SECTION 8
DESIGN OF CULVERTS

8.01 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 which will meet these requirements.

8.02 QUANTITY OF FLOW

The design storm flow shall be determined by the Rational Method as set forth in Section 2 of this manual.

8.03 HEADWALLS AND ENDWALLS

A. General

The normal functions of properly designed headwalls and endwalls are to anchor the culvert to prevent movement due to lateral pressures, to control erosion and scour resulting from excessive velocities and turbulence, and to prevent adjacent soil from sloughing into the waterway opening. All headwalls shall be constructed of reinforced concrete and may be either straight parallel headwalls, flared headwalls, or warped headwalls with or without aprons as may be required by site conditions.

B. Conditions at Entrance

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

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

h_e = Entrance head loss in feet

V_2 = Velocity of flow in culvert.

V_1 = Velocity of approach in fps.

K_e = Entrance loss coefficient as shown in Table 8-1.

TABLE 8-1
VALUES OF ENTRANCE LOSS COEFFICIENTS "K_e"

Type of Structure and Entrance Design	Value of K_e
Box, Reinforced Concrete	
Submerged Entrance	
Parallel Wingwalls	0.5
Flared Wingwalls	0.4
Free Surface Flow	
Parallel Wingwalls	0.5
Flared Wingwalls	0.15
Pipe, Concrete	
Projecting from fill, socket end	0.2
Projecting from fill, sq cut end	0.5
Headwall or headwall and 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 slope	0.5

In order to compensate for the retarding effect on the velocity of approach in channels produced by the creation of the headwater pools at culvert entrances, the velocity of approach in the channel (v_a) shall be reduced by the factors as shown in Table 8-2.

TABLE 8-2
REDUCTION FACTORS FOR VELOCITY OF APPROACH

Velocity of Approach "Va" (fps)	Description of Conditions	V_1 to be used in formula for h_e
0-6	All culverts	$V_1 = V_a$
Above 6	Good alignment of the approach channel; headwater pool permissiable within the right-of-way	$V_1 = 0.5\ V_a$
Above 6	Good alignment of the approach channel; channel slopes have been lined; limited backwater pool permissible within the right-of-way.	$V_1 = 0$

C. Type of Headwall or Endwall

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

Parallel Headwall and Endwall

1. Approach velocities are low (below 6 fps).
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.

Flared Headwall and Endwall

1. Channel is well defined.
2. Approach velocities are between 6 and 10 fps.
3. Medium amounts of debris exist.

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

Warped Headwall and Endwall

1. Channel is well defined and concrete lined.
2. Approach velocities are between 8 and 20 fps.
3. Medium amounts of debris exist.

These headwalls are effective with drop down aprons to accelerate flow through culvert, and are effective end-walls 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.

8.04 CULVERT DISCHARGE VELOCITIES

The velocity of discharge from culverts should be limited as shown in Table 8-3. Consideration must be given to the effect of high velocities, eddies or other turbulence on the natural channel, downstream property and roadway embankment.

TABLE 8-3
CULVERT DISCHARGE - VELOCITY LIMITATIONS

Downstream Condition	Maximum Allowable Discharge Velocity (fps)
Earth	6 fps
Sod Earth	8 fps
Paved or Riprap Apron	15 fps
Shale	10 fps
Rock	15 fps

8.05 SELECTION OF CULVERT SIZE AND TYPE

A. Culvert Types

Culverts shall be selected based on hydraulic principles economy of size and shape, and with a resulting head-water depth which will not cause damage to adjacent property. It is essential to the proper design of a culvert that the conditions under which the culvert will operate are known. Five types of operating conditions are listed below with a discussion of each following.

TYPE 1 Flowing Part Full with Outlet Control and Tailwater Depth Below Critical Depth. (Fig. 8-1)

TYPE II Flowing Part Full with Outlet Control and Tailwater Depth Above Critical Depth. (Fig. 8-2)

TYPE III Flowing Part Full with Inlet Control. (Fig. 8-1)

TYPE IVA Flowing Full with Submerged Outlet. (Fig. 8-4)

TYPE IVB Flowing Full with Partially Submerged Outlet. (Fig. 8-5)

Type 1
Culvert Flowing Part Full With Outlet Control and Tailwater Depth Below Critical Depth

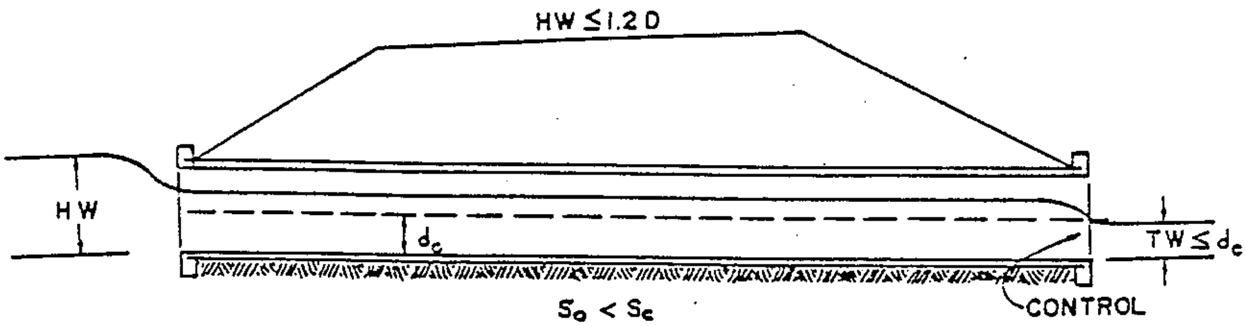


Figure 8-1

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 the culvert in feet. Headwater must be equal to or less than 1.2D or entrance is submerged and Type 4 operation will result.

dc = 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.

$$h_e = K_e \frac{V_c^2}{2g}$$

K_e = Entrance loss coefficient (See Table 8-1)

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 1.1 d_c (See Figs. 8-7 and 8-11)

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

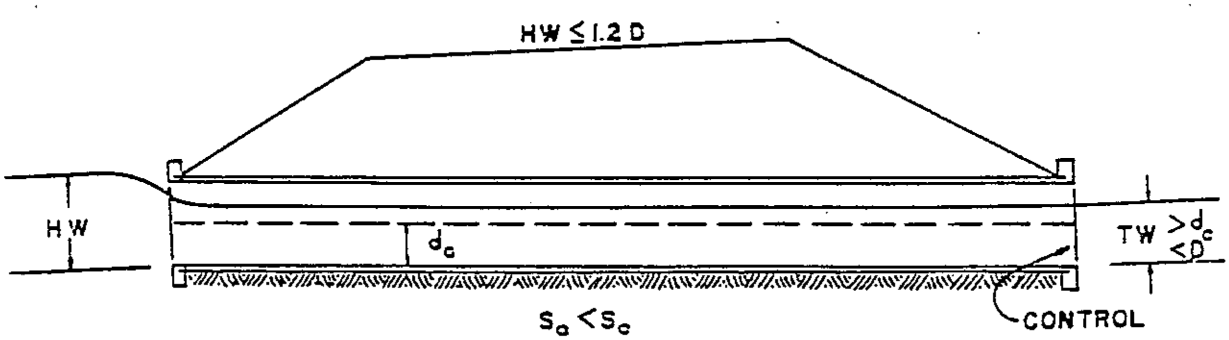


Figure 8-2

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 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 in feet

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 (See Table 8-1).

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 culvert in feet per foot.

L = Length of culvert in feet.

Type III

Culvert Flowing Part Full With Inlet Control

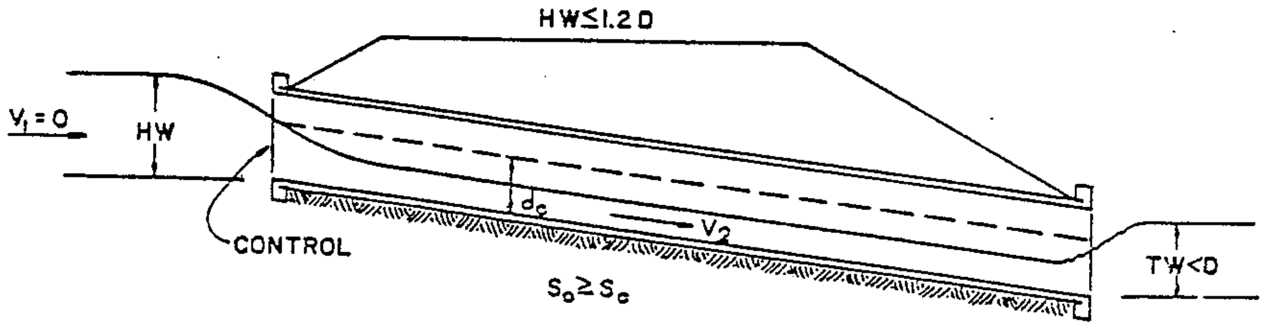


Figure 8-3

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 a 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 (See Table 8-1).

Type IV-A

Culvert Flowing Full With Submerged Outlet

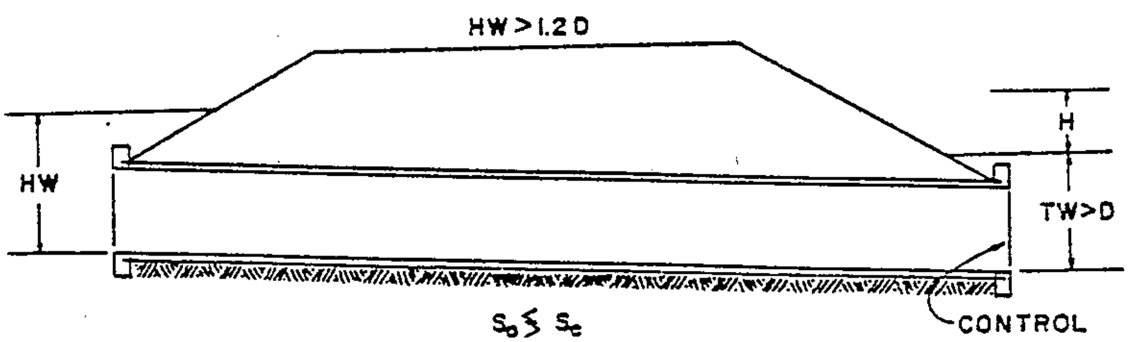


Figure 8-4

CONDITIONS

(Submerged Outlet)

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

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.

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

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.

TW = Tailwater depth in feet.

S_o = Slope of culvert in feet per foot.

L = Length of culvert in feet.

Type IV-B

Culvert Flowing Full With Partially Submerged Outlet

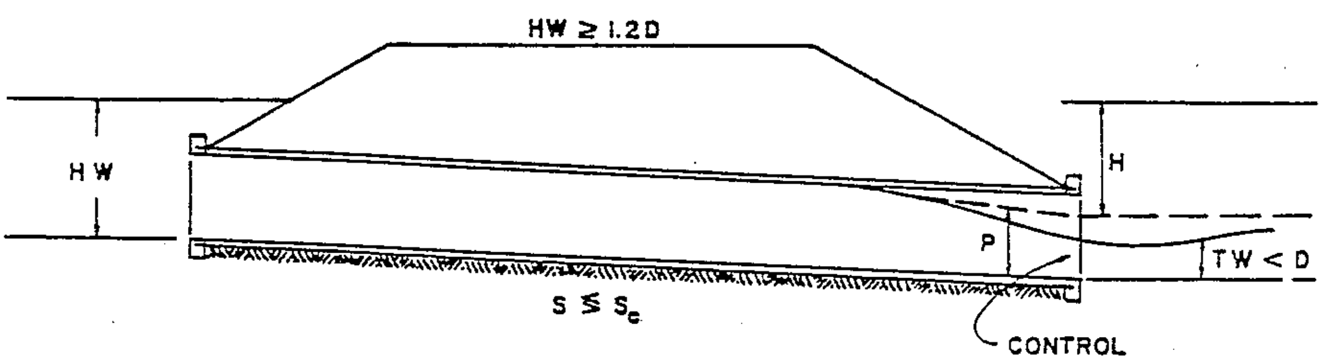


Figure 8-5

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 1.2 D for entrance to be submerged.

H = Head for culverts flowing full.

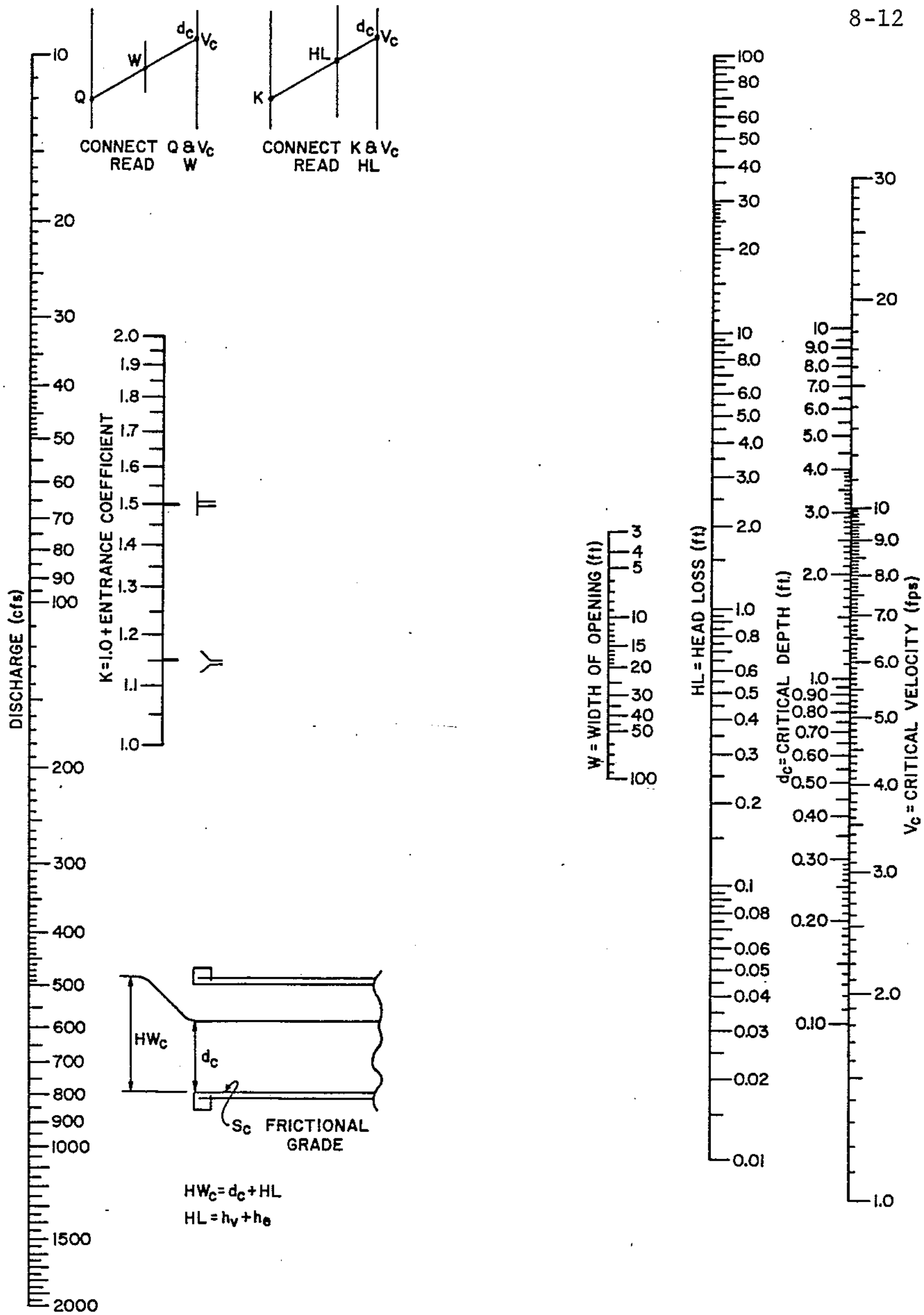
P = Pressure line height = $\frac{d_c + D}{2}$

d_c = Critical depth in feet

D = Diameter of height of structure in feet.

S_o = Slope of culvert in feet per foot.

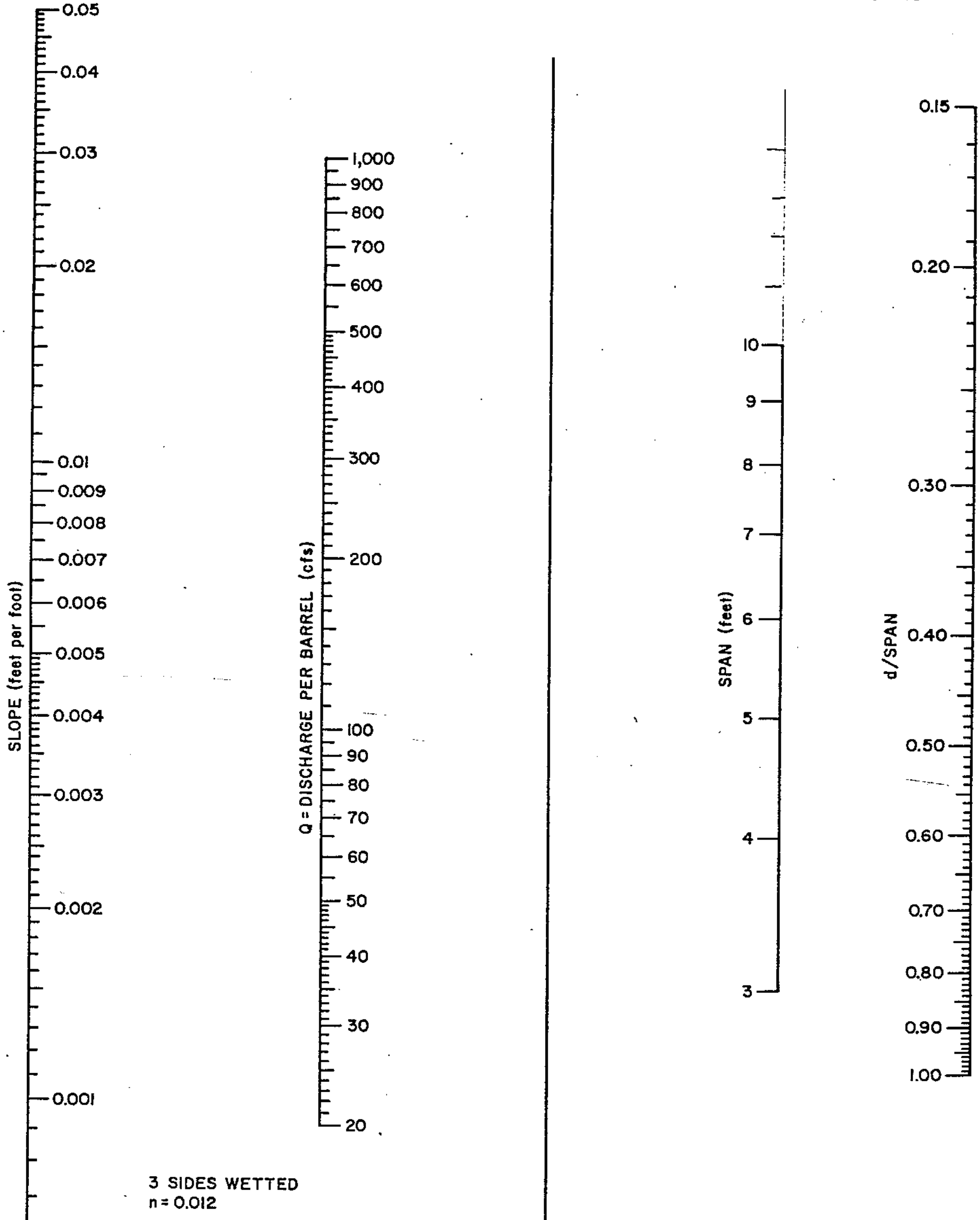
L = Length of culvert in feet.



CRITICAL FLOW FOR
BOX CULVERTS

TEXAS HIGHWAY DEPARTMENT

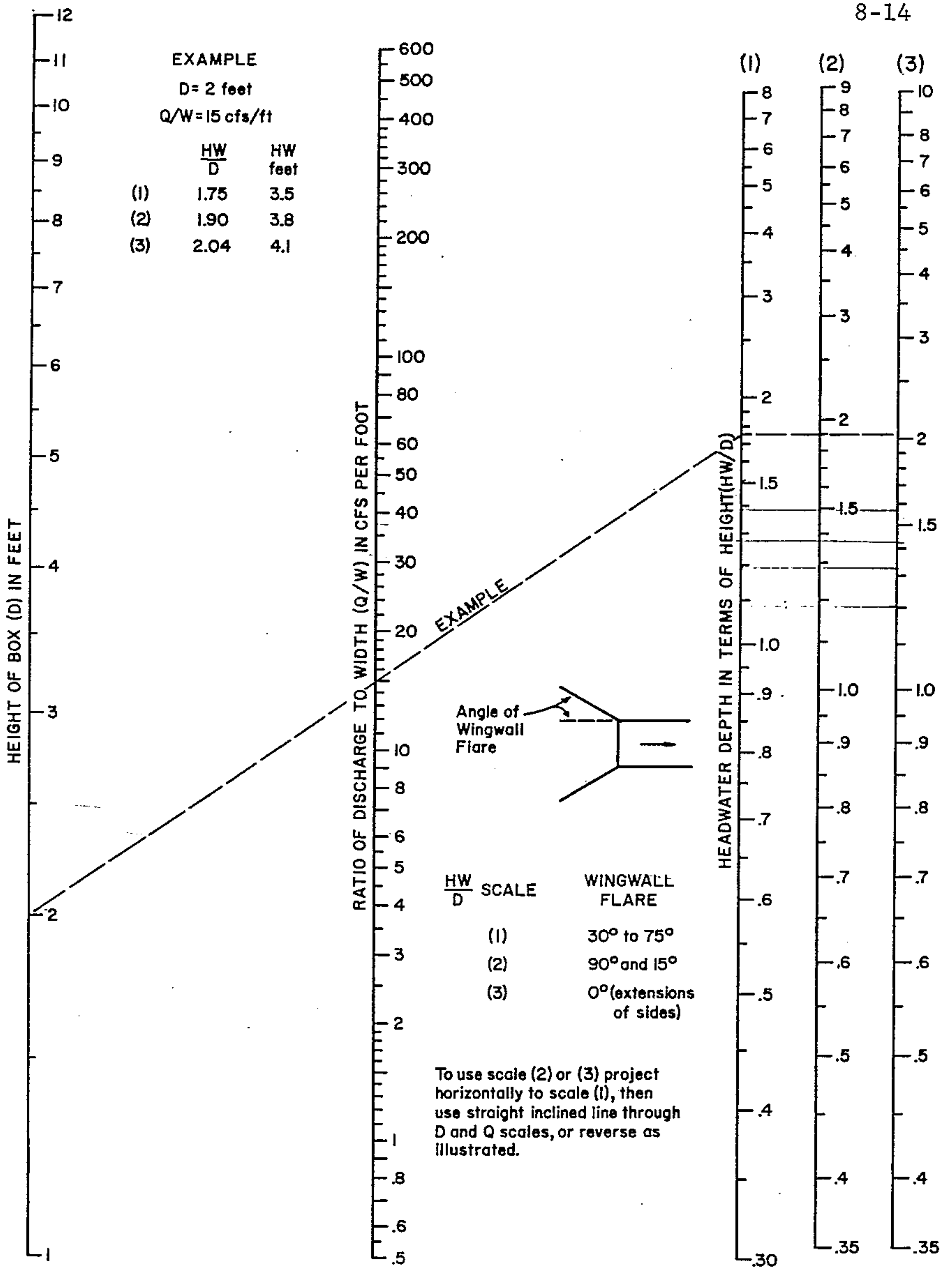
Figure 8-6



UNIFORM FLOW FOR
BOX CULVERTS

TEXAS HIGHWAY DEPARTMENT

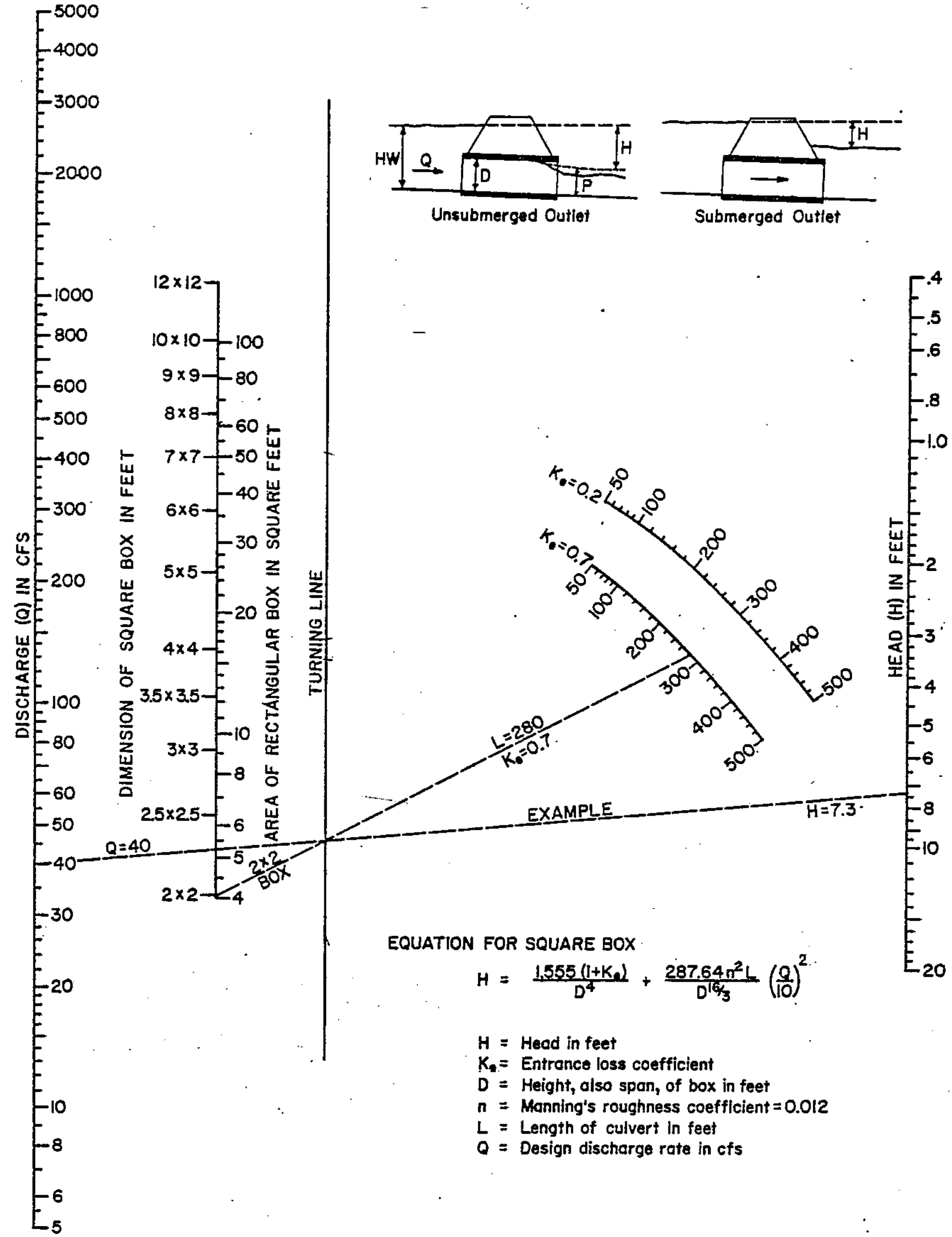
Figure 8-7



HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

TEXAS HIGHWAY DEPARTMENT

Figure 8-8



EQUATION FOR SQUARE BOX

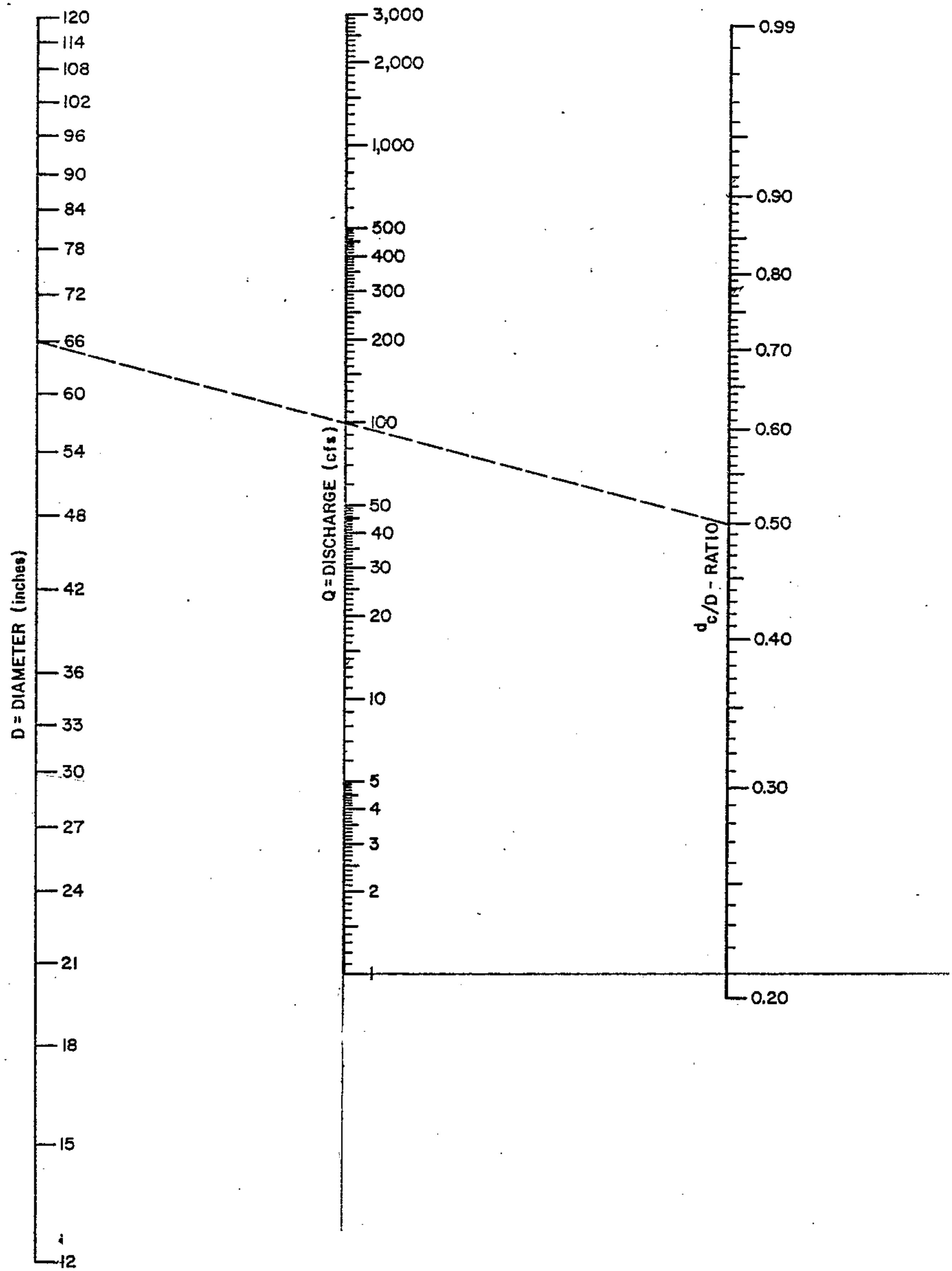
$$H = \frac{1.555\,(1+K_e)}{D^4} + \frac{287.64\,n^2 L}{D^{16/3}} \left(\frac{Q}{10}\right)^2$$

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

HEAD FOR CONCRETE BOX CULVERTS FLOWING FULL

TEXAS HIGHWAY DEPARTMENT

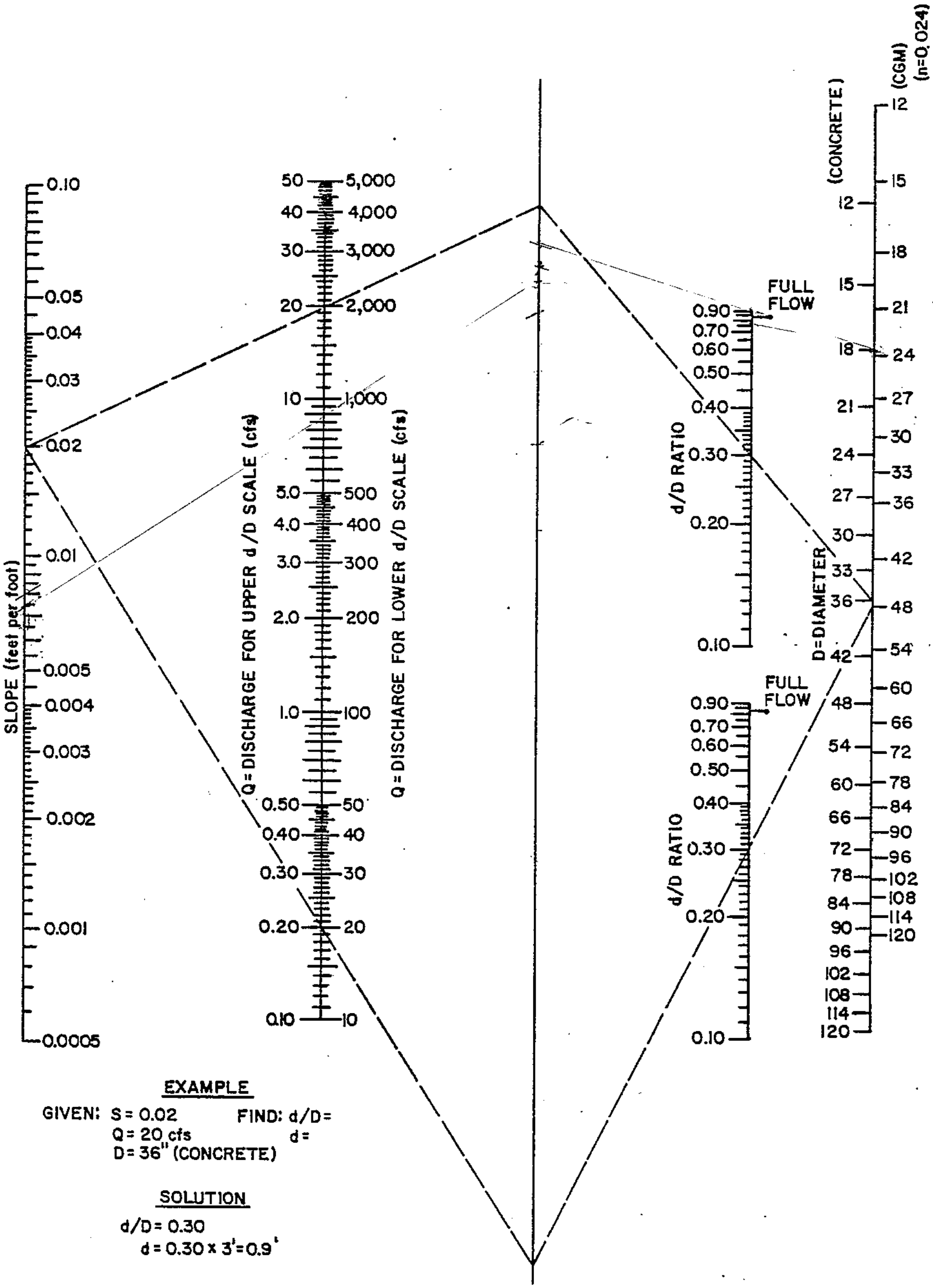
Figure 8-9



CRITICAL DEPTH OF FLOW
FOR CIRCULAR CONDUITS

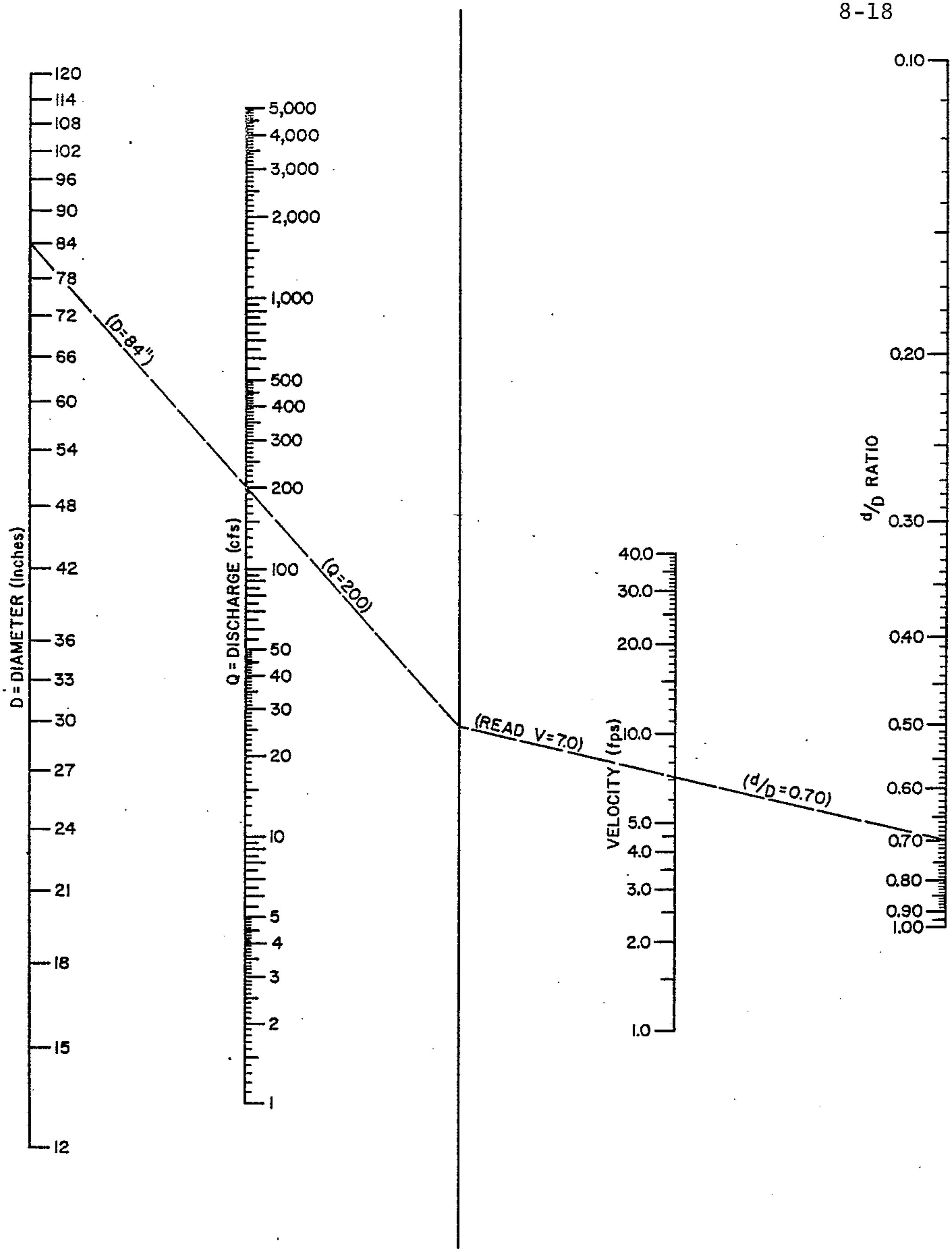
Figure 8-10

TEXAS HIGHWAY DEPARTMENT



UNIFORM FLOW FOR
PIPE CULVERTS

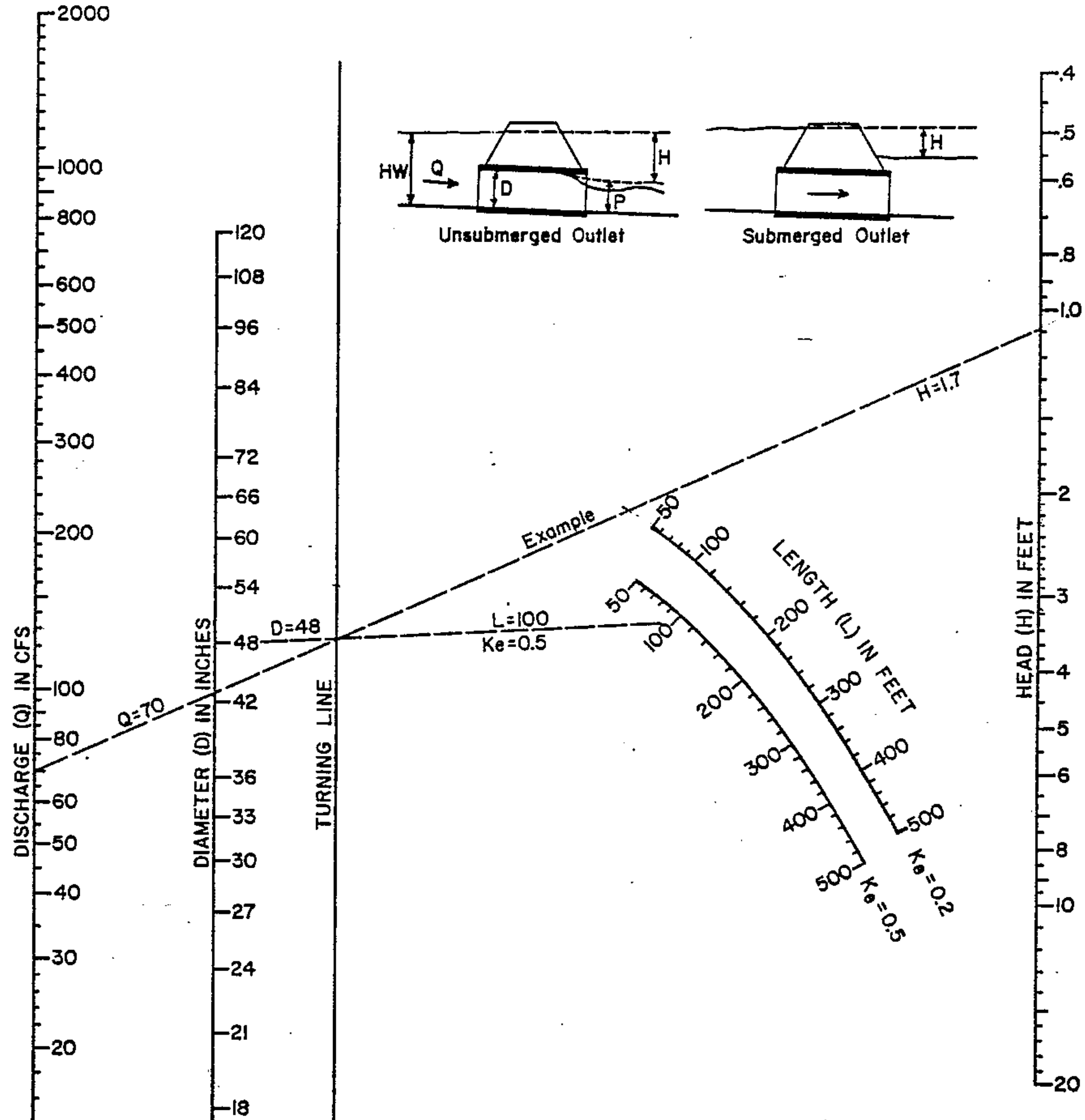
Figure 8-11



VELOCITY IN PIPE CONDUITS

TEXAS HIGHWAY DEPARTMENT

Figure 8-12

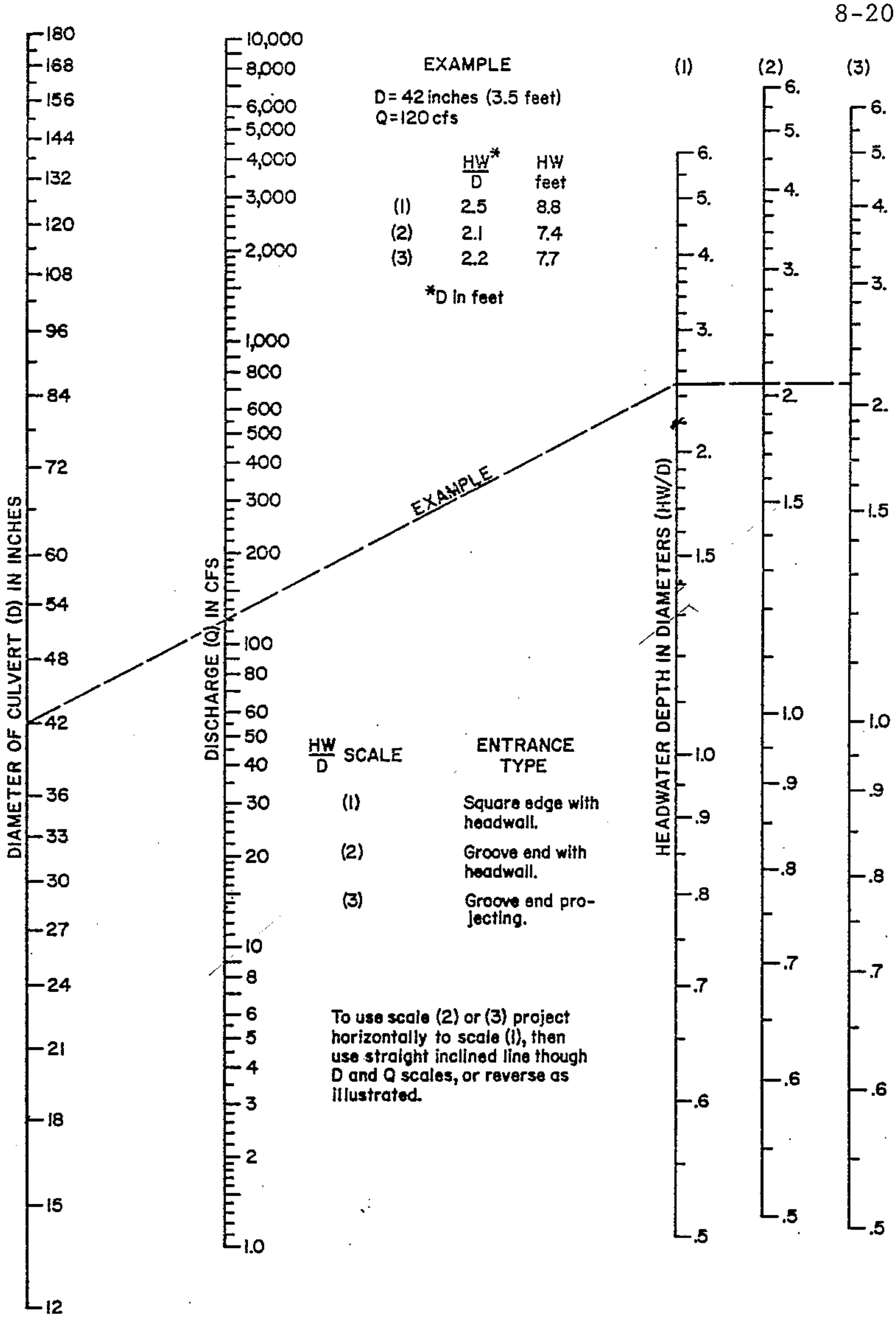


EQUATION $H = \frac{2.52(1+Ke)}{D^4} + \frac{466.18n^2L}{D^{16/3}}\left(\frac{Q}{10}\right)^2$

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

HEAD FOR CONCRETE PIPE CULVERTS FLOWING FULL

Figure 8-13



HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

TEXAS HIGHWAY DEPARTMENT

Figure 8-14

B. 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 Fig. 8-6 with Q = 326 and $V_c = 8.0$ and read approximate width of opening. W = 20', and dc = 2.0'; then connect K value for flared wings = 1.15 with $V_c = 8.0$ and read HL = 1.2'. Then

$HW_c = d_c + HL$ or 2.0 = 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 Fig. 8-7 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

$$Q = \frac{326}{4} = 81.5 \text{ and read } S_c = 0.0037$$

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'

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

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

(For K_e see Table 8-1)

$h_f = S_fL$ Enter Fig. 8-7 with

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

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

$h_f = 0.0019 \times 200 = 0.38'$

$S_oL = 0.002 \times 200 = 0.40'$

$$HW = 2.60 + 0.61 + 0.09 + 0.38 - 0.40 = 3.28'$$

The computation of the headwater depth confirms the Type II operation since HW $\leq$ 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 Fig. 8-6 $d_c = 2.65$, $V_c = 9.30$

(2) From Fig. 8-7 $S_c = 0.0035$ ft/ft

since $S_o < S_c$
and $TW < d_c$
We have a Type I operation with control at the outlet providing $HW \leq 1.2D$.

(3) Check HW for Type I operations:

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

$$d_c = 2.65'$$

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

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

$h_f = S_fL$ Enter Fig. 8-7 with

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

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

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

$$S_oL = 0.002 \times 200 = 0.40'$$

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

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 is 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:

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

(1) Area of one barrel = 5 x 4 = 20 sq. ft. Length of Culvert = 200 ft K_e (Flared Wingwalls) = 0.4 (Table 8-1)

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

(2) Use Fig. 8-9. 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 Fig. 8-6 with Q = 326, W = 10 and read d_c = 3.1'.

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

and $HW = 2.3 + 3.55 - (0.002 \times 200)$

$HW = 5.45'$

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

Note: Had TW been higher than D 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 Fig. 8-6 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 Fig. 8-7 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

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

check HW:
Enter Fig. 8-8 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 Fig. 8-7 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 Fig. 8-14, 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 = 1.2 x 6.7 = 8.0' the designer trys 2-60" pipes, and HW = 1.2 x 5.0 = 6.0'.

(2) Use Fig. 8-10; connect $Q = \frac{326I}{2y} = 163$ with D = 60"

and read $\frac{d_c}{D} = 0.73$.

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

(3) Use Fig. 8-11; connect 60" with $\frac{d_c}{C} = 0.73$ and

intersect turning line. Connect turning line with Q = 163 and determine $S_c = 0.0046$ for concrete pipe.

We have now 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 $HW \leq 1.2D$.

(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 (Fig. 8-12) = 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 Fig. 8-11 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 Fig. 8-10; 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 Fig. 8-11; Connect 66" with $\frac{d_c}{D} = 0.65$ and interesect 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.

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

$d_c = 3.58'$

For $\frac{d_c}{D} = 0.65$; from Fig. 8-12, $V_c = 10.0$ fps

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

$h_e = 0.5 \times 1.55 = 0.78'$

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

From Fig. 8-11 with D = 66", $\frac{d}{c} = 0.72$, and Q = 163; determine $S_f = 0.0032$

$h_f = S_fL = 0.0032 \times 200 = 0.64'$

$S_oL = 0.002 \times 200 = 0.40'$

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

(10) Since HW < 1.2D, the pipe will function as a 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 is 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	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.

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

$\frac{HW}{D}$ (Fig. 8-14 - 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 Fig. 8-11 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 $\geq$ 2.25 the outlet velocity is based on TW depth as follows:

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

Enter Fig. 8-12 with D = 60", Q = 163 and the

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

V (outlet-Conc.) = 19.0 fps

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