Design Data 12

American Concrete Pipe Association

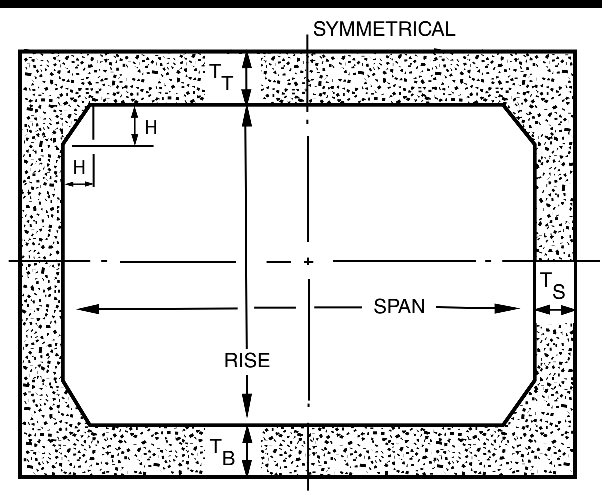
Hydraulic Capacity of Precast Concrete Boxes

Under certain conditions the hydraulic or structural characteristics of reinforced concrete box sections offer advantages over the circular and non-circular pipe shapes commonly used for sewers and culverts. The cost-effective advantages of precast concrete pipe productions and construction methods are available in a product manufactured in accordance with the ASTM Standard C1433, Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains and Sewers and Standard C1577, Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains, and Sewers Designed According to AASHTO LRFD. The American Concrete Pipe Association's CP Info, Precast Concrete Box Sections, presents the development and verification of the design method and standard sizes.

STANDARD DESIGNS

The standard precast concrete box section produced under Standards C1433 and C1577 is shown in *Figure 1*, and the standard sizes and wall thicknesses are shown in *Tables 1 and 2*. The standard sizes have 45-degree haunches with a leg dimension equal to the wall thickness. The availability and construction details of box sections should be discussed with local concrete pipe producers. Precast box designs other than standard are available through American Concrete Pipe Association member companies.

Figure 1 Standard Box Section



Note: The haunch dimension H, is equal to the wall thickness T_S.

Table 1 Standard Box Sizes

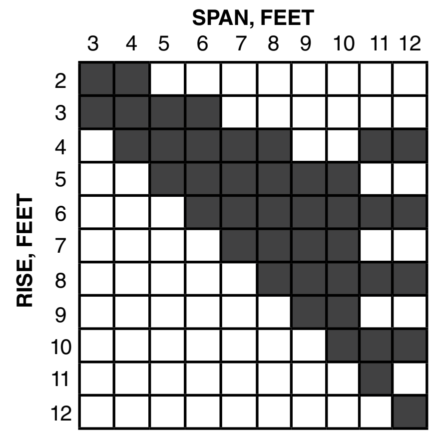


Table 2 Standard Thicknesses

Span Feet	T_T, inches		T_B, inches		T_S, inches	
	> 2' cover	< 2' cover	> 2' cover	< 2' cover	> 2' cover	< 2' cover
3	4	7	4	6	4	4
4	5	7 1/2	5	6	5	5
5	6	8	6	7	6	6
6	7	8	7	7	7	7
7	8	8	8	8	8	8
8	8	8	8	8	8	8
9	9	9	9	9	9	9
10	10	10	10	10	10	10
11	11	11	11	11	11	11
12	12	12	12	12	12	12

HYDRAULICS OF SEWERS

The hydraulic characteristics of precast concrete box sections are similar to those for circular, arch and elliptical pipe. The most widely accepted formula for evaluating the hydraulic capacity of non-pressure conduit is the Manning Formula. This formula is:

$$Q = \frac{1.486}{n} \times A \times R^{2/3} \times S^{1/2} \qquad (1)$$

Where:

Q = discharge in cubic feet per second
n = Manning's roughness coefficient
A = cross-sectional area of flow, square feet

Table 3 Full Flow Section and Hydraulic Properties - Precast Concrete Box Sections

Size Span x Rise (Feet)	A Area (Square Feet)	R Hydraulic Radius (A/P Feet)	C = $1.486/n(AxR^{2/3})$*	
			n = 0.012	n = 0.013
3 x 2	5.78	0.63	520	480
3 x 3	8.78	0.78	920	850
4 x 2	7.65	0.69	740	690
4 x 3	11.65	0.89	1,340	1,240
4 x 4	15.65	1.04	1,990	1,840
5 x 2	9.50	0.74	960	890
5 x 3	14.50	0.98	1,770	1,630
5 x 4	19.50	1.16	2,660	2,460
5 x 5	24.50	1.30	3,620	3,340
6 x 3	17.32	1.04	2,200	2,030
6 x 4	23.32	1.25	3,350	3,100
6 x 5	29.32	1.42	4,590	4,240
6 x 6	35.32	1.56	5,880	5,430
7 x 3	20.11	1.09	2,640	2,440
7 x 4	27.11	1.33	4,050	3,740
7 x 5	34.11	1.52	5,580	5,160
7 x 6	41.11	1.68	7,200	6,650
7 x 7	48.11	1.82	8,880	8,200
8 x 3	23.11	1.13	3,110	2,870
8 x 4	31.11	1.39	4,790	4,420
8 x 5	39.11	1.60	6,630	6,120
8 x 6	47.11	1.78	8,570	7,920
8 x 7	55.11	1.94	10,610	9,790
8 x 8	63.11	2.07	12,710	11,730
9 x 4	34.88	1.44	5,500	5,080
9 x 5	43.88	1.67	7,650	7,060
9 x 6	52.88	1.87	9,950	9,180
9 x 7	61.88	2.05	12,350	11,400
9 x 8	70.88	2.20	14,840	13,700
9 x 9	79.88	2.33	17,400	16,060
10 x 4	38.61	1.48	6,220	5,740
10 x 5	48.61	1.73	8,690	8,020
10 x 6	58.61	1.95	11,330	10,460
10 x 7	68.61	2.14	14,110	13,030
10 x 8	78.61	2.31	17,010	15,700
10 x 9	88.61	2.46	19,990	18,450
10 x 10	98.61	2.59	23,040	21,270
11 x 4	42.32	1.52	6,930	6,390
11 x 5	53.32	1.79	9,720	8,970
11 x 6	64.32	2.02	12,720	11,750
11 x 7	75.32	2.22	15,900	14,670
11 x 8	86.32	2.41	19,200	17,720
11 x 9	97.32	2.57	22,620	20,880
11 x 10	108.32	2.72	26,120	24,110
11 x 11	119.32	2.85	29,710	27,420
12 x 4	46.00	1.55	7,630	7,050
12 x 5	58.00	1.83	10,750	9,930
12 x 6	70.00	2.08	14,120	13,040
12 x 7	82.00	2.30	17,690	16,330
12 x 8	94.00	2.50	21,420	19,770
12 x 9	106.00	2.67	25,280	23,340
12 x 10	118.00	2.83	29,250	27,000
12 x 11	130.00	2.98	33,320	30,760
12 x 12	142.00	3.11	37,470	34,580

* Values have been rounded due to the empirical nature of the terms used to calculate the constant.

R = hydraulic radius in feet (equals the area of the flow divided by the wetted perimeter)
S = slope of conduit, feet of vertical drop per foot of horizontal distance

Since the designer is usually concerned with selecting a box size for a given design flow and slope, the Manning Formula is more conveniently expressed as:

$$\frac{Q}{S^{1/2}} = \frac{1.486}{n} \times A \times R^{2/3} \qquad (2)$$

By evaluating the values of $1.486/n \times A \times R^{2/3}$ for the various box sizes available, a size can be selected for any $Q/S^{1/2}$ value. *Table 3* lists the area A, hydraulic radius R, and C ($1.486/n \times A \times R^{2/3}$) a constant for the full flow condition. Based on Manning's Formula, these tabular values are equal to $Q/S^{1/2}$ for full flow. For any $Q/S^{1/2}$ value, the size of box required can be read directly.

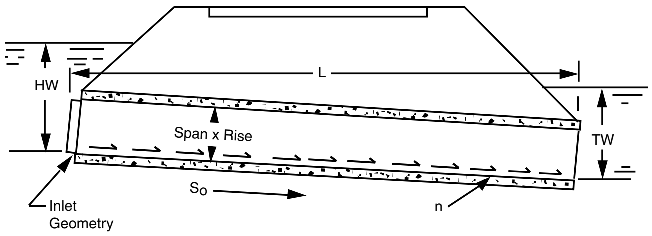
It is important to note that in sewer design, a hydraulic comparison between various shapes cannot be made solely on the basis of cross-sectional areas or peripheries. For two conduits of similar materials and different shapes to be hydraulically equivalent, it is necessary for the factor $A \times R^{2/3}$ to be the same for both. Multiplying this factor by 1.486/n accounts for the surface roughness of the conduit material and determines the hydraulic capacity. Under any given flow condition, the area A and hydraulic radius R are constant for a particular size and shape and therefore, hydraulic capacity is primarily dependent on n, the roughness coefficient. Commonly used roughness coefficients for precast concrete sewers range between the values of 0.012 to 0.013. The higher value is used to account for the possibility of slime or grease build-up in sanitary sewers. When this build-up can be prevented by higher velocities or effluent characteristics, the lower n value should be used. Minimum velocities for self cleansing action are generally considered under full flow conditions to be 2 feet per second for sanitary sewers and 3 feet per second for storm sewers.

HYDRAULICS OF CULVERTS

Box sections used for culverts are evaluated by the major factors affecting the hydraulic capacity as illustrated in *Figure 2*. For any given headwater depth, these factors interact to control the hydraulic capacity by one of the following means:

a. Geometry of the inlet;
b. Combined influence of size, shape, slope and surface roughness of the culvert.
c. Tailwater conditions at the outlet.

Figure 2   Factors Affecting Culvert Capacity



Span = inside horizontal span of box
Rise = inside vertical height of box
HW = headwater depth at culvert entrance
L = length of culvert
n = surface roughness of the box wall, usually expressed in terms of Manning's n
S_O = slope of the box culvert
TW = tailwater depth at culvert outlet

The type of control a box culvert will operate under for any given set of conditions can be definitely established through detailed analysis using nomographs from the Hydraulic Engineering Circular Number 5, Federal Highway Administration. Because the designer is basically concerned with providing an adequate capacity to carry a design discharge without exceeding an allowable headwater depth, use of headwater-discharge performance curves can greatly reduce the time consuming mathematical calculations. Such performance curves are presented in Design Data 15, Hydraulic Sizing of Box Culverts.

The type of control under which a particular box culvert operates is dependent on the location of the control section, which limits the maximum discharge through the culvert. In the hydraulic design of box culverts where the outlet is not submerged, the two principal types of control usually considered are inlet control and outlet control.

Under inlet control, the control section is located at or near the culvert entrance and, for any given shape and size of culvert, the discharge capacity is entirely dependent on the inlet geometry and headwater depth. Inlet control will exist as long as water can pass through the culvert at a greater rate than water can enter through the inlet. Since the control section is at the inlet, the capacity is not affected by hydraulic factors beyond the culvert entrance such as culvert slope, length or surface roughness. Culverts operating under inlet control will always flow part full.

Under outlet control, the control section is located at or near the culvert outlet and for any given shape and size of culvert, the discharge capacity is dependent on all of the hydraulic factors upstream from the outlet tailwater. *Table 4* presents entrance loss coefficients as recommended by the Federal Highway Administration. Outlet control will exist as long as water can enter the culvert through the inlet at a greater rate than water can flow away from the outlet. Culverts operating under outlet control can flow either part full or full. *Figures 3* and *4* are the inlet and outlet nomographs provided by Hydraulic Engineering Circular Number 5 for the selection of box culvert sizes. The design procedure for using these nomographs is presented in the example problems.

An important consideration in the hydraulic design of culverts flowing part full is critical slope. Critical slope is the minimum slope at which maximum discharge will be realized without causing the culvert to flow full. Culverts installed on slopes less than critical will approach full flow at relatively low headwater depths and require correspondingly higher headwater depths to carry the same amount of water as culverts placed on slopes greater than critical slope.

Table 4   Entrance Loss Coefficients

Coefficient k_e to apply velocity head $V^2/2g$ for determination of head loss at entrance to a structure, such as a culvert or conduit, operating full or partly full with *control at the outlet*.

Entrance head loss $H_e = k_e V^2/2g$

Type of Structure and Design of Entrance Box, Reinforced Concrete	Coefficient k_e
Headwall parallel to embankment (no wing walls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius* of span/12 or rise/12 or beveled edges on 3 sides	0.2
Wing walls at 30° to 75° to barrel	
Square-edged at crown	0.4
Crown edge rounded to radius of rise/12 or beveled top edge	0.2

Type of Structure and Design of Entrance Box, Reinforced Concrete	Coefficient k_e
Wing walls at 10° to 25° to barrel	
Square-edged at crown	0.5
Wing walls parallel (extension of sides)	
Square-edged at crown	0.7
Side-or-slope-tapered inlet	0.2

* Dimension of radius is related to the opening dimension at right angels to the edge

Federal Highway Administration hds-5 2005

Figure 3 Headwater Depth for Concrete Box Culverts With Inlet Control

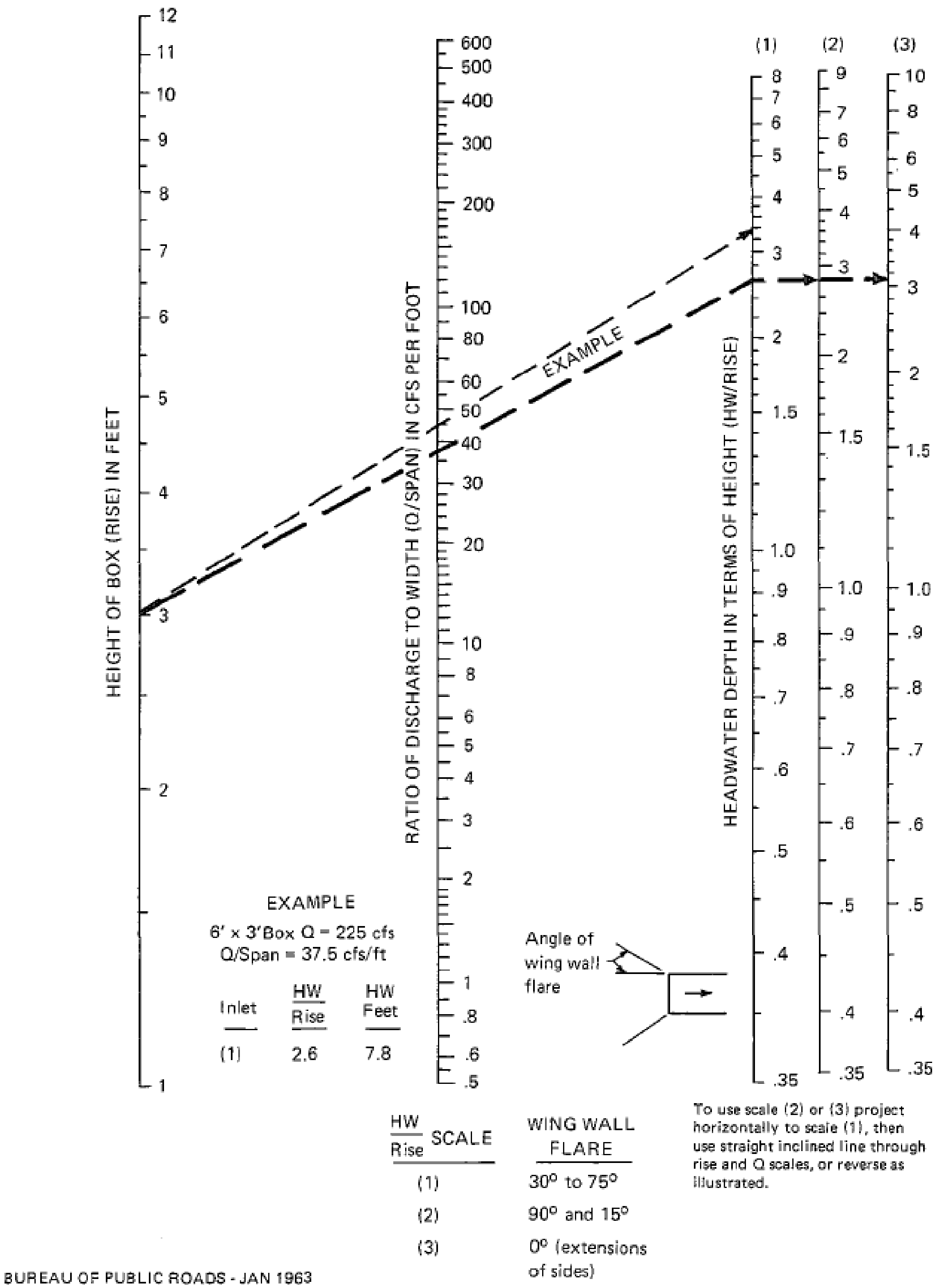


Figure 4 Head for Concrete Box Culverts Flowing Full, n = 0.012

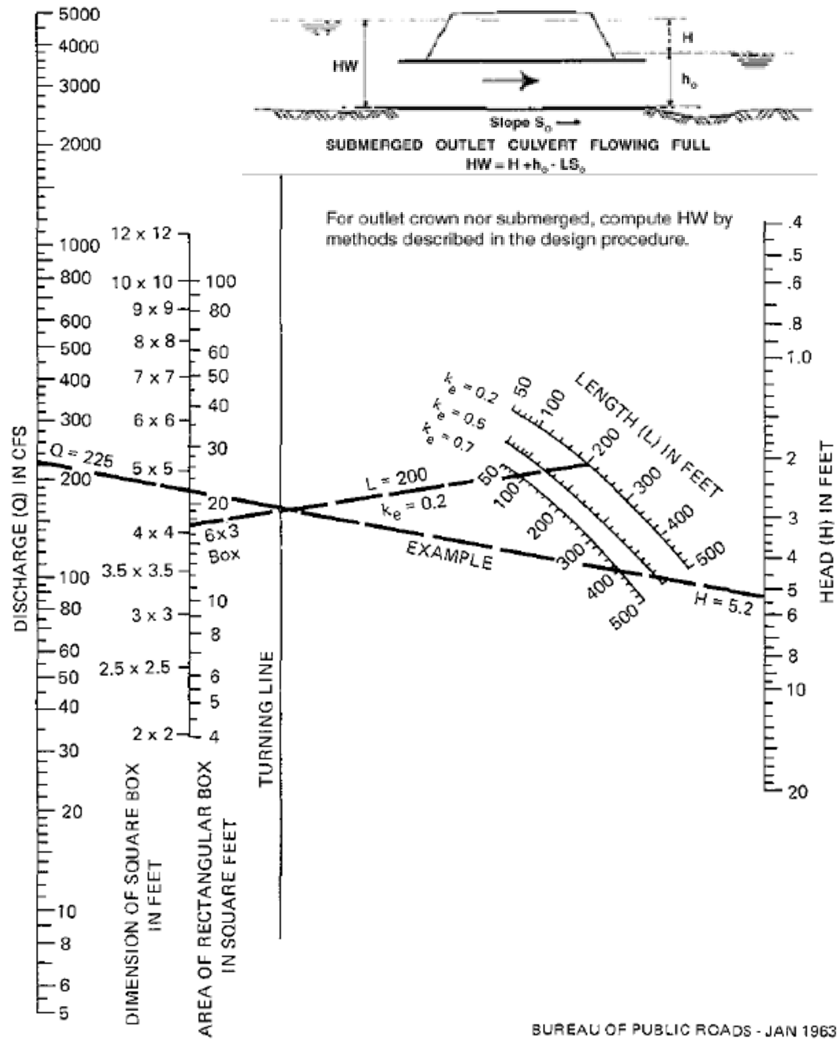
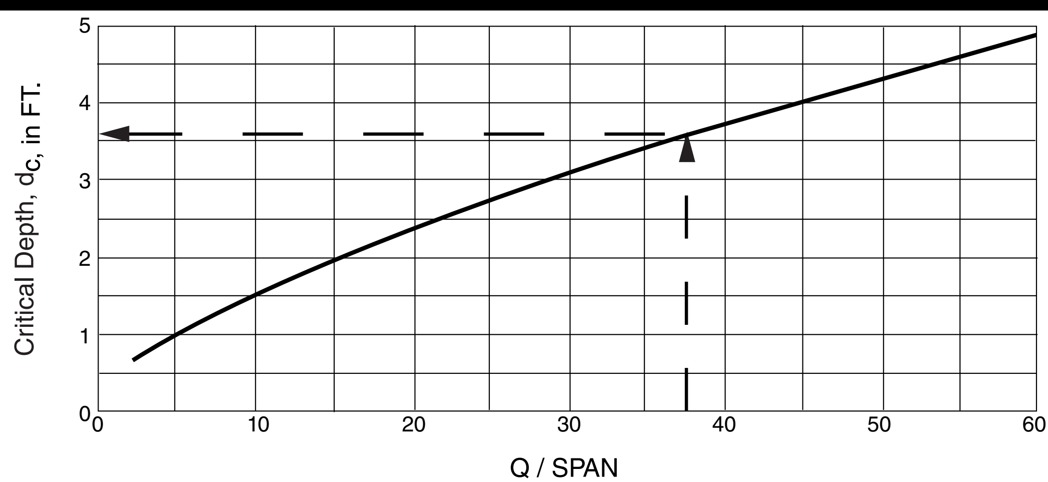
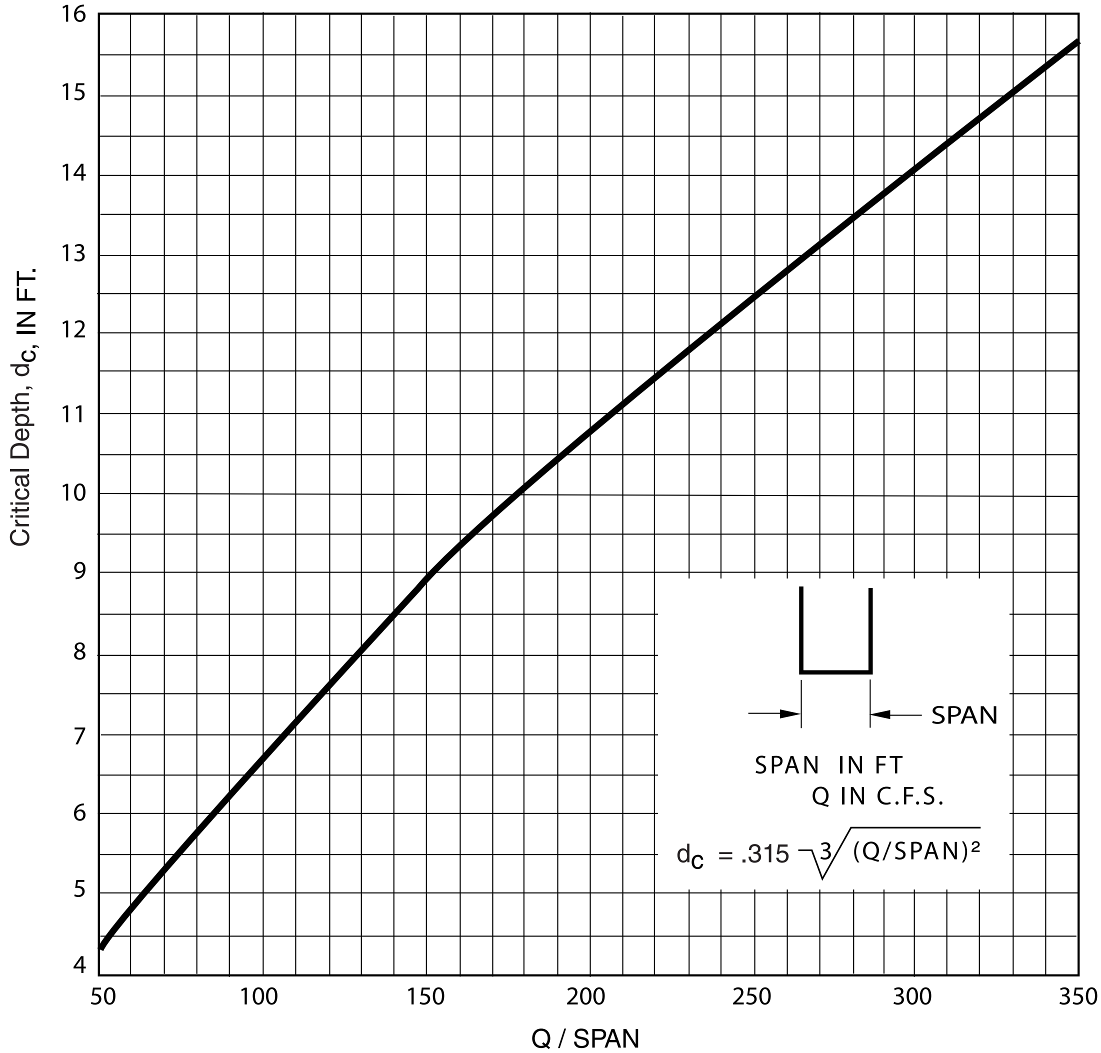


Figure 5 Critical Depth - Rectangular Section



NOTE: d_c CANNOT EXCEED RISE

Figure 6 Critical Depth - Rectangular Section



NOTE: d_C CANNOT EXCEED RISE

Figures 5 and *6* provide curves of critical depth. These curves give the depth of flow at the outlet for a given discharge when a culvert is flowing with outlet control. This depth is used in the design procedure for determining full flow conditions.

EXAMPLE 1 - Sewer Design

Given:

Maximum Predicted Flow	Q_P = 200 c.f.s.
Slope of Sewer	S = 1.0 percent
Factor of Safety for Hydraulic Design	F.S. = 1.25
Manning's Roughness Coefficient Concrete Box	n = 0.012

Find: Size of Box Required for Full Flow

Solution: Design Flow = Factor of Safety x Maximum Predicted Flow

Q_d = F.S. x Q_P
= 1.25 x 200

$= 250$ c.f.s.

From Equation (2):

$$\frac{Q}{S^{1/2}} = \frac{250}{(0.01)^{1/2}} = 2500$$

Read size of box required from *Table 3* corresponding to values of 1.486/n x A x $R^{2/3}$ equal to or larger than 2500 with n=0.012.

Answer: The following box size will carry the design flow:

Box Size Span x Rise (feet)	Value of 1.486/n x A x $R^{2/3}$
5 x 4	2663

EXAMPLE 2 - Culvert Design

Nomograph Procedure

Given: Q = 225 cubic feet per second

L = 200 feet

S_o = 0.01 feet per foot

Allowable HW = 10 feet

TW = 2.0 feet for 50-year storm

Concrete box culvert with a 30 degree flared wing wall, entrance crown edge rounded, and n = 0.012

Maximum box rise = 3 feet

Find: *Trial Culvert Headwater Depth*

Solution: Try Inlet Control

For Q = 225 cubic feet per second, Rise = 3 feet and HW/Rise = 10/3 = 3.3.

On *Figure 3*, connect Rise of 3 feet to HW/Rise of 3.3 on scale (1).

Figure 3 indicates Q/Span = 43.

Therefore Span = 225/43 = 5.2.

Assuming Span = 6 feet. Q/Span = 37.5, and *Figure 3* indicates HW/Rise = 2.6.

Therefore HW = 3 x 2.6 = 7.8 feet which is less than allowable 10.

Try Outlet Control

TW = 2.0 feet is less than Rise = 3 feet

Table 4, $k_e = 0.2$

For Rise = 3 feet, Span = 6 feet, Q = 225 cubic feet per second, $k_e = 0.2$, *Figure 4* indicates H = 5.2 feet.

Q/Span = 225/6 =37.5,

Figure 5 indicates $d_c = 3.6$ feet.

Since d_c cannot exceed Rise, h_o = Rise = 3 ft.

Therefore as shown in Figure 4, HW = H + h_o - S_oL = 5.2 + 3 - (0.01 x 200) = 6.2 feet.

Answer: Inlet Control governs with a HW = 7.8 ft.

Find: *Outlet Velocity*

Solution: Outlet velocities for culverts flowing with *inlet control* may be approximated by computing the mean velocity for the culvert cross section using Manning's equation

$$V = \frac{1.486}{n} \times R^{2/3} \times S^{1/2}$$

Since the depth of flow is not known, the use of tables or charts is recommended in solving this equation. The outlet velocity as computed by this method will usually be high because the normal depth, assumed in using Manning's equation, is seldom reached in the relatively short length of the average culvert. Also, the shape of the outlet channel, including aprons and wing walls, have much to do with changing the velocity occurring at the end of the culvert barrel. Tailwater is not considered effective in reducing outlet velocities for most inlet control conditions.

In outlet control, the average outlet velocity will be the discharge divided by the cross-sectional area of flow at the outlet. This flow area can be either that corresponding to critical depth, tail-water depth (if below the crown of the culvert) or the full cross section of the culvert barrel.

Answer: Use a 6 x 3-foot box section with an actual headwater of 7.8 feet.