Design Data 12M

American Concrete Pipe Association

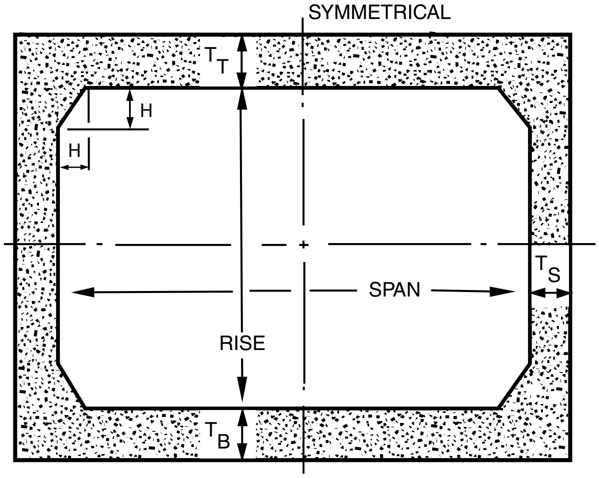
Hydraulic Capacity of Precast Concrete Boxes

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 C1433M, Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains and Sewers and Standard C1577M, 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 C1433M and C1577M 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

SPAN, Millimeters

RISE, Millimeters	900	1,200	1,500	1,800	2,100	2,400	2,700	3,000	3,300	3,600
600	■	■								
900	■	■	■	■						
1,200		■	■	■	■	■			■	■
1,500			■	■	■	■	■	■		
1,800				■	■	■	■	■	■	■
2,100					■	■	■	■		
2,400						■	■	■	■	■
2,700							■	■		
3,000								■	■	■
3,300									■	
3,600										■

Table 2 Standard Thicknesses

Span Milli-meters	T_T, millimeters		T_B, millimeters		T_S, millimeters	
	> 0.6 m cover	< 0.6 m cover	> 0.6 m cover	< 0.6 m cover	> 0.6 m cover	< 0.6 m cover
900	100	175	100	150	100	100
1,200	125	190	125	150	125	125
1,500	150	200	150	175	150	150
1,800	175	200	175	175	175	175
2,100	200	200	200	200	200	200
2,400	200	200	200	200	200	200
2,700	225	225	225	225	225	225
3,000	250	250	250	250	250	250
3,300	275	275	275	275	275	275
3,600	300	300	300	300	300	300

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:

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

Where:

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

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

Size Span x Rise (Meters)	A Area (Square Meters)	R Hydraulic Radius (Meters)	C = $^1/_n(AxR^{2/3})$*	
			n = 0.012	n = 0.013
900 x 600	0.537	0.191	15	14
900 x 900	0.815	0.238	26	24
1,200 x 600	0.712	0.212	21	19
1,200 x 900	1.083	0.273	38	35
1,200 x 1,200	1.456	0.318	56	52
1,500 x 600	0.881	0.225	27	25
1,500 x 900	1.343	0.297	50	46
1,500 x 1,200	1.808	0.352	75	69
1,500 x 1,500	2.264	0.394	101	94
1,800 x 900	1.609	0.317	62	58
1,800 x 1,200	2.169	0.382	95	88
1,800 x 1,500	2.718	0.432	129	119
1,800 x 1,800	3.286	0.476	167	154
2,100 x 900	1.864	0.332	74	69
2,100 x 1,200	2.516	0.404	115	106
2,100 x 1,500	3.155	0.461	157	145
2,100 x 1,800	3.815	0.512	203	188
2,100 x 2,100	4.454	0.553	250	231
2,400 x 900	2.148	0.345	88	81
2,400 x 1,200	2.894	0.423	136	125
2,400 x 1,500	3.626	0.487	187	173
2,400 x 1,800	4.383	0.543	243	224
2,400 x 2,100	5.115	0.590	300	277
2,400 x 2,400	5.871	0.632	360	333
2,700 x 1,200	3.238	0.438	156	144
2,700 x 1,500	4.060	0.508	215	199
2,700 x 1,800	4.909	0.570	281	260
2,700 x 2,100	5.731	0.622	348	321
2,700 x 2,400	6.581	0.669	420	387
2,700 x 2,700	7.403	0.709	491	453
3,000 x 1,200	3.590	0.452	176	163
3,000 x 1,500	4.504	0.527	245	226
3,000 x 1,800	5.449	0.595	321	296
3,000 x 2,100	6.363	0.652	398	368
3,000 x 2,400	7.308	0.704	482	445
3,000 x 2,700	8.222	0.748	565	521
3,000 x 3,000	9.161	0.790	652	602
3,300 x 1,200	3.935	0.463	196	181
3,300 x 1,500	4.941	0.543	274	253
3,300 x 1,800	5.980	0.616	361	333
3,300 x 2,100	6.986	0.677	449	414
3,300 x 2,400	8.026	0.734	544	502
3,300 x 2,700	9.032	0.783	639	590
3,300 x 3,000	10.064	0.829	740	683
3,300 x 3,300	11.087	0.869	841	777
3,600 x 1,200	4.277	0.473	216	200
3,600 x 1,500	5.374	0.557	303	280
3,600 x 1,800	6.508	0.634	400	369
3,600 x 2,100	7.605	0.700	500	461
3,600 x 2,400	8.739	0.761	607	560
3,600 x 2,700	9.837	0.814	714	660
3,600 x 3,000	10.964	0.863	828	765
3,600 x 3,300	12.079	0.908	944	871
3,600 x 3,600	13.195	0.948	1061	980

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

R = hydraulic radius in meters (equals the area of the flow divided by the wetted perimeter)
S = slope of conduit, meters of vertical drop per meter 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:

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

By evaluating the values of $1.0/n \times A \times R^{2/3}$ 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 ($1.0/n \times A \times R^{2/3}$) 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.

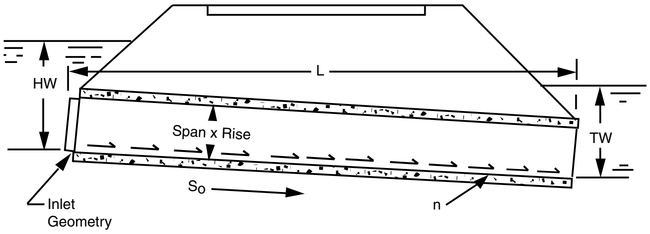
It is important to note that in sewer design, a hydraulic comparison between various shapes cannot be made solely on the basis of cross-sectional areas or peripheries. For two conduits of similar materials and different shapes to be hydraulically equivalent, it is necessary for the factor $A \times R^{2/3}$ to be the same for both. Multiplying this factor by 1.0/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 0.60 meters per second for sanitary sewers and 0.90 meters 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 = B
Rise = inside vertical height of box = D
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
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

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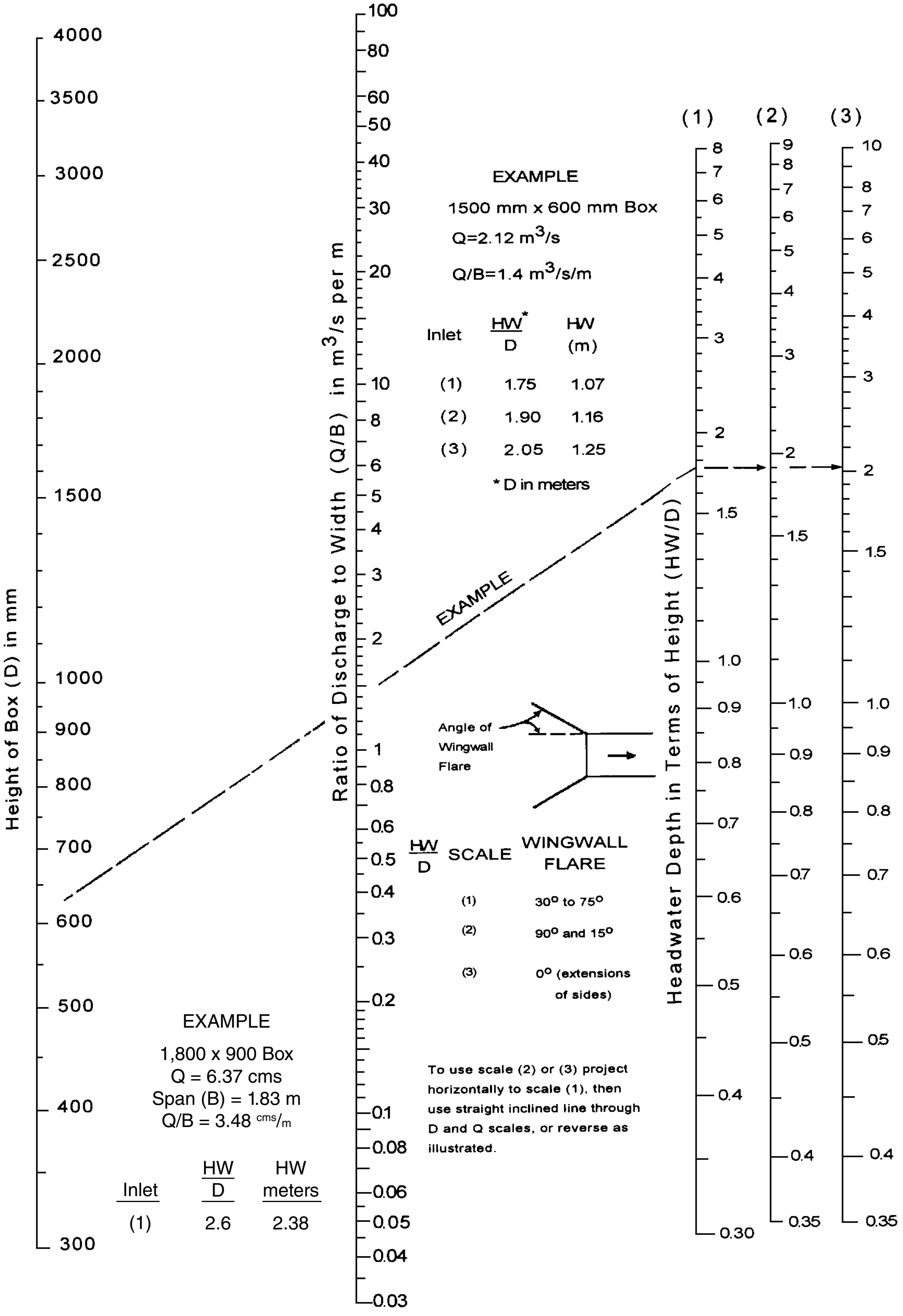
Figure 3 Headwater Depth for Concrete Box Culverts With Inlet Control



EXAMPLE

1500 mm x 600 mm Box

Q=2.12 m^3/s

Q/B=1.4 m^3/s/m

Inlet	HW* / D	HW (m)
(1)	1.75	1.07
(2)	1.90	1.16
(3)	2.05	1.25

* D in meters

HW / D SCALE	WINGWALL FLARE
(1)	30° to 75°
(2)	90° and 15°
(3)	0° (extensions of sides)

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.

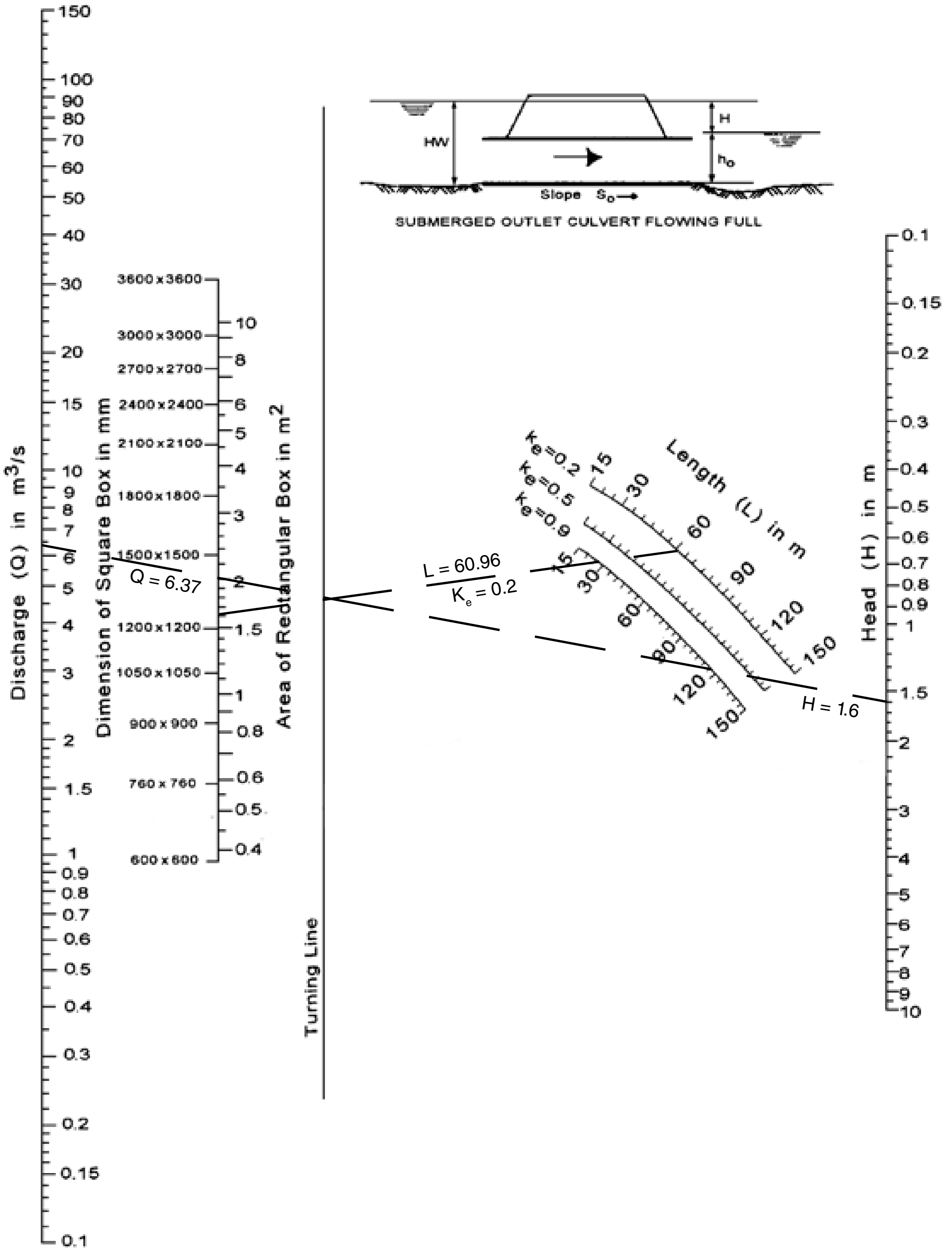
EXAMPLE

1,800 x 900 Box
Q = 6.37 cms
Span (B) = 1.83 m
Q/B = 3.48 cms/m

Inlet	HW / D	HW meters
(1)	2.6	2.38

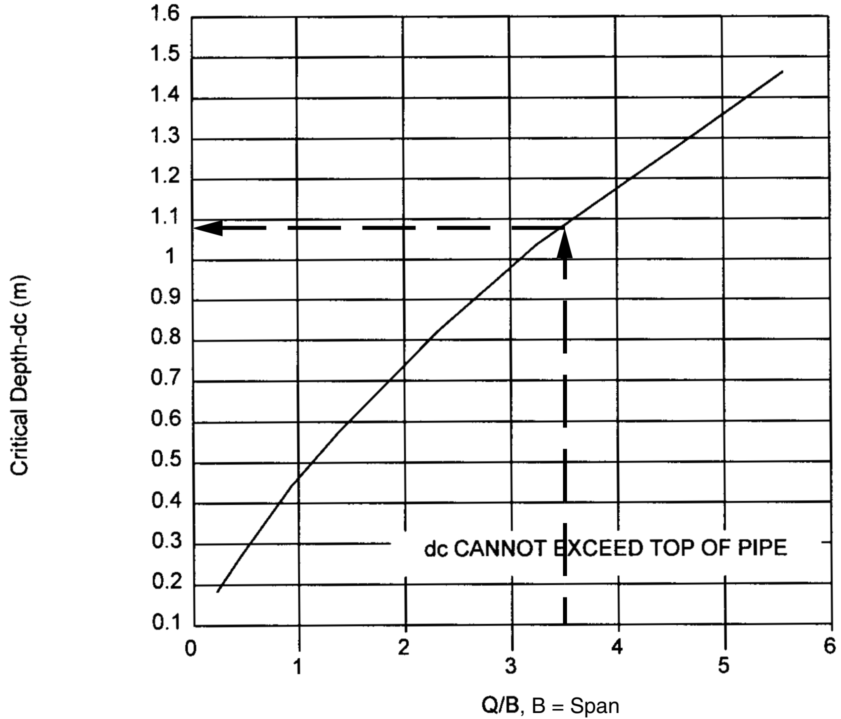
Adapted from
Bureau of Public Roads Jan. 1963

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



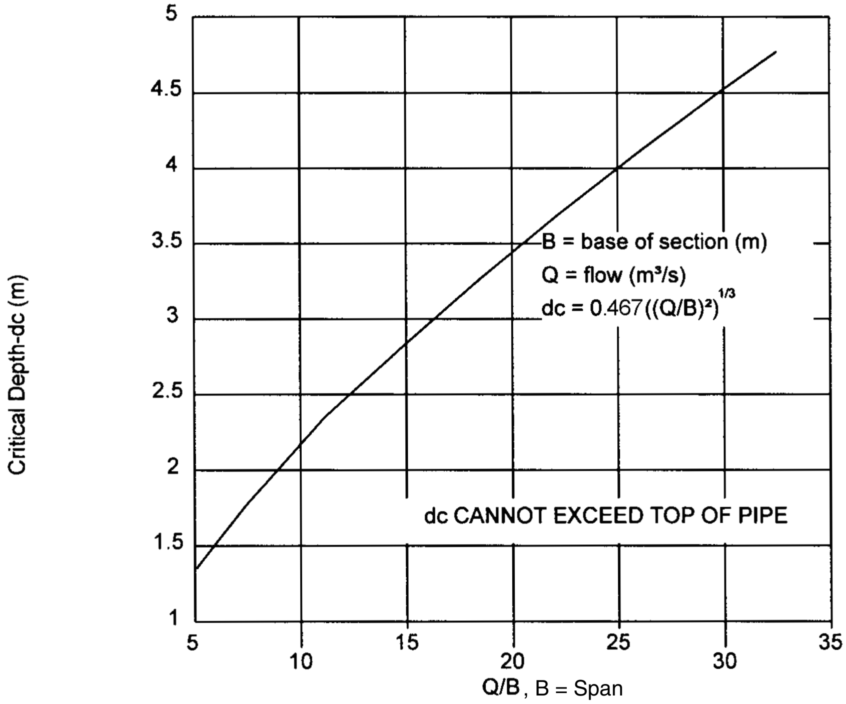
Adapted from
Burea of Public Roads Jan. 1963

Figure 5 Critical Depth - Rectangular Section



Adapted from Bureau of Public Roads

Figure 6 Critical Depth - Rectangular Section



Adapted from Bureau of Public Roads

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	$Q_P = 5.67\ m^3/sec$
	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

$$Q_d = F.S. \times Q_P$$
$$= 1.25 \times 5.67$$
$$= 7.08\ m^3/sec$$

From Equation (2):

$$\frac{Q}{S^{1/2}} = \frac{7.08}{(0.01)^{1/2}} = 70.8$$

Read size of box required from *Table 3* corresponding to values of 1/n x A x $R^{2/3}$ equal to or larger than 70.8 with n=0.012.

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

Box Size Span x Rise (meters)	Value of 1/n x A x $R^{2/3}$
1,500 x 1,200	75

EXAMPLE 2 - Culvert Design

Nomograph Procedure

Given:

$Q = 6.37\ m^3/sec$

L = 60.95 meters

$S_O = 0.01$ meters per meter

Allowable HW = 3.05 meters

TW = 0.61 meters 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 = 900 mm

Find: *Trial Culvert Headwater Depth*

Solution: Try Inlet Control

For $Q = 6.37\ m^3/sec$, Rise = 900 mm and HW/Rise = 3.05/.91 = 3.34

On *Figure 3*, connect Rise of 900 mm to HW/Rise of 3.3 on scale (1).

Figure 3 indicates Q/B = 4.0

Therefore Span = 6.37/4.0 = 1.59 m

Assuming Span = 1,800 mm Q/B = 6.37/1.83 = 3.5, and *Figure 3* indicates HW/Rise = 2.6.

Therefore HW = 0.91 x 2.6 = 2.37 meters which is less than allowable 3.05.

Try Outlet Control

TW = 0.61 m is less than Rise = 900 mm

Table 4, $k_e = 0.2$

For Rise = 900 mm, Span = 1,800 mm,

$Q = 6.37\ m^3/sec$, $k_e = 0.2$, *Figure 4* indicates

H = 1.6 meters

Q/B = 6.37/1.83 = 3.48

Figure 5 indicates $d_c = 1.09$ m

Since d_C cannot exceed Rise, h_O = Rise = 900 mm

Therefore as shown in Figure 4, $HW = H + h_O - S_O L = 1.6 + 0.91 - (0.01 \times 60.96) = 1.90$ m

Answer: Inlet Control governs with a HW = 2.37 m

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

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

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, tailwater depth (if below the crown of the culvert) or the full cross section of the culvert barrel.

Answer: Use a 1,800 x 900 mm box section with an actual headwater of 2.37 m.