2N-2 Culvert Hydraulics

A. Culvert flow controls and equations

Figure 1 depicts the energy grade line and the hydraulic grade line for full flow in a culvert barrel. The energy grade line represents the total energy at any point along the culvert barrel. HW is the depth from the inlet invert to the energy grade line. The hydraulic grade line is the depth to which water would rise in the vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel straight lines separated by the velocity head lines except in the vicinity of the inlet where the flow passes through a contraction.

The headwater and tailwater conditions as well as the entrance, friction, and exit losses are also shown in Figure 1. Equating the total energy at sections 1 and 2 (see Figure 1), upstream and downstream of the culvert barrel in figure, the following relationship results:

$$HW_o + \frac{V_1^2}{2g} = TW + \frac{V_d^2}{2g} + H$$ **Equation 1**

Where H = sum of all losses = $H_e + H_f + H_v$; $H = \left[1 + K_e + \frac{29n^2L}{R^{1.33}}\right]\frac{V^2}{2g}$ **Equation 2**

Where V = the mean or average velocity in the culvert barrel in ft/s

TW = tailwater depth in feet

g = acceleration of gravity (32.2 ft/s)

K_e = inlet loss coefficient (see Section 2N-1, Table 1)

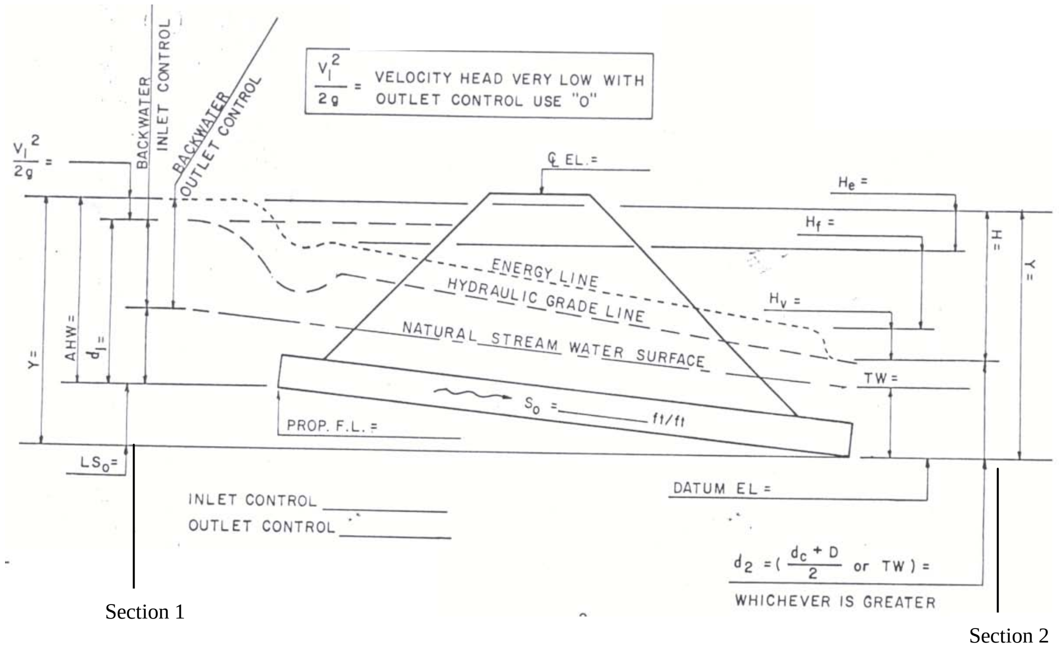
R = hydraulic radius = $\frac{\text{Cross sectional area of the fluid in the culvert}}{\text{Wetted perimeter of the culvert}}$

H_e = entrance head loss = $(K_e)\frac{V^2}{2g}$ **Equation 3**

H_f = barrel friction head loss = $(\frac{29n^2L}{R^{1.33}})\frac{V^2}{2g}$ **Equation 4**

H_v = velocity head loss = $\frac{V^2}{2g}$ **Equation 5**

Figure 1: Full Flow Energy and Hydraulic Grade Line



B. Inlet and outlet control

The design procedures contained in this section are for the design of culverts for a constant discharge considering inlet and outlet control. Generally, the hydraulic control in a culvert will be at the culvert outlet if the culvert is operating on a mild slope. Inlet control usually occurs if the culvert is operating on a steep slope.

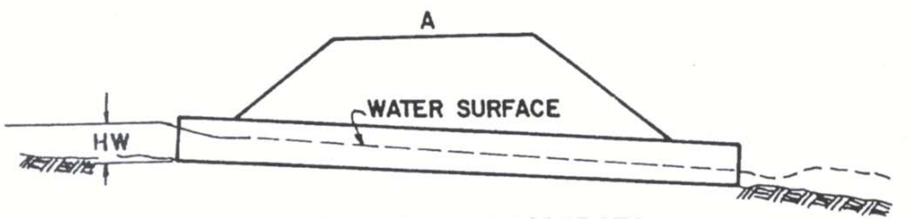
For inlet control, the entrance characteristics of the culvert are such that the entrance headlosses are predominant in determining the headwater of the culvert. The barrel will carry water through the culvert more efficiently than the water can enter the culvert. Proper culvert design and analysis requires checking for inlet and outlet control to determine which will govern particular culvert designs. For outlet control, the headlosses 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.

1. **Inlet control.** Since the control is at the upstream end in inlet control, only the headwater and the inlet configuration affect the culvert performance. The headwater depth is measured from the invert of the inlet control section to the surface of the upstream pool. The inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area, but for tapered inlets, the face area is enlarged, and the control section is at the throat.

   Examples of inlet control:
   Figures 1A-1D depict several different examples of inlet control flow. The type of flow depends on the submergence of the inlet and outlet ends of the culvert. In all of these examples, the control section is at the inlet end of the culvert. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

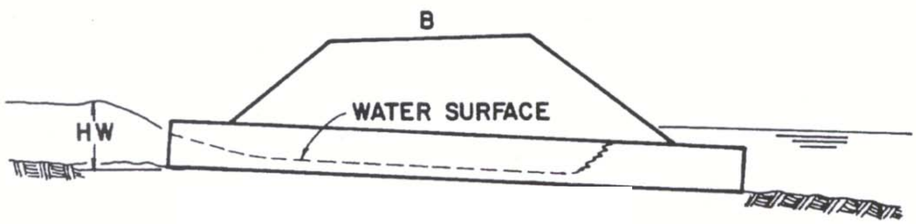
   a. Figure 1A depicts a condition where neither the inlet nor the outlet end of the culvert is submerged. The flow passes through critical depth just downstream of the culvert entrance and the flow in the barrel is supercritical. The barrel flows partly full over its length, and the flow approaches normal depth at the outlet end.

Figure 1A: Inlet/Outlet Unsubmerged[1]



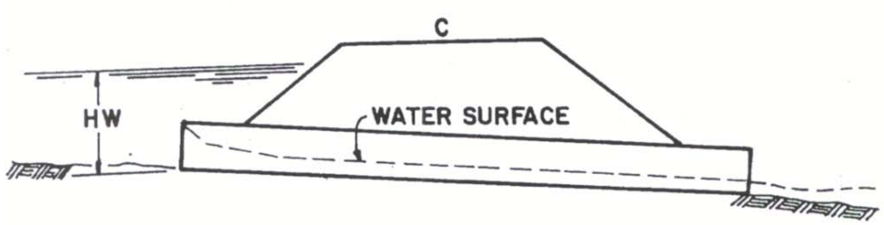
b. Figure 1B shows that submergence of the outlet end of the culvert does not assure outlet control. In this case, the flow just downstream of the inlet is supercritical and a hydraulic jump forms in the culvert barrel.

Figure 1B: Outlet Submerged, Inlet Unsubmerged[1]



c. Figure 1C is a more typical design situation. The inlet end is submerged and the outlet end flows freely. Again, the flow is supercritical and the barrel flows partly full over its length. Critical depth is located just downstream of the culvert entrance, and the flow is approaching normal depth at the downstream end of the culvert.

Figure 1C: Inlet Submerged[1]



d. Figure 1D is an unusual condition illustrating the fact that even submergence of both the inlet and the outlet ends of the culvert does not assure full flow. In this case, a hydraulic jump will form in the barrel. The median inlet provides ventilation of the culvert barrel. If the barrel were not ventilated, sub-atmospheric pressures could develop which might create an unstable condition during which the barrel would alternate between full flow and partly full flow.

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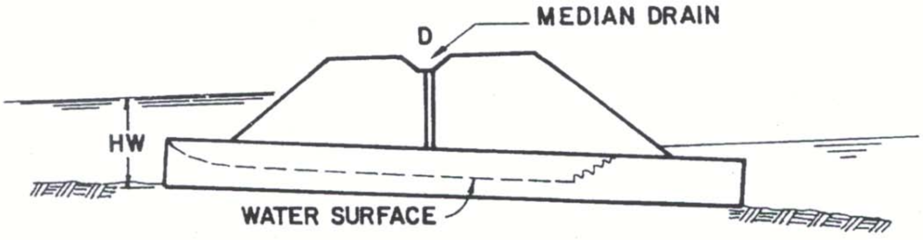
[1] Source: *Hydraulic Design of Highway Culverts*, FHWA, 1998.

Figure 1D: Inlet/Outlet Submerged[1]



2. **Outlet control.** All of the factors influencing the performance of a culvert 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.

   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 a hydraulic resistance coefficient such as the Manning n value.

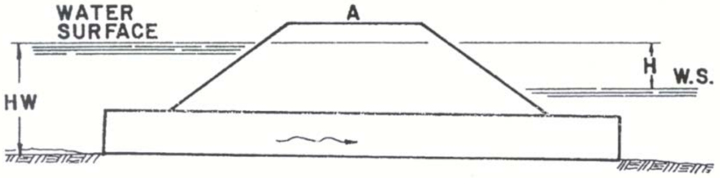
   The barrel area and barrel shape are self explanatory. The barrel length is the total culvert length from the entrance to the exit of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of the barrel length is usually necessary to begin the design process. The barrel slope is the actual slope of the culvert barrel. The barrel slope is often the same as the natural stream slope. However, when the culvert inlet is raised or lowered, the barrel slope is different from the stream slope.

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

   Hydraulics of outlet control:
   Full flow in the culvert barrel, as depicted in Figure 2A, is the best type of flow for describing outlet control hydraulics. Outlet control flow conditions can be calculated based on energy balance. The total energy (H_L) required to pass the flow through the culvert barrel is made up of the entrance loss (H_e), the friction loss through the barrel (H_f), and the exit loss (H_o). Other losses, including bend losses (H_b), losses at junctions (H_j), and losses at gates (H_g) should be included as appropriate.

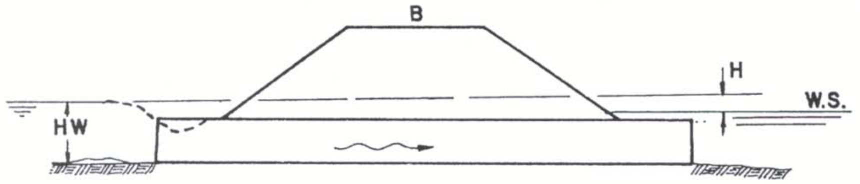
a. Figure 2A represents the classic full flow condition, with both inlet and outlet submerged. The barrel is in pressure flow throughout its length. This condition is often assumed in calculations, but seldom actually exists.

Figure 2A: Inlet/Outlet Submerged[1]



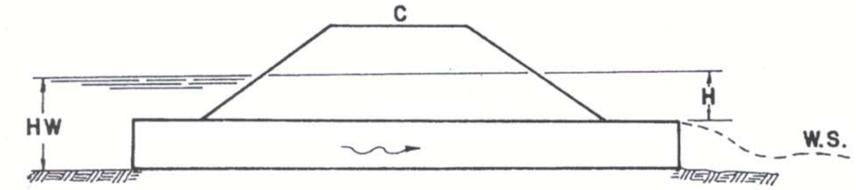
b. Figure 2B depicts the outlet submerged with the inlet unsubmerged. For this case, the headwater is shallow so that the inlet crown is exposed as the flow contracts to the culvert.

Figure 2B: Outlet Submerged, Inlet Unsubmerged[1]



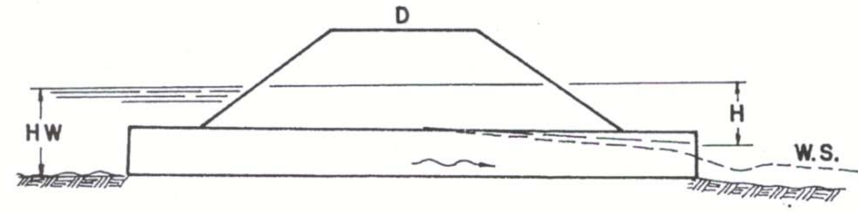
c. Figure 2C shows the entrance submerged to such a degree that the culvert flows full throughout its entire length while the exit is unsumberged. This is a rare condition. It requires an extremely high headwater to maintain full barrel flow with no tailwater. The outlet velocities are usually high under this condition.

Figure 2C: Inlet Submerged, Outlet Unsubmerged[1]



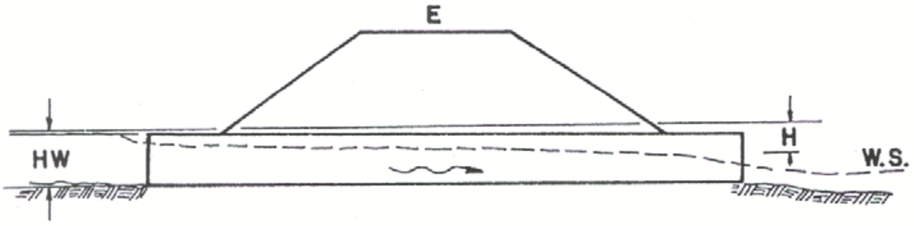
d. Figure 2D is more typical. The culvert entrance is submerged by the headwater and the outlet end flows freely with the low tailwater. For this condition, the barrel flows partly full over at least part of its length (subcritical flow) and the flow passes through critical depth just upstream from the outlet.

Figure 2D: Inlet Submerged, Outlet Partially Submerged[1]



e. Figure 2E is also typical, with neither the inlet nor the outlet end of the culvert submerged. The barrel flows partly full over its entire length, and the flow profile is subcritical.

Figure 2E: Inlet Unsubmerged, Outlet Unsubmerged[1]



C. Use of inlet and outlet control nomographs

The following design procedure provides a convenient and organized method for designing culverts for constant discharge, considering inlet and outlet control. The following will outline the design procedure for use of the nomographs. The designer may desire to use the *HY8 Culvert Analysis Microcomputer Program* rather than the nomographs, or Iowa DOT Culvert Program, which can be found at: http://www.dot.state.ia.us/bridge/prelprog.htm. The Rational Method or the TR-55 Method should be used rather than the Iowa Runoff Curve, which is utilized in the Culvert Program. The *HY8 Program* can be found in the AASHTO Model Drainage Manual, 1998.

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.

Figures 5-8 show examples for inlet-control nomographs that can be used to design concrete pipe culverts. Figures 9-11 show examples for outlet-control nomographs. For culvert designs not covered by these nomographs, refer to the complete set of nomographs given in Municipal Stormwater Management, Second edition, 2003 by Thomas N. Debo, Andrew J. Reese. Following is the design procedure that requires the use of inlet- and outlet-control nomographs:

1. **Step 1:** List design data

    - Q = discharge (cfs)
    - L = culvert length (ft)
    - S = culvert slope (ft/ft)
    - K_e = inlet loss coefficient
    - V = velocity (ft/s)
    - TW = tailwater depth (ft)
    - HW = allowable headwater depth for the design storm (ft)

2. **Step 2:** Determine trial culvert size by assuming a trial velocity 3-5 ft/s and computing the culvert area, A = Q/V. Determine the culvert diameter (inches).

3. **Step 3:** Find the actual HW for the trial-size culvert for inlet and outlet control.

    a. 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.

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

    c. To compute HW, connect the length of the scale for the type of 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 following equation:

    $$HW = H + h_o - LS$$ **Equation 6**

    where h_o = ½ (critical depth + D), or tailwater depth, whichever is greater.

4. **Step 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 trial size and find another HW with the outlet control nomographs. Because 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. **Step 5:** Calculate exit velocity and expected streambed scour to determine if an energy dissipater is needed. The stream degradation may be a pre-existing condition, and the reasons and rate of degradation need to be determined. The culvert cross-sectional area may need to be increased and culvert invert initially buried if stream degradation is probable. 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. Curves with length intervals of 25-50 feet are usually satisfactory for design purposes. Such computations are made much easier by available computer programs.

Figure 3A: Critical Depth Circular Pipe, Discharge = 0 to 100 cfs

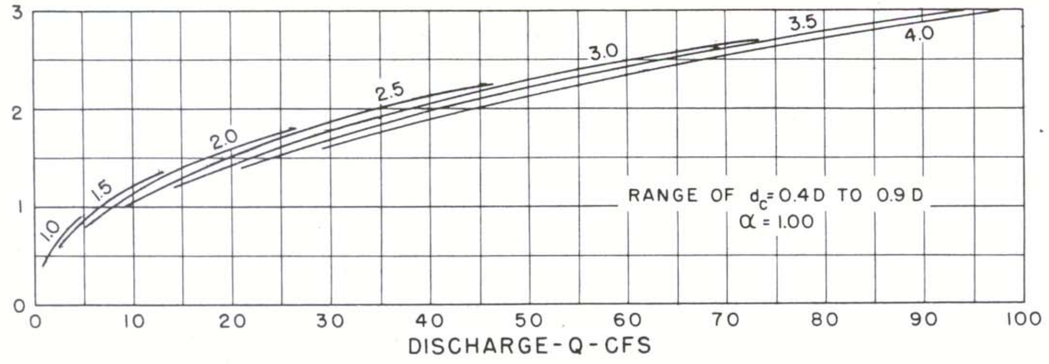


Figure 3B: Critical Depth Circular Pipe, Discharge = 0 to 1000 cfs

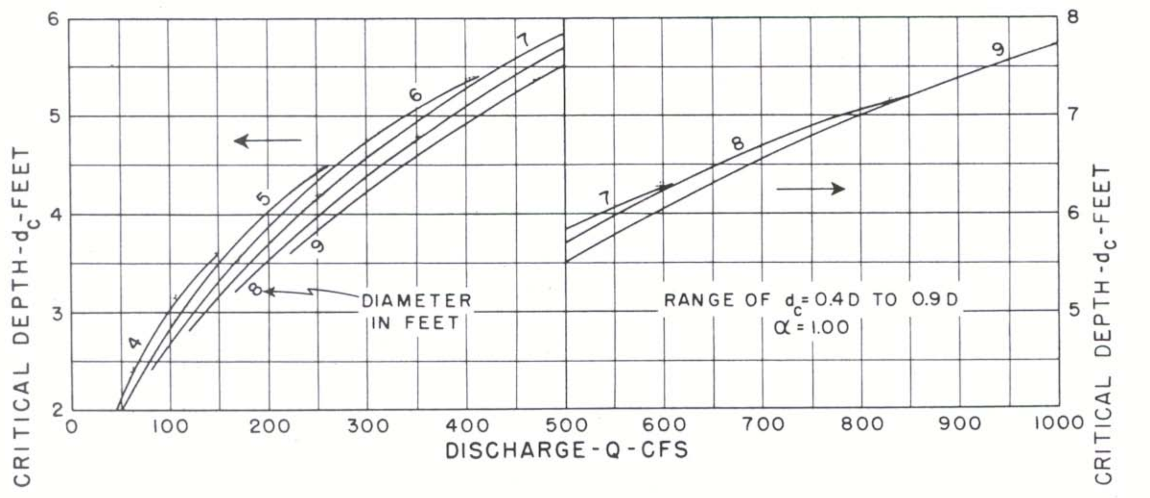


Figure 3C: Critical Depth Circular Pipe, Discharge = 0 to 4000 cfs

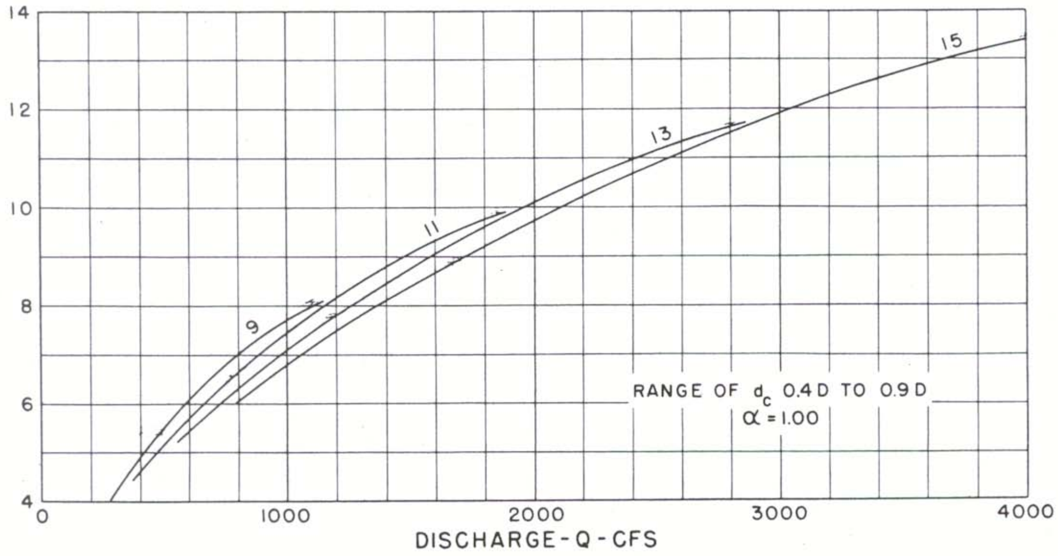


Figure 4A: Critical Depth Box Culvert, Q/B = 0 to 60 cfs

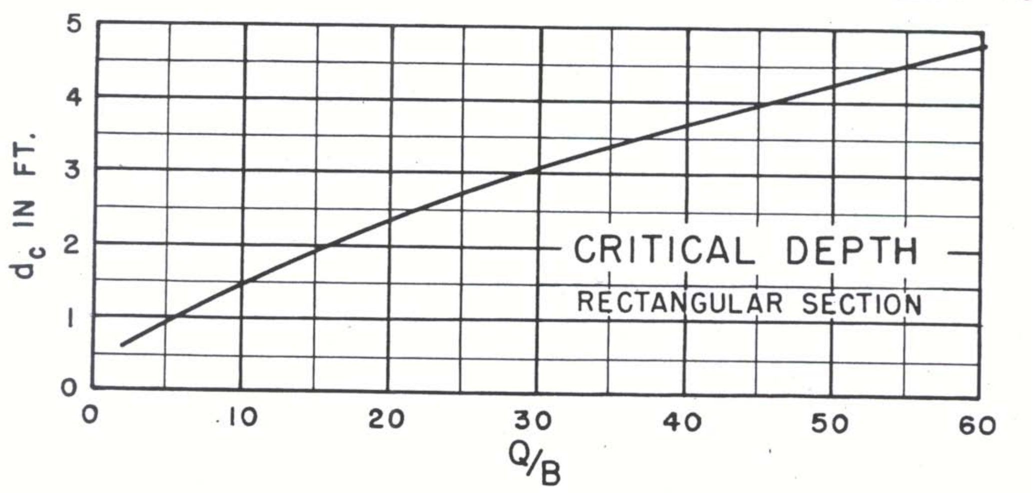


Figure 4B: Critical Depth Box Culvert, Q/B = 50 to 350 cfs

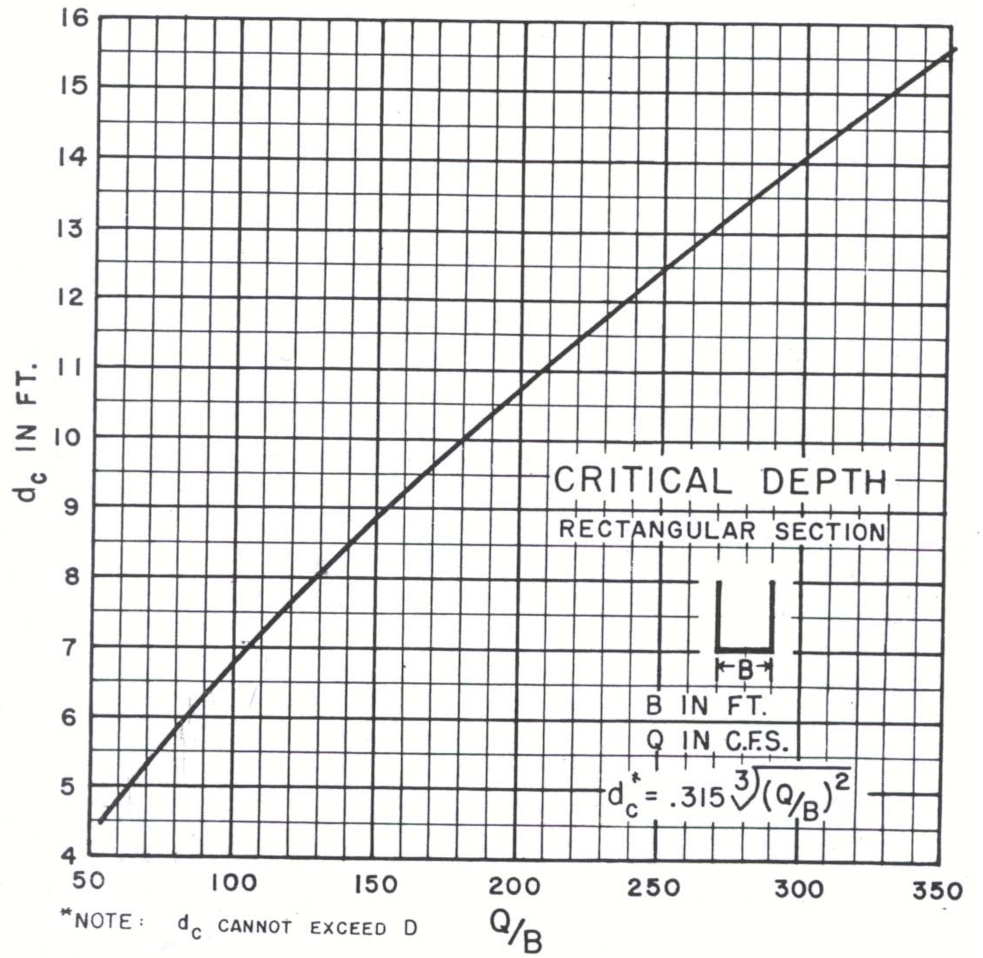
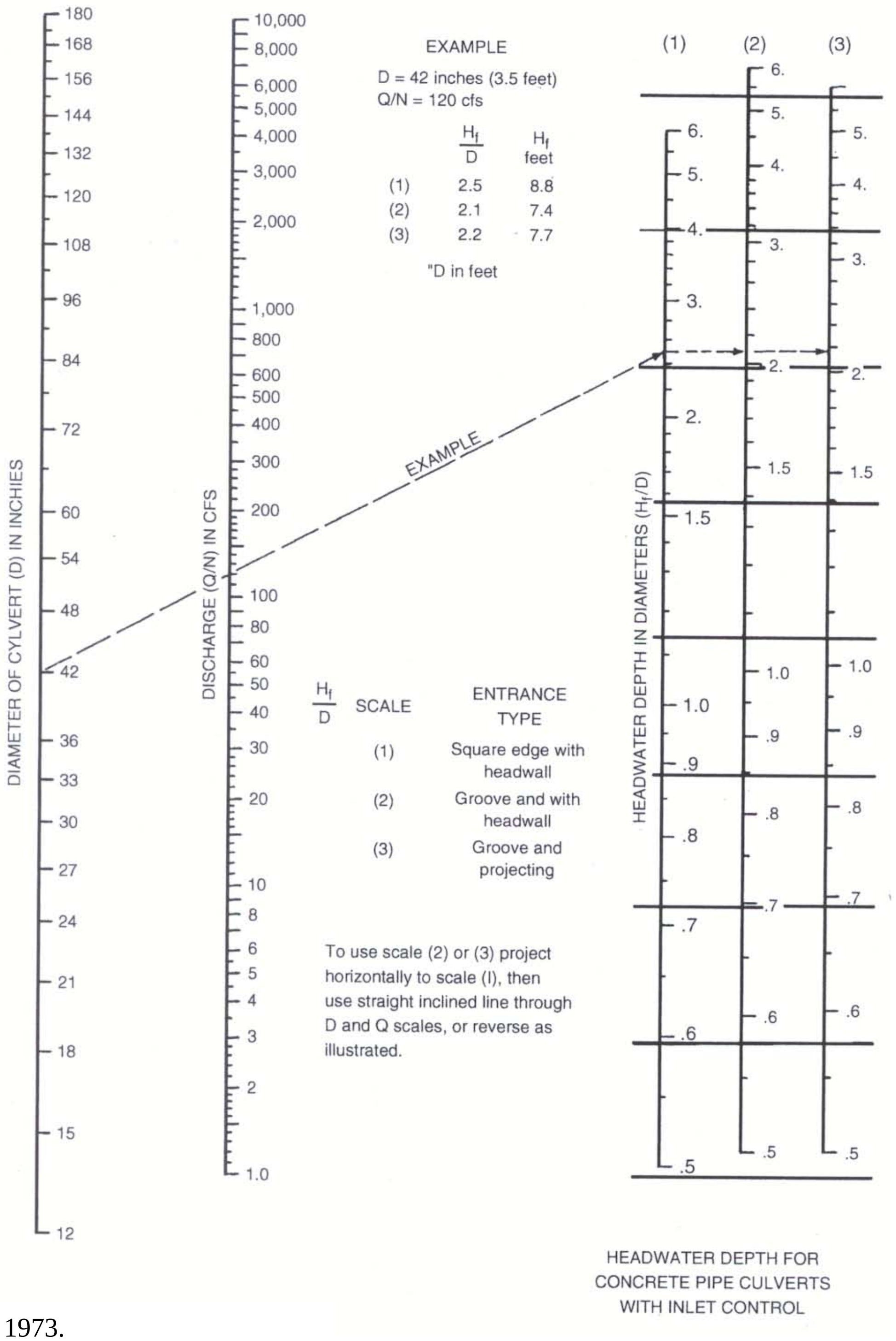


Figure 5: Inlet Control Nomograph



EXAMPLE

D = 42 inches (3.5 feet)
Q/N = 120 cfs

	$\frac{H_f}{D}$	H_f feet
(1)	2.5	8.8
(2)	2.1	7.4
(3)	2.2	7.7

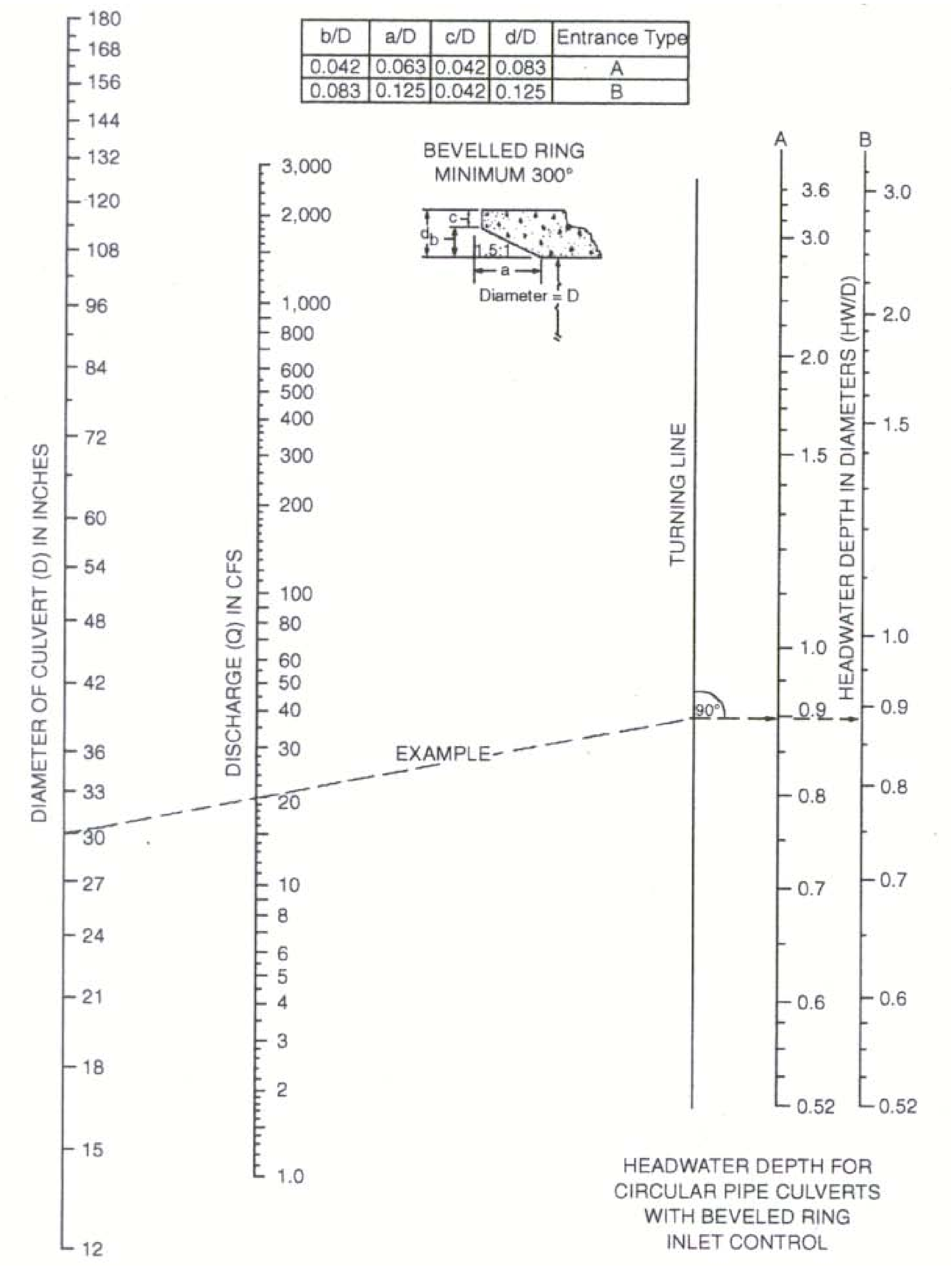
"D in feet

$\frac{H_f}{D}$ SCALE	ENTRANCE TYPE
(1)	Square edge with headwall
(2)	Groove and with headwall
(3)	Groove and projecting

To use scale (2) or (3) project horizontally to scale (I), then use straight inclined line through D and Q scales, or reverse as illustrated.

FHWA, 1973.

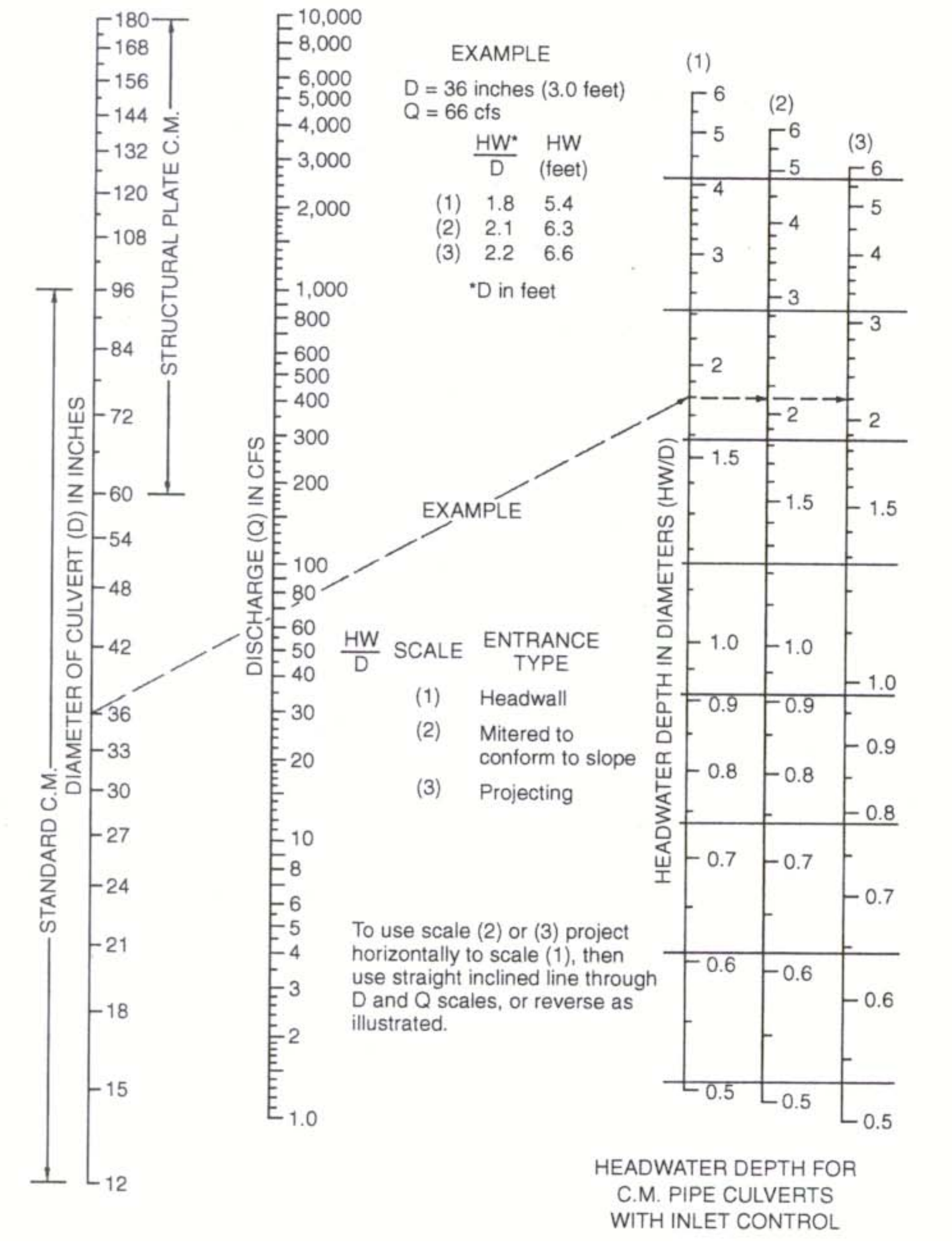
Figure 6: Inlet Control Nomograph



b/D	a/D	c/D	d/D	Entrance Type
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B

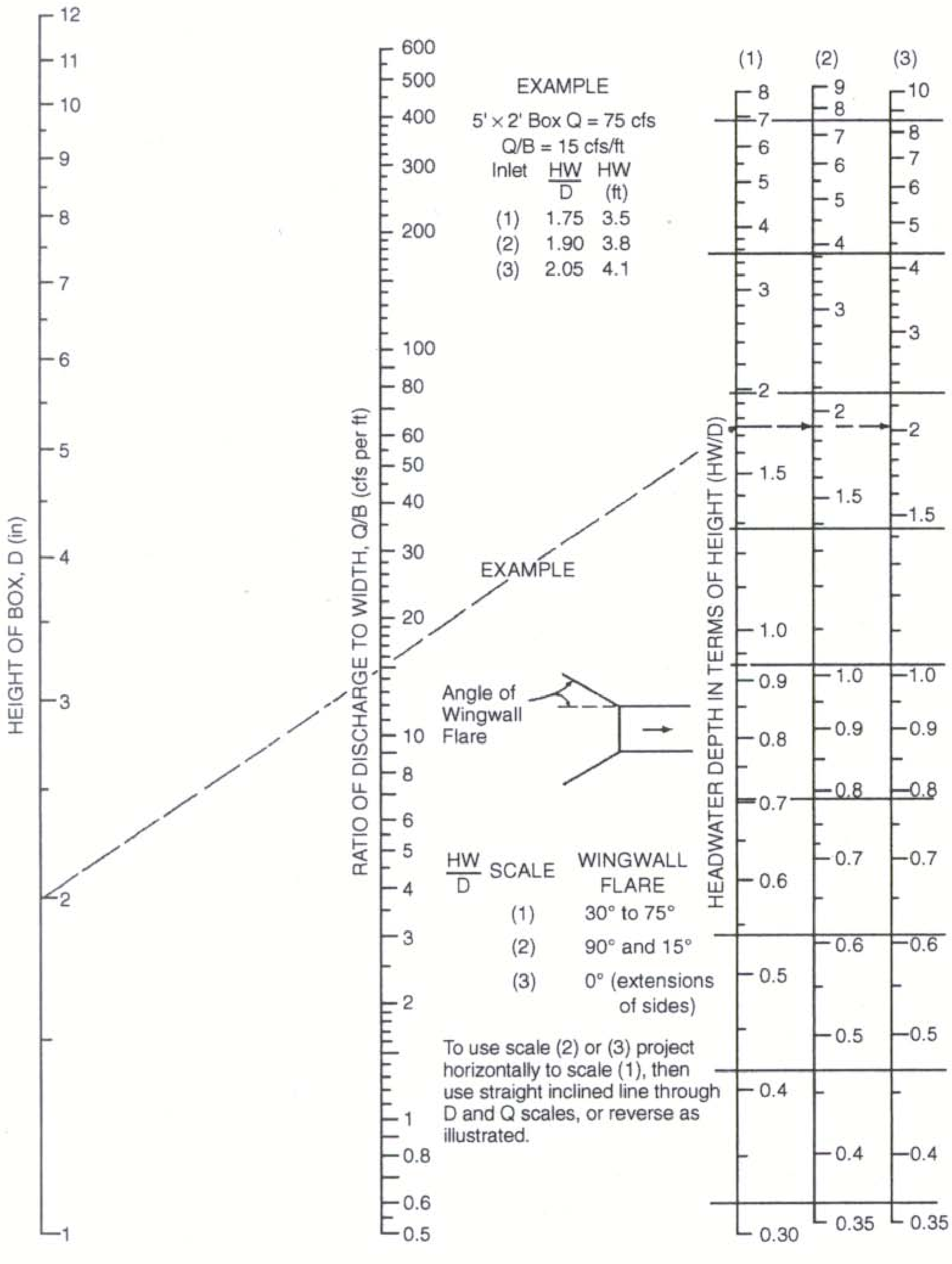
FHWA, May 1973.

Figure 7: Inlet Control Nomograph



Bureau of Public Roads, Jan. 1963.

Figure 8: Inlet Control Nomograph

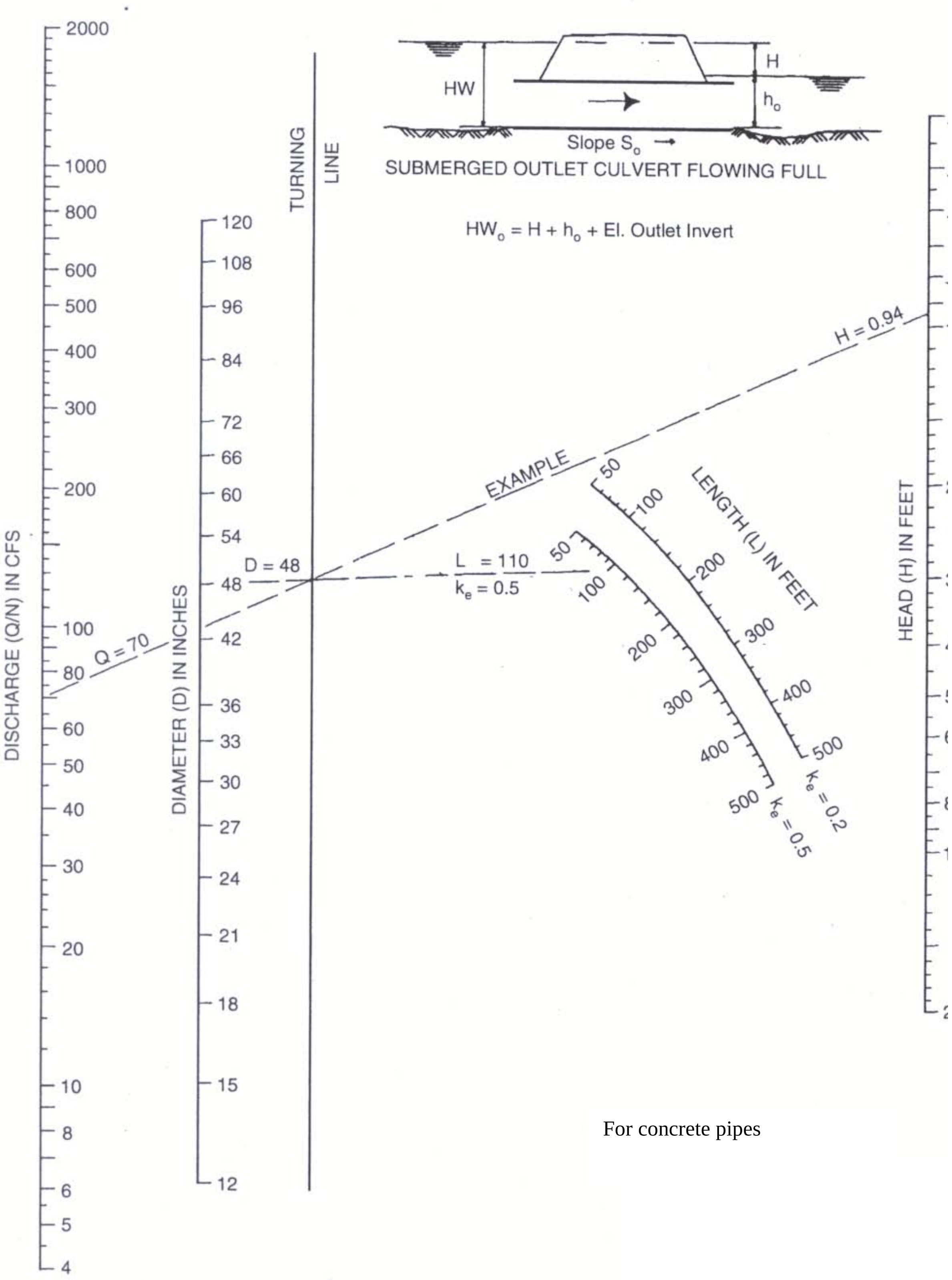


To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.

HEADWATER DEPTH
FOR BOX CULVERTS
WITH INLET CONTROL

Bureau of Public Roads, Jan. 1963.

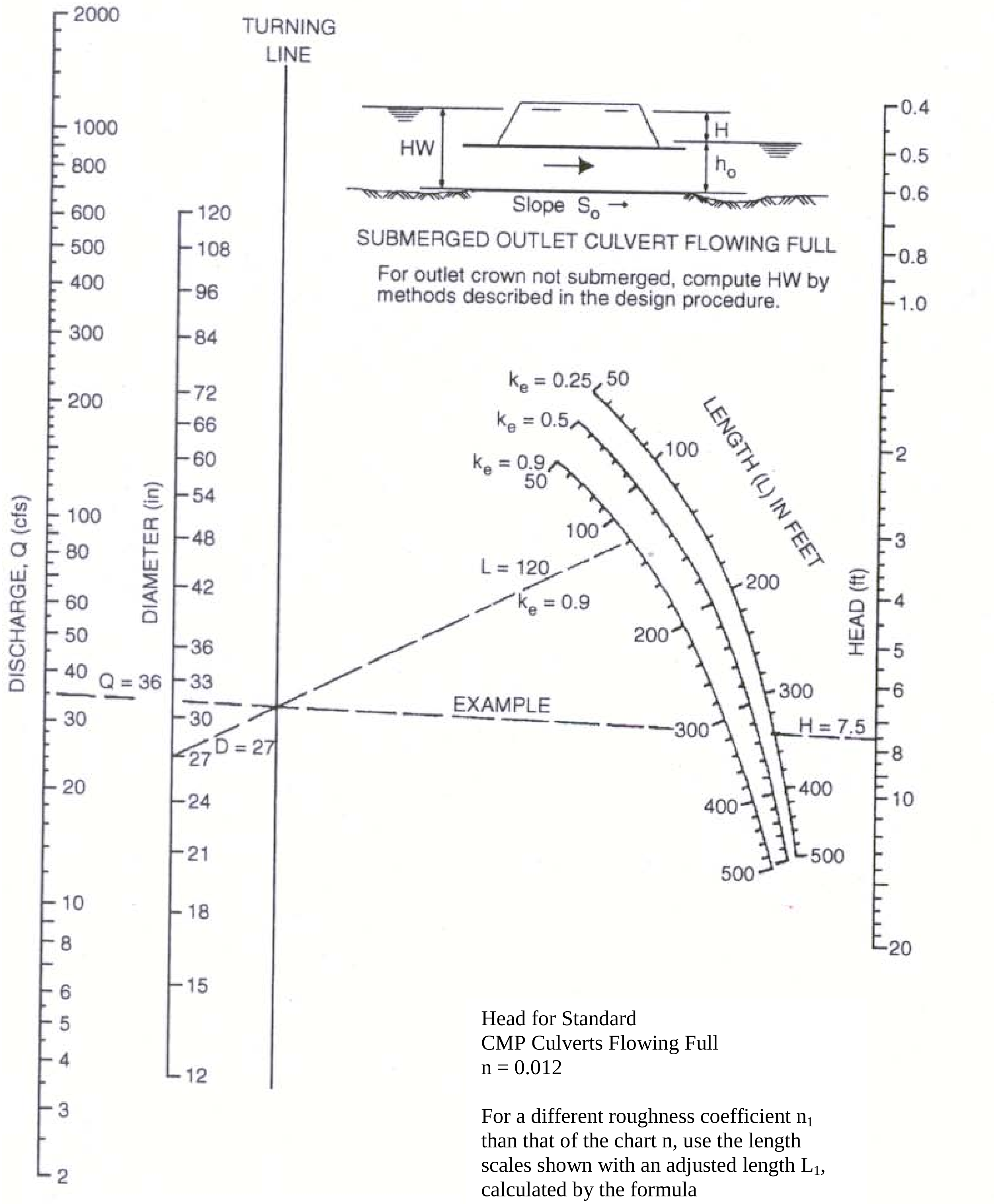
Figure 9: Outlet Control Nomograph



For concrete pipes

Bureau of Public Roads, 1963.

Figure 10: Outlet Control Nomograph



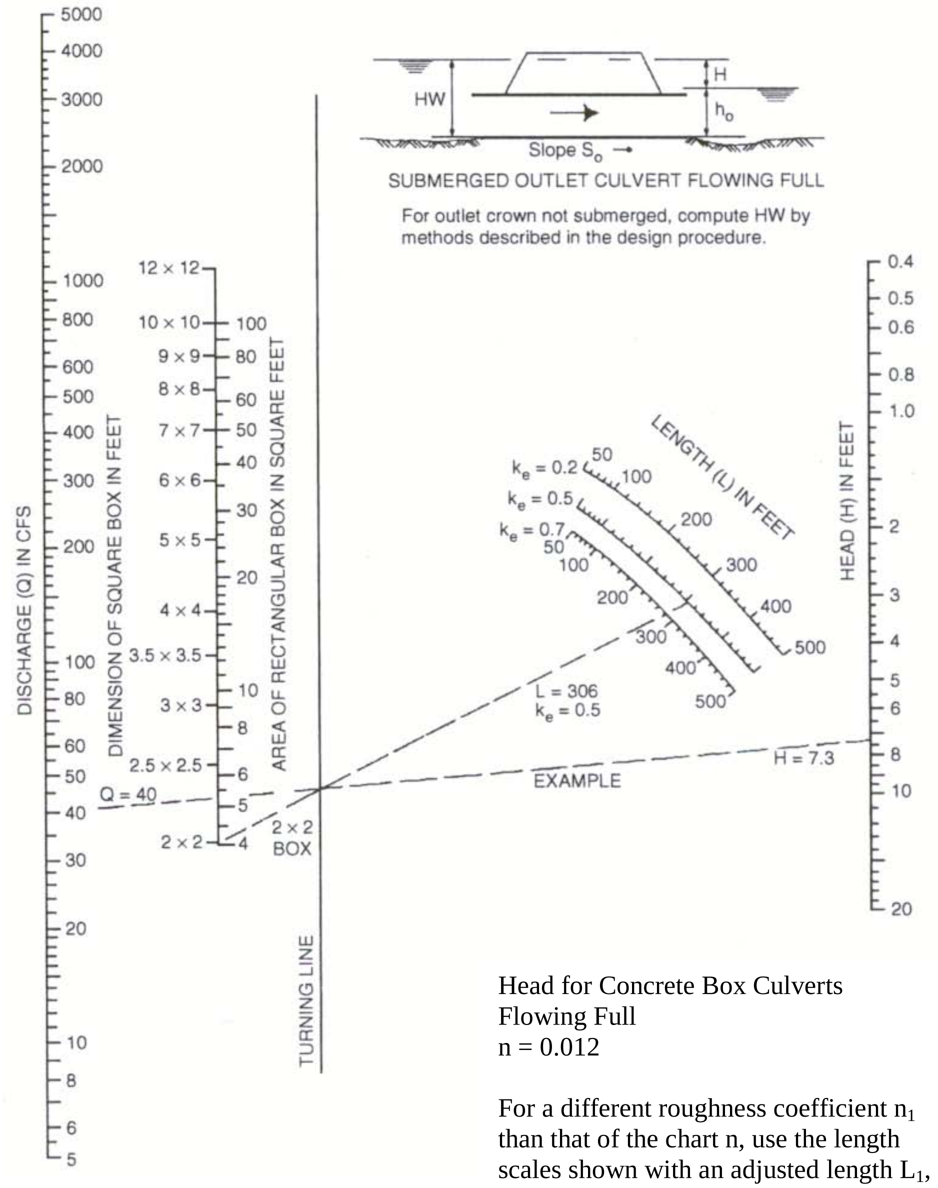
Head for Standard
CMP Culverts Flowing Full
n = 0.012

For a different roughness coefficient n_1 than that of the chart n, use the length scales shown with an adjusted length L_1, calculated by the formula

$$L_1 = L\left[\frac{n_1}{n}\right]^2$$

Bureau of Public Roads, Jan. 1963.

Figure 11: Outlet Control Nomograph



Head for Concrete Box Culverts
Flowing Full
n = 0.012

For a different roughness coefficient n_1 than that of the chart n, use the length scales shown with an adjusted length L_1, calculated by the formula

$$L_1 = L\left[\frac{n_1}{n}\right]^2$$

Bureau of Public Roads, Jan. 1963.

D. Culvert design example

The following example problem illustrates the procedures to be used in designing culverts using the nomographs. The example problem is as follows: Size a culvert given the following design conditions.

Input Data

- Discharge for 10-year flood = 70 cfs
- Discharge for 100-year flood = 176 cfs
- Allowable H_w for 10-year discharge = 4.5 feet
- Allowable H_w for 100-year discharge = 7.0 feet
- Length of culvert = 100 feet
- Natural channel invert elevations – inlet = 15.50 feet, outlet = 15.35 feet
- Culvert slope = 0.0015 feet per feet
- Tailwater depth for 10-year discharge = 3.0 feet
- Tailwater depth for 100-year discharge = 4.0 feet
- Tailwater depth is the normal depth in downstream channel
- Entrance type = groove end with headwall

STEP 1: Assume a culvert velocity of 5 feet per second
Required flow area = 70 cfs/5 feet per second = 14 sq ft (for the 10-year flood).

STEP 2: The corresponding culvert diameter is about 48 inches. This can be calculated by using the formula for area of a circle:
Area = $(3.14\ D^2)/4$ or D = $(\text{Area times } 4/3.14)^{0.5}$

Therefore: D = $[(14 \text{ sq ft} \times 4) / 3.14]^{0.5} \times 12$ inches per feet = 50.7 inches

STEP 3: A grooved-end culvert with a headwall is selected for the design. Using the inlet-control nomograph, with a pipe diameter of 48 inches and a discharge of 70 cfs; read an HW/D value of 0.93.

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

STEP 5: The culvert is checked for outlet control. With an entrance loss coefficient K_e of 0.20, a culvert length of 100 feet, and a pipe diameter of 48 inches, an H value of 0.77 feet 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, $h_o = T_w$ or 1/2 (critical depth in culvert + D), whichever is greater.
$h_o = 3.0$ feet or $h_o = 1/2\ (2.55 + 4.0) = 3.28$ feet

The headwater depth for outlet control is:
$HW = H + h_o – LS$

$HW = 0.77 + 3.28 – (100) \times (0.0015) = 3.90$ feet

STEP 6: Because HW for outlet control (3.90 feet) is greater than the HW for inlet control (3.72 feet), outlet control governs the culvert design. Thus, the maximum headwater expected for a 10-year recurrence flood is 3.90 feet, which is less than the allowable headwater of 4.5 feet.

STEP 7: The performance of the culvert is checked for the 100-year discharge. The allowable headwater for a 100-year discharge is 7 feet; critical depth in the 48-inch diameter culvert for the 100-year discharge is 3.96 feet. For outlet control, an H value of 5.2 feet 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 feet; thus, a larger size culvert must be selected. Repeat steps 1-7 as necessary.

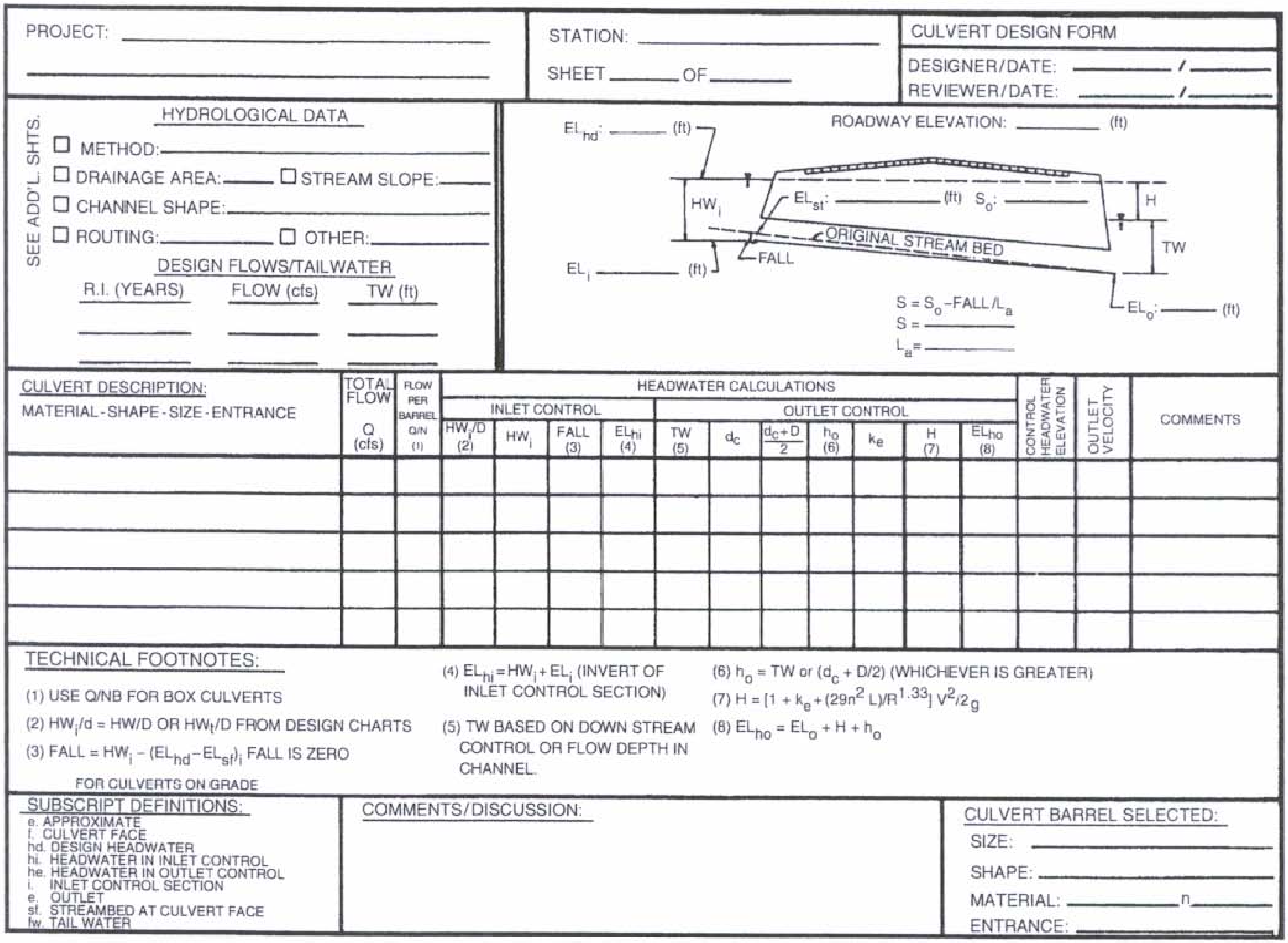
STEP 8: A 54-inch diameter culvert is tried and found to have a maximum headwater depth of 3.74 feet for the 10-year discharge and of 6.97 feet for the 100-year discharge. These values are acceptable for the design conditions.

STEP 9: Estimate outlet exit velocity. Because this culvert is on 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-foot diameter culvert, the exit velocity will be $Q = VA$. Therefore:
$V = 176 / (\pi(4.5)^2 /4 = 11.8$ ft/s.

With this high velocity, some energy dissipater may be needed downstream from this culvert for streambank protection.

STEP 10: The designer should check minimum velocities for low-frequency flows if the larger storm event (100-year) controls culvert design. Note: Figure 12 provides a convenient form to organize culvert design calculations.

Figure 12: Culvert Design Calculation[2]



PROJECT: ______________________
____

STATION: ______________________
SHEET ______ OF ______

CULVERT DESIGN FORM
DESIGNER/DATE: ________ / ________
REVIEWER/DATE: ________ / ________

HYDROLOGICAL DATA

SEE ADD'L. SHTS.

☐ METHOD: ______________
☐ DRAINAGE AREA: ______ ☐ STREAM SLOPE: ______
☐ CHANNEL SHAPE: ______________
☐ ROUTING: ________ ☐ OTHER: ________

DESIGN FLOWS/TAILWATER

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

ROADWAY ELEVATION: ________ (ft)

EL_{hd}: ______ (ft)
HW_i
EL_{st}: ________ (ft) S_o: ________
H
TW
ORIGINAL STREAM BED
FALL
EL_i ______ (ft)
EL_o: ______ (ft)

$S = S_o - FALL / L_a$
S = ________
L_a = ________

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW	FLOW PER BARREL	HEADWATER CALCULATIONS											CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
			INLET CONTROL				OUTLET CONTROL									
	Q (cfs)	Q/N (1)	HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)			

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS
(2) $HW_i/d = HW/D$ OR HW_t/D FROM DESIGN CHARTS
(3) $FALL = HW_i - (EL_{hd} - EL_{sf})_i$ FALL IS ZERO FOR CULVERTS ON GRADE
(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)
(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.
(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)
(7) $H = [1 + k_e + (29n^2 L)/R^{1.33}] V^2/2g$
(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

e. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
he. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
e. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAIL WATER

COMMENTS/DISCUSSION:

CULVERT BARREL SELECTED:
SIZE: ______________
SHAPE: ______________
MATERIAL: ________ n ______
ENTRANCE: ______________

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[2] From FHWA, Hydraulic Design of Highway Culverts, Hydraulic Design Series No. 5, 1985.