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 or Unit Hydrograph Method as set forth in Section 2 of this manual. The system shall accommodate a 100 year frequency storm including provision for limited overflows at bridges and culverts without exceeding minimum floor elevations of adjoining properties.

The designer shall consult the "Master Drainage Plan" before proceeding with the design of any storm drainage improvements. In the event the particular watershed or waterway is not covered by the "Master Drainage Plan", then the designer shall proceed with the design from the nearest downstream control, making allowances for future expansion of the drainage system.

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.

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

h_e = Entrance head loss in feet.

V_2 = Velocity of flow in culvert.

V_1 = Velocity of approach in 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 and	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

Table 8-1 (continued)

Values Of Entrance Loss Coefficients "K_e"

Type of Structure and Entrance Design	Value of K_e
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 V_a (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 permissible within the right-of-way.	$V_1 = 0.5V_a$
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 approaching 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 endwalls for transitioning flow from closed conduit flow to opened 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 principals, economy of size and shape, and with a resulting headwater 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 I Flowing part Full with Outlet Control and tailwater Depth below Critical Depth.

Type II Flowing Part Full with Outlet Control and tailwater Depth Above Critical Depth.

Type IIIA Flowing Part Full with Inlet Control.

Type IIIB Flowing Part Full with Inlet or Outlet Control.

Type IVA Flowing Full with Submerged Outlet.

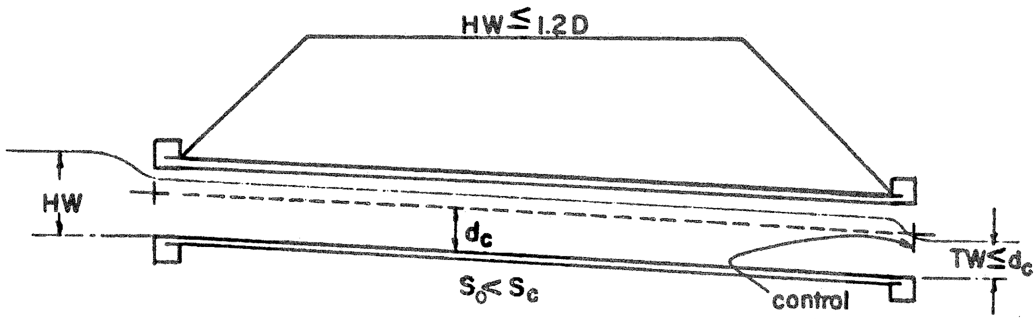
Type IVB Flowing Full with Partially Submerged Outlet.

Type 1

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 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.

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

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.

$$d_c = \left(\frac{q^2}{32.2}\right)^{1/3}$$

q = Discharge in cfs per foot.

D = Diameter of pipe or height of box.

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

h_e = Entrance head loss in feet.

$$h_e = K_e\left(\frac{(v_c)^2}{2g}\right)$$

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 I operation the friction slope is based upon $1.1 d_c$ (See Figures 8-2 and 8-5).

S_o = Slope of culvert in feet per foot.

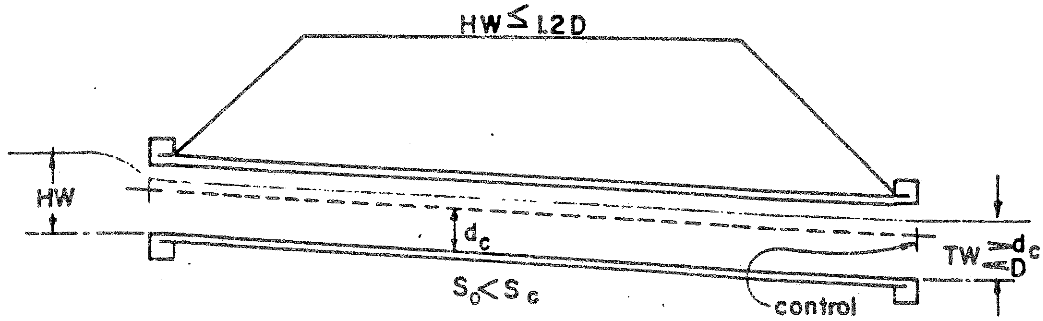
L = Length of culvert in feet.

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 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.

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

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

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

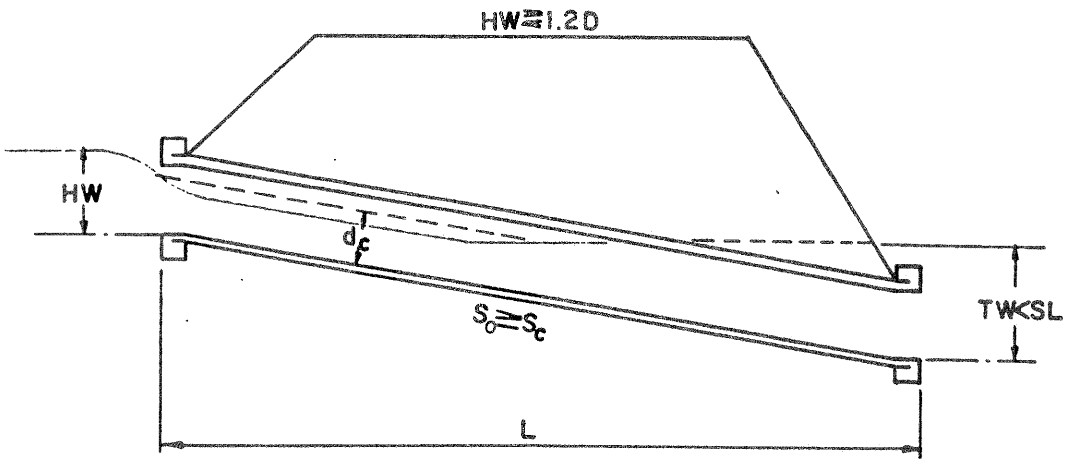
S_f = Friction slope or slope that will produce uniform flow. For Type II operation the friction slope is based upon TW depth.

S_o = Slope culvert in feet per foot.

L = Length of culvert in feet.

Type IIIA

Culvert Flowing Part Full With Inlet Control



CONDITIONS

> The entrance may be submerged or unsubmerged ($HW \neq 1.2D$) and, the slope at design discharge is equal or greater than critical slope. ($S_o \geq S_c$), the tailwater depth is less than the vertical drop in the culvert from the upstream flowline to the downstream flowline ($TW < S_oL$) (tailwater elevation is lower than upstream flowline). Tailwater depth with respect to D is inconsequential as long as the above conditions are true.

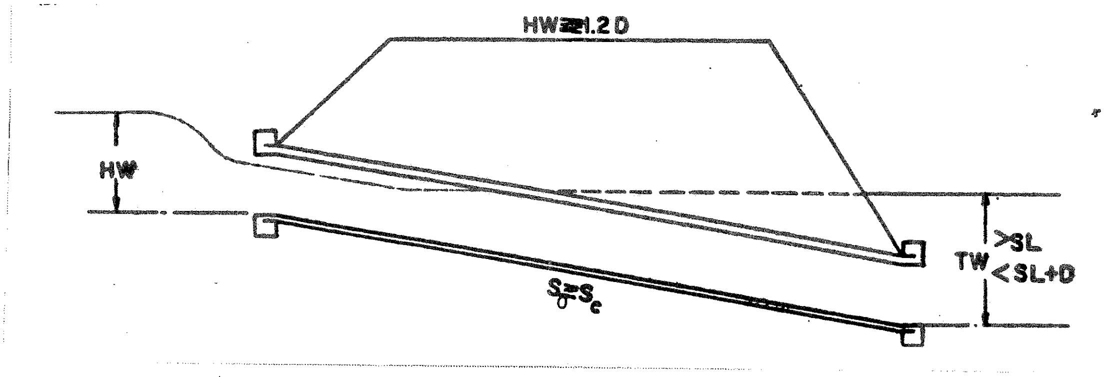
This condition is a common occurrence for culverts in rolling or mountainous country. The control is critical depth at the entrance for HW values up to about 1.2D. Control is the entrance geometry for HW values over about 1.2D.

HW is determined from empirical curves in the form of nomographs (See figures 8-3, 8-8, 8-9, 8-15, and 8-20).

If the TW is greater than D the outlet velocity is based on full flow at the culvert. If TW is less than D, the outlet velocity is based on uniform depth of the culvert.

Type IIIB

Culvert Flowing Part Full With Inlet or Outlet Control.



CONDITIONS

The entrance may be submerged or unsubmerged $(HW \neq 1.2D)$, the slope at design discharge is equal or greater than critical slope $(S_o \geq S_c)$, and TW depth is greater than the vertical drop in the culvert from the upstream flowline to the downstream flowline $(TW > S_o L)$ (TW elevation is above the upstream flowline) and TW depth is less than the sum of the vertical drop in the culvert from the upstream flowline to the downstream flowline and D. TW depth with respect to D is unconsequential as long as the above conditions are true.

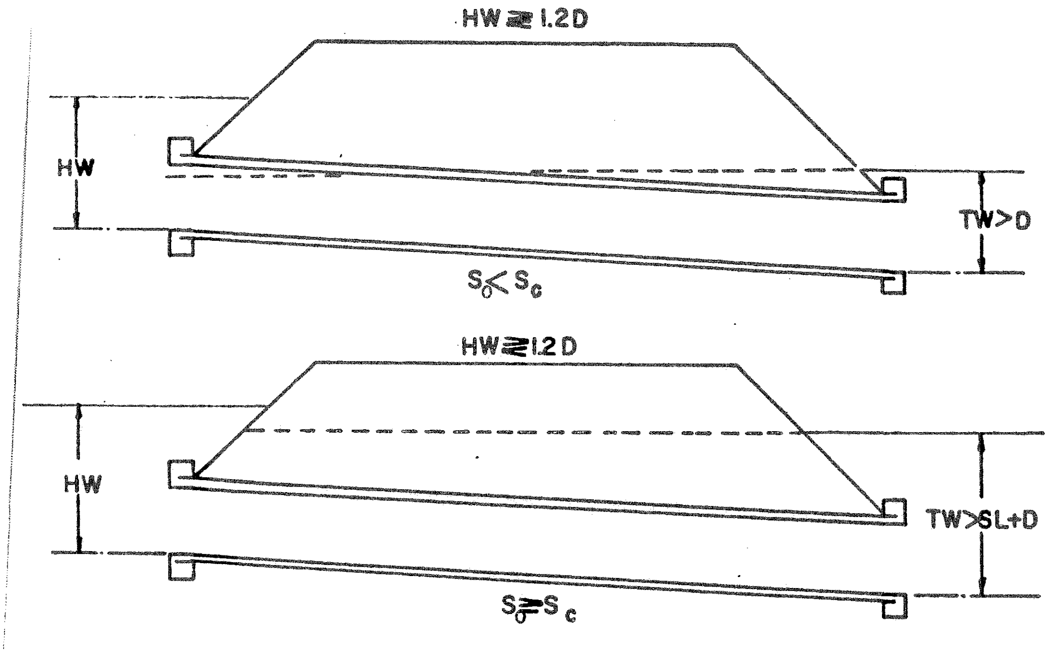
This condition is a common occurrence for culverts in rolling or mountainous country. The control for this may be at the entrance or the outlet or control may vaciliate between the two (slug flow).

For this reason, HW is determined for both entrance control and outlet control and the higher of the two determinations be used. Entrance control HW is determined from empirical curves in the form of nomographs (see figures 8-3, 8-8, 8-9, 8-15, and 8-20). Outlet control HW is determined by procedures indicated for Type IVA or Type IVB (depending on TW depth with respect to D).

If TW depth is less than D the outlet velocity should be based on TW depth. If TW depth is greater than D outlet velocity should be based on full flow at the outlet.

Type IVA

Culvert Flowing Full With Submerged Outlet



Conditions

(Submerged Outlet)

The entrance is usually submerged ($HW > 1.2D$) ,The slope at design discharge is less than critical slope ($S_0 < S_c$) and TW depth is greater than $D (TW > D)$. The tailwater completely submerges the outlet or the slope at design discharge is greater than or equal to critical slope ($S_0 \geq S_c$) and TW is greater than the sum of the vertical drop in the culvert from the upstream flowline to the downstream flowline and $D (TW > S_0 L + D)$

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.

$HW = H + TW - S_0 L$

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. $H = h_v + h_e + h_f$

where: h_v = velocity head $\frac{V^2}{2g}$

where: V is based on full flow in culvert

where: h_e = entrance head $K_e h_v$

where: h_f = friction head $= S_f L$

where: S_f is based on full flow in culvert

TW = Tailwater depth in feet

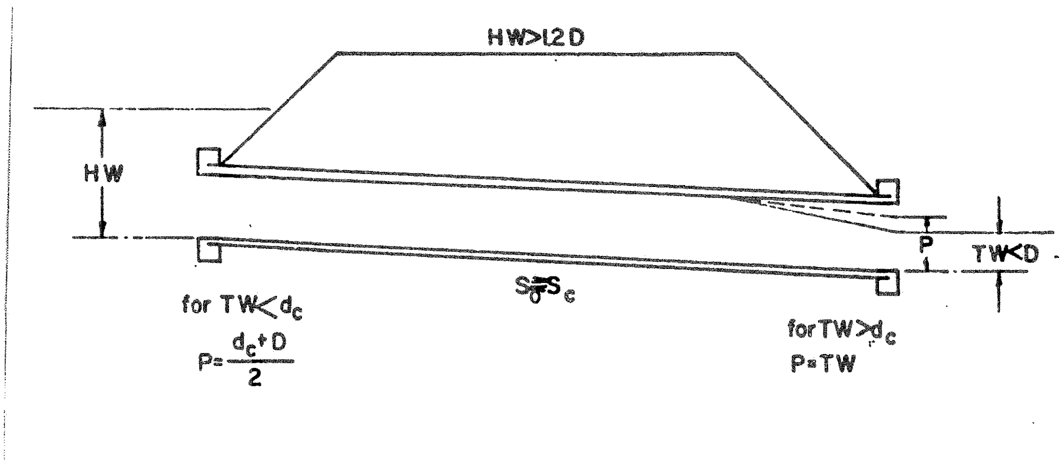
S_o = Slope of culvert in feet per foot

L = Length of culvert in feet.

Type IVB

Culvert Flowing Full

With Partially Submerged Outlet



Conditions

(Partially Submerged Outlet)

The entrance is submerged $(HW > 12D)$.
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. $H = h_v + h_e + h_f$

where: h_v = velocity head $\frac{V^2}{2g}$

where: V is based on full flow in culvert

where: h_e = entrance head $K_e h_v$

where: h_f = friction head = $S_f L$

where: S_f is based on full flow in culvert

$P = \frac{(d_c + D)}{2}$ if TW depth is less than critical depth at design discharge. If TW is greater than critical depth, then $P = TW$.

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.

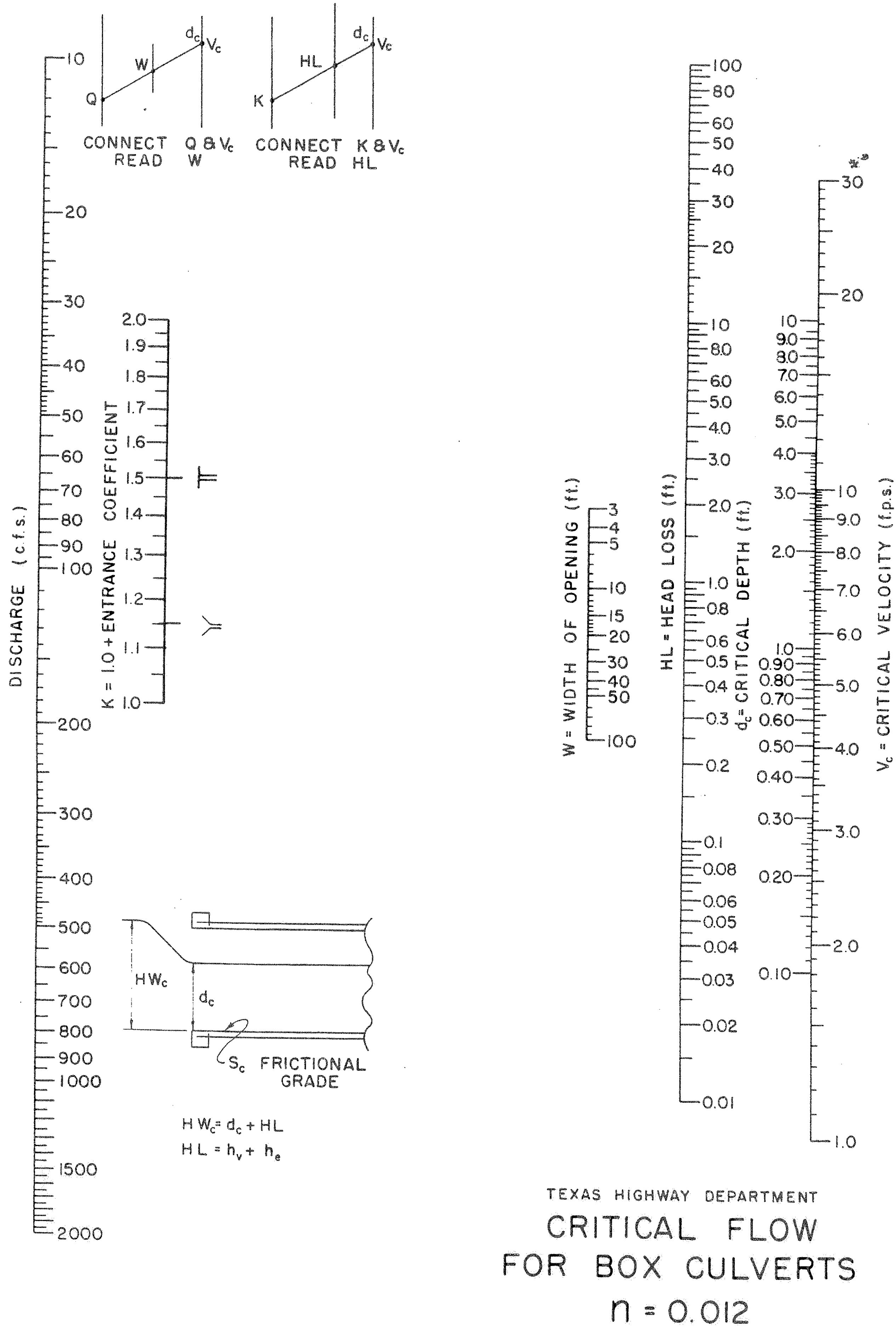

CONNECT Q & Vc
READ W
CONNECT K & Vc
READ HL
DISCHARGE (c.f.s.)
K = 1.0 + ENTRANCE COEFFICIENT
W = WIDTH OF OPENING (ft.)
HL = HEAD LOSS (ft.)
dc = CRITICAL DEPTH (ft.)
Vc = CRITICAL VELOCITY (f.p.s.)
HWc
dc
Sc FRICTIONAL GRADE
HWc = dc + HL
HL = hv + he
TEXAS HIGHWAY DEPARTMENT
CRITICAL FLOW
FOR BOX CULVERTS
n = 0.012

Figure 8-1

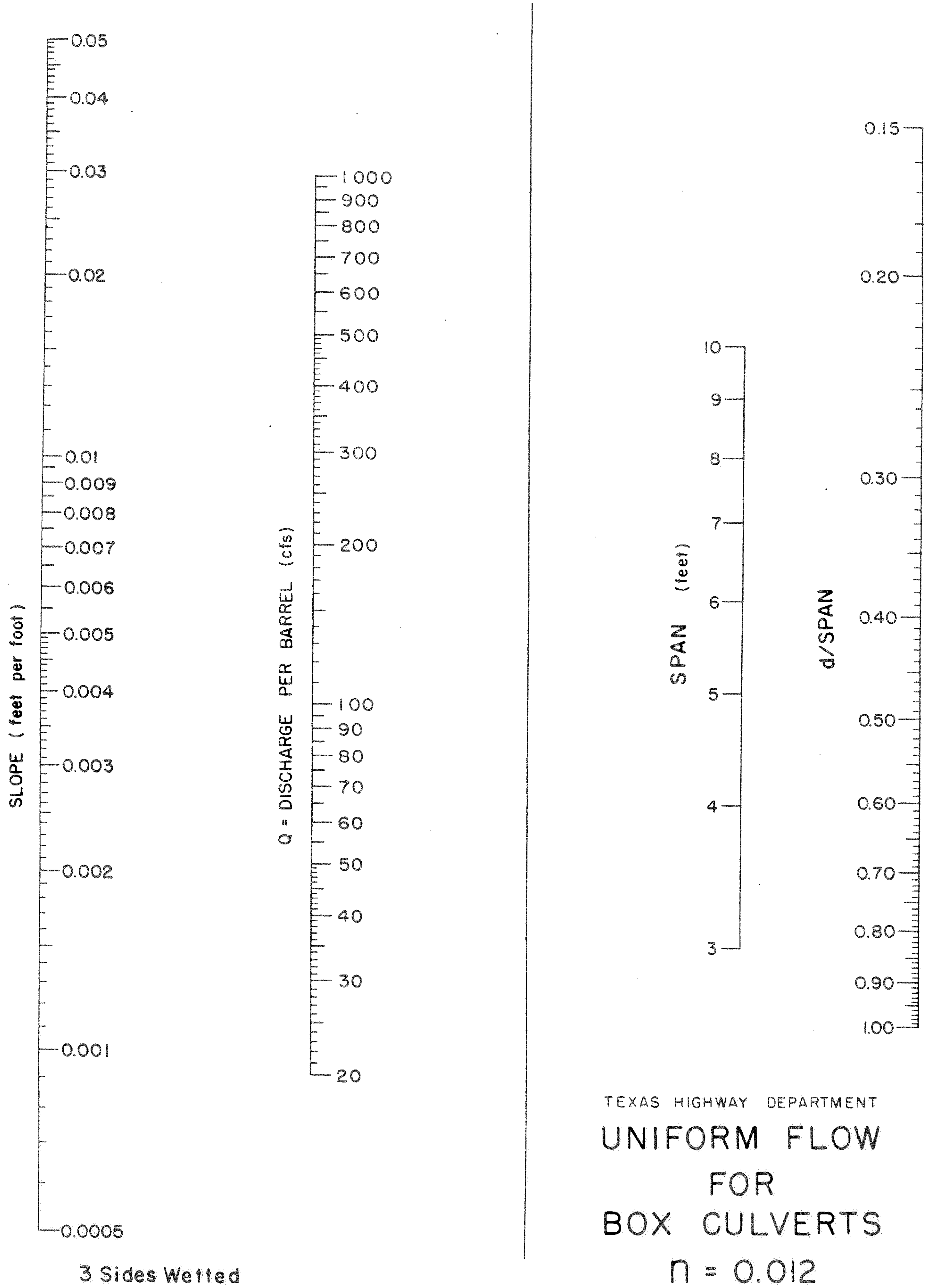
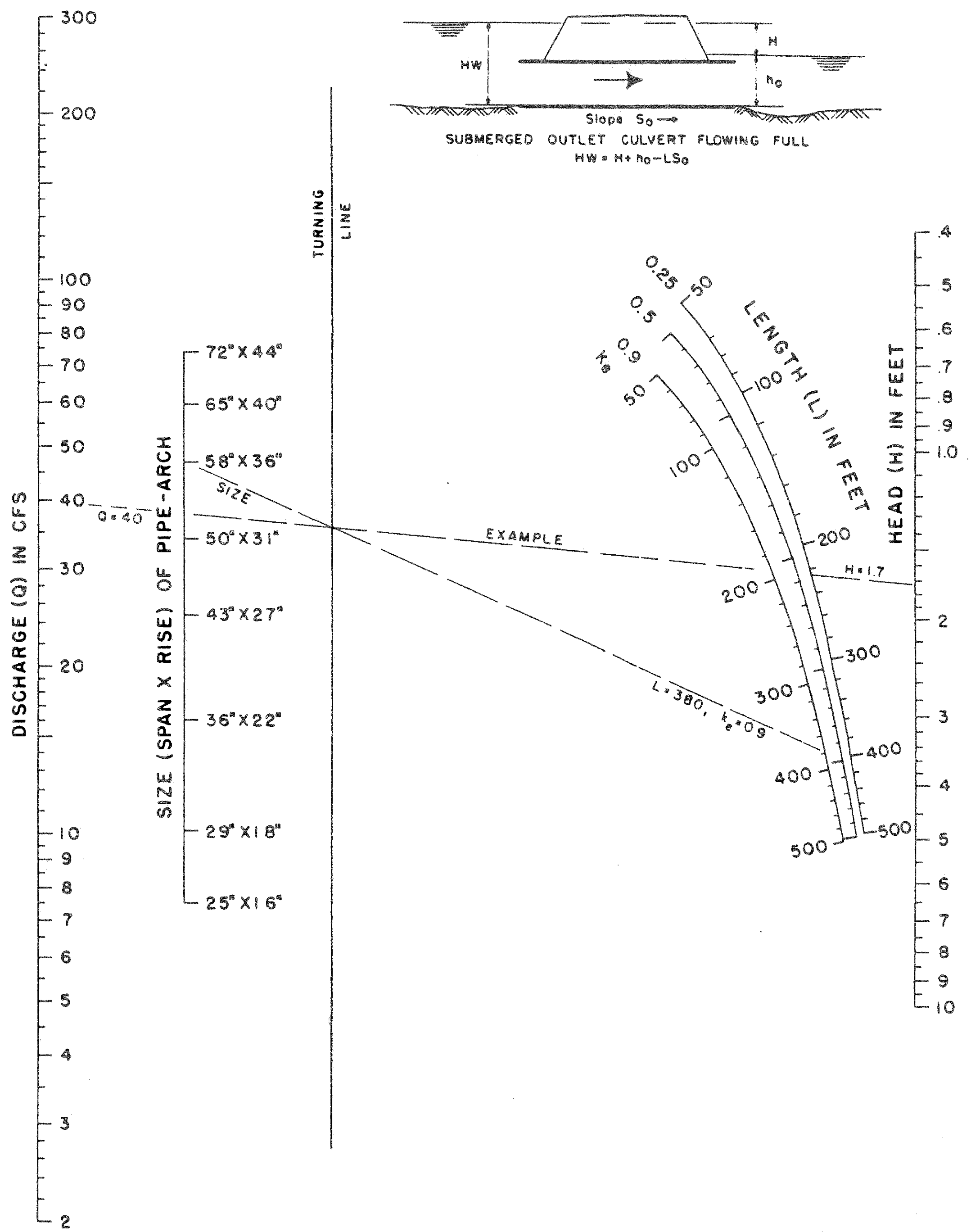

0.05
0.04
0.03
0.02
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0005
SLOPE (feet per foot)
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
Q = DISCHARGE PER BARREL (cfs)
10
9
8
7
6
5
4
3
SPAN (feet)
0.15
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
d/SPAN
3 Sides Wetted
TEXAS HIGHWAY DEPARTMENT
UNIFORM FLOW
FOR
BOX CULVERTS
n = 0.012

Figure 8-2



HEAD FOR
STANDARD C. M. PIPE-ARCH CULVERTS
FLOWING FULL
n=0.024

B.P.R.

Figure 8-21