4-4.1.6 **Tailwater Elevation Below the Top or Crown of the Culvert Barrel Outlet.** Figure 4-10, B, C, and D are three common types of flow for outlet control with this low TW condition (Figure 4-19). In these cases, h_o is found by comparing two values, TW depth in the outlet channel and $\frac{d_c + D}{2}$, and setting h_o equal to the larger value. The fraction $\frac{d_c + D}{2}$ is a simplified means of computing h_o when the TW is low and the discharge does not fill the culvert barrel at the outlet. In this fraction, d_c is critical depth as determined from Figures 4-20 through 4-25, and D is the culvert height. The value of d_c should never exceed D, making the upper limit of this fraction equal to D. Figure 4-21 shows the terms of Equation 4-3 for the cases discussed above. Equation 4-3 gives accurate answers if the culvert flows full for a part of the barrel length as illustrated by Figure 4-25. This condition of flow will exist if the headwater, as determined by Equation 4-3, is equal to or greater than the quantity:

$$HW \geq D + (1 + K_e)\frac{V^2}{2g} \tag{4-4}$$

4-4.1.6.1 If the headwater drops below this point, the water surface will be free throughout the culvert barrel as in Figure 4-10, D, and Equation 4-3 will yield answers with some error since the only correct method of finding headwater in this case is by a backwater computation starting at the culvert outlet. Equation 4-3 will give answers of sufficient accuracy for design purposes, however, if the headwater is limited to values greater than 0.75D. For lower headwaters, backwater calculations are required to obtain accurate headwater elevations.

4-4.1.6.2 The depth of TW is important in determining the hydraulic capacity of culverts flowing with outlet control. In many cases, the downstream channel is of considerable width and the depth of water in the natural channel is less than the height of water in the outlet end of the culvert barrel, making the tailwater ineffective as a control. There are instances, however, where the downstream water-surface elevation is controlled by a downstream obstruction or backwater from another stream. A field inspection of all major culvert locations should be made to evaluate downstream controls and determine water stages.

4-4.1.6.3 An approximation of the normal depth of flow in a natural stream (outlet channel) can be made by using Manning's equation, $V = \frac{1.486}{n} R^{2/3} S^{1/2}$, if the channel is reasonably uniform in cross section, slope, and roughness. Values of n for natural streams in Manning's formula are given in Table 5-1. Chart 14 of Appendix B provides the solution to Manning's equation for various channels. This chart could be used to quickly estimate the tailwater depth downstream of the culvert. If the water surface in the outlet channel is established by downstream controls, other means must be found to determine the tailwater elevation. Sometimes this necessitates studying the stage-discharge relation of another stream into which the stream in question flows or securing data on reservoir elevations if a storage dam is involved.

Figure 4-20. Circular Pipe Critical Depth

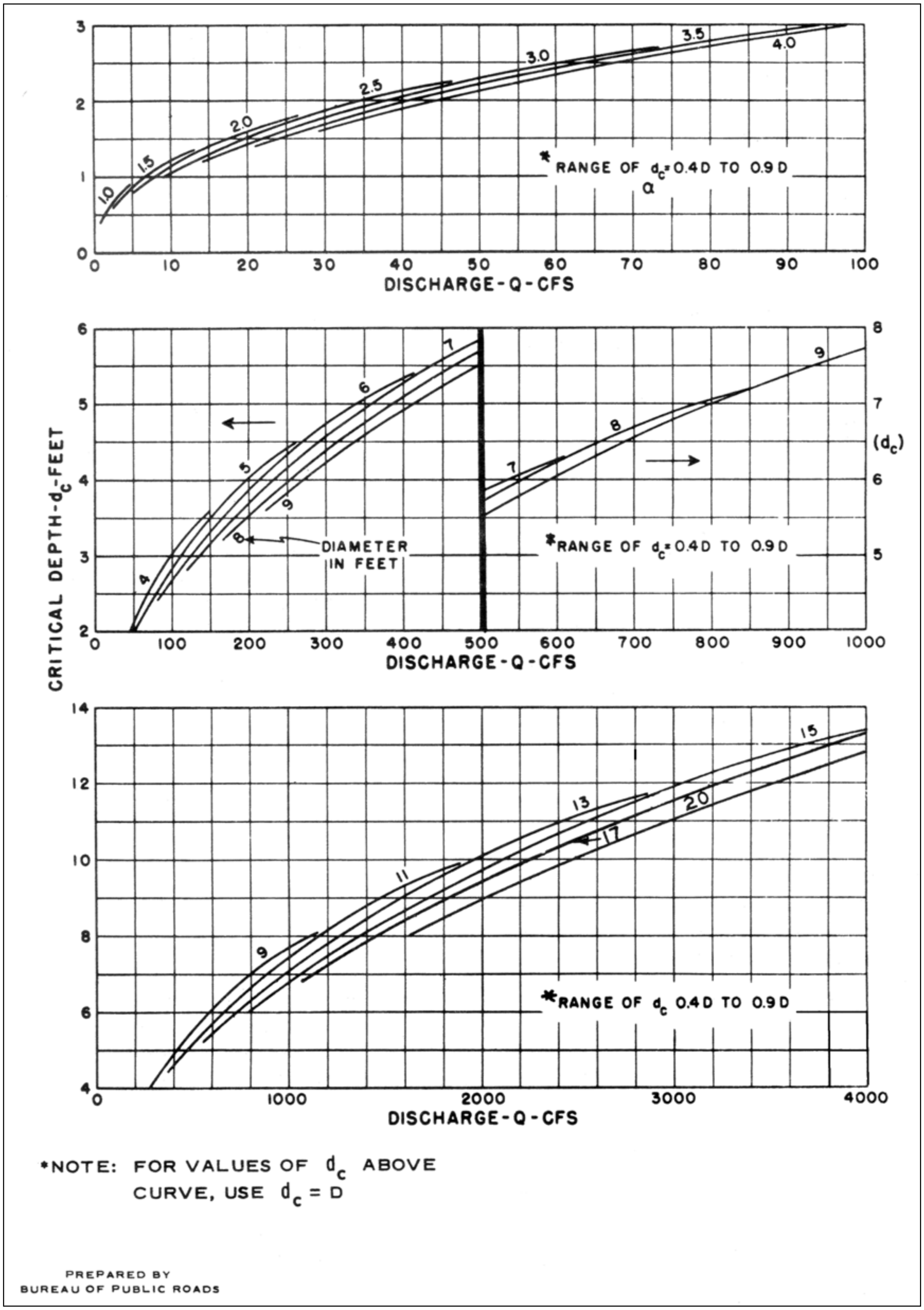


Figure 4-21. Oval Concrete Pipe Long Axis Horizontal Critical Depth

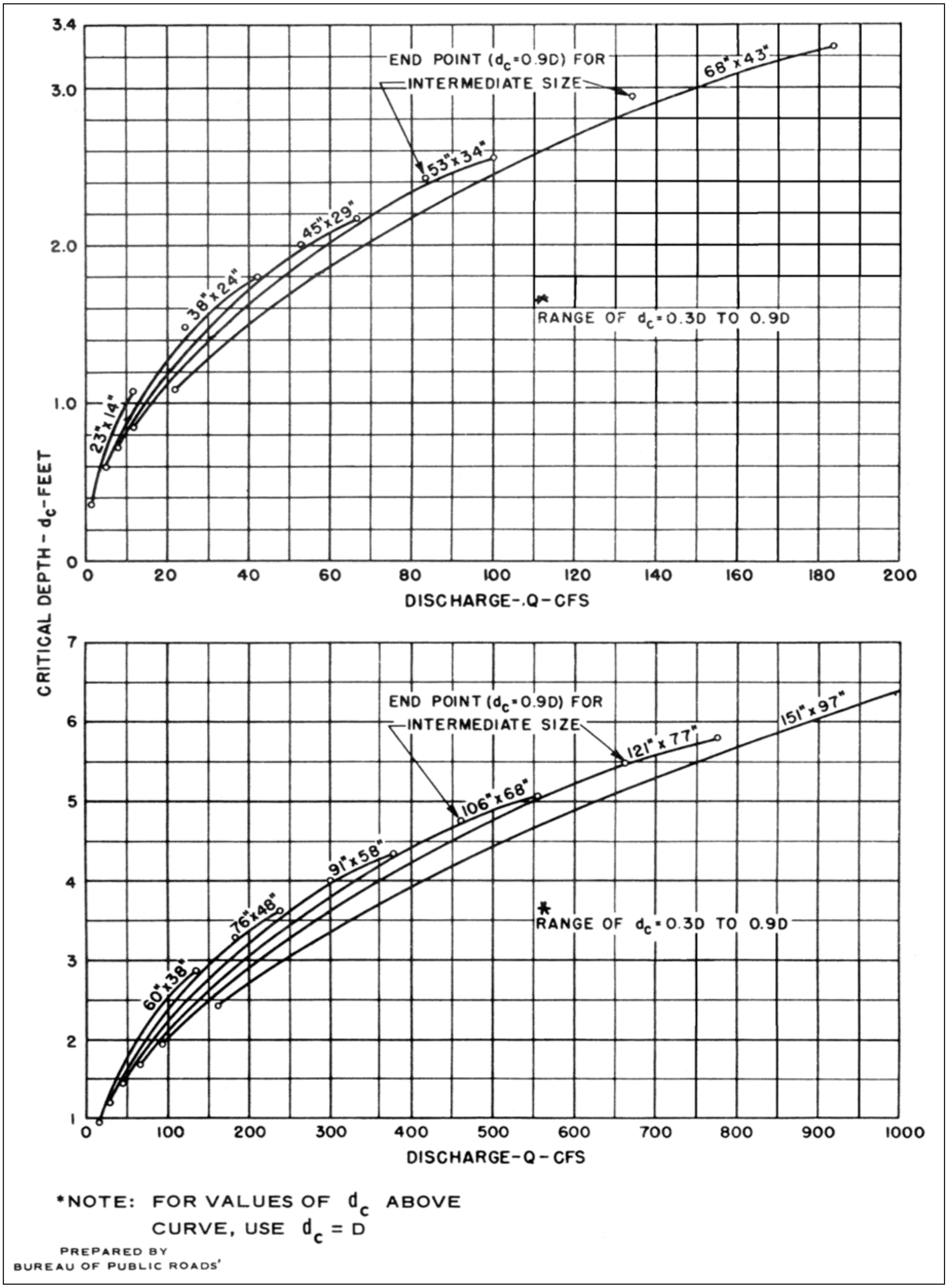


Figure 4-22. Oval Concrete Pipe Long Axis Vertical Critical Depth

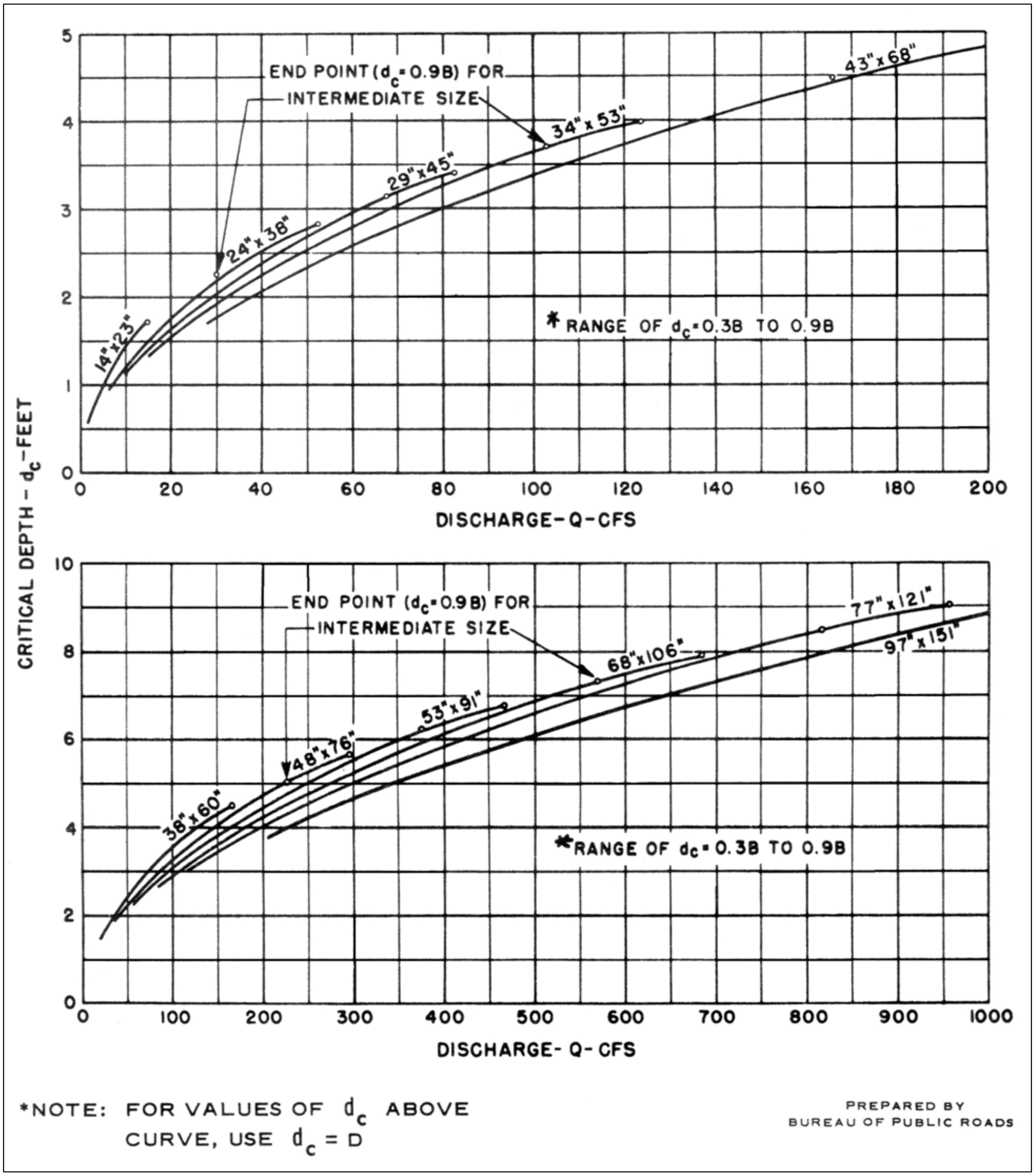


Figure 4-23. Standard Corrugated Metal Pipe-Arch Critical Depth

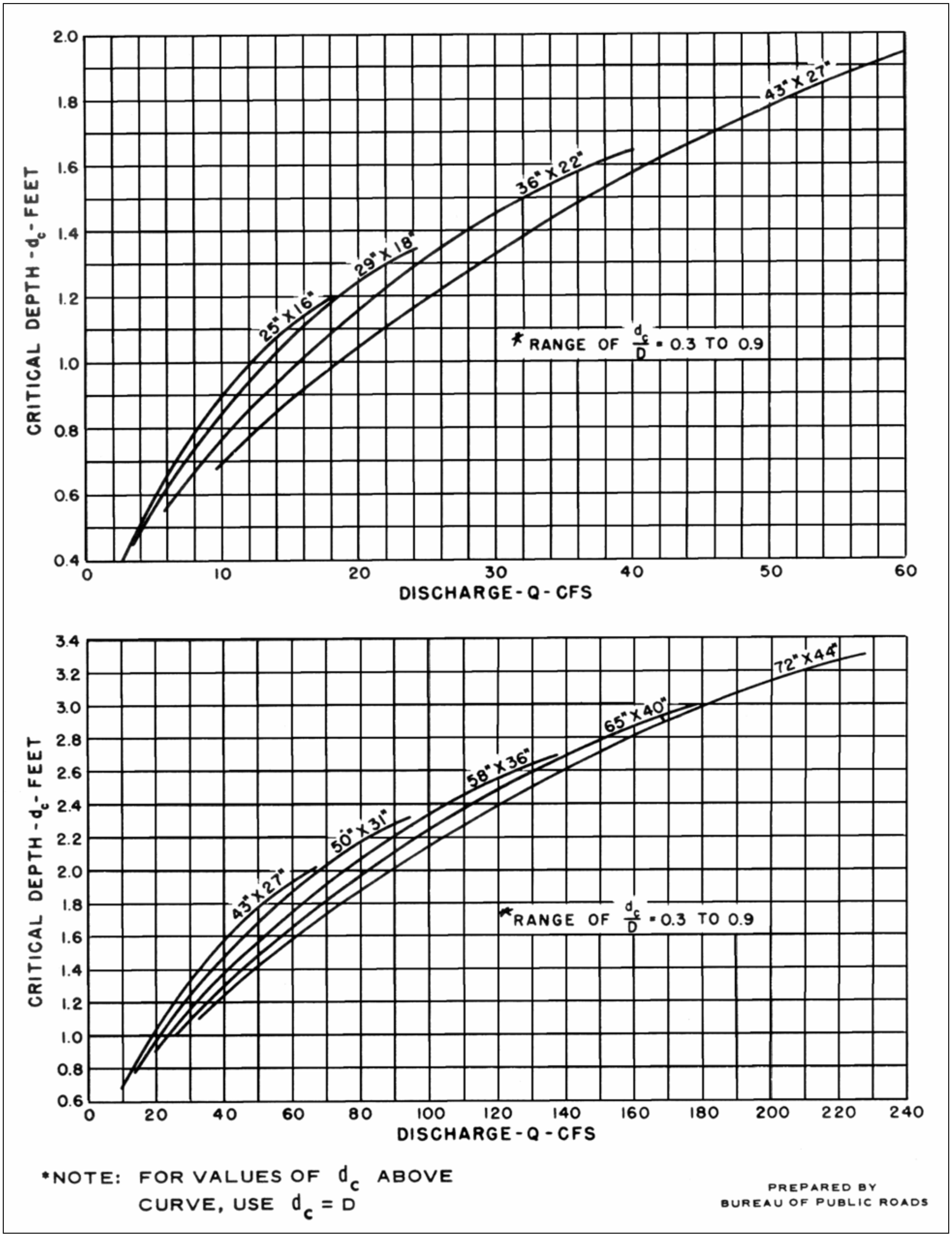


Figure 4-24. Structural Plate Pipe-Arch Critical Depth

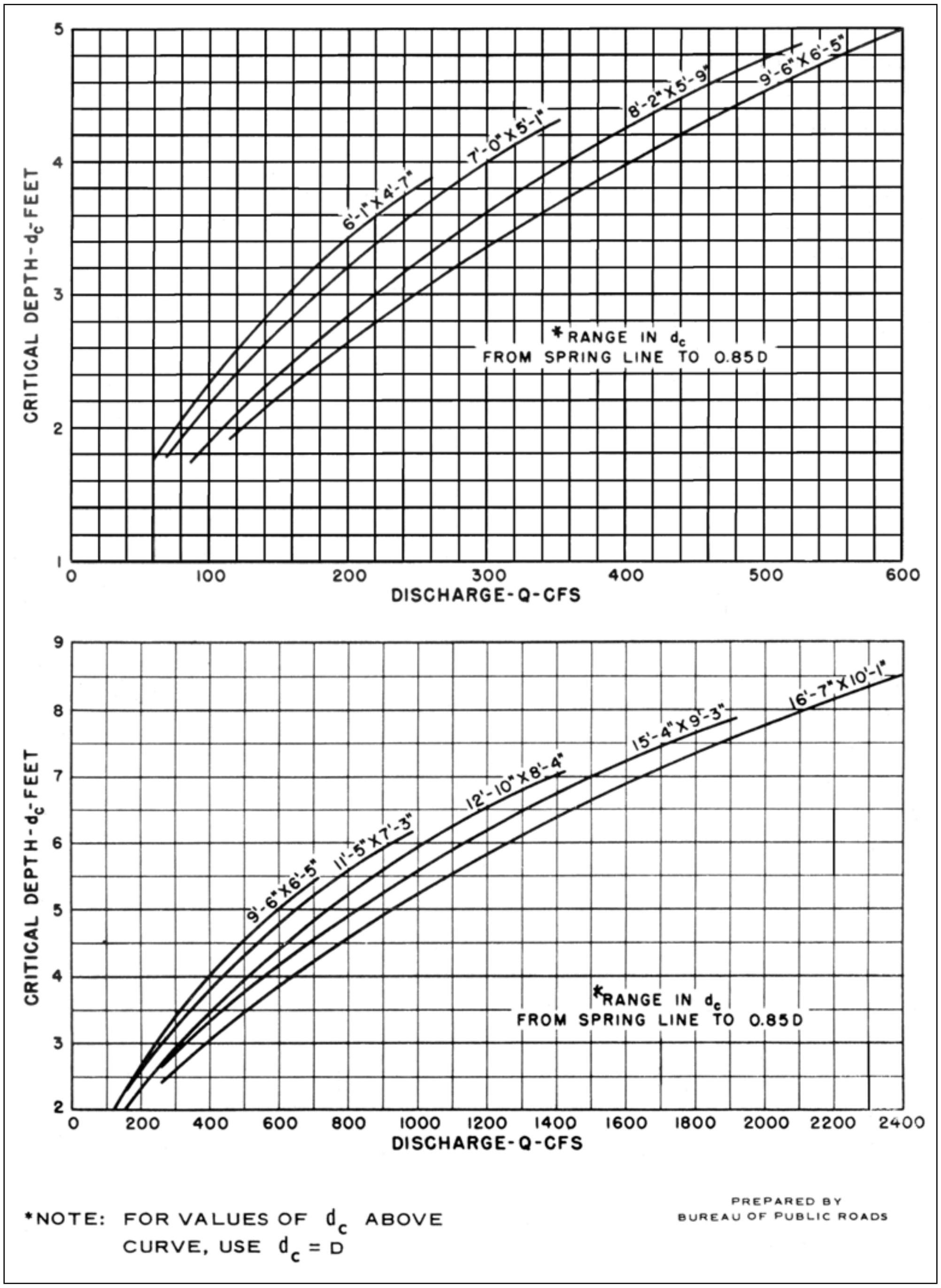
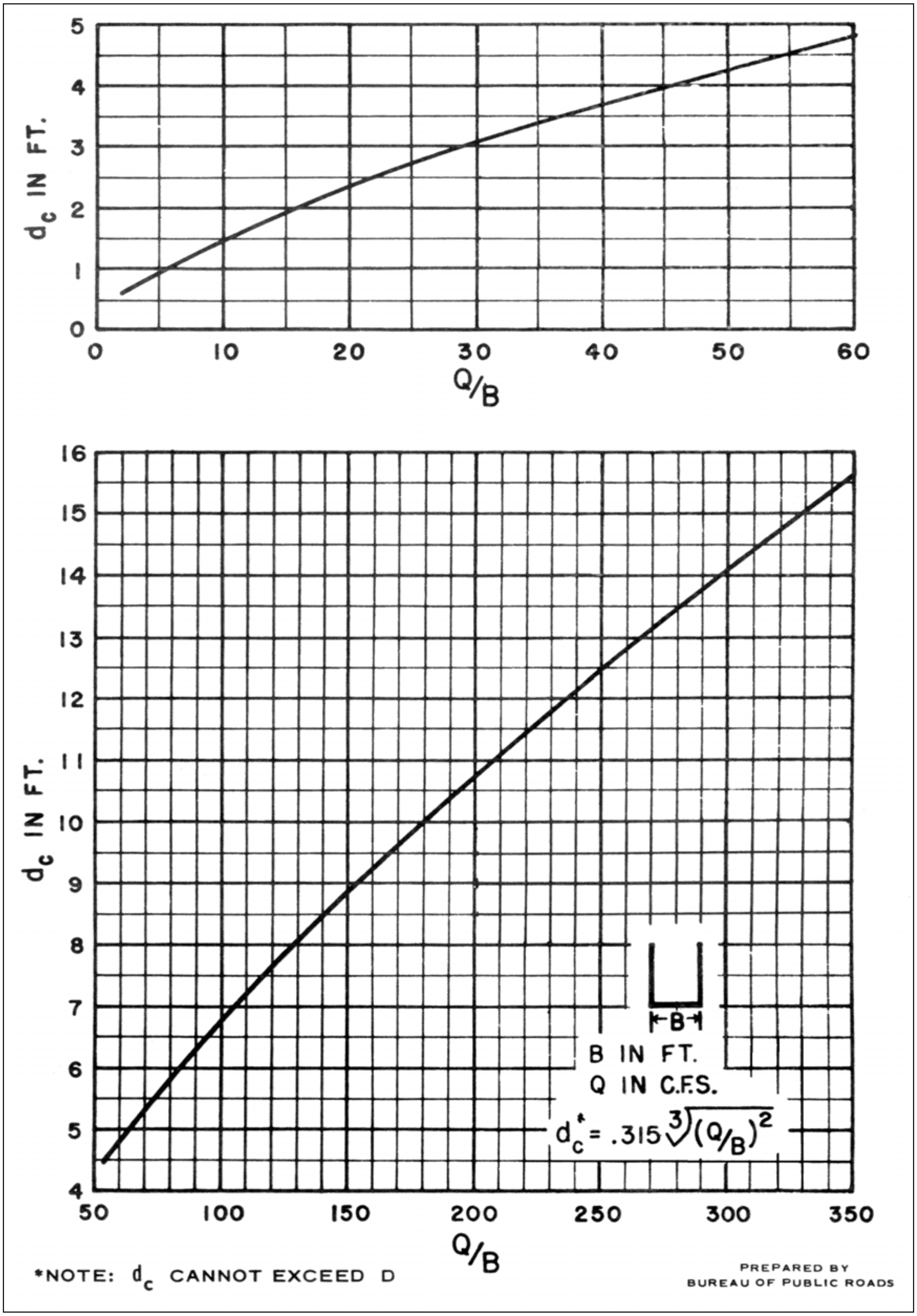


Figure 4-25. Critical Depth Rectangular Section



4-4.1.7 **Procedure for Selection of Culvert Size**

4-4.1.7.1 Using the Culvert Design Form (Figure 4-26) as a guide, perform the steps in paragraph 4-4.1.7.2 to design a culvert. Evaluate both inlet and outlet control conditions.

4-4.1.7.2 Select the culvert size by following these steps:

a. Step 1: List the given data.

(1) Design discharge, Q, in ft^3/s.

(2) Approximate length of the culvert, in feet.

(3) Allowable headwater depth, in feet, which is the vertical distance from the culvert invert (flow line) at entrance to the water-surface elevation permissible in the approach channel upstream from the culvert.

(4) Type of culvert, including barrel material, barrel cross-sectional shape, and entrance type.

(5) Slope of the culvert. (If the grade is given in percent, convert it to slope in feet per foot.)

(6) Allowable outlet velocity (if scour or fish passage are issues).

b. Step 2: Determine a trial culvert size.

(1) Refer to the inlet-control nomograph (Figures 4-2 through 4-9) for the selected culvert type.

(2) Using an $\frac{HW}{D}$ of approximately 1.25 and the scale for the entrance type to be used, find a trial-size culvert by following the instructions for the use of these nomographs. If there are reasons for less or greater relative depth of headwater in a particular case, another value of $\frac{HW}{D}$ may be used for this trial selection.

(3) If the trial size for the culverts is obviously too large because of limited height of embankment or availability of size, try a $\frac{HW}{D}$ value or multiple culverts by dividing the discharge equally for the number of culverts used. Raising the embankment height or using pipe-arch and box culverts with width greater than height should be considered. Selection should be based on an economic analysis.

Figure 4-26: Culvert Design Form

PROJECT: ____________________

STATION: ____________________

SHEET ______ OF ______

CULVERT DESIGN FORM

DESIGNER / DATE: __________ / __________

REVIEWER / DATE: __________ / __________

SEE ADD'L SHTS.

HYDROLOGICAL DATA

☐ METHOD: ____________________

☐ DRAINAGE AREA: ________ ☐ STREAM SLOPE: ________

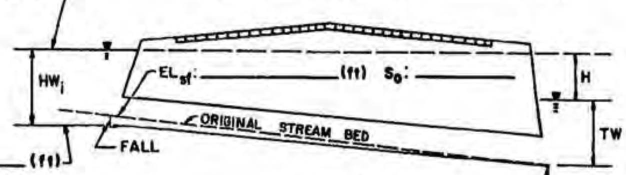
☐ CHANNEL SHAPE: ____________________

☐ ROUTING: ________ ☐ OTHER: ________

DESIGN FLOWS/TAILWATER

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

ROADWAY ELEVATION: ________ (ft)



$S \Rightarrow S_o - FALL / L_a$

$S =$ ________

$L_a =$ ________

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

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW/D$ OR HW_f/D FROM DESIGN CHARTS

(3) $FALL = HW_i - (EL_{hd} - EL_{sf})$; 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) $H = \left[1 + k_e + (29 n^2 L) / R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

CULVERT BARREL SELECTED:

SIZE: ____________________

SHAPE: ____________________

MATERIAL: ____________ n: ________

ENTRANCE: ____________________

c. Step 3: Find the headwater depth for the trial-size culvert.

(1) Determine and record the headwater depth by use of the appropriate inlet-control nomograph (Figures 4-2 through 4-9). Tailwater conditions are to be neglected in this determination. Headwater in this case is found by simply multiplying $\frac{HW}{D}$ obtained from the nomograph by D.

(2) Compute and record the headwater for outlet control using these instructions:

(a) Approximate the depth of the tailwater for the design flood condition in the outlet channel. The tailwater depth may also be due to backwater caused by another stream or some control downstream.

(b) For tailwater depths equal to or above the depth of the culvert at the outlet, set the tailwater equal to h_o and find the headwater by the following equation:

$$HW = h_o + H - S_o L$$

H is estimated from the outlet control nomographs (Figures 4-11 through 4-17).

(c) For tailwater elevations below the crown of the culvert at the outlet, use the following equation to find the headwater:

$$HW = h_o + H - S_o L$$

where $h_o = \frac{d_c + D}{2}$ or TW, whichever is greater. When d_c (Figures 4-20 through 4-25) exceeds the height of the culvert, h_o should be set equal to D. Again, H is estimated from the outlet control nomographs (Figures 4-11 through 4-17).

(3) Compare the headwater determined from the inlet control and outlet control computations. The higher headwater governs and indicates the flow control existing under the given conditions.

(4) Compare the higher headwater with that allowable at the site. If headwater is greater than allowable, repeat the procedure using a larger culvert. If headwater is less than allowable, repeat the procedure to investigate the possibility of using a smaller size.

d. Step 4: Check the outlet velocities for the selected size.

(1) If outlet control governs in Step 3(2)c, outlet velocity equals $\frac{Q}{A}$, where A is the cross-sectional area of flow at the outlet. If d_c or TW is less than the height of the culvert barrel, use a cross-sectional area corresponding to d_c or TW depth, whichever gives the greater area of flow. The total barrel area is used when the tailwater exceeds the top of the barrel.

(2) If inlet control governs in Step 3(2)c, outlet velocity can be assumed to equal normal velocity in open-channel flow as computed by Manning's equation for the barrel size, roughness, and slope of the selected culvert. The FHWA's HDS-3 contains many charts that can be used to estimate the normal depth exiting a culvert. Both circular and box shapes are represented in HDS-3.

e. Step 5: Try a culvert of another type or shape and determine the size and headwater by the same procedure.

f. Step 6: Record the final selection of culvert with size, type, outlet velocity, required headwater, and economic justification on the Culvert Design Form (Figure 4-26).

4-4.1.8 **Instructions for Using the Inlet-Control Nomographs (Figures 4-2 through 4-9)**

4-4.1.8.1 To determine headwater:

a. Connect with a straight edge the given culvert diameter or height, D, and the discharge, Q, or $\frac{Q}{B}$ for box culverts; mark the intersection of the straight edge on $\frac{HW}{D}$ scale 1.

b. If $\frac{HW}{D}$ scale 1 represents the entrance type used, read $\frac{HW}{D}$ on scale 1. If some other entrance type is used, extend the point of intersection ((a) above) horizontally to scale 2 or 3 and read $\frac{HW}{D}$.

c. Compute the headwater by multiplying $\frac{HW}{D}$ by D.

4-4.1.8.2 To determine the culvert size:

a. Given an $\frac{HW}{D}$ value, locate $\frac{HW}{D}$ on the scale for the appropriate entrance type. If scale 2 or 3 is used, extend $\frac{HW}{D}$ point horizontally to scale 1.

b. Connect the point on $\frac{HW}{D}$ scale 1 ((a) above) to the given discharge and read the required diameter, height, or size of the culvert.

4-4.1.8.3 To determine the discharge:

a. Given HW and D, locate $\frac{HW}{D}$ on the scale for the appropriate entrance type. Continue as in paragraph 4-4.1.8.2, step (a).

b. Connect the point on $\frac{HW}{D}$ scale 1 ((a) above) and the size of the culvert on the left scale and determine Q or $\frac{Q}{B}$ on the discharge scale.

c. If $\frac{Q}{B}$ is determined, multiply B to find Q.

4-4.1.9 **Instructions for Using the Outlet-Control Nomographs.** Figures 4-11 through 4-17 are nomographs to solve for the head when culverts flow full with outlet control. They are also used in approximating the head for some partially full flow conditions with outlet control. These nomographs do not give a complete solution for finding headwater.

a. Locate the appropriate nomograph for the selected type of culvert.

b. Begin finding the nomograph solution by locating a starting point on the length scale. To locate the proper starting point on the length scale, follow these instructions:

(1) If the n value of the nomograph corresponds to that of the culvert being used, find the proper K_e from Table 4-1, and on the appropriate nomograph, locate the starting point on the length curve for the K_e. If a K_e curve is not shown for the selected K_e, go to step 2, below. If the *n* value for the selected culvert differs from that of the nomograph, see step 3, below.

(2) For the *n* of the nomograph and a K_e intermediate between the given scales, connect the given length on adjacent scales by a straight line

and select a point on this line spaced between the two chart scales in proportion to the K_e values.

(3) For a different value of 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:

$$L_1 = L\left(\frac{n_1}{n}\right)^2 \tag{4-5}$$

where: L_1 = adjusted culvert length

L = actual culvert length

n_1 = desired n value

n = n value from the outlet control chart

c. Using a straight edge, connect the point on the length scale to the size of the culvert barrel and mark the point of crossing on the "turning line."

d. Pivot the straight edge on this point on the turning line and connect the given discharge rate. Read the head in feet on the head scale. For values beyond the limit of the chart scales, find H by solving the equation given in the nomograph or by using the FHWA's HY-8 computer program.

4-4.1.9.1 Table 4-1 is used to find the n value for the selected culvert.

4-4.1.9.2 To use the box-culvert nomograph (Figure 4-17) for full flow for other than square boxes:

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

NOTE: The area scale on the nomograph is calculated for barrel cross sections with span B twice the height D; its close correspondence with the area of square boxes assures that it may be used for all sections intermediate between square and $B = 2D$ or $B = 2/3D$. For other box proportions, use the equation shown in the nomograph for more accurate results.

b. Connect the proper point on the length scale to the barrel area and mark the point on the turning line.

c. Pivot the straight edge on this point on the turning line and connect the given discharge rate. Read the head in feet on the head scale.

4-4.2 Headwalls and Endwalls

4-4.2.1 The normal functions of a headwall or wingwall are to recess the inflow or outflow end of the culvert barrel into the fill slope to improve entrance flow conditions, to anchor the pipe and to prevent disjointing caused by excessive pressures, to control erosion and scour resulting from excessive velocities and turbulences, and to prevent adjacent soil from sloughing into the waterway opening.

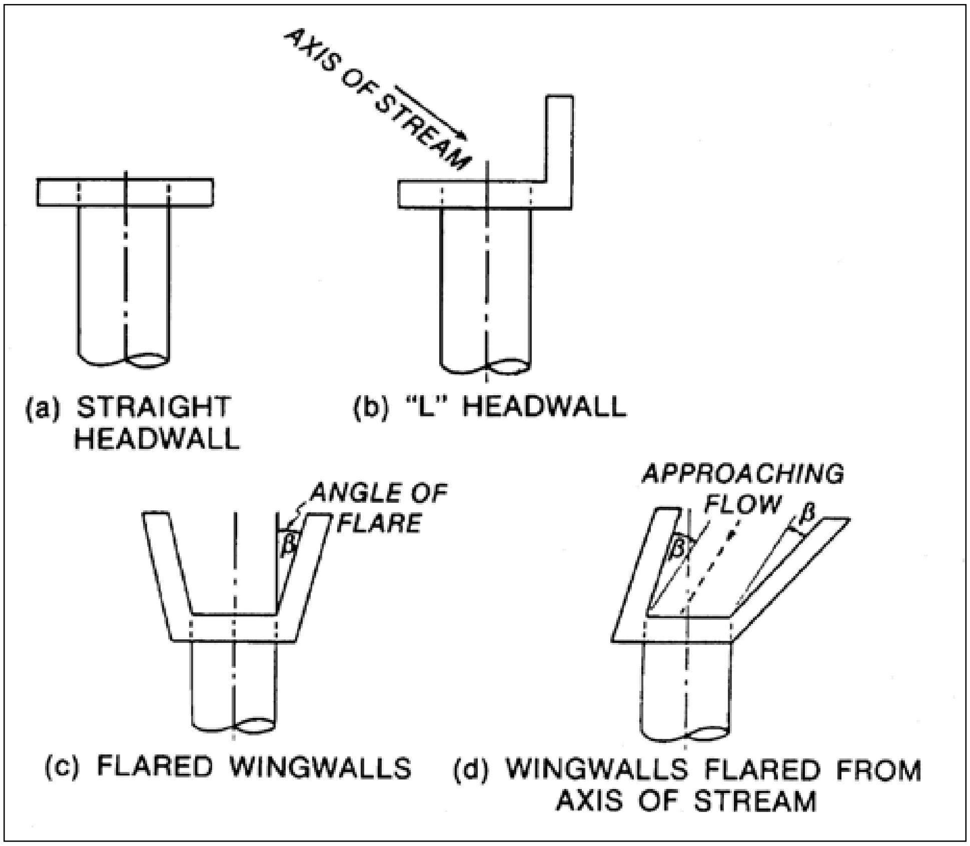
4-4.2.2 Headwalls are particularly desirable as a cutoff to prevent saturation sloughing, piping, and erosion of the embankment. Provisions for drainage should be made over the center of the headwall to prevent scouring along the sides of the walls.

4-4.2.3 Whether or not a headwall is desirable depends on the expected flow conditions and the embankment stability. Erosion protection such as riprap or sacked concrete with a sand-cement ratio of 9:1 may be required around the culvert entrance if a headwall is not used.

4-4.2.4 In the design of headwalls, some degree of entrance improvement should always be considered. The most efficient entrances would incorporate one or more of such geometric features as elliptical arcs, circular arcs, tapers, and parabolic drop-down curves. Elaborate inlet design for a culvert would be justifiable only in unusual circumstances. The rounding or beveling of the entrance in almost any way will increase the culvert capacity for every design condition. These types of improvements provide a reduction in the loss of energy at the entrance for little or no additional cost.

4-4.2.5 Entrance structures (headwalls and wingwalls) protect the embankment from erosion and, if properly designed, may improve the hydraulic characteristics of the culvert. The height of these structures should be kept to the minimum that is consistent with hydraulic, geometric, and structural requirements. Several entrance structures are shown in Figure 4-27. Straight headwalls (Figure 4-27a) are used for low to moderate approach velocity, light drift (small floating debris), broad or undefined approach channels, or small defined channels entering culverts with little change in alignment. The “L” headwall (Figure 4-27b) is used if an abrupt change in flow direction is necessary with low to moderate velocities; however, before an “L” headwall is considered, all efforts should be made to align the culvert with the natural stream. The change in flow direction often causes debris and sediment problems. Winged headwalls or wingwalls (Figure 4-27c) are used for channels with moderate velocity and medium floating debris. Wingwalls are most effective when set flush with the edges of the culvert barrel, aligned with the stream axis (Figure 4-27d), and placed at a flare angle of 18 to 45 degrees. Warped wingwalls (not shown) are used for well-defined channels with high-velocity flow and a free water surface. They are used primarily with box culverts. Warped headwalls are hydraulically efficient because they form a gradual transition from a trapezoidal channel to the barrel. The use of a drop-down apron in conjunction with these wingwalls may be particularly advantageous.

Figure 4-27. Culvert Headwalls and Wingwalls



4-4.2.6 Headwalls are normally constructed of plain or reinforced concrete or of masonry and usually consist of either a straight headwall or a headwall with wingwalls, apron, and cutoff wall, as required by local conditions. Definite design criteria applicable to all conditions cannot be formulated, but certain features require careful consideration to ensure an efficient headwall structure:

- Most culverts outfall into a waterway of relatively large cross section; only moderate tailwater is present, and except for local acceleration, if the culvert effluent freely drops, the downstream velocities gradually diminish. In such situations, the primary problem is usually not one of hydraulics but the protection of the outfall against undermining bottom scour, damaging lateral erosion, and perhaps degrading the downstream channel. The presence of tailwater higher than the culvert crown will affect the culvert performance and may possibly require protection of the adjacent embankment against wave or eddy scour. In any event, a determination must be made about downstream control, its relative permanence, and tailwater conditions likely to result. Endwalls (outfall headwalls) and wingwalls will not be used unless justifiable as an integral part of outfall energy dissipators or erosion protection works, or for reasons such as right-of-way restrictions and occasionally aesthetics.

- The system will fail if there is inadequate endwall protection. Usually the end sections are damaged first, thus causing flow obstruction and progressive undercutting during high runoff periods, which causes washout of the structure. For corrugated metal (pipe or arch) culvert installations, the use of prefabricated end sections may prove desirable and economically feasible. When a metal culvert outfall projects from an embankment fill at a substantial height above natural ground, either a cantilevered free outfall pipe or a pipe downspout will probably be required. In either case, the need for additional erosion protection requires consideration.

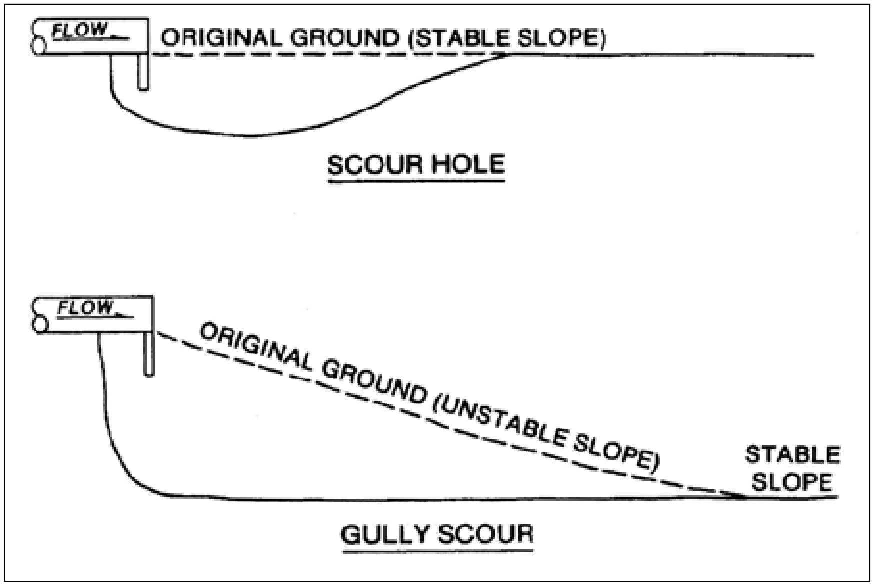
4-4.2.7 Headwalls and endwalls incorporating various designs of energy dissipators, flared transitions, and erosion protection for culvert outfalls are explained in detail in subsequent sections of this chapter.

4-4.2.8 Headwalls or endwalls will be adequate to withstand soil and hydrostatic pressures. In areas of seasonal freezing, the structure will also be designed to preclude detrimental heave or lateral displacement caused by frost action. The most satisfactory method of preventing such damage is to restrict frost penetration beneath and behind the wall to non-frost-susceptible materials. Positive drainage behind the wall is also essential. Criteria for determining the depth of backfill behind walls are given in UFC 3-220-03FA.

4-4.2.9 The headwalls or endwalls will be large enough to preclude the partial or complete stoppage of the drain by sloughing of the adjacent soil. This can best be accomplished by a straight headwall or by wingwalls. Typical erosion problems result from uncontrolled local inflow around the endwalls. The recommended preventive for this type of failure is the construction of a berm behind the endwall (outfall headwall) to intercept local inflow and direct it properly to protected outlets such as field inlets and paved or sodded chutes that will conduct the water into the outfall channel. The proper use of solid sodding will often provide adequate headwall and channel protection.

4-4.2.10 In general, two types of channel instability can develop downstream from storm sewer and culvert outlets: gully scour or a localized erosion termed a scour hole. Distinction between the two conditions can be made by comparing the original or existing slope of the channel or drainage basin downstream of the outlet relative to that required for stability as illustrated in Figure 4-28.

Figure 4-28. Types of Scour at Storm Drain and Culvert Outlets



4-4.2.10.1 Gully scour is to be expected when the Froude number of flow ($F= V/(gy)^{0.5}$ where F is the Froude Number, g is 32.3 ft/s^2, and y is the depth of water in the channel) in the channel exceeds that required for stability. It begins at a control point downstream where the channel is stable and it progresses upstream. If sufficient differential in elevation exists between the outlet and the section of stable channel, the outlet structure will be completely undermined. The primary cause of gully scour is the practice of siting outlets high, with or without energy dissipators relative to a stable downstream grade in order to reduce quantities of pipe and excavation. Erosion of this type may be extensive, depending upon the location of the stable channel section relative to that of the outlet in both the vertical and downstream directions. To prevent gully erosion, outlets and energy dissipators should be located at sites where the slope of the downstream channel or drainage basin is naturally moderate enough to remain stable under the anticipated conditions, or else it should be controlled by ditch checks, drop structures, and/or other means to a point where a naturally stable slope and cross section exist. Design of stable open channels is discussed later in this UFC.

4-4.2.10.2 A scour hole or localized erosion can occur downstream of an outlet even if the downstream channel is stable. The severity of damage to be anticipated depends upon the conditions existing or created at the outlet. In many situations, flow conditions can produce scour resulting in embankment erosion as well as structural damage to the apron, endwall, and culvert.

4-4.2.10.3 Empirical equations have been developed for estimating the extent of the anticipated scour hole in sand. These equations are based on knowledge of the design discharge, the culvert diameter, and the duration and Froude number of the design flow at the culvert outlet; however, the relationship between the Froude number of flow at the culvert outlet and a discharge parameter, or $Q/D_o^{5/2}$, can be calculated for any shape of outlet, and this discharge parameter is just as representative of flow conditions as is the Froude number. The relationship between the two parameters for partial and full pipe flow in square culverts is shown in Figure 4-29. Since the discharge parameter is easier to calculate and is suitable for application purposes, the original data were reanalyzed in terms of discharge parameter for estimating the extent of localized scour to be anticipated downstream of culvert and storm drain outlets. The equations for the maximum depth, width, length, and volume of scour and comparisons of predicted and observed values are shown in Figures 4-30 through 4-33. Minimum and maximum tailwater depths are defined as those less than $0.5D_o$ and equal to or greater than $0.5D_o$, respectively. Dimensionless profiles along the center lines of the scour holes to be anticipated with minimum and maximum tailwaters are presented in Figure 4-34 and Figure 4-35. Dimensionless cross sections of the scour hole at a distance of 0.4 of the maximum length of scour downstream of the culvert outlet for all tailwater conditions are also shown in Figure 4-34 and Figure 4-35.

Figure 4-29. Square Culvert Froude Number

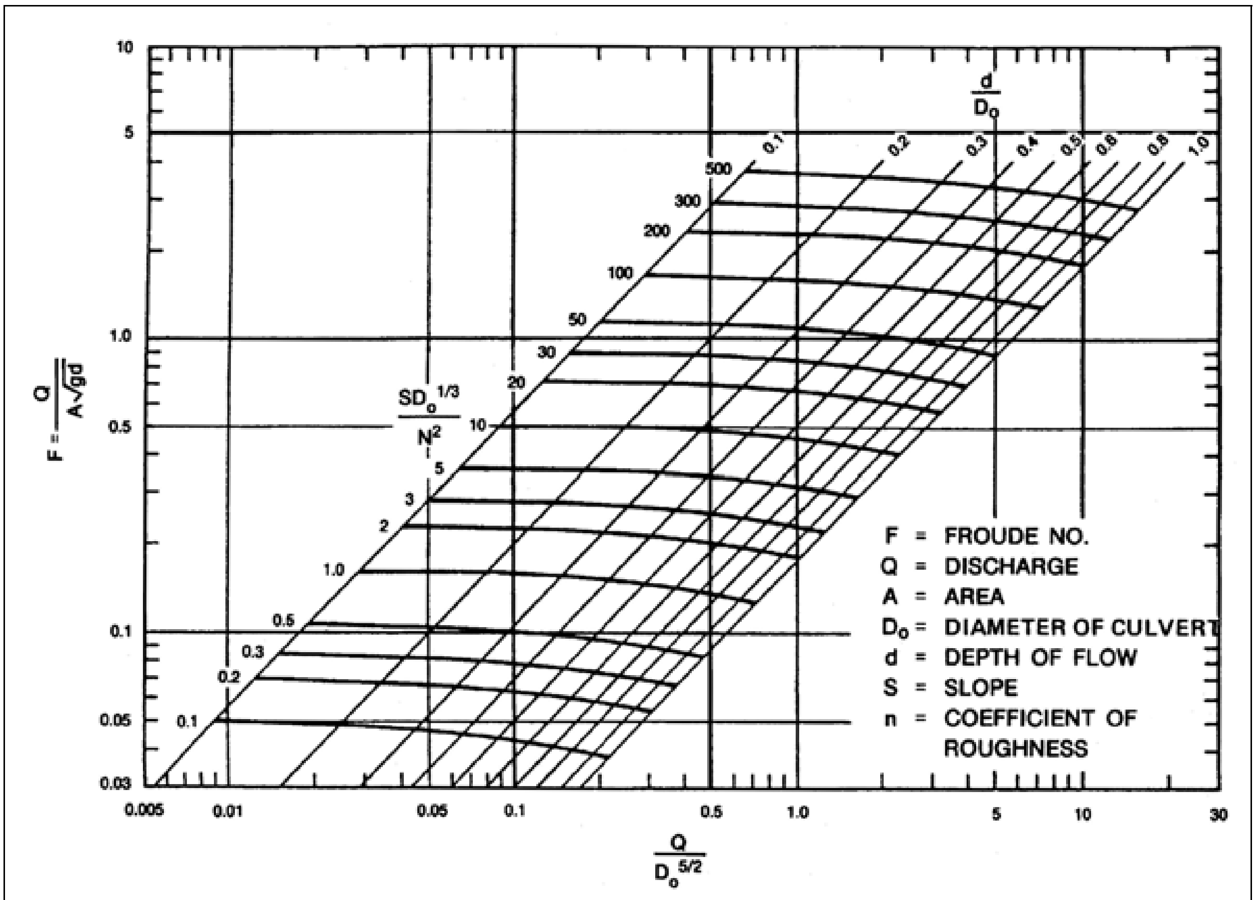


Figure 4-30. Predicted Scour Depth vs. Observed Scour Depth

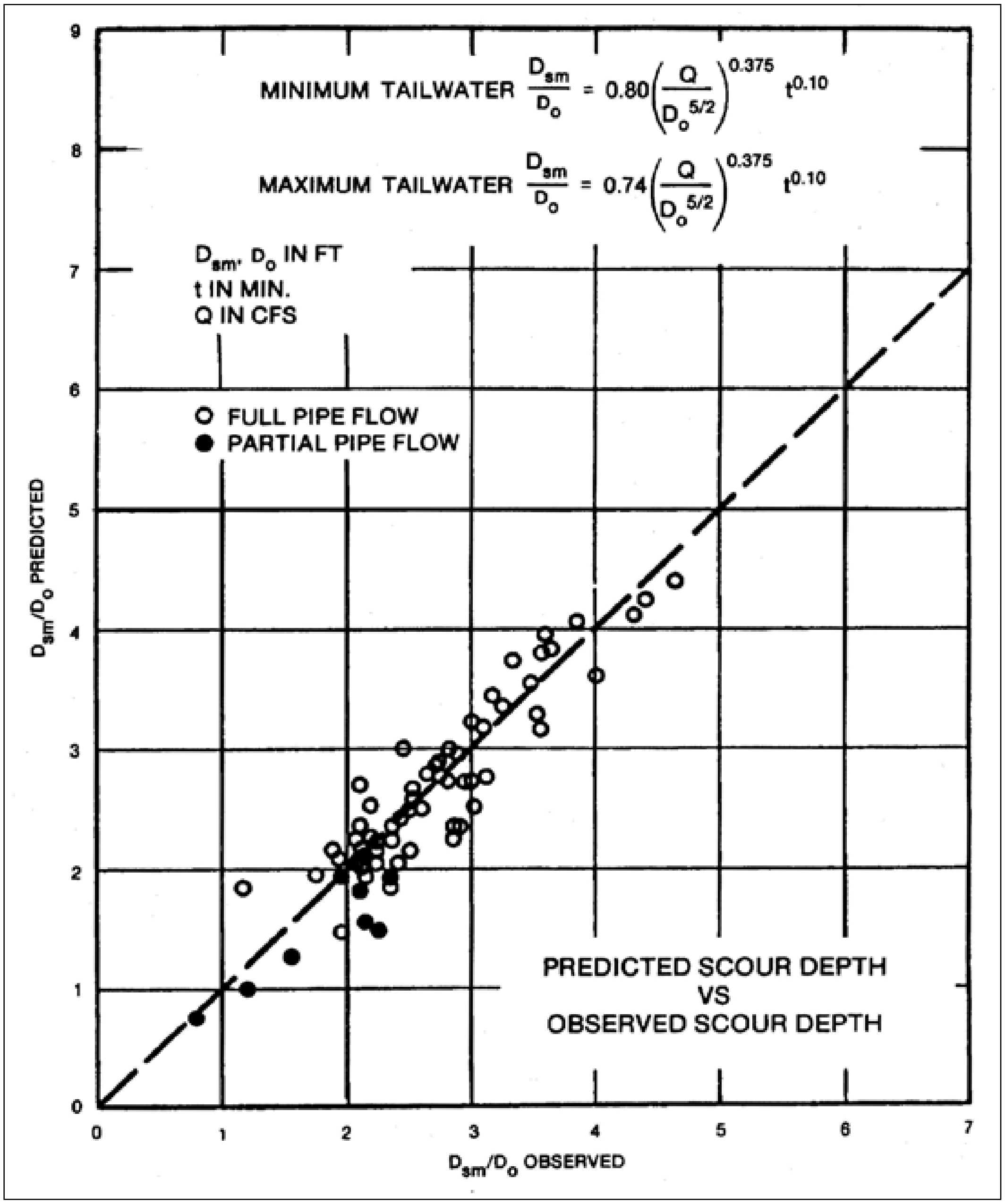


Figure 4-31. Predicted Scour Width vs. Observed Scour Width

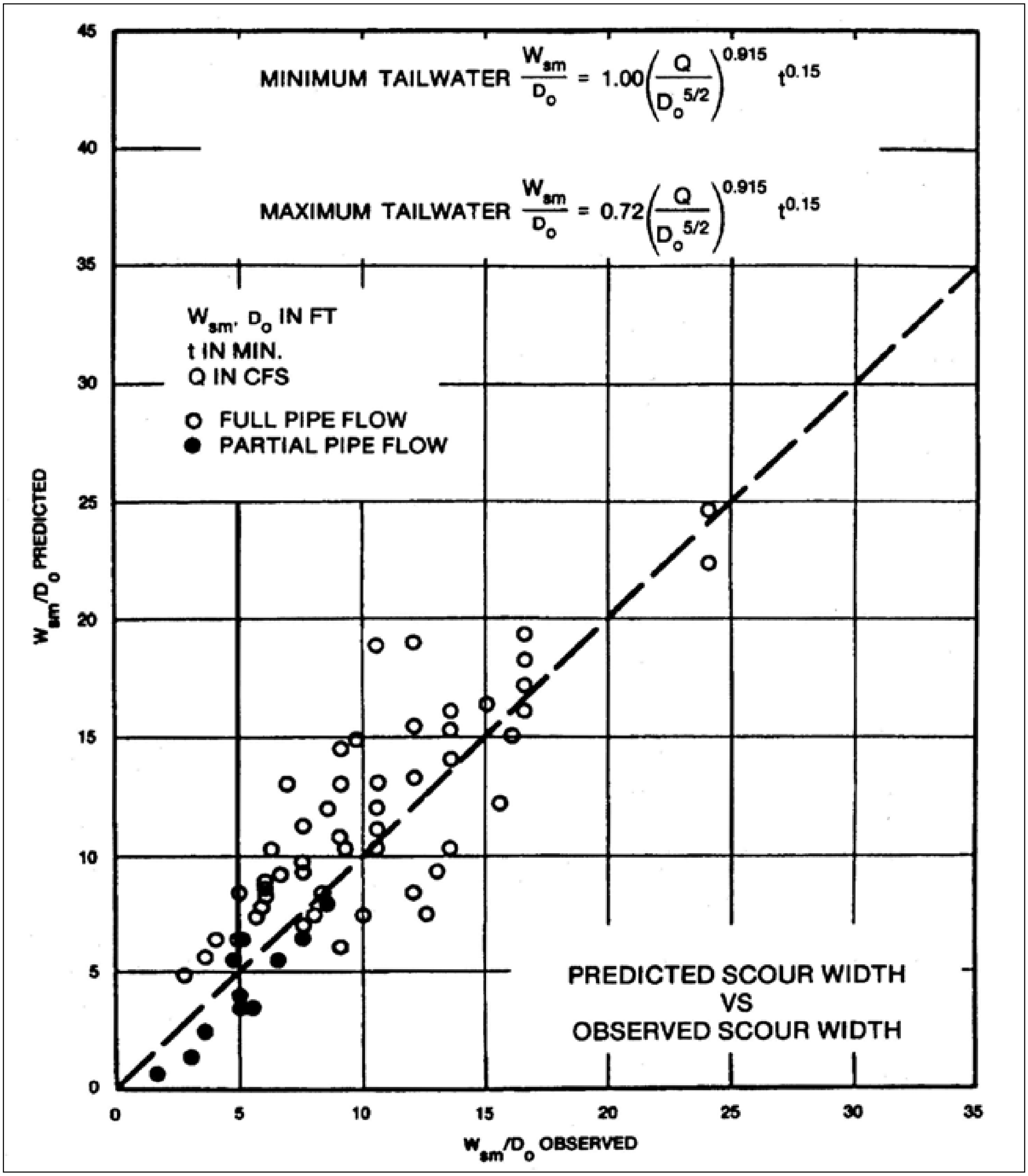


Figure 4-32. Predicted Scour Length vs. Observed Scour Length

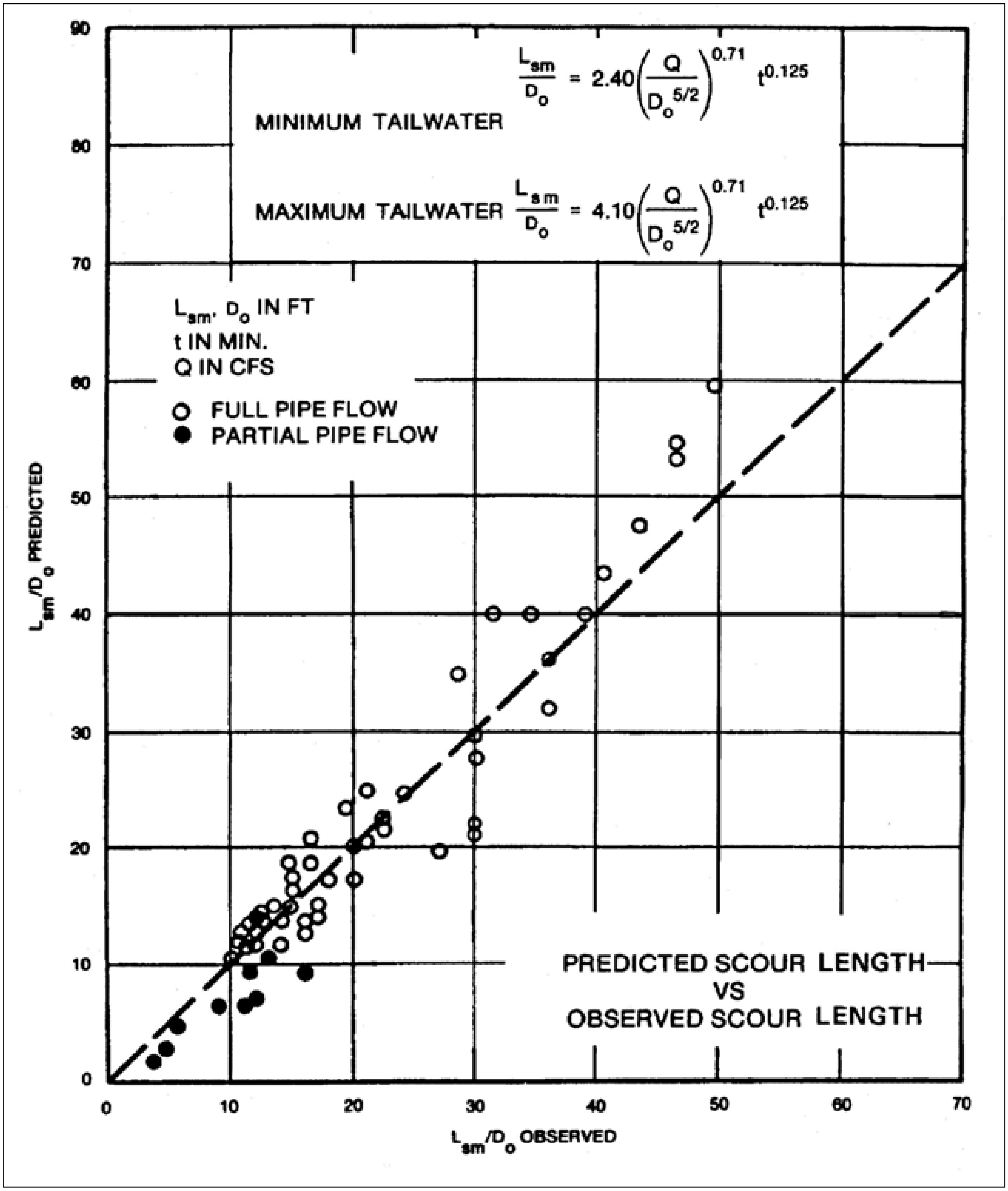


Figure 4-33. Predicted Scour Volume vs. Observed Scour Volume

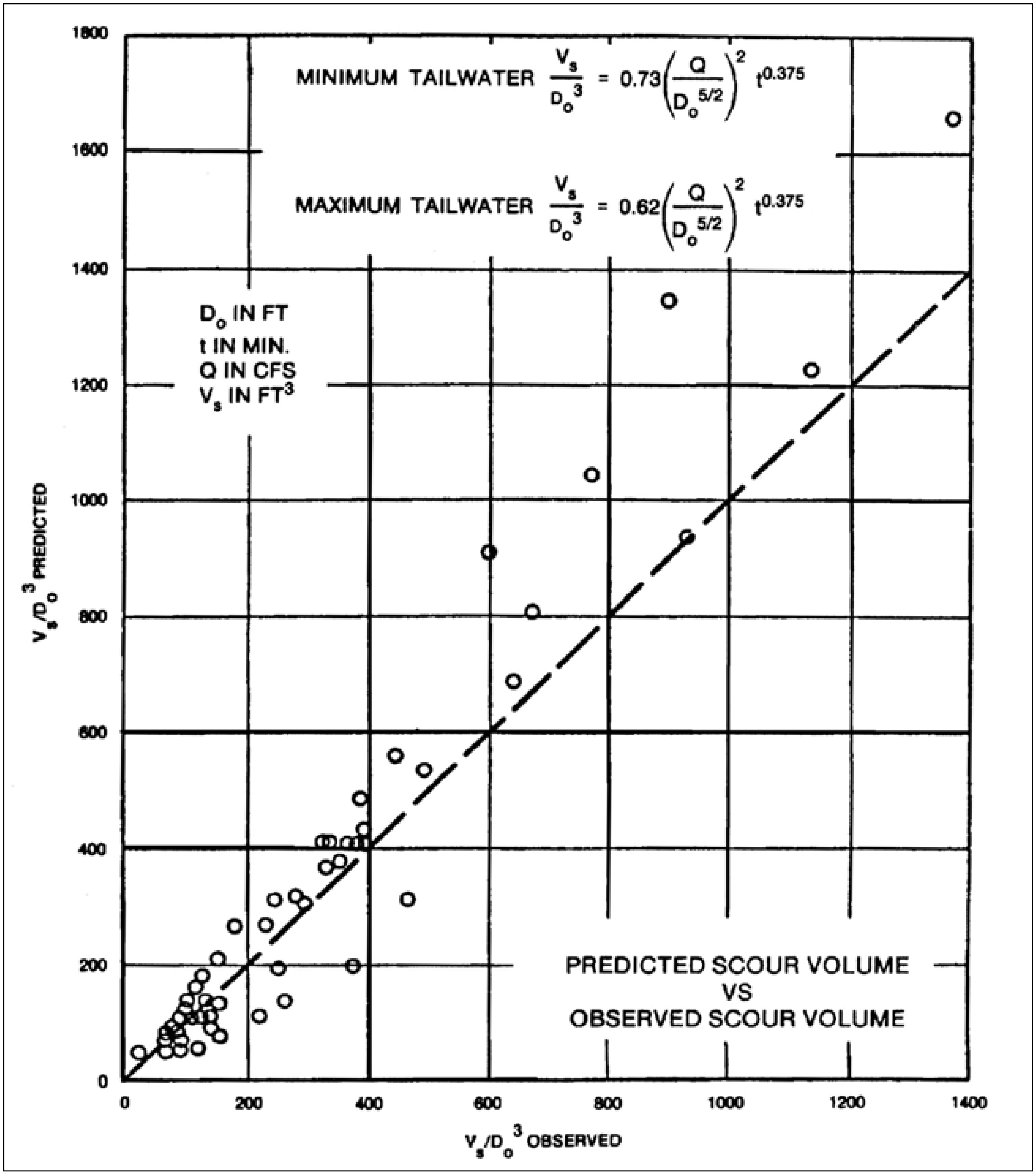


Figure 4-34. Dimensionless Scour Hole Geometry for Minimum Tailwater

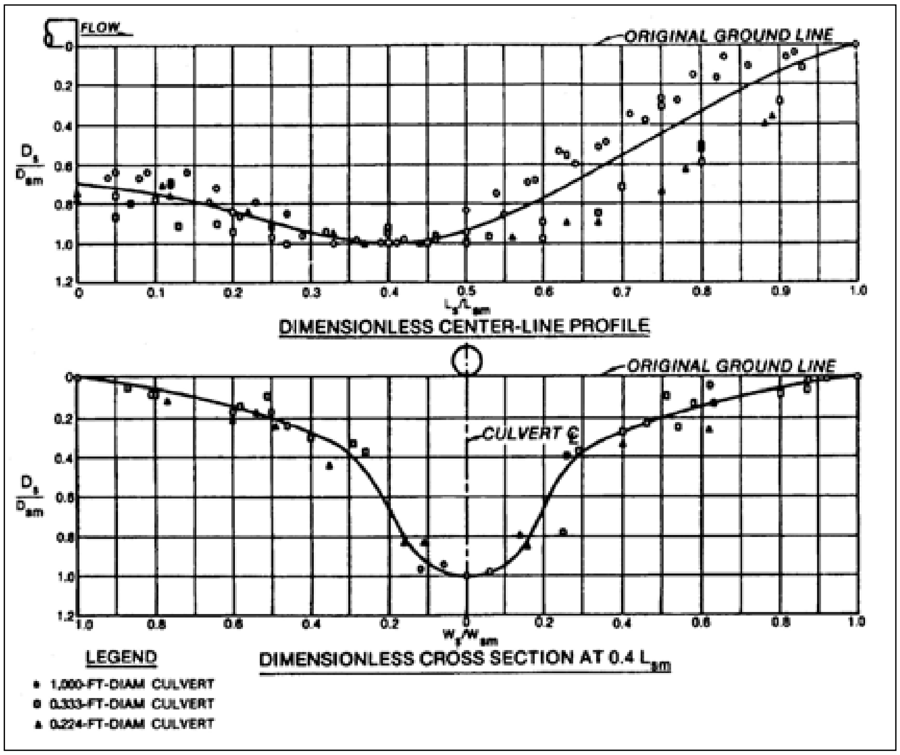
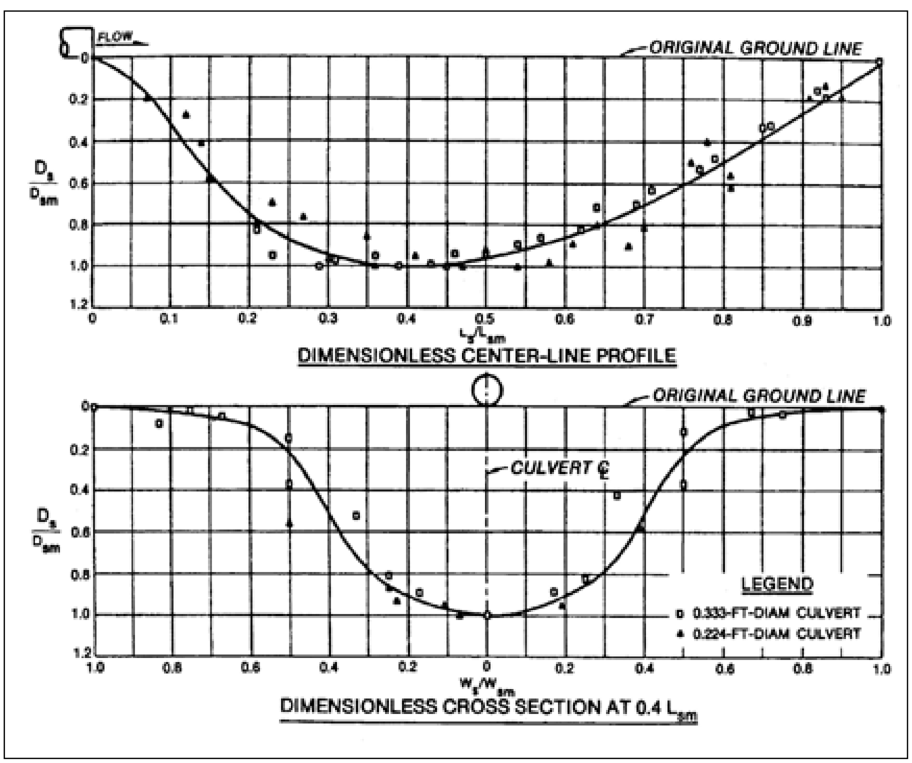


Figure 4-35. Dimensionless Scour Hole Geometry for Maximum Tailwater



4-4.3 **Erosion Control at Outlets**. There are various methods of preventing scour and erosion at outlets and protecting the structure from undermining. Some of these methods will be explained in subsequent paragraphs. For a complete description of scour at the outlet of culverts and the design of energy dissipators, refer to the FHWA's HEC-14. It has charts, nomographs, and tables necessary for estimating scour holes and the design of energy dissipators. In addition, the HY-8 culvert evaluation software, also available from the FHWA, uses the techniques discussed in HEC-14 to perform scour hole calculations and energy dissipator designs. HEC-14 and HY-8 are highly recommended for energy dissipater design.

4-4.3.1 In some situations, placement of riprap at the end of the outlet may be sufficient to protect the structure. The average size of stone (d_{50}) and configuration of a horizontal blanket of riprap at outlet invert elevation required to control or prevent localized scour downstream of an outlet can be estimated using the information in Figures 4-36 to 4-38. For a given design discharge, culvert dimensions, and tailwater depth relative to the outlet invert, the minimum average size of stone (d_{50}) for a horizontal blanket of protection can be determined using data in Figure 4-36. The length of stone protection (LSP) can be determined by the relations shown in Figure 4-37. The recommended configuration of the blanket is shown in Figure 4-38.

Figure 4-36. Recommended Size of Protective Stone