CHAPTER 11

CULVERTS

11-1. General.

a. Configuration. Culverts are generally of circular, oval, elliptical, arch, or box cross section and may be of either single or multiple construction, the choice depending on available headroom and economy. Culvert materials include plain concrete, reinforced concrete, asbestos cement, clay, and plastic. These pipes are considered smooth for flow characteristics; additional materials include corrugated metal and plastics (considered corrugated for flow characteristics). For the metal culverts, different kinds of coatings and linings are available for improvement of durability and hydraulic characteristics. The design of economical culverts involves consideration of many factors relating to requirements of hydrology, hydraulics, physical environment, imposed exterior loads, construction, and maintenance. With the design discharge and general layout requirements determined, the design requires detailed consideration of such hydraulic factors as shape and slope of approach and exit channels, tailwater levels, hydraulic and energy gradelines, and erosion potential. A selection from possible alternative designs may depend on practical considerations such as minimum acceptable size, available materials, local experience concerning corrosion and erosion, and construction and maintenance aspects.

b. Capacity. The capacity of a culvert is the ability of a culvert to admit, convey, and discharge water under specified conditions of potential and kinetic energy upstream and downstream. The hydraulic design of a culvert for a specified design discharge involves selection of a type and size, determination of the position of hydraulic control, and hydraulic computations to determine whether acceptable headwater depths and outfall conditions will result. In considering what degree of detailed refinement is appropriate in selecting culvert sizes, the relative accuracy of the estimated design discharge should be taken into account.

c. Culvert shapes. The majority of cases of culvert uses will involve round pipe or box culverts; therefore the following discussion will center around circular and square configuration culverts. Additional information on other configurations can be found in appendix A. Ponding at inlets to culverts immediately adjacent to runways and roads is discouraged. However, where large variances are present between the design storm and yearly peak storms indicating only rare occurrences of design storm magnitude, ponding for these rare occurrences will be permitted.

11-2. Culvert flow. Laboratory tests and field observations show two major types of culvert flow: flow with inlet control and flow with outlet control. In some instances the flow control changes with change in discharge, and occasionally the control fluctuates from inlet control to outlet control and vice versa for the same discharge. Thus, the design of culverts should consider both types of flow and should be based on the more adverse flow condition anticipated. The two types of flow are discussed briefly in subsequent paragraphs.

a. Inlet control. The discharge capacity of a culvert is controlled at the culvert entrance by the depth of headwater (HW) and the entrance geometry, including the area, slope, and type of inlet edge. Inlet flow for unsubmerged entrance is shown in figures 11-1a and submerged entrance in figure 11-1b. A mitered entrance produces little if any improvement in efficiency over that of the straight, sharp-edged, projecting inlet for inlet control. Both types of inlets tend to inhibit the culvert from flowing full. With inlet control the roughness and length of the culvert barrel and outlet conditions (including depths of tailwater) are not factors in determining culvert capacity. The effect of the barrel slope on inlet-control flow in conventional culverts is negligible. Nomographs (figures 11-2, 11-3, and 11-4) give headwater-discharge relations for most conventional culverts flowing with inlet control. See appendix A for nomographs with modified inlets (flared, tapered, beveled, etc.) or of noncircular shapes.

b. Outlet control. Culverts flowing with outlet control can flow with the culvert barrel full or part full for part of the barrel length or for all of it. Two common types of outlet-control flow are shown in figures 11-1c and 11-1d. The procedure given in this chapter for outlet-control flow does not give an exact solution for a free-water-surface condition throughout the barrel length shown in figure 11-1a. However, an approximate solution is given for this case when the headwater HW is equal to or greater than 0.75D, where D is the height of the culvert barrel. The head H required to pass a given quantity of water through a culvert flowing full with control at the outlet is made up of three major parts. These three parts are usually expressed in feet of water and include a velocity head, an entrance loss, and a friction loss.

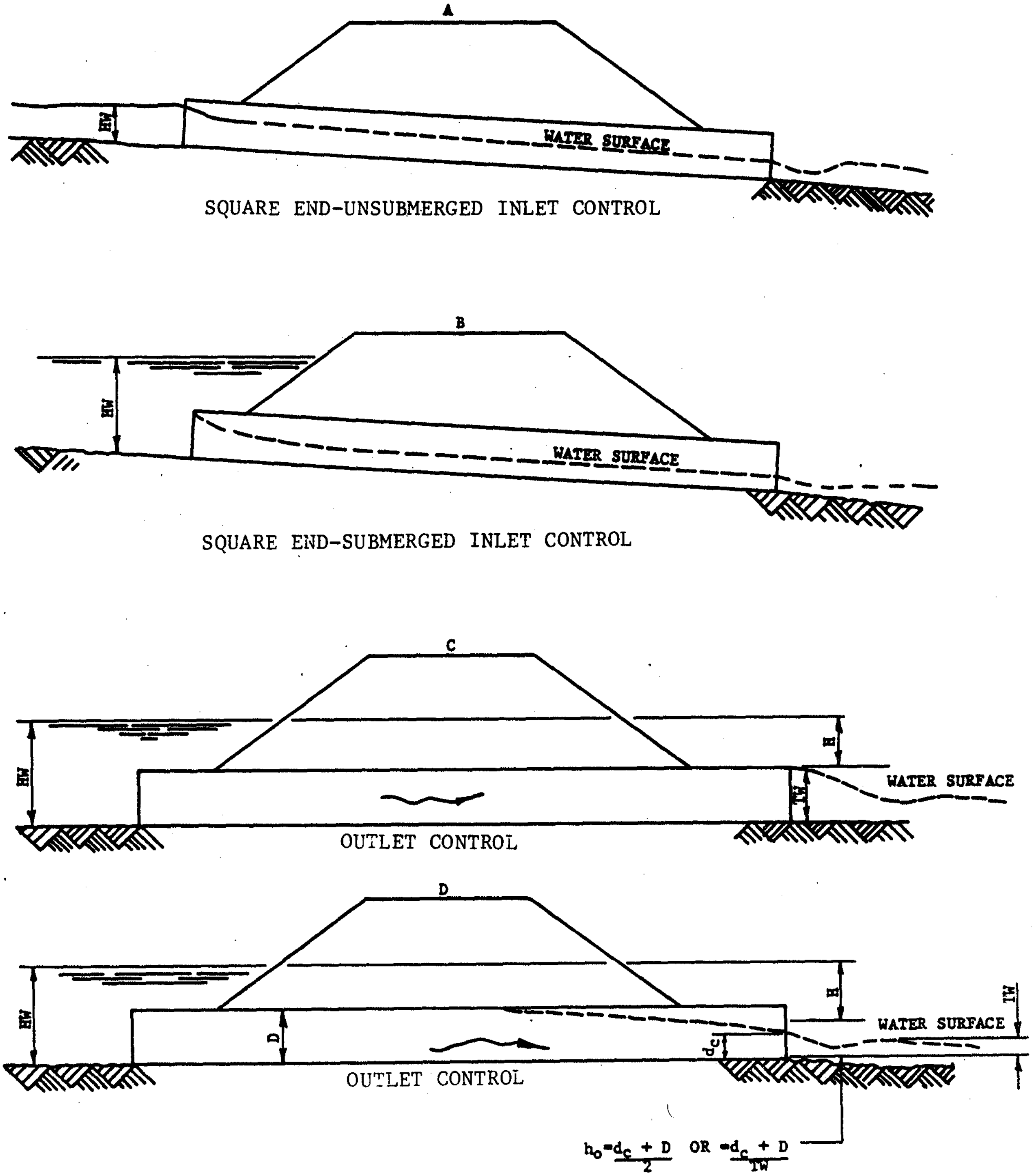

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FIGURE 11-1. INLET AND OUTLET CONTROL

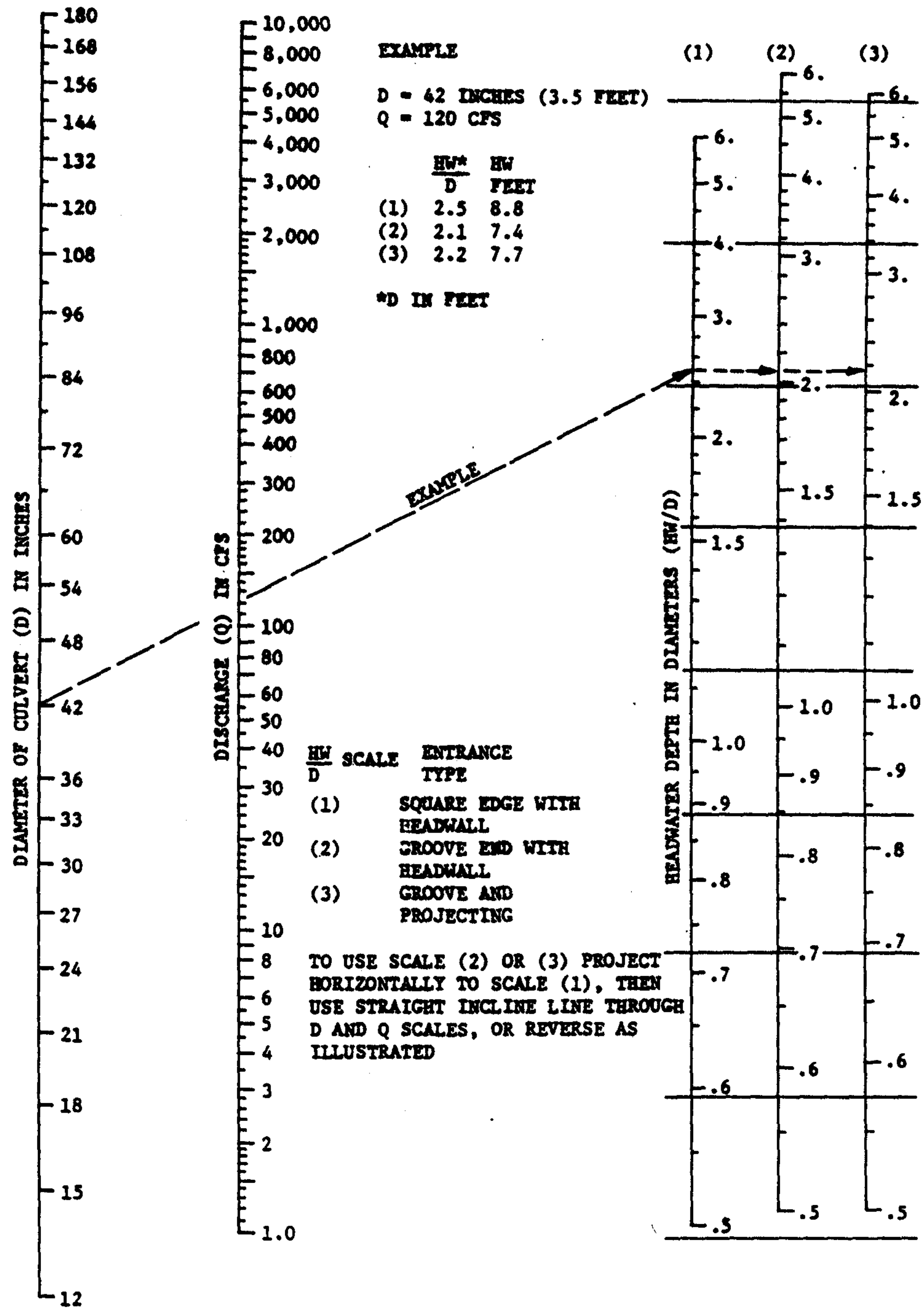

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FIGURE 11-2. HEADWATER DEPTH FOR SMOOTH PIPE CULVERTS WITH INLET CONTROL

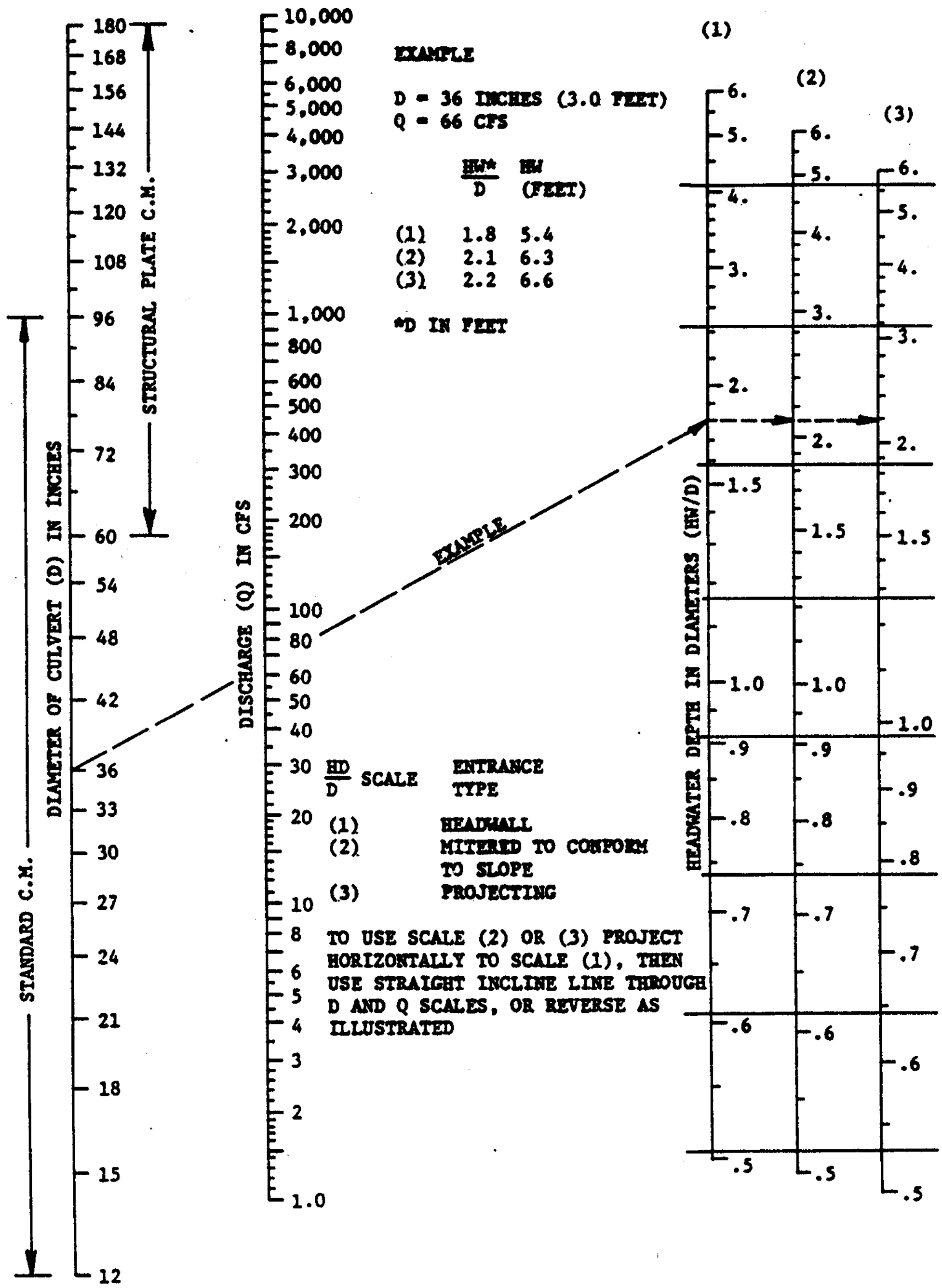

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FIGURE 11-3. HEADWATER DEPTH FOR CORRUGATED PIPE CULVERTS WITH INLET CONTROL

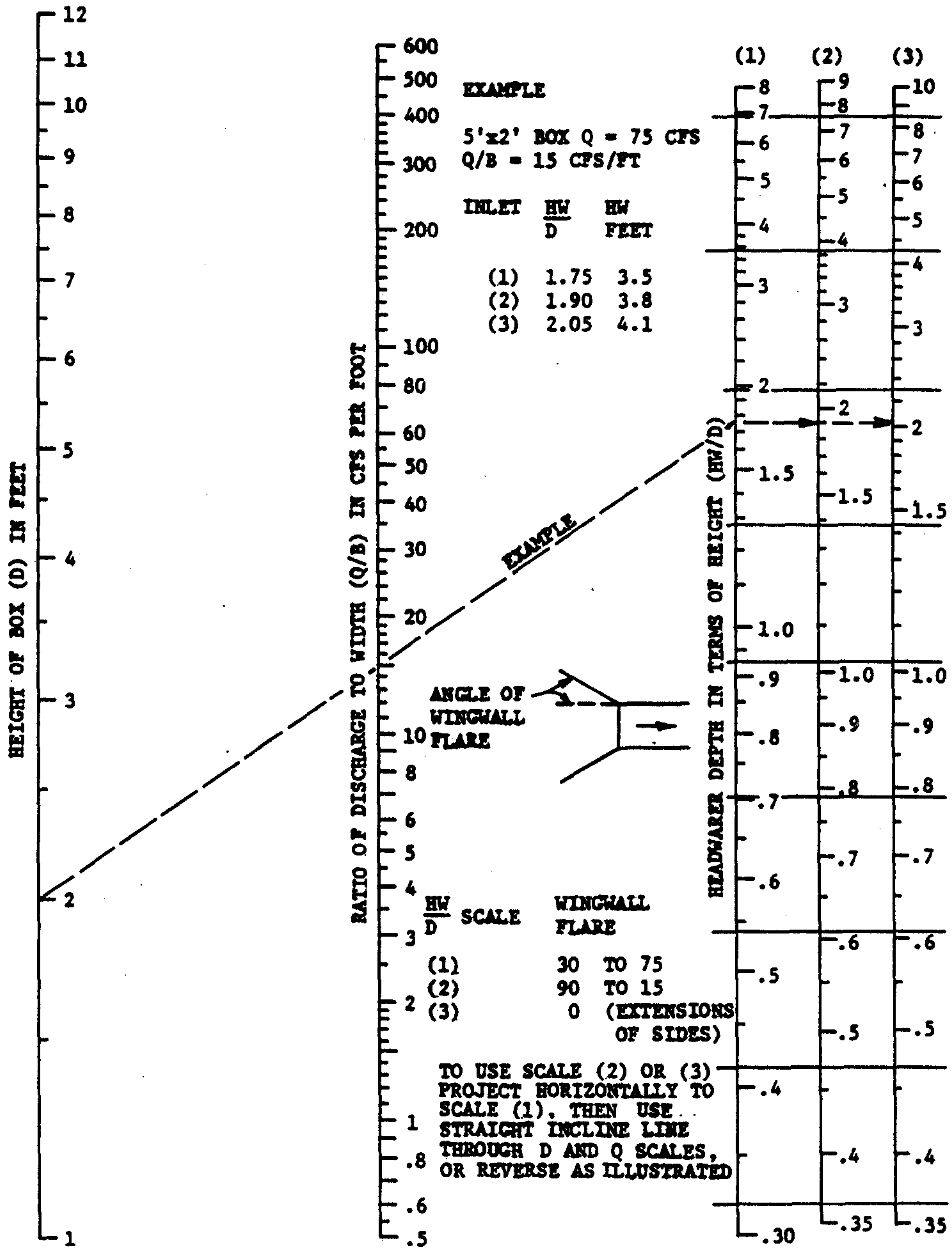

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FIGURE 11-4. HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

(1) The following equation represents the three parts when simplified for full pipe flow:

$$H = \left(1 + k_e + \frac{29n^2L}{R^{1.33}}\right) \frac{V^2}{2g}$$

where:

H = head in feet (see figure 11-1b)
k_e = entrance loss coefficient (See table 11-1)
n = Manning's friction factor
L = length of culvert barrel in feet
R = hydraulic radius in feet, or A/WP
A = area of flow for full cross section in square feet
WP = wetted perimeter in feet
V = mean velocity of flow in culvert barrel in feet per second
g = acceleration of gravity in feet per second^2 (32.16)

This equation can be solved readily by the use of full flow nomographs, figures 11-5, 11-6, and 11-7. Each nomograph is drawn for a single value of n as noted in the respective plate. These nomographs may be used for other values of n by modifying the culvert length as:

$$\text{Modified Length (to be entered in nomograph)} = \left(\frac{\text{Actual Length}}{\frac{\text{Desired n}}{\text{n (for nomograph)}}}\right)^2$$

(2) The value of H must be measured from some "control" elevation at the outlet which is dependent on the rate of discharge or the elevation of the water surface of the tailwater. For simplicity, a value h_o is used as the distance in feet from the culvert invert (flow line) at the outlet to the control elevation. The following equation is used to compute headwater in reference to the inlet invert:

$$HW = h_o + H - LS_o$$

where S_o is the slope of the flow line in feet per foot and all terms are in feet. The determination of h_o for various flow conditions at the outlet is discussed below.

(a) When the pipe is running full (fig 11-1c) tail water (TW) depth equals the depth of the culvert (D) equals h_o.

(b) When the tailwater elevation is below the top of the crown of the culvert outlet (fig 11-1d), h_o is the greater of TW (depth of outlet channel fig 11-1d) or the following.

Table 11-1.

Entrance Loss Coefficients Outlet Control,
Full or Partly Full
Entrance Head Loss $H_e = K_e V^2/2g$

Type of Structure and Design of Entrance	Coefficient 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 = 1/12D)	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 conform 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
Boxed, Reinforced Concrete	
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of 1/12 barrel dimension, 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 barrel dimension, or beveled top edge	0.2
Wingwall 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:"End Section conforming to fill slope," made of either metal or concrete, 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, incorporating a closed taper in their design, have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.

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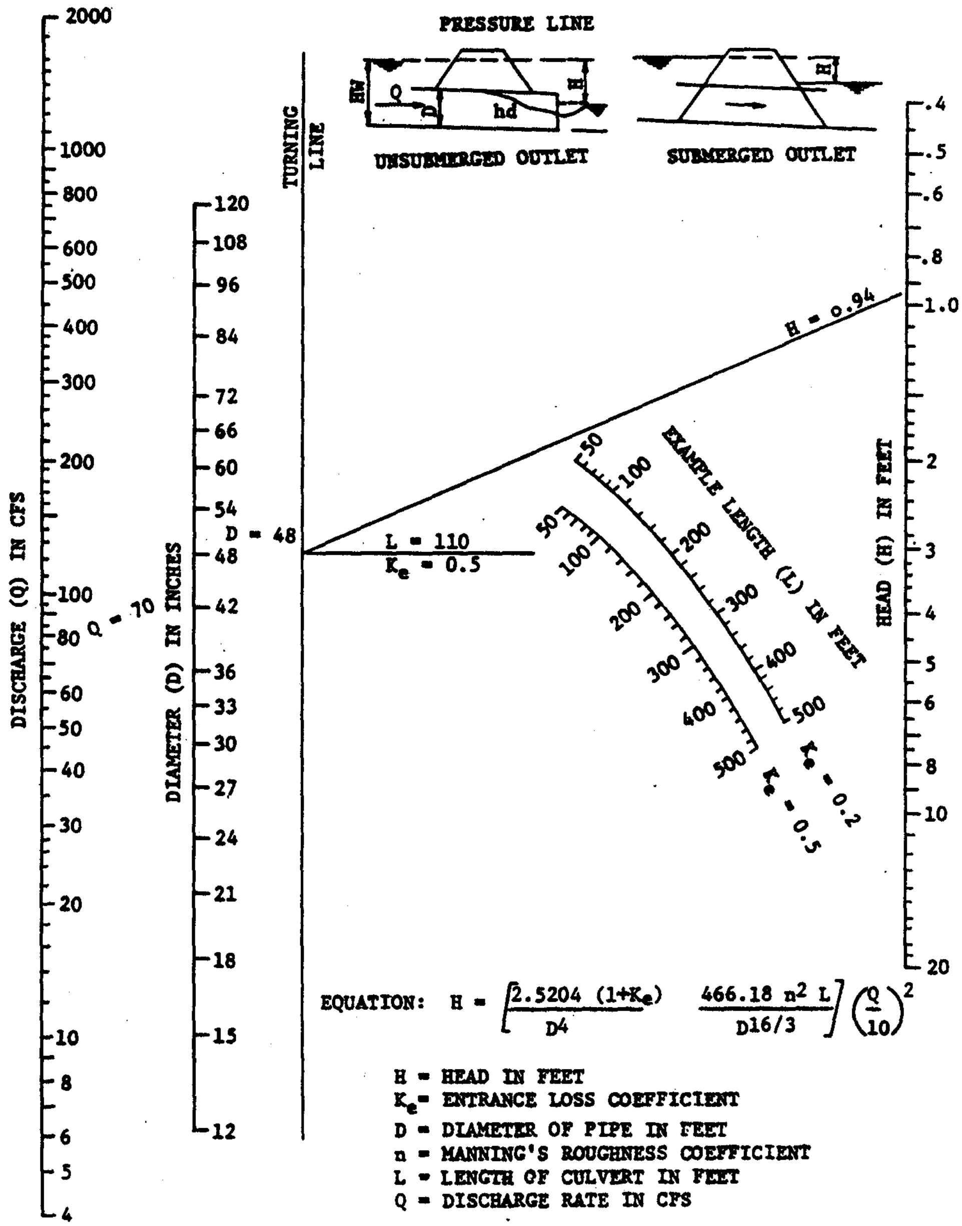

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FIGURE 11-5. HEAD FOR SMOOTH PIPE CULVERTS FLOWING FULL n = 0.012

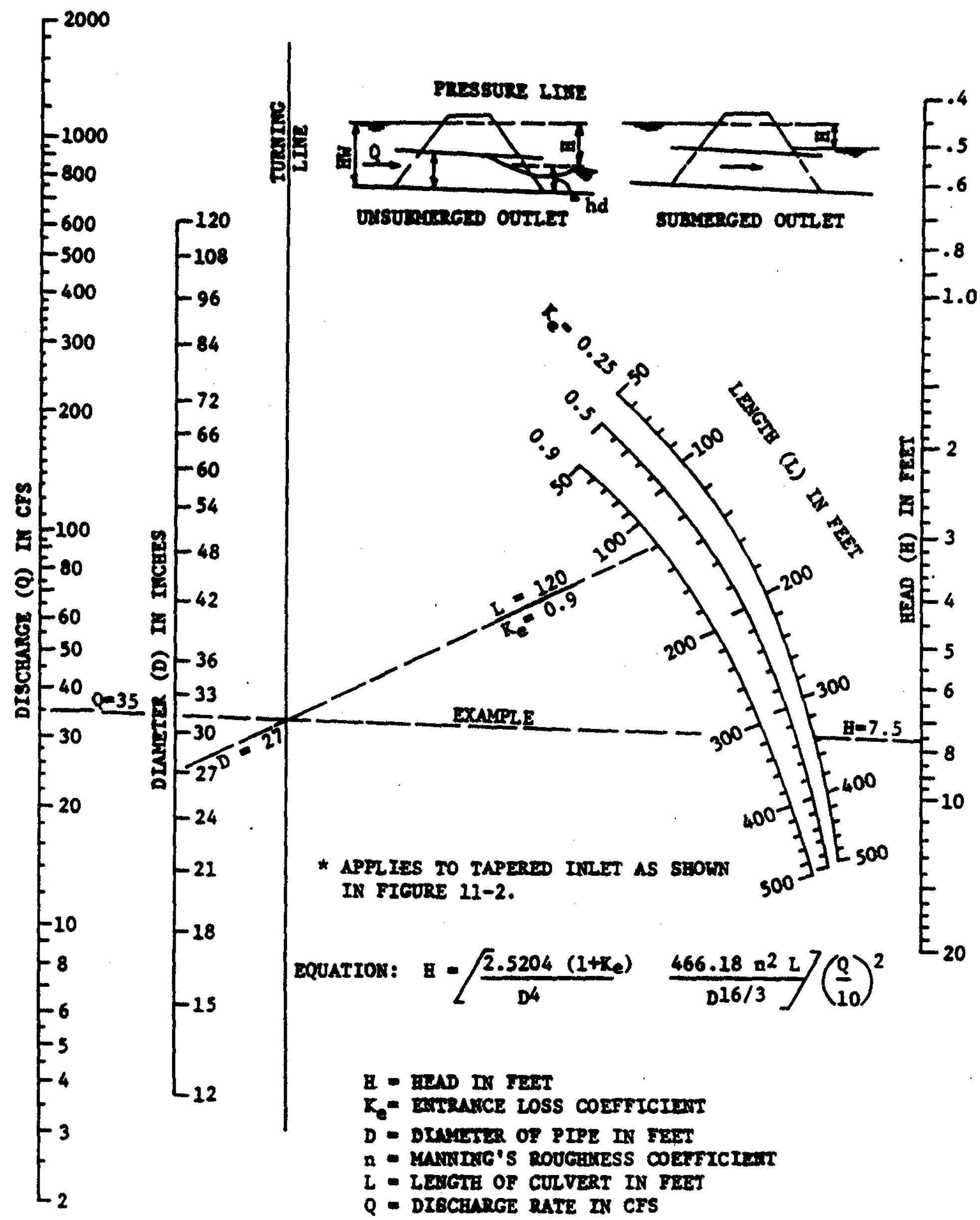

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FIGURE 11-6. HEAD FOR CORRUGATED PIPE CULVERTS FLOWING FULL n = 0.024

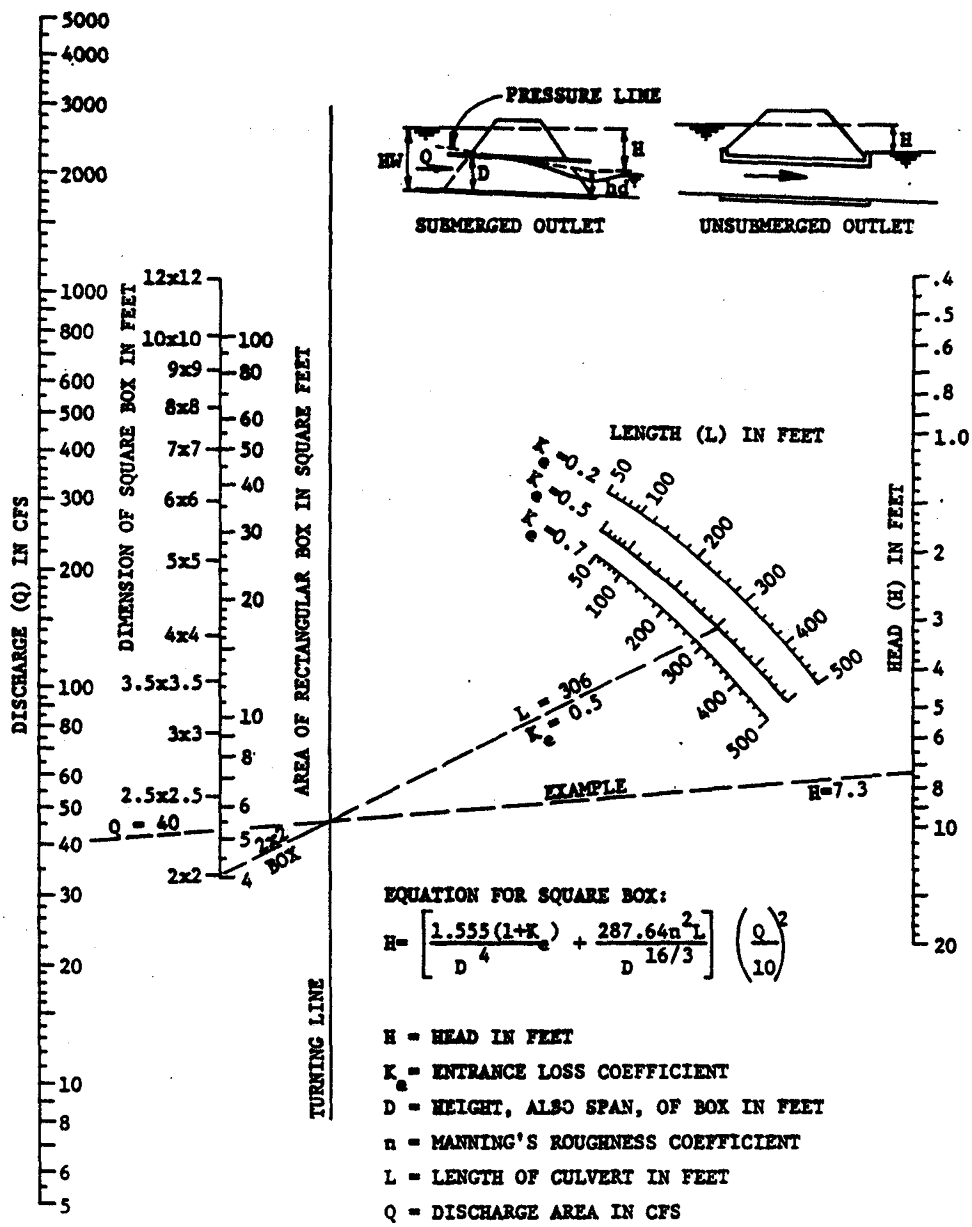

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FIGURE 11-7. HEAD FOR CONCRETE BOX CULVERTS FLOWING FULL n = 0.012

$$\frac{d_c + D}{2}$$

where d_c equals the critical depth as determined from figures 11-8 and 11-9. The value of d_c should never exceed D.

(3) If the headwater (HW), as determined by the equation $HW = h_o + H - LS_o$, is less than

$$HW = D + (1 + k_e)\ V^2/2g$$

and HW is less than 0.75D (similar to figure 11-1a) then a natural stream flow exists and water volume can be determined by using Manning's equation $V = (1.486/n)\ R^{2/3}\ S^{1/2}$. See table 11-2 for typical n values.

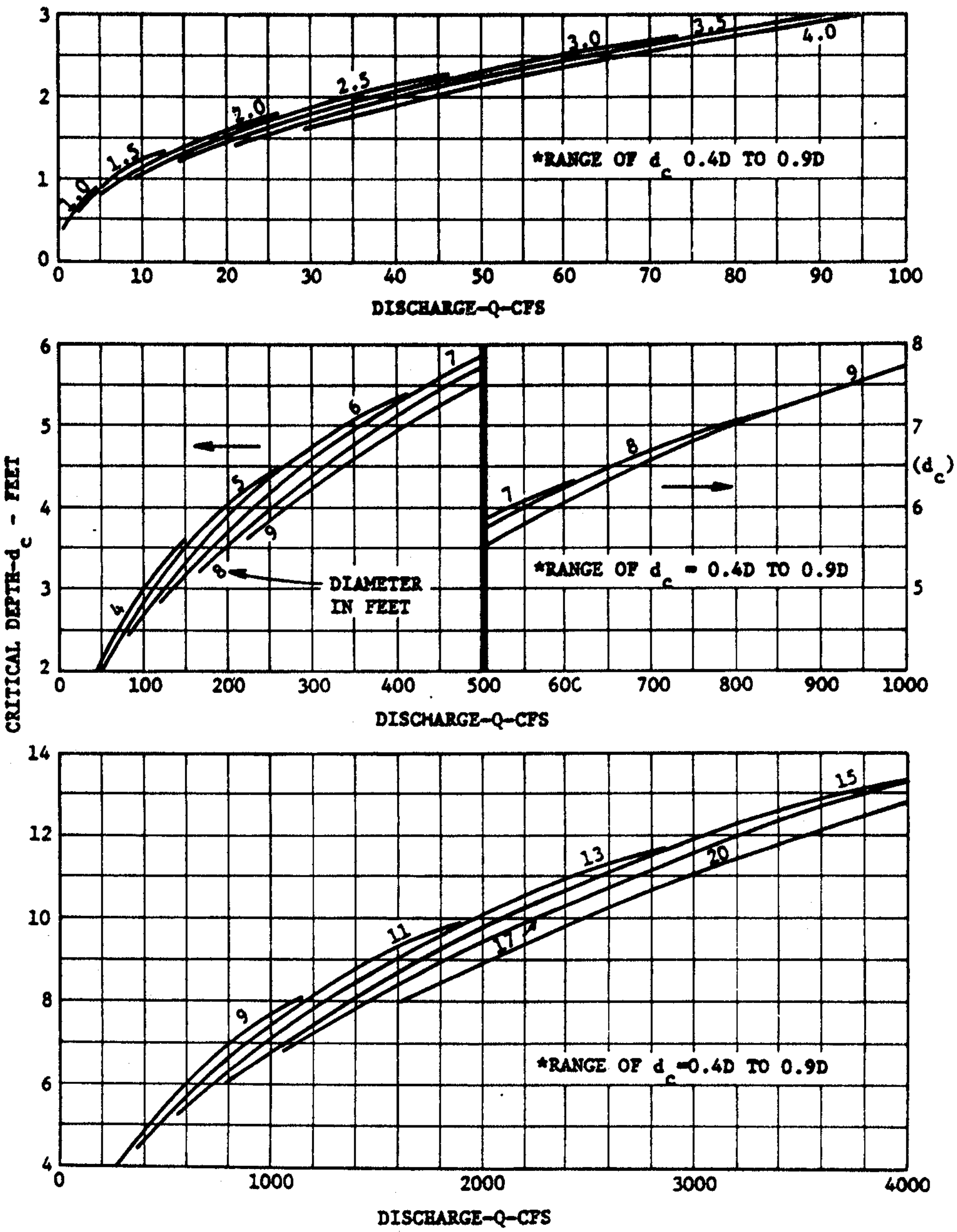
Table 11-2. Manning's n for Natural Stream Channels
(Surface width at flood stage less than 100 feet)

Channel Type	Values of n
Fairly regular section:	
Some grass and weeds, little or no brush	0.030--0.035
Dense growth of weeds, depth of flow materially greater than weed height	0.035--0.05
Some weeds, light brush on banks	0.035--0.05
Some weeds, heavy brush on banks	0.05--0.07
Some weeds, dense willows on banks	0.06--0.08
For trees within channel, with branches submerged at high stage, increase all above values by	0.01--0.02
Irregular sections, with pools, slight channel meander; increase values given above about	0.01--0.02
Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
Bottom of gravel, cobbles, and few boulders	0.04--0.05
Bottom of cobbles, with large boulders	0.05--0.07

11-3. Procedure for selection of culvert size.

Step 1: List given data

a. Design discharge Q, in cubic feet per second.



*NOTE: FOR VALUES OF d_c ABOVE CURVE, USE d_c = D

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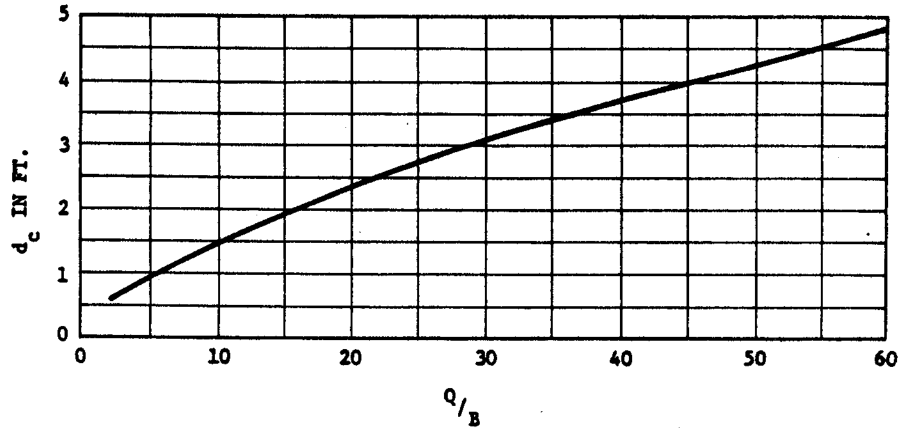
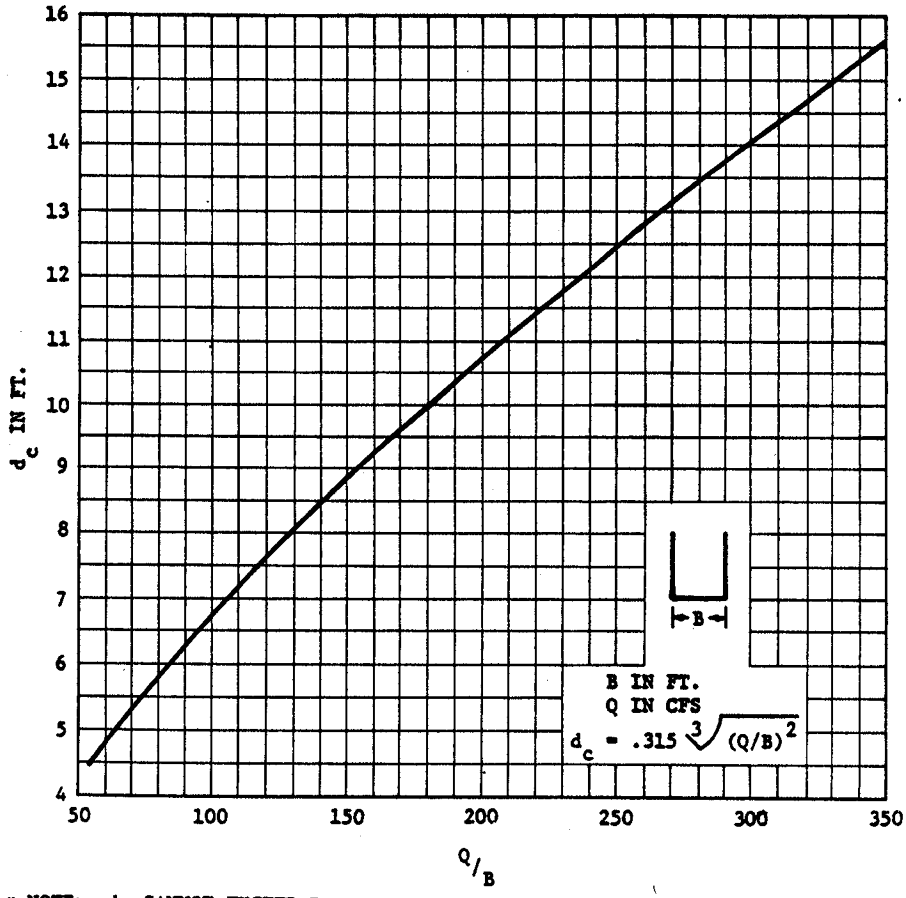
FIGURE 11-8. CIRCULAR PIPE CRITICAL DEPTH





* NOTE: d_c CANNOT EXCEED D

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FIGURE 11-9. CRITICAL DEPTH RECTANGULAR SECTION

b. Approximate length of culvert, in feet.

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

d. Type of culvert, including barrel material, barrel cross-sectional shape, and entrance type.

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

f. Allowable outlet velocity (if scour is a problem).

Step 2: Determine a trial-size culvert.

a. Refer to the inlet-control nomograph (figures 11-2, 11-3, and 11-4) for the culvert type selected.

b. Using an HW/D of approximately 1.5 and the scale for the entrance type to be used, find a trial-size culvert by following the instructions for use of these nomographs. If reasons for lesser or greater relative depth of headwater in a particular case should exist, another value of HW/D may be used for this trial selection.

c. If the trial size for the culverts is obviously too large because of limited height of embankment or availability of size, try a different HW/D value or multiple culverts by dividing the discharge equally for the number of culverts used. Raising the embankment height or the use of pipe arch and box culverts with width greater than height should be considered. Selection should be based on an economic analysis.

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

a. Determine and record headwater depth by use of the appropriate inlet-control nomograph (figures 11-2, 11-3, and 11-4). Tailwater conditions are to be neglected in this determination. Headwater in this case is found by simply multiplying HW/D obtained from the nomograph by D.

b. Compute and record headwater for outlet control as instructed below:

(1) Approximate the depth of 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.

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

$$HW = h_o + H - S_oL$$

where:

HW = vertical distance in feet from culvert invert (flow line at entrance to pool surface upstream.
h_o = vertical distance in feet from culvert flow line at outlet to control point. (In this case h_o equals TW.)
H = head loss in feet as determined from the appropriate nomograph (figures 11-5, 11-6, and 11-7).
S_o = slope of barrel in feet per foot.
L = culvert length in feet.

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

$$HW = h_o + H - S_oL$$

where:

$h_o = \frac{d_c + D}{2}$ or TW, whichever is greater.

Note: where d_c exceeds D in a rectangular section, h_o should be set equal to D.

d_c = critical depth in feet (figure 11-8 and 11-9)

D = culvert height in feet.

Other terms are as defined in (2) above.

c. Compare the headwater found in step 3a and step 3b (inlet control and outlet control). The higher headwater governs and indicates the flow control existing under the given conditions.

d. Compare the higher headwater above 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.

Step 4: Check outlet velocities for size selected.

a. If outlet control governs in step 3c, outlet velocity equals 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 corresponding to d_c or TW depth, whichever gives the greater area of flow.

b. If inlet control governs in step 3c, 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 culvert selected.

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

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

11-4. Instructions for use of inlet-control nomographs.

a. To determine headwater.

(1) Connect with a straight edge 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 1.

(2) If HW/D scale 1 represents entrance type used, read HW/D on scale 1. If some other entrance type is used, extend the point of intersection (see subparagraph 11-4a(1) above) horizontally to scale 2 or 3 and read HW/D.

(3) Compute headwater by multiplying HW/D by D.

b. To determine culvert size.

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

(2) Connect point on HW/D scale 1 as found in subparagraph 11-4b(1) to given discharge and read diameter, height, or size of culvert required.

c. To determine discharge.

(1) Given HW and D, locate HW/D on scale for appropriate entrance type. Continue as in subparagraph 11-4b(1).

(2) Connect point on HW/D scale 1 as found in subparagraph 11-4c(1) and the size of culvert on the left scale and read Q or Q/B on the discharge scale.

(3) If Q/B is read, multiply by B to find Q.

11-5. Instructions for use of outlet-control nomographs. These nomographs solve for head when culverts flow full with outlet control. They are also used in approximating the head for some part-full flow conditions with outlet control. These nomographs do not give a complete solution for finding headwater.

a. To determine head for given culvert and discharge.

(1) Locate appropriate nomograph for type of culvert selected.

(2) Begin nomograph solution by locating starting point on length scale. To locate the proper starting point on the length scales, follow instructions below:

(a) If the n value of the nomograph corresponds to that of the culvert being used, find the proper k_e from table 11-1 and on the appropriate nomograph locate starting point on length curve for that k_e. If a k_e curve is not shown for the selected k_e, see (b) below. If the n value for the culvert selected differs from that of the nomograph, see (c) below.

(b) For the n 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 chart scales in proportion to the k_e values.

(c) 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:

$$L_1 = L(n_1/n)^2$$

(See subparagraph b below for n values.)

(3) Using a straightedge, connect point on length scale to size of culvert barrel and mark the point of crossing on the "turning line." See instruction c below for size considerations for rectangular box culvert.

(4) Pivot the straightedge on this point on the turning line and connect given discharge rate. Read head in feet on the head scale. For values beyond the limit of the chart scales, find H by solving equation given in nomograph or by $H = KQ^2$ where K is found by substituting values of H and Q from chart.

b. To find the n value for a culvert. To find the n value for the culvert selected, refer to the following tabulation:

n value for concrete		n value for corrugated metal			
		Small corrugations (1/2 by 2-2/3 in.)		Large corrugations (2 by 6 in.)	
Pipe	Boxes				
0.013	0.013	Unpaved	0.024	Unpaved	0.033
		25% paved	0.021	25% paved	0.027
		Fully paved	0.013		

c. To use the box-culvert nomograph. To use the box-culvert nomograph (fig 11-7) for full flow for other than square boxes:

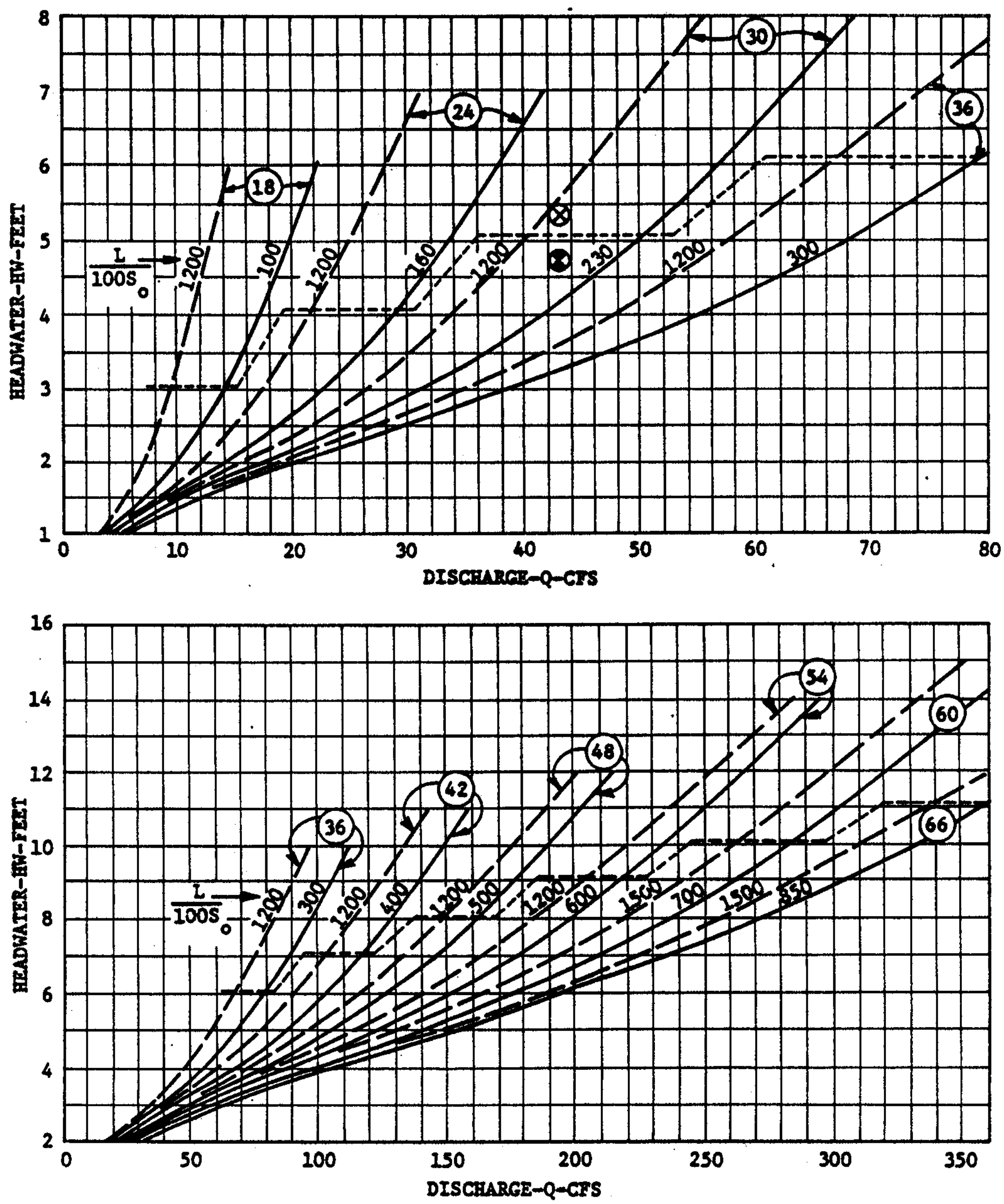
(1) Compute cross-sectional area of the rectangular box.

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

(2) Connect proper point (see subparagraph 11-5a) on length scale to barrel area and mark point on turning line.

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

11-6. Culvert capacity charts. These charts, figures 11-10, 11-11, and 11-12, present headwater discharge relations convenient for use in design of culverts of the most common types and sizes. The solid-line curve for each type and size represents for a given length: slope ratio the culvert capacity with control at the inlet; these curves are based generally on model data. For those culvert types for which a dashed-line curve is shown in addition to a solid-line curve, the dashed line represents for a given length:slope ratio the discharge capacity for free flow and control at the outlet; these curves are based on experimental data and backwater computations. The length: slope ratio is $L/100S_o$ where L is culvert length in feet and S_o is culvert barrel slope in feet per foot. The length: slope ratio given on the solid line curve in each case is the value at which the discharge with outlet control equals the dischatge with inlet control. For culverts with free flow and control at the outlet, interpolation and extrapolation for different $L/100S_o$ values is permitted in the range of headwater depths equal to or less than twice the barrel height. The upper limits of this range of headwater depths are designated by a horizontal dotted line on the charts. Values of $L/100S_o$ less than those given in the chart do not impose any limitation; merely read the solid-line curves. The symbol AHW means allowable headwater depth. The charts permit rapid selection of a culvert size to meet a given headwater limitation for various entrance conditions and types and shapes of pipe. One can enter with a given



EXAMPLE

⊗ **GIVEN:**
43 CFS; AHW = 5.4 FT.
L=120 FT.; S_o=0.002

SELECT 30"
HW=4.7 FT.

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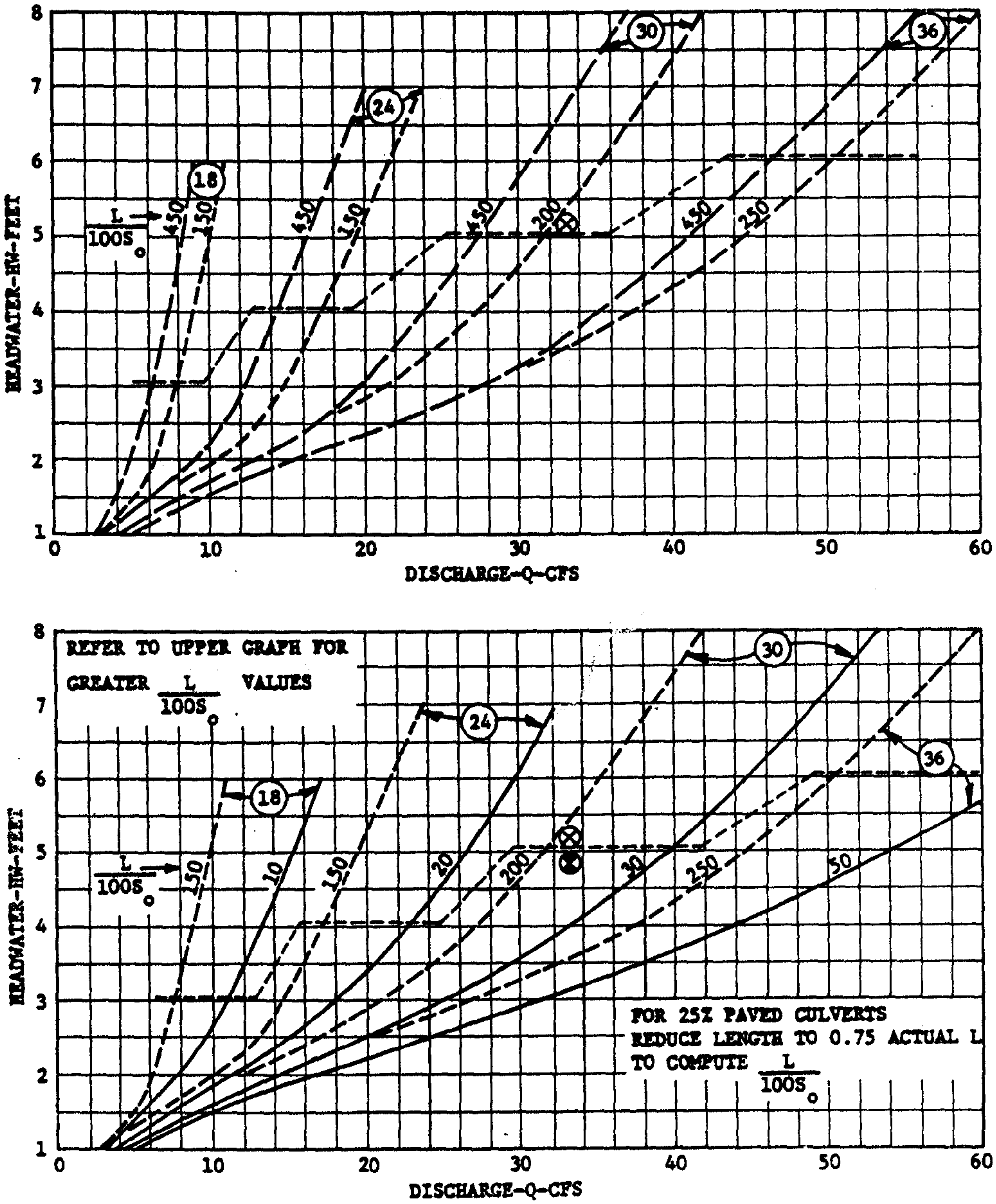
FIGURE 11-10. CULVERT CAPACITY CIRCULAR SMOOTH PIPE
GROOVE-EDGE ENTRANCE 18" TO 66"



EXAMPLE

⊗ GIVEN:
33 CFS; AHW=5.2 FT.
L=70 FT.; S_o=0.005

⊗ SELECT 30" UNPAVED
HW=4.9 FT.

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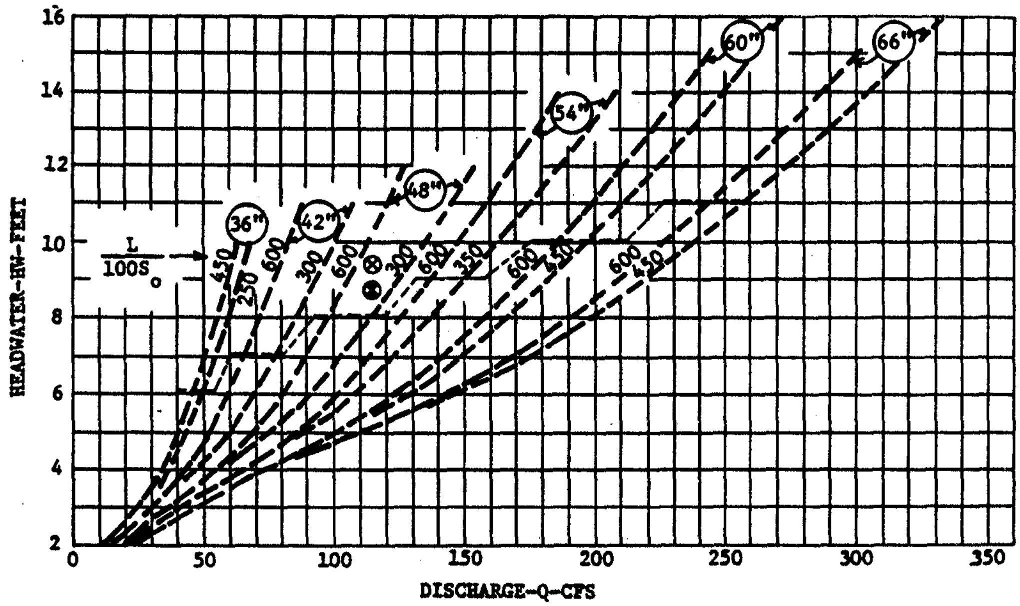
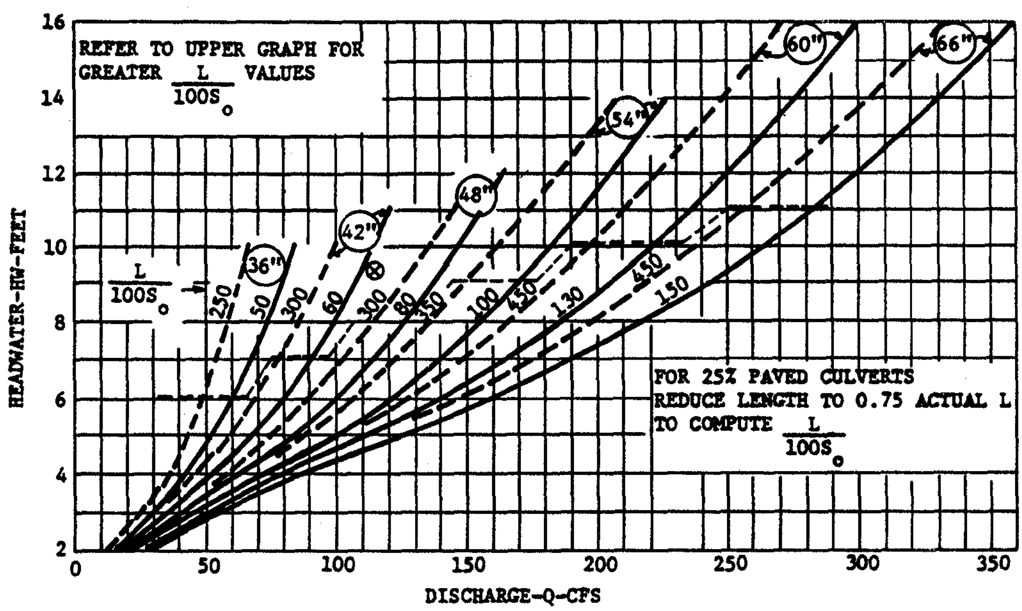
FIGURE 11-11. CULVERT CAPACITY STANDARD CIRCULAR CORRUGATED PIPE PROJECTING ENTRANCE 18" TO 36" ◯





EXAMPLE

⊗ GIVEN:
115 CFS; AHW=9.4 FT.
L=135 FT.; S_o=0.0034

⊛ SELECT 48" UNPAVED
HW=8.6 FT.

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FIGURE 11-12. CULVERT CAPACITY STANDARD CIRCULAR CORRUGATED PIPE PROJECTING ENTRANCE 36"-66" discharge and read vertically upward to the pipe size that will carry the flow to satisfy the headwater limitation of the design criteria. The major restriction on the use of the charts is that free flow must exist at the outlet. In most culvert installations, free flow exists, i.e., flow passes through critical depth near the culvert outlet. For submerged flow conditions, the solution can be obtained by use of the outlet-control nomographs.