CHAPTER 5

DESIGN OF CULVERTS

5.1 OVERVIEW

5.1.1 Definitions

Culverts are structures used to convey surface runoff from one side of the road to another and are usually covered with an embankment composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert. For economy and hydraulic efficiency, culverts should be designed to operate with the inlet submerged during flood flows, if conditions permit. Cross-drains are those culverts and pipes that are used to convey runoff from one side of a roadway to another.

5.1.2 Performance Curves

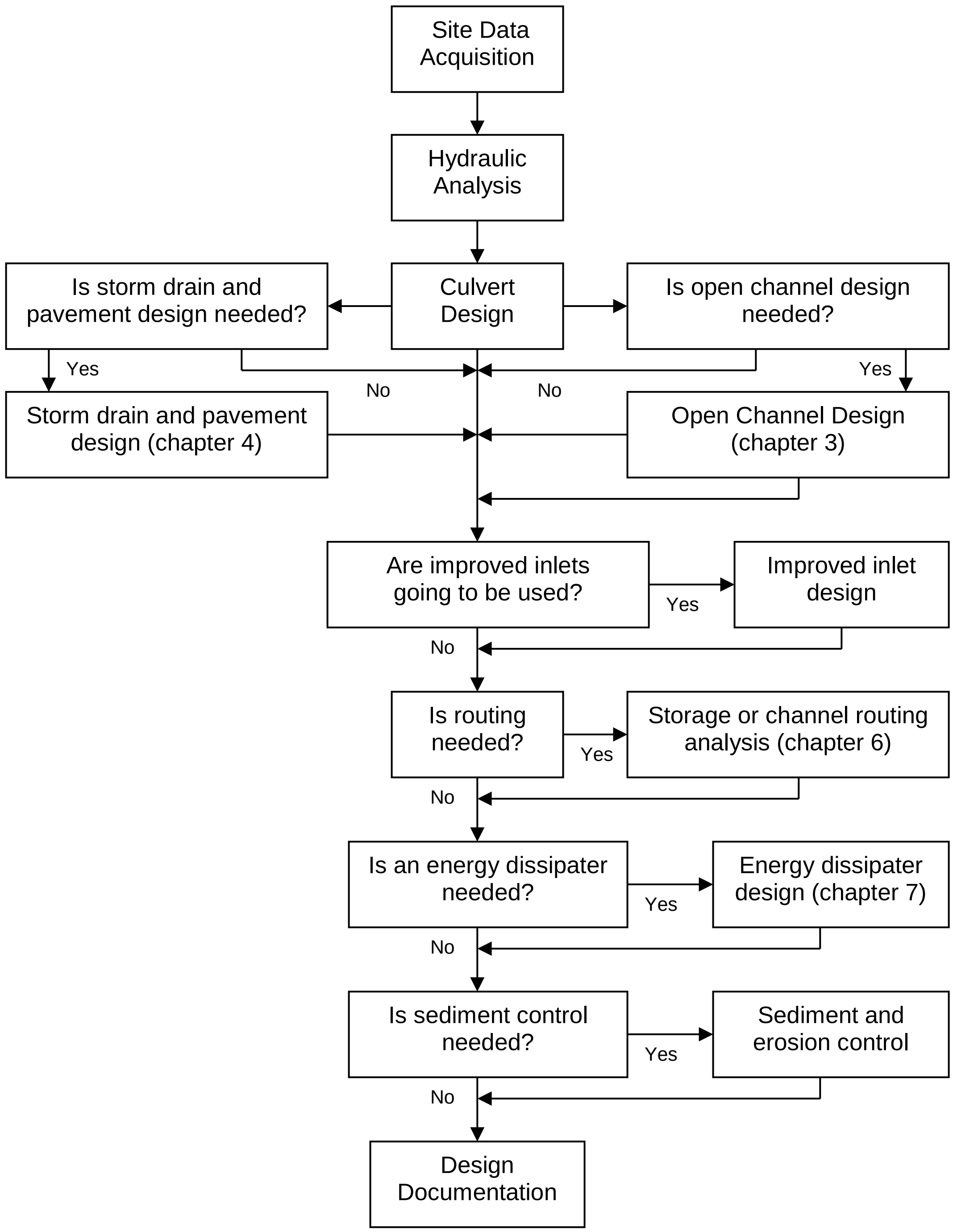
Performance curves should be developed for all culverts for evaluating the hydraulic capacity of a culvert for various headwaters. These curves will display the consequences of high flow rates at the site and any possible hazards. Sometimes a small increase in flow rate can affect a culvert design. If only the design peak discharge is used in the design, the engineer cannot assess what effect increases in the essential design discharge will have on the culvert design.

5.2 CULVERT DESIGN PROCEDURE FLOWCHART

5.2.1 Purpose and Use

The purpose of the culvert design procedure flow chart is to show the relationship between the different stages in culvert design and the alternatives that should be considered.

5.2.2 Design Flowchart



5.3 ENGINEERING DESIGN CRITERIA

5.3.1 Introduction

The design of a culvert should take into account many different engineering and technical aspects at the culvert site and adjacent areas. The following design criteria should be considered for all culvert designs where applicable.

5.3.2 Criteria

Engineering Aspects

- Flood frequency
- Velocity limitations

Site Criteria

- Needed length and available slope
- Debris control

Design Limitations

- Headwater
- Tailwater conditions
- Ground cover
- Utility conflicts
- Regulated floodway requirements

Design Options

- Culvert inlets
- Inlets with headwalls
- Wingwalls and aprons
- Improved inlets
- Material selection
- Culvert skews
- Culvert sizes

Other Design Considerations

- Weep holes
- Outlet protection
- Erosion and sediment control
- Environmental considerations

Some culvert designs are relatively simple involving a straight-forward determination of culvert size and length. Other designs are more complex where structural, hydraulic, environmental, or other considerations must be evaluated and provided for in the final design.

The following sections discuss each of the above criteria as it relates to culvert siting and design.

5.3.3 Flood Frequency

The appropriate flood frequency for determining the flood carrying-capacity of a culvert is dependent upon:

- the level of risk associated with failure of the culvert crossing; and
- the level of risk associated with increasing the flood hazard to upstream (backwater) or downstream (redirections of floodwaters or loss of attenuation) properties.

For specific design storm frequencies for culvert crossings, reference Section 2.3.1, Design Frequencies. Also, in compliance with the National Flood Insurance Program, it is necessary to consider the 100-year frequency flood at locations identified as being special flood hazard areas. The design engineer should review the City and County floodway regulations for more information related to floodplain regulations.

5.3.4 Velocity Limitations

Both minimum and maximum velocities should be considered when designing a culvert. The maximum velocity should be consistent with channel stability requirements at the culvert outlet. As outlet velocities increase, the need for stabilization at the culvert outlet increases. If velocities exceed permissible velocities for the various types of nonstructural outlet lining material available, the installation of structural energy dissipaters is required.

5.3.5 Debris Control

In designing debris control structures it is recommended that the U.S. Army Corps of Engineers, Hydraulic Engineering Circular No. 9 entitled “Debris – Control Structures” be consulted.

5.3.6 Headwater Limitations

The allowable headwater elevation is determined from an elevation of land use upstream of the culvert and the proposed or existing roadway elevation. Headwater is the depth of water above the culvert invert at the entrance end of the culvert.

The following criteria related to headwater shall be used (based on the design storm event):

- The allowable headwater for design frequency conditions should allow for the following upstream controls:
  - 12-inch freeboard for culverts up to 3 feet in diameter
  - 18-inch freeboard for culverts larger than 3 feet in diameter
  - Upstream property damage
  - Elevations established to delineate flood plain zoning
  - Low point in the road grade that is not at the culvert location
  - Ditch elevation of the terrain that will permit flow to divert around culvert
  - $HW/D \leq 1.2$
- The headwater should be checked for the 100-year flood to ensure compliance with the locally adopted floodway ordinance and 100 + 1 criteria.
- The maximum acceptable outlet velocity should be identified. Either the headwater should be set to produce acceptable velocities, or stabilization or energy dissipation should be provided.

- Other site-specific design considerations should be addressed as required.
- In general, the constraint which gives the lowest allowable headwater elevation establishes the criteria for the hydraulic calculations.

If there is insufficient headwater elevation to convey the required discharge, it will be necessary to either use a larger culvert, lower the inlet invert, use an irregular cross-section, use an improved inlet if in inlet control, multiple barrels, or use a combination of these measures. If the inlet invert is lowered, special consideration must be given to scour.

5.3.7 Tailwater Considerations

The hydraulic conditions downstream of the culvert site shall be evaluated to determine a tailwater depth for a range of discharge. At times there may be a need for calculating backwater curves to establish the tailwater conditions.

If the culvert outlet is operating with a free outfall, the critical depth and equivalent hydraulic grade line should be determined.

For culverts which discharge to an open channel, the tailwater depth is the normal depth for the design storm in an open channel. See Chapter 3, Open Channel Hydraulics.

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 water body, the expected high water elevation for the culvert design frequency of the particular water body may establish the culvert tailwater.

5.3.8 Culvert Inlets

Selection of the inlet type is an important part of culvert design, particularly with inlet control. Hydraulic efficiency and cost can be significantly affected by inlet conditions.

The inlet coefficient K_e, is a measure of the hydraulic efficiency of the inlet, with lower values indicating greater efficiency. All methods described in this chapter, directly or indirectly, use inlet coefficients. Inlet coefficients are given in the table shown on the next page.

Table 5-1
Inlet Coefficients

Type of Structure and Design of Entrance	Coefficients K_e
PIPE, CONCRETE	
Projecting from fill, socket end (groove-end)	0.2
Projecting from fill, square cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe (groove-end)	0.2
Square-edge	0.5
Rounded [radius = 1/12 (D)]	0.2
Mitered to conform to fill slope	0.7
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7” or 45” bevels	0.2
Side- or slope-tapered inlet	0.2
PIPE, OR PIPE-ARCH, CORRUGATED METAL	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls square-edge	0.5
Mitered to fill slope, paved or unpaved slope	0.7
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7” or 45” bevels	0.2
Side- or slope-tapered inlet	0.2
BOX, REINFORCED CONCRETE	
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of [1/12 (D)] 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 (D)] or beveled top edge	0.2
Wingwalls at 10° or 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

*Note: Concrete end sections conforming to fill slope are the sections commonly available from manufacturers. From limited hydraulic tests they are equivalent in operation to a headwall in both inlet and outlet control. Some end sections, incorporate a closed taper in their design to yield more efficient hydraulic performance.

5.3.9 Inlets with Headwalls

Headwalls may be used for a variety of reasons:

1) Increasing the efficiency of the inlet
2) Providing embankment stability
3) Providing embankment protection against erosion
4) Providing protection from buoyancy
5) Shorting the length of the required structure

The relative efficiency of the inlet depends on the conduit. Structures or flared end sections are required at all inlets and outlets of all pipe systems. Headwalls are required for all metal and HDPE culverts. Concrete flared end sections may be utilized in lieu of headwalls upon approval of the City Engineer. The figure below illustrates the use of headwalls and wingwalls.

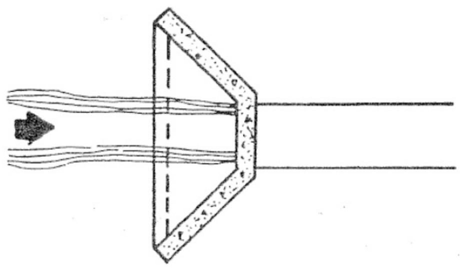
Corrugated metal pipe in a headwall is essentially square-edged with an inlet coefficient of about 0.5.

The primary reasons for using headwalls are for embankment protection, buoyancy control, and ease of maintenance.

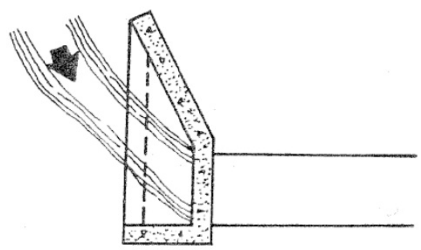
5.3.10 Wingwalls and Aprons

Wingwalls are used where the side slopes of the channel adjacent to the entrance are unstable or where the culvert is skewed to the normal channel flow.

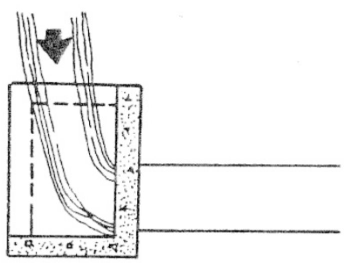
Little increase in hydraulic efficiency is realized with the use of wingwalls, regardless of the pipe material used, and, therefore, the use should be justified for other reasons. Wingwalls can be used to increase hydraulic efficiency if designed as a side-tapered inlet (See Appendix 5B for more information on the design of side-tapered inlets). The figure shown below illustrates several uses of wingwalls.



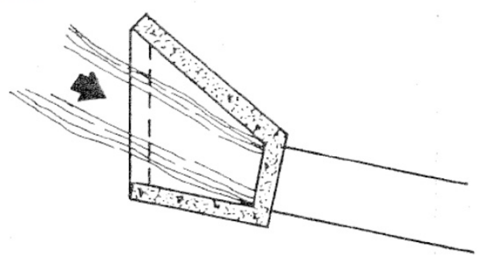
Flow Normal to Embankment – Preferred



Flow Skewed to Embankment – Undesirable



Flow Parallel to Embankment – Undesirable



Flow and Culvert Skewed to Embankment– Preferred

Source: www.lincoln.ne.gov/city/pworks/watrshed/require/drainage/pdf/chapt4.pdf

If high headwater depths are to be encountered, or the approach velocity in the channel will cause scour, a short channel apron should be provided at the toe of the headwall. This apron should extend at least the barrel depth upstream from the entrance, and the top of the apron should not protrude above the normal streambed elevation.

5.3.11 Improved Inlets

Where inlet conditions control the amount of flow that can pass through the culvert, improved inlets can greatly increase the hydraulic performance at the culvert. For these designs refer to Appendix 5B which describes the design of improved inlets.

5.3.12 Material Selection

For culvert selection, only reinforced concrete pipe is allowed within the street right-of-way except for culverts equal to or greater than 60 inches. For culverts equal to or greater than 60 inches in diameter, aluminum or aluminized steel pipe is allowed.

5.3.13 Outlet Protection

See Chapter 7, Energy Dissipation, for information on the design of outlet protection.

5.3.14 Environmental Considerations

In addition to controlling erosion, sedimentation and debris at the culvert site, care must be exercised in selecting the location of the culvert site. Environmental considerations are a very important aspect of culvert selection and design.

This selection must consider the entire site and include provisions for maintaining existing stream cross section at the inlet and outlet while providing passage of aquatic life.

5.4 CULVERT FLOW AND CONTROLS AND EQUATIONS

5.4.1 Introduction

Generally, the hydraulic control in a culvert will be at the culvert outlet if the culvert is operating on a mild slope. Entrance control usually occurs if the culvert is operating on a steep slope.
For outlet control, the head losses due to tailwater and barrel friction are predominant in controlling the headwater of the culvert. The entrance will allow the water to enter the culvert faster than the backwater effects of the tailwater, and barrel friction will allow it to flow through the culvert.

For inlet control, the entrance characteristics of the culvert are such that the entrance head losses are predominant in determining the headwater of the culvert. The barrel will carry water through the culvert more efficiently than the water can enter the culvert.

Each culvert flow, however classified, is dependent upon one or both of these controls; due to the importance of these controls, further discussion follows.

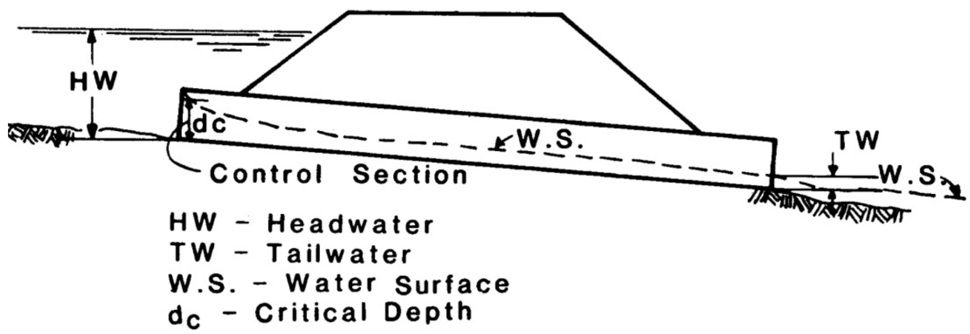
5.4.2 Inlet and Outlet Control

Inlet Control - If the culvert is operating on a steep slope, it is likely that the entrance geometry will control the headwater and the culvert will be on inlet control.

Outlet Control - If the culvert is operating on a mild slope, the outlet will probably control the flow and the culvert will be on outlet control.

Proper culvert design and analysis requires checking for both inlet and outlet control to determine which will govern particular culvert designs. For more information on inlet and outlet control see the Federal Highway Administration publication entitled Hydraulic Design of Highway Culverts, HDS-5, 2005.

The following diagram illustrates the terms and dimensions used in the culvert headwater equations.



Source: http://isddc.dot.gov/OLPFiles/FHWA/012545.pdf

5.4.3 Equations

There are many combinations of conditions which may classify a particular culvert's hydraulic operation. By consideration of a succession of parameters, the engineer may arrive at the appropriate calculation procedure. The most common types of culvert operations for any barrel type are classified as follows.

5.4.3.1 Mild Slope

Critical Depth – Outlet Control – The entrance is unsubmerged ($HW \leq 1.5D$), the critical depth is less than uniform depth at the design discharge ($dc < du$), and the tailwater is less than or equal to critical depth ($TW \leq dc$). This condition is a common occurrence where the natural channels are on flat grades and have wide, flat flood plains. The control is critical depth at the outlet.

$$\mathbf{HW = d_c + V_c^2/(2g) + H_e + H_f - SL} \qquad \mathbf{(5.1)}$$

Where: HW = Headwater depth (ft)

d_c = critical depth (ft)

V_c = critical velocity (ft/sec)

$g = 32.2$ ft/sec^2

H_e = entrance headloss (ft)

H_f = friction headloss (ft)

S = slope of culvert (ft/ft)

L = length of culvert (ft)

Tailwater Depth – Outlet Control – The entrance is submerged (HW ≤ 1.5D), the critical depth is less than uniform depth at design discharge ($d_c < d_u$), TW is greater than critical depth (TW > d_c) and TW is less than D (TW < D). This condition is a common occurrence where the channel is deep, narrow and well defined. The control is tailwater at the culvert outlet. The outlet velocity is the discharge divided by the area of flow in the culvert at tailwater depth.

$$\mathbf{HW = TW + V^2/(2g) + H_e + H_f - SL} \qquad \textbf{(5.2)}$$

Where: HW = Headwater depth (ft)

TW = tailwater at the outlet (ft)

V= velocity based on tailwater depth (ft/sec)

g = 32.2 ft/sec^2

H_e = entrance headloss (ft)

H_f = friction headloss (ft)

S = slope of culvert (ft/ft)

L = length of culvert (ft)

Tailwater Depth > Barrel Depth - Outlet Control – This condition will exist if the critical depth is less than uniform depth at the design discharge ($d_c < d_u$) and TW depth is greater than D (TW > D), or; the critical depth is greater than the uniform depth at the design discharge ($d_c > d_u$) and TW is greater than SL + D, [TW > (SL + D)]. The HW may not be greater than 1.5D, though often it is greater. If the critical depth of flow is determined to be greater than the barrel depth (only possible for rectangular culvert barrels), then this operation will govern. Outlet velocity is based on full flow at the outlet.

$$\mathbf{HW = H + TW - SL} \qquad \textbf{(5.3)}$$

Where: HW = Headwater depth (ft)

H = total head loss of discharge through culvert (ft)

TW = tailwater at the outlet (ft)

S = slope of culvert (ft/ft)

L = length of culvert (ft)

Tailwater < Barrel – Outlet Control – The entrance is submerged (HW > 1.5D) and the tailwater depth is less than D (TW < D). Normally, the engineer should arrive at this type of operation only after previous consideration of the operations depth covered when the critical depth, tailwater depth, or “slug” flow controls the flow in outlet control conditions. On occasion, it may be found that (HW ≥ 1.5D) for the three previously outlined conditions but (HW < 1.5D) for equation 5.4. If so, the higher HW should be used. Outlet velocity is based on critical depth if TW depth is less than critical depth. If TW depth is greater than critical depth, outlet velocity is based on TW depth.

$$\mathbf{HW = H + P - SL} \qquad \mathbf{(5.4)}$$

Where: HW = Headwater depth (ft)

H = total head loss of discharge through culvert (ft)

P = empirical approximation of equivalent hydraulic grade line. P = (d_c + D)/2 if TW depth is less than critical depth at design discharge. If TW is greater than critical depth, then P = TW

S = slope of culvert (ft/ft)

L = length of culvert (ft)

5.4.3.2 Steep Slope

Tailwater Insignificant – Inlet Control – The entrance may be submerged or unsubmerged, the critical depth is greater than uniform depth at the design discharge ($d_c < d_u$), TW depth is less than SL (tailwater elevation is lower than the upstream flowline). Tailwater depth with respect to the diameter of the culvert is inconsequential as long as the above conditions are met. This condition is a common occurrence for culverts in rolling or hilly country. The control is critical depth at the entrance for HW values up to about 1.5D. Control is the entrance geometry for HW values over about 1.5D. HW is determined from empirical curves in the form of nomographs that are discussed later in this chapter. If TW is greater than D, outlet velocity is based on full flow at the outlet. If TW is less than D, outlet velocity is based on uniform depth for the culvert.

5.4.3.3 “Slug” Flow

Inlet or Outlet Control – For “slug” flow operation, the entrance may be submerged or unsubmerged, critical depth is greater than uniform depth at the design discharge ($d_c > d_u$), TW depth is greater than (SL + d_c) (TW elevation is above the critical depth at the entrance), and TW depth is less than SL + D (TW elevation is below the upstream crown). TW depth with respect to D alone is inconsequential as long as the above conditions are met. This condition is a common occurrence for culverts in rolling or hilly country. The control for this type of operation may be at the entrance or the outlet or control may transfer itself back and forth between the two (commonly called “slug” flow). For this reason, it is recommended that HW be determined for both entrance control and outlet control and that the higher of the two determinations be used. Entrance control HW is determined from the inlet control nomographs and outlet control HW is determined by equations 5.3 or 5.4 or the outlet control nomographs.

If TW depth is less than D, outlet velocity should be based on TW depth. It TW depth is greater than D, outlet velocity should be based on full flow at the outlet.

5.5 DESIGN PROCEDURES

5.5.1 Procedures

There are two procedures for designing culverts: (1) the manual use of inlet and outlet control nomographs; and (2) the use of a computer model.

The following will outline the design procedures for use of the nomographs. The use of computer models will follow the discussion on improved inlets. Other computer programs can be used if approved by the City or County Engineering Department.

5.5.2 Tailwater Elevations

In some cases culverts fail to perform as intended because of tailwater elevations high enough to create backwater. The problem is more severe in areas where gradients are very flat, and in some cases in areas with moderate slopes. Thus, as part of the design process, the normal depth of flow in the downstream channel at discharges equal to those being considered should be computed.

If the tailwater computation leads to water surface elevations below the invert of the culvert exit, there are obviously no problems; if elevations above the culvert invert are computed, the culvert capacity will be somewhat less than assumed. The tailwater computation can be simple, and on steep slopes requires little more that the determination of a cross section downstream where normal flow can be assumed, and a Manning's equation calculation. (See Chapter 3, Open Channel Hydraulics, for more information on open channel analysis). Conversely, with sensitive flood hazard sites, if the slopes are flat, or natural and man-made obstructions exist downstream, a water surface profile analysis reaching beyond these obstructions may be required.

5.5.3 Nomographs

The use of nomographs requires a trial and error solution. The solution is quite easy and provides reliable designs for many applications. It should be remembered that velocity, hydrograph routing, roadway overtopping, and outlet scour require additional, separate computations beyond what can be obtained from the nomographs.

Following is an example of an inlet control and outlet control nomograph that can be used to design concrete pipe culverts. For culvert designs not covered by these nomographs, refer to the complete set of nomographs given in Appendix 5C at the end of this chapter.

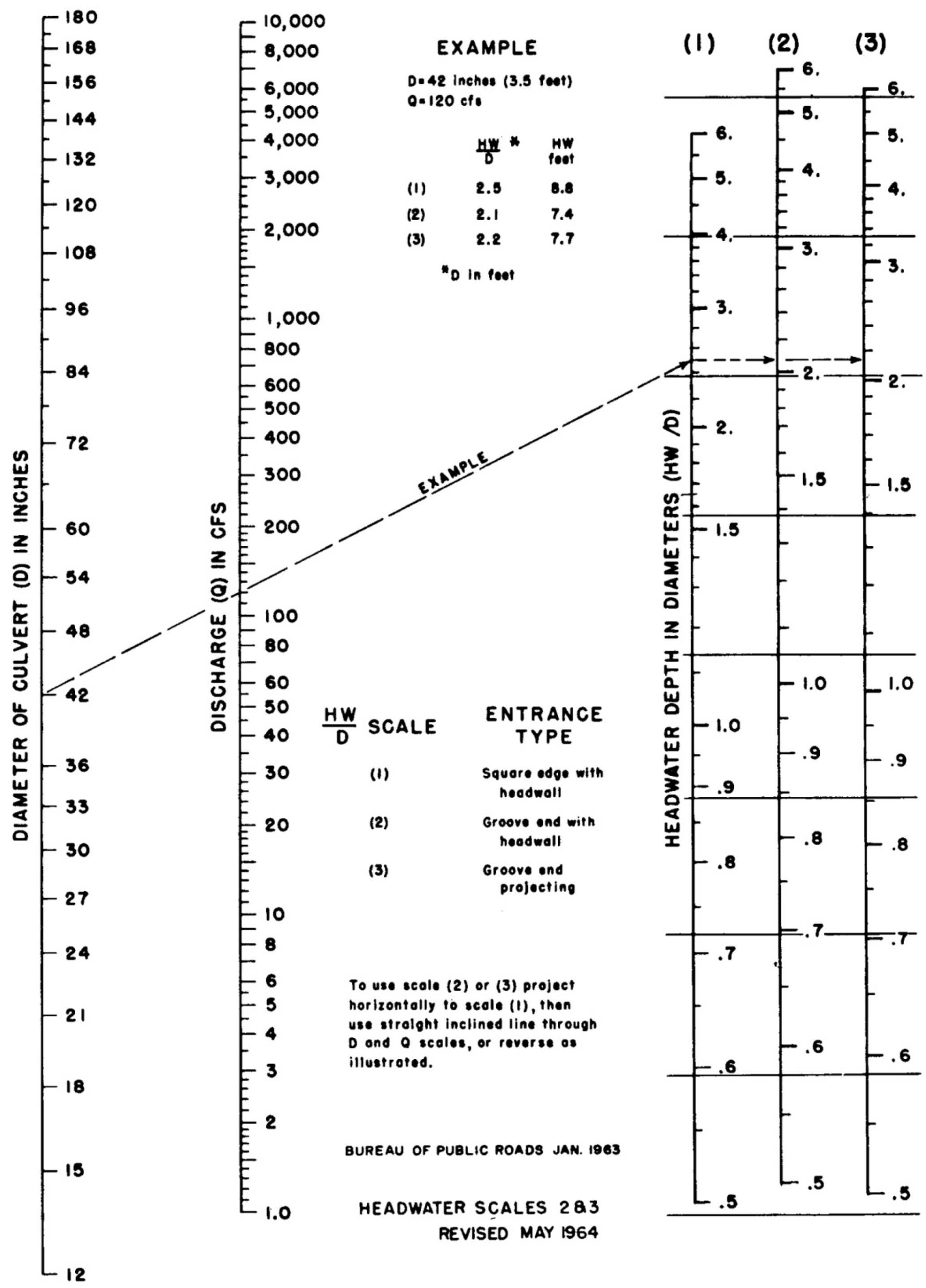


Figure 5-1 Headwater Water Depth for Concrete Pipe Culverts with Inlet Control – English Units

Source: www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/supp_figures_chap_6.pdf, page 23

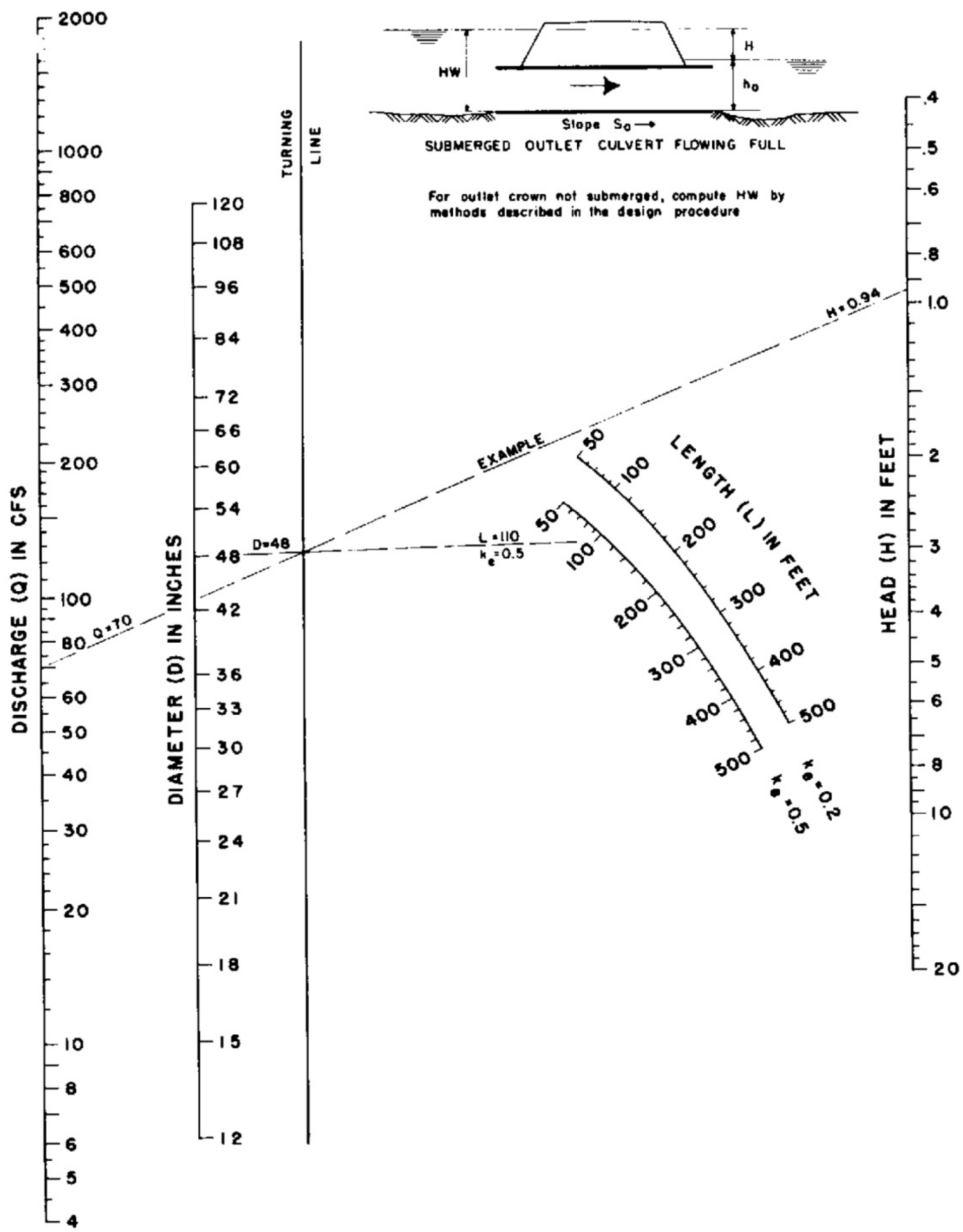


Figure 5- 2 Head for Concrete Pipe Culverts Flowing Full; n = 0.012
Source: www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/supp_figures_chap_6.pdf, page 24

5.5.4 Steps in Design Procedure

The design procedure requires the use of both inlet and outlet nomographs

1) List design data:
   Q = discharge (cfs)
   L = culvert length (ft)
   S = culvert slope (ft/ft)
   HW = allowable headwater depth for the design storm (ft)
   V = velocity for trial diameter (ft/s)

K_e = inlet loss coefficient
TW = tailwater depth (ft)

2) Determine trial culvert diameter by assuming a trial velocity 3 - 5 ft/s and computing the culvert area, A = Q/V

3) Find the actual HW for the trial size culvert for both inlet and outlet control.

   - For *inlet control*, enter inlet control nomograph with D and Q and find HW/D for the proper entrance type.

   - Compute HW and, if too large or too small, try another culvert size before computing HW for outlet control.

   - For *outlet control* enter the outlet control nomograph with the culvert length, entrance loss coefficient, and trial culvert diameter.

   - To compute HW, connect the length scale for the type entrance condition and culvert diameter scale with a straight line, pivot on the turning line and draw a straight line from the design discharge through the turning point to the head loss scale H. Compute the headwater elevation HW from the equation.

     $$\mathbf{HW = H + h_o - L} \qquad \textbf{(5.5)}$$

4) Compare the computed headwaters and use the higher HW nomograph to determine if the culvert is under inlet or outlet control.

   If outlet control governs and the HW is unacceptable, select a larger size and find another HW with the outlet control nomographs. Since the smaller size of culvert had been selected for allowable HW by the inlet control nomographs, the inlet control for the larger pipe need not be checked.

5) Calculate exit velocity and expected streambed scour to determine if an energy dissipater is needed.

5.5.5 Performance Curves

A performance curve for any culvert can be obtained from the nomographs by repeating the steps outlined above for a range of discharges that are of interest for that particular culvert design. A graph is then plotted of headwater versus discharge with sufficient points so that a curve can be drawn through the range of interest. These curves are applicable through a range of headwater velocities, and scour depths versus discharges for a length and type of culvert. Usually charts with length intervals of 25 to 50 feet are satisfactory for design purposes. Such computations are made much easier by the computer program discussed in the next section of this manual.

5.5.6 Roadway Overtopping

To complete the culvert design, roadway overtopping should be analyzed. A performance curve showing the culvert flow as well as the flow across the roadway is a useful analysis tool. Rather than using a trial and error procedure to determine the flow division between the overtopping flow and the culvert flow, and overall performance curve can be developed. The performance curve depicts the sum of the flow through the culvert and across the roadway.

The overall performance curve can be determined as follows:

1) Select a range of flow rates and determine the corresponding headwater elevations for the culvert for the culvert flow alone. The 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.

2) Combined 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 equation 5.6 to calculate flow rates across the roadway.

$$\mathbf{Q = C_d L HW_r^{1.5}} \qquad \textbf{(5.6)}$$

Where: Q = overtopping flow rate (ft^2/s)

C_d = overtopping discharge coefficient

L = length of roadway (ft)

HW_r = upstream depth, measured from the roadway crest to the water surface upstream of the weir drawdown (ft)

Note: For more information on calculating overtopping flow rates see the Hydraulic Design of Highway Culverts, HDS No. 5, Federal Highway Administration.

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

5.6 CULVERT DESIGN EXAMPLE

5.6.1 Introduction

The following example problem illustrates the procedure to be used in designing culverts using the nomographs.

5.6.2 Problem

Size a culvert given the following design conditions which were determined by physical limitations at the culvert site and hydraulic procedures described elsewhere in this handbook.

5.6.3 Input Data

Discharge for 10-year flood = 70 cfs
Discharge for 100-year flood = 176 cfs
Allowable HW for 10-year discharge = 4.5 ft
Allowable HW for 100-year discharge = 7.0 ft
Length of culvert = 100 ft
Natural channel invert elevations

Inlet = 15.50 ft
Outlet = 15.35 ft
Culvert slope = 0.0015 ft/ft
Tailwater depth for 10-year discharge = 3.0 ft
Tailwater depth for 100-year discharge = 4.0 ft
Tailwater depth is the normal depth in downstream channel
Entrance type = Groove end with headwall

5.6.4 Computations

1) Assume a culvert velocity (3 - 5 ft/s is usually a good place to start).

   Required flow area = (70 cfs)/(5 ft/s) = 14 ft^2 (for the 10-year recurrence flood).

2) The corresponding culvert diameter is about 48 in.

   This can be calculated by using the formula for area of a circle:

   Area = $(3.14D^2)/4$ or D = $(\text{Area times } 4/3.14)^{0.5}$

   Therefore: D = $[(14\ ft^2 \times 4/3.14)^{0.5} \times 12\ in/ft]$

   D = 50.7 in

3) A grooved end culvert with a headwall is selected for the design. Using the inlet control nomograph (Figure 5-1), with a pipe diameter of 48 in and a discharge of 70 cfs; read a HW/D value of 0.93.

4) The depth of headwater (HW) is (0.93) x (4) = 3.72 ft which is less than the allowable headwater of 4.5 ft.

5) The culvert is checked for outlet control by using Figure 5-2.

   With an entrance loss coefficient K_e of 0.20, a culvert length of 100 ft, and a pipe diameter of 48 in, an H value of 0.77 ft is determined. The headwater for outlet control is computed by the equation:

   $HW = H + h_o – LS$

   For the tailwater depth lower than the top of culvert,

   h_o = TW or ½ (critical depth in culvert + D) whichever is greater.

   h_o = 3.0 ft or h_o = ½ (2.55 + 4.0) = 3.28 ft

   The headwater depth for outlet control is:

   $HW = H + h_o – LS$
   HW = 0.77 + 3.28 – (100) x (0.0015) = 3.90 ft

6) Since HW for outlet control (3.90 ft) is greater than the HW for inlet control (3.72 ft), outlet control governs the culvert design.

Thus, the maximum headwater expected for a 10-year recurrence flood is 3.90 ft, which is less than allowable headwater of 4.5 ft.

7) The performance of the culvert is checked for the 100-year discharge.

   The allowable headwater for a 100-year discharge is 7 ft; critical depth in the 48 in. diameter culvert for the 100-year discharge is 3.96 ft.

   For outlet control, an H value of 5.2 is read from the outlet control nomograph. The maximum headwater is:

   $HW = H + h_o – LS$
   $HW = 5.2 + 4.0 - (100) \times (0.0015) = 9.05$ ft

   This depth is greater than the allowable depth of 7 ft, thus a *larger size culvert must be selected*.

8) A 54 in diameter culvert is tried and found to have a maximum headwater depth of 3.74 ft for the 10-year discharge and of 6.97 ft for the 100-year discharge. These values are acceptable for the design conditions.

9) Estimate outlet exit velocity. Since this culvert is in outlet control and discharges into an open channel downstream, the culvert will be flowing full at the flow depth in the channel.

   Using the 100-year design peak discharge of 176 cfs and the area of a 54 inch or 4.5 ft diameter culvert the exit velocity will be:

   $Q = VA$

   Therefore: $V = 176 / (63.62/4) = 11.1$ ft/s

   With this high velocity, an energy dissipater may be needed downstream from the culvert for streambank protection. It will first be necessary to compute a scour hole depth and then decide if protection is needed. See Chapter 7, Energy Dissipation, for design procedures related to energy dissipaters.

10) The Design engineer should check minimum velocities for low frequency flow if the larger storm event (100-year) controls culvert design.

   Figure 5-3 on the next page provides a convenient form to organize culvert design calculations.

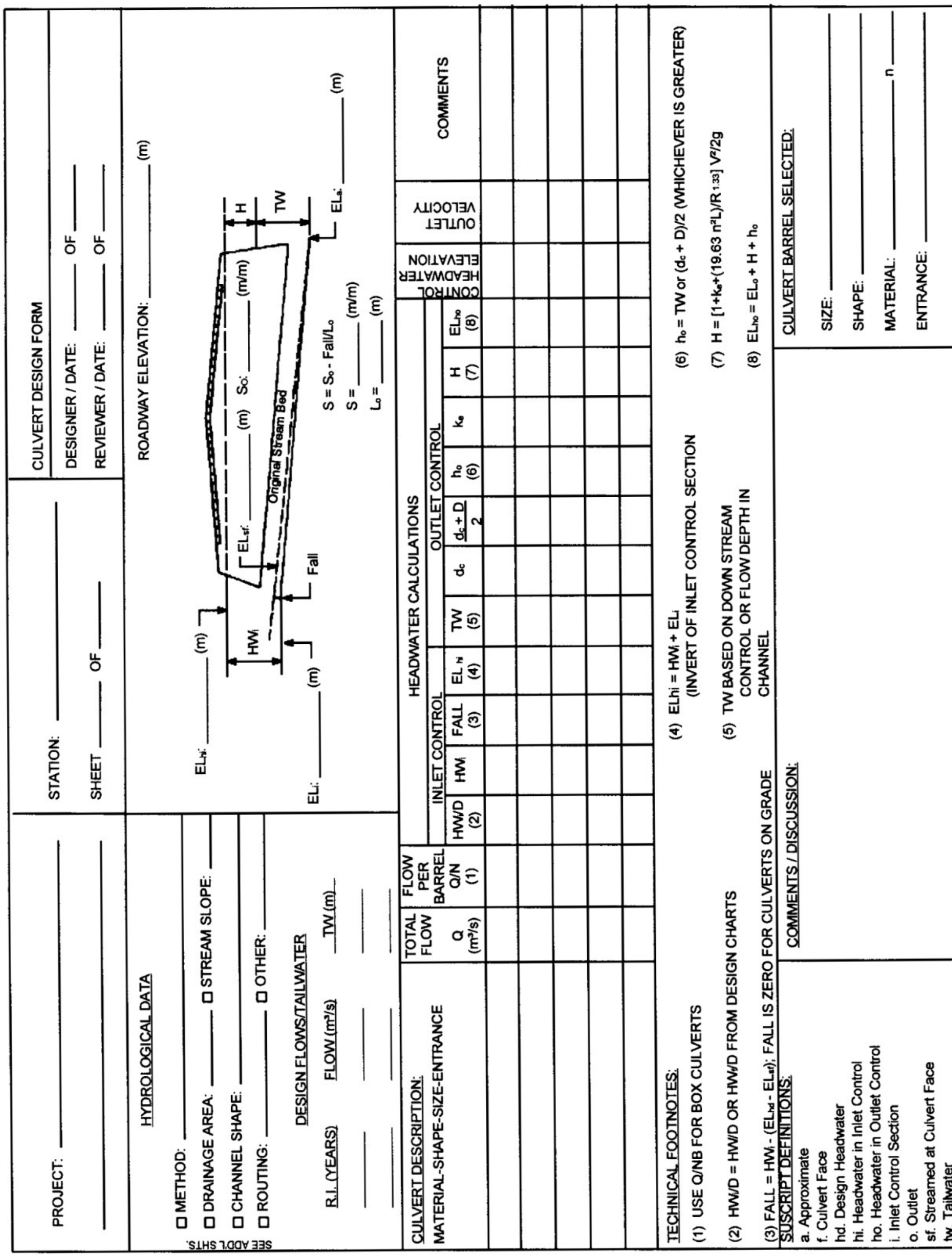


Figure 5-3 Culvert Design Form – Metric Version
Source: www.ct.gov/dot/lib/dot/documents/ddrainage/8.C.pdf, Appendix C

5.7 LONG SPAN CULVERTS

5.7.1 Introduction

Long span culverts are better defined on the basis of structural design aspects than on the basis of hydraulic considerations. According to the AASHTO Specifications for Highway Bridges, long span structural plate structure: 1) exceed certain defined maximum sizes for pipes, pipes-arches, and arches, or 2) may be special shapes of any size that involve a long radius of curvature in the crown or side plates. Special shapes include vertical and horizontal ellipses, underpasses, low and high profile arches, and inverted pear shapes. Generally, the spans of long span culverts range from 20 feet to 40 feet.

5.7.2 Structural Aspects

Long span culverts depend on interaction with the earth embankment for structural stability. Therefore, proper bedding and selection and compaction of backfill are of utmost importance. For multiple barrel structures, care must be taken to avoid unbalanced loads during backfilling.

Anchorage of the ends of long span culverts is required to prevent flotation or damage due to high velocities at the inlet. This is especially true for mitered inlets. Severe miters and skews are not recommended.

5.7.3 Hydraulic Considerations

Long span culverts generally are hydraulically short (low length to equivalent diameter ratio) and flow partly full at the design discharge. The same hydraulic principles apply to the design of long span culverts as to other culverts. However, due to their large size and variety of shapes, it is very possible that design nomographs are not available for the barrel shape of interest. For these cases, dimensionless inlet control design curves have been prepared. For the nomographs and design curves consult the publication, Hydraulic Design of Highway Culverts, Federal Highway Administration, HDS No. 5.

For outlet control, backwater calculations are usually appropriate, since design headwaters exceeding the crowns of these conduits are rare. The bridge design techniques of HDS No. 1, Hydraulics of Bridge Waterways, are appropriate for the hydraulic design of most long span culverts.

5.8 CONSTRUCTION AND MAINTENANCE CONSIDERATIONS

An important step in the design process involves identifying whether special provisions are warranted to properly construct or maintain proposed facilities. Maintenance concerns of storm system design centers on adequate physical access for cleaning and repair.

Culverts must be kept free of obstructions. Sand and sediment deposits should be removed as soon as possible. During major storms, critical areas should be patrolled and the inlets kept free of debris. Inlet and outlet channels should be kept in alignment and vegetation should be controlled in order to prevent any significant restriction of flow. Preventative maintenance should be used to inspect for structural problems, replacement needs, and scheduling of needed repairs.

APPENDIX 5A
CRITICAL DEPTH CHARTS

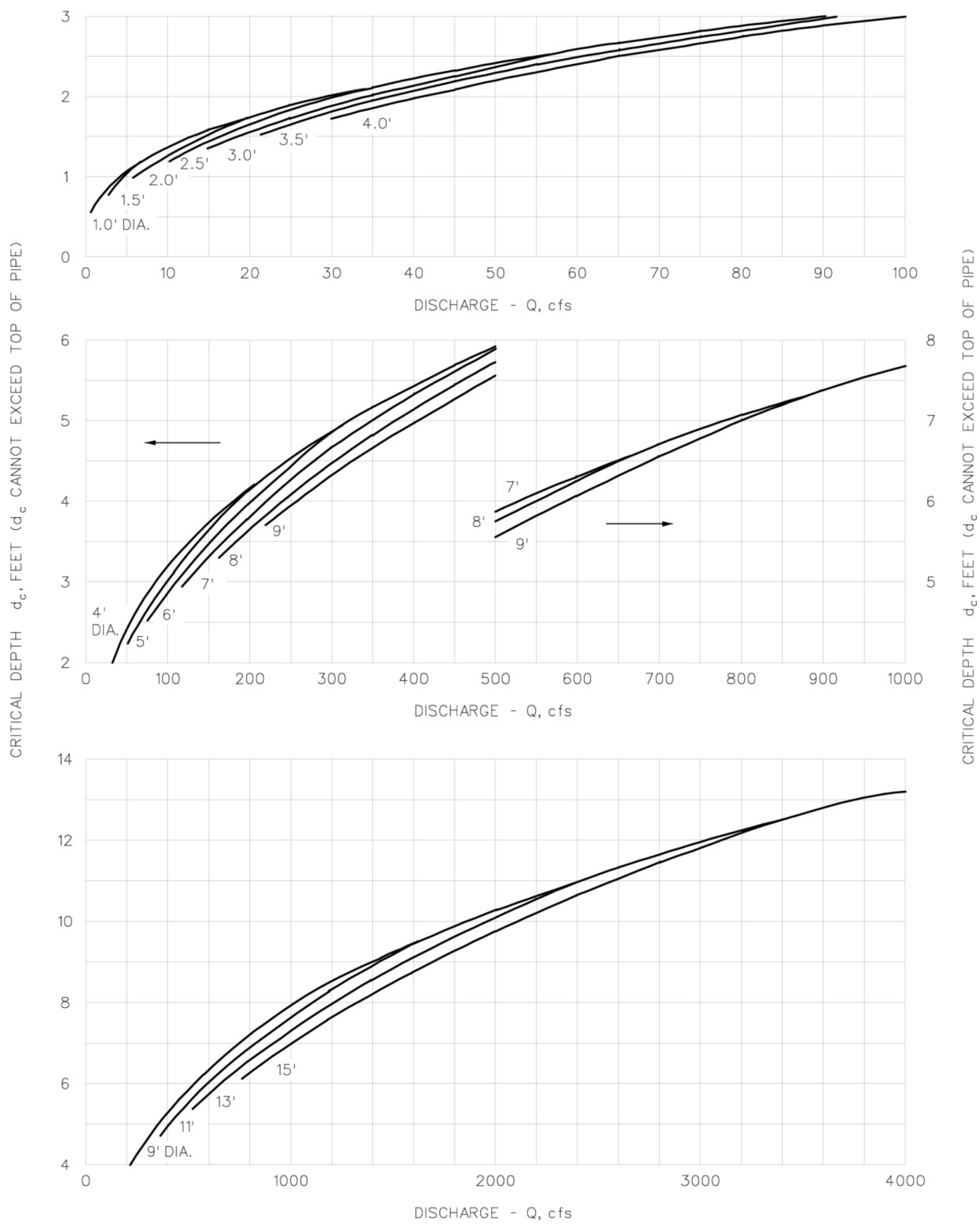
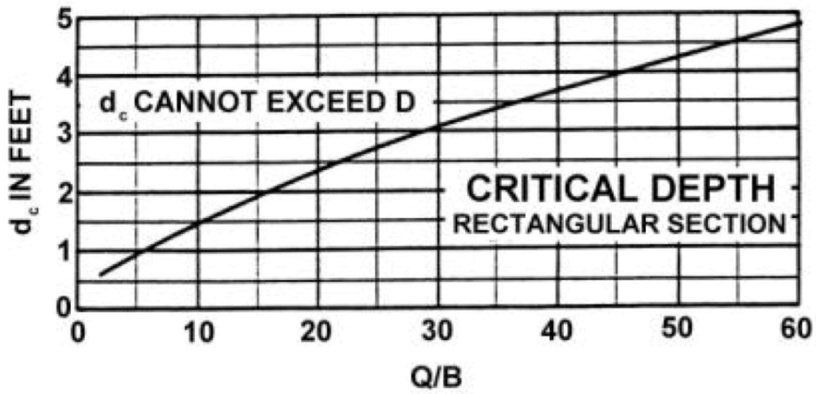


Figure 5A-1 Critical Depth for Circular Pipe

Source: http://epg.modot.org/files/9/96/750.2_Critical_Depth_for_Circular_Pipe.pdf



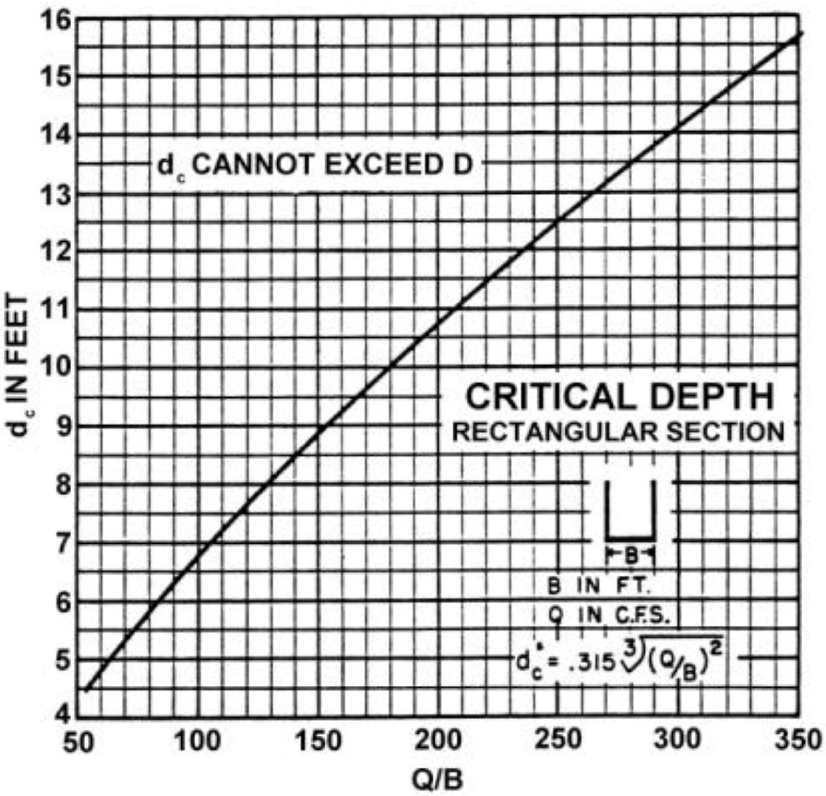


Figure 5A-2 Critical Depth for Rectangular Section
Source: http://Michigan.gov/documents/deq/lwm-smg-e_202862_7.pdf, page 2

APPENDIX 5B
DESIGN OF IMPROVED INLETS

5B.1 Introduction

A culvert operates in either inlet or outlet control. For a culvert operating under outlet control, the following characteristics influence the capacity of the culvert: headwater depth, tailwater depth, entrance configuration, and barrel characteristics.

The entrance configuration is defined by the barrel cross sectional area, shape, and edge condition, while the barrel characteristics are area, shape, slope, length and roughness.

5B.2 Outlet Control

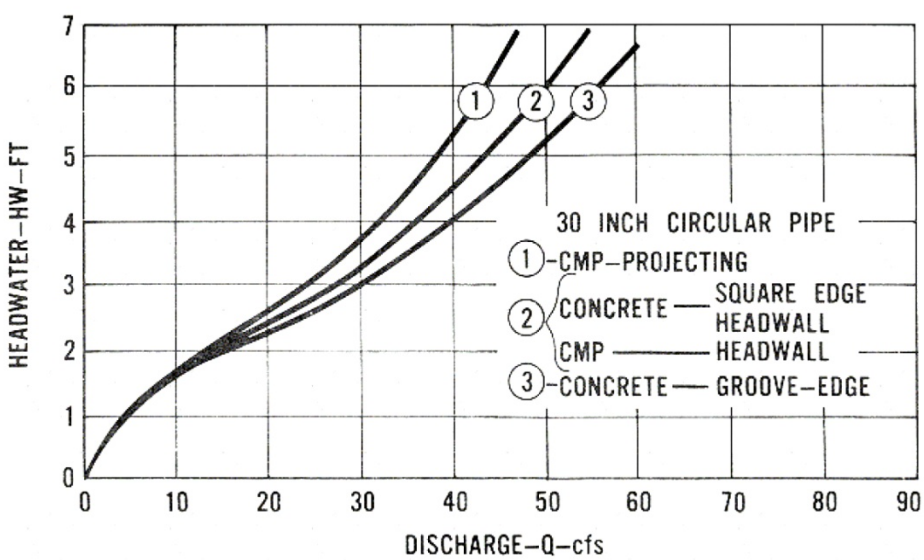
The flow condition for outlet control may be full or partly full for all or part of the culvert length. The design discharge usually results in full flow. Inlet improvements in these culverts reduce the entrance losses, which are only a small portion of the total headwater requirements. Therefore, only minor modifications of the inlet geometry (which result in little additional cost) are justified.

5B.3 Inlet Control

In inlet control, only entrance configuration and headwater depth determine the culvert's hydraulic capacity. Barrel characteristics and tailwater depth are of no consequence. These culverts usually lie on relatively steep slopes and flow only partly full. Entrance improvements can result in full or nearly full flow, thereby increasing culvert capacity significantly.

5B.4 Common Entrances

The figure below illustrates the performance of a 30-inch circular culvert in inlet control with three commonly used entrances: thin-edged projecting, square-edged, and groove-edged.

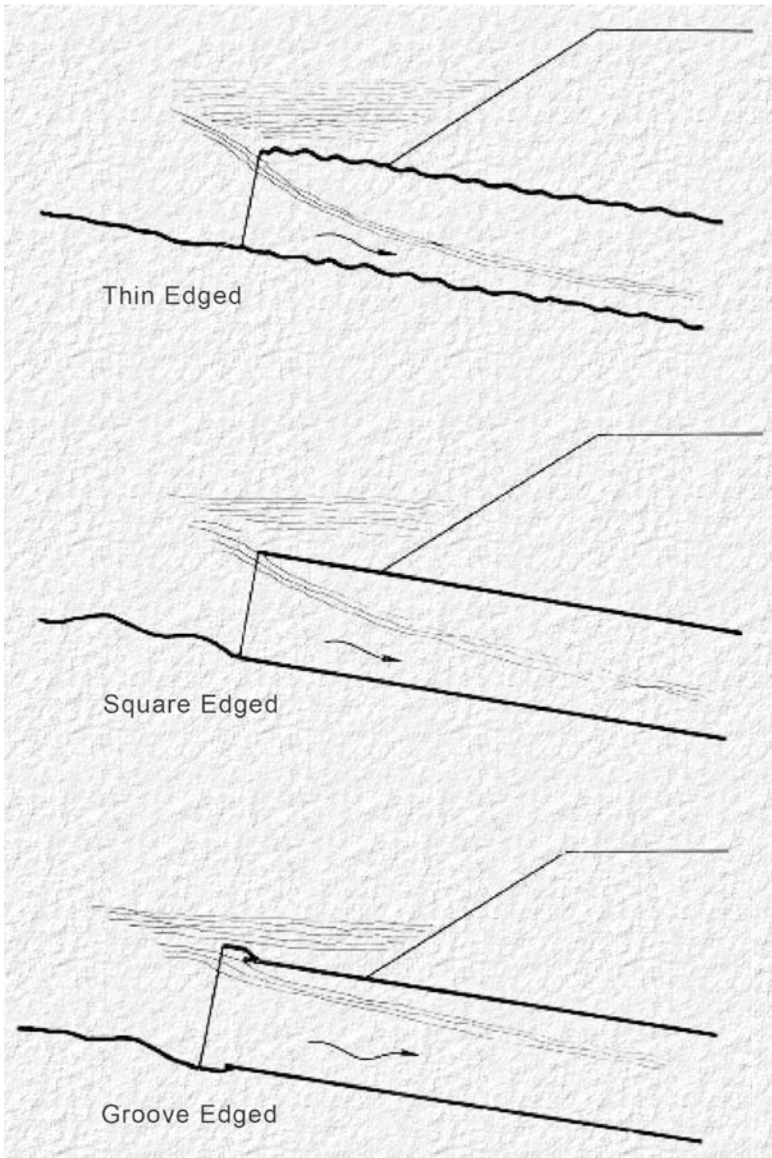


Source: www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec13.pdf

5B.5 Capacity Determinations

It is clear that inlet type and headwater depth determine the capacities of many culverts. For a given headwater, a groove-edged inlet has a greater capacity than a square-edged inlet, which in turn out performs a thin-edged projecting inlet.

The performance of each inlet type is related to the degree of flow contraction. A high degree of contraction requires more energy, or headwater, to convey a given discharge than a low degree of contraction. The figure below shows schematically the flow contractions of the three inlet types.



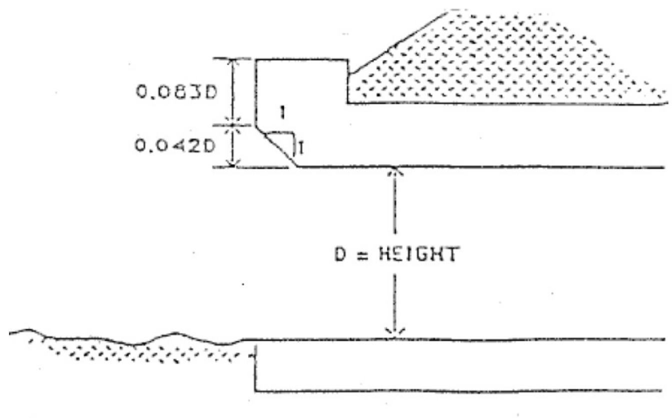
Source: www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec13.pdf

5B.6 Improved Inlets

Improved inlets include inlet geometry refinements beyond those normally used in conventional culvert design practice. Several degrees of improvements are possible, including bevel-edged, side tapered, and slope-tapered inlets. Detailed design criteria and example designs are outlined in the FHWA, HDS-5 publication. The use of improved inlets must be approved by the City or County Engineering Department.

5B.7 Bevel-edged Inlet

The first degree of inlet improvement is a bevel-edged. The bevel is proportioned based on the culvert barrel or face dimension and operates by decreasing the flow contraction at the inlet. A bevel is similar to a chamfer except that a chamfer is smaller and is generally used to prevent damage to sharp concrete edges during constructions.



Source: www.lincoln.ne.gov/city/pworks/watrshed/require/drainage/pdf/chapt4.pdf

Adding bevels to a conventional culvert design with a square-edged inlet increases culvert capacity by 5 to 20 percent. The higher increase results from comparing a bevel-edged inlet with a square-edged inlet at high headwaters. The lower increase is the result of comparing inlets with bevels, with structures having wingwalls of 30 to 45 degrees. Although the bevels referred to in the publication are plane surfaces, rounded edges which approximate the bevels are also acceptable. As a minimum, bevels should be used on all culverts which operate in inlet control, both conventional and improved inlet types. An exception to this is circular concrete culverts where the socket end performs much the same as a beveled edge.

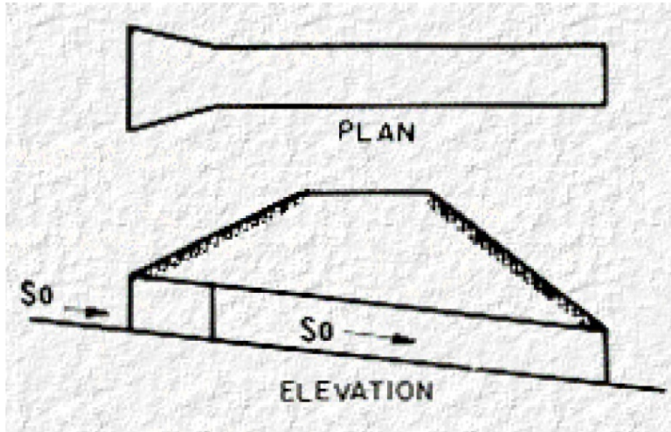
Culverts flowing in outlet control cannot be improved as much as those in inlet control, but the entrance loss coefficient, k_e, is reduced from 0.5 for a square edge to 0.2 for beveled edges.

It is recommended that bevels be used on all culvert entrances if little additional cost is involved.

5B.8 Side-Tapered Inlet

The second degree of improvement is a side-tapered inlet. This inlet has an enlarged face area with the transition to the culvert barrel accomplished by tapering sidewalls. 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. If a headwall and wingwall are going to be used at the culvert entrance, side-tapered inlets should add little if any to the overall cost while significantly increasing hydraulic efficiency. The side-tapered inlet provides an increase in flow capacity of 25 to 40 percent over that of a conventional culvert with a square edged inlet.

Whenever increased inlet efficiency is needed or when a headwall and wingwalls are planned to be used for a culvert installation, a side-tapered inlet should be considered.



Source: www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec13.pdf

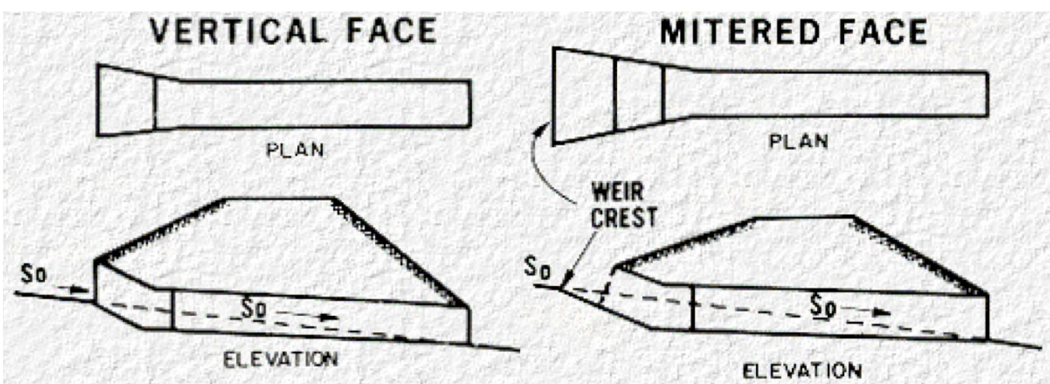
5B.9 Slope-Tapered Inlet

A slope-tapered inlet is the third degree of improvement. Its tapered advantage over the side-tapered inlet without a depression is that more head is available at the inlet. This is accomplished by incorporating a fall in the enclosed entrance section.

The slope-tapered inlet can have over 100 percent greater capacity than a conventional culvert with square edges. The degree of increased capacity depends largely upon the amount of fall available. Since this may vary, a range of increased capacities is possible.

Side- and slope-tapered inlets should be used in culvert design when they can economically be used to increase the inlet efficiency over a conventional design.

For a complete discussion of tapered inlets including figures and illustrations, see FHWA, HDS-5, 2005.



Source: www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec13.pdf

5.B.10 Improved Inlet Performance

The two tables below compare the inlet control performance of the different inlet types. The first table shows the increase in discharge that is possible for a headwater depth of 8 feet. The bevel-edged inlet, side-tapered inlet and slope-tapered inlet show increases in discharge over the square-edged inlet of 16.7, 30.4 and 55.6 percent, respectively. It should be noted that the slope-tapered inlet incorporates only a minimum fall. Greater increases in capacity are often possible if a larger fall is used.

The second table depicts the reduction in headwater that is possible for a discharge of 500 cfs. The headwater varies from 12.5 ft for the square-edged inlet to 7.6 ft for the slope-tapered inlet. This is a 39.2 percent reduction in required headwater.

Table 5B-1

Comparison of Inlet Performance at Constant Headwater for 6 ft x 6 ft Concrete Box Culvert

Inlet Type	Headwater	Discharge	% Improvement
Square-edged	8.0 feet	336 cfs	0
Bevel-edged	8.0 feet	392 cfs	16.7
Side-tapered	8.0 feet	438 cfs	30.4
Slope-tapered*	8.0 feet	523 cfs	55.6

*Minimum fall in inlet = D/4 = 6/4 = 1.5 ft

Comparison of Inlet Performance at Constant Discharge for 6 ft x 6 ft Concrete Box Culvert

Inlet Type	Discharge	Headwater	% Improvement
Square-edged	500 cfs	12.5 feet	0
Bevel-edged	500 cfs	10.1 feet	19.2
Side-tapered	500 cfs	8.8 feet	29.6
Slope-tapered*	500 cfs	7.6 feet	39.2

*Minimum fall in inlet = D/4 = 6/4 = 1.5 ft

APPENDIX 5C
CONVENTIONAL NOMOGRAPHS

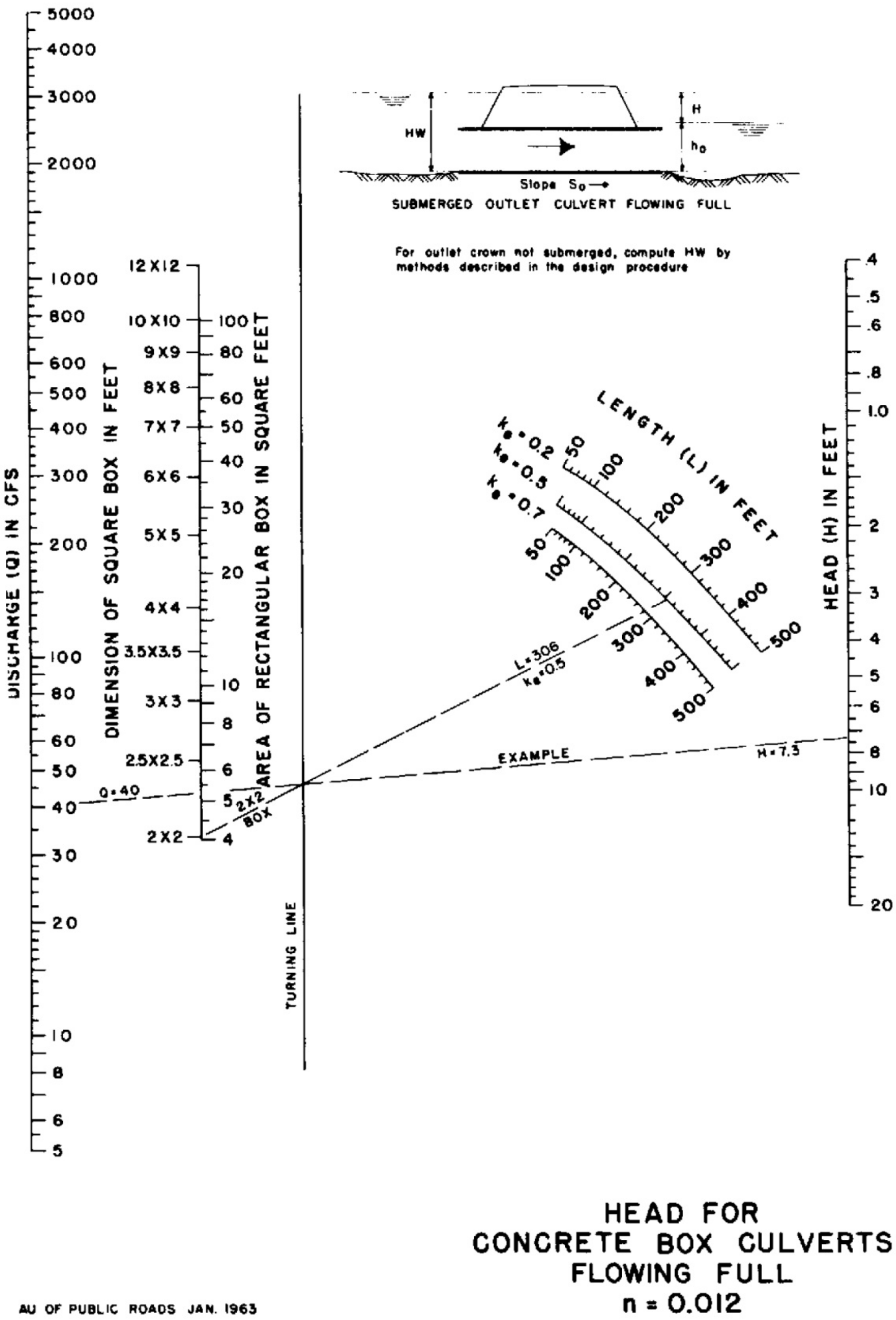


Figure 5C-1 Head for Concrete Box Culverts Flowing Full
Source: www.extranet.vdot.state.va.us/locdes/drainage/drain-manual-app-08.pdf

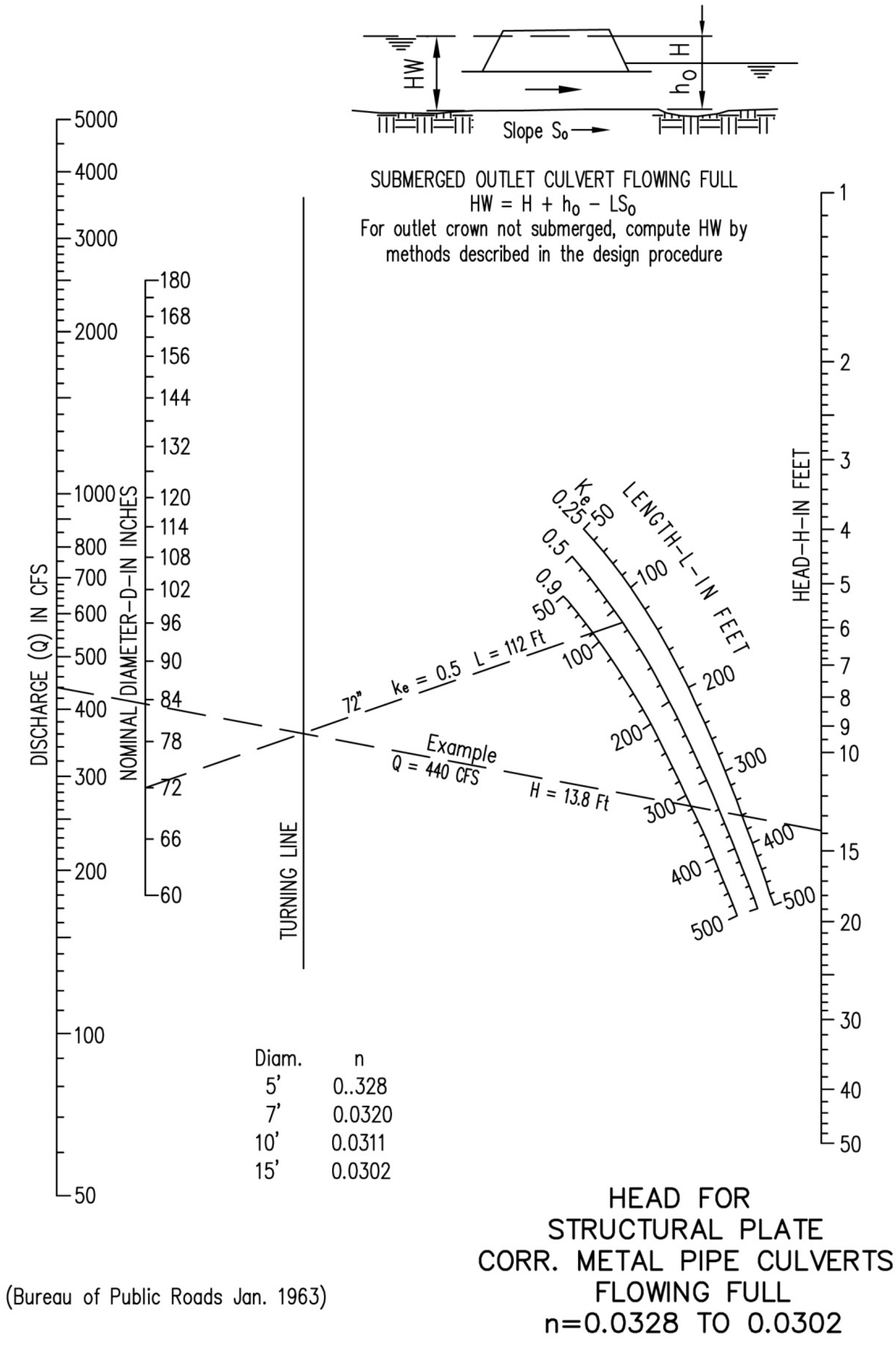


Figure 5C-2 Head for Structural Plate Corr. Metal Pipe Culverts Flowing Full
Source: ftp://ftp-fc.sc.egov.usda.gov/IL/engineer/supplements/3-94.5.pdf

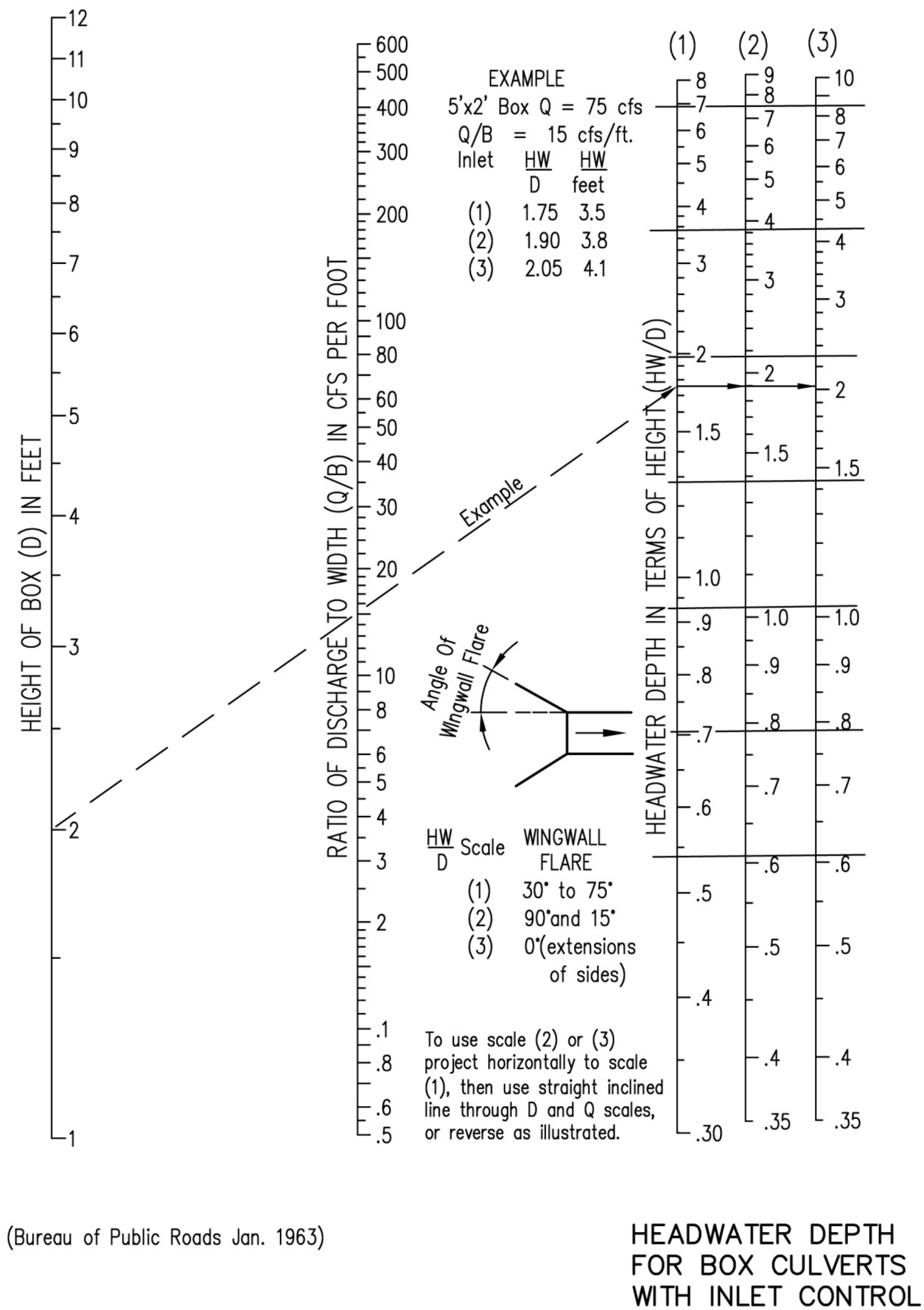


Figure 5C-3 Headwater Depth for Box Culverts with Inlet Control
Source: ftp://ftp-fc.sc.egov.usda.gov/IL/engineer/supplements/3-94.5.pdf

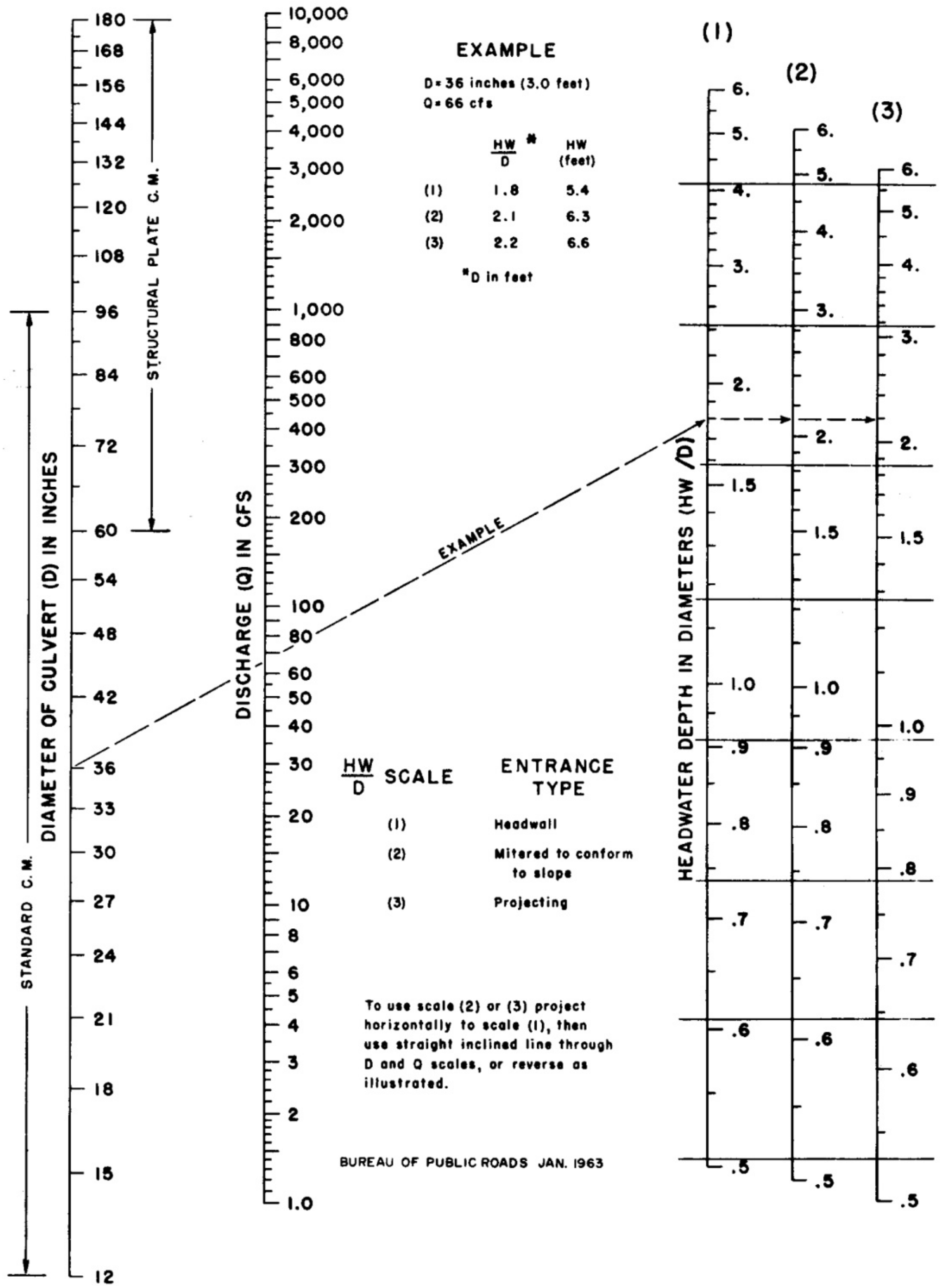


Figure 5C-4 Headwater Depth for CM Pipe Culverts with Inlet Control
Source: www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/supp_figures_chap6.pdf

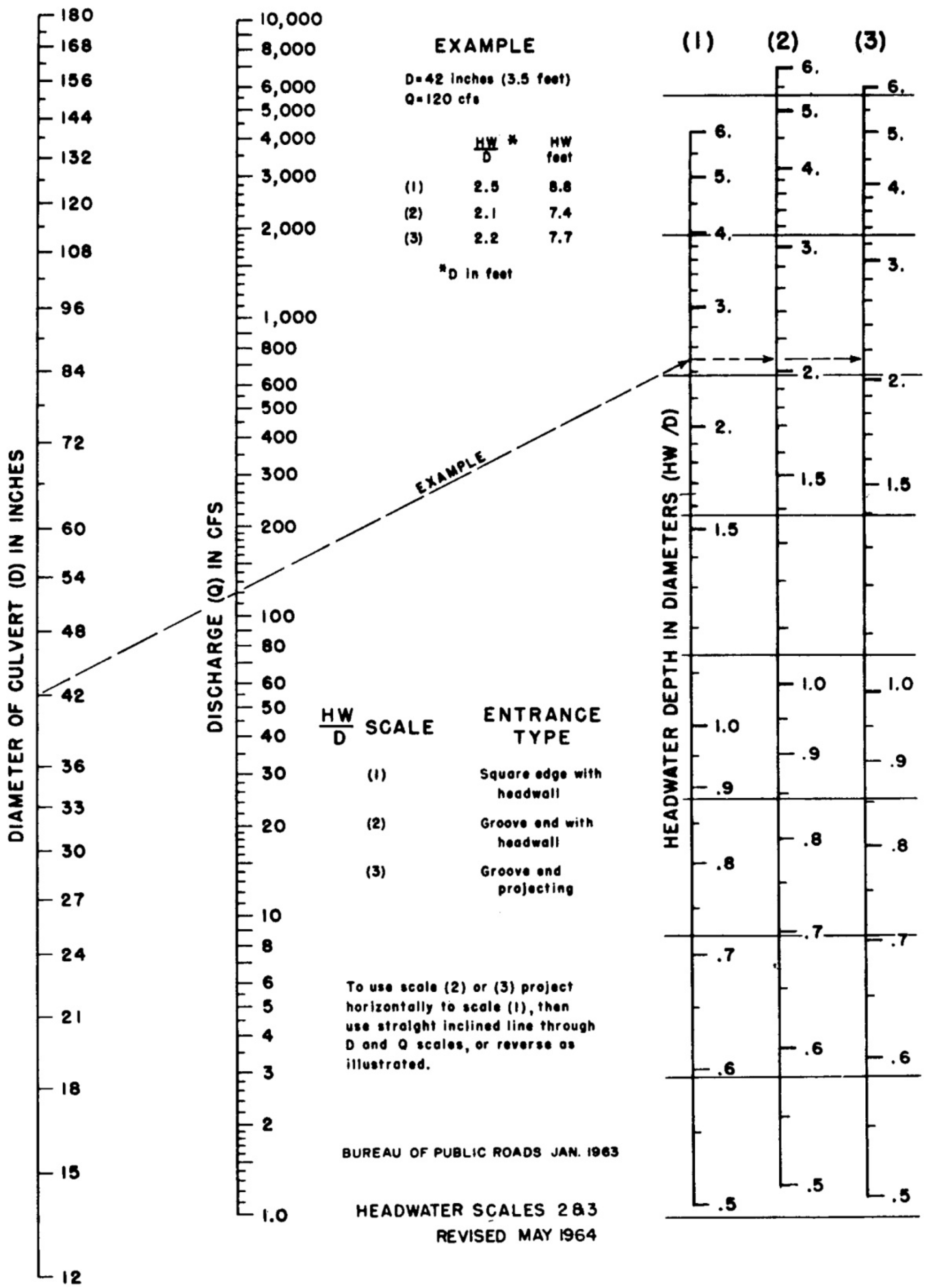


Figure 5C-5 Headwater Depth for Concrete Pipe Culverts with Inlet Control
Source: www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/supp_figures_chap6.pdf