SECTION 7 – CULVERTS

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SECTION 7 - CULVERTS

7.1.0 GENERAL

The function of a drainage culvert is to pass the design storm flow without causing excessive backwater or overtopping of the structure and without creating excessive downstream velocities. The designer shall keep energy losses and discharge velocities within allowable limits when selecting a structure that will meet these requirements. The design storm flow shall be determined by the hydrologic methods as set forth in Section 2 of this Manual. The system shall accommodate the runoff from a 100 year frequency storm meeting the limitations for overflows at bridges and culverts set forth in Section 1.2.4C. and 1.2.4D. of this Manual.

7.2.0 CULVERT HEADWALLS

7.2.1 General

The normal functions of properly designed headwalls and endwalls are to anchor the culvert in order to prevent movement due to hydraulic and soil pressures, to control erosion and scour resulting from excessive velocities and turbulence and to prevent adjacent soil from sloughing into the waterway opening. All headwalls shall be constructed of reinforced concrete and may be either straight-parallel, flared or warped. They may or may not require aprons, as determined by site conditions. Headwalls should be aligned with the direction of the receiving flow when discharging into a waterway. Precast headwalls and endwalls may be used if all other criteria are satisfied; generally precast headwalls/endwalls are available for smaller culverts eighteen (18) and twenty-four (24) inches diameter.

7.2.2 Conditions at Entrance

The operating characteristics of a culvert may be completely changed by the shape or condition at the inlet or entrance. Therefore, design of culverts must involve consideration of energy head losses that may occur at the entrance. Entrance head losses may be determined by the following equation:

$$h_e = K_e(V_2{}^2 - V_1{}^2)/2g \qquad\qquad \text{(Eq. 7-1)}$$

where,

h_e = Entrance head loss, feet

V_2 = Velocity of flow in culvert, ft/sec

V_1 = Velocity of flow approaching culvert, ft/sec

K_e = Entrance loss coefficient as shown in Table 7-1

g = Acceleration due to gravity

7.2.3 Type Of Headwall

The common types of headwall entrances are shown in Figure 7-1 in Appendix B of this Manual, but are not limited to the designs shown there. The following guidelines can be used in the selection of the type of headwall. Approach velocities are measured immediately upstream of the headwall under normal operating conditions.

<table>
<tr><td colspan="2" align="center">**Table 7-1**
Values of Culvert Entrance Loss Coefficients</td></tr>
<tr><td align="center">**Type of Entrance**</td><td align="center">Entrance Coefficient, K_e</td></tr>
<tr><td colspan="2">*Pipe*</td></tr>
<tr><td>Headwall (no wingwalls)
    Grooved edge
    Rounded edge (0.15D radius)
    Rounded edge (0.25D radius)
    Square edge (cut concrete and CMP)</td><td align="center">
0.20
0.15
0.10
0.40</td></tr>
<tr><td>Headwall with 45° Wingwalls
    Grooved edge
    Square edge</td><td align="center">
0.20
0.35</td></tr>
<tr><td>Headwall with Parallel Wingwalls Spaced 1.25D apart
    Grooved edge
    Square edge</td><td align="center">0.30
0.40
0.25</td></tr>
<tr><td>Projecting Entrance (no headwall or wingwalls)
    Grooved edge (RCP)
    Square edge (RCP)
    Sharp edge, thin walls (CMP)</td><td align="center">0.25
0.50
0.90</td></tr>
<tr><td>Sloping Entrance (no headwall or wingwalls)
    Mitered to conform to slope
    Flared-end section</td><td align="center">0.70
0.50</td></tr>
</table>

Table 7-1 (Continued) Values of Culvert Entrance Loss Coefficients	
Type of Entrance	Entrance Coefficient, K_e
Box, Reinforced Concrete	

Headwall Parallel to Embankment (no wingwalls)
    Square edge on sides of opening
    Rounded on 3 edges to radius of 1/12 barrel dimension
	0.50
	0.20

Wingwalls at 30° to 75° to barrel axis
    Square edged at crown
    Crown edge rounded to radius of 1/12 barrel dimension
	0.40
	0.20

Wingwalls at 10° to 30° to barrel Square edged at crown	0.50
Wingwalls parallel (extension of culvert walls) Square edged at crown	0.70
RCP: Reinforced Concrete Pipe CMP: Corrugated Metal Pipe NOTE: The entrance loss coefficients are used to evaluate the culvert or sewer capacity operating under outlet control.	
Source: WRC Engineering, Inc. <u>Boulder County Storm Drainage Criteria Manual</u>, 1984.	

A.   **Parallel Headwall.**

    1.   Approach velocities are low (below six (6) feet per second).

    2.   Backwater pools are permitted.

B.   **Flared Headwall.**

    1.   Approach velocities are between six (6) and ten (10) feet per second.

    2.   Ample right of way or easement is available.

The wings of flared walls should be located with respect to the direction of the approaching flow, not the culvert axis as in Figure 7-1 in Appendix B of this Manual.

C.   **Warped Headwall.**

Approach velocities are between eight (8) and twenty (20) feet per second.

Warped headwalls are effective with aprons to accelerate flow through the culvert.

7.2.4 Debris Fins.

For conditions where more than one (1) box culvert is required, the upstream face of the structure shall incorporate debris deflector fins to prevent debris buildup. For multiple-pipe situations installations of debris fins may be used but are not required.

The debris fin is an extension of the interior walls of a multiple-box culvert. The wall thickness shall be designed to satisfy structural requirements and reduce impact and turbulence to the flow.

A debris fin is constructed to the height of the culvert. A fin length of one and five tenths (1.5) times the height of the box culvert is required. Since the debris fins are subject to the same erosive forces as bridge piers, care must be taken in the design of the footing. A toewall at the upstream end of the debris fin and the apron is recommended. Figure 7-2 in Appendix B of this Manual depicts the conceptual design for debris deflector fins. It should be noted that alternate types of wingwalls can be used other than the parallel shown in Figure 7-2 in Appendix B of this Manual.

7.3.0 CULVERT DISCHARGE VELOCITIES

High discharge velocities from culverts can cause eddies or other turbulence which could damage unprotected downstream properties and roadway embankments. To prevent damage from scour and erosion in these conditions, culvert outlet protection is needed. This outlet protection is based on the discharge velocity.

Velocity	Outlet Protection
Below six (6) ft/sec	Riprap protection. (Four (4) inch minimum thickness) or alternate approved material.
Above six (6) ft/sec	Structurally reinforced apron, six (6) inch minimum thickness with toe wall.

The minimum apron length which provides transition from a culvert outlet to an open channel shall be calculated from the following equation:

$$L = 0.2 \, VD \qquad\qquad\qquad\qquad\qquad \text{(Eq. 7-2)}$$

 where,

> L = Apron length, feet
> V = culvert discharge velocity, ft/sec
> D = height of box culvert or diameter of pipe culvert, feet

7.4.0 SELECTION OF CULVERT SIZE AND FLOW CLASSIFICATION

Laboratory tests and field observations show that there are two (2) major types of culvert flow: (1) flow with inlet control; and (2) flow with outlet control. Under inlet control, the cross-sectional area of the barrel, the inlet configuration or geometry and the amount of headwater are the factors affecting capacity. Outlet control involves the additional consideration of the tailwater in the outlet channel and the slope, roughness and length of barrel. Under inlet control conditions, the slope of the culvert is steep

enough so that the culvert does not flow full and the tailwater does not affect the flow.

7.4.1 Culvert Hydraulics

A. **Inlet Control Condition.**

Inlet control for culverts may occur in two (2) ways.

1. Unsubmerged: The headwater is not sufficient to submerge the top of the culvert opening and the culvert inlet slope is supercritical. The culvert inlet acts like a weir (Condition A, Figure 7-3 in Appendix B of this Manual).

2. Submerged: The headwater submerges the top of the culvert but the pipe does not flow full. The culvert inlet acts like an orifice (Condition B, Figure 7-3 in Appendix B of this Manual).

The discharge capacity for several culvert materials, shapes, and inlet configurations under inlet control conditions are presented in Figures 7-5 to 7-10 in Appendix B of this Manual. These nomographs were developed empirically by the Bureau of Public Roads, the Federal Highway Administration and various pipe manufacturers. The nomographs are recommended for use in all inlet-control culvert calculations.

B. **Outlet Control Condition.**

There are three (3) types of outlet control culvert flow conditions:

1. The headwater submerges the culvert opening, and the culvert outlet is submerged by the tailwater. The culvert will flow full (Condition A, Figure 7-3 in Appendix B of this Manual).

2. The headwater submerges the culvert opening, the culvert outlet is not submerged by the tailwater (Condition B or C, Figure 7-3 in Appendix B of this Manual).

3. The headwater is insufficient to submerge the top of the culvert opening. The culvert slope is subcritical and the tailwater depth is lower than critical depth for the culvert (Condition D, Figure 7-3 in Appendix B of this Manual).

The capacity of a culvert for outlet control is calculated using Bernoulli's Equation, which is based on the conservation of energy principle. In the application of this equation, an energy balance is determined between the headwater at the culvert inlet and the tailwater at the culvert outlet. This balance is a function of inlet losses, friction losses and velocity head (See Figure 7-4 in Appendix B of this Manual).

Bernoulli's Equation is:

$$d_1 + V_1{}^2/2g + LS_0 = TW + h_e + h_f + h_v \qquad\qquad \text{(Eq. 7-3)}$$

The sum of the first two (2) terms on the left-hand side of Equation 7-3 is equal to the headwater (HW). That is:

$$HW = d_1 + V_1{}^2/2g \qquad\qquad \text{(Eq. 7-4)}$$

Substituting Equation 7-4 into Equation 7-3 and isolating the head losses on the right

side results in the following equation:

$$HW + LS_0 - TW = h_e + h_f + h_v \tag{Eq. 7-5}$$

From Figure 7-4 (in Appendix B of this Manual),

$$HW + LS_0 = H_L + TW$$

Thus the total head loss can be determined from this relationship as shown in Equation 7-6:

$$H_L = HW + LS_0 \quad TW \tag{Eq. 7-6}$$

Substituting Equation 7-6 into Equation 7-5, the following results:

$$H_L = h_e + h_f + h_v \tag{Eq. 7-7}$$

$$\text{in which} \quad h_v = V^2/2g. \tag{Eq. 7-8}$$

For inlet losses, the governing equation is Equation 7-1:

$$h_e = K_e(V_2^2 - V_1^2)/2g$$

From Equation 7-4, the headwater (HW) is above the actual depth by the velocity head of the approaching water. However, with water ponded at the entrance, this velocity head (V_1) is usually considered to be negligible, therefore,

$$h_e = K_e V^2/2g \tag{Eq. 7-9}$$

where K_e is the entrance loss coefficient, as shown in Table 7-1 and V is the velocity of flow in the culvert.

Friction loss is the energy required to overcome the roughness of the culvert material and is expressed as:

$$h_f = (29n^2 L/R^{1.33})(V^2/2g) \tag{Eq. 7-10}$$

where   n = Manning's coefficient
L = Length of culvert, feet
R = Hydraulic radius, feet
V = Velocity of flow in the culvert, ft/sec

Combining Equations 7-7, 7-8, 7-9 and 7-10 and simplifying the terms results in the following equation:

$$H = (K_e + 1 + 29n^2 L/R^{1.33})V^2/2g \tag{Eq. 7-11}$$

Equation 7-11 can be used to calculate directly the capacity of the culvert flowing under outlet condition A or B in Figure 7-3 in Appendix B of this Manual. This is because conditions A and B have tailwater depths at or above the top of the culvert and conditions C and D have tailwater depths which are less than critical depth. The method for calculating headwater depth for conditions C and D is discussed in the following section.

C. **Depths of Tailwater and Headwater.**

In culverts flowing with outlet control, tailwater is an important factor in computing both the headwater depth and the hydraulic capacity of a culvert. Thus, in many culvert designs, it becomes necessary to determine tailwater depth in the outlet channel.

Much engineering judgment and experience are needed to evaluate possible tailwater conditions during storms. A field inspection should be made to check on downstream controls and to determine water stages. Tailwater is often controlled by a downstream obstruction or by water stages in another stream.

An approximation of the depth of flow in a natural stream (outlet channel) can be made by using Manning's equation in the channel with normal flow condition (see Section 6.2.1, Uniform Flow of this Manual). If the water surface in the outlet channel is established by downstream controls, a backwater analysis is required (see Section 6.2.2, Gradually Varied Flow of this Manual).

The headwater depth can be calculated by the summation of head loss, tailwater depth and the elevation difference of the inlet and outlet, as shown in the following equation:

$$HW = H + h_0 \quad LS_0 \qquad\qquad \text{(Eq. 7-12)}$$

where,

HW = vertical distance from flow line at the entrance to the pool surface, feet

H = head loss, feet (use appropriate nomograph)

h_0 = vertical distance from flow line at the outlet to the hydraulic grade line, feet
(In this case h_0 equals TW, measured in feet above the flow line.)

S_0 = slope of barrel, ft/ft

L = culvert length, feet

Equation 7-12 has the same form shown in Equation 7-6, which was derived from Bernoulli's Equation. For a tailwater depth equal to or greater than the top of the culvert at the outlet (outlet control conditions A and B in Figure 7-3 in Appendix B of this Manual), h_0 can be set equal to TW and the headwater depth can be found by Equation 7-12. For tailwater elevation less than the top of the culvert at the outlet (outlet control conditions C and D in Figure 7-3 in Appendix B of this Manual), h_0 in Equation 7-12 will be assumed as

$$h_0 = (d_c + D)/2 \text{ or TW}, \qquad\qquad \text{(Eq. 7-13)}$$

where,

d_c = critical depth in feet (d_c cannot exceed D)
D = height of culvert opening in feet whichever value is greater.

Headwater depth determined by Equations 7-12 and 7-13 becomes increasingly less accurate as the headwater computed by this method falls below the value of D +

$(1+K_e)V^2/2g.$

A series of nomographs for various culvert materials and shapes have been developed by the Federal Highway Administration and the various pipe manufacturers. The nomographs presented herein include inlet control conditions (Figures 7-5 to 7-10 in Appendix B of this Manual) and outlet control conditions (Figures 7-11 to 7-17 in Appendix B of this Manual). The critical depth for pipes of different shapes are shown in Figures 7-18 to 7-22 in Appendix B of this Manual.

7.4.2 Design Procedures

The State Highway Department's THYSYS program can be used for culvert design in addition to help calculate the culvert size and related computations. Design procedures are as follows:

A.   Step 1. List design data.

    1.   Design discharge Q, cfs

    2.   Approximate length L of culvert, feet

    3.   Slope of culvert, ft/ft

    4.   Allowable headwater depth, which is 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, feet

    5.   Allowable flow velocities in natural stream

    6.   Type of culvert for first trial selection, including material, cross-   sectional shape and entrance type.

B.   Step 2. Determine the first trial size culvert.

    Since the procedure given is one of trial and error, the initial trial size can be determined by one of the following ways:

    1.   Make an arbitrary selection.

    2.   Use an approximating equation such as Q/V = A assuming a V for the trial culvert.

    3.   Use inlet control nomographs for the culvert type selected (Figures 7-5 to 7-10 in Appendix B of this Manual). If this method is used, an HW/D must be assumed. If any trial size is too large because of height restrictions or structure availability, multiple culverts may be used by dividing the discharge equally between the number of barrels used.

C.   Step 3. Find headwater depth for trial size culvert assuming inlet control or outlet control.

1.   Assuming Inlet Control

    a. Using the trial size from Step 2 above, find the headwater depth HW by use f the appropriate inlet control nomograph (Figures 7-5 to 7-10 in Appendix B of this

manual). HW in this case is found by multiplying HW/D obtained from the nomograph by the height of the culvert (D). Tailwater (TW) conditions are neglected in this determination.

b. If HW is greater or less than the desired results, try another size until HW is acceptable for inlet control before computing HW for outlet control.

2.   Assuming Outlet Control

a. Determine the depth of tailwater (TW), in feet, for the design flood condition at the outlet.

b. For a TW elevation equal to or greater than the outlet soffit of the culvert, set ho equal to the TW and find HW by Equation 7-12.

c. For a tailwater elevation less than the outlet soffit of the culvert, find headwater HW by Equation 7-12 and Equation 7-13.

3.   Compare the headwaters found in Step 3-1 and Step 3-2 above (Inlet Control and Outlet Control). The higher headwater governs and indicates the type of flow control for the given conditions and culvert size selected.

D.   Step 4. If outlet control governs but the HW is too high select a larger culvert size and recalculate HW as instructed in Step 3-2 above. If the previously calculated inlet control governs, the smaller size is satisfactory as determined under Step 3-1 above.

E.   Step 5. Compute the outlet velocity for the size selected and determine its compatibility with the criteria of Section 7.3.0 of this Manual. If the computed velocity is too high, go back to Step 2 above and select a larger culvert size.

1.   If outlet control governs in Step 3-3 above, the outlet velocity equals Q/A_0, where A_0 is the cross-sectional area of flow in the culvert at the outlet. If d_c or TW is less than the height of the culvert barrel, use A_0 corresponding to d_c or TW depth, whichever gives the greater area of flow. A_0 should not exceed the total cross-sectional area A of the culvert barrel.

2.   If inlet control governs in Step 3-3 above, outlet velocity can be assumed to equal mean velocity in open-channel flow in the barrel as computed by Manning's Equation for the rate of flow, barrel size, roughness and slope of culvert selected.

F.   Step 6. Record final selection of culvert with size, type, required headwater and outlet velocity.

7.4.3 Instructions For Using Nomographs

A.   Inlet-Control Nomographs (Figures 7-5 to 7-10 in Appendix B of this Manual).

1.   To determine HW, given Q, and size and type of culvert:

a.   Connect with a straightedge the given culvert diameter or height (D) and the discharge Q, or Q/B for box culverts; mark intersection of straightedge

on HW/D scale marked (1).

    b.   If HW/D scale marked (1) represents entrance type used, read HW/D on scale (1). If another of the three entrance types listed on the nomograph is used, extend the point of intersection in (a) horizontally to scale (2) or (3) and read HW/D.

    c.   Compute HW by multiplying HW/D by D.

2.   To determine discharge (Q) per barrel, given HW, and size and type of culvert.

    a.   Compute HW/D for given conditions.

    b.   Locate HW/D on scale for appropriate entrance type. If scale (2) or (3) are used, extend HW/D point horizontally to scale (1).

    c.   Connect point on HW/D scale (1) as found in paragraph 2.(b) above and the size of culvert on the left scale. Read Q or Q/B on the discharge scale.

    d.   If Q/B is read in (c) multiply by B (span of box culvert) to find Q.

3.   To determine culvert size, given Q, allowable HW and type culvert.

    a.   Using a trial size, compute HW/D.

    b.   Locate HW/D on scale for appropriate entrance type. If scale (2) or (3) is used, extend HW/D point horizontally to scale (1).

    c.   Connect point on HW/D scale (1) as found in paragraph 3.(b) above to given discharge and read diameter, height or size of culvert required for HW/D value.

    d.   If D is not that originally assumed, repeat procedure with a new D.

B.   **Outlet-Control Nomographs (Figures 7-11 to 7-17 in Appendix B of this Manual).**

Outlet control nomographs can be used to solve Equation 7-11 for head H when the culvert barrel flows full for its entire length. They are also used to determine H for some part-full flow conditions with outlet control. These nomographs do not give a complete solution for HW, since they give only H in the equation $HW = H + h_0 - LS_0$.

1.   To determine H for a given culvert and discharge Q:

    a.   Select appropriate nomograph for type of culvert selected. Find K_e for entrance type from Table 7-1.

    b.   Begin nomograph solution by locating starting point on length scale. To locate the proper starting point on the length scales, follow the three (3) steps provided below.

Step 1. If the n value of the nomograph corresponds to that of the culvert being used, select the length curve for the proper K_e and locate the starting point at the given culvert length. If a K_e curve is not shown for the selected K_e, see Step 2 below. If the n value for the culvert selected differs from that of the nomograph, see Step 3 below.

Step 2. For then 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 (2) chart scales in proportion to the K_e values.

Step 3. For a different roughness coefficient n1 than that of the chart n, use the length scales shown with an adjusted length L_1, calculated by the following equation:

$$L_1 = L(n_1/n)^2 \qquad\qquad\qquad (Eq. 7-14)$$

    c.   Using a straightedge, connect point on length scale to size of culvert barrel and mark the point of crossing on the "turning line." See subsection 7.4.3A.2. below for size considerations for rectangular box culvert.

    d.   Pivot the straightedge on this point on the turning line and connect given discharge rate. Read head in feet on the head (H) scale. For values beyond the limit of the chart scales, find H by solving Equation 7-13.

2.   To use the box culvert nomograph (Figure 7-13 in Appendix B of this Manual) for full flow for other than square boxes:

    a.   Compute cross-sectional area of the rectangular box.

    b.   Connect proper point (see subsection 7.4.3A.1. above) on length scale to barrel area and mark point on turning line.

    c.   The area scale on the nomograph is calculated for barrel cross- sections with span B twice the height D; its close correspondence with area of square boxes assures it may be used for all sections intermediate between square and B = 2D or B = 0.5D. For other box proportions use Equation 7-11 for more accurate results.

    d.   Pivot the straightedge on this point on the turning line and connect given discharge rate. Read head in feet on the head (H) scale.

7.4.4 Example 7-1

The following example problem utilizes computation Table 7-2 for a culvert rating curve calculation.

Given:

	Culvert size	= 48 inches RCP
	length L	= 110 feet
	n value	= 0.012
	Inlet elevation	= 720.0 feet
	outlet elevation	= 718.8 feet
	slope S_0	= 0.010
Entrance condition (square edge), K_e		= 0.50
Maximum elevation for embankment		= 732.0 ft.

Find: Culvert rating curve

Table 7-2 is used to take the computations for the culvert design.

Step 1. List the elevations for headwater depths in Column 1. Then put headwater depth and ratio of headwater depth to culvert height (or pipe diameter) in Column 2 and Column 3.

Step 2. Based on the inlet control conditions, the ratio of HW/D is used to find the flows (Q) which are put in Column 4. In this example, Item (B) in Figure 7-5 in Appendix B of this Manual is utilized.

Step 3. For outlet control conditions, the flow rate Q in Column 4 is used to determine the head loss (H) in Column 5. In this example, Figure 7-12 in Appendix B of this Manual is utilized.

Step 4. If the tailwater rating curve is available, the tailwater (TW) depth can be entered in Column 6. If the tailwater rating curve is not available, an estimate of the tailwater can be used.

Step 5. If the tailwater depth is less than the diameter of the culvert, Columns 7 and 8 should be calculated. If TW is larger than D, the TW value is entered in Column 9 for h_0.

Step 6. The critical depth (cd) is found from Figures 7-18 to 7-22 in Appendix B of this manual, and then used to compile Column 8.

Step 7. The headwater depth (HW) now can be computed from Equation 7-12.

Step 8. Compare the two (2) headwater depth values from Column 2 and Column 10. The controlling headwater depth and type of control are recorded in Column 11 and Column 12, respectively. The calculated elevation is written in Column 14.

Step 9. The rating curve for the culvert can be plotted from the values in Column 4 and Column 13.

To size a culvert crossing, the same table can be used, with some variation in the basic data. First a design Q value is selected and the maximum allowable headwater is determined. An inlet type i.e., headwall) is selected and the invert elevations and culvert slope are estimated based upon site constraints. A culvert type is then selected and first rated for inlet control then outlet control. If the controlling headwater exceeds the maximum allowable headwater, the input data is modified and the procedure repeated until the desired results are achieved.

7.5.0 HYDRAULIC CONSIDERATIONS IN BRIDGE DESIGN

7.5.1 General

Section 1.2.4C. and Section 1.2.4D. of this Manual state the City's position concerning storm water overtopping bridge structures. The current policy for overtopping of residential streets is a maximum of twelve (12) inches for the 100 year frequency storm, and for any street other than residential, the allowable maximum is six (6) inches for the 100 year frequency storm.

Several hydraulic parameters should be considered in bridge design. Among these considerations should be, but should not be limited to, the following:

    A.   Channel transitions into and out of the bridge opening.

B. Overall length and height of bridge.

C. Cross-sectional opening of bridge.

D. Location of the bridge opening relative to the main channel.

E. Bridge alignment relative to general flow of main channel i.e., "skewed" crossing.

F. Number of crossings or bridge openings.

G. Other obstructions to flow i.e., piers, abutments, deck width and clearances.

H. Design flows for bridge opening to pass.

I. Any freeboard requirements for channel design.

7.5.2 Types Of Flow For Bridge Design

Three (3) types of flow caused by bridge construction on a flood plain are shown in Figure 7-23 in Appendix B of this Manual. The three (3) flow types are described below:

A. **Type I Flow.**

Referring to Item A of Figure 7-23 in Appendix B of this Manual, it can be observed that normal water surface is above critical depth at all points. This has been labeled Type I, or subcritical flow, the type usually encountered in practice. The backwater expression for Type I flow is obtained by applying the conservation of energy principle between cross-sections 1 and 4.

B. **Type IIA Flow.**

There are at least two (2) variations of Type II flow which will be described here as Types IIA and IIB. For Type IIA flow, Item B of Figure 7-23 in Appendix B of this Manual, normal water surface in the unconstricted channel again remains above critical depth in the constriction. Once critical depth is penetrated, the water surface upstream from the constriction, and thus the backwater, becomes independent of conditions downstream (even though the water surface returns to normal stage at cross-section 4).

C. **Type IIB Flow.**

The water surface for Type IIB flow, Item C of Figure 7-23 in Appendix B of this Manual, starts out above both normal water surface and critical depth upstream, passes through critical depth in the constriction and then returns to normal. The return to normal depth can be rather abrupt as in Item C of Figure 7-23 in Appendix B of this Manual, taking place in the form of a poor hydraulic jump, since normal water surface in the stream is above critical depth.

D. **Type III Flow.**

In Type III Flow, Item D of Figure 7-23 in Appendix B of this Manual, the normal water surface is below critical depth at all points and the flow throughout is supercritical. This is an unusual case requiring a steep gradient but such conditions do exist, particularly in mountainous regions. Theoretically, backwater should not occur for this type, since the flow throughout is supercritical. It is more

than likely that an undulation of the water surface will occur in the vicinity of the constriction, as indicated on Item D of Figure 7-23 in Appendix B of this Manual.

A more thorough and complete discussion of these parameters and preliminary design procedures are presented in Chapters 1 and 11 of Hydraulics of Bridge Waterways by U.S. Department of Transportation Federal Highway Administration, Second Edition, September, 1973.

7.5.3 Modeling Hydraulic Conditions

The most commonly used backwater program for modeling hydraulic conditions at existing or proposed bridge crossings is the U.S. Army Corps of Engineers HEC-RAS Water Surface Profiles Program. The normal and special bridge routines contained within the program are widely used. A thorough discussion of the application of these bridge routines are presented in the HEC-RAS User's Manual. HEC-RAS software is available from the U.S. Army Corps of Engineers Hydrologic Engineering Center.

Table 7-2 Calculation Table for Culvert Design

CALCULATION TABLE FOR CULVERT DESIGN

PROJECT:

TOTAL LOSSES

$$H = he + hf + hv$$

TYPE=
INLET=
Ke=

So=
L=
SoL=

n=
Q FULL=
V FULL=

(1) $Hw = H + ho - LSo$

(2) For $Tw < D$; $ho = \frac{dc+D}{2}$ or Tw
(Whichever is greater)

For $Tw > D$; $ho = Tw$

(3) For Box Culvert : $dc = 0.315 \left(\frac{D}{B}\right)^{\frac{2}{3}} \leq D$

ELEV.	INLET CONTROL		Q	OUTLET CONTROL EQUATIONS					HW	CON-TROLLED HW	CONTROL HW	CAL-CULATED ELEV.
	HW	HW/D		H	Tw	Tw < D		Tw>D				
						dc	ho=$\frac{dc+D}{2}$	ho				
1	2	3	4	5	6	7	8	9	10	11	12	13

Source: City of Austin Drainage Criteria

Example Table 7-2 Calculation Table for Culvert Design

CALCULATION TABLE FOR CULVERT DESIGN

PROJECT:

TOTAL LOSSES

$$H = he + hf + hv$$

TYPE= 48" RCP
INLET=SQUARE EDGE
Ke= 0.5

So=0.010
L= 110'
SoL=1.10

n= 0.012
Q FULL=160 CFS
V FULL=12.4 fps

(1) $Hw = H + ho - LSo$

(2) For $Tw < D$; $ho = \frac{dc+D}{2}$ or Tw
    (Whichever is greater)
    For $Tw > D$; $ho = Tw$

(3) For Box Culvert : $dc = 0.315 \left(\frac{Q}{B}\right)^{\frac{2}{3}} \leq D$

ELEV.	INLET CONTROL						OUTLET CONTROL EQUATIONS					CON-TROLLED HW	CONTROL	CAL-CULATED ELEV.
	HW	$\frac{HW}{D}$	Q	H	Tw	\multicolumn{2}{c}{Tw < D}	Tw>D	HW			
						dc	$ho=\frac{dc+D}{2}$	ho				
1	2	3	4	5	6	7	8	9	10	11	12	13
720	0	0	0									720.0
724	4	1	70	0.94		2.55	3.28		3.12	4	INLET	724.0
725	5	1.25	95	1.72		2.90	3.45		4.07	5	INLET	725.0
726	6	1.5	115	2.60		3.20	3.60		5.10	6	INLET	726.0
728	8	2.0	150	4.50		3.60	3.80		7.20	8	INLET	728.0
730	10	2.5	170	5.80		3.85	3.93		8.63	10	INLET	730.0

Source: City of Austin Drainage Criteria Manual