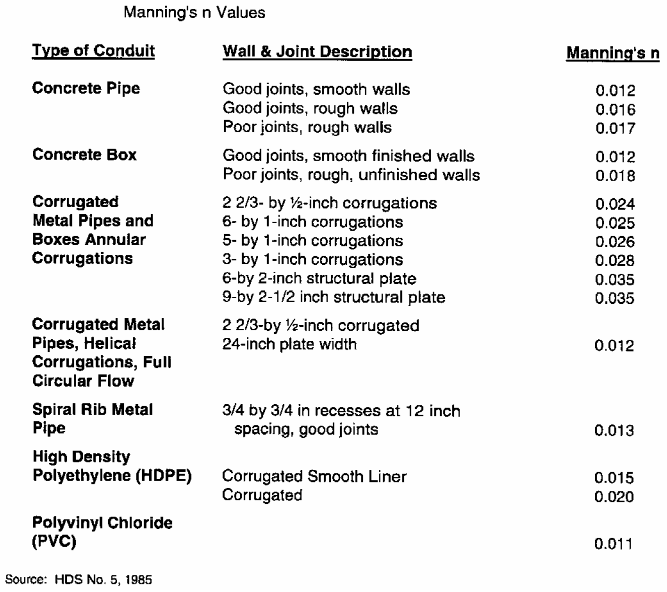
Culverts

A culvert is a short conduit that coveys stormwater under an embankment. The main factors affecting the capacity of a given culvert include some or all of the following:

- Allowable upstream water depth (headwater – HW) . This is typically linked to the top of the embankment or to other upstream structures that must be protected from flooding.
- Downstream water surface elevation (tailwater – TW). The tailwater elevation is determined by conditions downstream. Undersized culverts, debris or obstructions may back up water into the outlet of the culvert. Frequently, the tailwater may be taken to be normal depth, as predicted by the Manning equation. Backwater calculations may also be used to determine the TW.
- Slope (s) Culverts are typically constructed on grade, following the natural slope of the existing channel.
- Culvert material. Culvert material include concrete and CMP. See the table below for recommended Manning's roughness coefficients.



Manning's n Values

Type of Conduit	Wall & Joint Description	Manning's n
Concrete Pipe	Good joints, smooth walls Good joints, rough walls Poor joints, rough walls	0.012 0.016 0.017
Concrete Box	Good joints, smooth finished walls Poor joints, rough, unfinished walls	0.012 0.018
Corrugated Metal Pipes and Boxes Annular Corrugations	2 2/3- by ½-inch corrugations 6- by 1-inch corrugations 5- by 1-inch corrugations 3- by 1-inch corrugations 6-by 2-inch structural plate 9-by 2-1/2 inch structural plate	0.024 0.025 0.026 0.028 0.035 0.035
Corrugated Metal Pipes, Helical Corrugations, Full Circular Flow	2 2/3-by ½-inch corrugated 24-inch plate width	0.012
Spiral Rib Metal Pipe	3/4 by 3/4 in recesses at 12 inch spacing, good joints	0.013
High Density Polyethylene (HDPE)	Corrugated Smooth Liner Corrugated	0.015 0.020
Polyvinyl Chloride (PVC)		0.011

Source: HDS No. 5, 1985

- Length (L).
- Entrance geometry. This includes headwalls, wingwalls, alignment and culvert edge configuration.

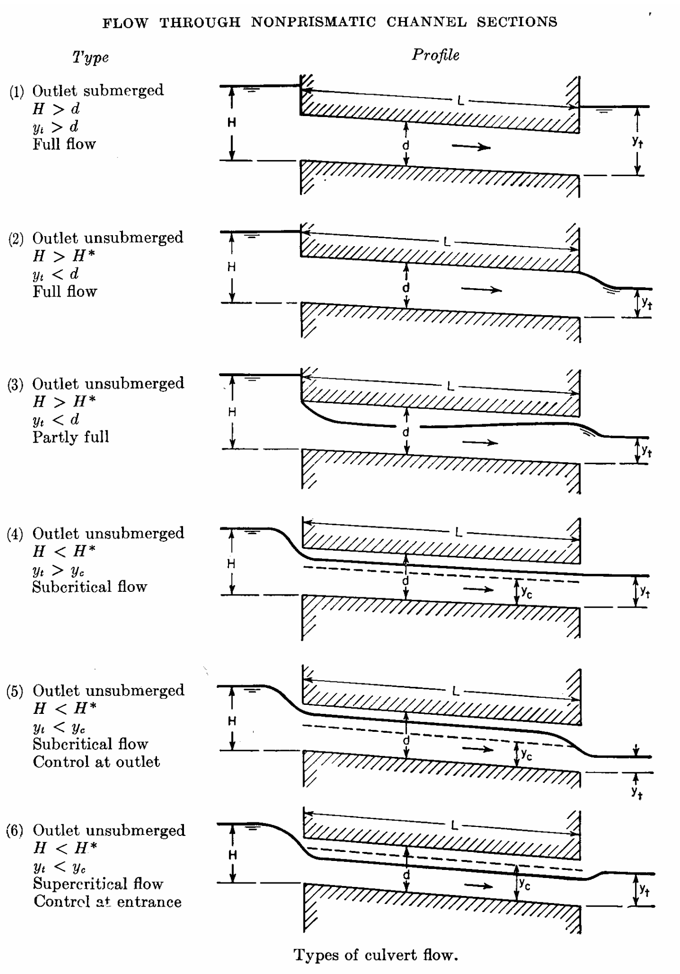
Design Considerations

- Maximum velocity for CMP is 15 ft/s
- Minimum velocity 2.5 ft/s for 2-year event
- Maximum slopes: $S_{concrete}$=10%, S_{CMP}=14%
- Maximum fall is 10 ft

- Recommended freeboard 18”
- For flow area less than 30 ft2 HW/D <= 1.5
- For flow area greater than 30 ft2 HW/D <= 1.2
- Maximum outlet velocity consistent with channel stability requirements
- Upstream channel apron should extend at least 1 diameter.
- Concrete culvert recommended
    - under roadway
    - for slope < 1%
    - for all flowing streams
- Outlet protection required for the 25 year storm

Hydraulics of Culverts

The defining hydraulic feature of a culvert is that it may or may not flow full. This distinction has some practical implications and presents the designer with some difficulties. Specifically, normal flow cannot be assumed in a culvert and the Manning equation is not appropriate. There are, in fact, many different flow patterns that develop in culverts, depending on such the factors listed above. In practice, flow may be classified into six types as shown below. (Chow)



FLOW THROUGH NONPRISMATIC CHANNEL SECTIONS

Type *Profile*

(1) Outlet submerged
$H > d$
$y_t > d$
Full flow

(2) Outlet unsubmerged
$H > H^*$
$y_t < d$
Full flow

(3) Outlet unsubmerged
$H > H^*$
$y_t < d$
Partly full

(4) Outlet unsubmerged
$H < H^*$
$y_t > y_c$
Subcritical flow

(5) Outlet unsubmerged
$H < H^*$
$y_t < y_c$
Subcritical flow
Control at outlet

(6) Outlet unsubmerged
$H < H^*$
$y_t < y_c$
Supercritical flow
Control at entrance

Types of culvert flow.

Although there are six flow types, there are two major flow conditions that determine the hydraulics of culvert flow. They are *Inlet Control* and *Outlet Control.* A culvert is considered to operate under inlet control when the control section is located near the inlet to the pipe. Outlet control occurs when the control section is near the outlet to the culvert. A control section is a point in the channel that establishes either the upstream or downstream depth, depending on the state of flow. Equations are available to evaluate the hydraulics of culverts, but the computations involved can be quite involved. There are, however, design aids available to assist in the process of culvert design and analysis. Different design aids are used depending on whether a culvert flows under inlet or outlet control. (Inlet Control Nomographs & Outlet Control Nomographs)

Inlet Control

Under inlet control, the barrel of the pipe can convey more flow than can enter the pipe. Therefore, for a given HW only factors affecting the inlet of the culvert influence the capacity. These would include inlet geometry, diameter, and headwater. Specifically, the configuration of the inlet edge is a major factor in determining the performance of the culvert. Beveled edges, for instance, can significantly increase culvert capacity. The effect of edge configuration is incorporated in a term called the entrance loss coefficient (Ke). The table below gives recommended values for this parameter. (ARC)

Inlet Coefficients

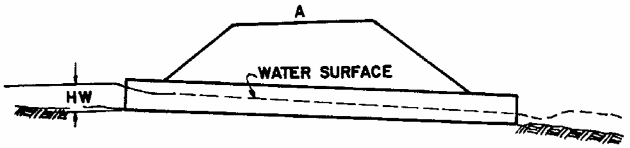
Type of Structure and Design of Entrance	Coefficient K_e
Pipe, Concrete	
Projecting from fill, socket end (grove-end)	0.2
Projecting from fill, square cut end	0.5
Headwall or headwall and wingwalls	
Socket end of pipe (groove-end)	0.2
Square-edge	0.5
Rounded [radius = 1/12(D)]	0.2
Mitered to conform to fill slope	0.7
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side- or slope-tapered inlet	0.2
Pipe, or Pipe-Arch, Corrugated Metal[1]	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls square-edge	0.5
Mitered to fill slope, paved or unpaved slope	0.7
*End-Section conforming to fill slope	0.5
Beveled edges, 33.7° or 45° bevels	0.2
Side- or slope-tapered inlet	0.2
Box, Reinforced Concrete	
Headwall parallel to embankment (no wingwalls)	
Square-edged on 3 edges	0.5
Rounded on 3 edges to radius of [1/12(D)] or beveled edges on 3 sides	0.2
Wingwalls at 30° to 75° to barrel	
Square-edged at crown	0.4
Crown edge rounded to radius of [1/12(D)] or beveled top edge	0.2
Wingwalls at 10° or 25° to barrel	
Square-edged at crown	0.5
Wingwalls parallel (extension of sides)	
Square-edged at crown	0.7
Side- or slope-tapered inlet	0.2

[1] Although laboratory tests have not been completed on K_e values for High-Density Polyethylene (HDPE) pipes, the K_e values for corrugated metal pipes are recommended for HDPE pipes.

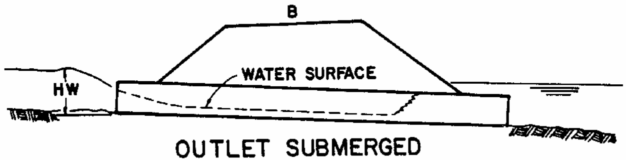
* Note: End Section conforming to fill slope, made of either metal or concrete, are the sections commonly available from manufacturers. From limited hydraulic tests they are equivalent in operation to a headwall in both inlet and outlet control.

Source: HDS No. 5, 1985

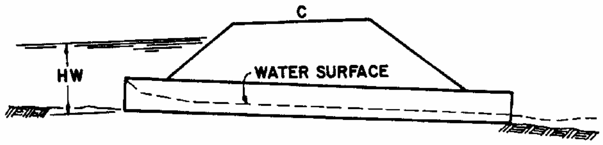
The figure below shows various types of inlet control. (FHWA –IP-85-15)



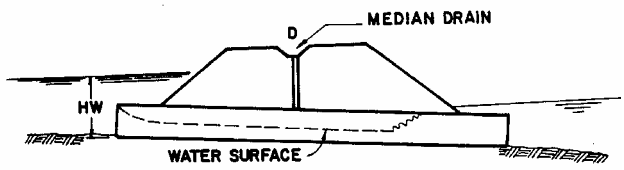
OUTLET UNSUBMERGED



OUTLET SUBMERGED
INLET UNSUBMERGED



INLET SUBMERGED

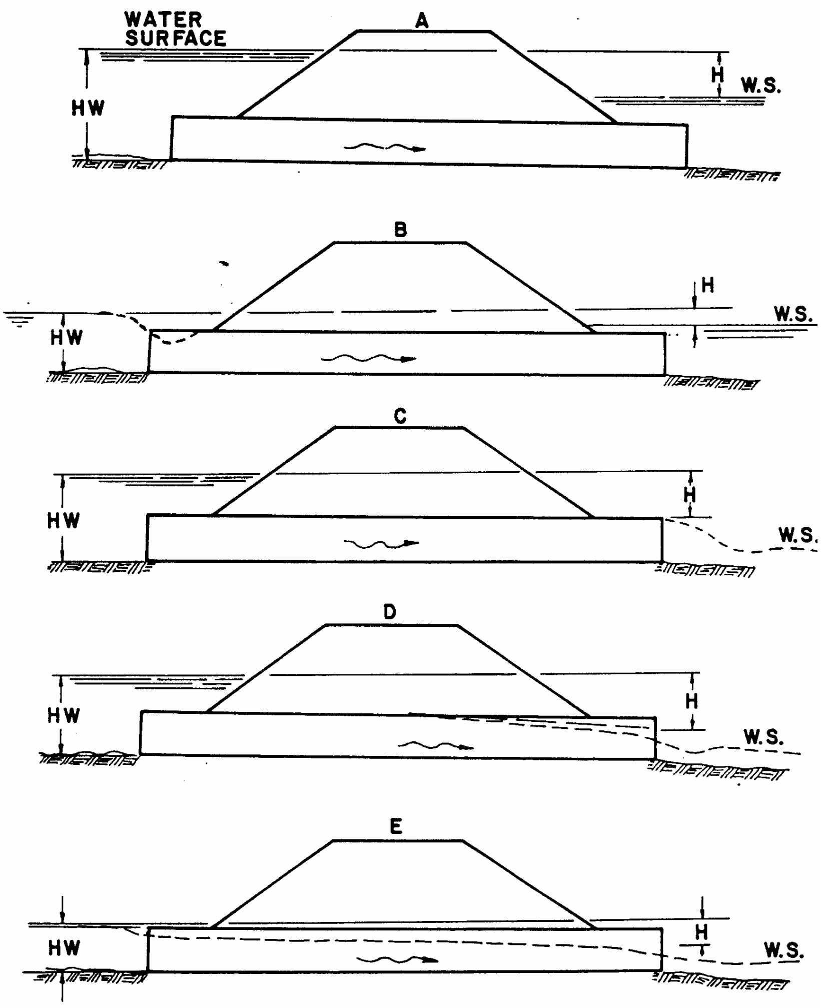


OUTLET SUBMERGED

Types of inlet control.

Outlet Control

When a culvert operates under outlet control, all of the factors listed above influence the capacity of the culvert. Thus, HW, TW, L, s, material, and diameter all come into play. The most common cause of outlet control is flooding (submergence) of the downstream end of the pipe as shown below. (FHWA –IP-85-15)



Types of outlet control.

Design Procedure (ARC)

- Develop Design Data
  - Peak flow
  - Slope
  - Length
  - Tailwater
  - Inlet loss coefficient
  - Headwater allowable

- Approximate a trial culvert size based on an assumed velocity of 3 to 5 ft/s using Q=AV or

$$D = \sqrt{\frac{4Q}{\Pi v^2}}$$

- Determine the required HW to pass the design peak flow rate for both inlet and outlet control conditions

Inlet Control

1) Enter the inlet control nomogrpah with D and Q and determine the ratio of HW to the diameter of the pipe (HW/D)
2) Compute HW (HW/D x D) and compare to the allowable HW. Revise culvert size, if required. (Before proceeding to check outlet control)

Outlet Control

1) Enter outlet control nomograph with L, entrance loss coefficient, K_e, and D from above.
2) Determine the energy loss term, H, using the nomograph. (Note that the nomograph does not give the HW. It yields the energy lost the culvert.)
3) Determine the height of the control section, h_o, using the larger of

$$ho = \text{tailwater}$$

OR

$$h_o = 0.5(Critical\ Dpeth + D)$$

Critical depth may be determined using equations or graphs at the end of this section. In the case of a rectangular section D=H. Critical depth cannot exceed the height of the culvert.

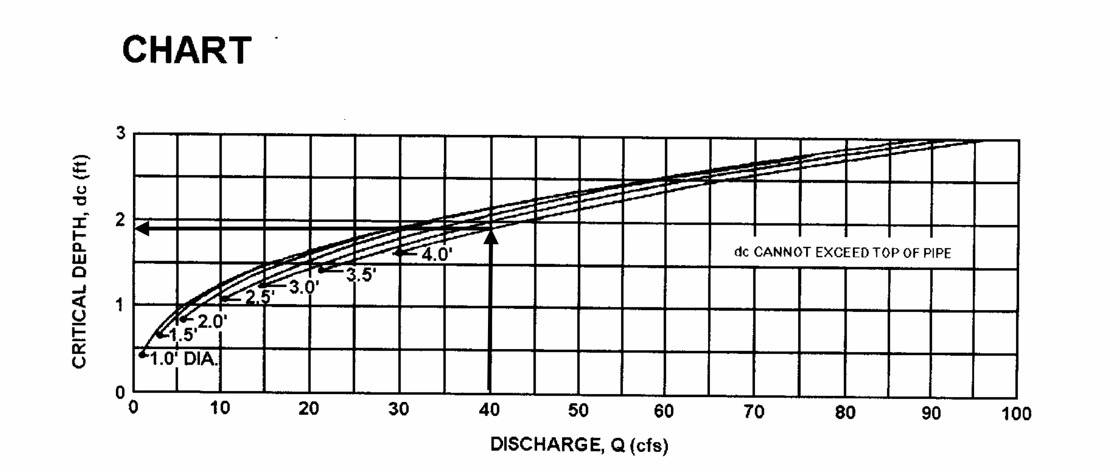
4) Compute the outlet control HW required using

$$HW = H + H_o - LS$$

- Compare the HW computed for inlet and outlet control. If inlet HW is larger, then the selection is complete. If outlet control governs, and the HW is above the allowable, increase the culvert size and recomputed the HW for outlet control.

Determine the critical depth for a 48 inch circular pipe conveying 40 cfs. Use Chart 4 and Chart 16

From Chart 4 with Q=40 cfs



Critical Depth dc=1.9 ft

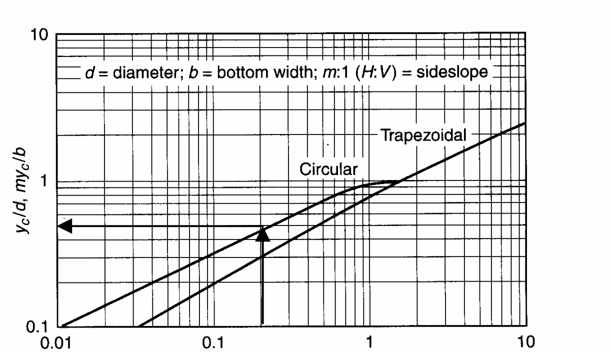
From Chart 16.

Calculate Z

$$Z = \frac{Q}{g^{1/2} d^{5/2}} = \frac{40}{\sqrt{32.2}(4)^{5/2}} = 0.22$$

From Graph with z = 0.22

$$\frac{Y}{d} = 0.49 \text{ or } Y = (0.49)(4\text{ ft}) = 1.96\text{ ft}$$



Example
Determine the critical depth in a 6 ft trapezoidal channel carrying 50 cfs. The side-slopes are 2:1 (H:V)

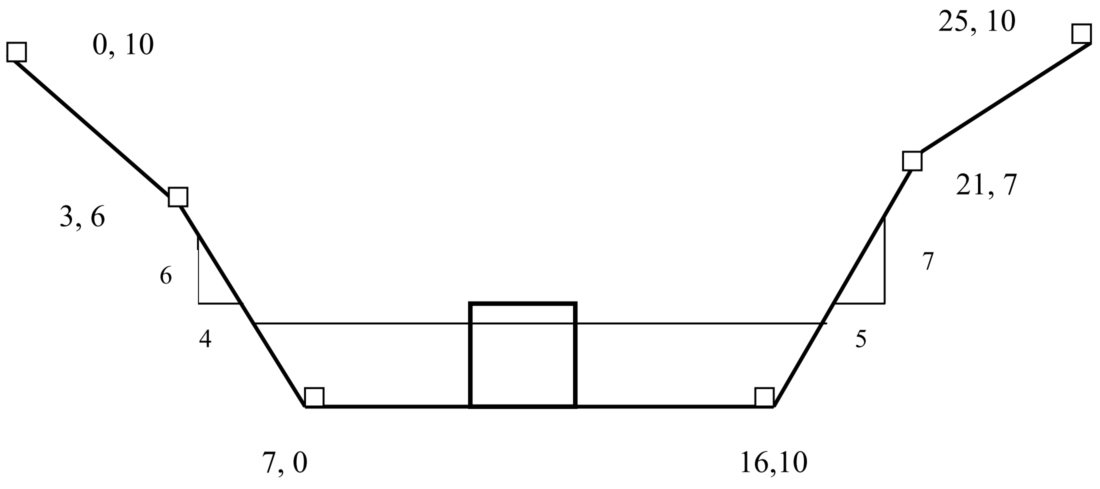
$$Z = \frac{Qm^{3/2}}{g^{1/2}b^{5/2}} = \frac{50(2)^{2/3}}{g^{1/2}6^{5/2}} = 0.28$$

From Fig 16 with Z=0.28

$$\frac{my_c}{b} = \frac{2(y_c)}{6} = 0.37$$

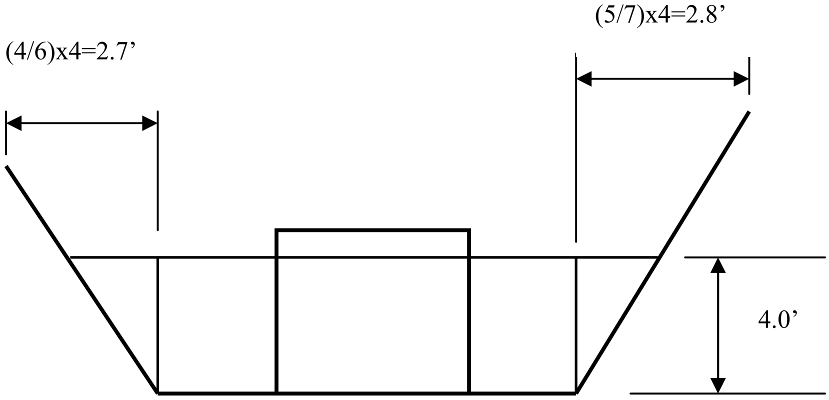
$$y_c = \frac{6(0.37)}{2} = 1.1ft$$

Example
A 4x4 box culvert is to be placed in the channel given below. Determine the tailwater (TW) depth and the height of the control secton (h_0) The channel slope is 0.007 and the Manning roughness coefficient is 0.035. The channel is defined by station (x) and elevation (Y) values as shown. The flow in the channel is 200 cfs. Also determine the headwater required to convey 200 cfs through the pipe. (L=200 ft)



Solution by hand calculations requires a trial and error method. Assume a water surface and calculate the flow rate. Revise the water surface until Q=200 cfs.

First trial assume WS=4.0 ft



Calculate wet perimeter, area, hydraulic radius and flow rate.

$$WP = \sqrt{2.7^2 + 4^2} + 9 + \sqrt{2.8^2 + 4^2} = 4.8 + 9.0 + 4.9 = 18.7\ ft$$

$$A = \frac{1}{2}(2.7x4) + 9(4) + \frac{1}{2}(2.8x4) = 47.05\ ft^2$$

$$R = \frac{47.0}{18.8} = 2.5'$$

$$Q = \frac{1.49}{0.035}(47.0)(2.5)^{2/3}(0.007)^{1/2} = 309 \quad \textit{Too high}\ (> 200\ cfs)$$

Revise the estimation of the water surface.

Trial and Error Solution to Mannings with Q=200 cfs				
Water Surface Elevation	Area ft^2	WP ft	R ft	Q ft^3/s
4.0	47.0	18.7	2.5	309
3.5	40.0	17.5	2.3	246
3.0	33.2	16.3	2.0	190
3.1	34.5	16.5	2.1	200

The tailwater depth in the channel is 3.1 ft.

The height of the control section (h_o) in the culvert is the larger of the tailwater or $0.5(d_c+D)$. The critical depth for a rectangular section is given by

$$d_c = \sqrt[3]{\frac{(Q/w)^2}{g}} = \sqrt[3]{\frac{(200/4)^2}{32.2}} = 4.26\ ft$$

$0.5(d_c+D).= 0.5(4.26+4)=4.13$, but the control section can not exceed 4’ so

The height of the control section is therefore 4.0 ft

In order to determine the required headwater, we must evaluate both inlet and outlet control conditions.

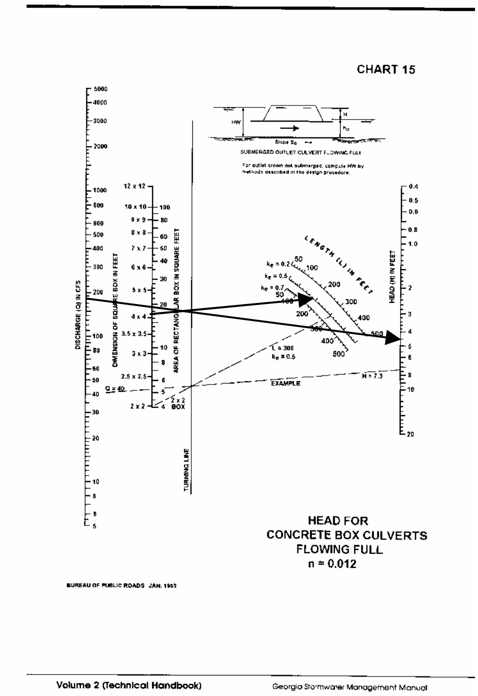
Inlet control:

Q/B = 200/4 = 50 cfs/ft

From Inlet control nomograph for box culverts ⟶ HW/D = 2.3

HW = 2.3(D) = 2.3(4) = 9.2 ft

Outlet control (Length = 200 ft, n=0.012, square edged entrance $K_e = 0.5$)



H = 5.5 ft (Energy loss in the culvert)

$$HW = H + ho - LS$$

$$HW = 5.5' + 4.0 - 200(0.007) = 8.1\ \text{ft}$$

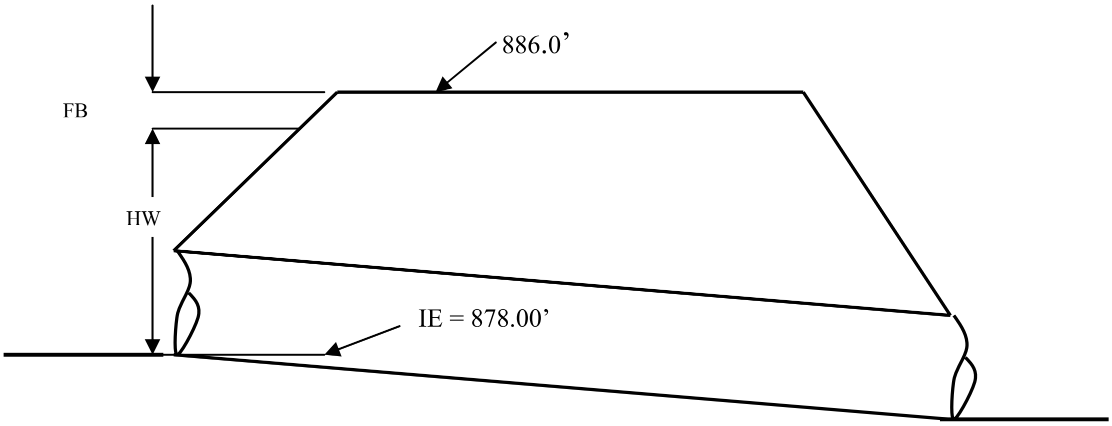
The required HW depth is the larger of HW_{inlet} or $HW_{outlet} \longrightarrow$

$$HW = 9.2\ \text{ft}$$

Example

Select a CMP culvert(s) to carry 220 cfs (L=200 ft). The low point of the road is 886.00' and the required freeboard is 1.0 ft. The streambed elevation is 878.00' and the required cover is 4.0 ft. The channel has a slope of 5% and n=0.03

The downstream channel is a 10 ft wide trapezoidal channel with 2:1 (H:V) sideslopes and a Manning's roughness of 0.03



Determine the allowable headwater

$$HW = 886.00 - 1.0 - 878.00 = 7.0\ \text{ft}$$

Determine the tailwater depth using Manning's

TW = 1.43 ft (Calculations not shown)

Try 2 circular CMPs. Maximum culvert height is 886.00 – 4.0 – 878.00 = 4.0 ft. Design using Q/2 = 110 cfs. Approximate diameter using v= 4.5 ft/s and

$$D = \sqrt{\frac{4Q}{\Pi v^2}} = \sqrt{\frac{4(110)}{\Pi (4.5)^2}} = 2.6\ ft = 31''$$

Consider two 36” CMPs

Check Inlet Control

HW/D = 4.0

HW = 4(36”/12) = 12 ft. ⟶ Too high. Increase diameter.

Consider two 48” CMPs

- Check Inlet Control

  Q/2 = 110 cfs

  HW/D = 1.45 ⟶

  HW = 1.45(48/12) = 6.54 ft. OK

- Check Outlet Control

  From Full Flowing CMP Nomograph (L=200’, Ke=0.5, Q=73.3 cfs)
  H = 8.0 ft

  Determine ho. (Larger of 0.5(dc+d) or TW)

  Determine dc for the pipe using chart 16 (or Chart 4)

$$Z = \frac{Q}{g^{1/2} d^{5/2}} = \frac{110}{\sqrt{32.2}(4)^{5/2}} = 0.6$$

$$\frac{Y_c}{d} = 0.55 \text{ or Y=(0.55)(4 ft) = 2.2 ft}$$

$$\frac{1}{2}(d_c + D) = \frac{1}{2}(2.2 + 4) = 3.1'$$

So TW=1.43 and 0.5(dc+D)=3.1 ft. ⟶ h_o=3.1

Calculate the outlet control $HW=H+h_o-LS$

$$HW=8 + 3.1 - 200(0.007) = 1.1 \text{ ft}$$

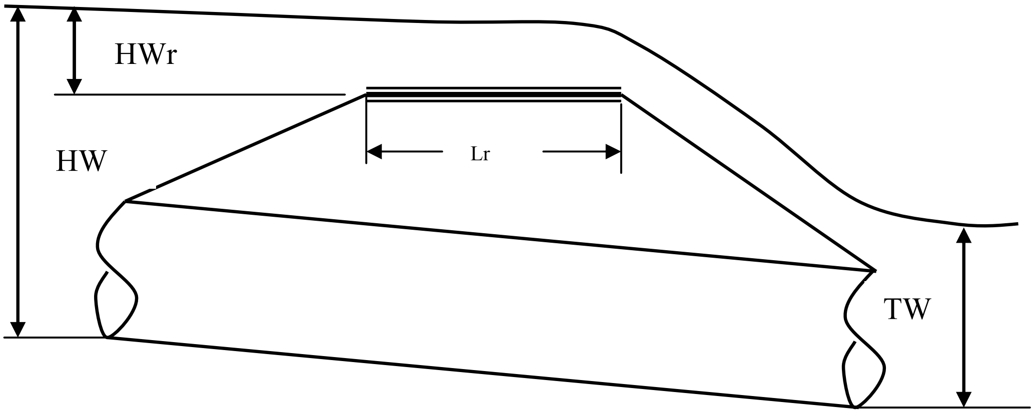
The HW_{inlet} is the larger and is assumed to control. Since it is less than the HW allowable, two 48-inch culverts will work.

Roadway Overtopping

Where water flows both over the roadway and through a culvert (see Figure 8-14), a definition of hydraulic characteristics requires a flow distribution analysis. This is a common problem where a discharge of high design frequency (low probability of occurrence) is applied to a facility designed for a lower design frequency.

Overtopping with low TW (Free discharge)

If the TW is lower than the critical depth then the TW will not affect the headwater depth upstream. Critical depth over the roadway can be approximated using 0.67Hh or can be calculated using the roadway (centerline) profile. (Hand calculation of dc involves trial and error for an irregular profile and is best handled by a computer.)



The headwater depth upstream may be calculated using a trial and error method.

- Using the design discharge, assume a flow split between the culvert and the roadway that acts as a weir. One reasonable starting point is to assume a velocity 0f 5.0 ft/s in the culvert and calculate the flow.

- Develop a discharge-rating curve for the culvert considering inlet and outlet control. (Plot discharge verses water surface elevation)

- Use the discharge-rating curve to obtain the HW elevation to convey the culvert discharge assumed above. Compute the WS elevtion required.

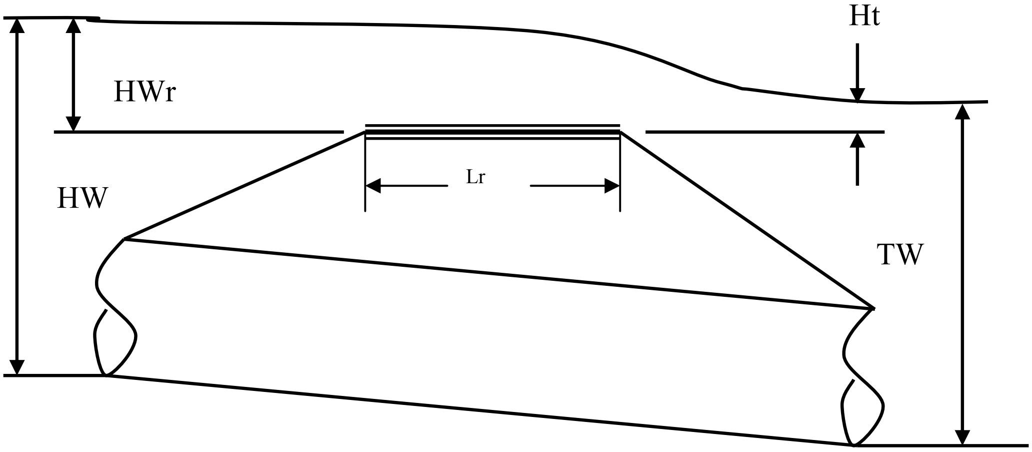
- Use the WS elevation to obtain Hh and calculate the weir flow over the roadway using the weir flow equation below (C from Chart 17, L=roadway length along road centerline, kf=1.0 for TW< dc.) Note that the discharge coefficient, C, is typically 3.0.

  $$Q = k_f C_r L(HWr)^{3/2}$$

  Check $Q_{culvert} + Q_{roadway}$. If this is less than the design discharge, decrease the flow through the culvert and recalculate the flow over the road.

- Repeat the steps above until $Q_{culvert} + Q_{roadway} = Q_{design}$

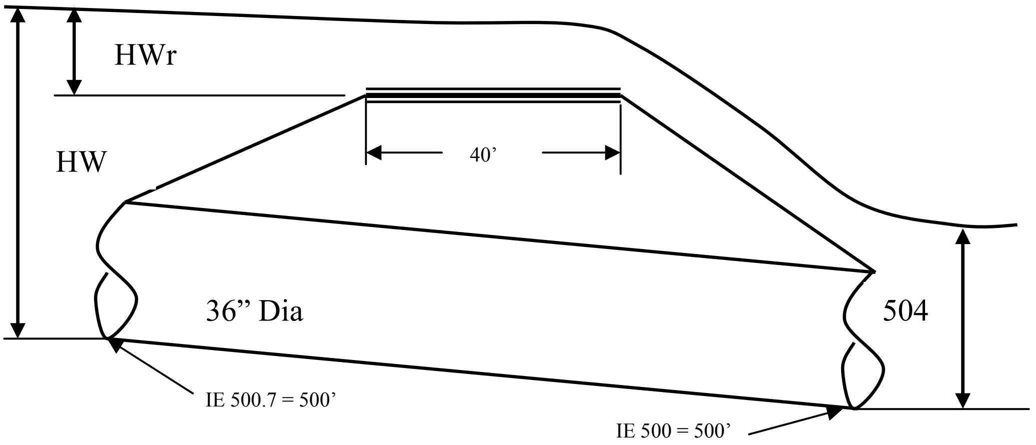
Overtopping with High TW



Overtopping in the case of a high TW (TW > dc) is similar to the case above, but the downstream submergence reduces the flow over the roadway. In this case, an adjustment factor, Kf can be obtained from the Chart 17 and applied to the weir equation.

Example

Determine the HW for the concrete culvert and roadway below. The length and slope of the culvert are 100 ft and 0.007. The TW is based on a 25-year FEMA flood elevation of 504.00



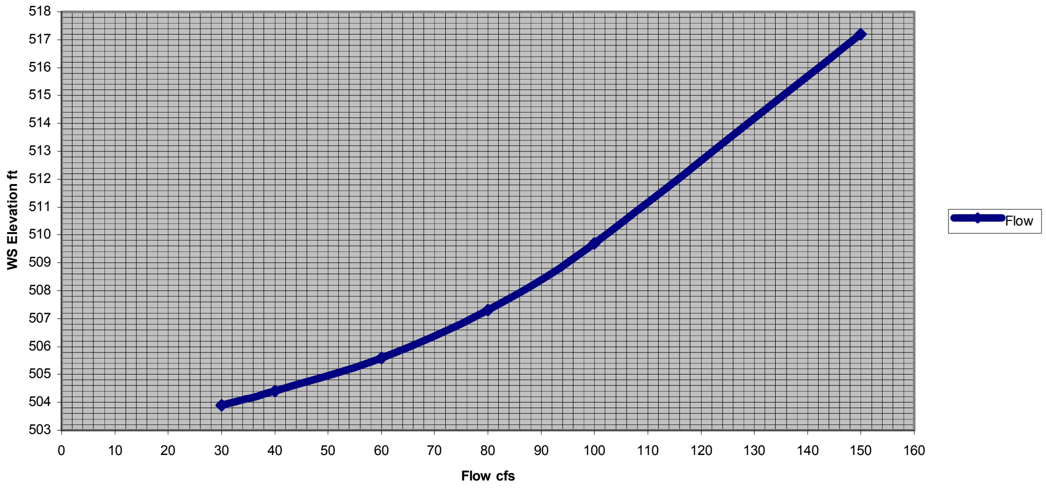
Note that the culvert is full flowing (outlet controlled) and the tailwater is lower than the roadway and hence lower than dc . The first step is to use the outlet control nomograph to construct a discharge-rating curve. Determine the energy loss in the culvert, H, in the equation below using the nomograph

$$WS = IE + HW = IE + (H + TW - LS) = H + 503.3\text{ft}$$

Q cfs	H ft	WS ft
30	0.6	503.9
40	1.1	504.7
60	2.3	505.6
80	4.0	507.3
100	6.4	509.7
150	13.9	517.2

The discharge-rating curve (DRC) is plotted on the next page

Discharge Rating Curve
26 inch RCP Outlet Control



Trial 1

Assume a flow split. $Q_{cul} = 60$ cfs
Use DRC to find WS = 505.60.
Since this is not above the roadway, there is no flow over the road
$Q_{cul} + Q_{rd} = 60$ cfs.
This is less than the design flow rate of 200 cfs.
Increase Qcul

Trial 2

$Q_{cul} = 80$ cfs
WS = 507.4
$Q_{rd} = 3.0(40\text{ ft})(WS - 507.00) = 30$ cfs
$Q_{cul} + Q_{rd} = 80 + 30 = 110$ cfs
Increase Q_{cul}

Trial 3

$Q_{cul} = 90$ cfs
WS = 508.4
$Q_{rd} = 3.0(40\text{ ft})(WS - 507.00) = 199$ cfs
$Q_{cul} + Q_{rd} = 90 + 199 = 289$ cfs
Decrease Q_{cul}

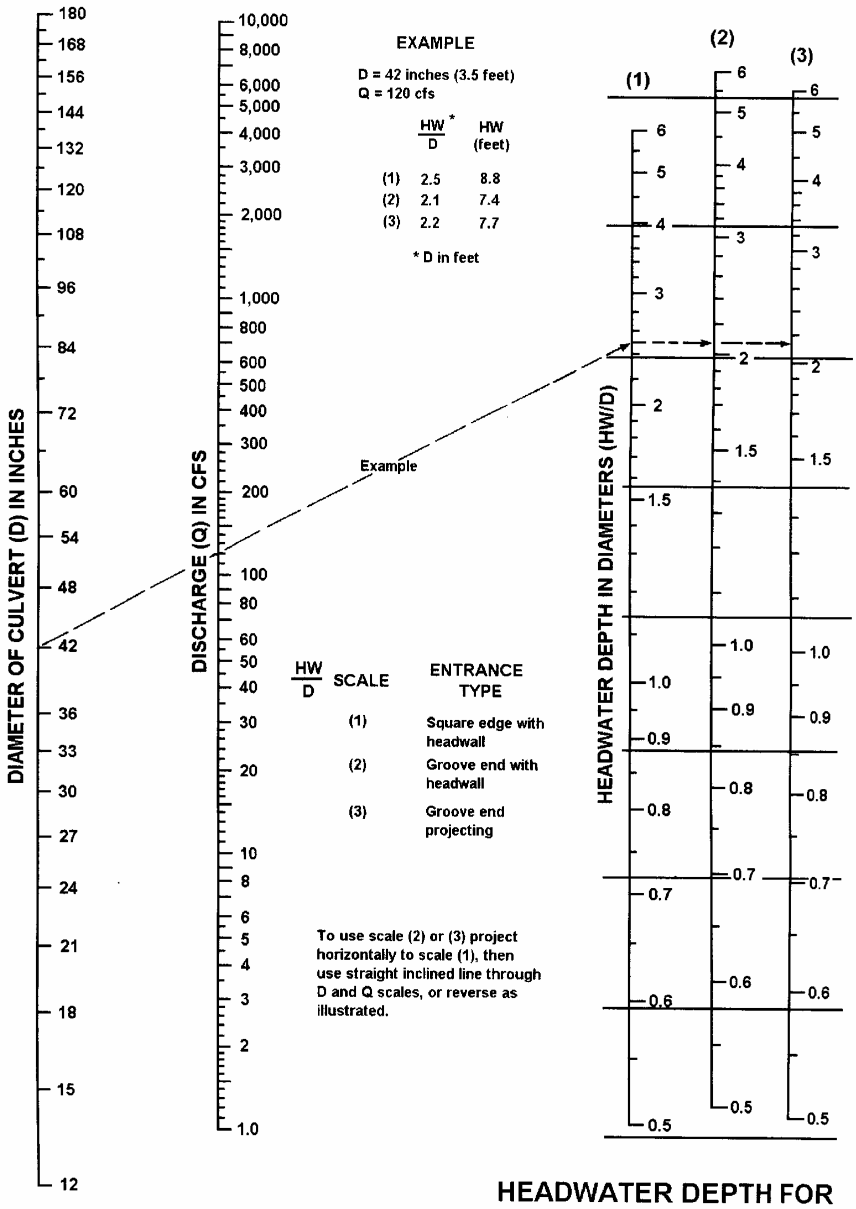
Trial 4

$Q_{cul} = 85$ cfs
WS = 508.0
$Q_{rd} = 3.0(40\text{ ft})(WS - 507.00) = 120$ cfs
$Q_{cul} + Q_{rd} = 85 + 120 = 205$ cfs ← Close enough

Culvert Design Charts and Nomographs

All of the figures in this section are from the AASHTO Model Drainage Manual, 1991.

CHART 1



EXAMPLE

D = 42 inches (3.5 feet)
Q = 120 cfs

	$\frac{HW}{D}$*	HW (feet)
(1)	2.5	8.8
(2)	2.1	7.4
(3)	2.2	7.7

* D in feet

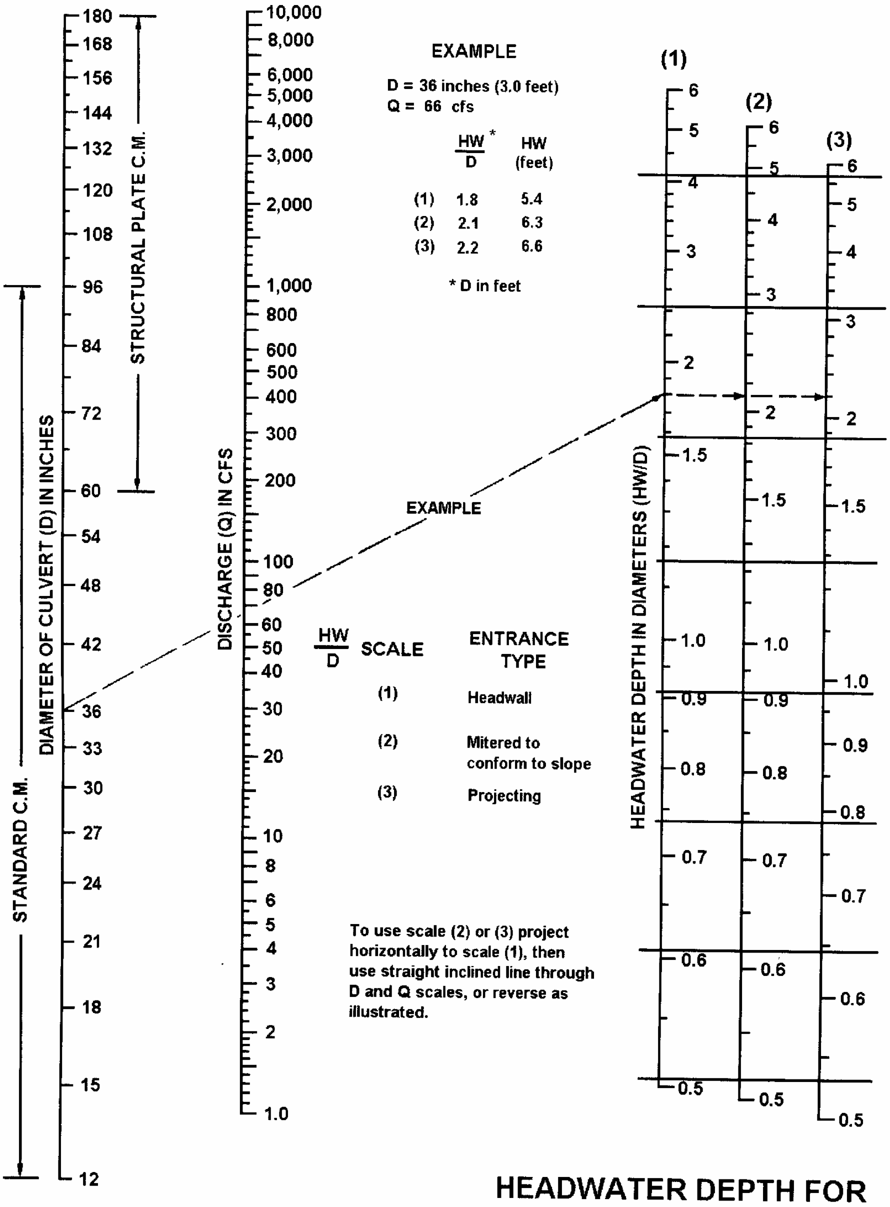
$\frac{HW}{D}$ SCALE	ENTRANCE TYPE
(1)	Square edge with headwall
(2)	Groove end with headwall
(3)	Groove end projecting

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.

BUREAU OF PUBLIC ROADS JAN. 1963
HEADWATER SCALES 2&3 REVISED MAY 1964

HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

CHART 2



EXAMPLE

D = 36 inches (3.0 feet)
Q = 66 cfs

	$\frac{HW}{D}$*	HW (feet)
(1)	1.8	5.4
(2)	2.1	6.3
(3)	2.2	6.6

* D in feet

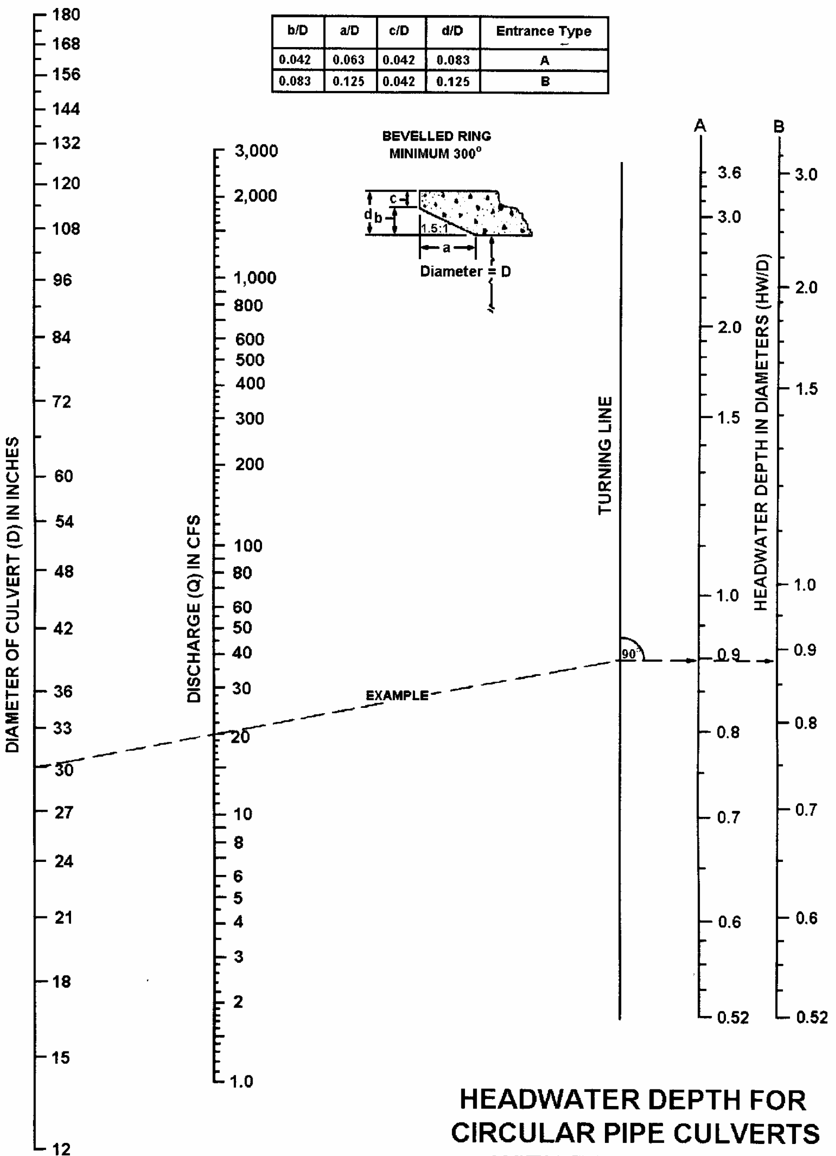
$\frac{HW}{D}$ SCALE	ENTRANCE TYPE
(1)	Headwall
(2)	Mitered to conform to slope
(3)	Projecting

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.

HEADWATER DEPTH FOR C.M. PIPE CULVERTS WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 3

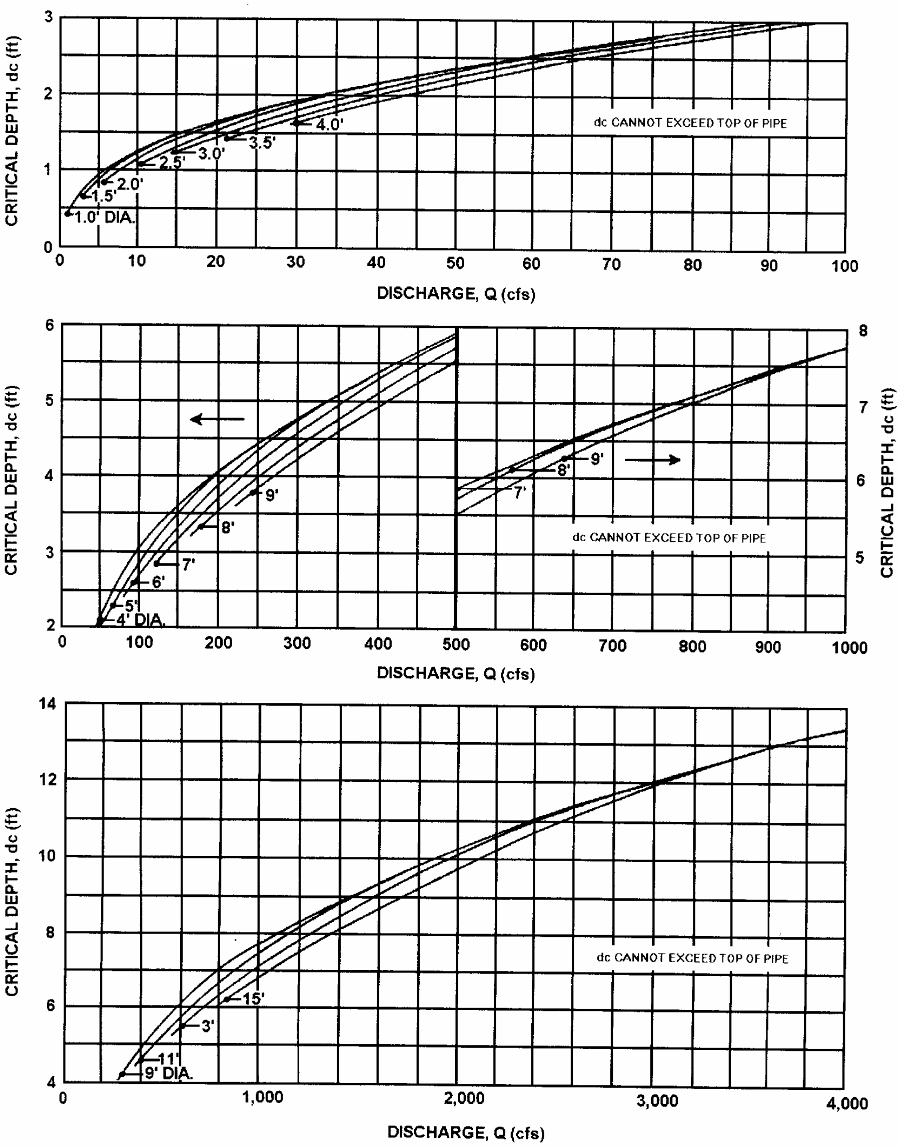


b/D	a/D	c/D	d/D	Entrance Type
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B

FEDERAL HIGHWAY ADMINISTRATION MAY 1973

HEADWATER DEPTH FOR
CIRCULAR PIPE CULVERTS
WITH BEVELED RING
INLET CONTROL

CHART 4



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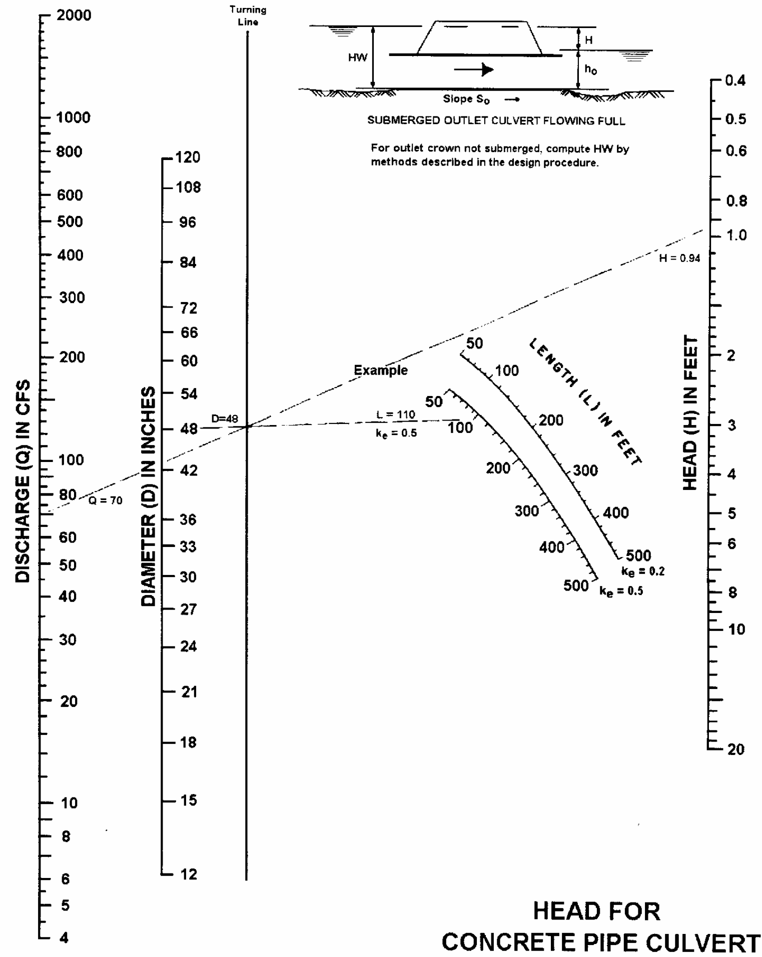
CRITICAL DEPTH
CIRCULAR PIPE

CHART 5



SUBMERGED OUTLET CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure.

HEAD FOR
CONCRETE PIPE CULVERTS
FLOWING FULL
n = 0.012

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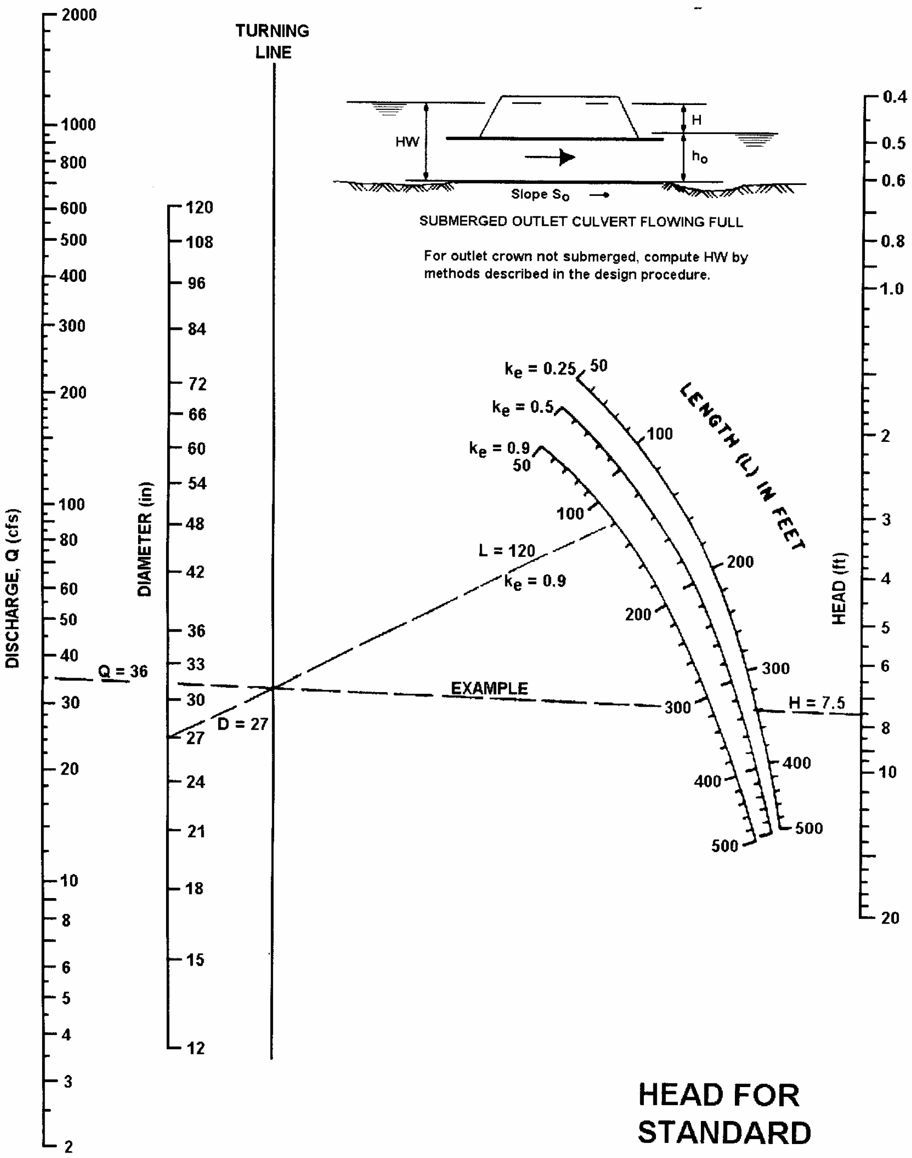
CHART 6



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

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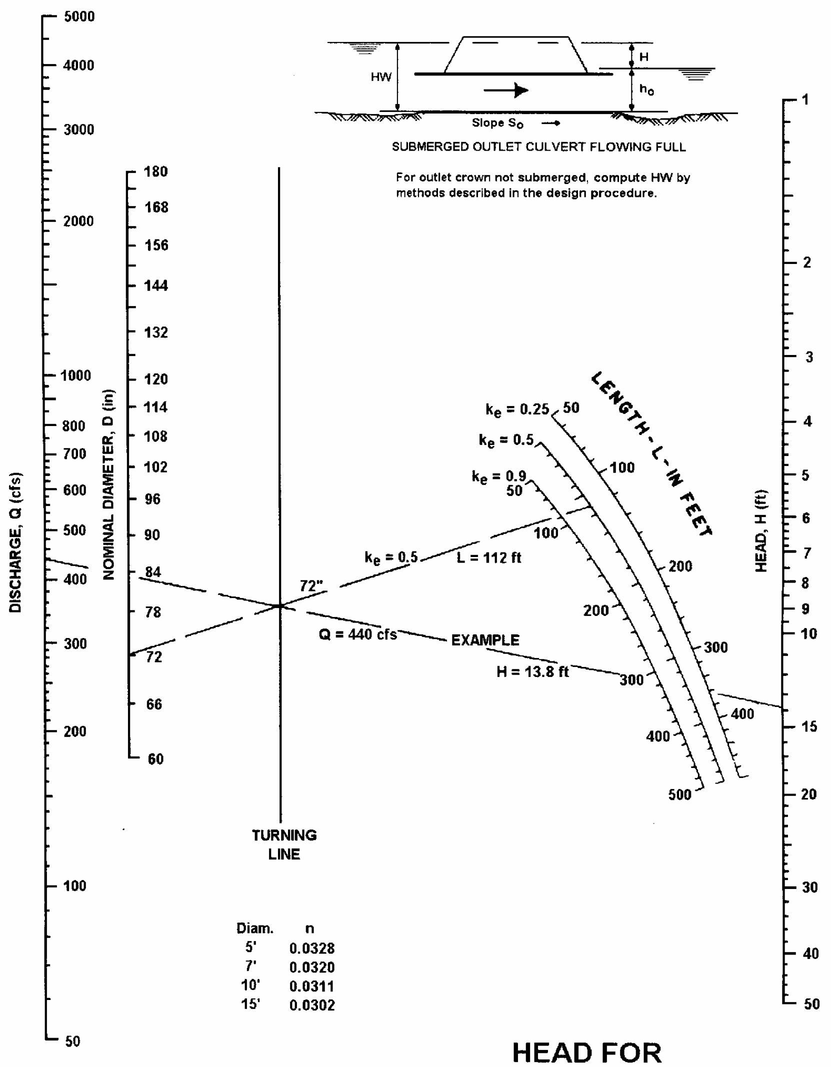
CHART 7



Diam.	n
5'	0.0328
7'	0.0320
10'	0.0311
15'	0.0302

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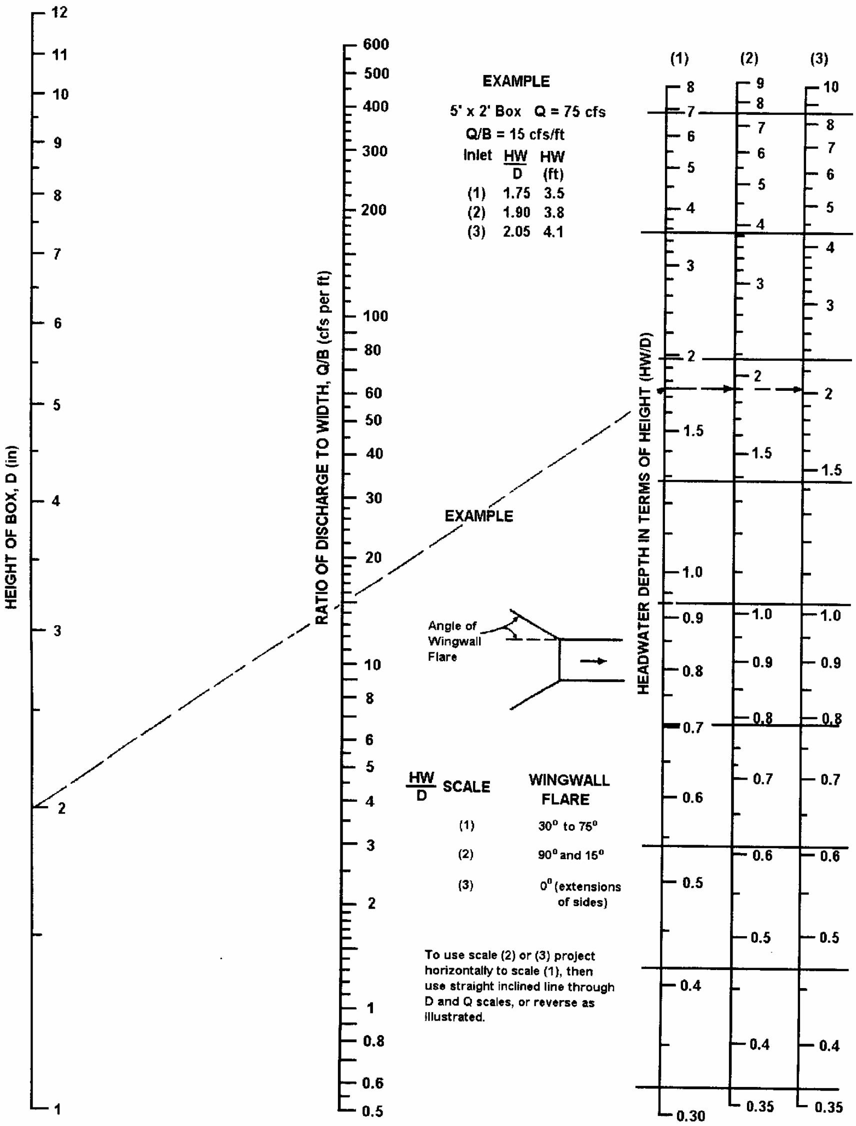
HEAD FOR STRUCTURAL PLATE CORR. METAL PIPE CULVERTS FLOWING FULL n = 0.0328 TO 0.0302

CHART 8



EXAMPLE

5' x 2' Box Q = 75 cfs

Q/B = 15 cfs/ft

Inlet	$\frac{HW}{D}$	HW (ft)
(1)	1.75	3.5
(2)	1.90	3.8
(3)	2.05	4.1

$\frac{HW}{D}$ 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.

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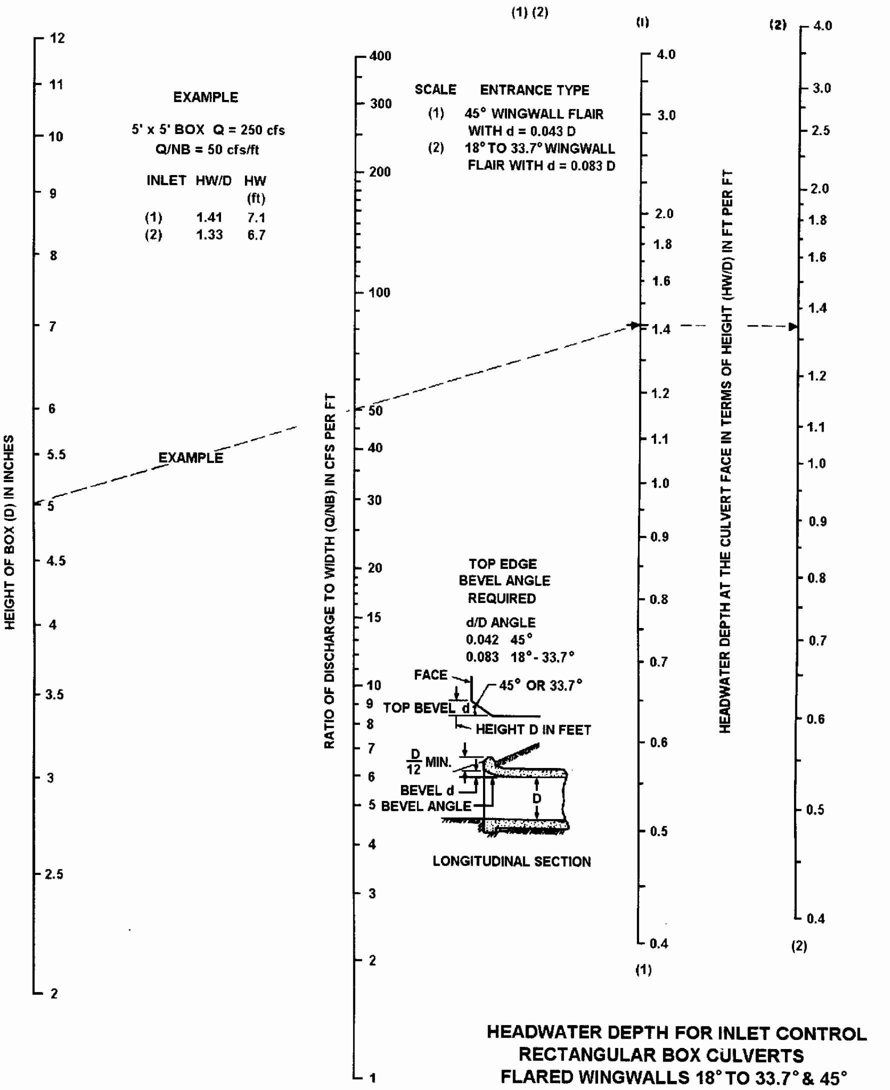
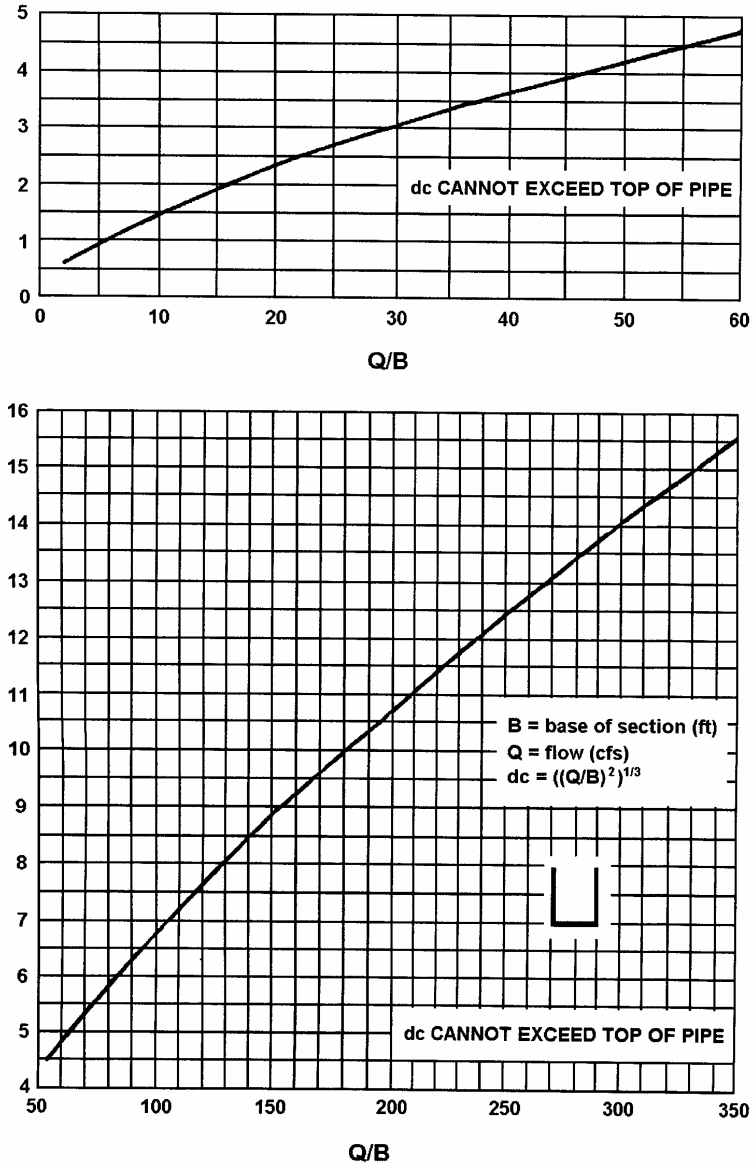
HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

CHART 9



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS 18° TO 33.7° & 45°
WITH BEVELED EDGE AT TOP OF INLET

CHART 14



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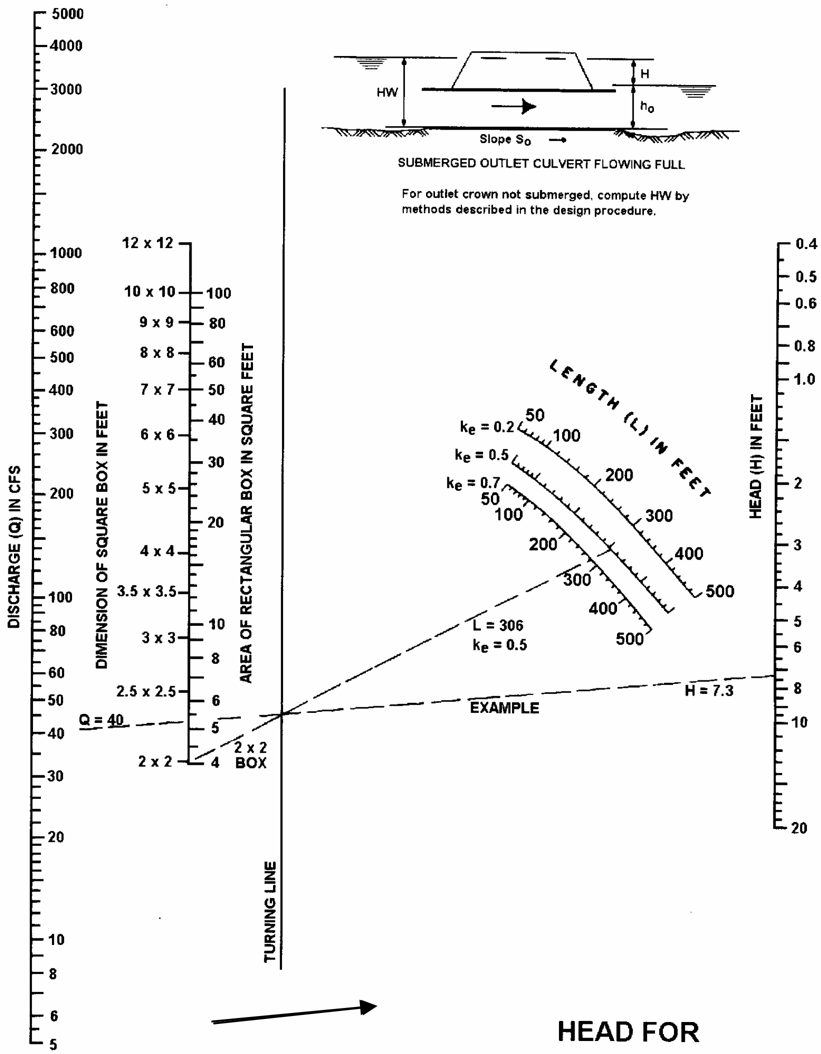
CRITICAL DEPTH
RECTANGULAR SECTION

CHART 15



HEAD FOR CONCRETE BOX CULVERTS FLOWING FULL
n = 0.012

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Chart 16
Critical Depth for Circular and Trapezoidal Channels (French Open Channel Flow)

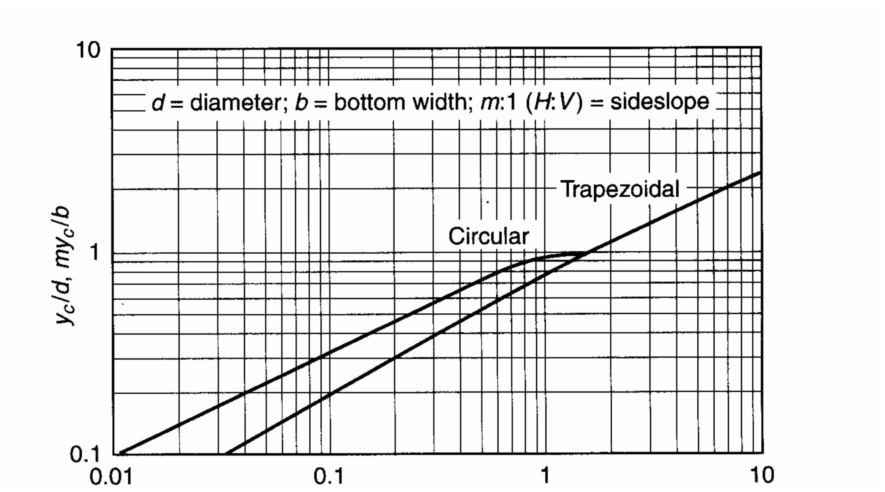
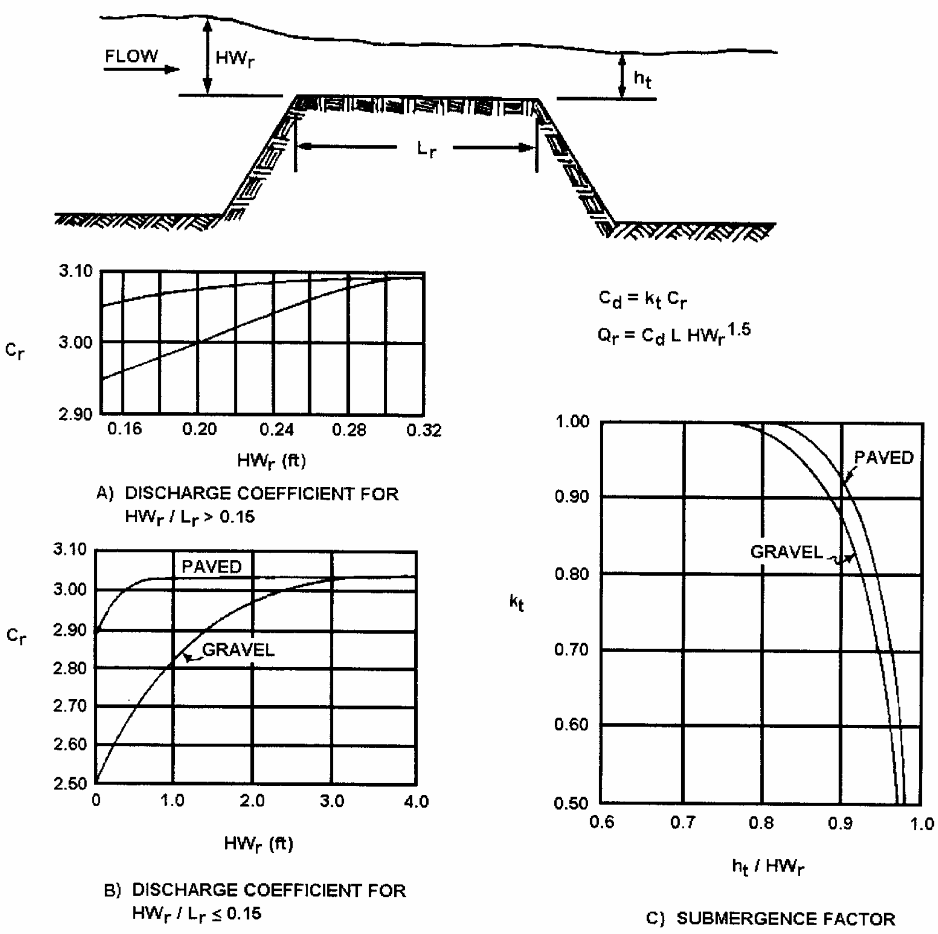


Chart 17



$C_d = k_t C_r$

$Q_r = C_d L HW_r^{1.5}$

A) DISCHARGE COEFFICIENT FOR $HW_r / L_r > 0.15$

B) DISCHARGE COEFFICIENT FOR $HW_r / L_r \leq 0.15$

C) SUBMERGENCE FACTOR

DISCHARGE COEFFICIENTS FOR ROADWAY OVERTOPPING

t De