TABLE OF CONTENTS - SECTION IV

SECTION IV - CULVERT HYDRAULICS

4.0 GENERAL

The function of a drainage culvert is to pass the design storm flow under a roadway or railroad without causing excessive backwater and without creating excessive downstream velocities. The designer shall keep energy losses and discharge velocities within reasonable limits when selecting a structure.

Culvert flow may be separated into two major types of flow - inlet or outlet control. Under inlet control, the cross sectional area of the barrel, the shape of the inlet and the amount of ponding (headwater) at the inlet are primary design considerations. Outlet control is dependent upon the depth of water in the outlet channel (tailwater), the slope of the barrel, type of culvert material and length of the barrel.

4.1 INLET CONTROL

The size of a culvert operating with inlet control is determined by the size and shape of the inlet and the depth of ponding allowable (headwater) between the flowline elevation of a culvert and the elevation of a finished grade surface or surrounding buildings and facilities. See Figure 4.1. Factors not effecting inlet control design are the barrel roughness, slope and length and depth of the tailwater.

The headwater (HW) depth for a culvert of a given diameter or height (D) where a discharge is given can be determined by obtaining the HW/D value from current Hydraulic Design Series #5, FHWA. A desirable maximum headwater for a culvert should not be greater than the diameter or height plus 2'. The elevation of adjacent facilities (i.e., buildings, etc.) must be reviewed for flooding.

4.2 OUTLET CONTROL

A culvert will operate under outlet control when the depth of the tailwater, the length, the slope or roughness of the culvert barrel act as the control on the quantity of water able to pass through a given culvert. See Figure 4.2. Energy head required for a culvert to operate under outlet control is comprised of velocity head (H_v), entrance loss (H_e) and friction loss (H_f). This energy head (H) is obtained from current Hydraulic Design Series #5, FHWA, and entrance loss coefficients from Table 4.1.

The headwater depth (HW) at the culvert entrance is calculated by means of the following formula:

$HW = H + h_o - LS_o$

Where: H = energy head

L = length of culvert (ft.)

S_o = slope of barrel (feet per foot)

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

d_c = critical depth of flow in the barrel.
Critical depth may be determined by using Hydraulic Design Series #5, FHWA.

D = height of pipe or box

TW = tailwater depth

The maximum desirable headwater depth for culverts operating under outlet control shall be the same as described in Section 4.1.

See Section 4.7 for detailed types of culvert flow. See Section 4.8 and Examples 1-6 for examples of culvert sizing computations. Computer generated computations and output are accepted and subject to review by City Engineer.

4.3 HEADWALLS AND ENDWALLS

4.3.1 GENERAL

The normal functions of properly designed headwalls and end walls are to anchor the culvert, to prevent movement due to the lateral pressures, to control erosion and scour resulting from excessive velocities and turbulence, and to prevent adjacent soil from sloughing into the waterway opening. Headwalls shall be constructed of reinforced concrete and may either be straight parallel headwalls, flared headwalls, or warped headwalls with or without aprons as may be required by site conditions. Multi-barrel culvert crossings of roadways at an angle of 15° or greater shall be accompanied by adequate inlet and outlet control sections.

4.3.2 CONDITIONS AT ENTRANCE

It is important to recognize that the operational characteristics of a culvert may be completely changed by the shape or condition at the inlet or entrance. Design of culverts involve consideration of energy losses that occur at the entrance. The entrance head losses may be determined by the following equation:

$$h_e = \frac{K_e \ (V_2^2 - V_1^2)}{2g}$$

h_e = entrance head loss in feet

V_2 = velocity of flow in culvert

V_1 = velocity of approach in feet per sec.

K_e = entrance loss coefficient as shown in Table 4.1.

TABLE 4.1

VALUES OF ENTRANCE LOSS COEFFICIENTS "K_e"

Type of Structure & Entrance Design	value of K_e
Box, Reinforced Concrete	
Submerged Entrance	
Parallel wing walls	0.5
Flared wing walls	0.4
Free Surface Flow	
Parallel wing walls	0.5
Flared wing walls	0.15
Pipe, Concrete	
Project from fill, socket end	0.2
Project from fill, square cut end	0.5
Headwall or headwall & wingwalls	
Socket end of pipe	0.2
Square – edge	0.5
End - Section conforming to fill slope	0.5
Pipe, or Pipe-Arch, Corrugated Metal	
Projecting from fill (No headwall)	0.9
Headwall or headwall and wingwalls	
Square – Edge	0.5
End - Section conforming to fill	0.5

4.3.3 SELECTION OF HEADWALL OR ENDWALL

In general, the following guidelines should be used in the selection of the type of headwalls or endwalls.

<u>Straight/Parallel Headwalls and Endwalls</u>

(1) Approach velocities are low (below 6 feet per sec.).

(2) Backwater pools may be permitted.

(3) Approach channel is undefined.

(4) Ample right-of-way or easement is available.

(5) Downstream channel protection is not required.

<u>Flared Headwall and Endwall:</u>

(1) Channel is well defined.

(2) Approach velocities are between 6 and 10 feet per second.

(3) Medium amounts of debris exists.

The wings of flared walls should be located with respect to the direction of the approaching flow instead of the culvert axis.

<u>Warped Headwall and Endwall:</u>

(1) Channel is well defined and concrete lined.

(2) Approach velocities are between 8 and 20 feet per second.

(3) Medium amounts of debris exists.

These headwalls are effective with drop down aprons to accelerate flow through the culvert, and are effective for transitioning flow from closed conduit flow to open channel flow. This type of headwall should be used only where the drainage structure is large and right-of-way or easement is limited.

4.4 CULVERT DISCHARGE VELOCITIES

The velocity of discharge from culverts should be limited as shown in Table 4.2. Consideration must be given to the effect of high velocities, eddies, or other turbulence on the natural channel, downstream property, and roadway embankment.

Table 4.2
Culvert Discharge - Velocity Limitations

Downstream Condition	Maximum Allowable Discharge Velocity (FPS)
Bare Earth (Only when adjacent to undeveloped areas)	2 FPS
Sodded Earth	5 FPS
Paved or Riprap Apron	15 FPS
Rock	15 FPS
Other	(as approved by City Engineer)

4.4.1 Energy Dissipators

Energy dissipators are used to dissipate excessive kinetic energy in flowing water that could promote erosion. An effective energy dissipator must be able to retard the flow of fast moving water without damage to the structure or to the channel below the structure.

Impact-type energy dissipators direct the water into an obstruction that diverts the flow in many directions and in this manner dissipates the energy in the flow. Baffled outlets and baffled aprons are two (2) impact-type energy dissipators.

Other energy dissipators use the hydraulic jump to dissipate the excess head. In this type of structure, water flowing at a higher than critical velocity is forced into a hydraulic jump, and energy is dissipated in the resulting turbulence. Stilling basins are this type of dissipator, where energy is diffused as flow plunges into a pool of water.

Generally, the impact-type of energy dissipator is considered to be more efficient than the hydraulic jump-type. Also the impact-type energy dissipator results in smaller and more economical structures.

The design of energy dissipators is based on the empirical data resulting from a comprehensive series of model structure studies by the U.S. Bureau of Reclamation, as detailed in its book Hydraulic Design of Stilling Basins and Energy Dissipators.

4.5 CULVERT TYPES AND SIZES

The permissible types of culverts under all roadways and embankments are reinforced concrete box, round, or elliptical concrete pipe or pipe arch.

The minimum size of pipe for all culverts shall be 18" or the equivalent sized elliptical pipe or arch pipe. Box culverts may be constructed in sizes equal to or larger than 3' x 2' (width versus height), except as approved by the City Engineer.

If material other than reinforced concrete pipe is to be used, it shall be approved by the City Engineer.

Flared, precast concrete and metal pipe aprons may be used in lieu of headwalls to improve the hydraulic capabilities of the culverts. Plastic and HDPE end sections are prohibited.

4.6 FILL HEIGHTS AND BEDDING

The minimum cover over any culvert or box culvert shall be 18", or a minimum of 6" from the bottom of the pavement subgrade, unless approved by City Engineer. Minimum cover less than these values shall be fully justified in writing and approved by the City Engineer prior to proceeding with final plans. Maximum fill heights shall be based on pipe manufacturer's recommendations. Bedding descriptions are shown on Figures 4.17 and 4.18. Box culverts shall be structurally designed to accommodate earth and live load to be imposed upon the culvert. Refer to the Arkansas Highway and Transportation Departments Standard Plans for Typical Box Culvert Designs. When installed within public right-of-ways, all culverts shall be capable of withstanding minimum H-20 loading.

Where culverts under railroad facilities are necessary, the designer shall obtain approval from the affected railroad.

4.7 TYPES OF CULVERT FLOW

Type I	Flow Part Full with Outlet Control and Tailwater Depth Below Critical Depth. (Figure 4.3)
Type II	Flowing Part Full with Outlet Control and Tailwater Depth Above Critical Depth. (Figure 4.4)
Type III	Flowing Part Full with Inlet Control. (Figure 4.5)
Type IVA	Flowing Full with Submerged Outlet. (Figure 4.6)
Type IVB	Flowing Full with Partially Submerged Outlet. (Figure 4.7)

4.8 CULVERT DESIGN PROCEDURE:

Computer generated computations and output are accepted and subject to review by City Engineer.

STEP 1 - SELECTING CULVERT SIZE:

The computations involved in selecting the smallest feasible barrel which can be used without exceeding the design headwater elevation is summarized in the tabulation sheet, titled "Culvert Computations", Table 4.3.

INITIAL DATA:

Enter initial data and complete required information for first approximation. The square feet of opening for the initial trial size may be estimated by the ratio of design discharge divided by 10.

TAILWATER:

The tailwater depth is influenced by conditions downstream of the culvert outlet. If the culvert outlet is located near the inlet of a downstream culvert, then the headwater elevation of the downstream culvert may define the tailwater depth for the upstream culvert. If the culvert outlet is operating in a free outfall condition then the tailwater is taken as 0.0.

If the culvert discharges into an open channel, then tailwater conditions should be determined by either backwater conditions, normal depth (subcritical flow) or critical depth (supercritical flow). Figure 9.1, provides a graphical solution for normal depth of flow which may be calculated by Mannings Formula:

$$Q = \frac{1.486}{n} AR^{2/3} S^{1/2}$$

In any case, the tailwater depth is defined as the depth of water measured from the flow line of the culvert (invert) at the outlet to the water surface elevation at the outlet.

Enter tailwater depth in Column 8 and applicable stream data in upper left hand portion of Culvert Computation Form.

STEP 2 - PERFORM OUTLET CONTROL CALCULATIONS (TABLE 4.3):

These calculations are performed before inlet control calculations in order to select the smallest feasible barrel, which can be used without the required headwater elevation in outlet control exceeding the allowable headwater elevation.

Column 1: Enter the span times height dimensions (or diameter of pipe) of culvert.

Column 2: Enter the type of structure and design of entrance.

Column 3: Enter the design discharge or quotient of design discharge divided by the applicable denominator.

Column 4: Enter the Entrance Loss Coefficient from Table 4.1.

Column 5: Enter the head from the applicable outlet control nomograph, in the example problem use Figure 4.11.

Column 6: Enter the critical depth from appropriate nomograph, in the example problem use Figure 4.8. Critical depth cannot exceed height of culvert opening.

Column 7: For tailwater elevations less than the top of the culvert at the outlet, hydraulic grade line is found by solving for h_o using the following equation:

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

where:

h_o = vertical distance in feet from culvert invert at outlet to the hydraulic grade line in feet

d_c = critical depth in feet

D = height of culvert opening in feet

Column 8: Enter the tailwater elevation from initial data shown at top of form. Refer to tailwater comments under STEP 1 for additional guidelines.

Column 9: Enter the product of culvert length times the slope.

Column 10: Headwater elevation required for culvert to pass flow in outlet control (HW_o) is computed by the following equation:

$$HW_o = H + h_o - LS$$

Note: Use TW elevation in lieu of h_o where $TW > h_o$

Additional trials may be required. Space for additional trials is provided on Culvert Computations Form.

STEP 3 - PERFORM INLET CONTROL CALCULATIONS FOR CONVENTIONAL AND BEVELED EDGE CULVERT:

After minimum barrel size has been determined under STEP 2, the next procedure is similar to that used in FHWA's Hydraulic Design Series #5, "Hydraulic Design of Highway Culverts".

The computations involved in computing inlet headwater elevation is summarized in the tabulation sheet used in STEP 2, titled "Culvert Computations", Table 4.3.

Column 11: Enter ratio of headwater to height of structure from Figure 4.10.

Column 12: HW is derived by multiplying Column 11 by the height (or diameter) of culvert.

Column 13: Enter greater of two headwaters (Column 10 or 12).

Column 14: Inlet control governs, outlet velocity equals Q/A, where A is defined by the cross-sectional area of normal depth of flow in the culvert barrel. Figures 4.9 and 4.13 provide a graphical solution for estimating normal depth of flow and velocity. Manning's Formula may also be used:

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

If outlet control governs, outlet velocity equals Q/A, where A is the cross-sectional area of flow in the culvert barrel at the outlet.

Column 15: Figures shown in this column are believed to be self-explanatory.

IMPROVED INLETS:

A. See Arkansas Highway and Transportation Department's Manual for improved inlet or side tapered inlet design.

FORM HYD 4-1

CULVERT COMPUTATIONS
(SQUARE AND BEVELED EDGES)

PROJECT: ____________

DESIGNER: ____________

DATE: ____________

HYDROLOGIC AND CHANNEL INFORMATION

HYDROLOGY

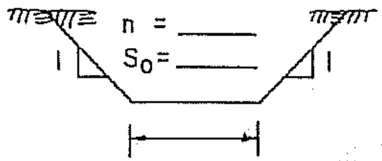
Q_1 ______ = ______ cfs

Q_2 ______ = ______ cfs

STREAM DATA

Tw_1 = ______

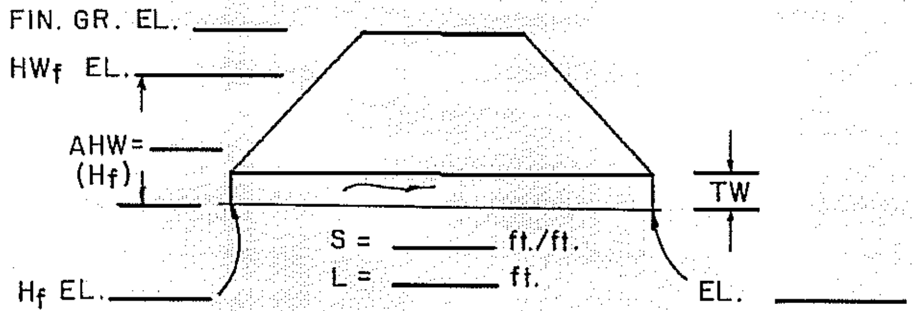
Tw_2 = ______



OUTLET CHANNEL
(APPROX. DIMENSIONS)

SKETCH

STATION: ______



TRIAL NO.	SIZE	STRUCTURE TYPE & ENTRANCE DESIGN	Q / Q/NB / $\frac{Q}{NBD^{3/2}}$	HEADWATER COMPUTATION — OUTLET CONTROL: (a) K_e	H	(b) d_c	(c) h_o	(d) TW	LS	(e) HW_o	INLET CONT.: $\frac{HW}{D}$ (f)	HW	CONTROL-LING HW	OUTLET VELOCITY ft./sec.	COST	COMMENTS
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

(a) Entrance loss coefficient, Refer to Table **4.1**, page **IV-4**
(b) "d_c" cannot exceed D.
(c) $h_o = \frac{d_c + D}{2}$ or TW, whichever is larger.
(d) TW = d_n in natural channel, or other downstream control.
(e) $HW_o = H + H_o - LS$
(f) **Use Inlet control nomographs.**

Table 4.3

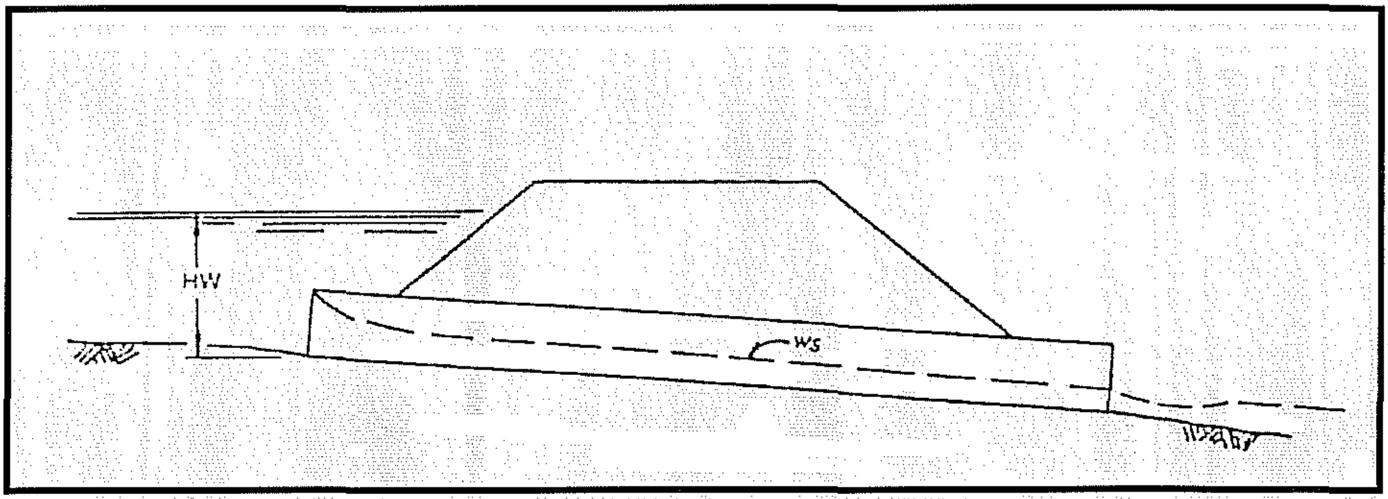
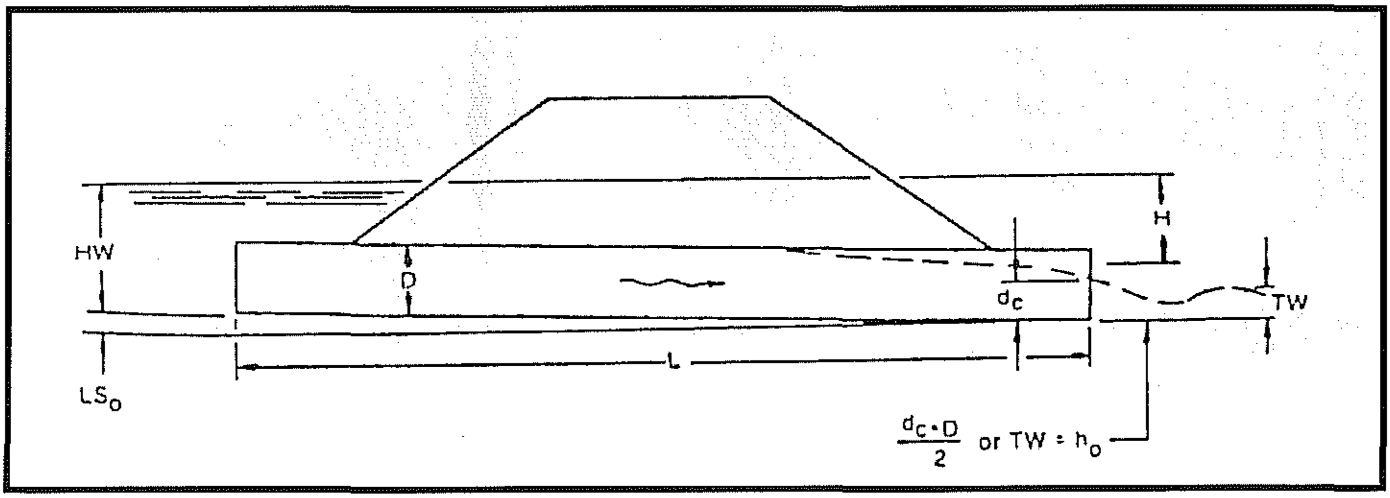


Figure 4.1

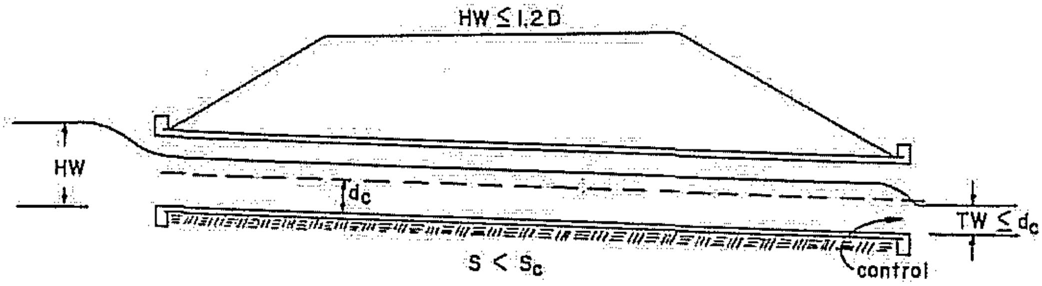
INLET CONTROL



OUTLET CONTROL

Figure 4.2

Type I
Culvert Flowing Part Full
With Outlet Control and Tailwater Depth
Below Critical Depth



Conditions

The entrance is unsubmerged (HW$\leq$ 1.2D), the slope at design discharge is sub-critical (S_o<S_c), and the tailwater is below critical depth (TW$\leq$ d_c).

The above condition is a common occurrence where the natural channels are on flat grades and have wide, flat flood plains. The control is critical depth at the outlet.

In culvert design, it is generally considered that the headwater pool maintains a constant level during the design storm. If this level does not submerge the culvert inlet, the culvert flows part full.

If critical flow occurs at the outlet the culvert is said to have "Outlet Control". A culvert flowing part full with outlet control will require a depth of flow in the barrel of the culvert greater than critical depth while passing through critical depth at the outlet.

The capacity of a culvert flowing part full with outlet control and tailwater depth below critical depth shall be governed by the following equation when the approach velocity is considered zero.

$$HW = d_c + \frac{V_c^2}{2g} + h_e + h_f - S_oL$$

HW = Headwater depth above the invert of the upstream end of the culvert in feet. Headwater must be equal to or less than 1.2D or entrance is submerged and Type IV operation will result.

d_c = Critical depth of flow in feet = $\sqrt[3]{\frac{q^2}{32.2}}$

D = Diameter of pipe or height of box.

q = Discharge in cfs per foot.

V_c = Critical Velocity in feet per second occurring at critical depth.

h_e = Entrance head loss in feet.

$$h_e = Ke\left(\frac{Vc^2}{2g}\right)$$

K_e = Entrance loss coefficient

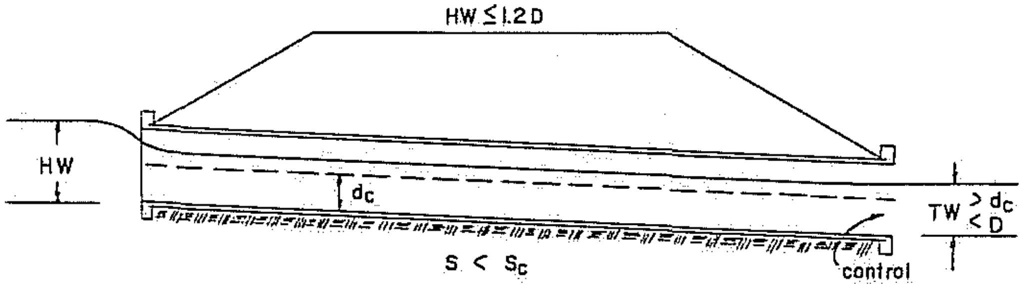
h_f = Friction head loss in feet = S_fL.

S_f = Friction slope or slope that will produce uniform flow. For Type I operation the friction slope is based upon $1.1d_c$

S_o = Slope of culvert in feet per foot.

L = Length of culvert in feet.

Type II
Culvert Flowing Part Full
With Outlet Control and Tailwater Depth
Above Critical Depth



Conditions

The entrance is unsubmerged ($HW \leq 1.2D$), the slope at design discharge is subcritical ($S_o < S_c$), and the tailwater is above critical depth ($TW > d_c$).

The above condition is a common occurrence where the channel is deep, narrow and well defined.

If the headwater pool elevation does not submerge the culvert inlet, the slope at the design discharge is subcritical, and the tailwater depth is above critical depth the control is said to occur at the outlet; and the capacity of the culvert shall be governed by the following equation when the approach velocity is considered zero.

$$HW = TW + \frac{V_{TW}^2}{2g} + h_e + h_f - S_o L$$

HW = Headwater depth above the invert of the upstream end of the culvert in feet. Headwater depth must be equal to or less than 1.2D or entrance is submerged and Type IV operation will result.

TW = Tailwater depth above the invert of the downstream end of the culvert.

V_{TW} = Culvert discharge velocity in feet per second at tailwater depth.

h_e = Entrance head loss in feet.

$$h_e = K_e \frac{V_{TW}^2}{2g}$$

K_e = Entrance loss coefficient.

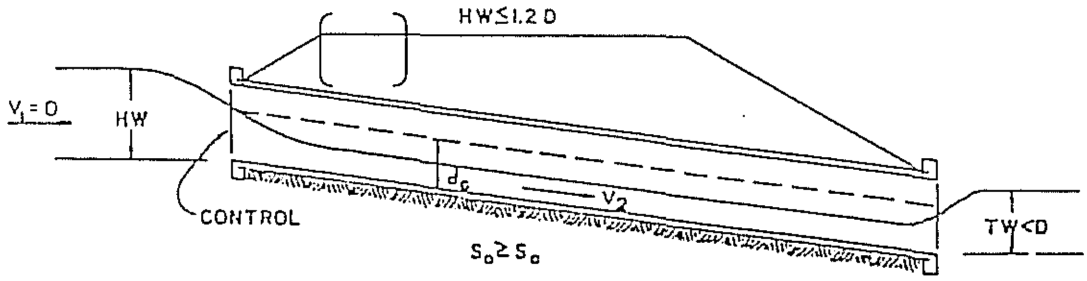
h_f = Friction head loss in feet = $S_f L$.

S_f = Friction slope or slope that will produce uniform flow. For Type II operation the friction slope is based upon TW depth.

S_o = Slope of culvert in feet per foot.

L = Length of culvert in feet.

Type III
Culvert Flowing Part Full With Inlet Control



Conditions

The entrance is unsubmerged ($HW \leq 1.2D$) and the slope at design discharge is equal to or greater than critical (Supercritical) ($S_o \geq S_c$).

This condition is a common occurrence for culverts in rolling or mountainous country where the flow does not submerge the entrance. The control is critical depth at the entrance.

If critical flow occurs near the inlet, the culvert is said to have "Inlet Control". The maximum discharge through a culvert flowing part full occurs when flow is at critical depth for a given energy head. To assure that flow passes through critical depth near the inlet, the culvert must be laid on a slope equal to or greater than critical slope for the design discharge. Placing culverts which are to flow part full on slopes greater than critical slope will increase the outlet velocities but will not increase the discharge. The discharge is limited by the section near the inlet at which critical flow occurs.

The capacity of a culvert flowing part full with control at the inlet shall be governed by the following equation when the approach velocity is considered zero.

$$HW = d_c + \frac{V_2^2}{2g} + K_e \frac{V_2^2}{2g}$$

HW = Headwater depth above the invert of the upstream end of the culvert in feet. Headwater depth must be equal to or less than 1.2D or entrance is submerged and Type IV operation will result.

d_c = Critical depth of flow in feet = $\sqrt[3]{\frac{q^2}{32.2}}$

q = Discharge in cfs per foot.

V_2 = Velocity of flow in the culvert in feet per second.

The velocity of flow varies from critical velocity at the entrance to uniform velocity at the outlet provided the culvert is sufficiently long. Therefore, the outlet velocity is the discharge divided by the area of flow in the culvert.

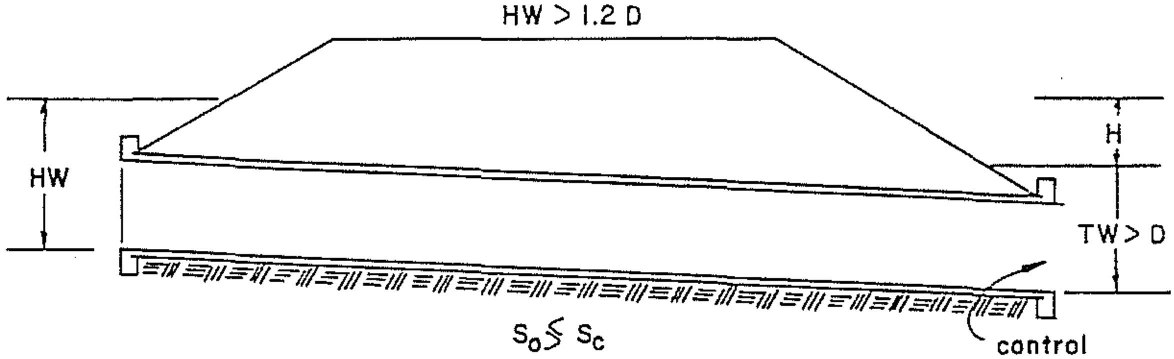
K_e = Entrance loss coefficient.

TYPES OF CULVERT FLOW – TYPE III

SOURCE: City of Austin, TX

Figure 4.5

Type IV-A
Culvert Flowing Full With Submerged Outlet



Conditions
(Submerged Outlet)

The entrance is submerged (HW>1.2D). The tailwater completely submerges the outlets.

Most culverts flow with free outlet, but depending on topography, a tailwater pool of a depth sufficient to submerge the outlet may form at some installation. Generally, these will be considered at the outlet. For an outlet to be submerged, the depth at the outlet must be equal to or greater than the diameter of pipe of height of box. The capacity of a culvert flowing full with a submerged outlet shall be governed by the following equation when the approach velocity is considered zero. Outlet Velocity is based on full flow at the outlet.

$$HW = H + TW - S_oL$$

HW = Headwater depth above the invert of the upstream end of the culvert. Headwater depth must be greater than 1.2D for entrance to be submerged.

H = Head for culvert flowing full.

TW = Tailwater depth in feet.

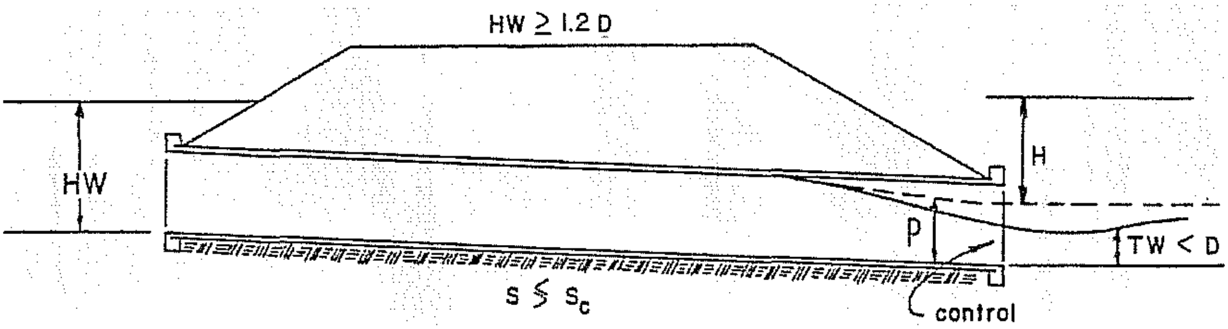
S_o = Slope of culvert in feet per foot.

L = Length of culvert in feet.

TYPES OF CULVERT FLOW – TYPE IV-A

SOURCE: City of Austin, TX

Type IV-B
Culvert Flowing Full With Partially Submerged Outlet



Conditions
(Partially Submerged Outlet)

The entrance is submerged (HW>1.2D). The tailwater depth is less than D (TW<D).

The capacity of a culvert flowing full with a partially submerged outlet shall be governed by the following equation when the approach velocity is considered zero. Outlet velocity is based on critical depth if TW depth is less than critical depth. If TW depth is greater than critical depth, outlet velocity is based on TW depth.

$HW = H + P - S_o L$

HW = Headwater depth above the invert of the upstream end of the culvert. Headwater depth must be greater than 1.2D for entrance to be submerged.

H = Head for culvert flowing full.

P = Pressure line height = $\frac{d_c + D}{2}$

d_c = Critical depth in feet.

D = Diameter or height of structure in feet.

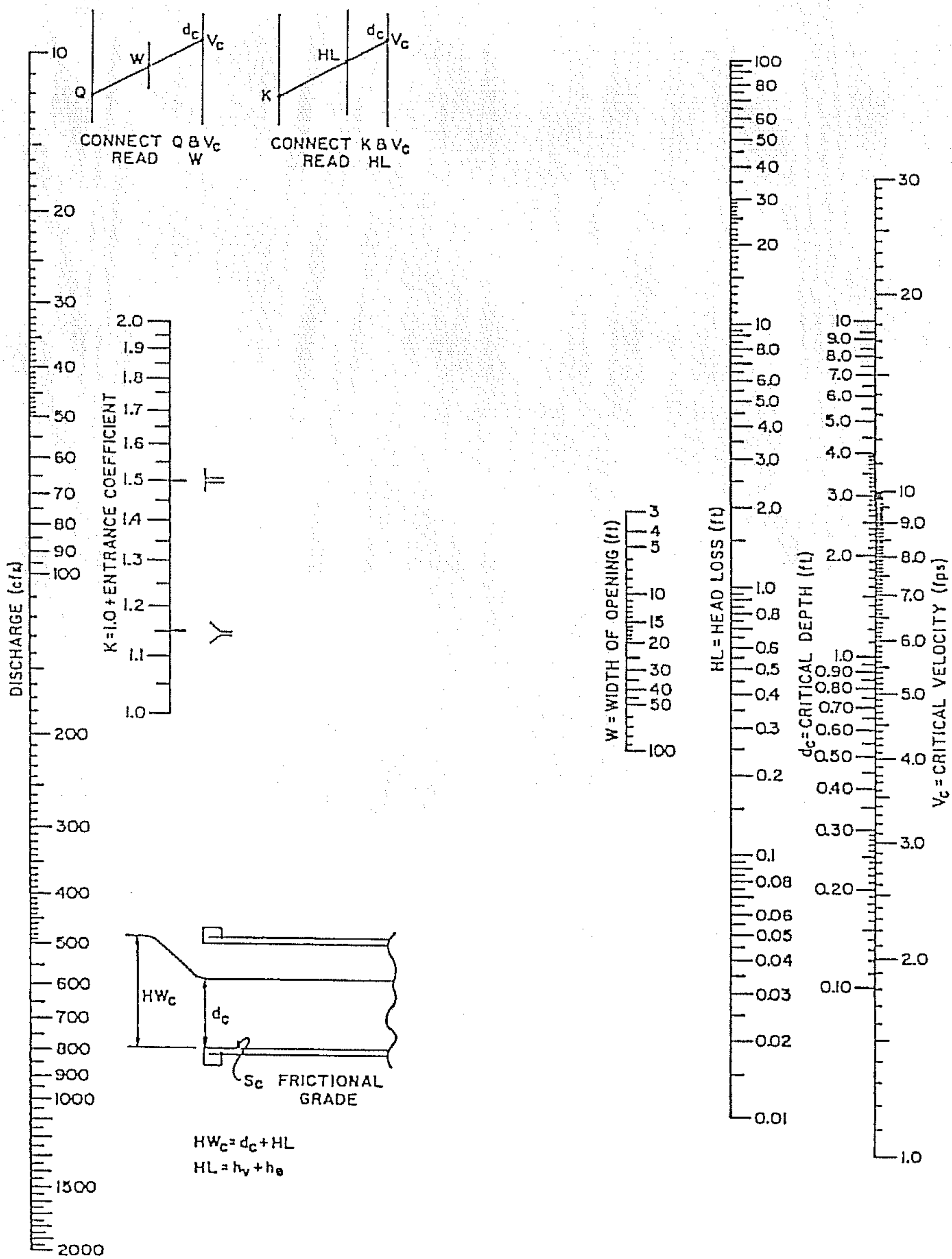
S_o = Slope of culvert in feet per foot.

L = Length of culvert in feet.

TYPES OF CULVERT FLOW - TYPE IV-B

SOURCE: City of Austin, TX

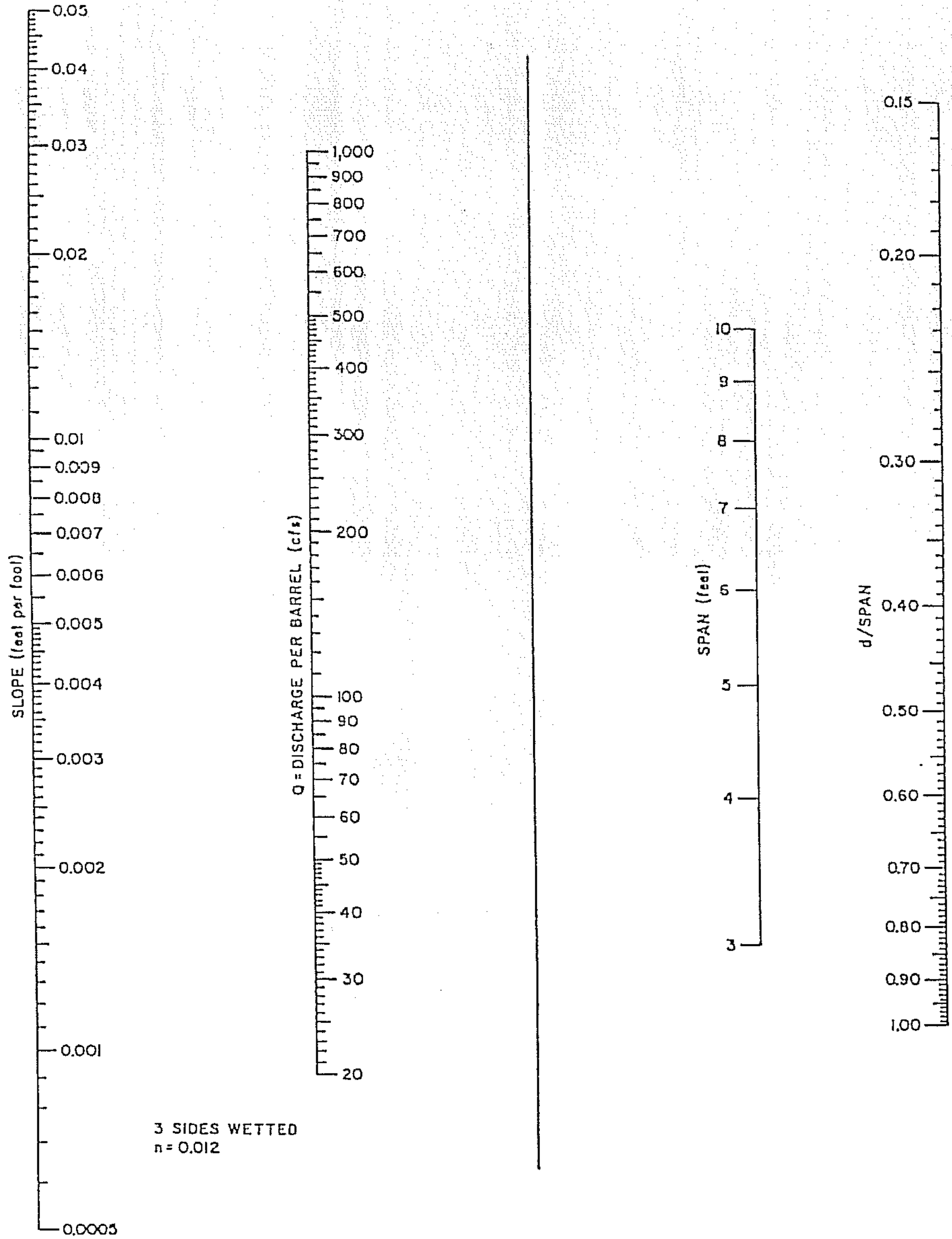
Figure 4.7



CRITICAL FLOW FOR BOX CULVERTS

SOURCE: Texas Highway Department

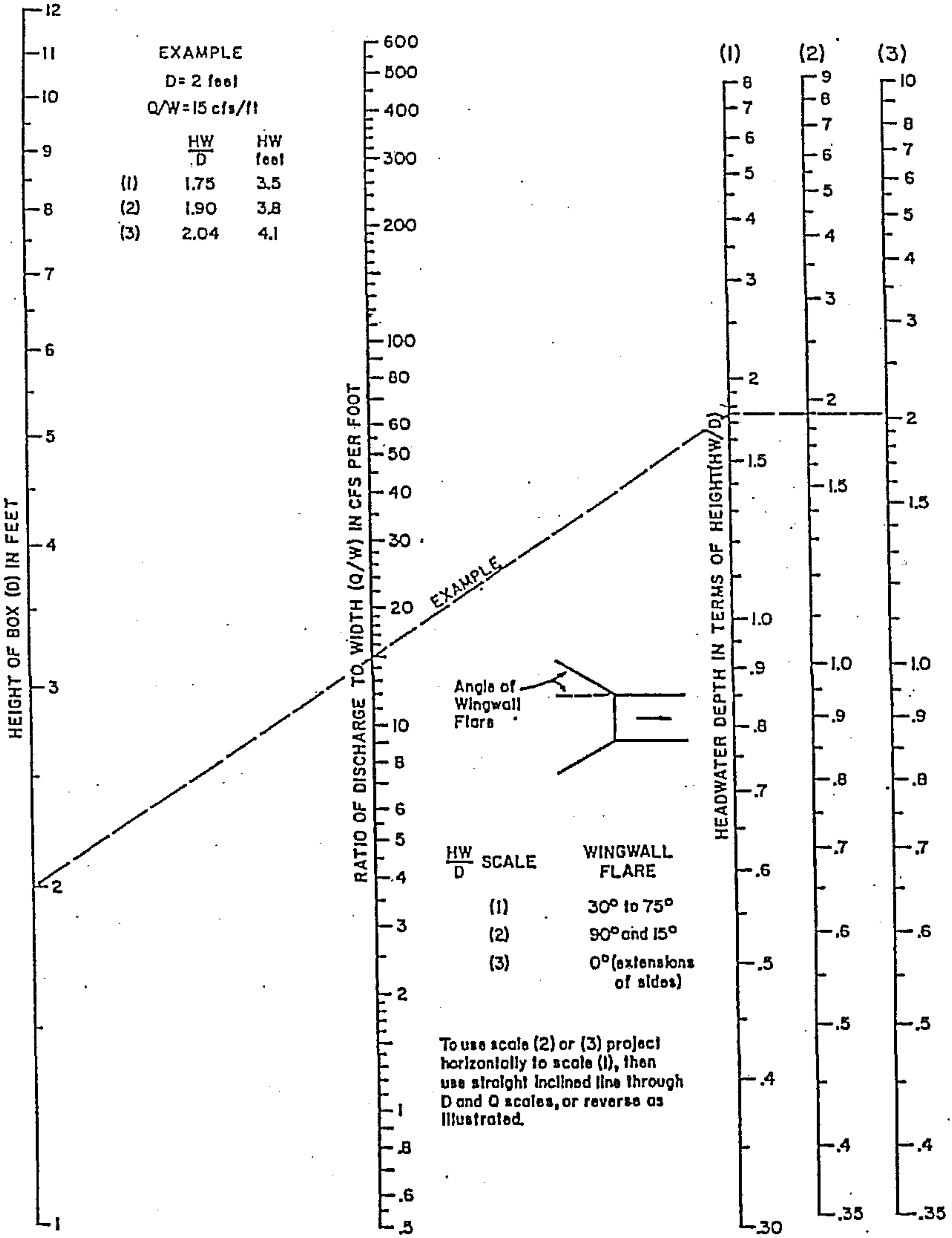
Figure 4.8



UNIFORM FLOW FOR BOX CULVERTS

SOURCE: Texas Highway Department

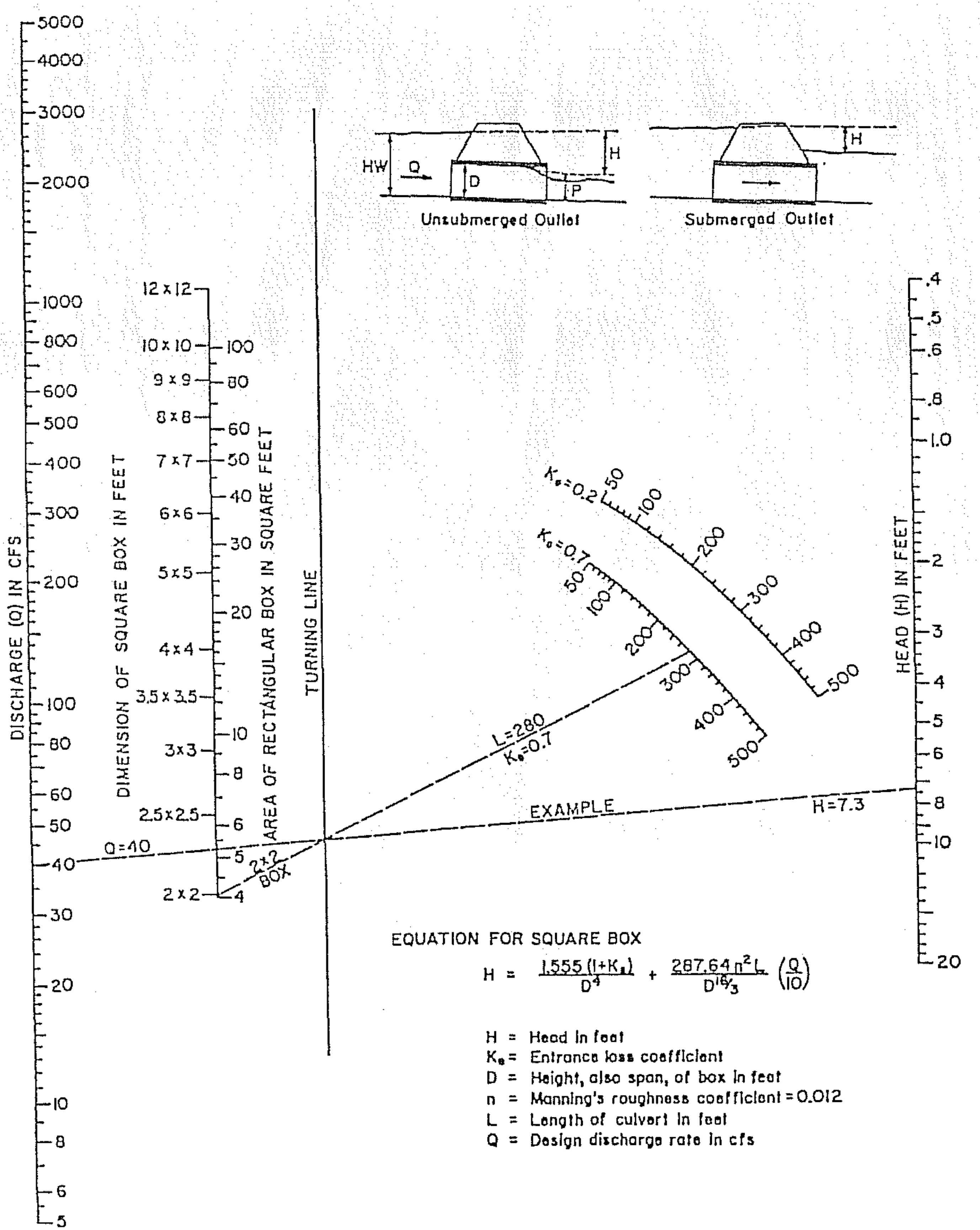
Figure 4.9



HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

SOURCE: Texas Highway Department

Figure 4.10



EQUATION FOR SQUARE BOX

$$H = \frac{1.555(1+K_e)}{D^4} + \frac{287.64\,n^2 L}{D^{16/3}}\left(\frac{Q}{10}\right)$$

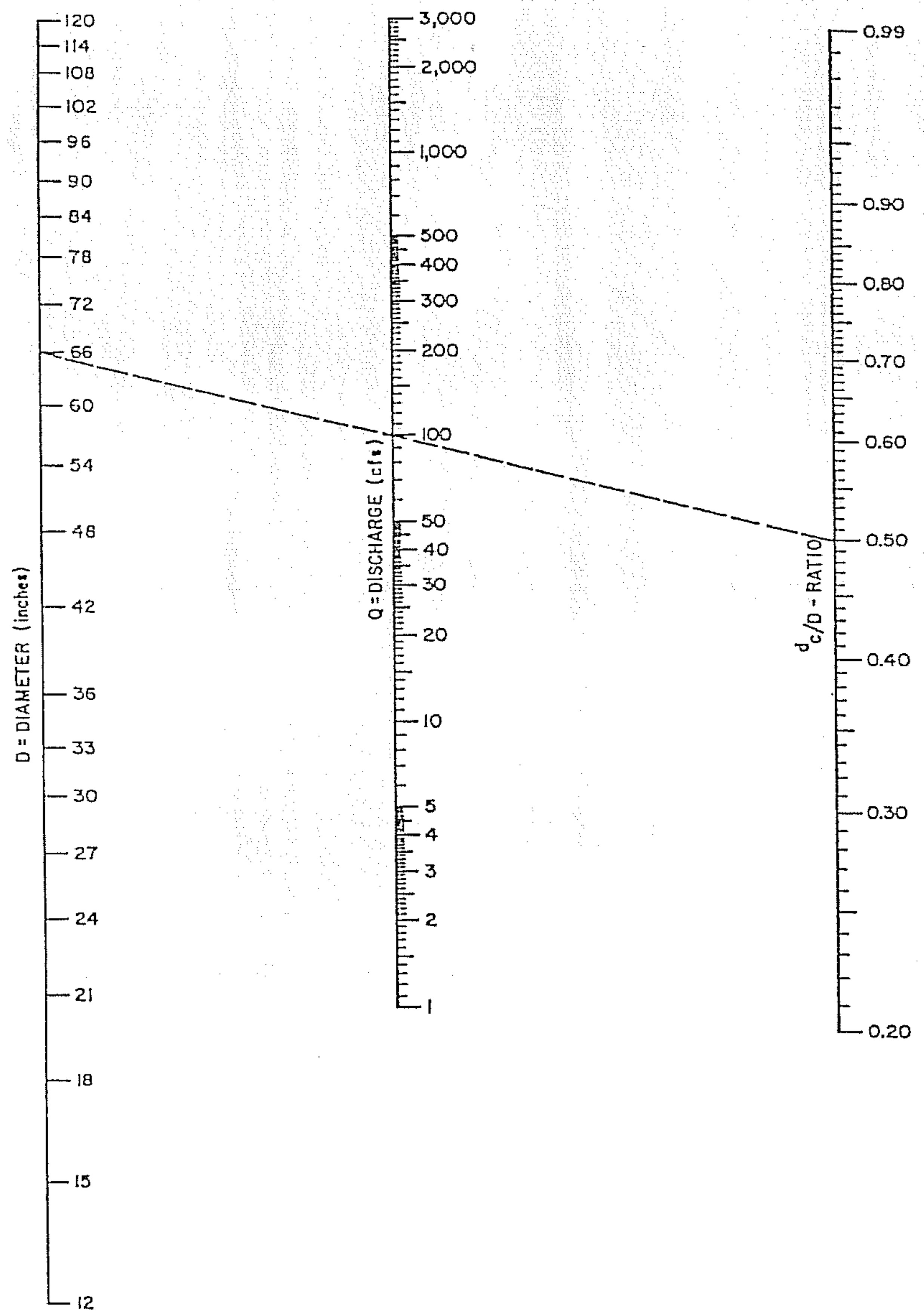
H = Head in feet
K_e = Entrance loss coefficient
D = Height, also span, of box in feet
n = Manning's roughness coefficient = 0.012
L = Length of culvert in feet
Q = Design discharge rate in cfs

n = 0.012

HEAD FOR CONCRETE BOX
CULVERTS FLOWING FULL

SOURCE: Texas Highway Department

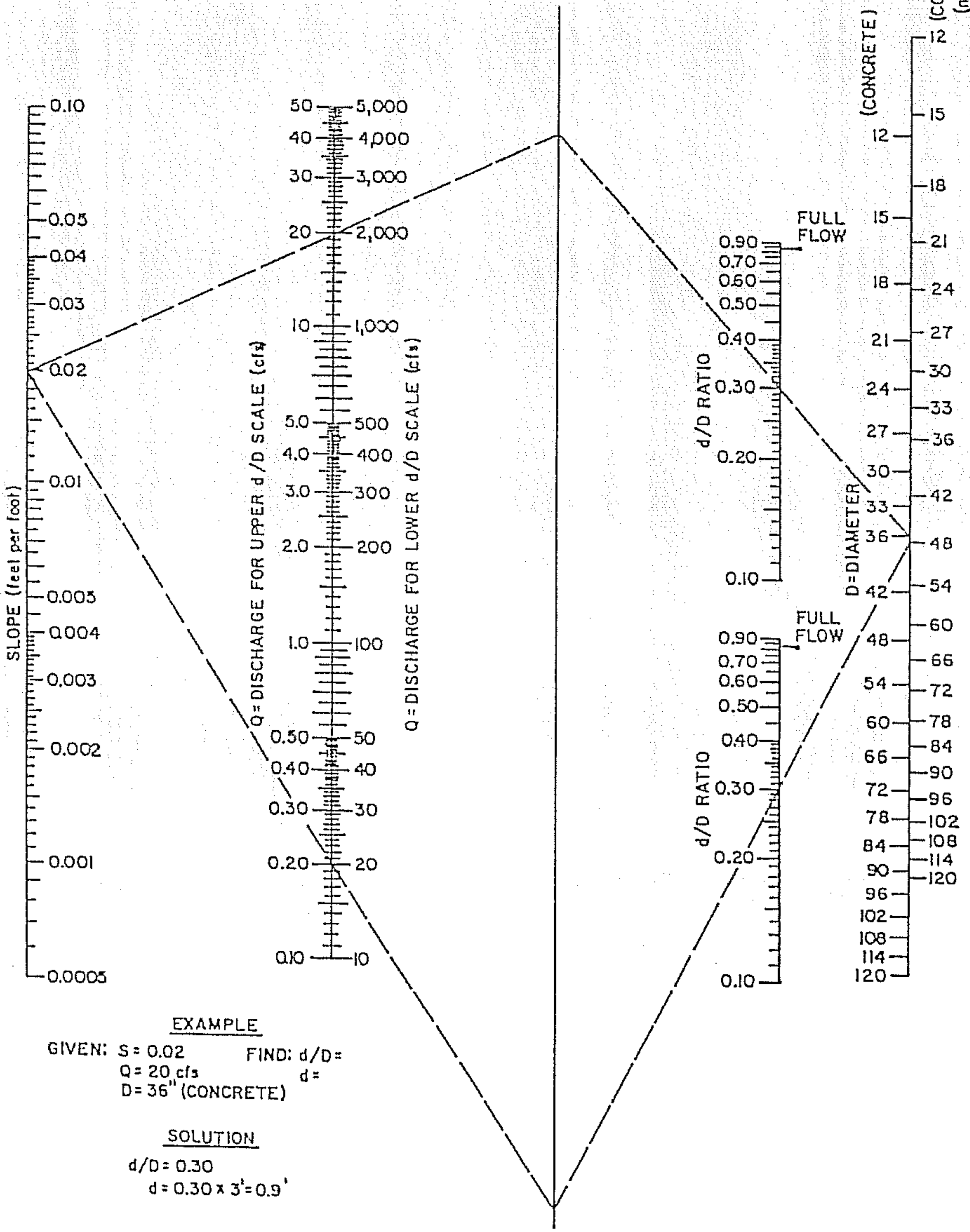
Figure 4.11



CRITICAL DEPTH OF FLOW
FOR CIRCULAR CONDUITS

SOURCE: Texas Highway Department

Figure 4.12



EXAMPLE

GIVEN: S = 0.02
Q = 20 cfs
D = 36" (CONCRETE)

FIND: d/D =
d =

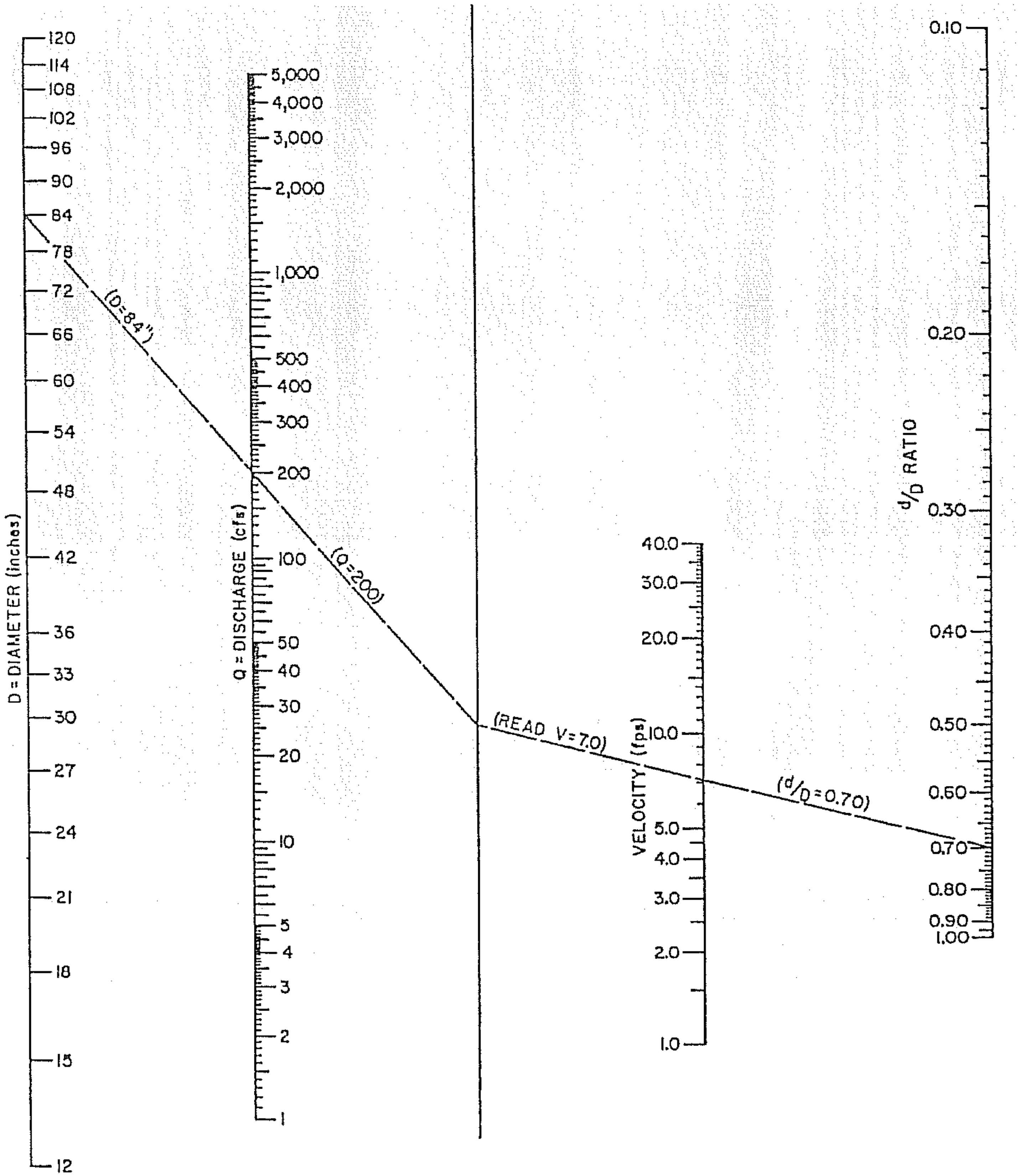
SOLUTION

d/D = 0.30
d = 0.30 x 3' = 0.9'

UNIFORM FLOW FOR PIPE CULVERTS

SOURCE: Texas Highway Department

Figure 4.13

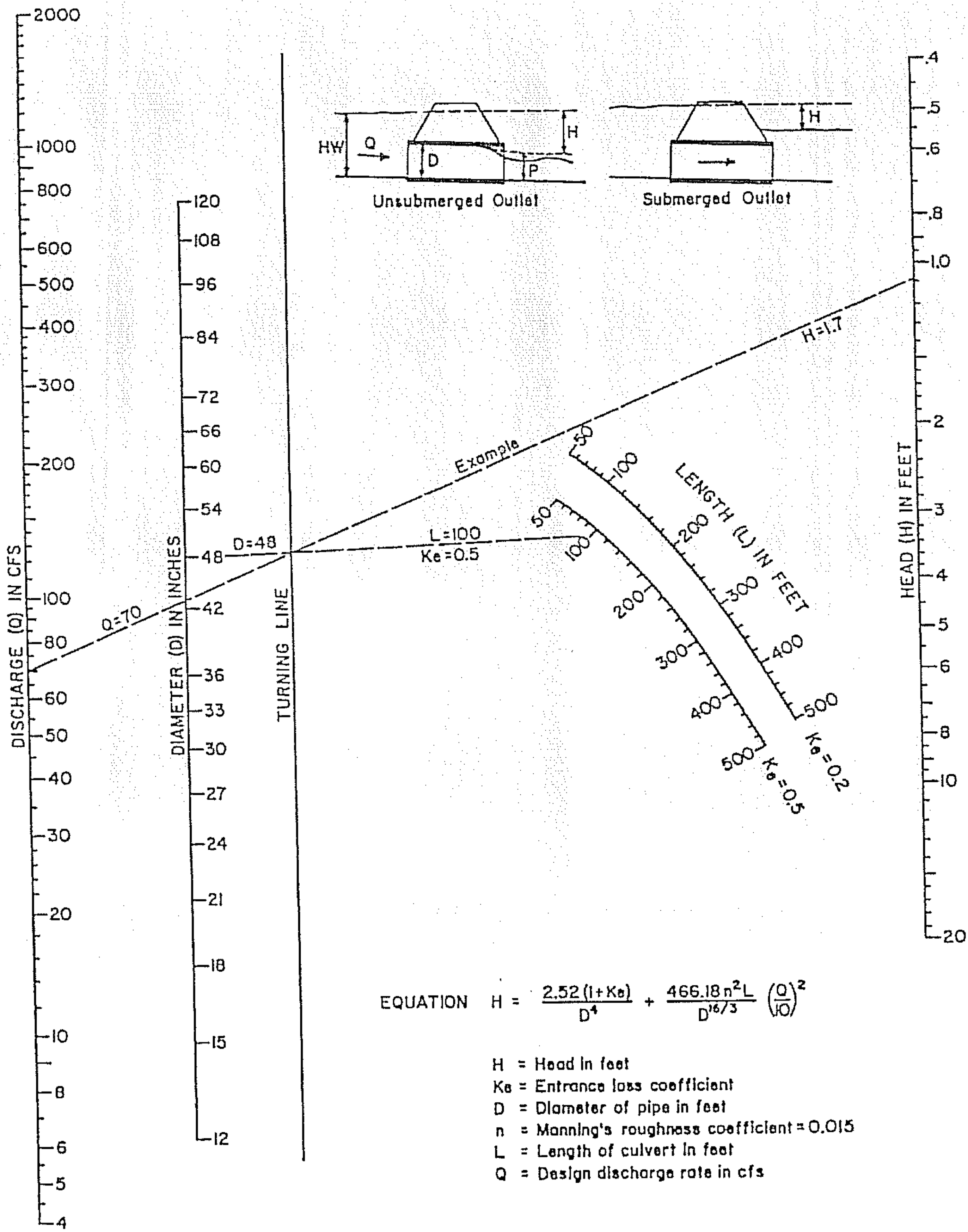


THE CITY OF BENTONVILLE

VELOCITY IN PIPE CONDUITS

SOURCE: Texas Highway Department

Figure 4.14



EQUATION $H = \frac{2.52(1+K_e)}{D^4} + \frac{466.18 n^2 L}{D^{16/3}} \left(\frac{Q}{10}\right)^2$

H = Head in feet
Ke = Entrance loss coefficient
D = Diameter of pipe in feet
n = Manning's roughness coefficient = 0.015
L = Length of culvert in feet
Q = Design discharge rate in cfs

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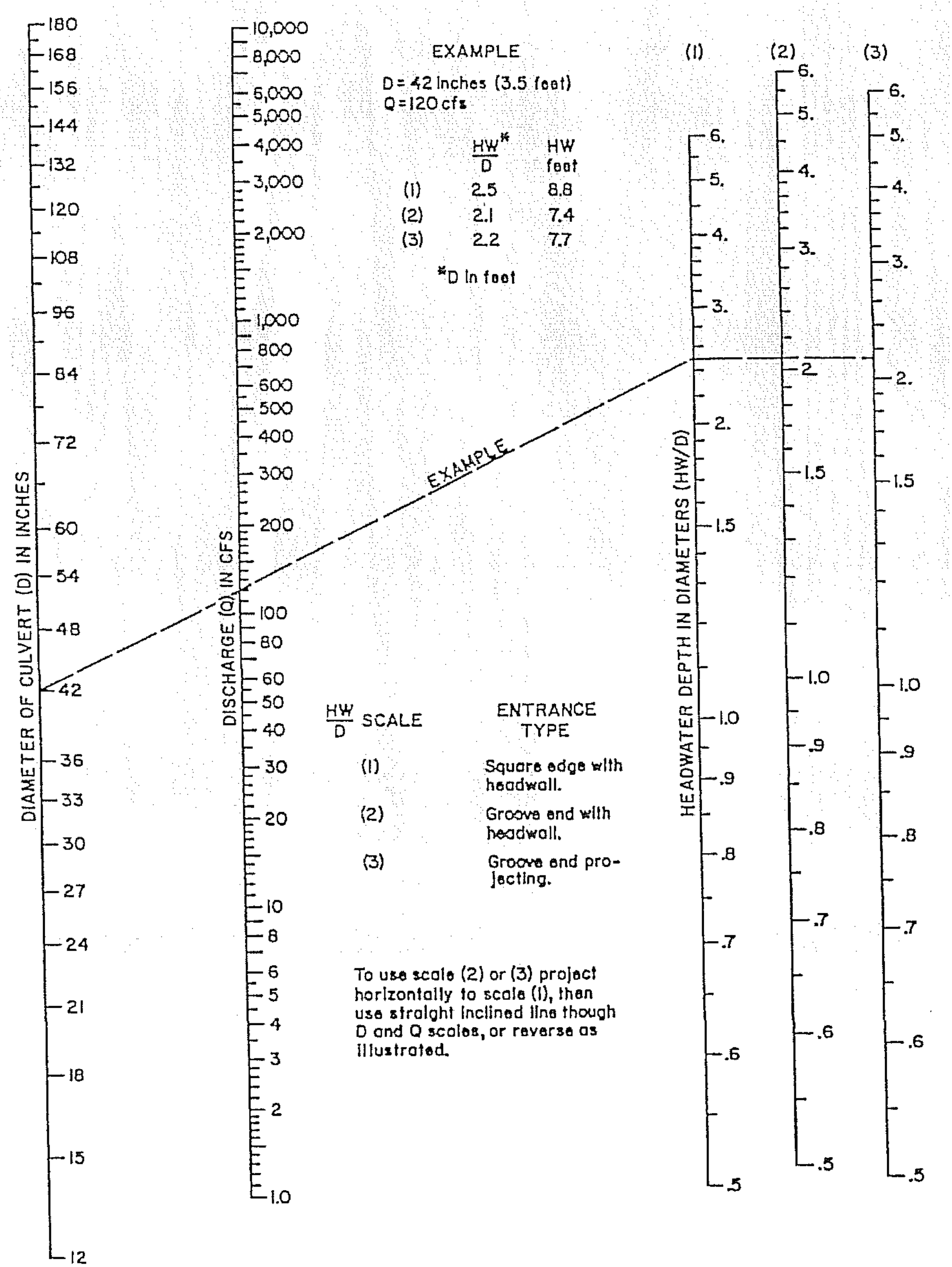
HEAD FOR CONCRETE PIPE CULVERTS FLOWING FULL

SOURCE: Texas Highway Department

Figure 4.15



HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

Figure 4.16

CONCRETE PIPE

DIAM. OF PIPE D (INCHES)	CLASS "B" BEDDING (H) MAXIMUM ALLOWABLE COVER-FEET				CLASS "C" BEDDING (H) MAXIMUM ALLOWABLE COVER-FEET			
	II*	III	IV	V	II	III	IV	V
18	11	13	20	25	9	12	18	22
24	12	14	21	26	10	13	19	23
36	13	16	23	28	11	14	20	24
48	14	16	24	29	11	15	21	25
60	14	17	24	29	12	15	21	26
72	14	17	24	30	12	16	22	26
84	15	17	25	30	13	16	22	27
96	15	18	25	31	13	16	23	27
108	15	18	26	32	13	17	23	28

* ASTM C76-72 Table Designation

THE CITY OF BENTONVILLE

DEPTH OF COVER TABLES

Figure 4.17

CORRUGATED METAL PIPE

3" x 1" CORRUGATIONS

DAIM. OF PIPE D (INCHES)	MIN. COVER ABOVE PIPE (INCHES)	(H) MAXIMUM ALLOWABLE COVER-FEET									
		16 GA. (0.064")		14 GA. (0.079")		12 GA. (0.109")		10 GA. (0.138")		8 GA. (0.168")	
		Round	Elong	Round	Elong	Round	Elong	Round	Elong	Round	Elong
36	18	27	40	31	50	40	74				
42	18	21	34	23	42	29	58				
48	18	17	30	19	37	23	46				
54	18	15	27	16	32	19	38				
60	18	13	24	15	29	16	33				
66	18	13	22	13	27	15	30				
72	18	12	20	12	25	14	27				
78	18	12	18	12	23	13	26				
84	18			12	21	12	24	13	26		
90	18					12	24	12	35	13	26
96	18					11	23	12	24	12	25
102	24							12	23	12	24
108	24									12	23
114	24									11	23
120	24									11	20

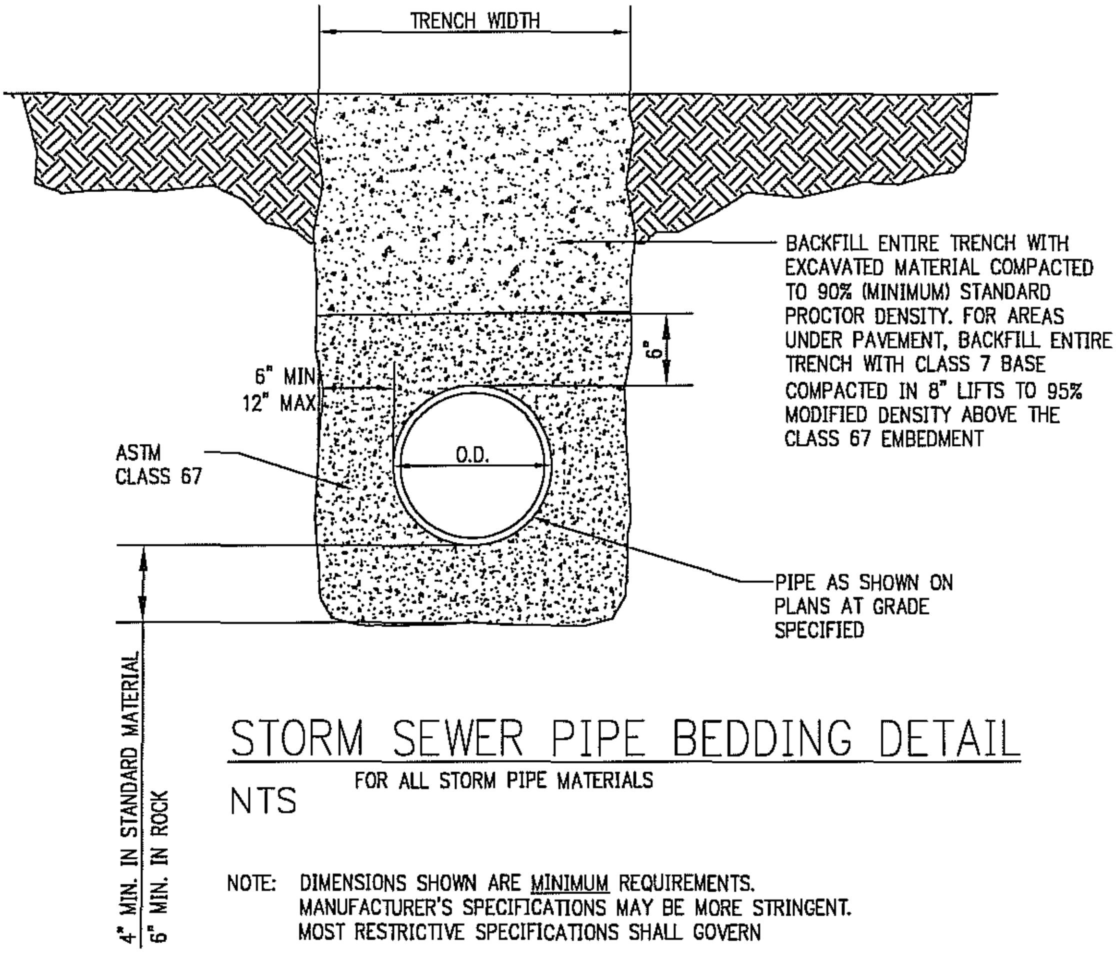
2 2/3" x 1/2" CORRUGATIONS

DAIM. OF PIPE D (INCHES)	MIN. COVER ABOVE PIPE (INCHES)	(H) MAXIMUM ALLOWABLE COVER-FEET									
		16 GA. (0.064")		14 GA. (0.079")		12 GA. (0.109")		10 GA. (0.138")		8 GA. (0.168")	
		Round	Elong	Round	Elong	Round	Elong	Round	Elong	Round	Elong
12	18	70		76							
15	18	56		61							
18	18	40		48		64					
24	18	23		26		33					
30	18			18	30	22	43	25	51		
36	18			15	25	17	33	19	38		
42	18					14	28	16	31	17	34
48	18					13	25	14	27	15	29
54	18					12	24	13	25	13	26
60	18							12	23	12	25
66	18							11	22	12	23
72	18							11	17	11	21
78	18									11	17
84	18									11	13

CORRUGATED METAL PIPE ARCH

3" x 1" CORRUGATIONS								
SPAN (INCHES)	RISE (INCHES)	RC (INCHES)	MIN. COVER ABOVE PIPE (INCHES)	(H) MAXIMUM ALLOWABLE COVER-FEET				
				16 GA. (0.064")	14 GA. (0.079")	12 GA. (0.109")	10 GA. (0.138")	8 GA. (0.168")
43	27	7.75	18	6	6			
50	31	9	18	6	6			
58	36	10.5	18	6	6			
65	40	12	18	6	6			
72	44	13.25	18	6	6			
73	55	18	18	8	8			
81	59	18	18		7	7		
87	63	18	18		7	7		
95	67	18	18		6	6		
103	71	18	24			6		
112	75	18	24			5		
117	79	18	24			5		
128	83	18	24				5	

2 2/3" x 1/2" CORRUGATIONS								
SPAN (INCHES)	RISE (INCHES)	RC (INCHES)	MIN. COVER ABOVE PIPE (INCHES)	(H) MAXIMUM ALLOWABLE COVER-FEET				
				16 GA. (0.064")	14 GA. (0.079")	12 GA. (0.109")	10 GA. (0.138")	8 GA. (0.168")
18	11	3.5	18	6	6			
22	13	4	18	6	6			
25	16	4	18	5	5			
29	18	4.5	18	5	5			
36	22	5	18	5	5			
43	27	5.5	18	4	4			
50	31	6	18			4	4	4
58	36	7	18			4	4	4
65	40	8	18			4	4	4
72	44	9	18				4	4
79	49	10	18					4
85	54	11	18					4



STORM SEWER PIPE BEDDING DETAIL

NTS

FOR ALL STORM PIPE MATERIALS

NOTE: DIMENSIONS SHOWN ARE MINIMUM REQUIREMENTS.
MANUFACTURER'S SPECIFICATIONS MAY BE MORE STRINGENT.
MOST RESTRICTIVE SPECIFICATIONS SHALL GOVERN

Recommended Distance Between Pipes for Trenches with Multiple Pipes

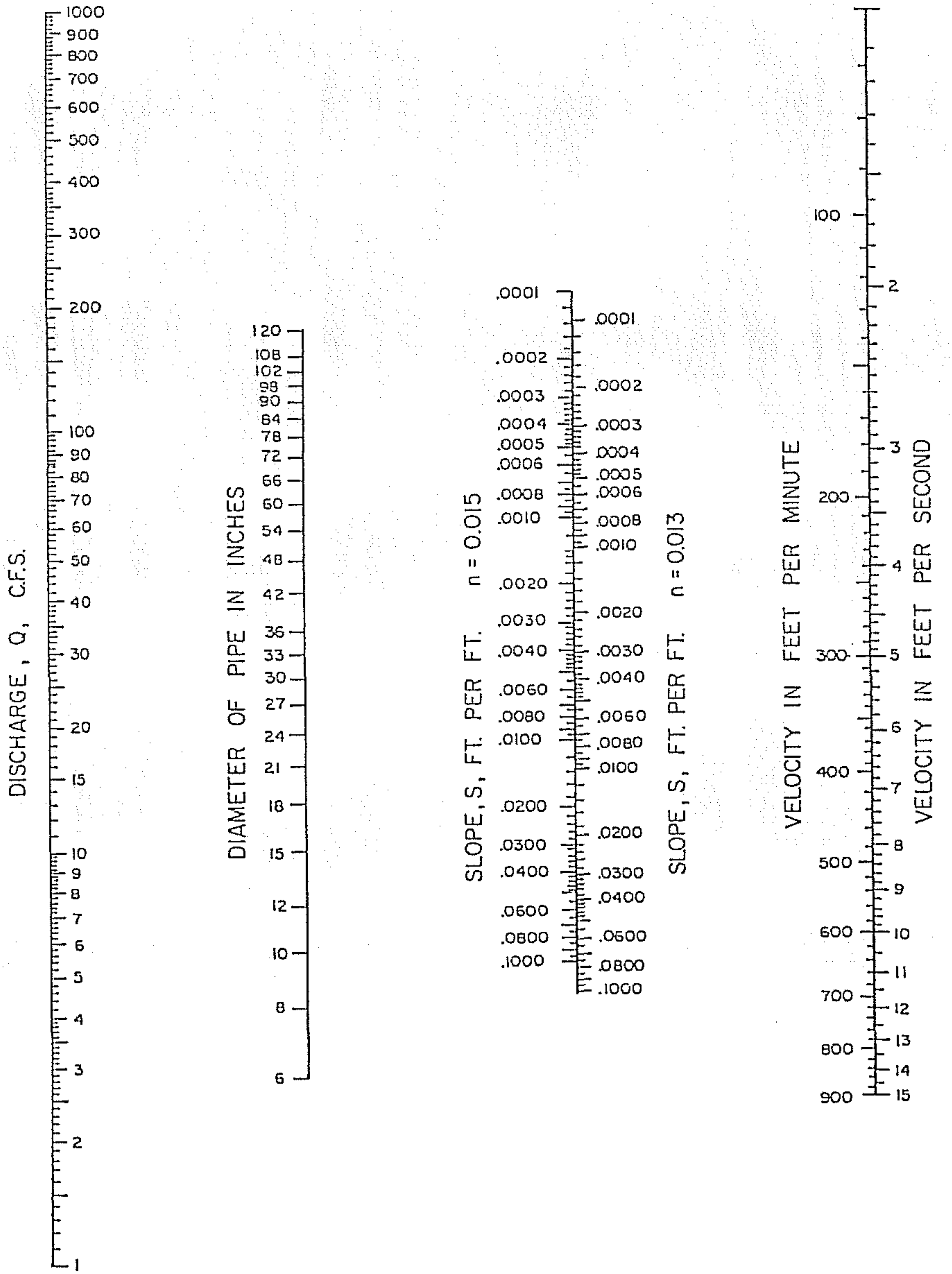
PIPE MATERIAL	MINIMUM DISTANCE BETWEEN MULTIPLE PIPES (FEET)
RCP	6"
CMP	1'
HDPE	1'
PVC	1'

NOTE: DIMENSIONS SHOWN ARE MINIMUM REQUIREMENTS.
MANUFACTURER'S SPECIFICATIONS MAY BE MORE STRINGENT.
MOST RESTRICTIVE SPECIFICATIONS SHALL GOVERN

THE CITY OF BENTONVILLE

PIPE BEDDING

Figure 4.18

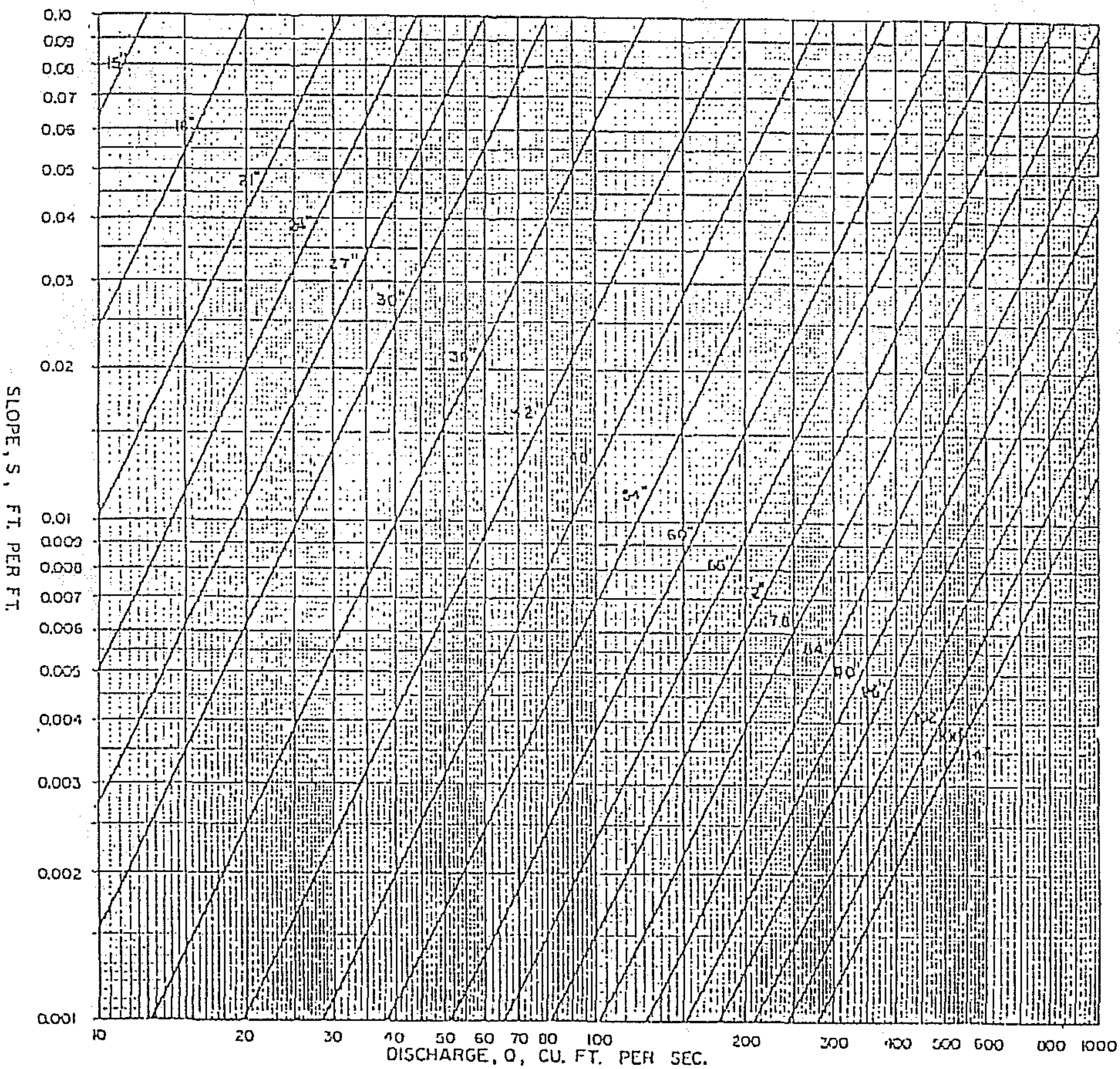


NOMOGRAPH FOR PIPES FLOWING FULL

n = 0.015 and 0.013

SOURCE: City of Shreveport, LA

Figure 4.19



DISCHARGE FOR CIRCULAR PIPE FLOWING FULL

n = 0.021

SOURCE: City of Shreveport, LA

Figure 4.20

4.9 Examples of Culvert Sizing Computations

Example 1:

Given:

$Q = 326$ cfs

$S_o = 0.002$ ft./ft.

Allowable headwater depth, HW=6.0 ft.

Allowable outlet velocity, V=8.0 fps

Length of Culvert, L=200 ft.±

Tailwater depth, TW=2.6 ft.

Flared Wingwalls

Required: The most economical concrete box culvert that will pass the design discharge.

Solution:

(1) Enter Figure 4.8 with Q=326 and V_c=8.0 and read approximate width of opening. W=20' and d_c=2.0', then connect K value for flared wings = 1.15 with Vc=8.0 and read HL=1.2'. Then

$HW_c = d_c + HL$ or $2.0 + 1.2 = 3.2'$

From the above calculations it appears that a culvert having a width of 20' and a height of 3.2' will adequately pass the design discharge. In order to fit a standard design it is decided to try a 4 - 5' x 4' multiple box culvert.

(2) The next step is to determine the type of culvert operation. This is accomplished by first determining the critical slope by entering Figure 4.9 with $\frac{d_c}{W} = \frac{2}{5} = 0.4$ and W=5 and establishing a point on the turning line. Connect the point on turning line with $Q = \frac{326}{4} = 81.5$ and read S_c=0.0037.

We have now assembled the following data:

Existing Channel	Culvert
$S_o = 0.002$ ft./ft.	$S_c = 0.0037$
TW = 2.6'	$d_c = 2.0'$
	D = 4.0'

Also we know the following:

$S_o < S_c$

$TW > d_c$

$TW < D$

This culvert will function as a Type II operation with the control at the outlet providing HW<1.2D.

(3) The next step is to determine the actual headwater depth and to confirm the Type II operation.

$$HW = TW + \left(\frac{V_{TW}}{2g}\right)^2 + h_e + h_f - S_oL$$

TW = 2.6'

$$\left(\frac{V_{TW}}{2g}\right)^2 = \frac{\left(\frac{Q}{A}\right)^2}{64.4} = \frac{\left(\frac{326}{20 \times 2.6}\right)^2}{64.4} = \frac{39.31}{64.4} = 0.61'$$

$$h_e = K_e \left(\frac{\left(V_{TW}\right)^2}{2g}\right) = 0.15 \times 0.61 = 0.09$$

$h_f = S_f L$ Enter Figure 4.9 with

$$\frac{d_{TW}}{W} = \frac{2.6}{5} = 0.52, W = 5 \text{ and}$$

$$Q = \frac{326}{4} = 81.5 \text{ and read } S_f = 0.0019 \text{ ft./ft.}$$

$h_f = 0.0019 \times 200 = 0.38'$

$S_o L = 0.002 \times 200 = 0.40'$

HW = 2.60 + 0.61 + 0.09 + 0.38 – 0.40 = 3.28'

The computation of the headwater depth confirms the Type II operation since HW≤1.2D.

(4) The outlet velocity $= \frac{Q}{A} = \frac{326}{20 \times 2.6} = 6.3$ fps

Since the calculated HW=3.27' which is substantially less than the allowable HW=6.0' and the calculated V=6.3 fps which is less than the allowable V = 8.0 fps, the above structure is considered uneconomical.

Example 2:
Given: Same data as in Example 1.
Try 2 – 6.5' x 4' multiple box culvert.
Solution:

(1) From Figure 4.8 d_c=2.65, V_c=9.30

(2) From Figure 4.9 S_c=0.0035 ft./ft.
since S_o<S_c
since TW<d_c
We have a Type I operation with control at the outlet providing HW≤1.2D.

(3) Check HW for Type I operations:

$$HW = d_c + \frac{V_c^2}{2g} + h_e + h_f - S_oL$$

$$d_c = 2.65'$$

$$\frac{V_c^2}{2g} = \frac{(9.30)^2}{64.4} = 1.34'$$

$$h_e = K_e\left(\frac{V^2}{2g}\right) = 0.15 \times 1.34' = 0.20'$$

$h_f = S_fL$ Enter Figure with

$$\frac{1.1\ d_c}{W} = \frac{1.1 \times 2.65}{6.5} = 0.45,\ W = 6.5'$$

$Q = \frac{326}{2} = 163$ and read $S_f = 0.00275$ ft./ft.

$h_f = S_fL = 0.00275 \times 200 = 0.55'$

$S_oL = 0.002 \times 200 = 0.40'$

$HW = 2.65 + 1.34 + 0.20 + 0.55 - 0.40 = 4.34'$

Since HW<1.2D the installation will function as a Type I operation.

(4) Outlet Velocity = V_c = 9.30 fps.

HW is still lower than the allowable HW=6.0'; however, the outlet velocity is greater than the allowable which was assumed to be 8 fps. The designer has the choice to provide riprap in the downstream channel, select a multiple box culvert of greater width or consider Type IV operation.

Example 3:
Given: Same data as in Example 1.
Required: Multiple Box Culvert for Type IV operation.
Solution:

For the given data let us select a 2 – 5' x 4' multiple box culvert. HW must be equal to or greater than 1.2D, or HW=1.2 x 4.0 = 4.8' minimum. A partially submerged outlet (Type IV-B) will be considered. Under these conditions:

$$HW = H + P - S_oL$$

(1) Area of one barrel= 5x4=20 sq. ft. Length of Culvert= 200 ft. K_e (Flared Wingwalls)= 0.4

$$Q \text{ per barrel} = \frac{326}{2} = 163 \text{ cfs}$$

(2) Use Figure 4.11, Connect area of one barrel–20 sq. ft. with 200 ft. length on K_e=0.4 scale. The position of K_e=0.4 must be interpolated between the limits K_e=0.2 and K_e=0.7. Mark point on turning line. Connect this point with Q=163 and read H=2.3'

(3) According to the definition,

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

Enter Figure 4.8 with Q=326, W=10 and read d_c=3.1'

$$\text{Then } P = \frac{3.1 + 4.0}{2} = 3.55'$$

And HW = 2.3 + 3.55 – (0.002 x 200)   HW=5.45'

(4) $V\text{ (outlet)} = \frac{Q}{A} = \frac{326}{10 \times 3.1} = 10.5$ fps (concrete apron req'd.)

Note: Had TW been higher than I) we would have had a submerged outlet and Type IV-A Flow would have controlled

$HW = H + TW – S_oL$ and $V\text{ (outlet)} \ \frac{Q}{A}$

Example 4:

Given: To illustrate Type III operation assume the same data as in Example 1 except that $S_o = 0.005$ and the allowable outlet velocity = 10.0 fps.

Required: To determine the size of concrete box culvert.

Solution:

(1) Enter Figure 4.8 with Q=326 cfs and V_c=10.0 fps and read W=10', d_c=3.1' and HL=1.3'. Then

$$HW_c = d_c + HL = 3.1 + 1.3 = 4.4'$$

(2) 10' x 5' single box culvert.

To determine the type of operation first find S_c by entering Figure 4.9 with $\frac{d_c}{W} = \frac{3.1}{10} = 0.31$, W=10'

and establish a point on the turning line. Connect this point with Q=326 cfs and read S_c=0.00295 ft./ft.

We now have assembled the following data:

Existing Channel	Culvert
S_o=0.005 ft./ft.	S_c=0.00295 ft./ft.
TW=2.6'	d_c=3.1'

Since $S_o > S_c$
And TW<D

indications are the structure will function as Type III operation providing the HW<1.2D.

(3) For Type III operation the control is critical depth at the entrance and

$$HW = \frac{HW}{D} \text{ (from Nomograph) x D}$$

Check HW:

Enter Figure 4.10 with $\frac{Q}{W} = \frac{326}{10} = 32.6$ and D=5'

and determine $\frac{HW}{D} = 1.0$

Then HW = 1.0 x D = 1.0 x 5 = 5'

(4) The velocity for Type III culverts varies from critical velocity at the entrance to uniform velocity at the outlet provided the culvert is sufficiently long. We assume in this example that the outlet velocity is equal to the uniform velocity which is computed as follows:

Enter Figure 4.9 with S_o=0.005, Q=326 and W=10 and determine $\frac{d}{W} = 0.26$

d = 0.26W = 0.26 x 10 = 2.6

A = 10 x 2.6 = 26.0 sq. ft.

V (uniform) = $\frac{Q}{A} = \frac{326}{26.0} = 12.5$ fps (Outlet requires riprap)

Example 5:
Given:

$Q = 326$ cfs

$S_o = 0.002$ ft./ft.

Allowable headwater depth, HW = 6.5 ft.

Allowable outlet velocity, V = 8.0 fps

Length of Culvert, L = 200 ft. ±

Tailwater depth, TW = 2.6 ft.

Square edge with headwall

Required: Determine size of concrete pipe culvert to pass the design discharge.

Solution:

(1) Use Figure 4.16, connect $\frac{HW}{D} = 1.2$ with Q = 326 and read approximate opening required = 80 inches. Since the allowable HW is restricted to 6.5' and HW for 80" pipe =1.2x 6.7=8.0' the designer tries 2 – 60" pipes, and HW =1.2 x 5.0 = 6.0'.

(2) Use Figure 4.12, connect $Q = \frac{326}{2} = 163$ with D=60" and read $\frac{d_c}{D} = 0.73$

$d_c = 0.73D = 0.73 \times 5.0 = 3.65'$

(3) Use Figure 4.13, connect 60" with $\frac{d_c}{D} = 0.73$ and intersect turning line. Connect turning line with Q=163 and determine $S_c = 0.0046$ for concrete pipe.

We now have assembled the following data:

Existing Channel	Culvert
S_o=0.002 ft./ft.	S_c=0.0046 ft./ft. (Conc.)
TW=2.6'	d_c=3.65'
	D = 5.0'

Since $S_o < S_c$ and TW< d_c, we have a Type I operation with control at the outlet, providing HW≤1.2D.

(4) The next step in this design is to determine the actual headwater depth and to confirm the Type I operation.

$$HW = d_c + \frac{V_c^2}{2g} + h_e + h_f - S_oL$$

$d_c = 3.65'$

For $\frac{d_c}{D} = 0.73'$ V_c (Figure 4.14) = 10.7 fps

$$\frac{V_c^2}{2g} = \frac{(10.7)^2}{64.4} = 1.77'$$

$h_e = 0.5 \times 1.77 = 0.89'$

h_f is calculated as follows:

$1.1\ d_c = 1.1 \times 3.65 = 4.01'$

$$\frac{1.1\ d_c}{D} = \frac{4.01}{5.0} = 0.8$$

To determine the friction slope, S_f,

enter Figure 4.13 with D = 60", $\frac{d_c}{D} = 0.8$

Q = 163 and determine $S_f = 0.0038$

$h_f = S_f L = 0.0038 \times 200 = 0.76'$

$S_o L = 0.002 \times 200 = 0.40'$

$HW = 3.65 + 1.77 + 0.89 + 0.76 - 0.40 = 6.67'$

(5) Since HW>1.2D for the concrete pipe, the concrete pipe will not function as Type I operation. Also the HW exceeds the allowable.

(6) The designer must now try another pipe size to carry the design flow. Try 2 – 66" pipes.

(7) Use Figure 4.12, connect Q = 163 cfs with D=66" and read $\frac{d_c}{D} = 0.65$

$$\frac{d_c}{D} = 0.65D = 0.65 \times 5.5 = 3.58'$$

(8) Use Figure 4.13, connect 66" with $\frac{d_c}{D} = 0.65$ and intersect turning line. Connect turning line with Q=163 and determine $S_c = 0.004$.

We have now assembled the following data:

Existing Channel	Culvert
S_o=0.002 ft./ft.	S_c=0.004 ft./ft.
TW=2.6'	d_c=3.58'
	D = 5.5'

Since $S_o < S_c$ and TW< d_c, we have a Type I operation, providing HW<1.2D.

(9) Check to determine the actual headwater depth and to confirm the Type I operation.

$$HW = d_c + \frac{V_c^2}{2g} + h_e + h_f - S_o L$$

$d_c = 3.58'$

For $\frac{d_c}{D} = 0.65$; from Figure 4.14, $V_c = 10.0$ fps

$$\frac{V_c^2}{2g} = \frac{(10)^2}{64.4} = 1.55'$$

$h_e = 0.5 \times 1.55 = 0.78'$

$$\frac{1.1\ d_c}{D} = \frac{1.1 \times (3.58)}{5.5} = 0.72$$

From Figure 4.13 with D = 66", $\frac{d}{c}$ = 0.72, and Q=163 determine S_f = 0.0032

$h_f = S_f L$ = 0.0032 x 200 = 0.64'

$S_o L$ = 0.002 x 200 = 0.40'

HW = 3.58+ 1.55 + 0.78 + 0.64 – 0.40 = HW = 6.1'

(10) Since HW<1.2D, the pipe will function as Type I operation. Also the headwater is calculated to be less than the allowable.

(11) Check outlet velocity to determine if within allowable.

Outlet velocity = V_c = 10 fps

This velocity is greater than allowable. The designer must consider providing riprap in the downstream channel or some type of energy dissipation method or try another size pipe culvert.

Example 6:

Given: To illustrate Type III operation assume the same data as in Example 5 except that $S_o = 0.02$ and the allowable outlet velocity = 15 fps due to a solid rock channel.
Solution:

Follow the same procedure as in Example 5 for determining the initial size, critical depth and critical slope which is summarized below:

Existing Channel	Culvert
S_o=0.02 ft./ft.	S_c=0.0046 ft./ft. (Conc.)
TW=2.6'	d_c=3.65'
	D = 5.0'

Since $S_o > S_c$ and TW< D, the installation will function as Type III operation, providing the entrance is unsubmerged, i.e. HW<1.2D.

(1) The next step in this design is to determine the actual headwater depth and to confirm the Type III operation.

$$HW = \frac{HW}{D} \times D$$

$\frac{HW}{D}$ (Figure 4.16 = 1.13 for concrete pipe.)

HW (Conc. – grooved end with headwall) = 1.13D = 1.13 x 5.0 = 5.65'

Since HW<1.2D the concrete pipe will function as Type III operation.

(2) The velocity for Type III operation varies from critical velocity at the entrance to uniform velocity at the outlet, providing the installation is sufficiently long and the TW depth = uniform depth.

Enter Figure 4.13 with S_o = 0.02, Q = 163

D = 60" and determine

$\frac{d}{D} = 0.45$, d = 0.45D = 0.45 x 5.0 = 2.25

Since TW≥2.25 the outlet velocity is based on TW depth as follows:

$$\frac{d_{TW}}{D} = \frac{2.25}{5.0} = 0.45$$

Enter Figure 4.14 with D = 60", Q = 163 and the controlling

$\frac{d}{D}$ ratios and determine

V (outlet – Conc.) = 19.0 fps

Some provisions must be made to reduce the outlet velocity to the allowable velocity.