in Part D of Figure 5-1 were not ventilated, subatmospheric pressures could develop, possibly creating an unstable condition in which the barrel would alternate between full and partially full flow.

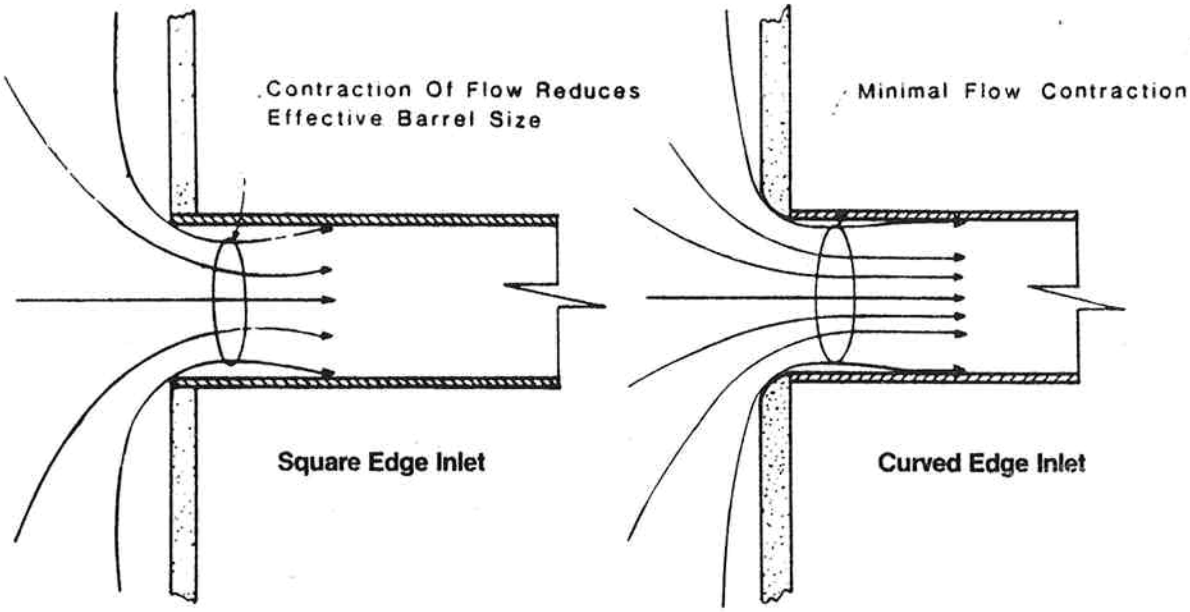
5.2.2 PERFORMANCE VARIABLES

As listed in Table 5-1, only the headwater and inlet configuration influence inlet control performance. Components of the inlet configuration include the area, edge configuration, and shape. The <u>inlet area</u> is the cross-sectional area of the culvert face. This area is the same as the barrel area, except when tapered inlets are used to enlarge the face relative to the barrel. The effect of the <u>edge configuration</u> is illustrated in Figure 5-2. Because the



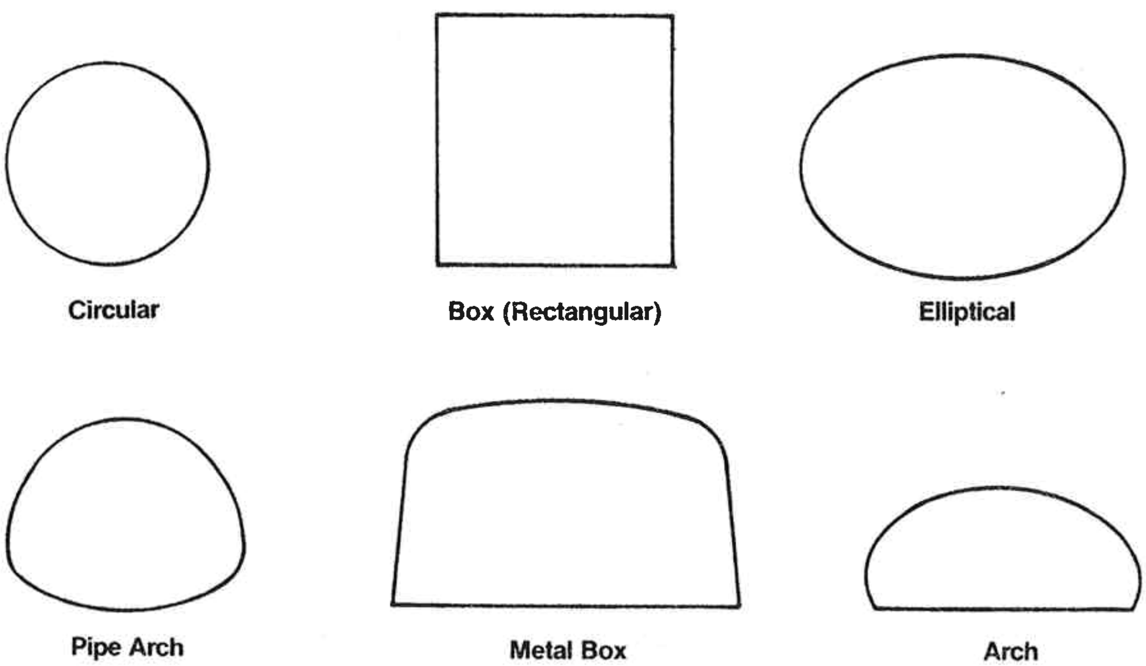
Reference: USDOT, FHWA, HDS-5 (1985).

FIGURE 5-1
Types of Inlet Control



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

FIGURE 5-2
Flow Contraction at Square Edge and Curved Edge Culvert Inlets



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

FIGURE 5-3
Common Culvert Shapes

contraction of flow occurring at the culvert inlet reduces the effective barrel size, edge configurations that minimize flow contraction will increase culvert capacity for both inlet and outlet control conditions.

The inlet shape is the same as the culvert barrel, except when tapered inlets are used to enlarge the inlet. The most commonly used shapes, illustrated in Figure 5-3, are circular, box (rectangular), elliptical, pipe arch, metal box, and arch. Factors affecting shape selection include cost, allowable headwater, embankment height, and hydraulic performance. If the areas for two different culvert shapes are equal, the lower profile inlet (e.g., arch vs. circular) will have more capacity for the same headwater, because the head above the culvert crown is greater.

A common method for increasing inlet performance is the use of beveled edges at the entrance. Although any beveling helps performance, the three edge configurations reported in design procedures are 33.7-degree bevels (1 inch per foot of barrel width), 45-degree bevels (1/2 inch per foot of barrel width), and grooved end (socket) of concrete pipe. All options are considered equal for design purposes, but the larger 33.7-degree bevels provide slightly better inlet performance.

5.2.3 FLOW VERSUS HEADWATER

The headwater or depth of ponding at the culvert entrance is a major variable affecting inlet capacity. The headwater depth, HW, is the vertical distance from the culvert invert at the entrance to the energy line of the headwater pool (depth plus velocity head). Because of the low velocities in most entrance pools and the difficulty in determining the velocity head for all flows, the approach velocity is usually ignored and the water surface and energy line at the entrance are assumed to be coincident. For the purposes of measuring headwater, the culvert invert at the entrance is the low point in the culvert opening at the beginning of the full cross section of the culvert barrel.

The three regions of flow versus headwater that occur at culvert inlets are weir (unsubmerged), transition, and orifice (submerged) flow. The transitional zone between weir and orifice flow depends on inlet geometry and normally lies between a submergence ratio of 1.2 to 1.5. (Submergence ratio is the headwater depth divided by the culvert height.) Although mathematical relationships can be used to calculate weir and orifice flow rates, experimental test results from physical models are available for most culvert inlet configurations (USDOT, FHWA, HDS-5, 1985). These results are available in the form of design nomographs, which are presented in Volume 2.

5.3 OUTLET CONTROL

Culverts under outlet control can flow with the culvert barrel full or partially full for all or part of the barrel length. Full flow outlet control conditions are shown in Figure 5-4, Parts A, B, and C, while partially full outlet control conditions are shown in Figure 5-4, Parts D and E.

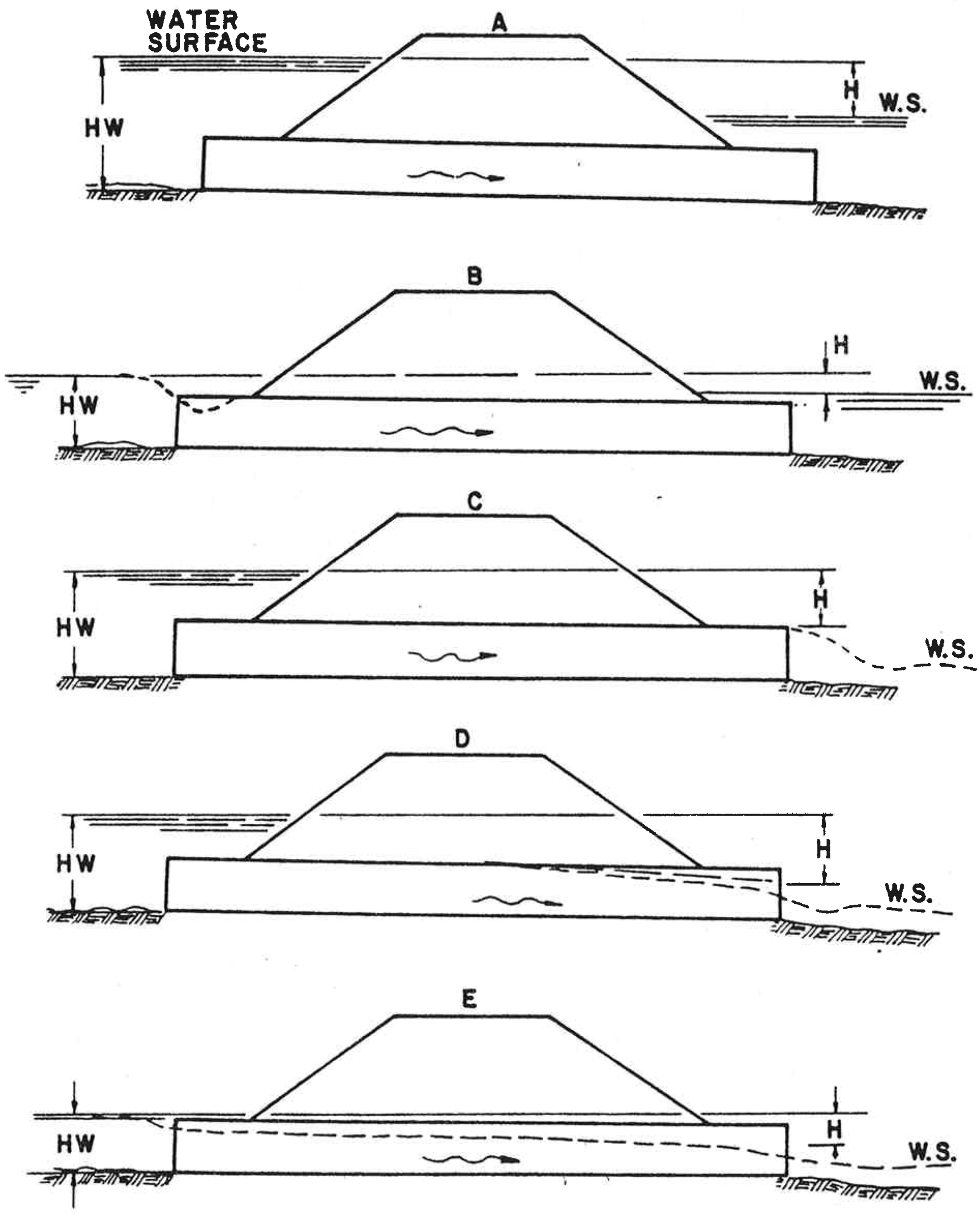
5.3.1 SUBMERGENCE CONFIGURATIONS

The five configurations of outlet control illustrated in Figure 5-4 present various combinations of submergence at the inlet and outlet ends of the culvert. Part A represents the classic full flow condition, with both inlet and outlet submerged. The barrel is in pressure flow throughout its length. This condition is suitable for most calculations.

Part B depicts the outlet submerged with the inlet unsubmerged. For this case, the headwater is shallow, so that the inlet crown is exposed as the flow contracts into the culvert.

Part C shows the entrance submerged to such a degree that the culvert flows full throughout its entire length while the exit is unsubmerged. This condition is rare, as it requires an extremely high headwater to maintain full barrel flow with no tailwater. The outlet velocities are usually high under this condition.

In Part D, the entrance is submerged by the headwater and the outlet flows freely with a low tailwater. For this condition, the barrel flows partially full over at least part of its length (subcritical flow) and the flow passes through critical depth just upstream of the outlet.



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

FIGURE 5-4
Types of Outlet Control

Part E shows neither the inlet nor the outlet end of the culvert submerged. The barrel flows partially full over its entire length, and the flow profile is subcritical.

5.3.2 PERFORMANCE VARIABLES

The variables influencing the performance of a culvert in inlet control also influence culverts in outlet control. In addition, the barrel characteristics (roughness, area, shape, length, and slope) and the tailwater elevation affect culvert performance in outlet control (see Table 5-1).

The barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by Manning's n value. Typical values for culverts are presented in Volume 2.

The barrel area and barrel shape are the same as the inlet, unless a tapered inlet is used. The barrel length is the total culvert length from the entrance to the exit of the culvert. As the length increases, the head loss caused by friction increases. The barrel slope is the actual slope of the culvert barrel and is often the same as the natural stream slope, unless the culvert inlet is raised or lowered.

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

5.3.3 FULL FLOW PERFORMANCE

Performance calculations for full flow outlet control can be made by accounting for energy losses resulting from entrance losses, friction losses, and outlet losses. These losses are expressed mathematically as:

$$H = H_e + H_f + H_o \qquad (5\text{-}1)$$

where:

H = Total head, or the elevation difference between the headwater, HW, and tailwater, TW, in feet

H_e = Entrance loss, in feet

H_f = Friction loss, in feet

H_o = Outlet loss, in feet

To evaluate the components of Equation 5-1, the average culvert velocity and velocity head are calculated using the equations:

$$v = Q/A \quad (5\text{-}2)$$

$$H_v = v^2/2g \quad (5\text{-}3)$$

where:

v = Average velocity in the culvert barrel, in feet/second

Q = Flow rate, in cfs

A = Cross-sectional area of culvert flow, in square feet

H_v = Velocity head, in feet

g = Acceleration due to gravity, 32.2 feet/second²

Using the velocity head, each component of Equation 5-1 can be calculated using the equations:

$$H_e = k_e \left(\frac{v^2}{2g}\right) \quad (5\text{-}4)$$

$$H_f = \left(\frac{29\ n^2\ L}{R^{1.33}}\right) \frac{v^2}{2g} \quad (5\text{-}5)$$

$$H_o = 1.0 \left[\frac{v^2}{2g} - \frac{v_d^2}{2g}\right] \quad (5\text{-}6)$$

where:

k_e = Entrance loss coefficient (design values reported in Volume 2)

n = Manning's roughness coefficient (design values reported in Volume 2)

L = Length of culvert barrel, in feet

R = Hydraulic radius of full culvert barrel = A/P, in feet

A = Cross-sectional area of full culvert flow, in square feet

P = Perimeter of culvert barrel, in feet

v = Average velocity in the culvert barrel, in feet/second

v_d = Downstream channel velocity, in feet/second

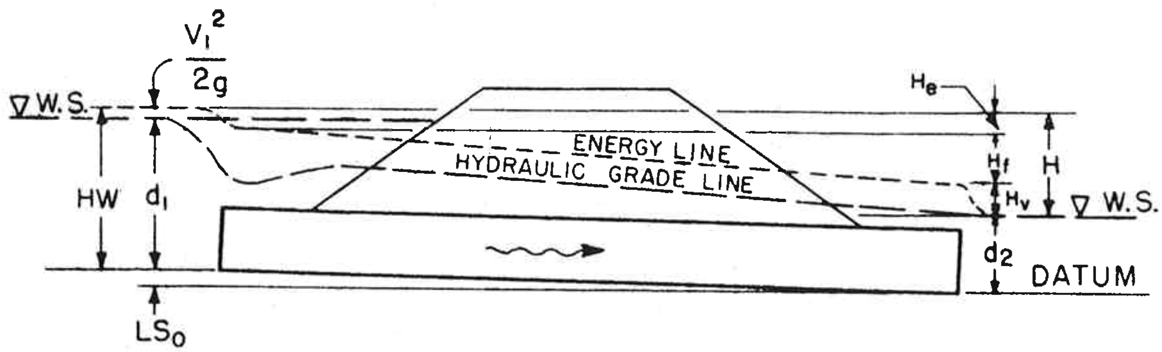
g = Acceleration due to gravity, 32.2 feet/second^2

Since the downstream channel velocity can usually be neglected, Equation 5-1 becomes:

$$H = \left[1.0 + k_e + \frac{29\ n^2\ L}{R^{1.33}} \right] \frac{v^2}{2g} \qquad (5\text{-}7)$$

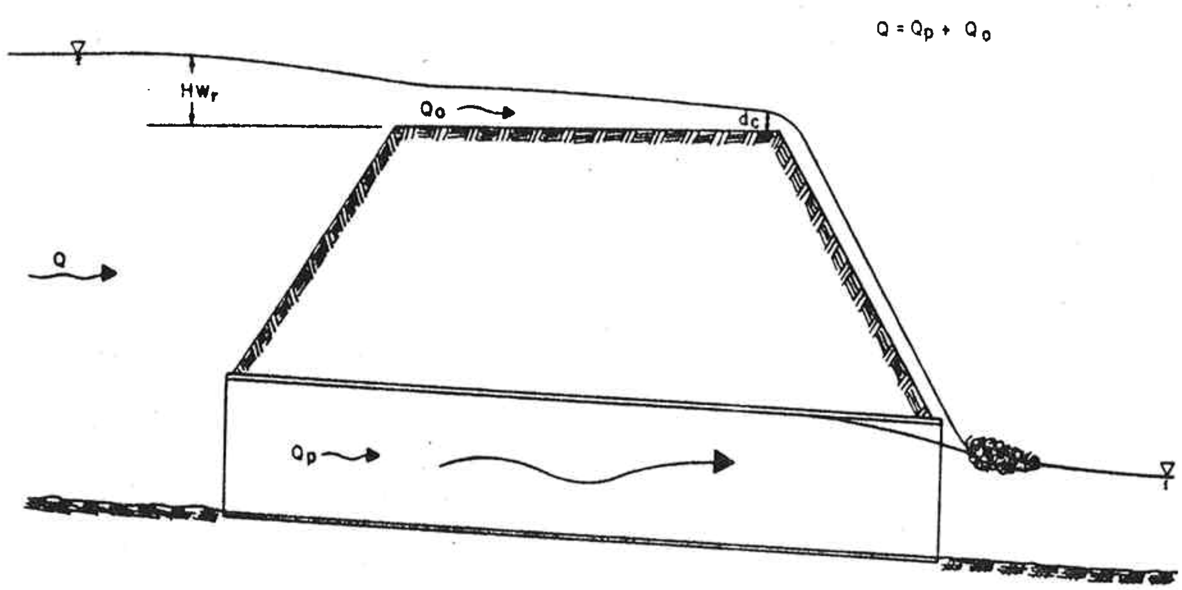
It may be necessary to build a culvert that has one or more bends in the alignment. If such a culvert is operating under outlet control, then losses caused by bends should be added to Equation 5-7. Theoretical aspects of evaluating head loss caused by bends are presented in Chapter 6.

Figure 5-5 illustrates the terms of Equation 5-7, the energy line, the hydraulic grade line, and the headwater depth, HW. The energy line represents the total energy at any point along the culvert barrel. The hydraulic grade line, or pressure line, is defined by the elevations to which water



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

FIGURE 5-5
Full Flow Outlet Control Energy and Hydraulic Gradients



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

FIGURE 5-6
Variables for Evaluating Roadway Overtopping

would rise in small vertical pipes attached to the culvert wall along its length. The energy line and the pressure line are parallel over the length of the barrel, except in the immediate vicinity of the inlet where the flow contracts and re-expands. The difference in elevation between these two lines is the velocity head, $v^2/2g$.

As shown in Figure 5-5, the head, H, is the difference between the elevations of the hydraulic grade line at the outlet and the energy line at the inlet (neglecting downstream velocity). Headwater depth is the vertical distance from the culvert invert at the entrance to the water surface, assuming the water surface (hydraulic grade line) and the energy line to be coincident. Since the velocity head at the inlet is usually small under ponded conditions, the water surface or headwater pool elevation is assumed to equal the elevation of the energy line. Thus, headwater depths based on a zero approach velocity are conservative.

Having established the total head loss, H, the headwater depth, HW, for outlet control can be computed as:

$$HW = H + h_o - LS_o \qquad (5-8)$$

where:

HW = Headwater depth for outlet control, in feet

H = Total head, in feet (see Equation 5-7)

h_o = Design tailwater, in feet

L = Length of culvert barrel, in feet

S_o = Barrel slope, in feet/foot

Outlet control nomographs for full pipe flow, presented in Volume 2, provide graphical procedures to evaluate the total head loss, H, for various culvert materials, cross sections, and inlet combinations (USDOT, FHWA, HDS-5, 1985). The depth of water at the culvert outlet due to downstream conditions is termed the <u>tailwater</u>, TW. The tailwater condition that prevails during the design event is called the design tailwater, h_o. The design tailwater may be a function of either downstream or culvert outlet conditions.

The tailwater depth is measured from the invert of the culvert to the water surface elevation at the outlet and can be influenced by conditions downstream of the outlet. If the outlet is operating in a free outfall condition, the tailwater may be equal to critical depth for the culvert. If the culvert discharges into an open channel, the tailwater may be equal to the normal depth of flow in that channel. If the culvert outlet is located near the inlet of a downstream culvert, the headwater elevation of the downstream culvert may define tailwater depth for the upstream culvert.

5.3.4 PARTIALLY FULL FLOW PERFORMANCE

Backwater calculations may be required for the partially full flow conditions shown in Figure 5-4, Parts D and E. These calculations begin at the water surface at the downstream end of the culvert and proceed upstream to the entrance of the culvert. The downstream water surface is based on critical depth at the culvert outlet or on the tailwater depth, whichever is higher. If the calculated backwater profile intersects the top of the barrel, as in Figure 5-4, Part D, a straight, full flow hydraulic grade line extends from that point upstream to the culvert entrance. From Equation 5-5, the full flow friction slope is:

$$S_n = \frac{H_f}{L} = \left(\frac{29\ n^2}{R^{1.33}}\right) \frac{V^2}{2g} \qquad (5\text{-}9)$$

where:

S_n = Full flow friction slope, in feet/foot

H_f = Friction loss, in feet

L = Length of culvert barrel, in feet

n = Manning's roughness coefficient (design values reported in Volume 2)

R = Hydraulic radius of full culvert barrel = A/P, in feet

A = Cross-sectional area of full culvert flow, in square feet

P = Perimeter of culvert barrel, in feet

v = Average velocity in the culvert barrel, in feet/second

g = Acceleration due to gravity, 32.2 feet/second^2

To avoid tedious backwater calculations, approximate methods have been developed to analyze partially full flow conditions. Based on numerous backwater calculations reported by the USDOT, FHWA, in HDS-5 (1985), it was found that a downstream extension of the full flow hydraulic grade line for the flow condition shown in Figure 5-4, Part D, pierces the plane of the culvert outlet at a point one-half way between critical depth and the top of the barrel. Therefore, it is possible to begin the hydraulic grade line at the equivalent hydraulic depth of $(d_c + D)/2$ above the outlet invert and extend the straight, full flow hydraulic grade line upstream to the inlet of the culvert at a slope of S_n. If the tailwater exceeds $(d_c + D)/2$, the tailwater is used to set the downstream end of the extended full flow hydraulic grade line. The inlet losses and the velocity head are added to the elevation of the hydraulic grade line at the inlet to obtain the headwater elevation.

This approximate method works best when the barrel flows full over at least part of its length (Figure 5-4, Part D). When the barrel is partially full over its entire length (Figure 5-4, Part E), the method becomes increasingly inaccurate as the headwater falls further below the top of the barrel at the inlet. Adequate results are obtained down to a headwater of 0.75D. For lower headwaters, backwater calculations are required to obtain accurate headwater elevations.

5.4 ROADWAY OVERTOPPING

The broad-crested weir equation is used to evaluate flow over the low point of a roadway. The equation is expressed as:

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

where:

Q_o = Overtopping flow rate, in cfs

C_d = Overtopping discharge coefficient

L = Length of the roadway crest, in feet

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

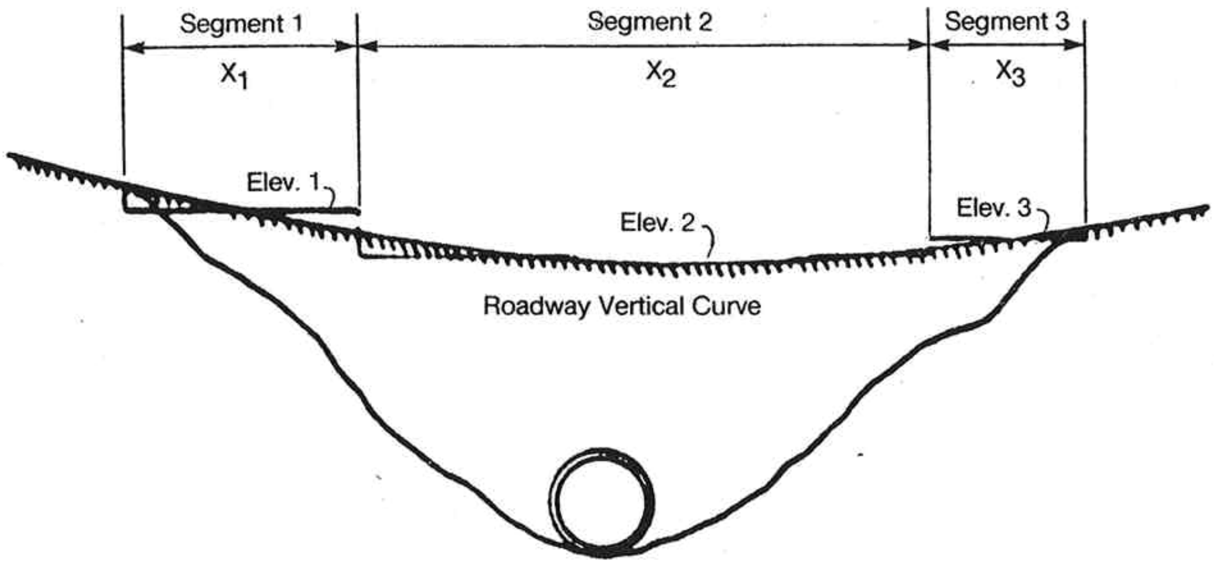
Variables of Equation 5-10, other than the discharge coefficient, are illustrated in Figure 5-6. The total flow, Q, consists of the pipe flow, Q_p, and the overtopping flow, Q_o. Graphical information is presented in Volume 2 for selecting appropriate discharge coefficient values.

When the roadway crest is defined by a sag vertical curve, the two methods illustrated in Figure 5-7 are suggested for setting the length and crest elevation. Method 1, shown in Part A of Figure 5-7, involves dividing the roadway vertical curve into a series of horizontal segments to approximate the curve of the roadway. The flow over each segment is calculated using Equation 5-10 and the incremental flows for each segment are added to give the total flow across the roadway. Method 2, shown in Part B of Figure 5-7, involves selecting a single horizontal line to represent the average depth of the upstream pool. In this case, Equation 5-10 is applied once to give an estimate of the total flow.

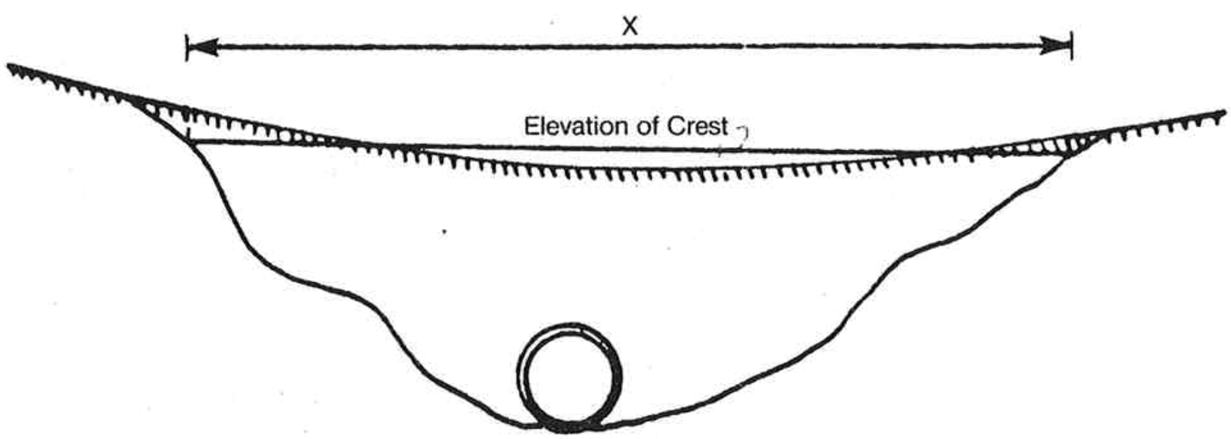
Since the total flow, Q, comprises both culvert flow and roadway overflow once the crest elevation is exceeded, a trial and error process is used to solve Equation 5-10. An approximate solution can be obtained by superimposing the culvert and roadway overflow performance curves.

5.5 OUTLET VELOCITY

Culvert outlet velocities, which are typically higher than natural stream velocities, may make channel stabilization or



A. Method 1 - Subdivision into Segments



B. Method 2 - Use of a Single Segment

FIGURE 5-7
Method for Setting Sag Vertical Curve Length and Crest Elevation

energy dissipation necessary. Because the type of flow affects the depth of flow at the outlet, different calculations are required for inlet and outlet control conditions.

In inlet control, backwater calculations may be necessary to determine the outlet velocity. As illustrated in Figure 5-8, these calculations begin at the culvert entrance and proceed downstream to the exit. The flow velocity is obtained from the flow and the cross-sectional area at the exit (use Equation 5-2).

An approximation may be used to avoid backwater calculations in determining the outlet velocity for culverts operating in inlet control. The water surface profile converges toward normal depth as calculations proceed down the culvert barrel. Therefore, if the culvert is of adequate length, normal depth will exist at the culvert outlet. Even in short culverts, normal depth can be assumed and used to define the area of flow at the outlet and obtain the outlet velocity (see Figure 5-8). The velocity calculated in this manner may be slightly higher than the actual velocity at the outlet. Normal depth can be estimated using Manning's Equation as presented in Chapter 4.

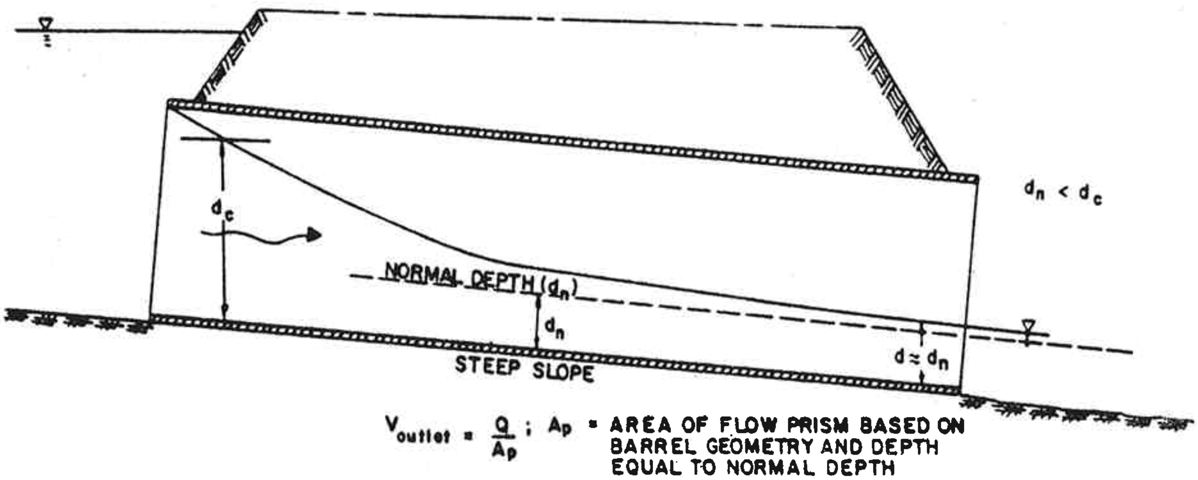
In outlet control, the depth of flow for computing the velocity is critical depth, d_c, tailwater depth, TW, or the height of the culvert, D, as defined in Figure 5-9. Critical depth is used when the tailwater is less than critical depth; the tailwater depth is used when the tailwater is greater than critical depth, but below the top of the barrel. The total barrel area is used when the tailwater exceeds the top of the barrel.

5.6 IMPROVED INLETS

In conditions of inlet control, techniques available to balance the inlet capacity with the outlet or barrel capacity include beveled inlet edges, side tapering the inlet, and slope tapering the inlet.

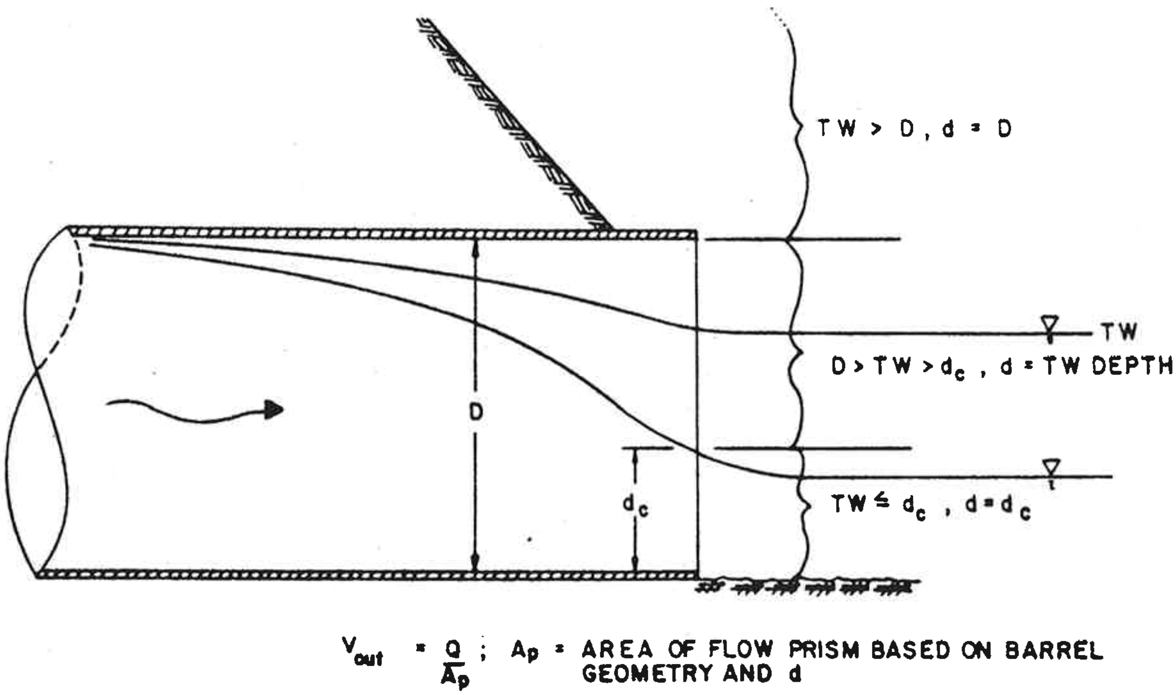
5.6.1 BEVELS

A bevel is similar to a chamfer, except that a chamfer is smaller and is generally used to prevent damage to sharp



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

FIGURE 5-8
Inlet Control Outlet Velocity Calculations



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

FIGURE 5-9
Outlet Control Outlet Velocity Calculations

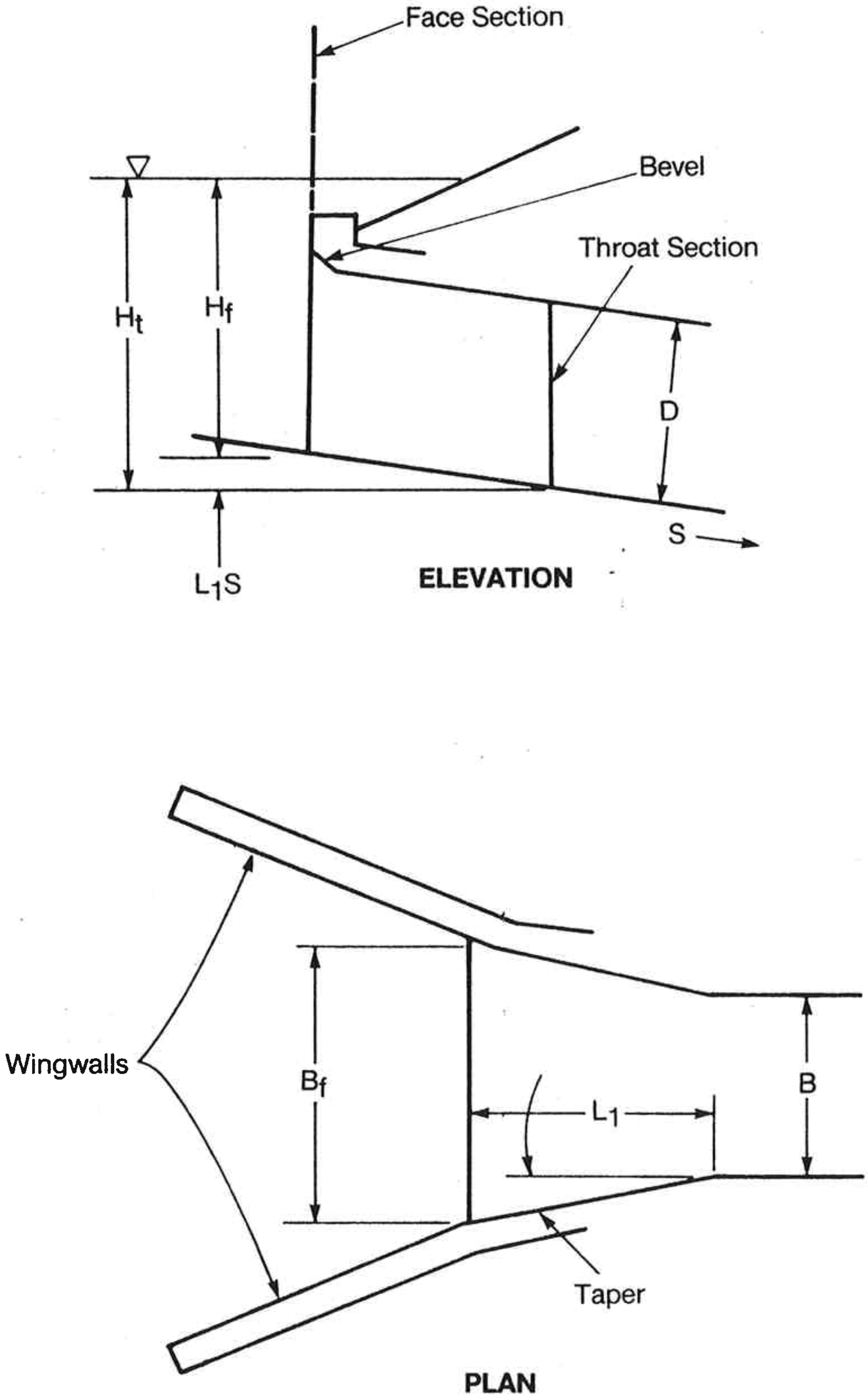
concrete edges during construction. The entrance loss coefficient, k_e, can be reduced from 0.7 for a square edge to 0.2 for beveled edges. Figures 5-10 and 5-11 illustrate bevels used in conjunction with other inlet improvements. It should be noted that the socket end of concrete pipe is comparable to a bevel in reducing the entrance loss coefficient and thus increases inlet capacity.

5.6.2 SIDE-TAPERED INLETS

Side-tapered inlets provide an enlarged culvert entrance with a transition to the original barrel dimensions. The inlet face has the same height as the barrel, and its top and bottom are extensions of the top and bottom of the barrel. The intersection of the sidewall tapers and barrel is defined as the throat section. Based on test results reported by the USDOT, FHWA, in HEC-13 (1972), the side-taper geometry shown in Figure 5-10 is recommended. The two possible control sections identified in Figure 5-10 are the face and the throat. Use of a side-tapered improvement is maximized by designing it so that the capacity is controlled by the throat.

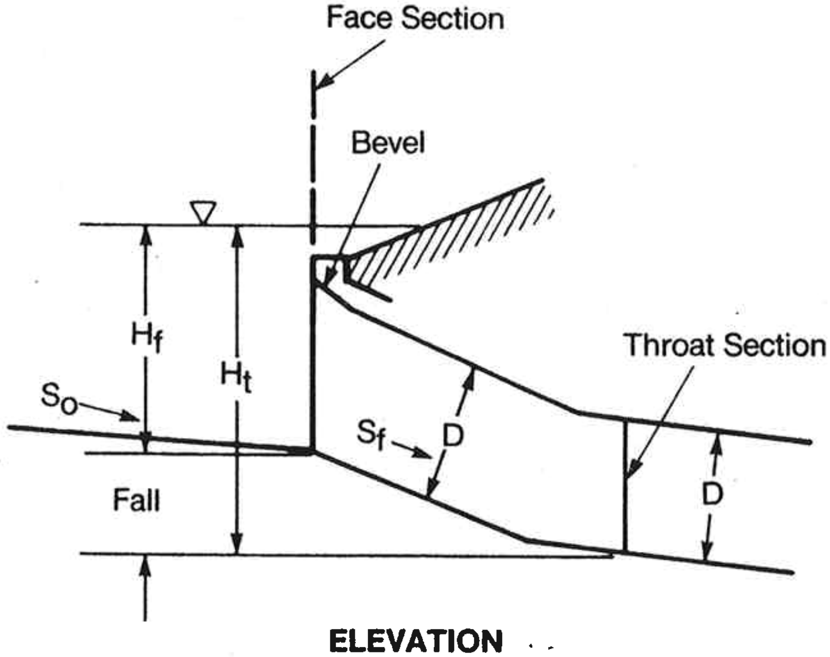
5.6.3 SLOPE-TAPERED INLETS

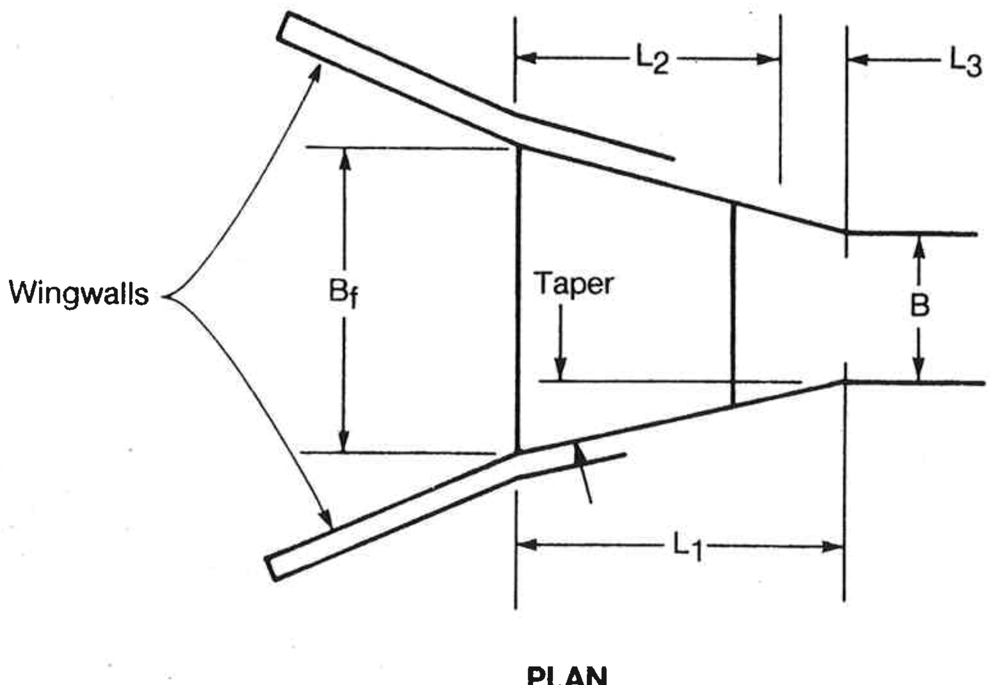
Slope-tapered inlets provide a steeper slope at the entrance than occurs throughout the remaining length of a culvert. The steeper slope increases the head on the throat section, making additional fall available. Depending on available fall, inlet capacities can be increased 100 percent or more above a conventional culvert with square edges. Based on test results reported by the USDOT, FHWA, in HEC-13 (1972), the slope-taper geometry shown in Figure 5-11 is recommended. As with side-tapered improvements, the slope-taper should be designed so that the throat section controls capacity.



Reference: USDOT, FHWA, HEC-13 (1972).

FIGURE 5-10
Typical Side-Tapered Inlet Detail





Reference: USDOT, FHWA, HEC-13 (1972).

FIGURE 5-11
Typical Slope-Tapered Inlet Detail