APPENDIX "K"
WEIR AND ORIFICE FLOW

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APPENDIX "K"
WEIR AND ORIFICE FLOW

A. WEIRS A weir is a notch of regular form through which water flows. The term is also applied to a structure containing such a notch (Brater & King). Weirs may be a depression in a tank or reservoir, and overflow drain, a channel, or other non-closed opening through which water may flow. Various types of weirs are further defined in Appendix "R".

1. Weir Shape Weirs are classifed by the shape of the opening, such as rectangular, triangular (V-notch), and trapezoidal. Typical weir shapes, along with parameter terms used herein, are shown on Figure "K-1" on page K-4.

2. Weir Profile Weirs are further classified by the cross sectional shape over which the water will flow, such as sharp-crested, not sharp-crested, and broadcrested weirs. These are depicted in Figure "K-2" on page K-5.

3. Weir Crest Length Weirs are also classifed by how wide the weir crest is with respect to the approach flow. Suppressed weirs are shown on Figure "K-3" (page K-6), and contracted weirs on Figure "K-4" (page K-7).

4. Weir Tailwater Another classification of weirs pertins to whether or not the weir operates under free or submerged discharge conditions, which is depicted on Figure "K-5" on page K-8.

5. Weir Equations Weir equations for the various classifications discussed above and depicted in Figures "K-1" through "K-5" are provided on Table "K-1" on page K-9, which also provides appropriate "C" values or refers to Table "K-2" or "K-3" on pages K-10 and 11.

6. Weir Roadway Overtopping This usually occurs at a sag vertical curve in a roadway. The flow will be similar to flow over a broadcrested weir, usually with the need to approximate head and length inasmuch as the roadway elevation is not constant. Procedures for analyzing roadway overtopping with or without culvert flow, and more detailed discharge "C" values for roadway overtopping, are provided in Appendix "L", Section B-2, and exemplified in Section B-4d.

B. ORIFICE An orifice is a horizontal or vertical opening with a closed perimeter through which water flows. If the perimeter is not closed, or if the horizontal or vertical opening has only partially full flow, the orifice acts as a weir.

1. Orifice Head The head "H" used in the orifice equation is the distance between the water surface and center of orifice for free discharge conditions, and the difference in elevation of water surfaces for submerged orifices. This is depicted on Figure "K-6" on page K-12.

2. When An Orifice Functions As A Weir

   a. Vertical Orifices With vertical openings, such as are used for curb opening inlets and small bleed-off facilities, orifices act as a weir up to the depth equal to the opening height, and as an orifice at depths above 1.4 times the opening height. Between 1.0 and 1.4 times the opening height, flow is in transition between weir and orifice flow.

   b. Horizontal Orifices The depth at which a horizontal orifice acts as a weir varies depending upon the opening size, shape, and grate type (if any). Based upon information provided in HEC-12, it appears that in the range of 1 ft^2 to 4 ft^2 (or 1 ft. diameter to 2 ft. diameter), weir flow governs up to a depth provided by the approximate relationship:

$$H = 0.08\,D + 0.35'$$

Where:

H = ponding depth, ft; and
D = orifice width (length), or diameter, ft.

Ponding depths above that provided by the equation above generally result in transitional flow, which is discussed below. Reference is made to Figure "K-7" on page K-13 and Figure "K-1" on page K-4.

3. Transitional Flow Transitional flow will likely be different than that calculated by either the orifice or weir equation. However, error will not be significant if the orifice equation is used for transitional depths, both for horizontal and vertical orifice openings.

4. Low Head Orifice Flow For stormwater drainage applications, orifices are used to meter outflow from a detention facility or as a hydraulic device which intercepts flow. In either application, the head on the orifice is often low, or at least the orifice is to function per design at low heads. The low head condition requires special consideration.

Where the head on an orifice, and in particular a vertical orifice, is small compared to the height (or size) of the orifice, the orifice equation provides results which may deviate significantly from theoretical and actual discharges. Rather than derive a separate equation for such conditions, the coefficient of discharge ("C"), which is the product of the coefficient of velocity and coefficient of contraction, may be adjusted to counteract discrepancies. Experimentally, the "C" value has been "calibrated" to provide acceptable results for various conditions, including low head, and therefore with use of the appropriate "C" value, the same orifice equation may be use under various conditions.

5. <u>Orifice Equation</u> Orifice flow shall be calculated by

$$Q = CA\,(2gH)^{0.5}$$

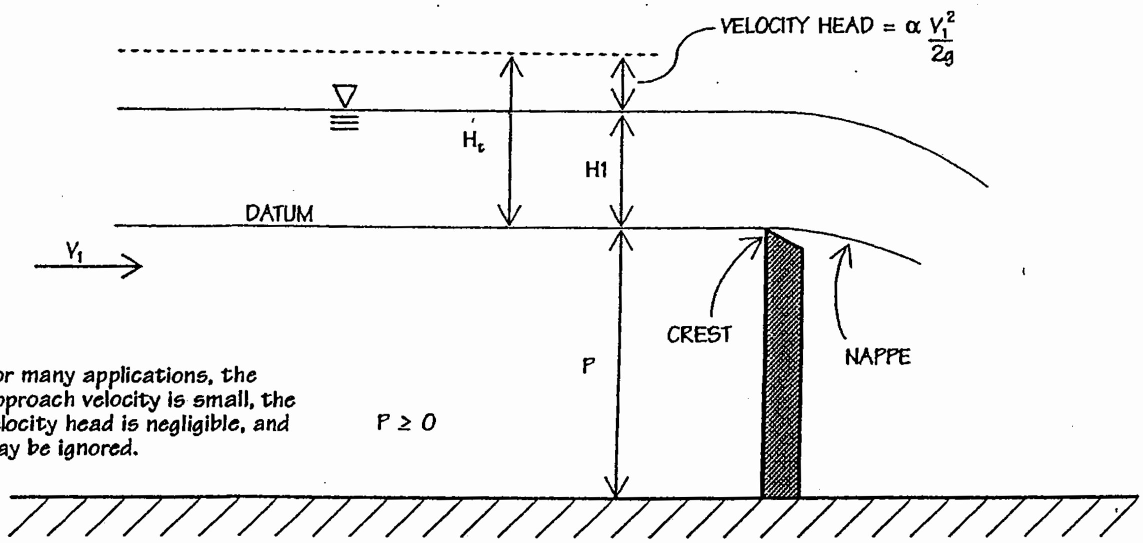
Where:

$Q =$ orifice outflow in CFS;
$C =$ coefficient, which varies with conditions;
$g =$ gravitational constant (which may be assumed to be 32.2 ft/sec^2); and
$H =$ height of head in feet, per Figure "K-6" on page K-12.

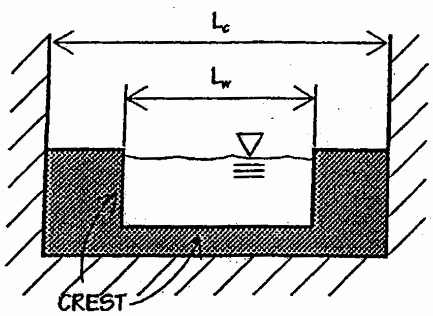
6. <u>"C" Values</u> "C" values have been found to vary minimally between free discharge and submerged condition, and therefore the difference is often ignored, the "C" value being adequate for both situations, all other conditions being the same.

Table "K-4" on page K-14 provides "C" values for use in most stormwater applications. This and other tables provide information which indicates that "C" values for sharp-edged orifices under most conditions range between 0.59 and 0.66. Under special conditions, such as prolonged bottom and sides (frequent stormwater application), values may be as low as 0.487; or for orifices which are rounded, values may be as high as 0.952.

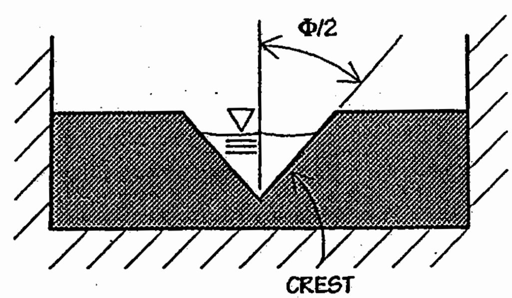
Per HEC-12, use a "C" value of 0.67 for stormwater inlets.



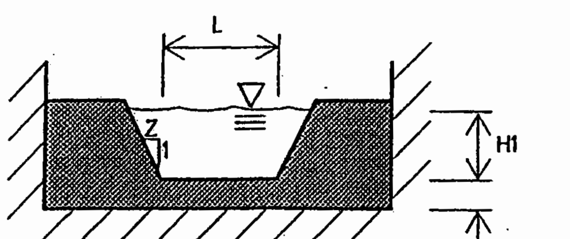
GENERAL TERMS



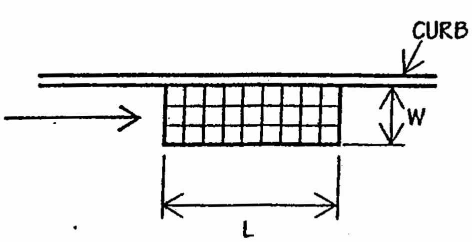
RECTANGULAR WEIR



TRIANGULAR (V-NOTCH) WEIR

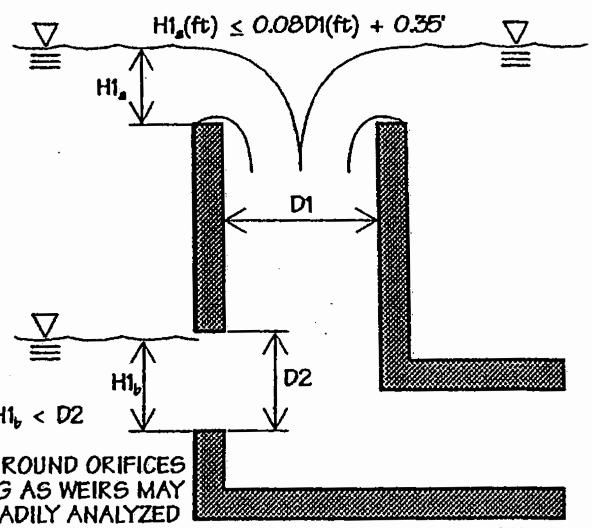


TRAPEZOIDAL



WEIR LENGTH (SUMP CONDITION) = L + 2W
WEIR LENGTH (ON GRADE SIDE FLOW) = L

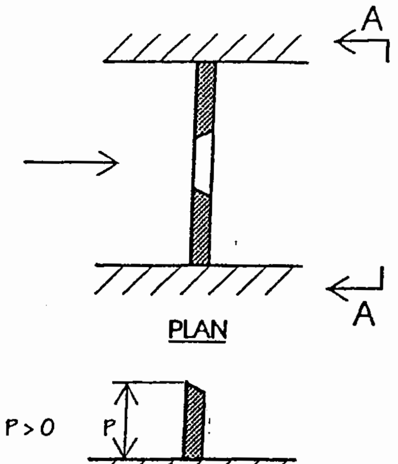
CATCH BASIN INLET



NOTE: ROUND ORIFICES ACTING AS WEIRS MAY BE READILY ANALYZED USING CULVERT NOMOGRAPHS IN HDS-5 OR APPENDIX "L"

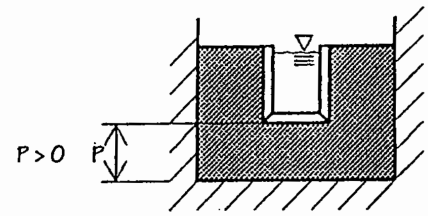
ORIFICES FUNCTIONING AS WEIRS
(UNDER H1 CONDITIONS SHOWN)

WEIR SHAPES AND TERMS | FIGURE K-1



PLAN

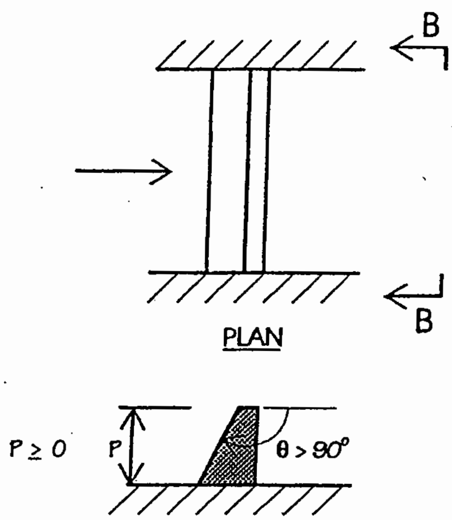
PROFILE



SECTION A-A

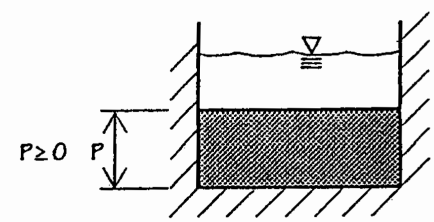
A WEIR THAT HAS A MAXIMUM OF 90° ANGLE ON THE UPSTREAM EDGE OF THE CREST, AND WHICH IS SHORT ENOUGH IN THE DIRECTION OF FLOW, OR IS ANGLED ENOUGH, THAT THE NAPPE WILL NOT BE SUPPORTED, NOR WILL HYDROSTATIC PRESSURES ON THE SIDES BE DEVELOPED, IS A SHARP-CRESTED WEIR. (Brater & King)

SHARP-CRESTED



PLAN

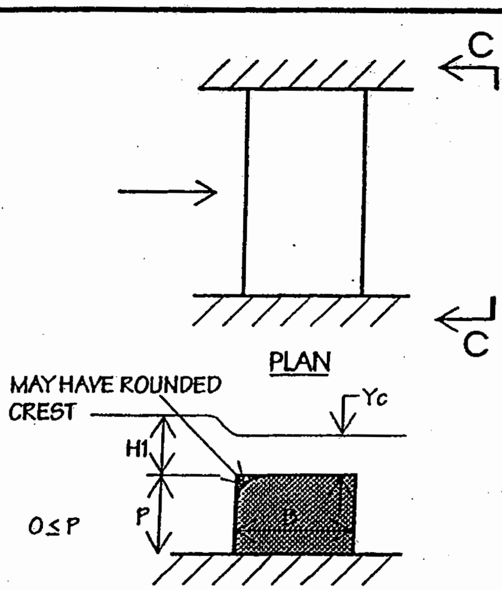
PROFILE



SECTION B-B

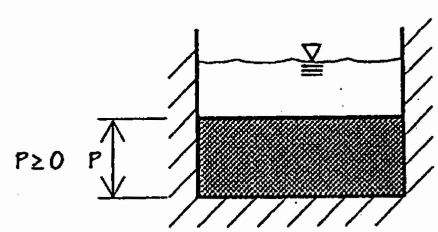
A WEIR THAT HAS A TRAPEZOIDAL, TRIANGULAR, OR OTHER PROFILE THAT HAS A GREATER THAN 90° UPSTREAM CREST ANGLE, IS A NOT SHARP-CRESTED WEIR.

NOT SHARP-CRESTED



PLAN

PROFILE



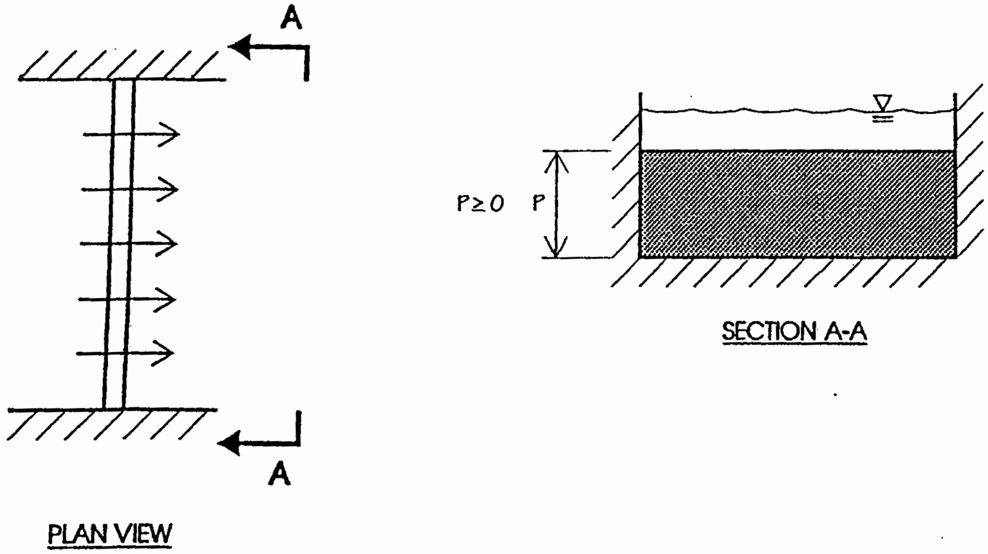
SECTION C-C

A WEIR WITH A HORIZONTAL OR NEAR HORIZONTAL CREST SUFFICIENTLY LONG IN THE DIRECTION OF FLOW SO THAT THE NAPPE WILL BE SUPPORTED AND HYDROSTATIC PRESSURES WILL BE FULLY DEVELOPED FOR AT LEAST A SHORT DISTANCE IS A BROAD-CRESTED WEIR. (Brater & King)

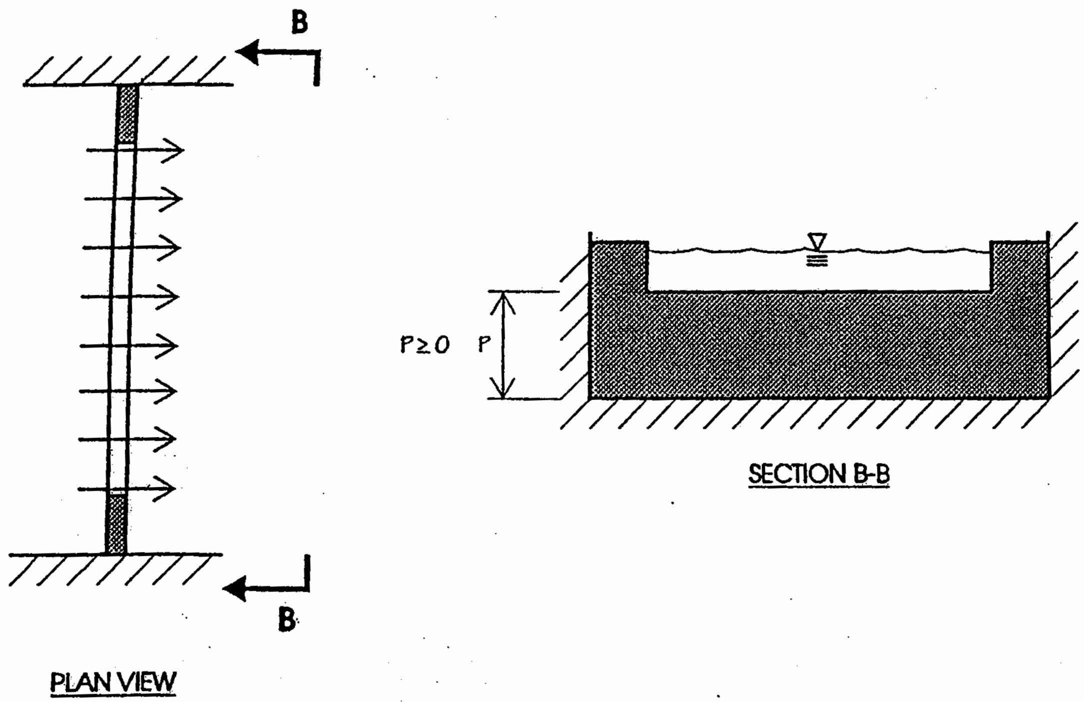
BROAD-CRESTED

(Special Case of Not Sharp-Crested)

SHARP, NOT SHARP, AND BROAD-CRESTED WEIRS	FIGURE K-2



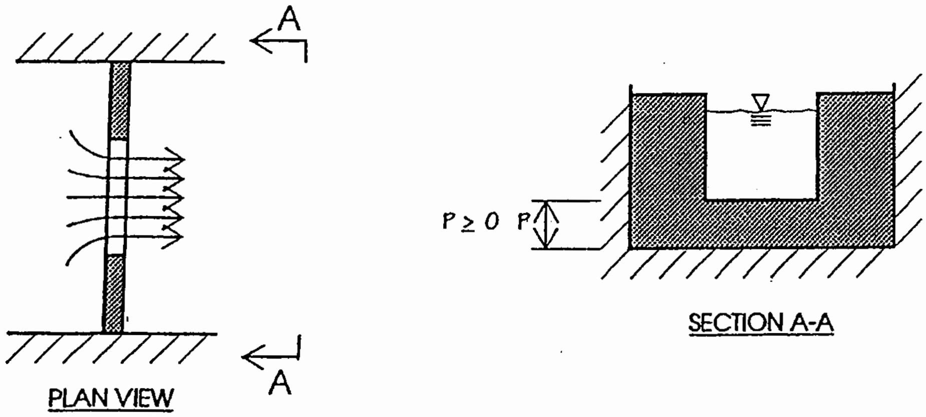
NO END OR SIDE CONTRACTIONS



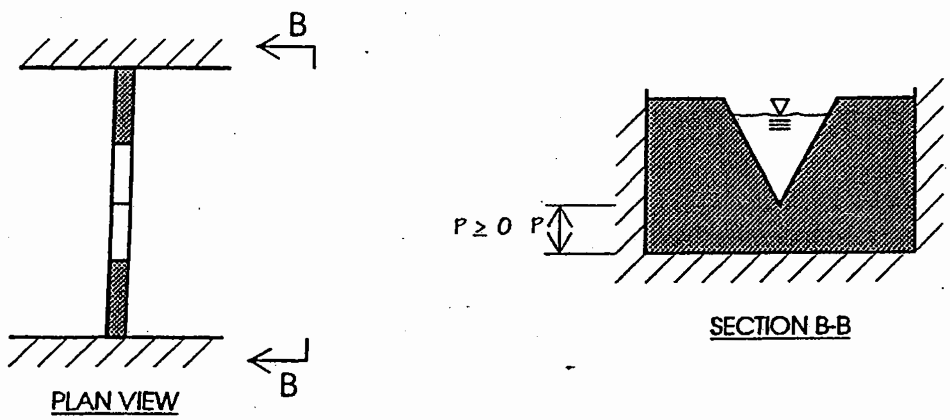
INSIGNIFICANT END CONTRACTIONS

SUPPRESSED WEIRS (Contractions are Suppressed)

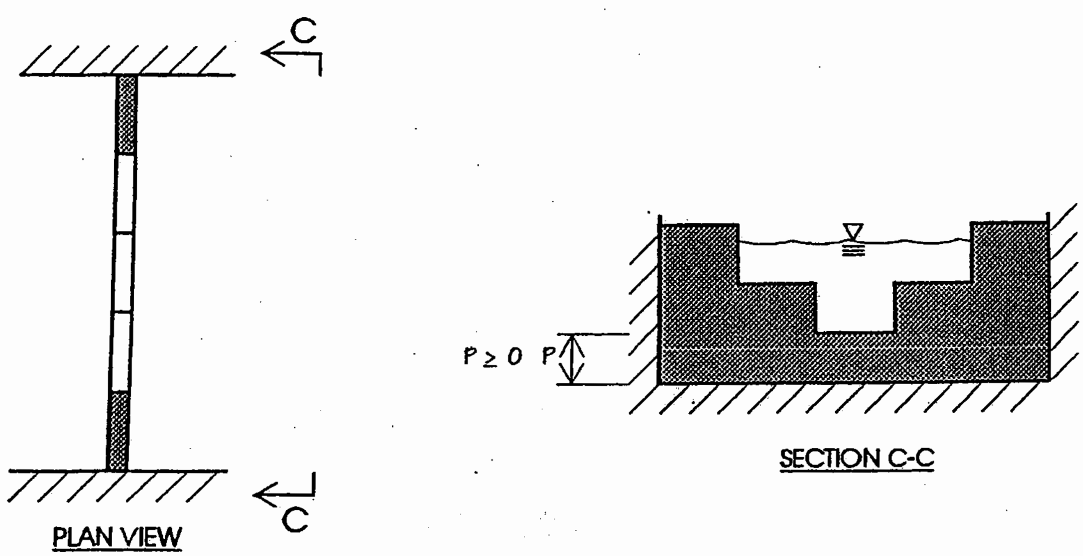
FIGURE K-3



RECTANGULAR WEIR

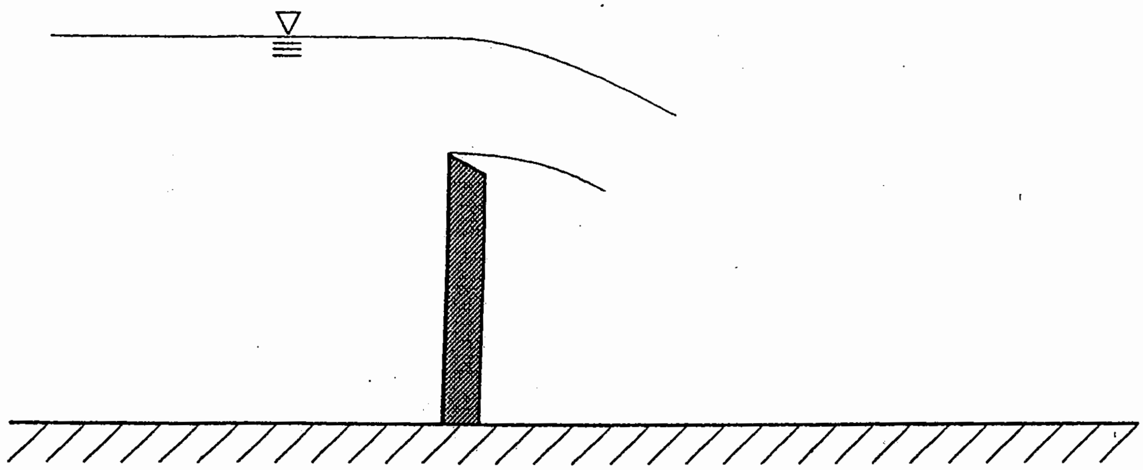


TRIANGULAR (V-NOTCH) WEIR



COMPOUND WEIR

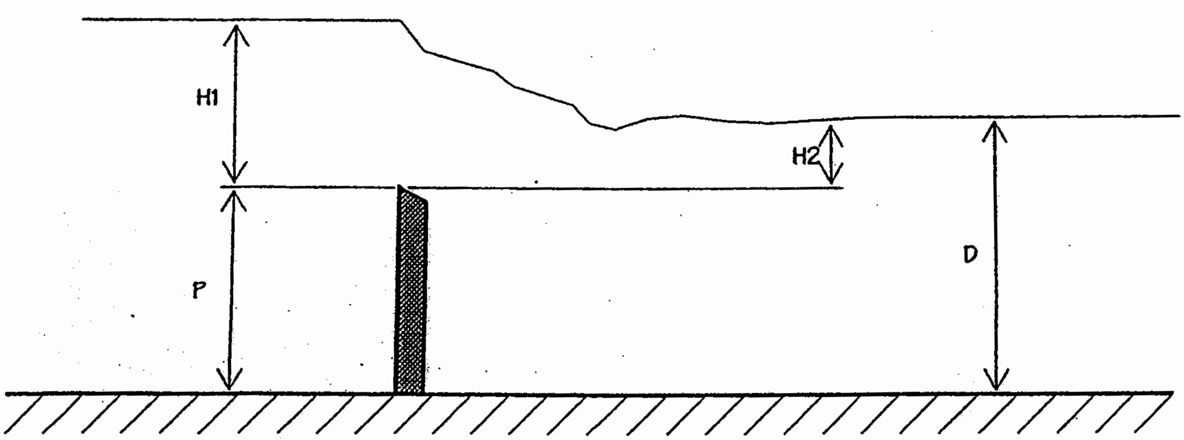
CONTRACTED WEIRS	FIGURE K-4



FREE DISCHARGE

- IF H2 ≤ 0.2 H1, TREAT THE WEIR AS THOUGH IT HAD FREE DISCHARGE (Merritt)
- IF H2 ≤ 0.66 H1, TREAT A BROAD-CRESTED WEIR AS THOUGH IT HAD FREE DISCHARGE (Merritt)
- IF D ≤ 0.85 (P+H1), TREAT A SHARP CRESTED WEIR AS THOUGH IT HAD FREE DISCHARGE (Merritt)
- FOR D > 0.85 (P+H1), REDUCE SHARP-CRESTED WEIR CAPACITY BY THE EQUATION BELOW (APWA). IT MAY BE REASONABLE TO USE THE SAME EQUATION TO CALCULATE BROAD-CRESTED CAPACITY FOR H2 > 0.66 H1.

$$Q_{submerged} = Q_{free\ discharge}\left[1 - \left(\frac{H2}{H1}\right)^{1.5}\right]^{0.385}$$ (Brater & King, Lindenburg)



SUBMERGED

FREE DISCHARGE & SUBMERGED WEIRS | **FIGURE K-5**

WEIR SHAPE			CREST TYPE		END CONDITIONS		WEIR EQUATION (See Notes 1 & 2)	Ht TERM (See Note 2)	C VALUES
RECT.	V-NOTCH	TRAP	SHARP	BROAD	SUPRESSED	CONTRACTED			
•				•	•	See Note 3	$Q_w = CL[Ht^{1.5}]$	$\left[\left(H1 + \frac{V^2}{2g}\right)^{1.5} - \left(\frac{V^2}{2g}\right)^{1.5}\right]$	See Table "K-2"
•			•	See Note 3	• (n = 0)	• (n = 1 if one side is conracted; and n = 2 if two sides are contracted)	$Q_w = C\left(L - \frac{nH1}{10}\right)[Ht^{1.5}]$ Francis Weir Equation (applicable for $H1 \leq L/3$)	$\left[\left(H1 + \frac{V^2}{2g}\right)^{1.5} - \left(\frac{V^2}{2g}\right)^{1.5}\right]$	3.33
•			•		•		$Q_w = C\left(\frac{2}{3}\right)L\sqrt{2g}\,[Ht^{1.5}]$ Basic or Theoretical Weir Equation	$\left[\left(H1 + \frac{V^2}{2g}\right)^{1.5} - \left(\frac{V^2}{2g}\right)^{1.5}\right]$	See Table "K-3"
•			•			•	$Q_w = CL^{1.02}[Ht^{1.47}]$	$\left[\left(H1 + \frac{V^2}{2g}\right)^{1.47} - \left(\frac{V^2}{2g}\right)^{1.47}\right]$	3.10
	•		•			•	$Q_w = C\left(\frac{8}{15}\right)Z\sqrt{2g}\,[Ht^{2.5}]$	$\left[\left(H1 + \frac{V^2}{2g}\right)^{2.5} - \left(\frac{V^2}{2g}\right)^{2.5}\right]$	0.58 to 0.60
		•	•			•	$Q_w = CL[Ht^{1.5}]$ Cipolletti weir, side slopes = 1H:4V	$\left[\left(H1 + \frac{V^2}{2g}\right)^{1.5} - \left(\frac{V^2}{2g}\right)^{1.5}\right]$	3.367
		•	•			•	$Q_w = C_2L[Ht_2^{1.5}] + C_3L[Ht_3^{2.5}]$	$\left[\left(H1 + \frac{V^2}{2g}\right)^{1.5} - \left(\frac{V^2}{2g}\right)^{1.5}\right]$ (Ht_2 Term) $\left[\left(H1 + \frac{V^2}{2g}\right)^{2.5} - \left(\frac{V^2}{2g}\right)^{2.5}\right]$ (Ht_3 Term)	C_2 & C_3 must be determined experimentally

NOTES:

1. Q_W shown is based upon free discharge. For submerged discharge, adjust Q_W per information provided on Figure "K-5".
2. If the approach velocity is insignificant, then H1 may be used for Ht. Otherwise, the Ht term is determined by the equations above.
3. An equation for a contracted broadcrested rectangular weir was not found. For that condition, the Francis weir equation is recommended using a "C" value of 3.0 instead of 3.33.

WEIR EQUATIONS AND "C" VALUES

TABLE K-1

TABLE K-2
VALUES OF C IN THE BROAD CRESTED WEIR EQUATION
(Table 5-3 in *Handbook of Hydraulics*, Brater and King, 6th Edition)

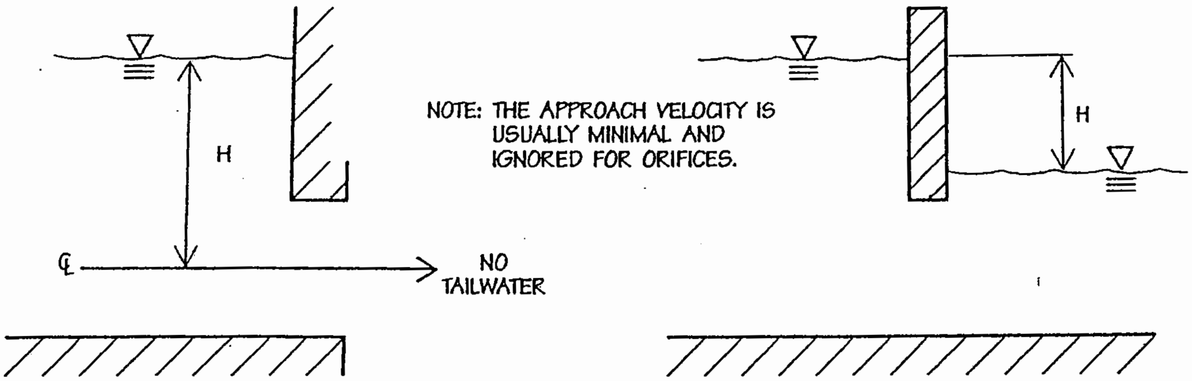
Measured head in feet, H	Breadth of Crest of Weir in Feet										
	0.50	0.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00	10.00	15.00
0.2	2.80	2.75	2.69	2.62	2.54	2.48	2.44	2.38	2.34	2.49	2.68
0.4	2.92	2.80	2.72	2.64	2.61	2.60	2.58	2.54	2.50	2.56	2.70
0.6	3.08	2.89	2.75	2.64	2.61	2.60	2.68	2.69	2.70	2.70	2.70
0.8	3.30	3.04	2.85	2.68	2.60	2.60	2.67	2.68	2.68	2.69	2.64
1.0	3.32	3.14	2.98	2.75	2.66	2.64	2.65	2.67	2.68	2.68	2.63
1.2	3.32	3.20	3.09	2.86	2.70	2.65	2.64	2.67	2.66	2.69	2.64
1.4	3.32	3.26	3.20	2.92	2.77	2.68	2.64	2.65	2.65	2.67	2.64
1.6	3.32	3.29	3.28	3.07	2.89	2.75	2.68	2.66	2.65	2.64	2.63
1.8	3.32	3.32	3.31	3.07	2.88	2.74	2.68	2.66	2.65	2.64	2.63
2.0	3.32	3.31	3.30	3.03	2.85	2.76	2.72	2.68	2.65	2.64	2.63
2.5	3.32	3.32	3.31	3.28	3.07	2.89	2.81	2.72	2.67	2.64	2.63
3.0	3.32	3.32	3.32	3.32	3.20	3.05	2.92	2.73	2.66	2.64	2.63
3.5	3.32	3.32	3.32	3.32	3.32	3.19	2.97	2.76	2.68	2.64	2.63
4.0	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.70	2.64	2.63
4.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.74	2.64	2.63
5.0	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.07	2.79	2.64	2.63
5.5	3.32	3.32	3.32	3.32	3.32	3.32	3.32	3.32	2.88	2.64	2.63

For "C" values and/or roadway overtopping conditions, reference is made to HDS-5 or Appendix "L", Section B-2.

Table K-3
Values of C and ΔL for use in Basic Rectangular Weir Equation (See Figure K-1)

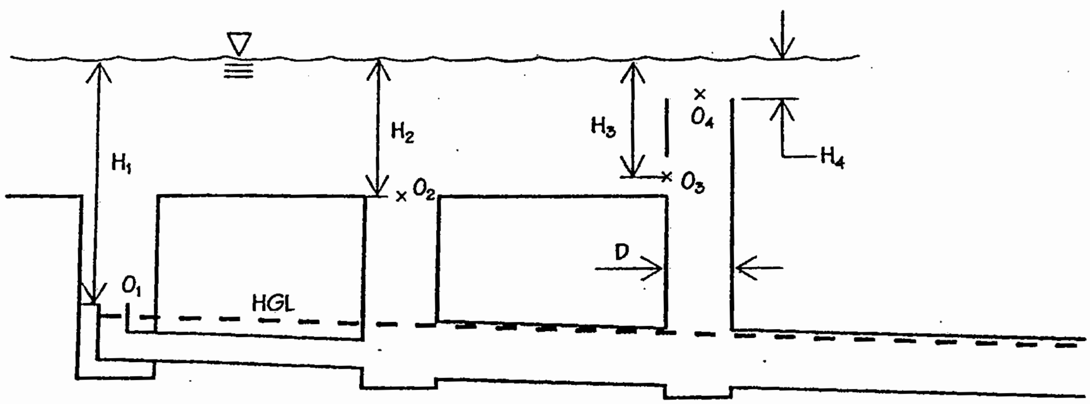
	weir crest/channel width = L_W/L_C							
H1/P	0	0.2	0.4	0.6	0.7	0.8	0.9	1.0
	Coefficient of discharge *C*							
0	0.587	0.589	0.591	0.593	0.595	0.597	0.599	0.603
0.5	0.586	0.588	0.594	0.602	0.610	0.620	0.631	0.640
1.0	0.586	0.587	0.597	0.611	0.625	0.642	0.663	0.676
1.5	0.584	0.586	0.600	0.620	0.640	0.664	0.695	0.715
2.0	0.583	0.586	0.603	0.629	0.655	0.687	0.72	0.753
2.5	0.582	0.585	0.608	0.637	0.671	0.710	0.760	0.790
3.0	0.580	0.584	0.610	0.647	0.687	0.733	0.791	0.827
	Adjustment for crest length ΔL/ft (Adjusted length $L_a = L_C + \Delta L$)							
Any	0.007	0.008	0.009	0.012	0.013	0.014	0.013	-0.005

Reproduced from Table 3.3.15, *Mark's Standard Handbook for Mechanical Engineers*



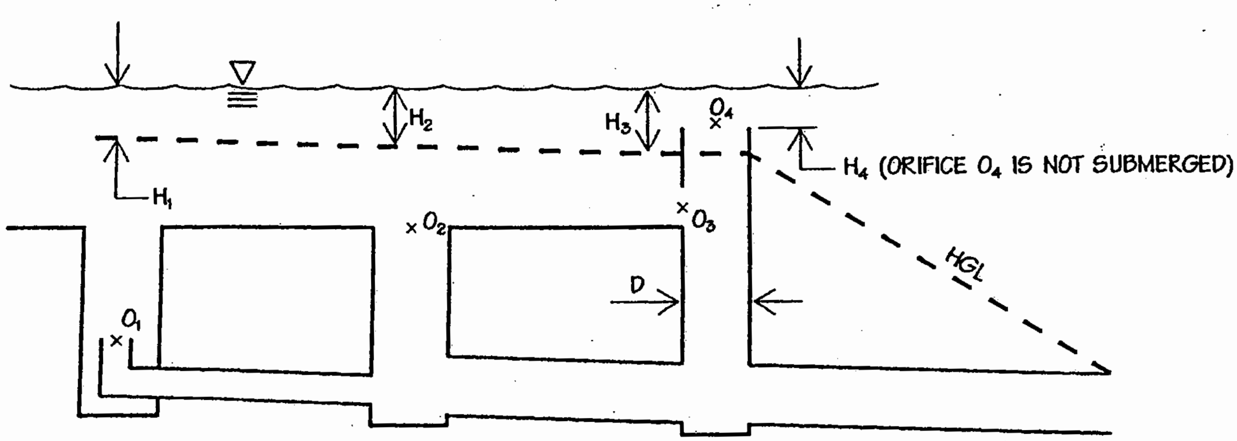
FREE DISCHARGE

SUBMERGED DISCHARGE



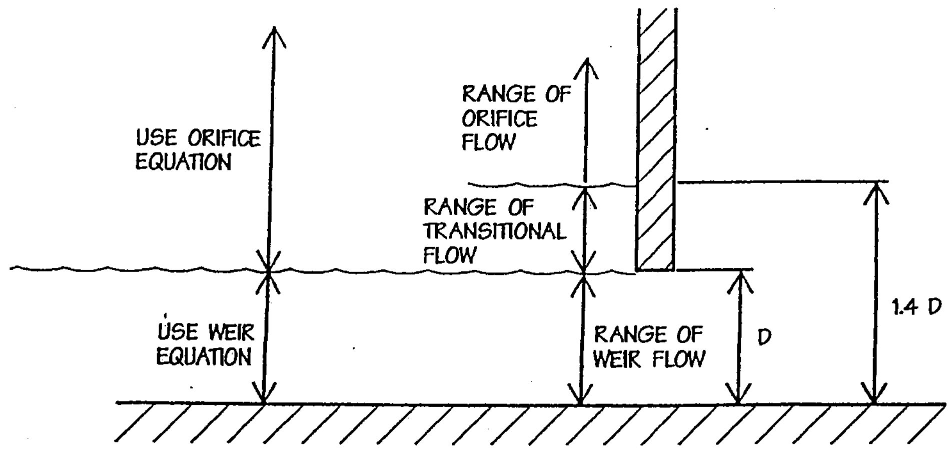
APPLICATIONS OF ORIFICE FREE DISCHARGE

FOR HORIZONTAL ORIFICES, H(ft) > 0.08D(ft) + 0.35'; OTHERWISE, WEIR FLOW CONDITIONS EXIST



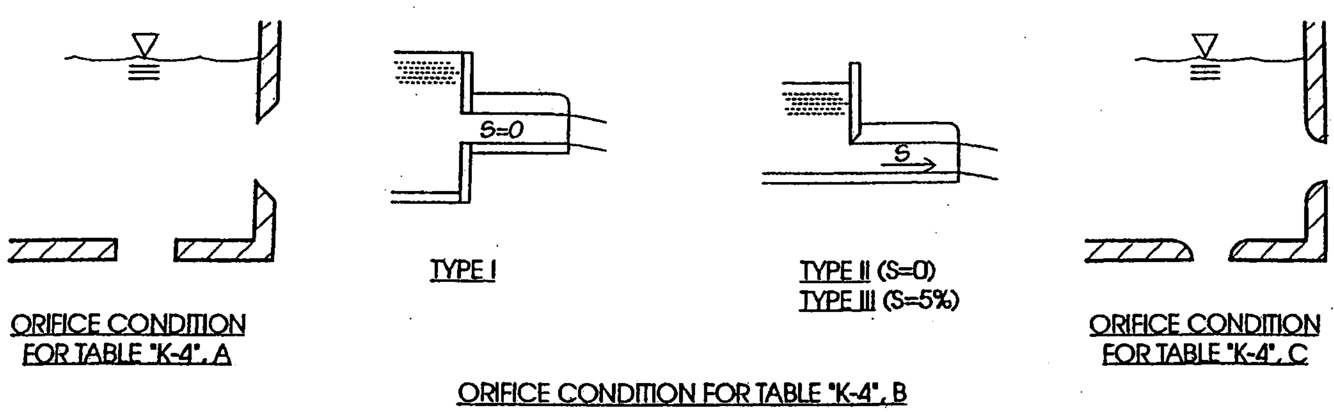
APPLICATIONS OF SUBMERGED ORIFICE

ORIFICE HEAD	FIGURE K-6



NOTE: FOR LARGE CIRCULAR VERTICAL ORIFICES, USE OF CULVERT NOMOGRAPHS IN THE FEDERAL HIGHWAY ADMINISTRATION'S HDS-5 OR APPENDIX "L" MAY BE HELPFUL. THE NOMOGRAPHS NOT ONLY ACCOUNT FOR WEIR, TRANSITIONAL, AND ORIFICE FLOW AT THE APPROPRIATE HEAD RANGES, BUT ALSO ELIMINATE THE NEED FOR WEIR FLOW CALCULATIONS ON A CIRCULAR WEIR.

ORIFICE, WEIR, & TRANSITIONAL FLOW | **FIGURE K-7**



ORIFICE "C" VALUE CONDITIONS | **FIGURE K-8**

NOTE: THIS IS A REPRODUCTION OF PORTIONS OR ALL OF TABLES 4-3, 4-7, AND 4-8 OF "HANDBOOK OF HYDRAULICS"

A. Smith's Coefficient of Discharge for Circular and Square Orifices with Full Contraction

Diameter of circular orifices, feet							Head, feet	Side of square orifices, feet						
0.02	0.04	0.07	0.1	0.2	0.6	1.0		0.02	0.04	0.07	0.1	0.2	0.6	1.0
.....	0.637	0.624	0.618				0.4	.....	0.643	0.628	0.621			
0.655	0.630	0.618	0.613	0.601	0.593		0.6	0.660	0.636	0.623	0.617	0.605	0.598	
0.648	0.626	0.615	0.610	0.601	0.594	0.590	0.8	0.652	0.631	0.620	0.615	0.605	0.600	0.597
0.644	0.623	0.612	0.608	0.600	0.595	0.591	1	0.648	0.628	0.618	0.613	0.605	0.601	0.599
0.637	0.618	0.608	0.605	0.600	0.596	0.593	1.5	0.641	0.622	0.614	0.610	0.605	0.602	0.601
0.632	0.614	0.606	0.604	0.599	0.597	0.595	2	0.637	0.619	0.612	0.608	0.605	0.604	0.602
0.629	0.612	0.605	0.603	0.599	0.598	0.596	2.5	0.634	0.617	0.610	0.607	0.605	0.604	0.602
0.627	0.611	0.604	0.603	0.599	0.598	0.597	3	0.632	0.616	0.609	0.607	0.605	0.604	0.603
0.623	0.609	0.603	0.602	0.599	0.597	0.596	4	0.628	0.614	0.608	0.606	0.605	0.603	0.602
0.618	0.607	0.602	0.600	0.598	0.597	0.596	6	0.623	0.612	0.607	0.605	0.604	0.603	0.602
0.614	0.605	0.601	0.600	0.598	0.596	0.596	8	0.619	0.610	0.606	0.605	0.604	0.603	0.602
0.611	0.603	0.599	0.598	0.597	0.596	0.595	10	0.616	0.608	0.605	0.604	0.603	0.602	0.601
0.601	0.599	0.597	0.596	0.596	0.596	0.594	20	0.606	0.604	0.602	0.602	0.602	0.601	0.600
0.596	0.595	0.594	0.594	0.594	0.594	0.593	50	0.602	0.601	0.601	0.600	0.600	0.599	0.599
0.593	0.592	0.592	0.592	0.592	0.592	0.592	100	0.599	0.598	0.598	0.598	0.598	0.598	0.598

B. Coefficients of Discharge for Types I, II, AND III Orifices

Figure	Depth of opening in feet	Values of C for various depths of water above top of orifice										
		0.07	0.1	0.3	0.5	0.7	1.0	2.0	3.0	5.0	7.0	10.0
I	0.656	.487	.495	.539	.562	.577	.588	.601	.601	.601	.601	.601
	0.164	.495	.550	.619	.630	.631	.630	.625	.624	.619	.612	.606
II	0.656	.487	.495	.530	.554	.573	.580	.595	.599	.602	.602	.601
	0.164	.495	.544	.600	.612	.618	.623	.627	.628	.627	.622	.617
III	0.656	.530	.535	.569	.584	.595	.600	.608	.610	.610	.609	.608
	0.164	.590	.600	.628	.640	.645	.649	.652	.651	.650	.650	.649

C. Coefficients of Discharge for Submerged Vertical Square Orifices with Rounded Corners

Dimensions of orifice in feet	Head in feet								
	3	4	5	6	8	10	12	14	18
Square, 1.0 by 1.0.......	.952	.948	.946	.945	.944	.943	.943	.944	.944

ORIFICE COEFFICIENTS OF DISCHARGE
(See Figure K-8 for application)

TABLE K-4

APPENDIX "L"
CULVERTS

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List of Figures

APPENDIX "L"
CULVERTS

A. INTRODUCTION

By reference, FHWA HDS-5 is the adopted design criteria for culvert analysis. For convenience, this appendix contains information, figures, and charts from the 1985 version of the HDS-5. However, it should be understood that culvert analysis and design criteria is based upon the current edition of HDS-5, and not necessarily the information provided in this appendix.

1. **General Discussion** HDS-5 combines information and methodology contained in FHWA Hydraulic Engineering Circulars (HEC) 5, 10, and 13 with other more recent culvert information developed by governmental agencies, universities, and culvert manufacturers. Information extracted therefrom and provided in this appendix is limited to:
   - Basic culvert hydraulic principles
   - Design procedures using HDS-5 charts
   - Examples using the charts
   - Reproduction of most of the design charts.

   For more information on culvert hydraulics, and also regarding improved inlets such as tapered inlets, the HDS-5 should be referred to.

2. **Overview of Culverts** A culvert is a hydraulically short conduit which conveys fluid. Culverts are constructed from a variety of materials, such as concrete, corrugated aluminum and steel, PVC, or polyethylene. Culverts may also be lined to improve abrasion resistance, reduce corrosion, or improve hydraulics. Culverts are available in a variety of shapes, the most common of which are shown in Figure "L-1". A variety of end treatments may also be used to more efficiently meet the requirements of a specific culvert. Common end treatment types are shown on Figure "L-2".

B. CULVERT HYDRAULICS

1. **Inlet and Outlet Flow Control** A culvert barrel may flow full over its entire length, which does not often occur, or only partly full. Usually only a part of the barrel flows full.

   In general, if the barrel does not flow full, or does so for only a short distance, flow capacity is governed by the inlet. This condition is called "inlet control," because it occurs when the culvert barrel is capable of conveying more flow than the inlet will accept. If the culvert flows full for all or most of its length, then it is likely that the barrel is incapable of conveying as much flow as the inlet opening will accept. The control section for flows under these conditions is at the culvert outlet or further downstream. Hence, this flow condition is said to be "outlet control". Factors influencing inlet and outlet control are shown in Table "L-1".

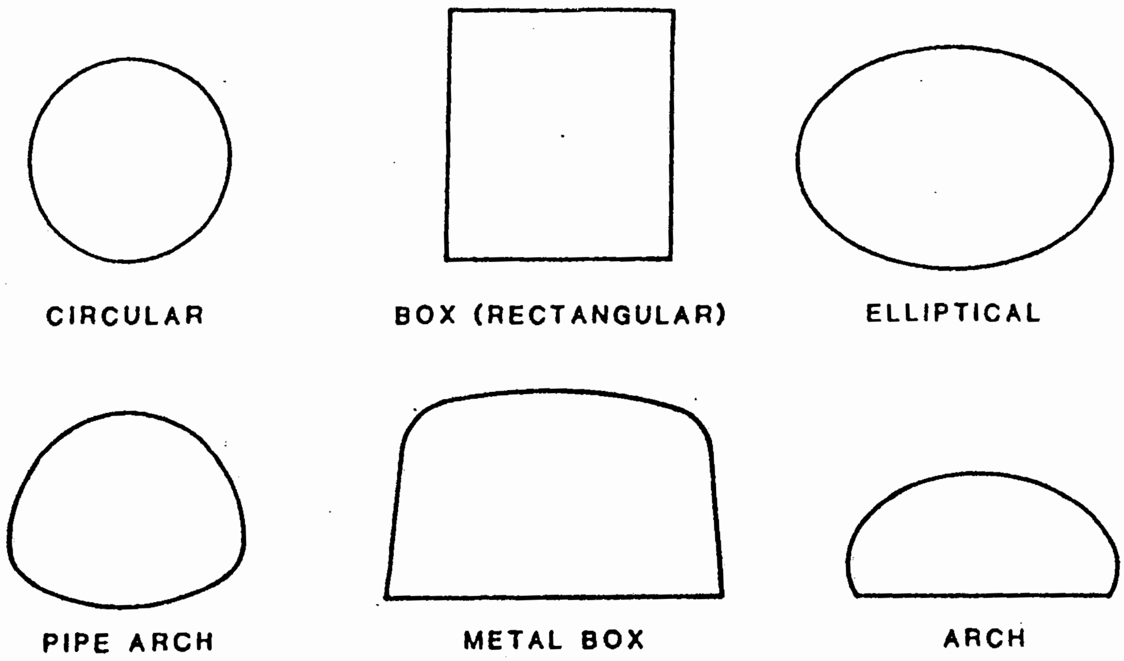


Figure "L-1" — Commonly Used Culvert Shapes

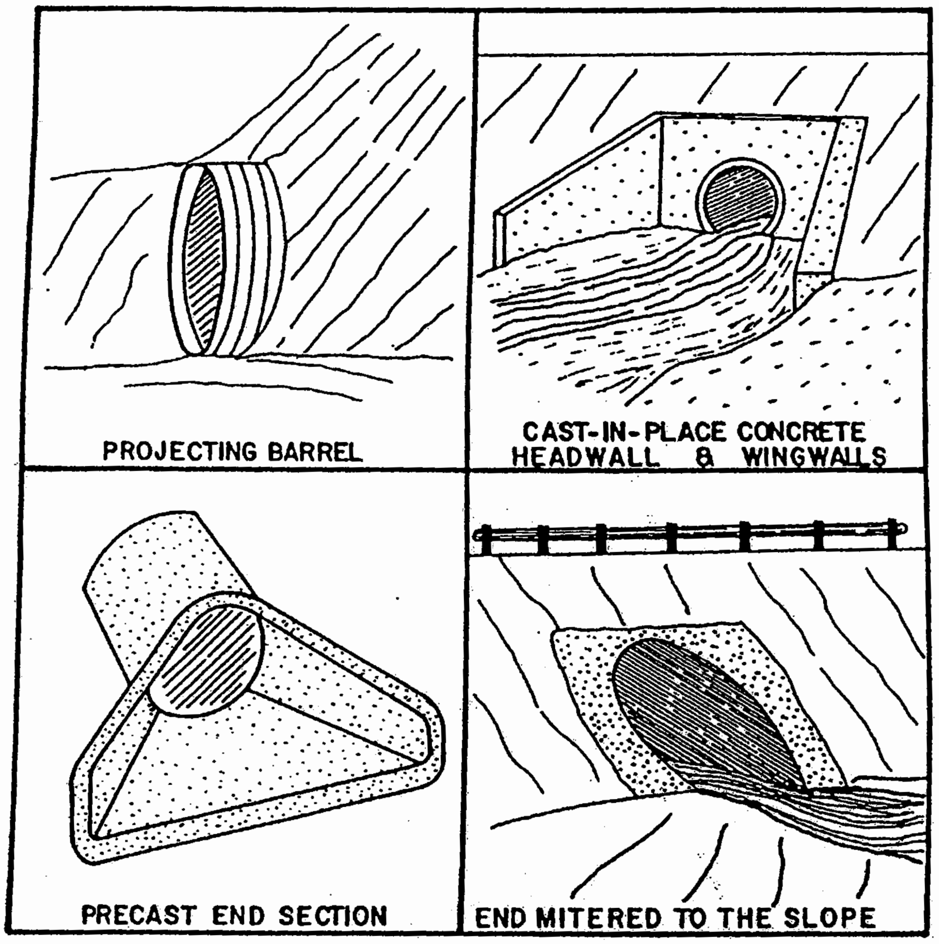


Figure "L-2" — Common Culvert End Treatments

Table "L-1"
Factors Influencing Culvert Performance

Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Inlet Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Shape		X
Barrel Length		X
Barrel Slope	*	X
Tailwater Elevation		X

* Barrel slope affects inlet control performance to a small degree, but may be neglected.

a. Inlet Control Examples Figure "L-3" depicts several different examples of inlet control flow. The type of flow depends on the submergence of the inlet and outlet ends of the culvert. In all of these examples, the control section is at the inlet end of the culvert. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

Condition "A" of Figure "L-3" depicts a condition where neither the inlet nor the outlet end of the culvert are submerged. The flow passes through critical depth just downstream of the culvert entrance and the flow in the barrel is supercritical. The barrel flows partly full over its length, and the flow approaches normal depth at the outlet end.

Condition "B" of Figure "L-3" shows that submergence of the outlet end of the culvert does not assure outlet control. In this case, the flow just downstream of the inlet is supercritical and a hydraulic jump forms in the culvert barrel.

Condition "C" of Figure "L-3" is a more typical design situation. The inlet end is submerged and the outlet end flows freely. Again, the flow is supercritical and the barrel flows partly full over its length. Critical depth is located just downstream of the culvert entrance, and the flow is approaching normal depth at the downstream end of the culvert.

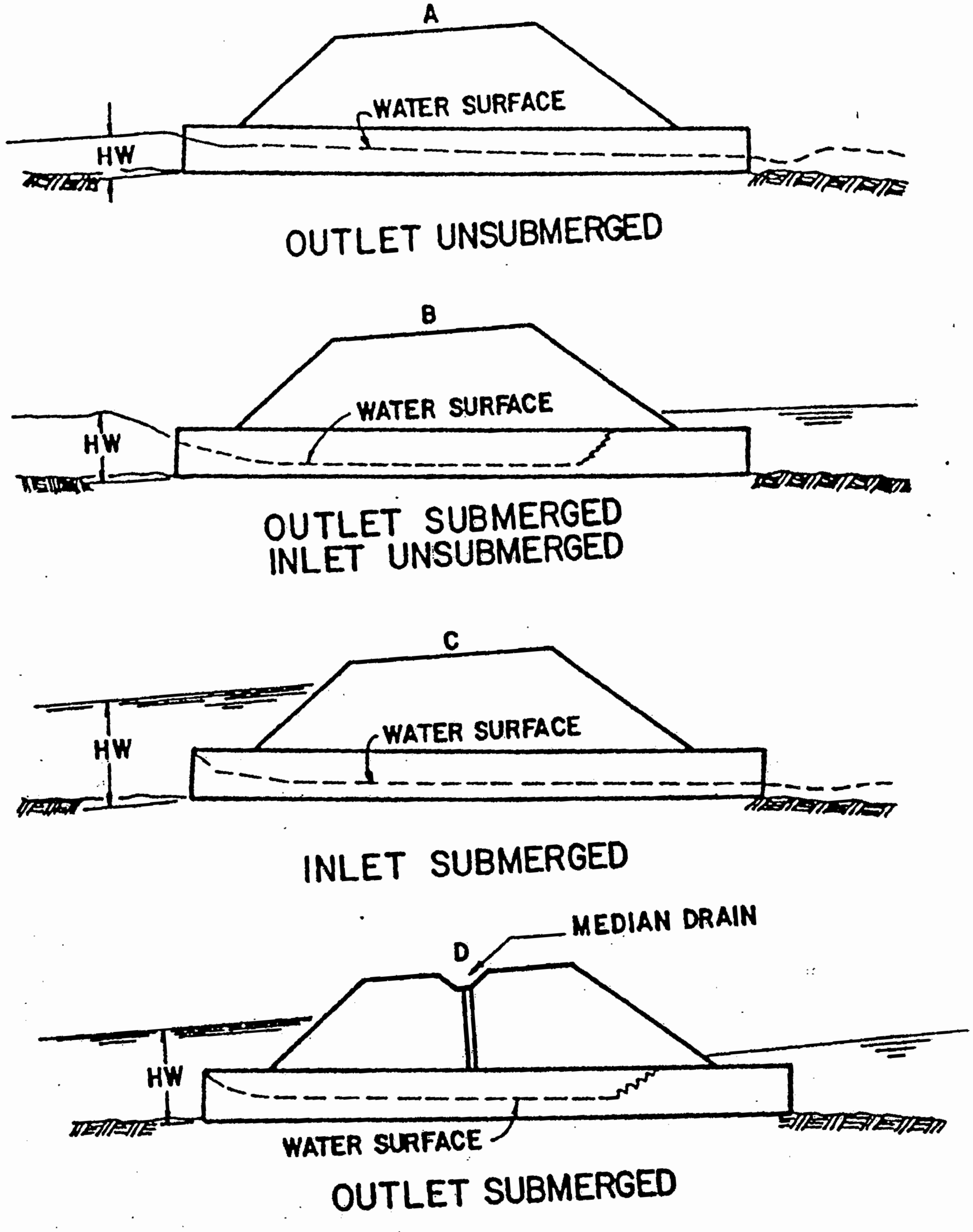


Figure "L-3" — Conditions of Inlet Control

Condition "D" of Figure "L-3" is an unusual condition illustrating the fact that even submergence of both the inlet and the outlet ends of the culvert does not assure full flow. In this case, a hydraulic jump will form in the barrel. The median inlet provides ventilation of the culvert barrel. If the barrel were not ventilated, sub-atmospheric pressures could develop which might create an unstable condition during which the barrel would alternate between full flow and partly full flow.

b. **Outlet Control Examples** Figure "L-4" illustrates various outlet control flow conditions. In all cases, the control section is at the outlet end of the culvert or further downstream. For the partly full flow situations, the flow in the barrel is subcritical.

Condition "A" of Figure "L-4" represents the classic full flow condition, with both inlet and outlet submerged. The barrel is in pressure flow throughout its length. This condition is often assumed in calculations, but seldom actually exists.

Condition "B" of Figure "L-4" depicts the outlet submerged with the inlet un-submerged. For this case, the headwater is shallow so that the inlet crown is exposed as the flow contracts into the culvert.

Condition "C" of Figure "L-4" shows the entrance submerged to such a degree that the culvert flows full throughout its entire length while the exit is unsubmerged. This is a rare condition. It requires an extremely high headwater to maintain full barrel flow with no tailwater. The outlet velocities are usually high under this condition.

Condition "D" of Figure "L-4" is more typical. The culvert entrance is submerged by the headwater and the outlet end flows freely with a low tailwater. For this condition, the barrel flows partly full over at least part of its length (subcritical flow) and the flow passes through critical depth just upstream of the outlet.

Condition "E" of Figure "L-4" is also typical, with neither the inlet nor the outlet end of the culvert submerged. The barrel flows partly full over its entire length, and the flow profile is subcritical.

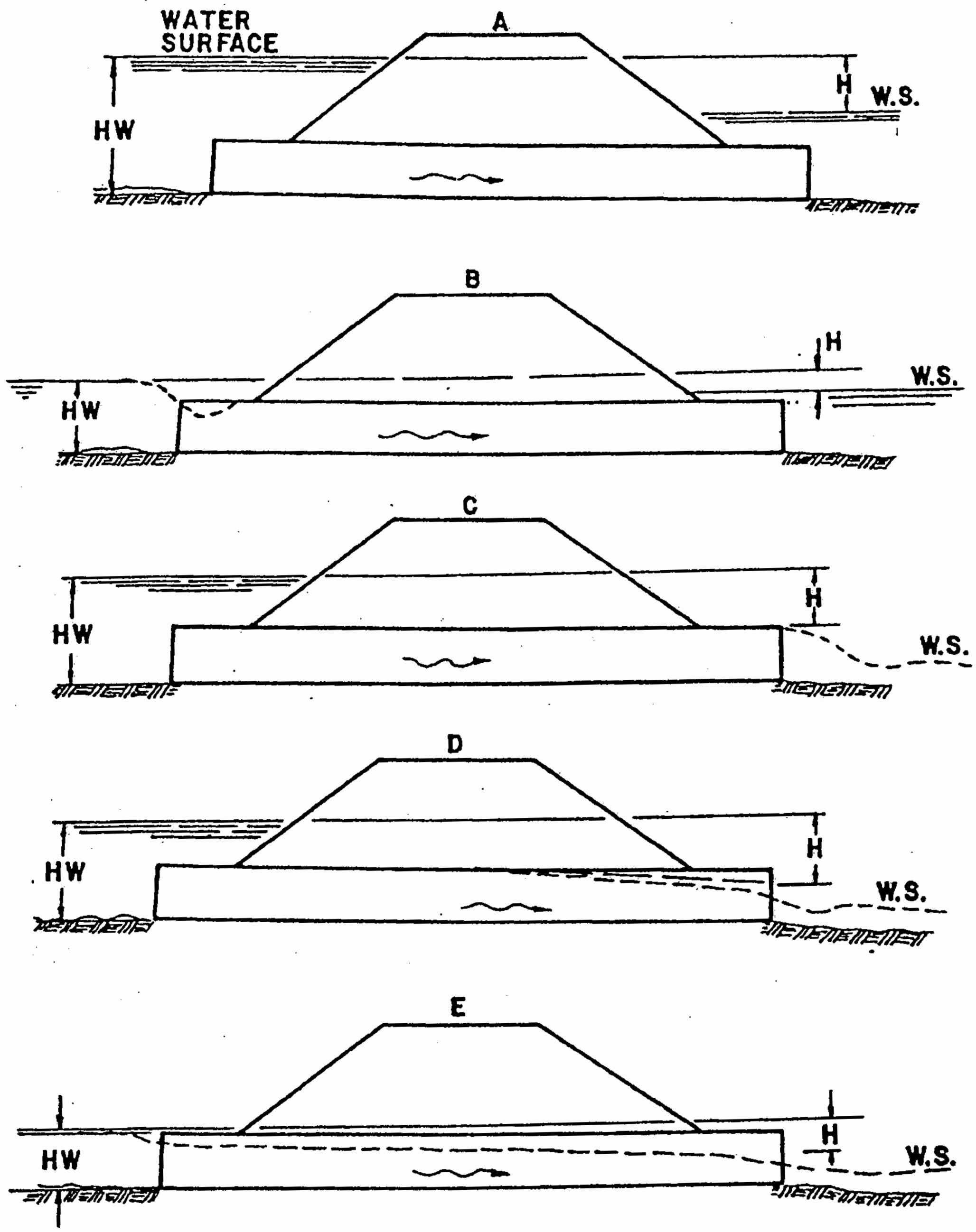


Figure "L-4" — Conditions of Outlet Control

2. <u>Roadway Overtopping</u> Overtopping will begin when the headwater rises to the elevation of the roadway. The overtopping will usually occur at the low point of a sag vertical curve on the roadway. The flow will be similar to flow over a broad crested weir. Flow coefficients for flow overtopping roadway embankments are found in HDS No. 1, "Hydraulics of Bridge Waterways", as well as in the documentation of HY-7, the "Bridge Waterways Analysis Model". Curves from the latter reference are shown in Figure "L-5". Figure "L-5"-A is for deep overtopping, Figure "L-5"-B is for shallow overtopping, and Figure "L-5"-C is a correction factor for downstream submergence. The broadcrested weir equation defines the flow across the roadway.

$$Q = C_d \, L \, HW_r^{1.5}$$

Q	is the overtopping flow rate in ft^3/s
C_d	is the overtopping discharge coefficient
L	is the length of the roadway crest, ft
HW_r	is the upstream depth, measured from the roadway crest to the water surface upstream of the weir drawdown, ft

The length and elevation of the roadway crest are difficult to determine when the crest is defined by a roadway sag vertical curve. The sag vertical curve can be broken into a series of horizontal segments as shown in Figure "L-6"-A. Using the weir equation, the flow over each segment is calculated for a given headwater. Then, the incremental flows for each segment are added together, resulting in the total flow across the roadway.

Representing the sag vertical curve by a single horizontal line (one segment) is often adequate for culvert design. (Figure "L-6"-B) The length of the weir can be taken as the horizontal length of this segment or it can be based on the roadway profile and an acceptable variation above and below the horizontal line. In effect, this method utilizes an average depth of the upstream pool above the roadway crest for the flow calculation.

It is a simple matter to calculate the flow across the roadway for a given upstream water surface elevation using the weir equation. The problem is that the roadway overflow plus the culvert flow must equal the total design flow. A trial and error process is necessary to determine the amount of the total flow passing through the culvert and the amount flowing across the roadway. Performance curves may also be superimposed for the culvert flow and the road overflow to yield an overall solution as is discussed later in this appendix.

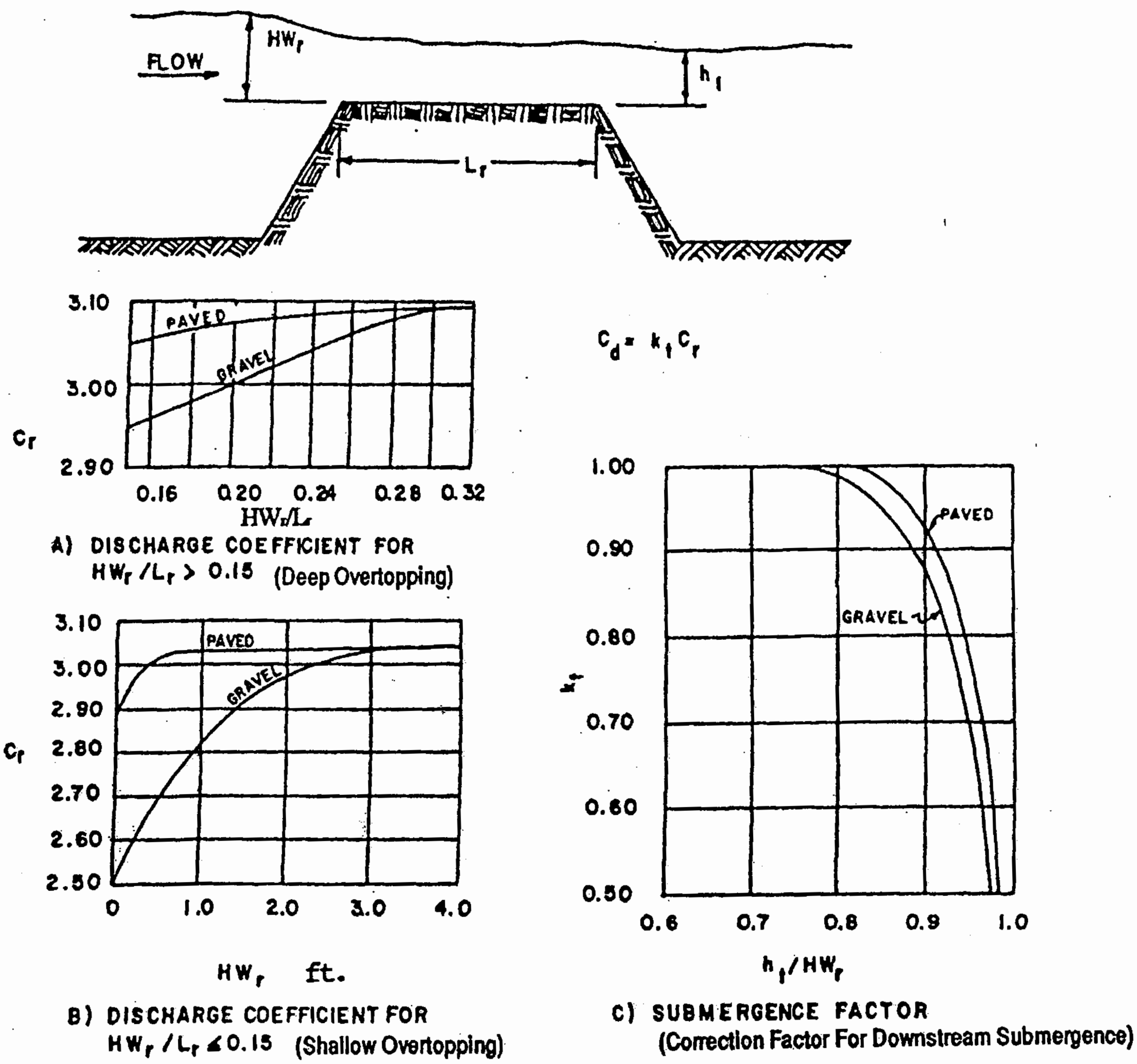


Figure "L-5" — Discharge Coefficients for Roadway Overtopping.

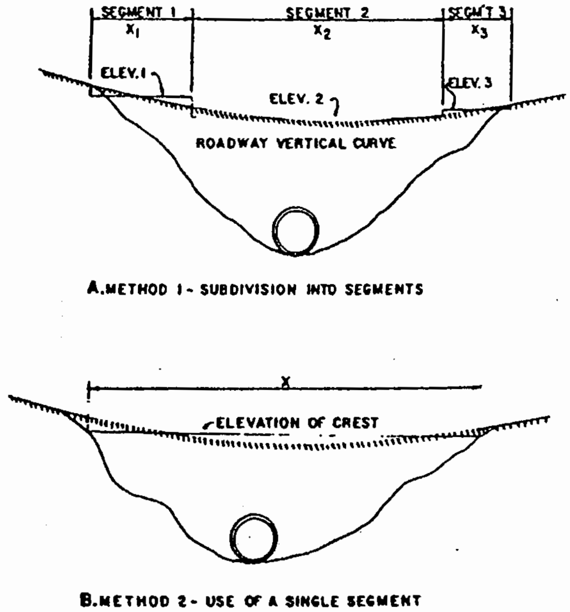


Figure "L-6" — Weir Crest Length Determinations for Roadway Overtopping.

3. Design Procedures

a. Method The design approach presented in HDS-5 is to analyze a culvert for various types of flow control (both inlet and outlet), and then design for the control which produces the minimum performance. Flow control for a given culvert may oscillate between inlet and outlet control under various flow conditions; however, using the "minimum performance" procedure, the culvert will be designed for the least favorable hydraulic conditions.

The culvert design method presented in HDS-5 (and herein) uses design charts and nomographs which are based upon data from numerous hydraulic tests and theoretical calculations. This culvert design method provides a convenient and organized procedure for designing culverts, and considers both inlet and outlet control. While it is possible to follow the design method without an understanding of culvert hydraulics, this is not recommended. The result could be an inadequate and possibly unsafe structure.

b. Culvert Design Form The Culvert Design Form, shown in Figure "L-7", has been formulated to guide the user through the design process. (Note — The FHWA Culvert Design Form shown in the example problems per HDS-5 has been modified and is presented as Table "L-5", Culvert Design Worksheet.) Summary blocks are provided at the top of the form for the project description, and the designer's identification. Summaries of hydrologic data of the form are also included. At the top right is a small sketch of the culvert with blanks for inserting important dimensions and elevations.

The central portion of the design form contains lines for inserting the trial culvert description and calculating the inlet control and outlet control headwater elevations. Space is provided at the lower center for comments and at the lower right for a description of the culvert barrel selected.

The first step in the design process is to summarize all known data for the culvert at the top of the Culvert Design Form. This information will have been collected or calculated prior to performing the actual culvert design. The next step is to select a preliminary culvert material, shape, size, and entrance type. The user then enters the design flow rate and proceeds with the inlet control calculations.

c. <u>Inlet Control</u> The inlet control calculations determine the headwater elevation required to pass the design flow through the selected culvert configuration in inlet control. The approach velocity head may be included as part of the headwater, if desired. The inlet control nomographs provided in Section D of this appendix are used in the design process. For the following discussion, refer to the schematic inlet control nomograph shown in Figure "L-8".

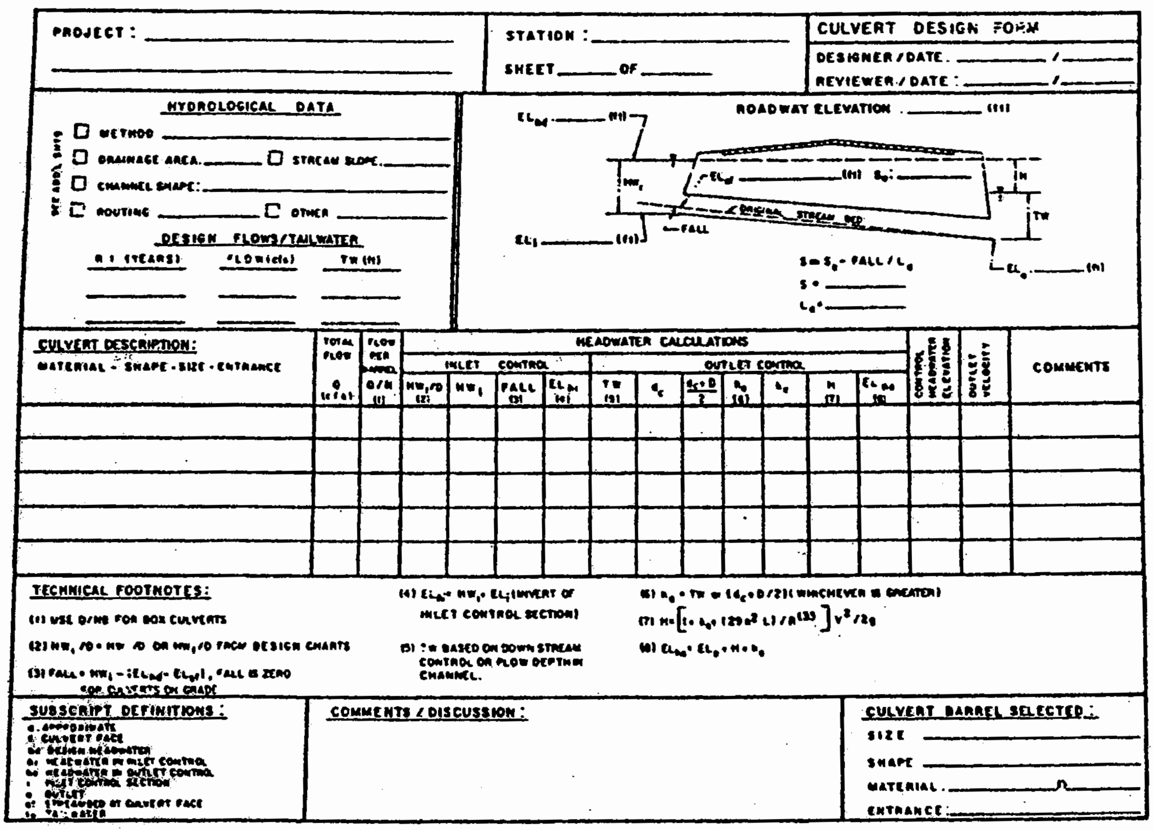


Figure "L-7" — Culvert Design Form.

1) Locate the selected culvert size (point 1) and flow rate (point 2) on the appropriate scales of the inlet control nomograph. (Note that for box culverts, the flow rate per foot of barrel width is used.)

2) Using a straightedge, carefully extend a straight line from the culvert size (point 1) through the flow rate (point 2) and mark a point on the first headwater/culvert height (HW/D) scale (point 3). The first HW/D scale is also a turning line.

(NOTE: If the nomographs are put into a notebook, a clean plastic sheet with a matte finish can be used to mark on so that the nomographs can be preserved.)

3) If another HW/D scale is required, extend a horizontal line from the first HW/D scale (the turning line) to the desired scale and read the result.

4) Multiply HW/D by the culvert height, D, to obtain the required headwater (HW) from the invert of the control section to the energy grade line. If the approach velocity is neglected, HW equals the required headwater depth (HW_i). If the approach velocity is included in the calculations, deduct the approach velocity head from HW to determine HW_i.

5) Calculate the required depression (FALL) of the inlet control section below the stream bed as follows:

$$HW_d = EL_{hd} - EL_{sf}$$

$$FALL = HW_i - HW_d$$

HW_d is the design headwater depth, ft (m)

EL_{hd} is the design headwater elevation, ft (m)

EL_{sf} is the elevation of the streambed at the face, ft (m)

HW_i is the required headwater depth, ft (m)

Possible results and consequences of this calculation are:

i) If the FALL is negative or zero, set FALL equal to zero and proceed to step f.

ii) If the FALL is positive, the inlet control section invert must be depressed below the streambed at the face by that amount. If the FALL is acceptable, proceed to step f.

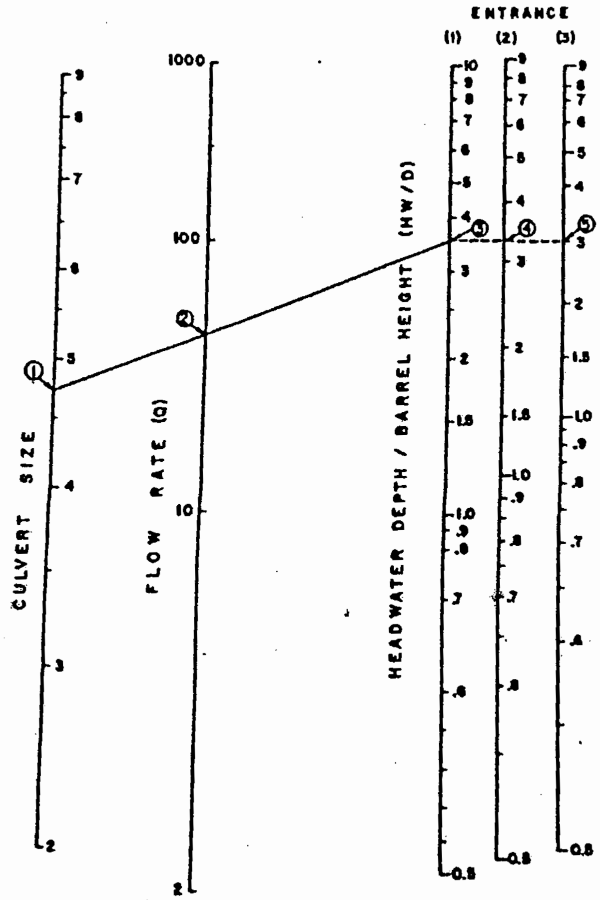


Figure "L-8" — Inlet Control Nomograph (Schematic).

iii) If the FALL is positive and greater than is judged to be acceptable, select another culvert configuration and begin again at step a.

6) Calculate the inlet control section invert elevation as follows:

$$EL_i = EL_{sf} - FALL$$

where EL_i is the invert elevation at the face of a culvert (EL_f) or at the throat of a culvert with a tapered inlet (EL_t).

d. <u>Outlet Control</u> The outlet control calculations result in the headwater elevation required to convey the design discharge through the selected culvert in outlet control. The approach and downstream velocities may be included in the design process, if desired. The critical depth charts and outlet control nomographs provided in Section D of this Appendix are used in the design process. For illustration, refer to the schematic critical depth chart and outlet control nomograph shown in Figures "L-9" and "L-10", respectively.

1) Determine the tailwater depth above the outlet invert (TW) at the design flow rate. This is obtained from backwater or normal depth calculations, or from field observations.

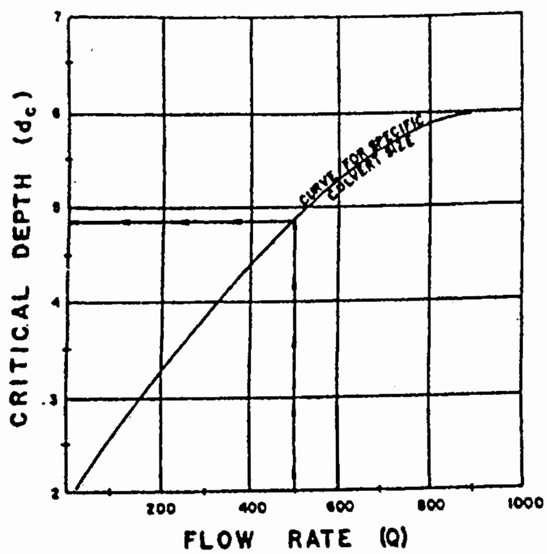


Figure "L-9" — Critical Depth Chart (Schematic).

2) Enter the appropriate critical depth chart (Figure "L-9") with the flow rate and read the critical depth (d_c). d_c cannot exceed D!

(NOTE: The d_c curves are truncated for convenience when they converge. If an accurate d_c is required for $d_c > .9D$ consult the Handbook of Hydraulics or other hydraulic references.

3) Calculate $(d_c + D)/2$

4) Determine the depth from the culvert outlet invert to the hydraulic grade line (h_o).

$$h_o = \text{TW or } (d_c + D/2)\text{, whichever is larger.}$$

5) From Table "L-4" in Section D, obtain the appropriate entrance loss coefficient, k_e, for the culvert inlet configuration.

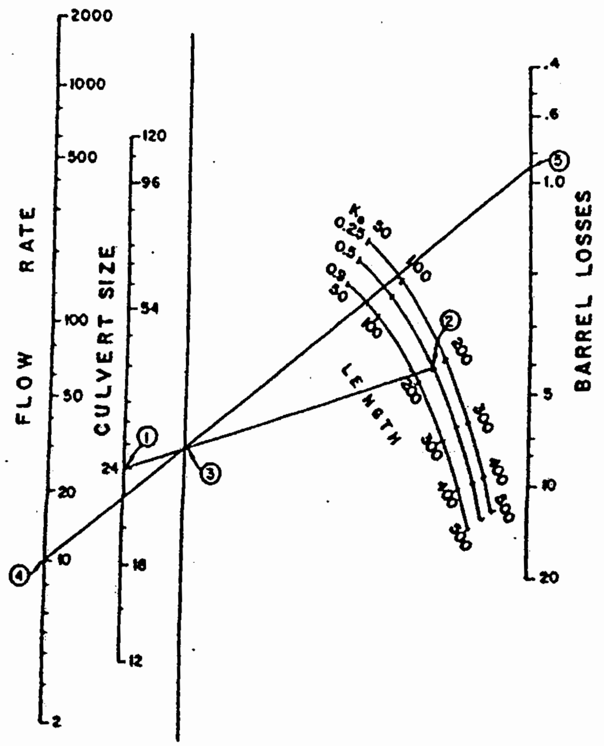


Figure "L-10" — Outlet Control Nomograph (Schematic).

6) Determine the losses through the culvert barrel, H, using the outlet control nomograph (Figure "L-10") or equation (5) or (6) if outside the range of the nomograph.

   i) If the Manning n value given in the outlet control nomograph is different than the Manning n for the culvert, adjust the culvert length using the formula:

$$L_1 = L\left(\frac{n_1}{n}\right)^2 \tag{9}$$

L_1	is the adjusted culvert length, ft (m)
L	is the actual culvert length, ft (m)
n_1	is the desired Manning n value
n	is the Manning n value from the outlet control chart.

Then, use L_1 rather than the actual culvert length when using the outlet control nomograph.

ii) Using a straightedge, connect the culvert size (point 1) with the culvert length on the appropriate k_e scale (point 2). This defines a point on the turning line (point 3).

iii) Again using the straightedge, extend a line from the discharge (point 4) through the point on the turning line (point 3) to the Head Loss (H) scale. Read H, which is the energy loss through the culvert, including entrance, friction, and outlet losses.

(NOTE: Careful alignment of the straightedge is necessary to obtain good results from the outlet control nomograph.)

7) Calculate the required outlet control headwater elevation.

$$EL_{ho} = EL_o + H + h_o \quad (10)$$

where EL_o is the invert elevation at the outlet.

8) If the outlet control headwater elevation exceeds the design headwater elevation, a new culvert configuration must be selected and the process repeated. Generally, an enlarged barrel will be necessary since inlet improvements are of limited benefit in outlet control.

e. <u>Outlet Velocity</u> Compare the headwater elevations calculated for inlet and outlet control. The higher of the two is designated the controlling headwater for at expected to operate with that higher headwater for at least part of the time.

The outlet velocity is calculated as follows:

1) If the controlling headwater is based on inlet control, determine the normal depth and velocity in the culvert barrel. The velocity at normal depth is assumed to be the outlet velocity.

2) If the controlling headwater is in outlet control, determine the area of flow at the outlet based on the barrel geometry and the following:

i) Critical depth if the tailwater is below critical depth. (This is an HDS-5 procedure, although HEC-14 advocates use of a theoretically more correct procedure of using the true culvert brink depth of Y_o);

ii) The tailwater depth if the tailwater is between critical depth and the top of the barrel; and

iii) The height of the barrel if the tailwater is above the top of the barrel.

Reference is made to Figure "L-11", which schematically shows culvert outflows and depths.

f. <u>Evaluation of Results</u> Repeat the design process until an acceptable culvert configuration is determined. Once the barrel is selected it must be fitted into the roadway cross section. The culvert barrel must have adequate cover, the length should be close to the approximate length, and the headwalls and wingwalls must be dimensioned.

If outlet control governs and the headwater depth referenced to the inlet invert) is less than 1.2D, it is possible that the barrel flows partly full through its entire length. In this case, caution should be used in applying the approximate method of setting the downstream elevation based on the greater of tailwater or $(d_c + D)/2$. If an accurate headwater is necessary, backwater calculations should be used to check the result from the approximate method. If the headwater depth falls below 0.75D, the approximate method should not be used.

If the selected culvert will not fit the site, return to the culvert design process and select another culvert.

4. <u>Example Problems</u> The following example problems illustrate the use of the design methods and charts for selected culvert configurations and hydraulic conditions. The problems cover the following situations:

i) <u>Problem No. 1</u> Circular pipe culvert, standard 2-2/3 by 1/2 in (6.8 by 1.3 cm) CMP with beveled edge and reinforced concrete pipe with groove end. No FALL.

ii) <u>Problem No. 2</u> Reinforced cast-in-place concrete box culvert with square edges and with bevels. No FALL.

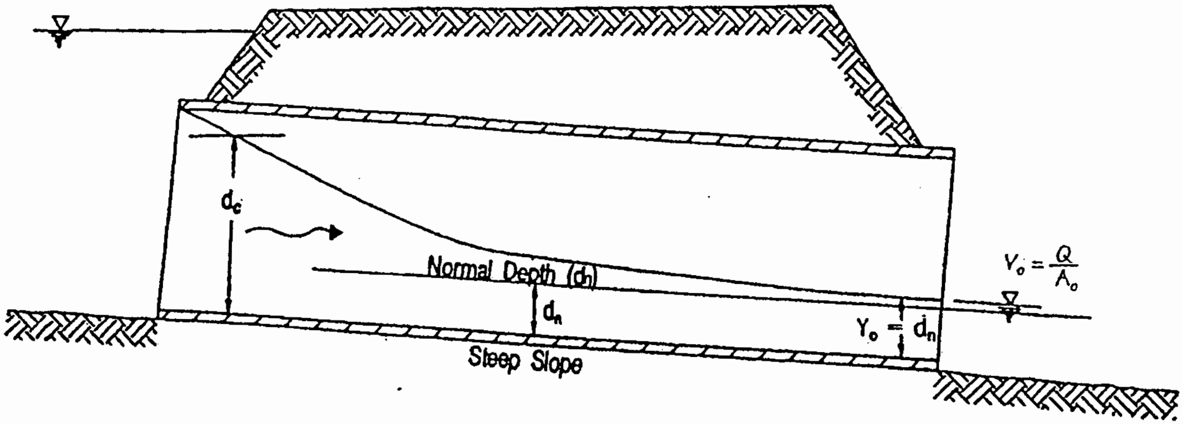
iii) <u>Problem No. 3</u> Elliptical pipe culvert with groove end and a FALL.

iv) <u>Problem No. 4</u> Analysis of an existing reinforced concrete box culvert with square edges, including road overtopping analysis.

MODIFIED FROM FIGURES 4.46 AND 4.47 IN (MARICOPA COUNTY)

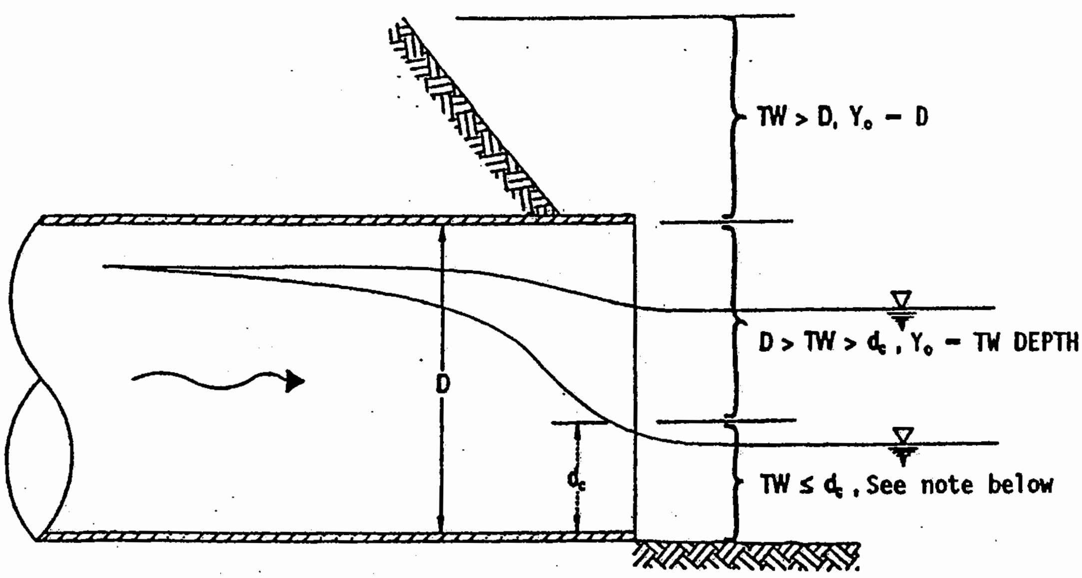
V_o = Flow velocity at the culvert outlet or brink (fps)
Q = Flow in conduct (cfs)
A_o = Area of flow at the culvert outlet or brink (ft2)
Y_o = Depth of flow at the culvert outlet or brink (ft)

TW = tailwater depth (ft)
d_n, d_c = normal & critical depth, respectively
D = Conduit depth or diameter (ft)



Note: With some tailwater conditions, there could be a backwater condition. However, unless special conditions prevent it, there will also be times when flow exits the culvert as supercritical flow. Therefore, it is common practice (HDS-5 & HEC-14) to set $Y_o = d_n$, and calculate A_o and V_o accordingly.

OUTLET VELOCITY - INLET CONTROL



Note: For TW < d_c, HDS-5 recommends setting $Y_o = d_c$, even though it is acknowledged therein that the flow surface actually crosses below dc a short distance upstream of the culvert brink. HEC-14 recommends using the lower depth that occurs right at the culvert brink, and provides design charts for calculating the theoretical Y_o. The latter method is arguably more accurate, and is also more conservative in that it results in a higher V_o estimate for outlet protection calculations. The choice of methods in obtaining Y_o is left up to the designer. A_o is based upon Y_o, and V_o calculated accordingly.

OUTLET VELOCITY - OUTLET CONTROL

OUTLET VELOCITY PARAMETERS | **FIGURE "L-11"**

a. **Example Problem No. 1**

A culvert at a new roadway crossing must be designed to pass the 25-year flood. Hydrologic analysis indicates a peak flow rate of 200 ft^3/s. Use the following site information:

Elevation at Culvert Face: 100 ft

Natural Stream Bed Slope: 1 percent = 0.01 ft/ft

Tailwater for 25-Year Flood: 3.5 ft

Approximate Culvert Length: 200 ft

Shoulder Elevation: 110 ft

Design a circular pipe culvert for this site. Consider the use of a corrugated metal pipe with standard 2-2/3 by 1/2 in corrugations and beveled edges and concrete pipe with a groove end. Base the design headwater on the shoulder elevation with a two ft freeboard (elevation 108.0 ft). Set the inlet invert at the natural streambed elevation (no FALL).

PROJECT: EXAMPLE PROBLEM NO. 1 — CHAPTER II, HDS No. 5

STATION: 1+00 — SHEET 1 OF 1

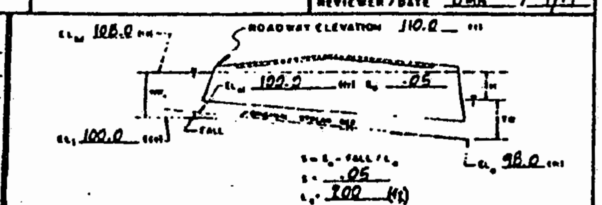
CULVERT DESIGN FORM — DESIGNER/DATE: WJJ / 7/18 — REVIEWER/DATE: JMH / 7/19

HYDROLOGICAL DATA

- METHOD: RATIONAL
- DRAINAGE AREA: 195 Ac. — STREAM SLOPE: 1.0%
- CHANNEL SHAPE: TRAPEZOIDAL
- ROUTING: N/A — OTHER:

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
25	200	3.5



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q	FLOW PER BARREL Q/N	INLET CONTROL HW_i/D	HW_i	FALL	EL_{hi}	OUTLET CONTROL TW	d_c	$\frac{d_c+D}{2}$	h_o	k_e	H	EL_{ho}	CONTROLLING HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CMP- CIRC.-72 IN.- BEVEL 45° IN HEADWALL	200	200	0.96	5.8	–	105.8	3.5	3.6	4.9	4.9	.002	2.6	105.6	105.8	8.6	TRY 60" CMP.
" " -60 IN.- " 45°			1.43	7.15	–	107.2		4.1	4.6	4.6		6.3	108.9	108.9	12.0	TRY 60" CONC.
CONC. " -60 IN.- GROOVE END			1.36	6.8	–	106.8			4.6	4.6		2.9	105.5	106.8	16.0	TRY 54" CONC.
" " -54 IN.- "			1.77	7.97	–	108.0			4.3	4.3		4.7	107.0	108.0	13.5	OK

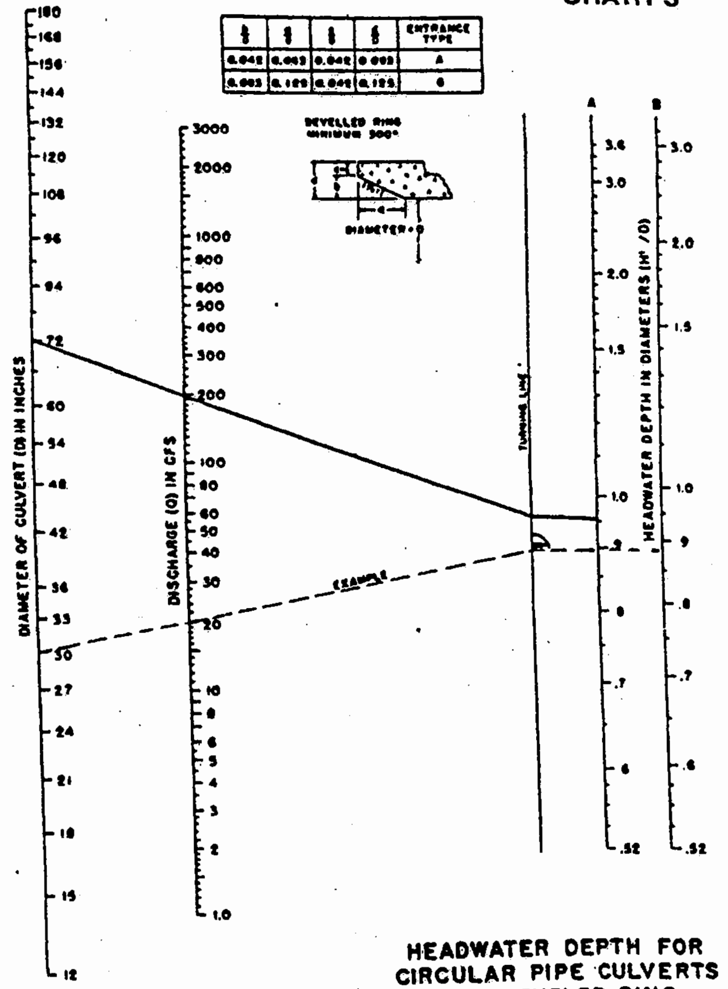
TECHNICAL FOOTNOTES:

SUBSCRIPT DEFINITIONS:

COMMENTS / DISCUSSION: HIGH OUTLET VELOCITY - OUTLET PROTECTION OR LARGER CONDUIT MAY BE NECESSARY

CULVERT BARREL SELECTED: SIZE: 54 IN. — SHAPE: CIRCULAR — MATERIAL: CONC. .012 — ENTRANCE: GROOVE END

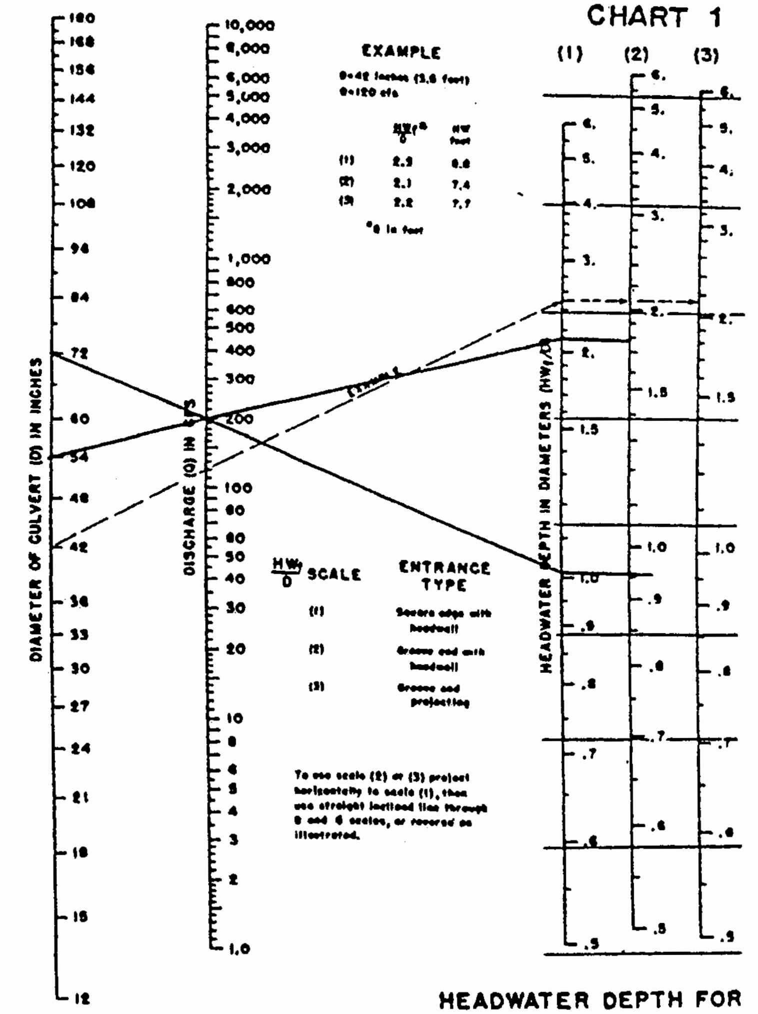
CHART 3



HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL

...ERAL HIGHWAY ADMINISTRATION
MAY 1973

CHART 1

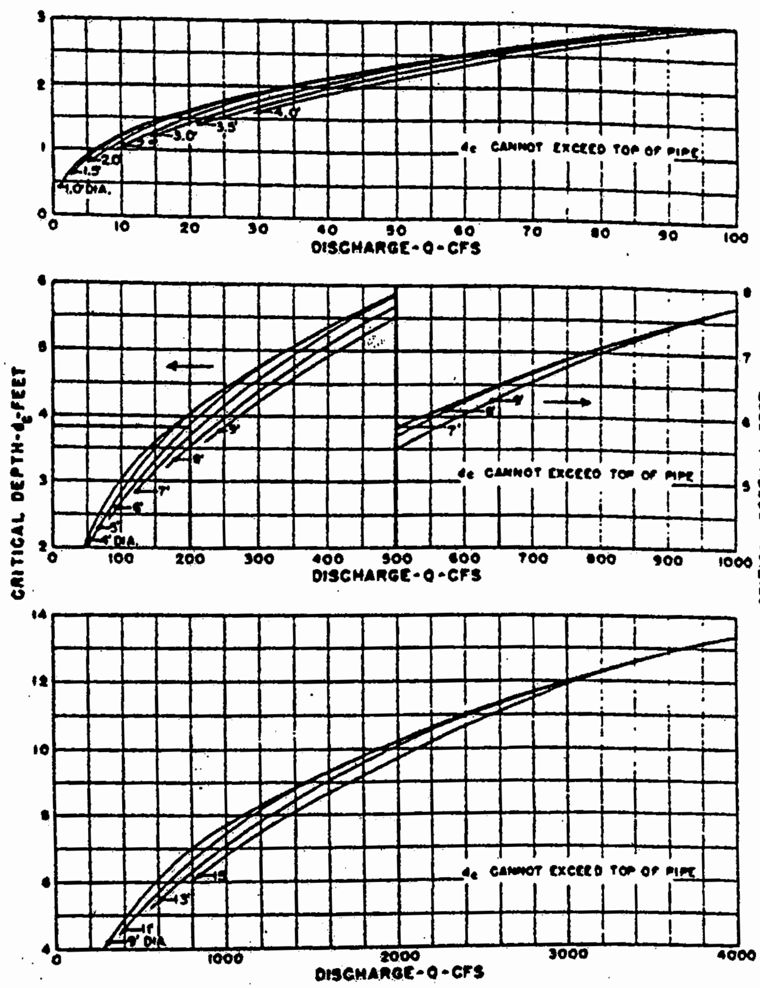


HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

HEADWATER SCALES 2&3
REVISED MAY 1964

BUREAU OF PUBLIC ROADS JAN. 1963

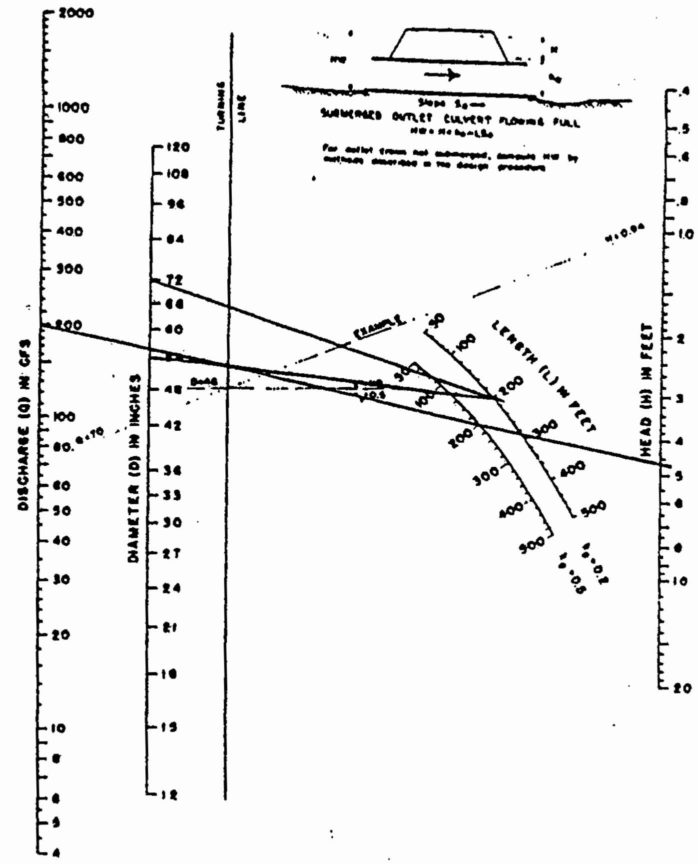
CHART 4



BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
CIRCULAR PIPE

CHART 5



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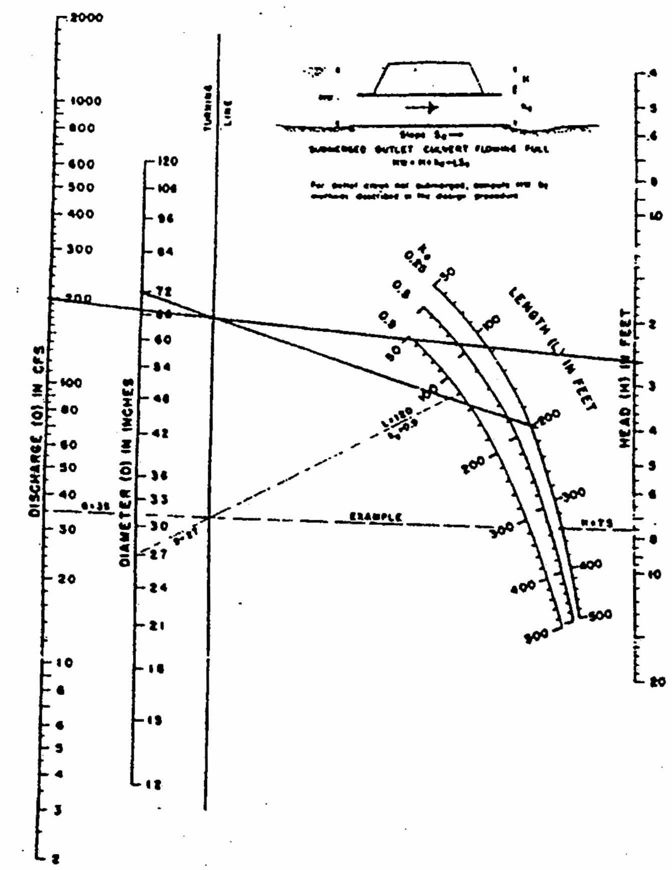
HEAD FOR
CONCRETE PIPE CULVERTS
FLOWING FULL
n = 0.012

CHART 6



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

BUREAU OF PUBLIC ROADS JAN 1963

b. <u>Example Problem No. 2</u>

A new culvert at a roadway crossing is required to pass a 50-year flow rate of 300 ft^3/s. Use the following site conditions:

EL_{hd}: 110 ft based on adjacent structures

Shoulder Elev: 113.5 ft

Elevation of Stream Bed at Culvert Face: 100.0 ft

Natural Stream Slope: 2 percent

Tailwater Depth: 4.0 ft

Approximate Culvert Length: 250 ft

Design a reinforced concrete box culvert for this installation. Try both square edges and 45-degree beveled edges in headwall. Do not depress the inlet (no FALL).

(NOTE: Design charts 8, 10, 14, and 15 are used in this solution.)

PROJECT: EXAMPLE PROBLEM NO. 2 CHAPTER III, HDS No. 5

STATION: 1+00

SHEET 1 OF 1

CULVERT DESIGN FORM

DESIGNER/DATE: WJJ / 7/16

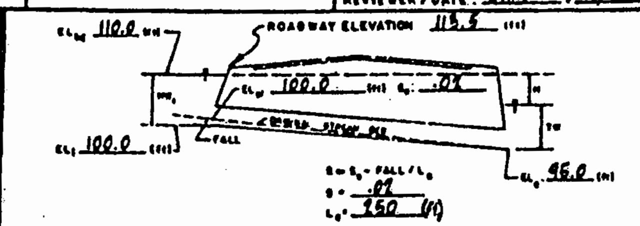
REVIEWER/DATE: JMN / 7/19

HYDROLOGICAL DATA

- ☐ METHOD: SCS
- ☐ DRAINAGE AREA: 100AC ☐ STREAM SLOPE: 2.0%
- ☐ CHANNEL SHAPE: TRAPEZOIDAL
- ☐ ROUTING: N/A ☐ OTHER

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50	300	4.0



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/B (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONCRETE - BOX - 6'x5' - SQ EDGE	300	50	1.57	7.9	-	107.9	4.0	4.2	4.6	4.6	0.5	3.55	103.2	107.9	11.7	OK TRY SM. BOX
" - " - 5'x5' - "	300	60	1.91	9.6	-	109.6	4.0	4.8	4.9	4.9	0.5	5.2	105.1	109.6	10.8	CHECK BEVELS
" - " - 5'x5' - 45° BEVEL	300	60	1.71	8.55	-	108.6	4.0	4.8	4.9	4.9	0.2	4.6	104.5	108.6	10.8	OK

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW_i/D$ OR HW_f/D FROM DESIGN CHARTS

(3) $FALL = HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L)/R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

a. APPROXIMATE
f. CULVERT FACE
hd. DESIGN HEADWATER
hi. HEADWATER IN INLET CONTROL
ho. HEADWATER IN OUTLET CONTROL
i. INLET CONTROL SECTION
o. OUTLET
sf. STREAMBED AT CULVERT FACE
tw. TAILWATER

COMMENTS / DISCUSSION:

5'x5' BOX WILL WORK WITH OR WITHOUT BEVELS. BEVELS PROVIDE ADDITIONAL FLOW CAPACITY

CULVERT BARREL SELECTED:

SIZE: 5 FT. X 5 FT.

SHAPE: RECTANGULAR

MATERIAL: CONC. n .012

ENTRANCE: SQ. EDGE - 90° HEADWALL

c. <u>Example Problem No. 3</u>

Design a culvert to pass a 25-year flow of 220 ft^3/s. Minimum depth of cover for this culvert is 2 ft.

EL_{hd}: 105 ft based on adjacent structures

Shoulder Elev.: 105.5 ft

Elevation of Stream Bed at Culvert Face (EL_{sf}): 100 ft

Original Stream Slope: 5 percent

Tailwater Depth: 4 ft

Approximate Culvert Length: 150 ft

Due to the low available cover over the conduit, use an elliptical concrete pipe. Use of a small depression (FALL) of about 1 ft at the inlet is acceptable.

(NOTE: Charts 29, 31 and 33 are used in this solution.)

PROJECT: EXAMPLE PROBLEM No. 3 CHAPTER III, HDS No. 5

STATION: 2+00

SHEET 1 OF 1

CULVERT DESIGN FORM

DESIGNER/DATE: WJJ / 7/18

REVIEWER/DATE: JMN / 7/19

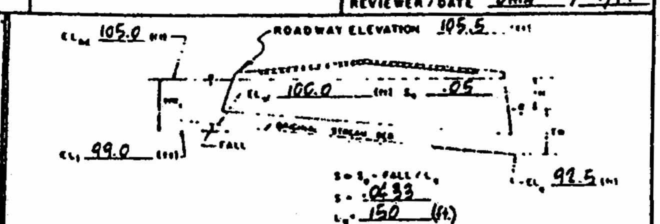
HYDROLOGICAL DATA

- ☐ METHOD: RATIONAL
- ☐ DRAINAGE AREA: 110 AC. ☐ STREAM SLOPE: 5.0%
- ☐ CHANNEL SHAPE: SEMI-CIRCULAR
- ☑ ROUTING: 40CFS RED. FROM PEAK ☐ OTHER: DEPTH OF COVER 2' MIN.

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
25	180*	4.0

* APPROX. ROUTED FLOW RATE



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE

Culvert description	Total flow Q (cfs)	Flow per barrel Q/N (1)	Inlet control HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	Outlet control TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	Controlling headwater elevation	Outlet velocity	Comments
CONC. - HORIZ. ELLIPSE - 68"x43" - SQ. EDGE	180	-	1.98	7.1	-	107.1	4.0	3.2	3.6	4.0	0.5	3.7	100.2	107.1	-	TRY GROOVE END W/HEADWALL
" - " - " x " - GROOVE END	180	-	1.63	5.8	-	105.8	4.0	3.2	3.6	4.0	0.2	3.2	99.7	105.8	-	EL_{hi} TOO HIGH USE FALL
" - " - " x " - "	180	-	1.63	5.8	1.0	104.8	4.0	3.2	3.6	4.0	0.2	3.2	99.7	104.8	14.9	OK - DEPTH OF COVER OK ALSO

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW/D$ OR HW_i/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) h_o = TW or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29 n^2 L)/R^{1.33}\right] V^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

- a. APPROXIMATE
- f. CULVERT FACE
- hd. DESIGN HEADWATER
- hi. HEADWATER IN INLET CONTROL
- ho. HEADWATER IN OUTLET CONTROL
- i. INLET CONTROL SECTION
- o. OUTLET
- sf. STREAMBED AT CULVERT FACE
- tw. TAILWATER

COMMENTS / DISCUSSION:

HIGH OUTLET VELOCITY - CHECK STREAM BED STABILITY

CULVERT BARREL SELECTED:

SIZE: 68" x 43"

SHAPE: HORIZONTAL ELLIPSE

MATERIAL: CONC. n = .012

ENTRANCE: GROOVE END

d. Example Problem No. 4

An existing 7 ft by 7 ft concrete box culvert was designed for a 50-year flood of 600 ft^3/s and a design headwater elevation of 114 ft. Upstream development has increased the 50-year runoff to 1,000 ft^3/s. The roadway is gravel with a width of 40 ft. The roadway profile may be approximated as a broad crested weir 200 ft long. Use Figure "L-5" to calculate overtopping flows, and the following site data:

Inlet Invert Elevation: 100 ft

Entrance Condition: Square Edges

Slope: 5 percent

Roadway Centerline Elevation: 116 ft

Culvert Length: 200 ft

Tailwater Information

Flow, ft^3/s	TW, ft
400	2.6
600	3.1
800	3.8
1000	4.1

Prepare a performance curve for this installation, including any roadway overtopping, up to a flow rate of 1,200 ft^3/s.

(NOTE: Charts 8, 14 and 15, and Figure "L-5" are used in this solution.)

PROJECT: EXAMPLE PROBLEM No. 1 CHAPTER III, HDS No. 5	STATION: 4+50 SHEET 1 OF 3	CULVERT DESIGN FORM DESIGNER/DATE: WJJ / 7/16 REVIEWER/DATE: JMN / 7/19

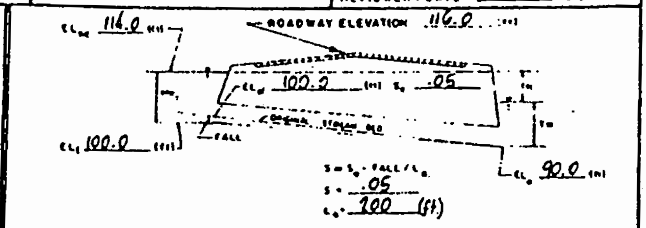
HYDROLOGICAL DATA

(See 4.05 Data)

- ☐ METHOD: SCS
- ☐ DRAINAGE AREA: 400 Ac. ☐ STREAM SLOPE: 5.0%
- ☐ CHANNEL SHAPE: TRAPEZOIDAL
- ☐ ROUTING: N/A ☐ OTHER:

DESIGN FLOWS/TAILWATER

R.I. (YEARS)	FLOW (cfs)	TW (ft)
50 (OLD)	600	3.1
50 (NEW)	1000	4.1



CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/B (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. - BOX - 7'x7' - SQ. EDGE	400	57.1	1.15	8.1	—	108.1	2.0	4.6	5.8	5.8	0.5	1.95	97.8	108.1	—	—
↓	600	85.7	1.65	11.6	—	111.6	3.1	6.1	6.6	6.6	↓	4.4	101.0	111.6	—	—
↓	700	100.0	1.95	13.7	—	113.7	3.5	6.8	6.9	6.9	↓	6.0	102.9	113.7	—	—
↓	800	114.3	2.35	16.5	—	116.5	3.8	≥ 7	7.0	7.0	↓	7.9	104.9	116.5	—	—
↓	850	121.9	2.55	17.9	—	117.9	3.9	↓	〃	〃	↓	9.0	106.0	117.5	—	—

TECHNICAL FOOTNOTES:

(1) USE Q/NB FOR BOX CULVERTS

(2) $HW_i/D = HW_f/D$ OR HW_i/D FROM DESIGN CHARTS

(3) FALL = $HW_i - (EL_{hd} - EL_{sf})$; FALL IS ZERO FOR CULVERTS ON GRADE

(4) $EL_{hi} = HW_i + EL_i$ (INVERT OF INLET CONTROL SECTION)

(5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.

(6) $h_o = TW$ or $(d_c + D/2)$ (WHICHEVER IS GREATER)

(7) $H = \left[1 + k_e + (29n^2 L)/R^{1.33}\right] v^2/2g$

(8) $EL_{ho} = EL_o + H + h_o$

SUBSCRIPT DEFINITIONS:

- a. APPROXIMATE
- f. CULVERT FACE
- hd. DESIGN HEADWATER
- hi. HEADWATER IN INLET CONTROL
- ho. HEADWATER IN OUTLET CONTROL
- i. INLET CONTROL SECTION
- o. OUTLET
- sf. STREAMBED AT CULVERT FACE
- tw. TAILWATER

COMMENTS / DISCUSSION:

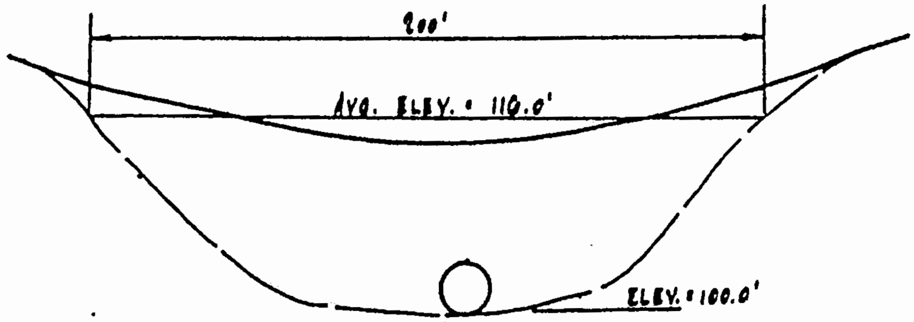
NEW Q_{50} RESULTS W ROADWAY OVERTOPPING. 2.5' ABOVE EL_{hd}

CULVERT BARREL SELECTED:

- SIZE: 7' x 7'
- SHAPE: RECTANGULAR
- MATERIAL: CONC. n .012
- ENTRANCE: SQ. EDGE W/HEADWALL

CULVERT DESCRIPTION: MATERIAL - SHAPE - SIZE - ENTRANCE	TOTAL FLOW Q (cfs)	FLOW PER BARREL Q/B (1)	INLET CONTROL HW_i/D (2)	HW_i	FALL (3)	EL_{hi} (4)	OUTLET CONTROL TW (5)	d_c	$\frac{d_c+D}{2}$	h_o (6)	k_e	H (7)	EL_{ho} (8)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS
CONC. - BOX - 7'x7' - SQ. EDGE	1000	142.9	3.21	22.5	-	122.5	4.1	≥ 7	7.0	7.0	0.5	1.26	109.6	122.5	—	—

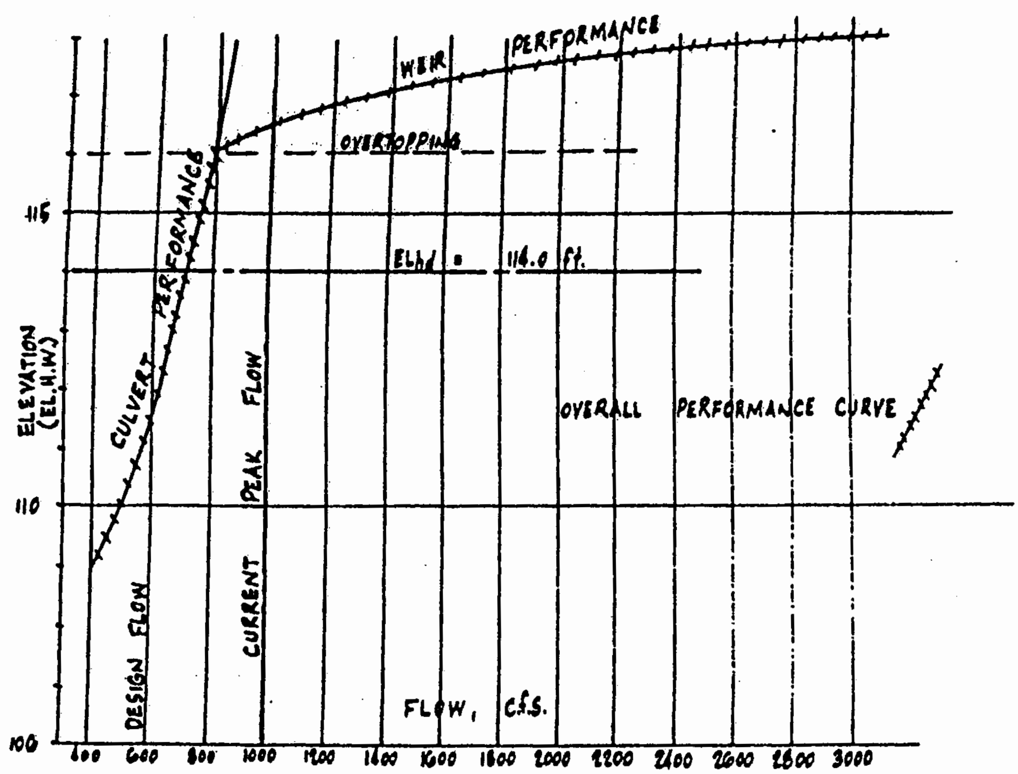
EXAMPLE PROBLEM No. 6 | CHAPTER III, HDS No. 5 | SHEET 3 OF 3



Q_c CULVERT FLOW	EL_h	H_o	Q_o OVERTOPPING FLOW	Q TOTAL FLOW
400	108.1	-	-	400
600	111.6	-	-	600
700	113.7	-	-	700
800	116.5	0.5	191	991
850	117.5	1.5	1073	1923
1000	122.5	6.0	-	-

FROM FIGURE "L-5B" : $C_d = 2.70$ @ $HW_r = .5$; $C_d = 2.92$ @ $HW_r = 1.5$ } $K_t = 1$

$Q = C_d L HW_r^{1.5}$



C. SPECIAL CONSIDERATIONS

Several special considerations are briefly mentioned here, noting that design information is available in HDS-5.

1. Improved Inlet Design Often a culvert operates under inlet control conditions. When this is the case, simply adding pre-manufactured flared end sections or other inlet improvements may often improve culvert hydraulic efficiency and be cost effective. For larger flows and culverts governed by inlet control, it may be economically advantageous to design a tapered inlet. Tapered inlets improve culvert performance primarily by reducing the contraction at the inlet control section. Methods and design charts are presented in Section IV of HDS-5 for side, slope, and combined side/slope tapered inlets.

2. Special Applications Special applications may not have frequent usage, but information regarding design is available in Section VI of HDS-5. These applications include flow control and measurement through use of culverts, low bend installations, bends, siphons, junctions, and fish passage.

3. Erosion Control This is an important aspect of culvert design. Riprap protection at outlets is discussed in Appendix "J". Additional information regarding erosion for inlets, outlets, and sedimentation is provided in Section VI of HDS-5 and also FHWA HEC-14, "Hydraulic Design of Energy Dissipators for Culverts and Channels".

4. Debris Control Debris includes some combination of floating material, suspended sediment, and bed load. Debris can accumulate at a culvert inlet or become lodged in the inlet or barrel. Various types of controls are briefly discussed in HDS-5, but a more comprehensive guide is provided in the FHWA HEC-9, "Debris Control Structures".

5. Service Life The service life of culverts is dependent upon factors such as soil and water corrosivity, culvert material and coating, sediment and abrasion potential, and loadings.

   a. Corrosion Resistance CDOT provides guidelines on the selection of corrosion resistant culverts. Table "L-2" is a reproduction of a CDOT laboratory guideline which assists in the determination of a CDOT "Corrosion Resistance" or CR number, which is then used with Table "L-3" (Table 624-1 in CDOT 1991) to indicate which culvert types will likely have acceptable service lives. Other guidance on soil and water PH and electrical resistance and resultant expected service life of metal culverts is provided in Chapter 5 of the "Handbook of Steel Drainage & Highway Construction Products".

b. <u>Abrasion</u> Guidelines are given in the AISC handbook for selection of coatings against abrasion for metal culverts. Concrete resists abrasion well, as does polyethylene pipe. Some coatings provided for corrosion resistance are also resistant to abrasion, but most are not. One must be cautious in selection of a coating that must meet both requirements.

TABLE "L-2"
GUIDELINES FOR SELECTION OF CORROSION RESISTANCE LEVELS
(Reproduced from a March 21, 1983 CDOT guideline)

	SOIL			WATER		
CR LEVEL	Sulfate (SO_4) % max	Chloride (Cl) % max	pH	Sulfate (SO_4) ppm max	Chloride (Cl) ppm max	pH
CR 0	0.05	0.05	6.0 - 8.5	250	250	6.0 - 8.5
CR 1	0.15	0.15	6.0 - 8.5	250	250	6.0 - 8.5
CR 2	0.05	0.05	6.0 - 8.5	500	500	6.0 - 8.5
CR 3	0.15	0.15	6.0 - 8.5	500	500	6.0 - 8.5
CR 4	0.50	1.00	5.0 - 9.0	1000	1000	5.0 - 9.0
CR 5	1.00	1.50	5.0 - 9.0	2000	2000	5.0 - 9.0
CR 6	>1.00	>1.50	<5.0 or >9.0	>2000	>2000	<5.0 or >9.0

<u>NOTES:</u>

1. No special corrosion protection is required when the CR level is zero.
2. This table is to be used as an aid in the selection of a CR Level. Observations of field conditions should always be considered in making final decision.
3. Concrete pipe used when the pH of either the soil or water is less than 5 should be coated in accordance with 706.10 of the CDOT Standard Specifications.

Corrosion Resistance Number				CR1	CR2	CR3	CR4	CR5	CR6
Corrosion Condition Description				Mild	Mild	Mild	Moderate	Severe	Extreme
Corrosion Condition Inside or Outside Pipe				Outside Only	Inside Only	Both	Both	Both	Both
Type of Pipe									
Corrosion I.D. No.	Material Description	Material Abbreviation	CDOT Specification						
1.	Corrugated Steel Pipe	CSP	707.02	NO	NO	NO	NO	NO	NO
2.	Bituminous Coated Corrugated Steel Pipe	Bit. Co. CSP	707.03	YES[1]	NO	NO	NO	NO	NO
3.	Aramid Fiber Bonded Corrugated Steel Pipe	A.F. Bo. CSP	707.03	YES	YES	YES	YES	YES	YES
4.	Corrugated Aluminum Pipe	CAP	707.06	YES[2]	YES[2]	YES[2]	YES[2]	YES	NO
5.	Precoated Corrugated Steel Pipe coated on both sides with 0.010 inch minumum	PCSP - both sides	707.10	YES	YES	YES	NO	NO	NO
6.	Reinforced or Nonreinforced Concrete Pipe, Type I Cement	RCP or NRCP	706.02 and .01	YES	YES	YES	NO	NO	NO
7.	Reinforced or Nonreinforced Concrete Pipe, Type II Cement	RCP or NRCP	706.02 and .01	YES	YES	YES	YES	NO[3]	NO
8.	Reinforced or Nonreinforced Concrete Pipe, Type V Cement	RCP or NRCP	706.02 and .01	YES	YES	YES	YES	YES	YES
9.	Polyvinyl Chloride	PVC	712.14	YES	YES	YES	YES	YES	YES
10.	Polyethylene	PE	712.14	YES	YES	YES	YES	YES	YES

[1] Coated Steel Structural Plate Pipe of equal or greater diameter, confrorming to CDOT Section 510, may be substituted for Bit. Co. CSP.

[2] Aluminum alloy Structural Plate Pipe of equal or greater diameter, conforming to CDOT Section 510, may be substituted for CAP.

[3] RCP or NRCP made with Type II cement having maximums of 5% C_3A and 25% (C_4AF+2C_3A) may be used for corrosion condition CR-5 if approved.

CULVERT SELECTION FOR CORROSION RESISTANCE | **TABLE "L-3"**

D. DESIGN CHARTS AND TABLES

Except for Table "L-5", and Figures "L-12" and "L-13", the tables and charts provided in this section are all taken from the 1985 edition of HDS-5. Not all of the HDS-5 design charts are provided, but what is provided should be applicable to most culvert applications. The tables and charts provided herein are listed below to assist in finding the desired material.

Corrugated Metal Box Culverts

Elliptical Culverts

Pipe/Arch Culverts

Arch Culverts

TABLE "L-4" — ENTRANCE LOSS COEFFICIENTS
Outlet Control, Full or Partly Full Entrance Head Loss

$$H_e = k_e \left(\frac{V^2}{2g} \right)$$

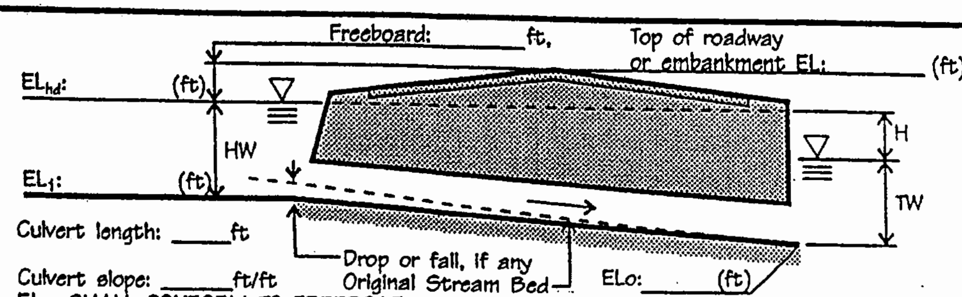
Type of Structure and Design of Entrance	Coefficient k_e
Pipe, Concrete	
Projecting from fill, socket end (groove-end)	0.2
Projecting from fill, sq. cut end	0.5
Headwall or headwall and wingwall	
Socket end of pipe (groove-end)	0.2
Square-edge	0.5
Rounded (radius = 1/12D)	0.2
Mitered to conform to fill 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	
Projecting from fill (no headwall)	0.9
Headwall or headwall and wingwalls square-edge	0.5
Mitered to conform 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 barrel dimension, 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 barrel dimension, or beveled top edge	0.2
Wingwall at 10° to 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

*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.

Project:________________ Location or Culvert I.D.:________ Design By:________________ Date:__________ Q_2:______cfs Q_{100}:______cfs

TEPS (1) to (21)
)-(8) Fill in applicable data.
) Divide total flow by # culverts and also by width for box culverts.
10) See pp. L-30 & 31 for applicable inlet control design chart.
11) & (12) Multiply (10) by (5) or (6) to get HW then add it to EL_i to get req'd HW elevation EL_{hi} for inlet control.
13) Enter pre-determined tailwater depth, or 0.4D if unobtainable.
14) & (15) See pp. L-30 & 31 for applicable critical depth chart. Use D from (5) or (6).
(16) ho is greater of (13) or (15).
(17) See Table "L-4", page L-32.
(18) See pp. L-30 & 31 for applicable outlet control design chart.
(19) Add (16) and (18) to EL_o to get req'd HW elevation EL_{ho} for outlet control.
(20) Enter "I" if (12) exceeds (19); otherwise, enter "O".
(21) Enter higher value of (12) and (19). Check sketch in (1). Will the culvert meet requirements? If not, return to step (2).

(1)



EL_{hd} SHALL CONFORM TO FREEBOARD, EASEMENT, AND INUNDATION POLICY.

TRIAL No. (2)	CULVERT DESCRIPTION: MAT'L TYPE (3)	CULV. SHAPE (4)	DIA. D (ft) (5)	HEIGHT D (ft) (6)	WIDTH B (ft) (7)	No. OF CULV. (8)	FLOW PER CULV. (cfs) (9)	HEADWATER CALCULATIONS — INLET CONTROL: HW/D (10)	HW (ft) (11)	EL_{hi} (ft) (12)	OUTLET CONTROL: TW (ft) (13)	dc (ft) (14)	(dc + D)/2 (15)	h_o (ft) (16)	K_e (17)	H (ft) (18)	EL_{ho} (ft) (19)	GOVERNING CONTROL: Type (20)	EL_{hd} (21)

STEPS (22) - (40)
22) Enter number of selected trial from above.
23 - (28) If (20) is "I", do (23) & (24) and skip (25) - (29). Otherwise, skip (23) & (24).
23) See Table "F-1d" on p. F-7 or see applicable outlet control design chart for "n".
24) Yo = d_n. Enter $Qn/(D^{8/3}S^{1/2})$ in Table "L-6", p. L-34 or $Qn/(1.486D^{8/3}S^{0.5})$ in Figure "L-12", p. L-35 and read corresponding d/D. Multiply by D, and obtain d = Yo. Skip to step (30).
(25) - (27) Calculate value for applicable column only. Use (9) and (5) or (6).
(28) Use (13) and (5) or (6)
(29) Enter (28) and (25) to (27) in Figure "L-13", pp. L-36 & 37read Yo/D. [Or, per HDS-5, skip (25) - (28), divide (14) by (5) or (6).]
(30) Enter (24)/D or (29) into Table "L-6", p. L-34, read corresponding A/D^2, multiply by $(5)^2$ or $(6)^2$ to get Ao.
(31) (9)/(30) = Vo
(32) For non-circular culverts, enter (24) or (29) x D. For circular culverts, obtain equivalent brink depth, Ye = $(Ao/2)^{0.5}$
(33) Froude number Fr = $Vo/(32.2Ye)^{0.5}$
(34) Enter permissible velocity for downstream channel per Appdendix "I" or Table "VII-1" in Section VII.
(35) If Vo/ Vp ≤ 1.3 & Fr < 0.86, only a flared end section is req'd. Otherwise, see Table "J-10" in Appendix "J".
(36) Enter value from Table "L-2", p. L-28.
(37) Enter corrosive I.D. No. from Table "L-3", p. L-29.
(38) - (39) Enter pipe and bedding specifications.
(40) Other remarks?

TRIAL No. (22)	DETERMINE CONDUIT OUTFLOW VELOCITY AND FROUDE NO. — CONTROL TYPE — INLET: PIPE "n" (23)	Yo (ft) (24)	OUTLET: Froude Parameter (U) $Q/D^{2.5}$ (25)	$Q/BD^{1.5}$ (26)	$q/D^{1.5}$ (27)	TW/D (28)	Yo/D (29)	BRINK FLOW VALUES: Ao (ft^2) (30)	Vo (fps) (31)	Ye (ft) (32)	Fr (33)	OUTLET PROTECTION REQUIRED?: Vp (fps) (34)	Vo/Vp (35)	CORROSION PROTECTION: CR No. (36)	PIPE CORR No. (37)	STRUCTURAL: PIPE: •Class •Gage •SDR (38)	Bed Class (39)	REMARKS (40)

CULVERT DESIGN WORKSHEET

TABLE "L-5"

REPRODUCED FROM FHWA HEC-14, TABLE III-2

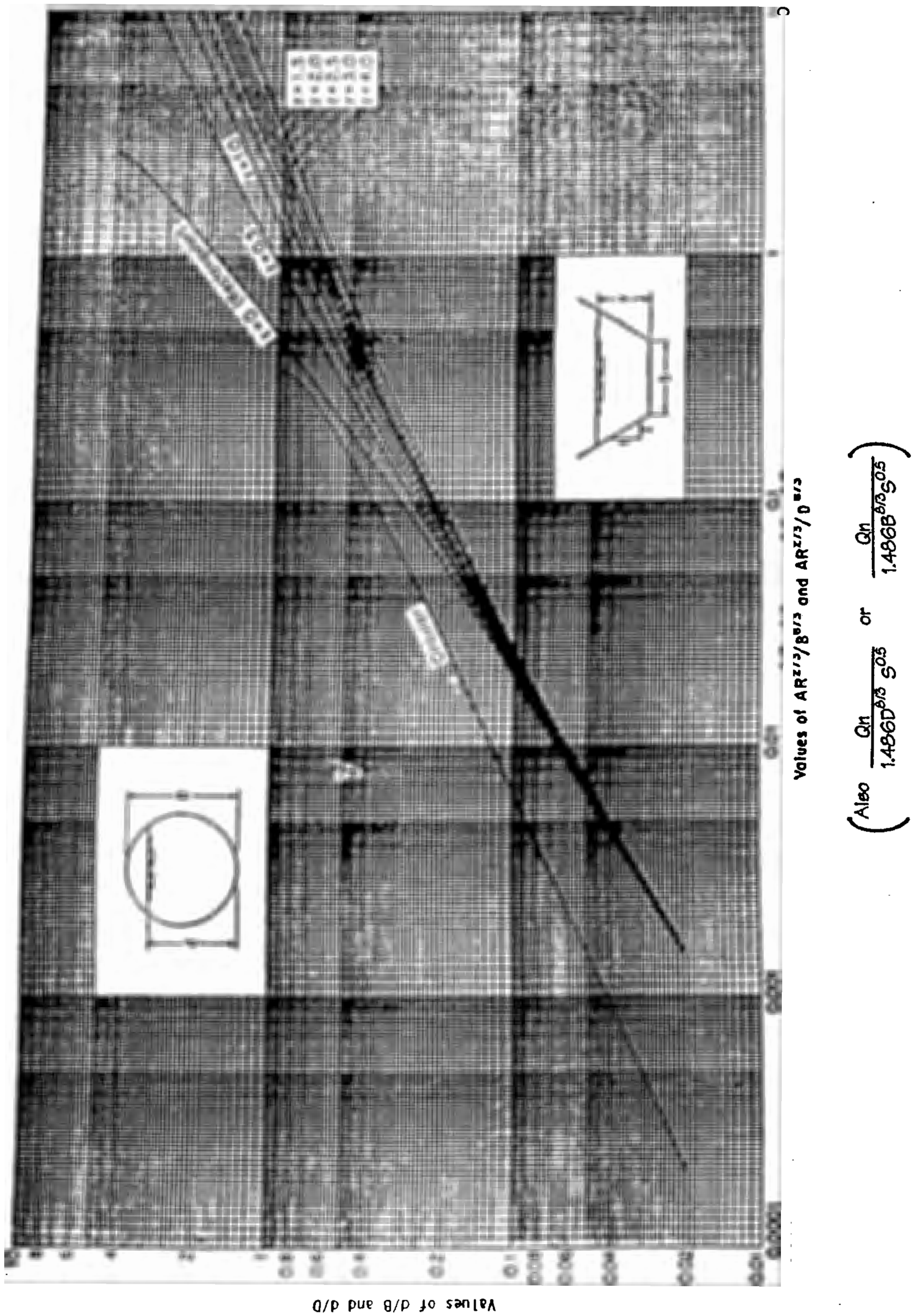
d = depth of flow (ft)
D = diameter of pipe (ft)
A = area of flow (ft^2)
R_h = hydraulic radius (ft)
Q = discharge in cubic feet per second by Manning's formula
n = Manning's coefficient
S = slope of the channel bottom and of the water surface (ft/ft)

$\frac{d}{D}$	$\frac{A}{D^2}$	$\frac{R_h}{D}$	$\frac{Qn}{D^{8/3}S^{1/2}}$	$\frac{Qn}{d^{8/3}S^{1/2}}$	$\frac{d}{D}$	$\frac{A}{D^2}$	$\frac{R_h}{D}$	$\frac{Qn}{D^{8/3}S^{1/2}}$	$\frac{Qn}{d^{8/3}S^{1/2}}$
0.01	0.0013	0.0066	0.00007	15.04	0.51	0.4027	0.2531	0.239	1.442
0.02	0.0037	0.0132	0.00031	10.57	0.52	0.4127	0.2562	0.247	1.415
0.03	0.0069	0.0197	0.00074	8.56	0.53	0.4227	0.2592	0.255	1.388
0.04	0.0105	0.0262	0.00138	7.38	0.54	0.4327	0.2621	0.263	1.362
0.05	0.0147	0.0325	0.00222	6.55	0.55	0.4426	0.2649	0.271	1.336
0.06	0.0192	0.0389	0.00328	5.95	0.56	0.4526	0.2676	0.279	1.311
0.07	0.0242	0.0451	0.00455	5.47	0.57	0.4625	0.2703	0.287	1.286
0.08	0.0294	0.0513	0.00604	5.09	0.58	0.4724	0.2728	0.295	1.262
0.09	0.0350	0.0575	0.00775	4.76	0.59	0.4822	0.2753	0.303	1.238
0.10	0.0409	0.0635	0.00967	4.49	0.60	0.4920	0.2776	0.311	1.215
0.11	0.0470	0.0695	0.01181	4.25	0.61	0.5018	0.2799	0.319	1.192
0.12	0.0534	0.0755	0.01417	4.04	0.62	0.5115	0.2821	0.327	1.170
0.13	0.0600	0.0813	0.01674	3.86	0.63	0.5212	0.2842	0.335	1.148
0.14	0.0668	0.0871	0.01952	3.69	0.64	0.5308	0.2862	0.343	1.126
0.15	0.0739	0.0929	0.0225	3.54	0.65	0.5404	0.2882	0.350	1.105
0.16	0.0811	0.0985	0.0257	3.41	0.66	0.5499	0.2900	0.358	1.084
0.17	0.0885	0.1042	0.0291	3.28	0.67	0.5594	0.2917	0.366	1.064
0.18	0.0961	0.1097	0.0327	3.17	0.68	0.5687	0.2933	0.373	1.044
0.19	0.1039	0.1152	0.0365	3.06	0.69	0.5780	0.2948	0.380	1.024
0.20	0.1118	0.1206	0.0406	2.96	0.70	0.5872	0.2962	0.388	1.004
0.21	0.1199	0.1259	0.0448	2.87	0.71	0.5964	0.2975	0.395	0.985
0.22	0.1281	0.1312	0.0492	2.79	0.72	0.6054	0.2987	0.402	0.965
0.23	0.1365	0.1364	0.0537	2.71	0.73	0.6143	0.2998	0.409	0.947
0.24	0.1449	0.1416	0.0585	2.63	0.74	0.6231	0.3008	0.416	0.928
0.25	0.1535	0.1466	0.0634	2.56	0.75	0.6319	0.3017	0.422	0.910
0.26	0.1623	0.1516	0.0686	2.49	0.76	0.6405	0.3024	0.429	0.891
0.27	0.1711	0.1566	0.0739	2.42	0.77	0.6489	0.3031	0.435	0.873
0.28	0.1800	0.1614	0.0793	2.36	0.78	0.6573	0.3036	0.441	0.856
0.29	0.1890	0.1662	0.0849	2.30	0.79	0.6655	0.3039	0.447	0.838
0.30	0.1982	0.1709	0.0907	2.25	0.80	0.6736	0.3042	0.453	0.821
0.31	0.2074	0.1756	0.0966	2.20	0.81	0.6815	0.3043	0.458	0.804
0.32	0.2167	0.1802	0.1027	2.14	0.82	0.6893	0.3043	0.463	0.787
0.33	0.2260	0.1847	0.1089	2.09	0.83	0.6969	0.3041	0.468	0.770
0.34	0.2355	0.1891	0.1153	2.05	0.84	0.7043	0.3038	0.473	0.753
0.35	0.2450	0.1935	0.1218	2.00	0.85	0.7115	0.3033	0.477	0.736
0.36	0.2546	0.1978	0.1284	1.958	0.86	0.7186	0.3026	0.481	0.720
0.37	0.2642	0.2020	0.1351	1.915	0.87	0.7254	0.3018	0.485	0.703
0.38	0.2739	0.2062	0.1420	1.875	0.88	0.7320	0.3007	0.488	0.687
0.39	0.2836	0.2102	0.1490	1.835	0.89	0.7384	0.2995	0.491	0.670
0.40	0.2934	0.2142	0.1561	1.797	0.90	0.7445	0.2980	0.494	0.654
0.41	0.3032	0.2182	0.1633	1.760	0.91	0.7504	0.2963	0.496	0.637
0.42	0.3130	0.2220	0.1705	1.724	0.92	0.7560	0.2944	0.497	0.621
0.43	0.3229	0.2258	0.1779	1.689	0.93	0.7612	0.2921	0.498	0.604
0.44	0.3328	0.2295	0.1854	1.655	0.94	0.7662	0.2895	0.498	0.588
0.45	0.3428	0.2331	0.1929	1.622	0.95	0.7707	0.2865	0.498	0.571
0.46	0.3527	0.2366	0.201	1.590	0.96	0.7749	0.2829	0.496	0.553
0.47	0.3627	0.2401	0.208	1.559	0.97	0.7785	0.2787	0.494	0.535
0.48	0.3727	0.2435	0.216	1.530	0.98	0.7817	0.2735	0.489	0.517
0.49	0.3827	0.2468	0.224	1.500	0.99	0.7841	0.2666	0.483	0.496
0.50	0.3927	0.2500	0.232	1.471	1.00	0.7854	0.2500	0.463	0.463

NORMAL FLOW d_n IN CIRCULAR SECTIONS FLOWING PARTLY FULL

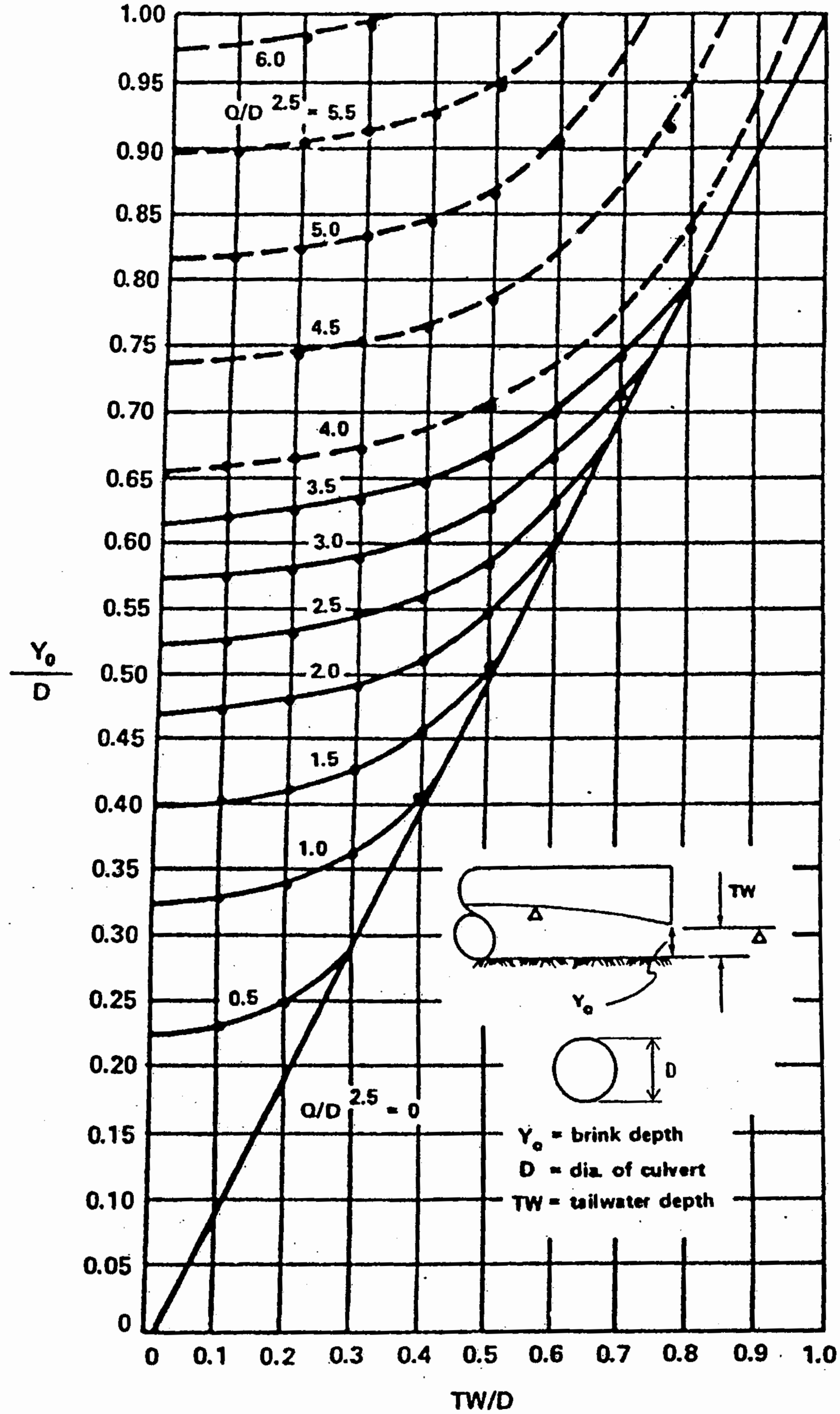
TABLE "L-6"

REPRODUCED FROM UD & FCD, FIGURE 2-1



NORMAL DEPTH FOR UNIFORM FLOW GRAPH	FIGURE "L-12"

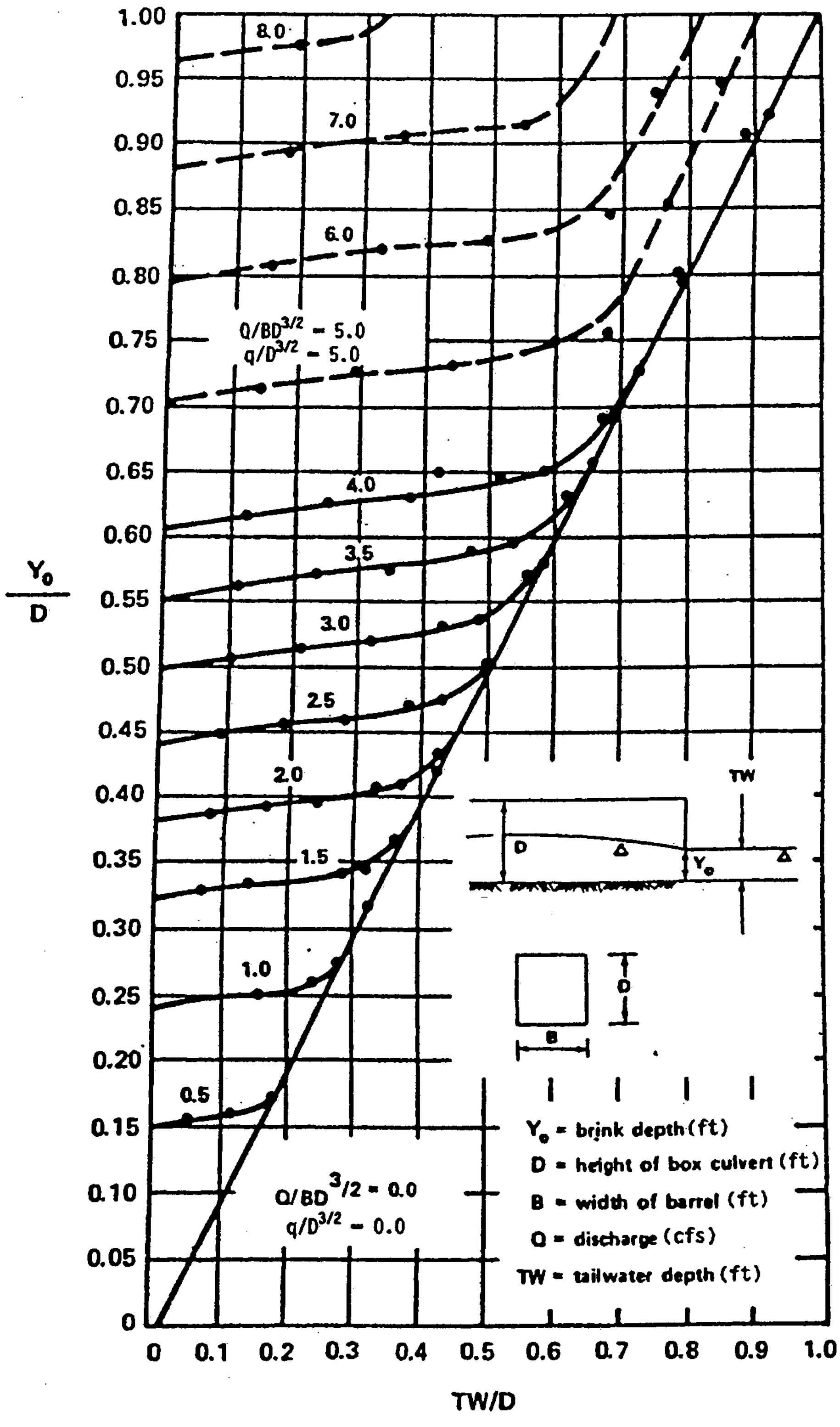
REPRODUCED FROM FIGURE III-10 IN HEC-14



Applicable for TW < d_c. Enter TW/D, go vertical to $Q/D^{2.5}$, read horizontal to Y_o/D.

SUBCRITICAL CULVERT BRINK FLOW: CIRCULAR	FIGURE "L-13a"

MODIFIED FROM FIGURE III-9 IN HEC-14



Applicable for TW < d_c. Enter TW/D, go vertical to $Q/BD^{1.5}$ or $q/D^{1.5}$, read horizontal to Y_o/D.

SUBCRITICAL CULVERT BRINK FLOW: RECTANGULAR | **FIGURE "L-13b"**

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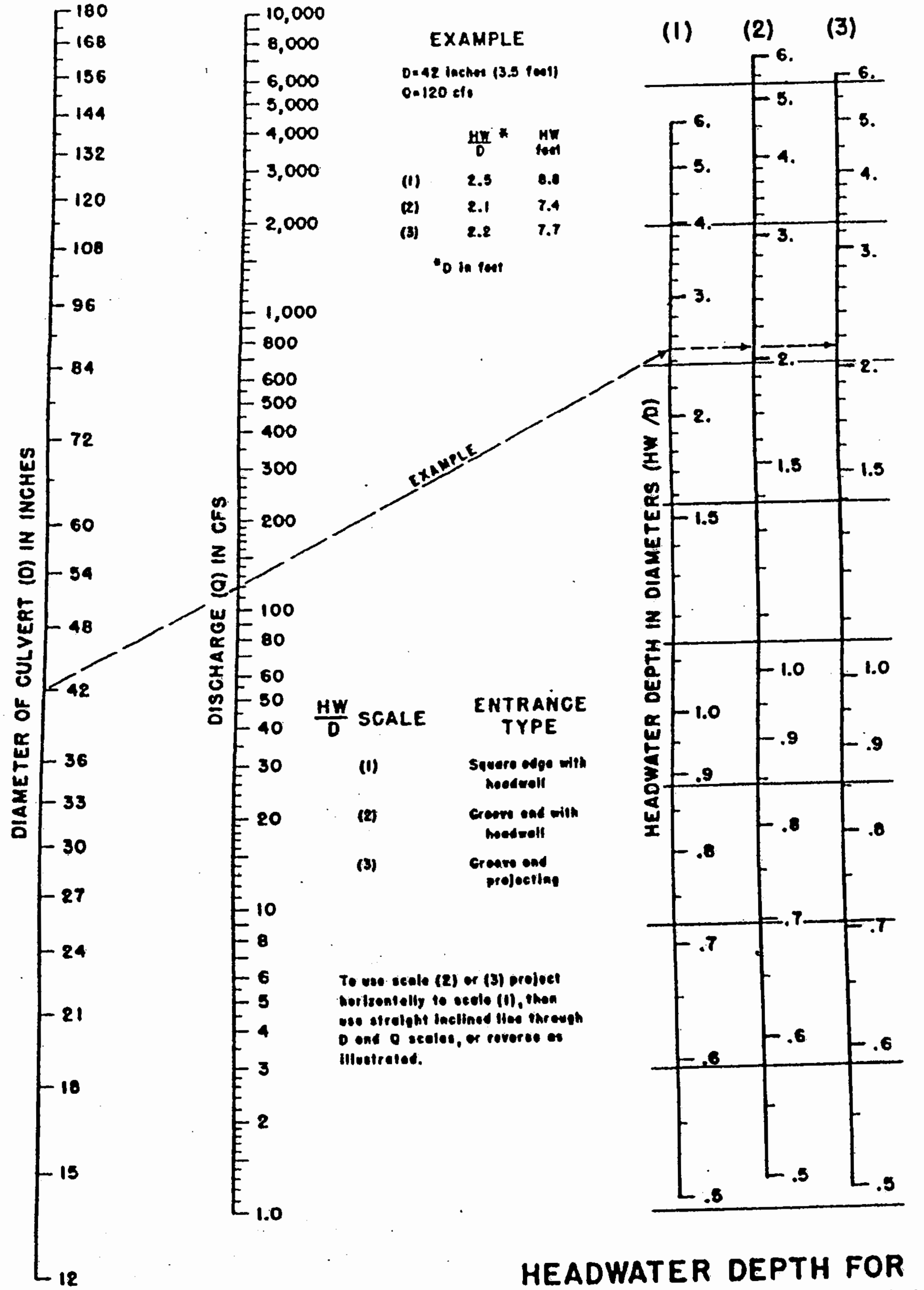
CHART 1

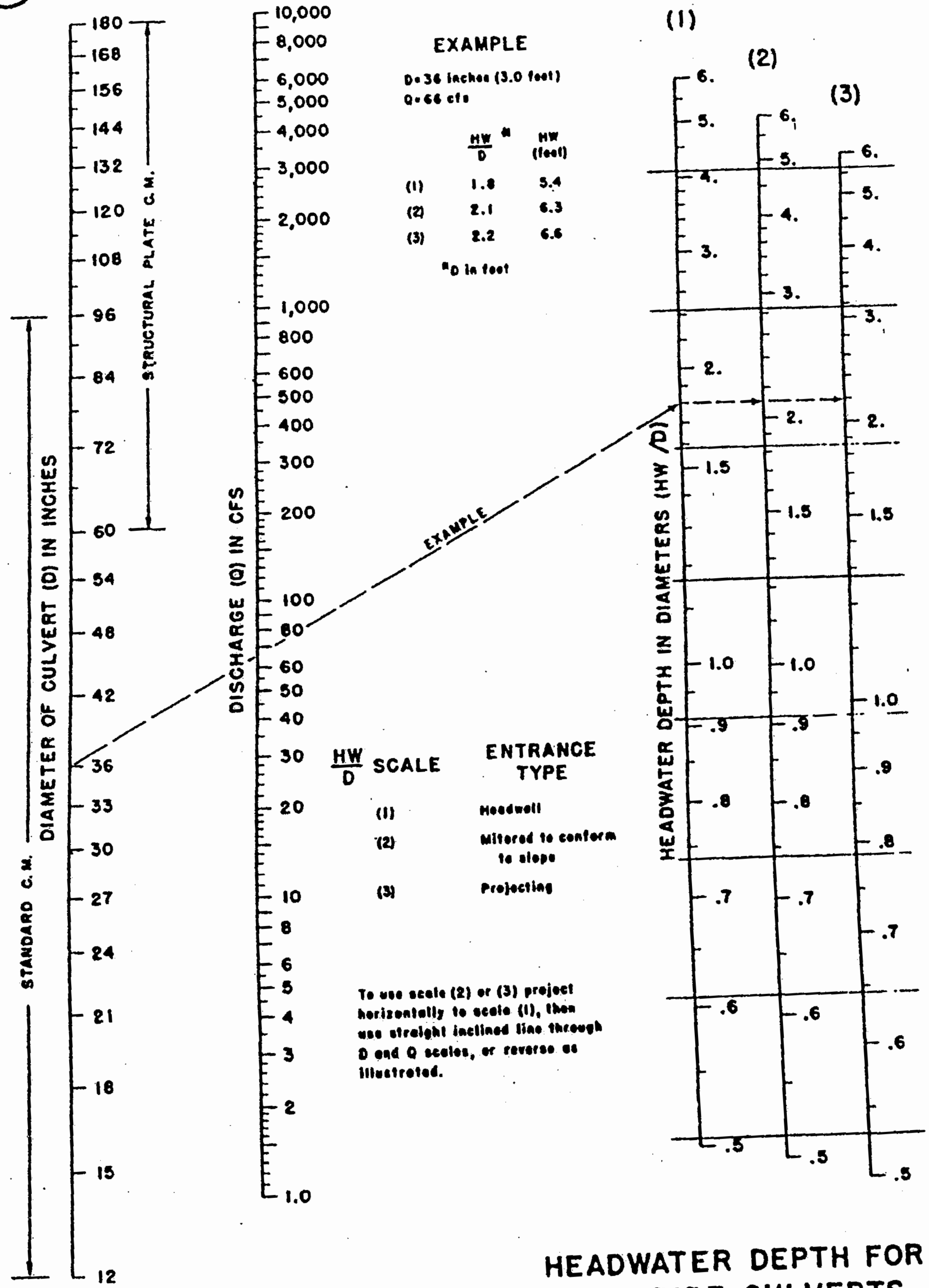


HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL

HEADWATER SCALES 2&3
REVISED MAY 1964

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 2

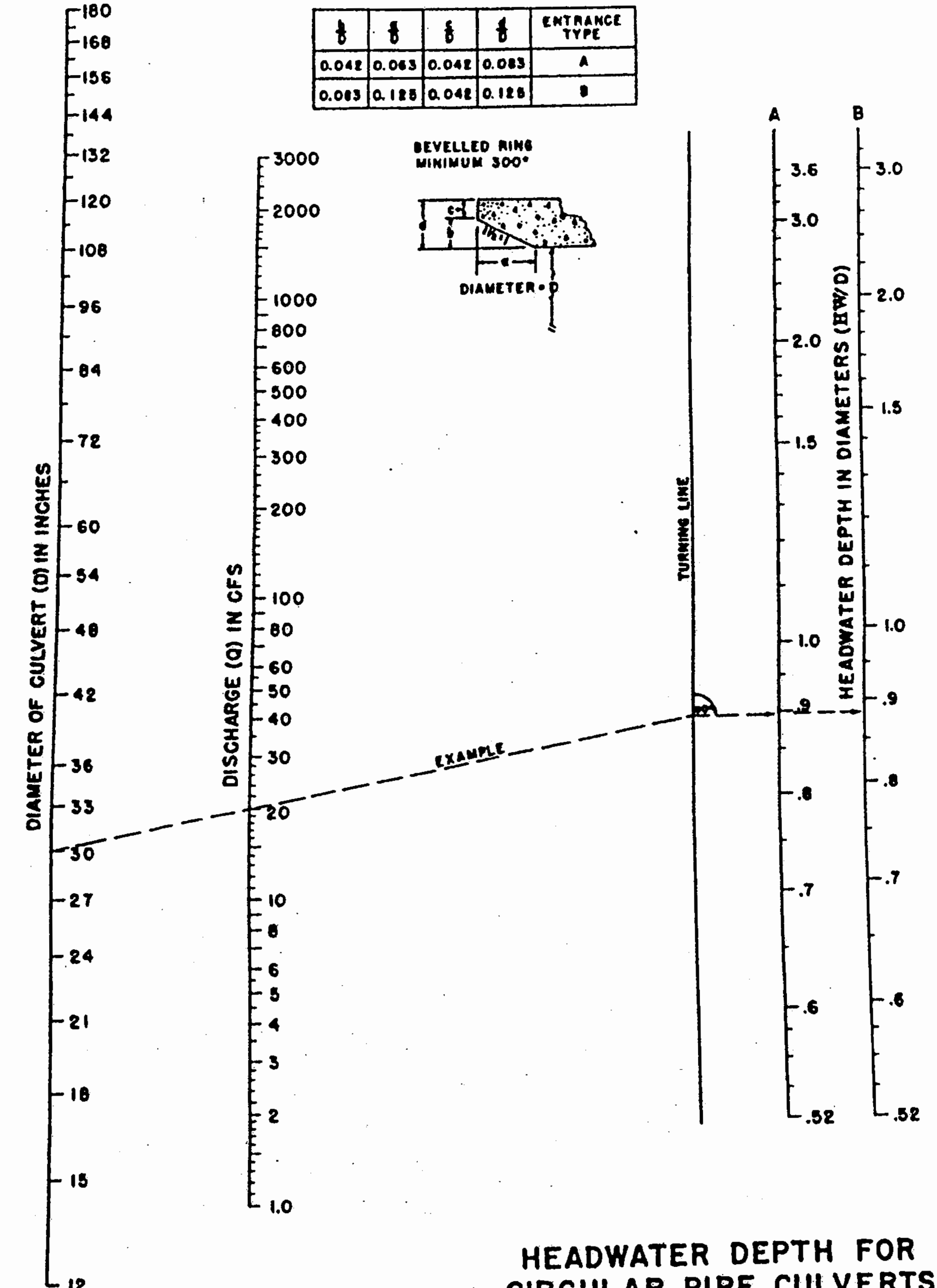


HEADWATER DEPTH FOR C. M. PIPE CULVERTS WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 3

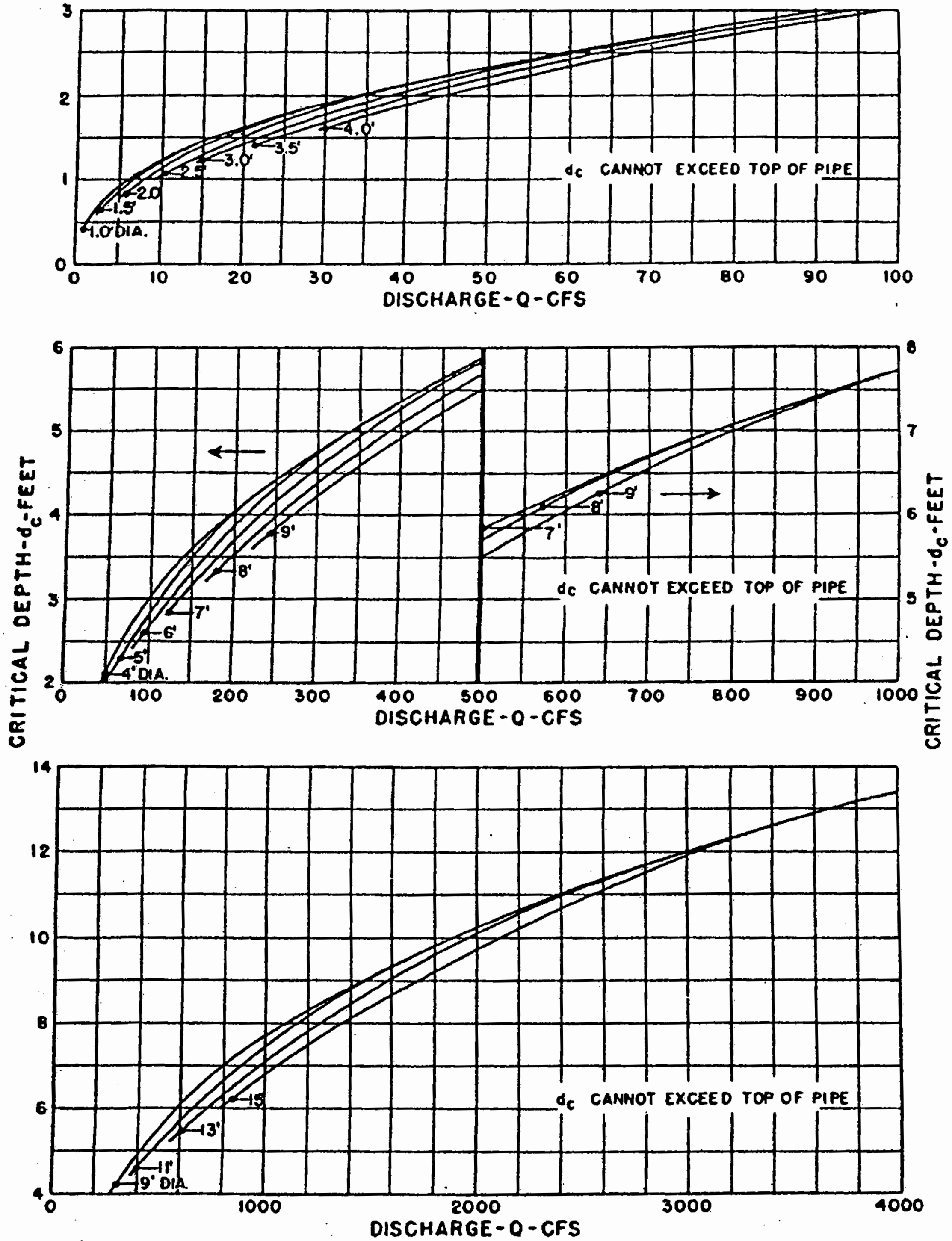
a/D	b/D	c/D	d/D	ENTRANCE TYPE
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B



ERAL HIGHWAY ADMINISTRATION
MAY 1973

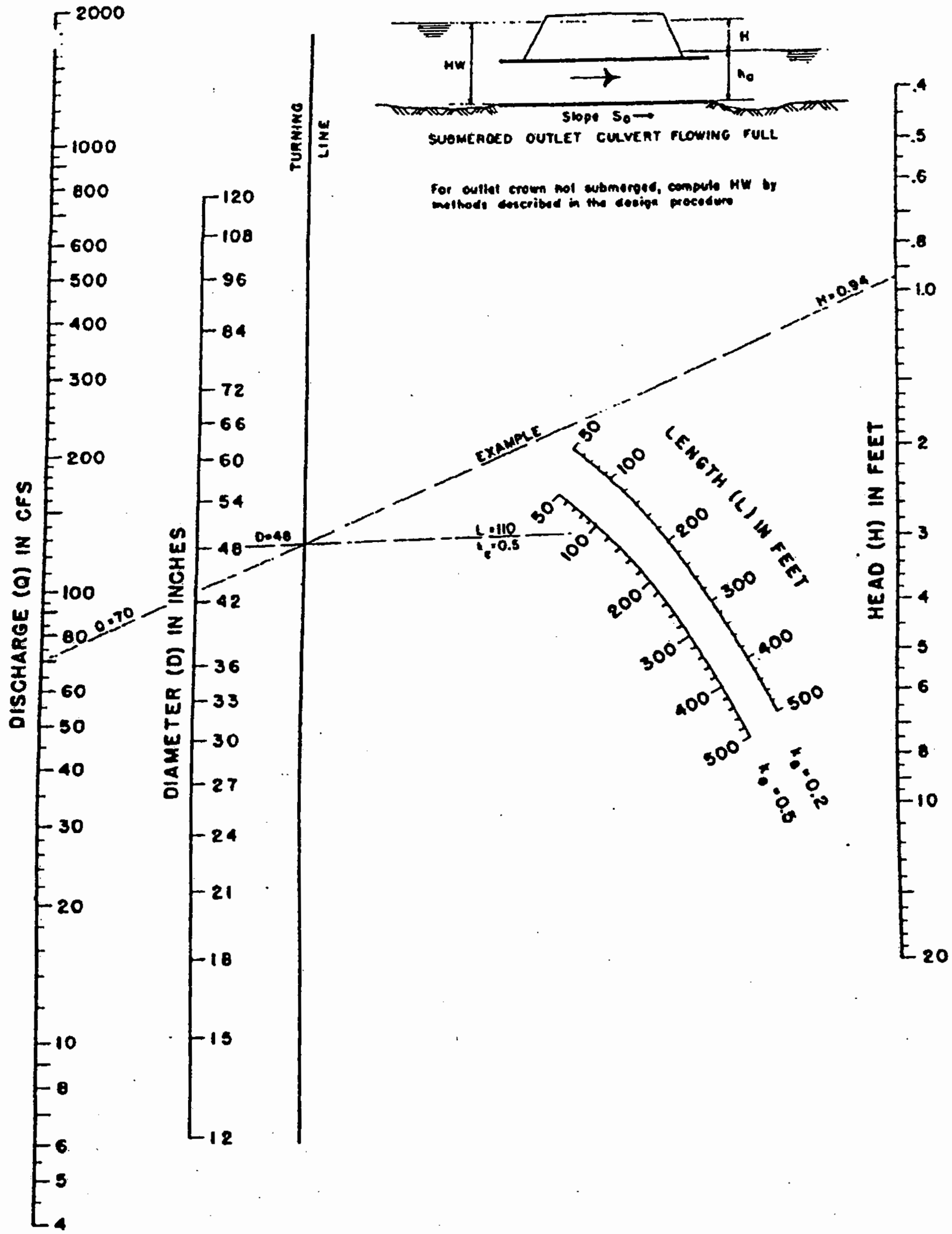
HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL

CHART 4



BUREAU OF PUBLIC ROADS
JAN. 1964

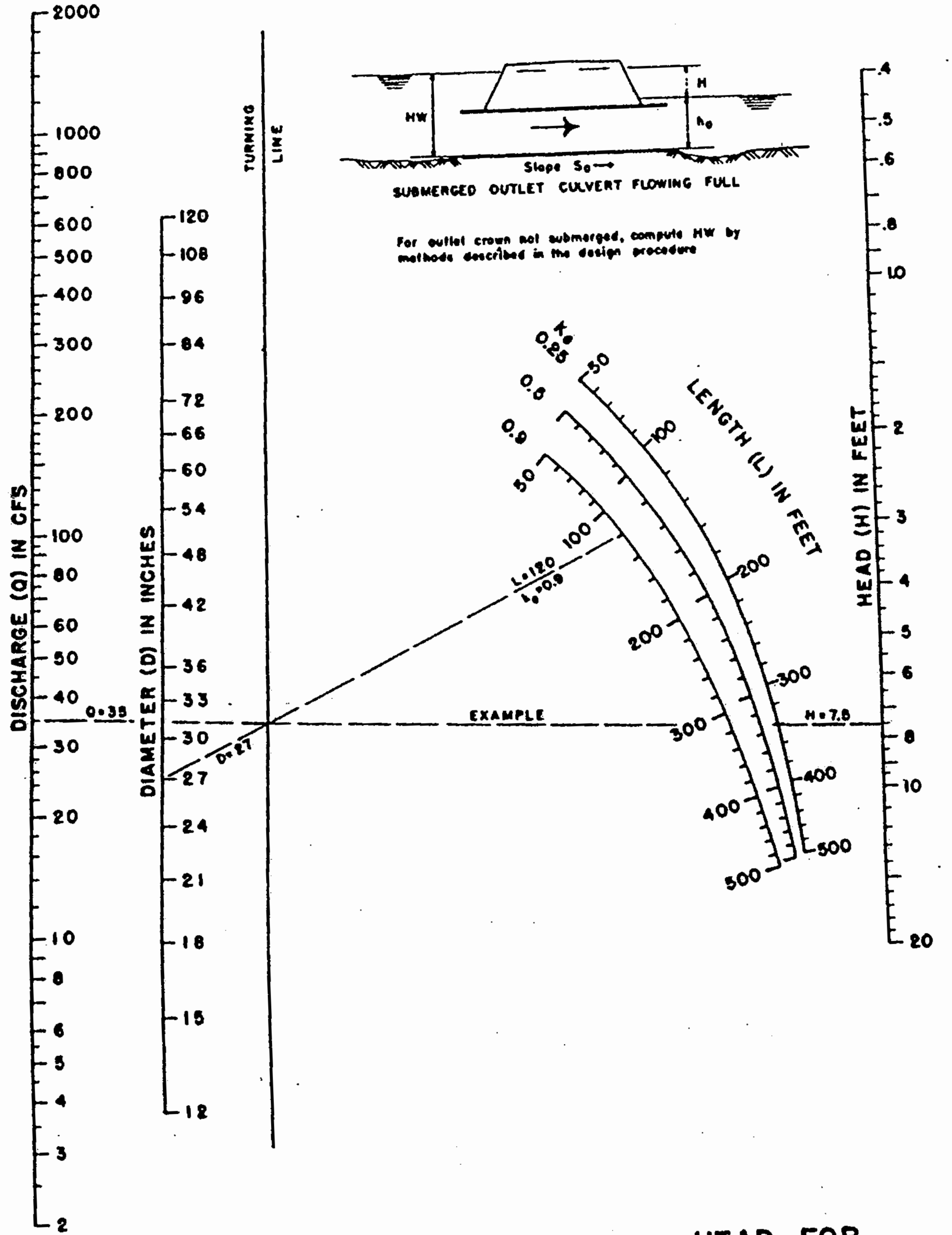
CRITICAL DEPTH
CIRCULAR PIPE



HEAD FOR CONCRETE PIPE CULVERTS FLOWING FULL
n = 0.012

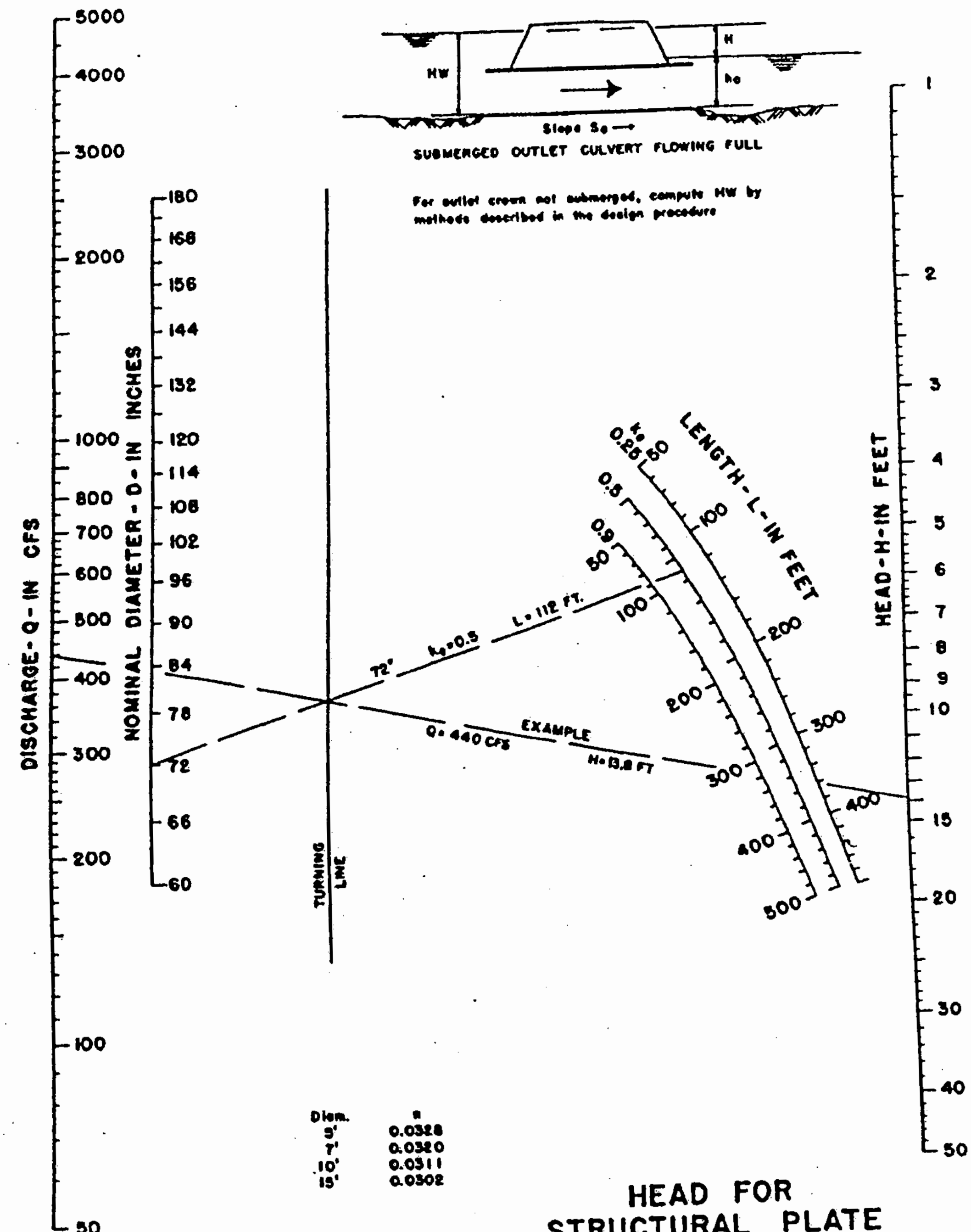
BUREAU OF PUBLIC ROADS JAN. 1963

CHART 6



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

BUREAU OF PUBLIC ROADS JAN. 1963

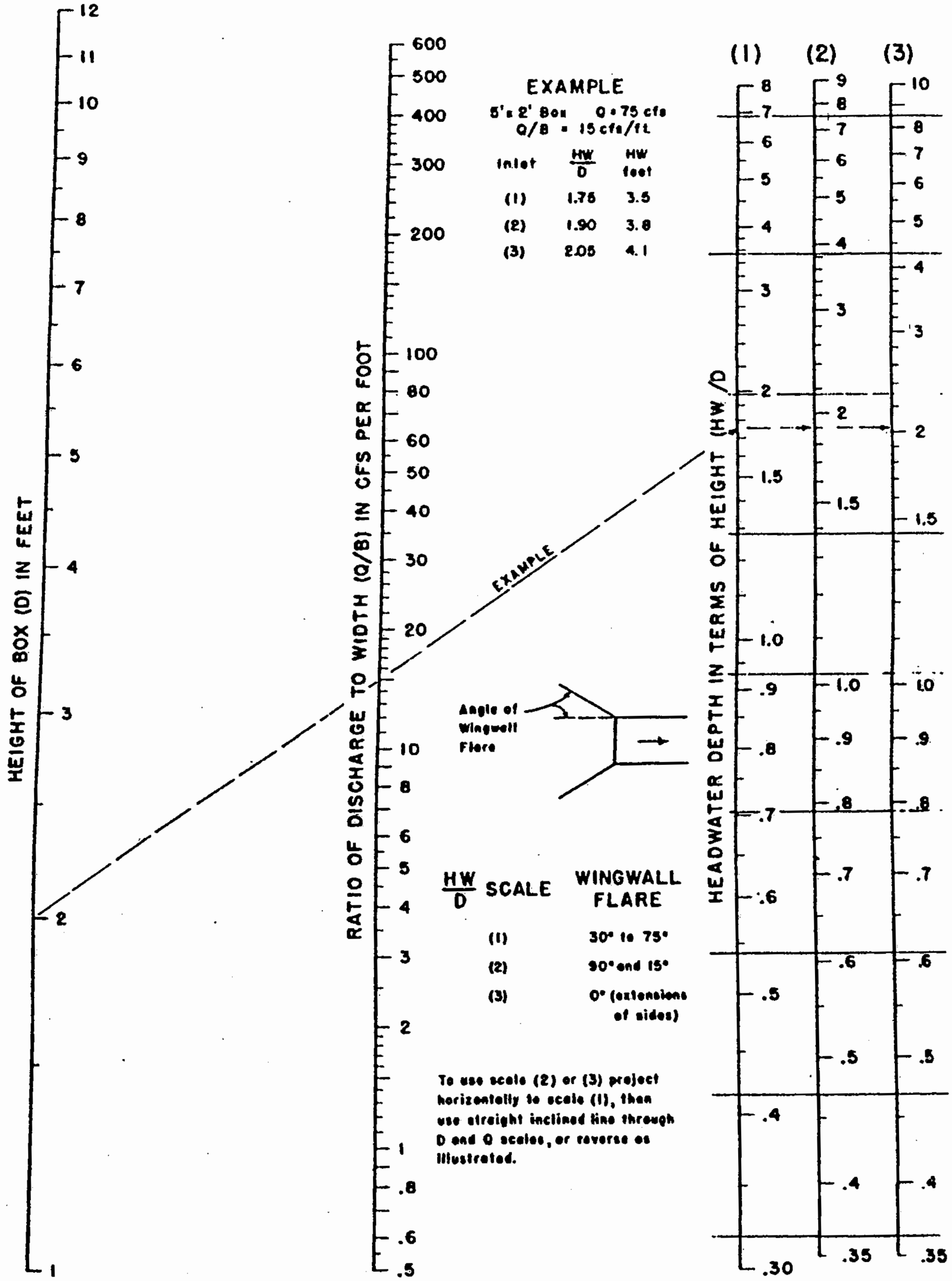


Diam.	n
5'	0.0328
7'	0.0320
10'	0.0311
15'	0.0302

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

BUREAU OF PUBLIC ROADS JAN. 1963

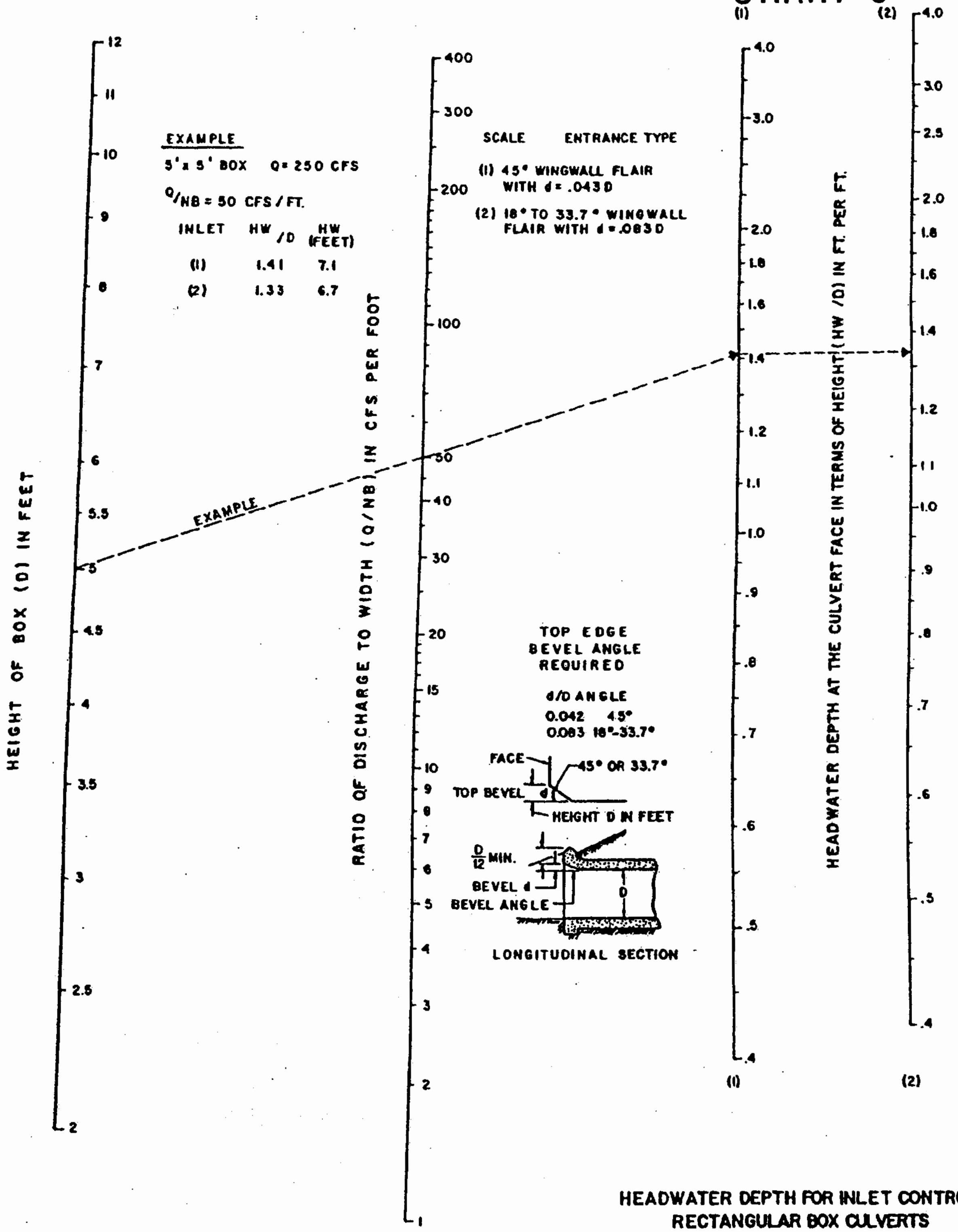
CHART 8



HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

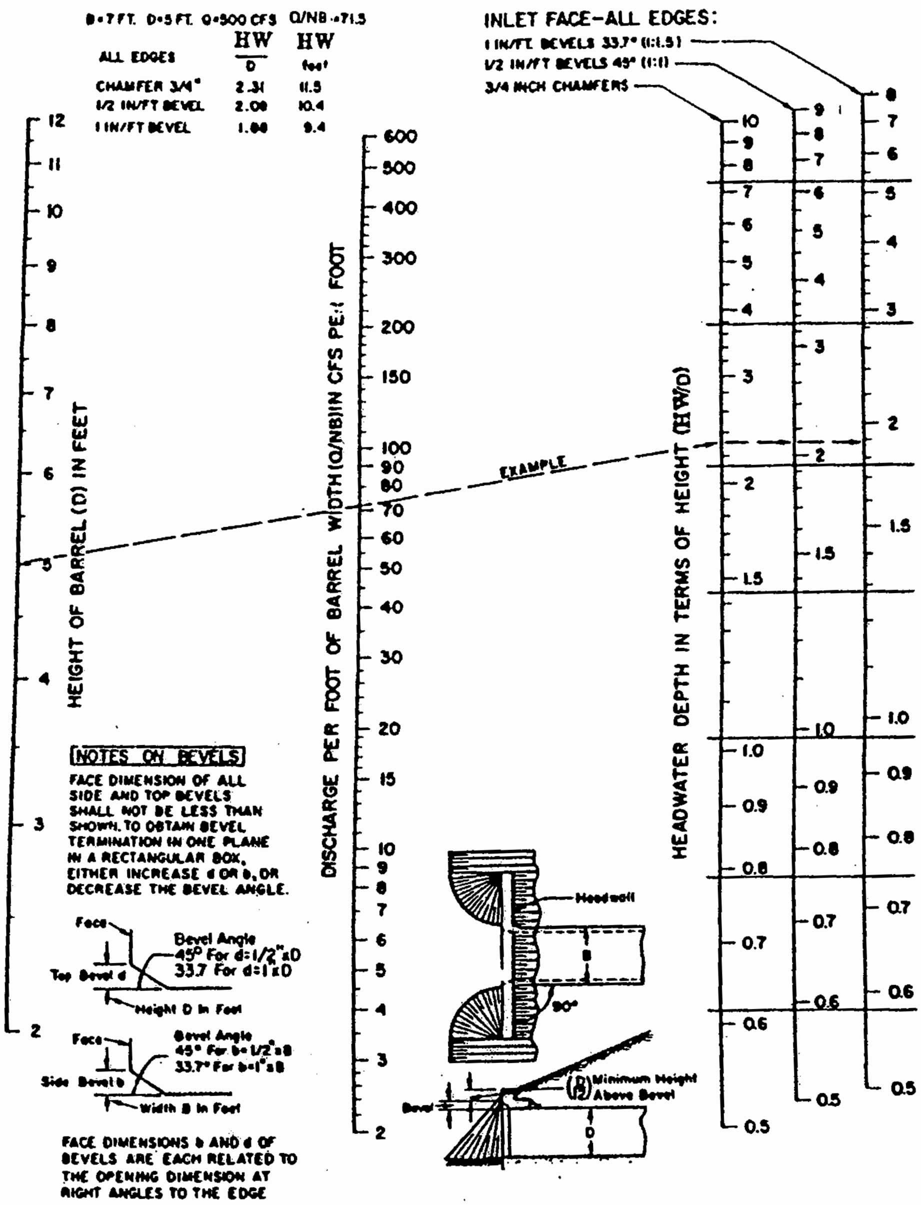
BUREAU OF PUBLIC ROADS JAN. 1963

CHART 9



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

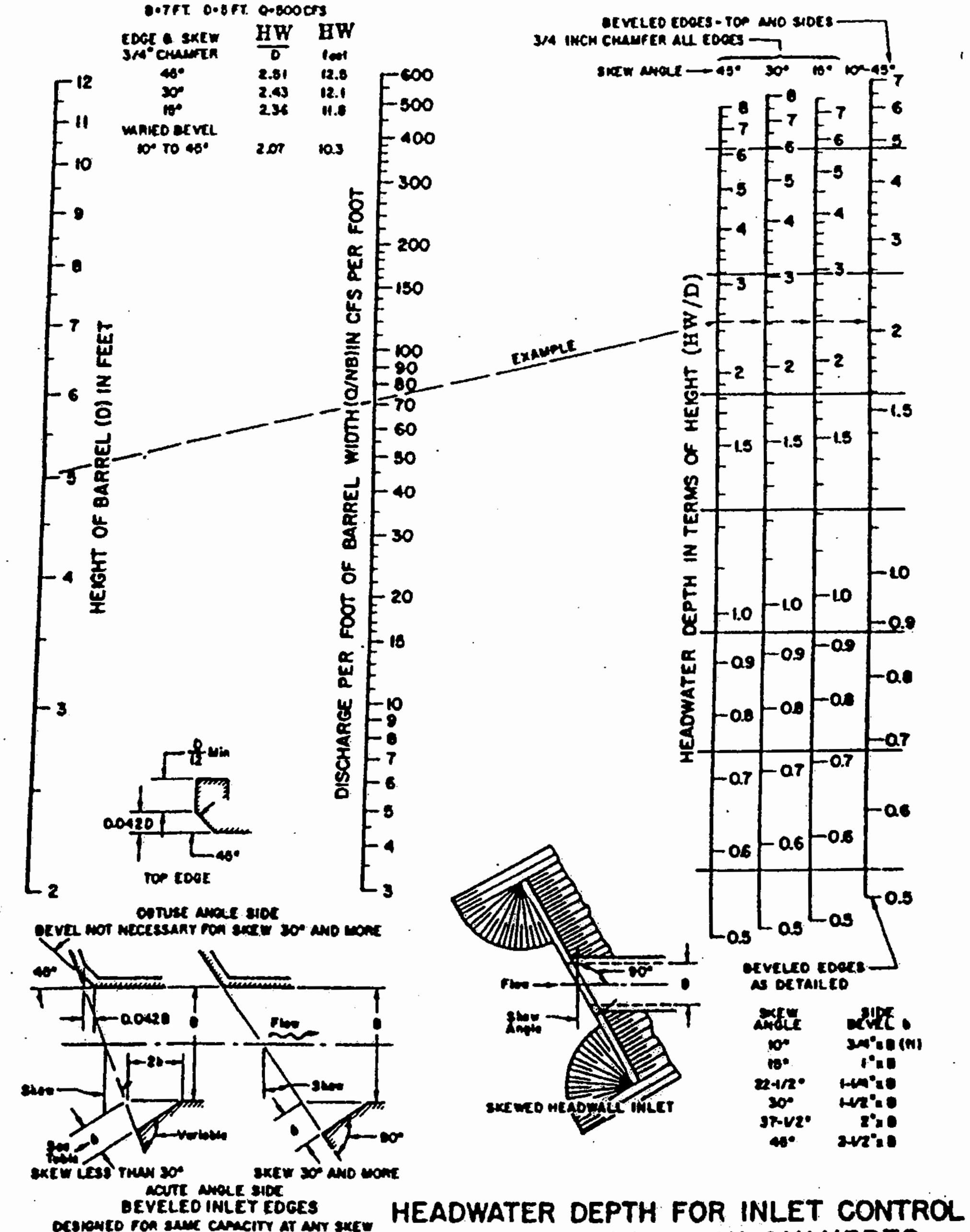
CHART 10



HEADWATER DEPTH FOR INLET CONTROL RECTANGULAR BOX CULVERTS 90° HEADWALL CHAMFERED OR BEVELED INLET EDGES

FEDERAL HIGHWAY ADMINISTRATION
MAY 1973

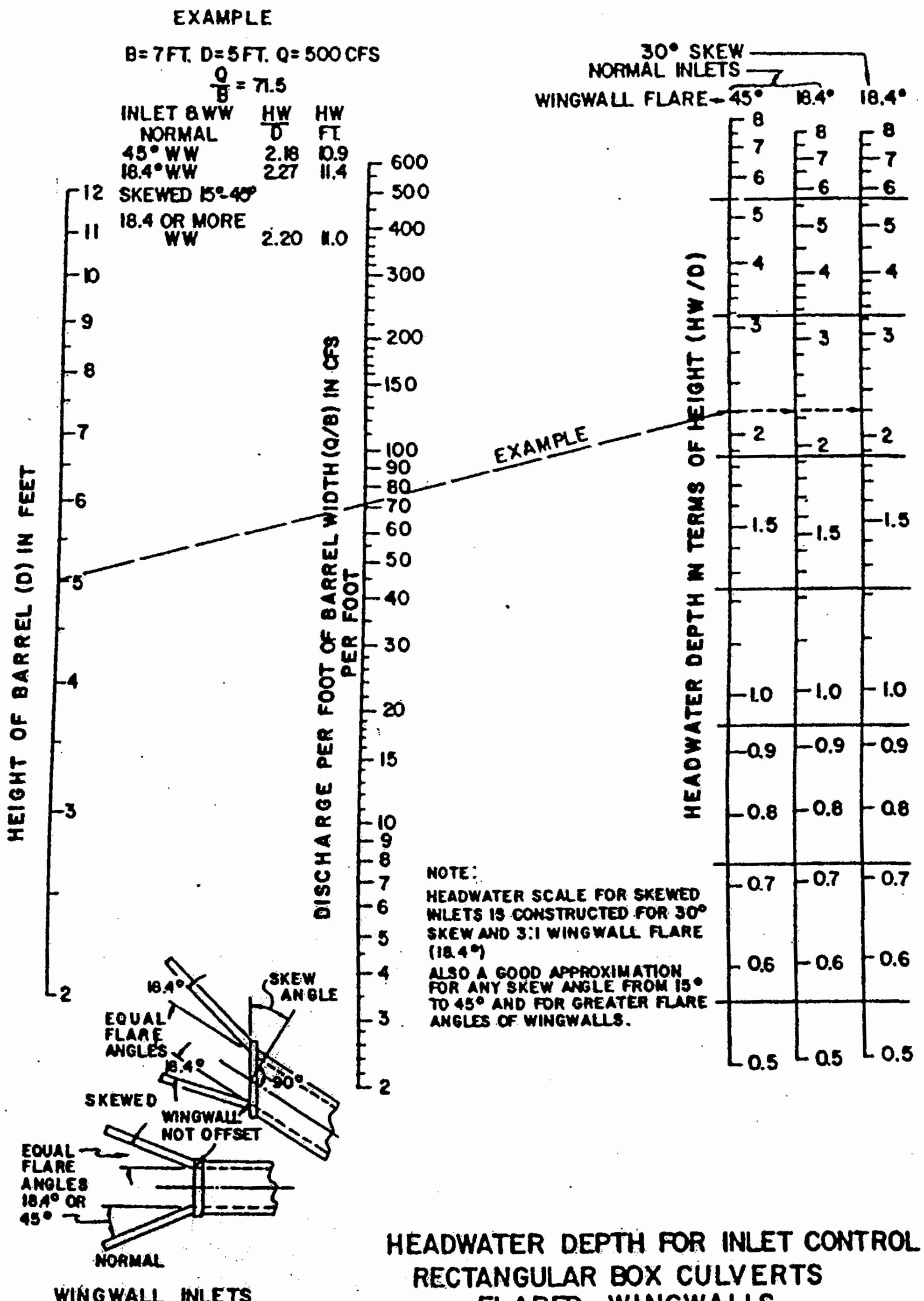
CHART 11



FEDERAL HIGHWAY ADMINISTRATION
MAY 1973

HEADWATER DEPTH FOR INLET CONTROL
SINGLE BARREL BOX CULVERTS
SKEWED HEADWALLS
CHAMFERED OR BEVELED INLET EDGES

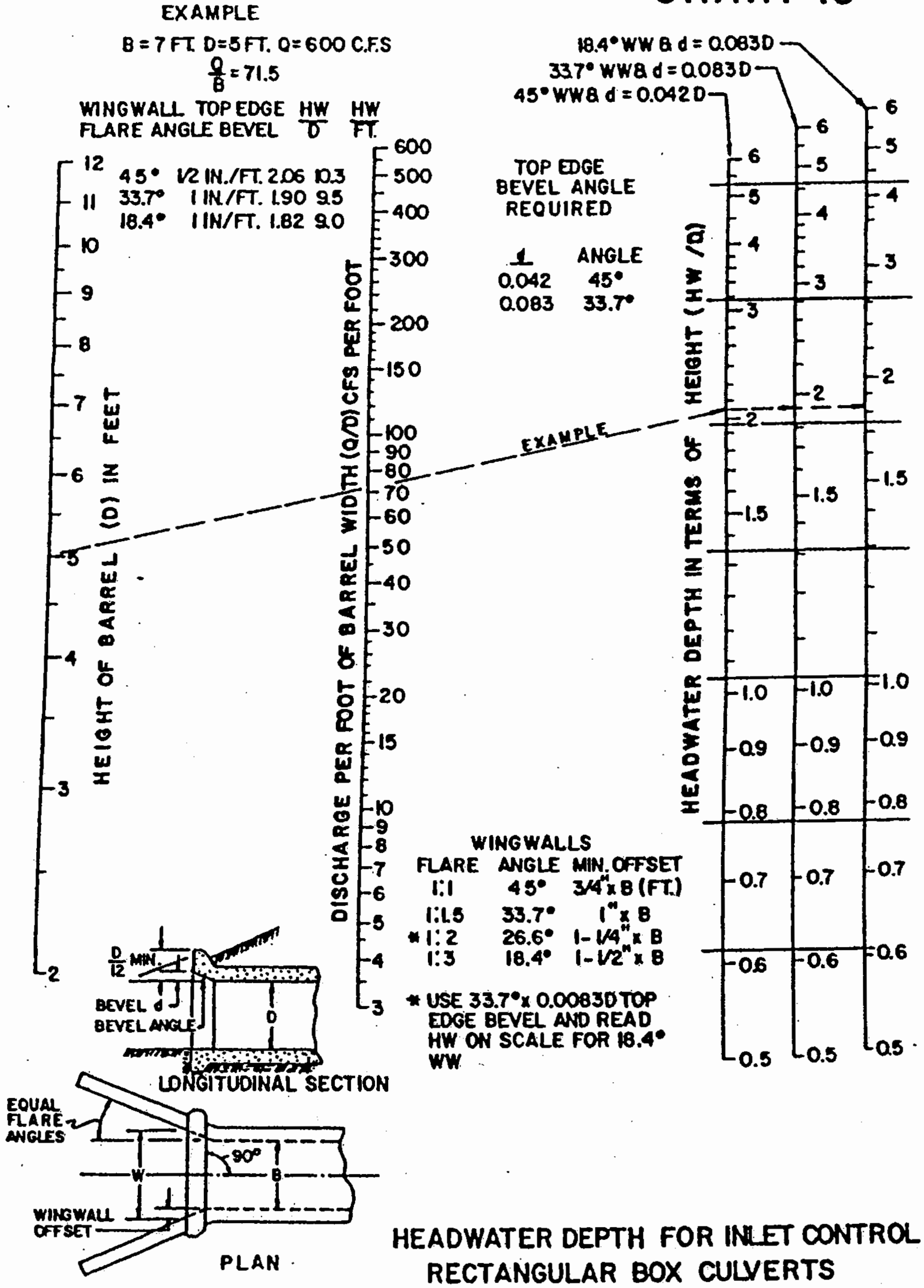
CHART 12



BUREAU OF PUBLIC ROADS
OFFICE OF R & D AUGUST 1968

HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS
NORMAL AND SKEWED INLETS
3/4" CHAMFER AT TOP OF OPENING

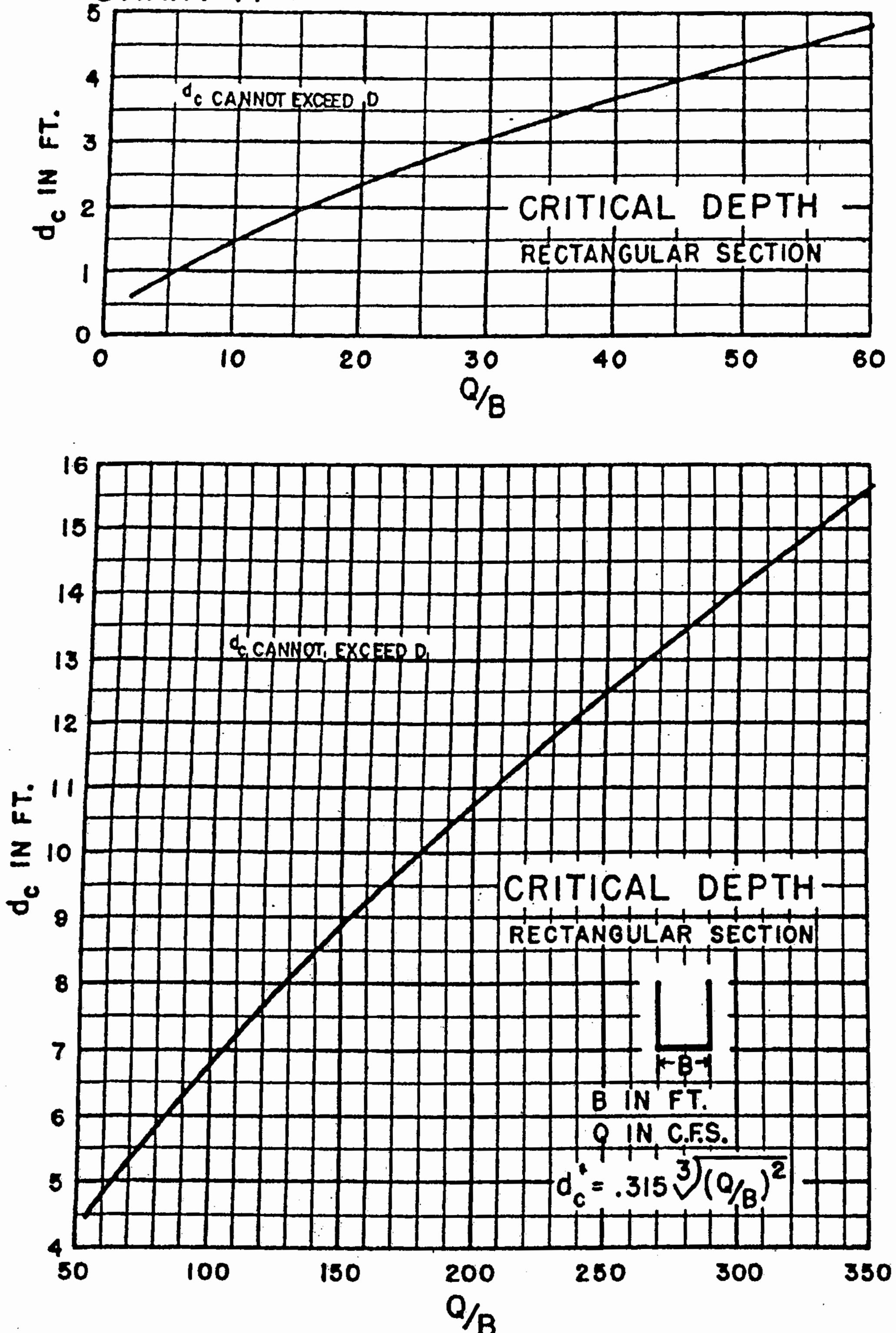
CHART 13



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
OFFSET FLARED WINGWALLS
AND BEVELED EDGE AT TOP OF INLET

BUREAU OF PUBLIC ROADS
OFFICE OF R & D AUGUST 1968

CHART 14

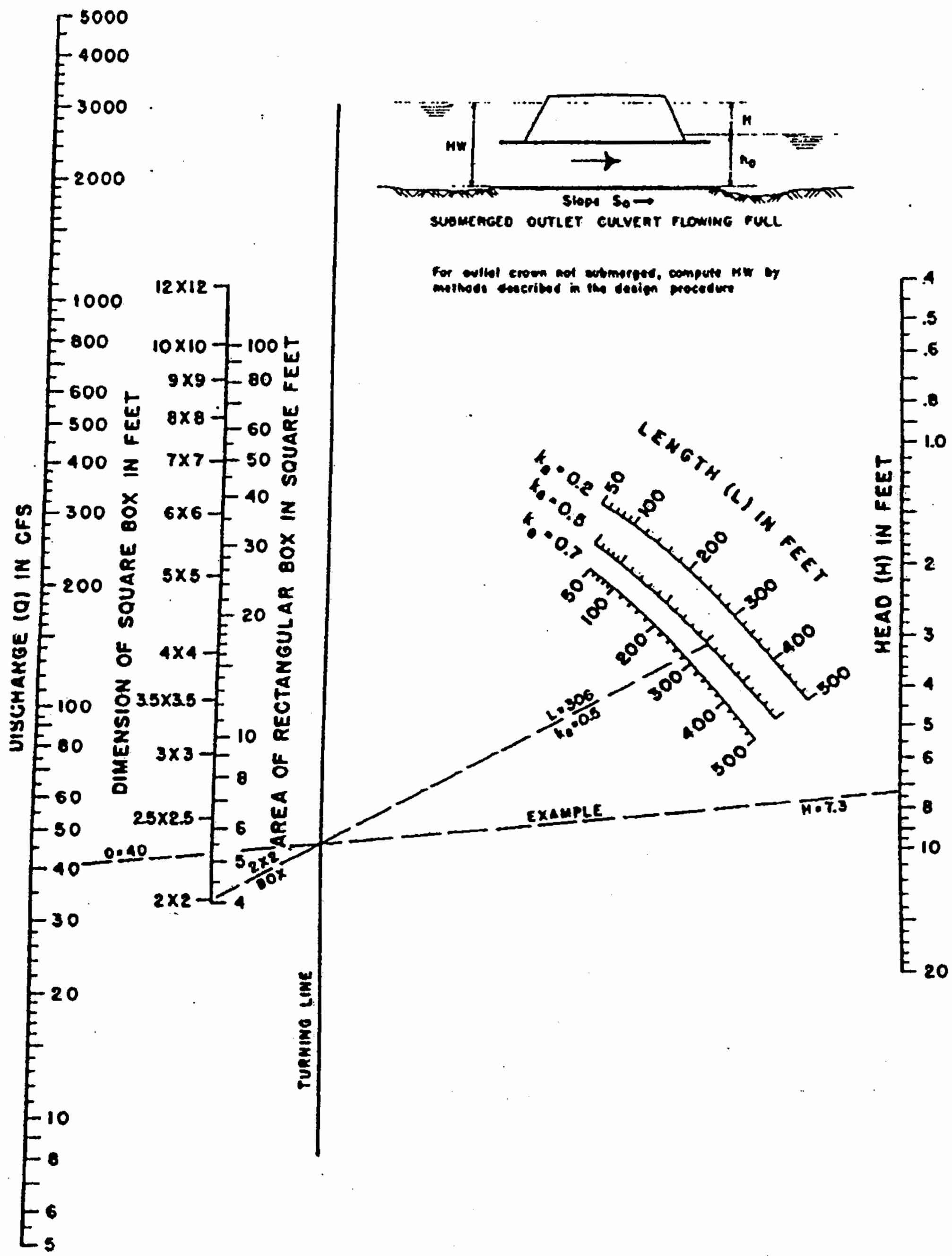


BUREAU OF PUBLIC ROADS JAN. 1963

CRITICAL DEPTH
RECTANGULAR SECTION

5-38

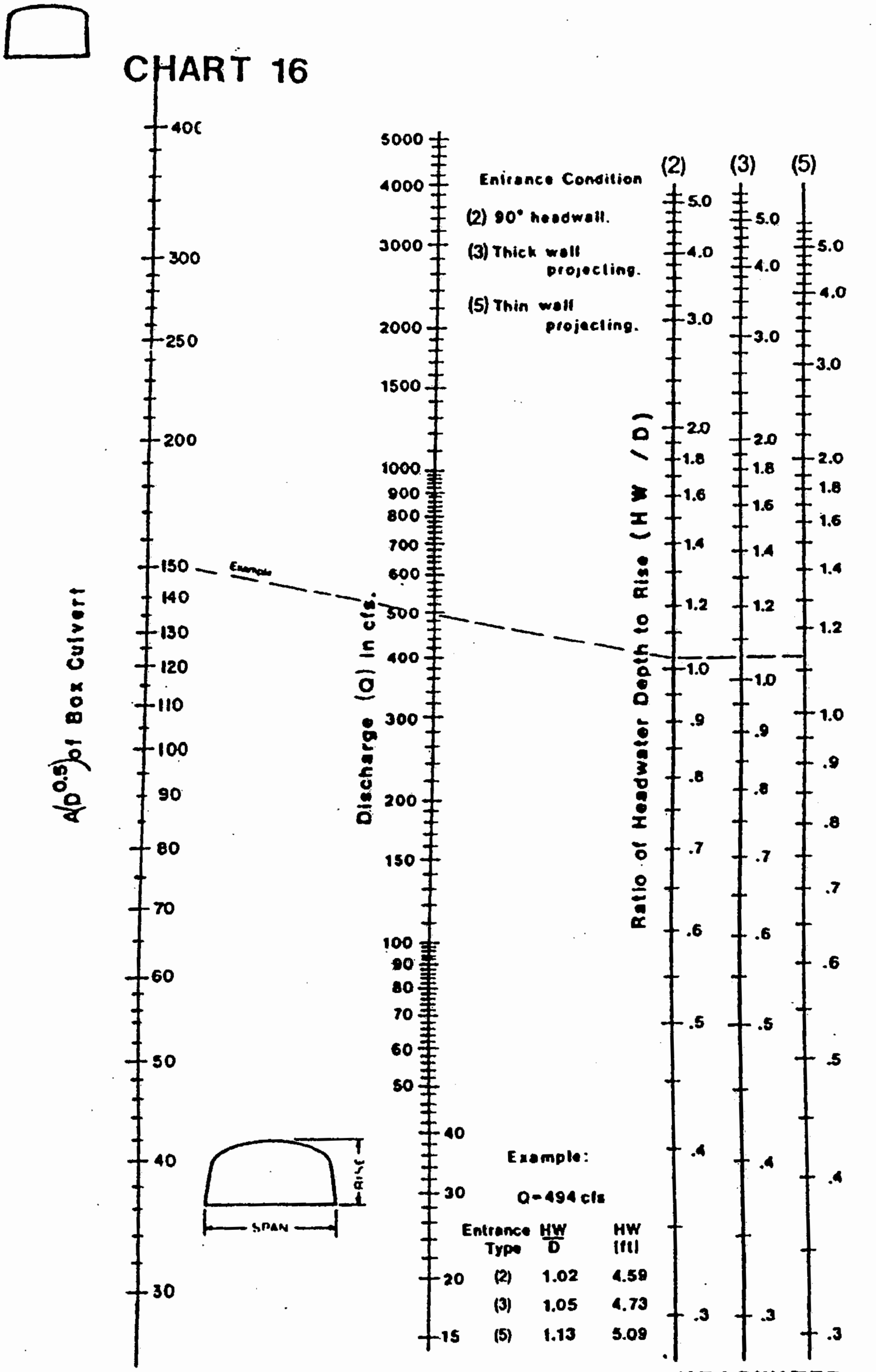
CHART 15



HEAD FOR CONCRETE BOX CULVERTS FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

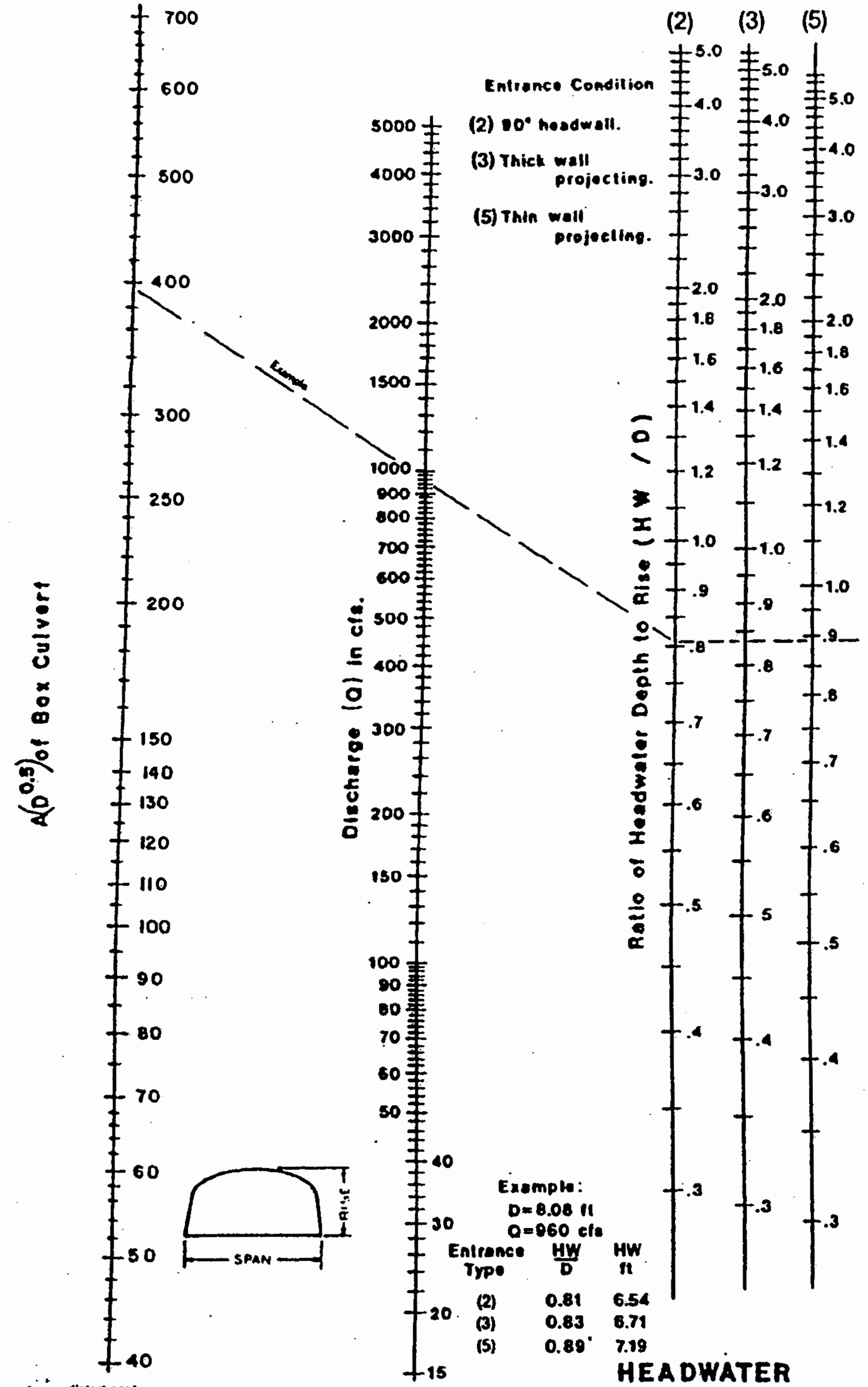
CHART 16



Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. BOX CULVERTS RISE / SPAN < 0.3 WITH INLET CONTROL

CHART 17

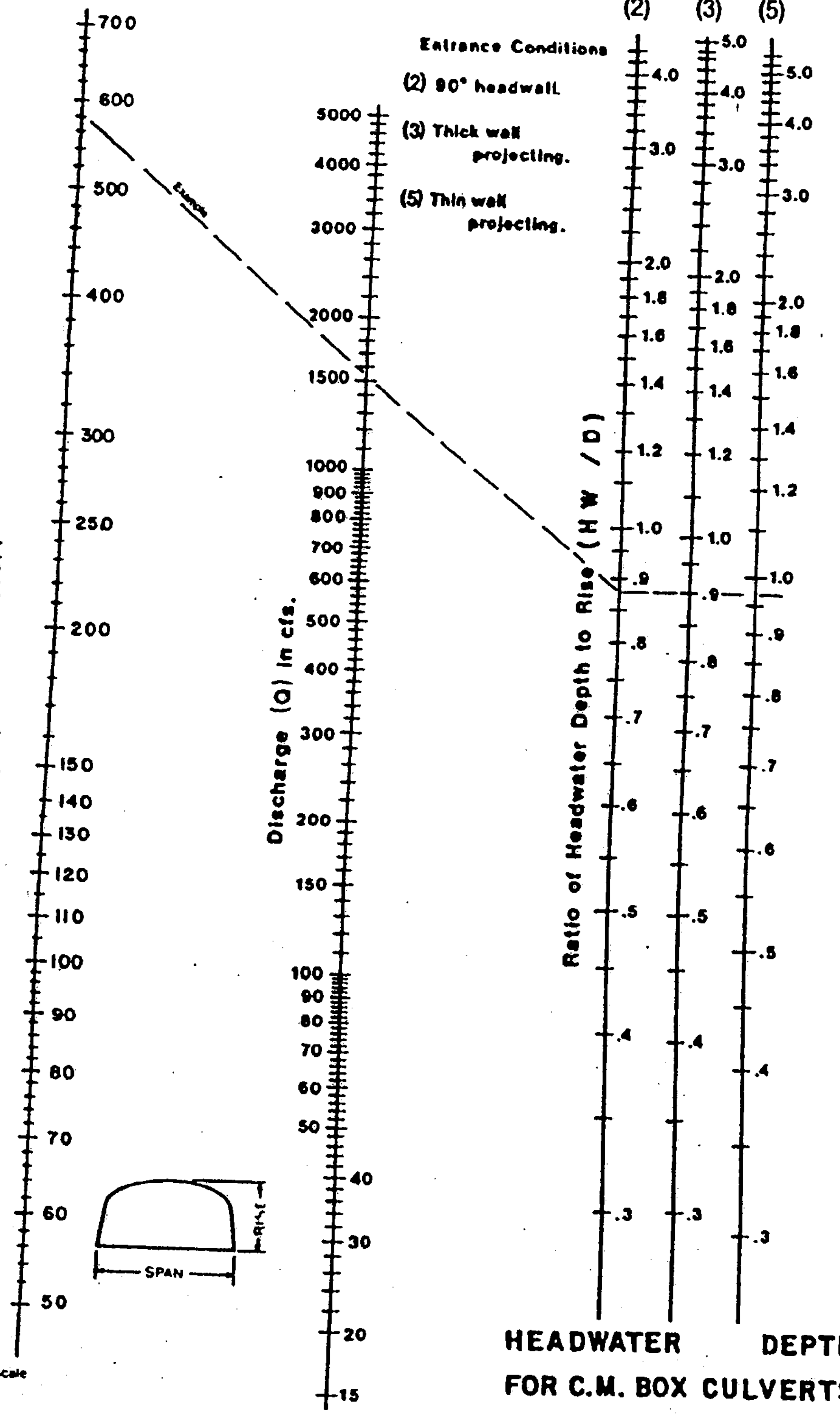


Duplication of this nomograph may distort scale

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.3 \leq$ RISE / SPAN < 0.4 WITH INLET CONTROL

CHART 18



Example:
D=9.67 ft
Q=1520 cfs

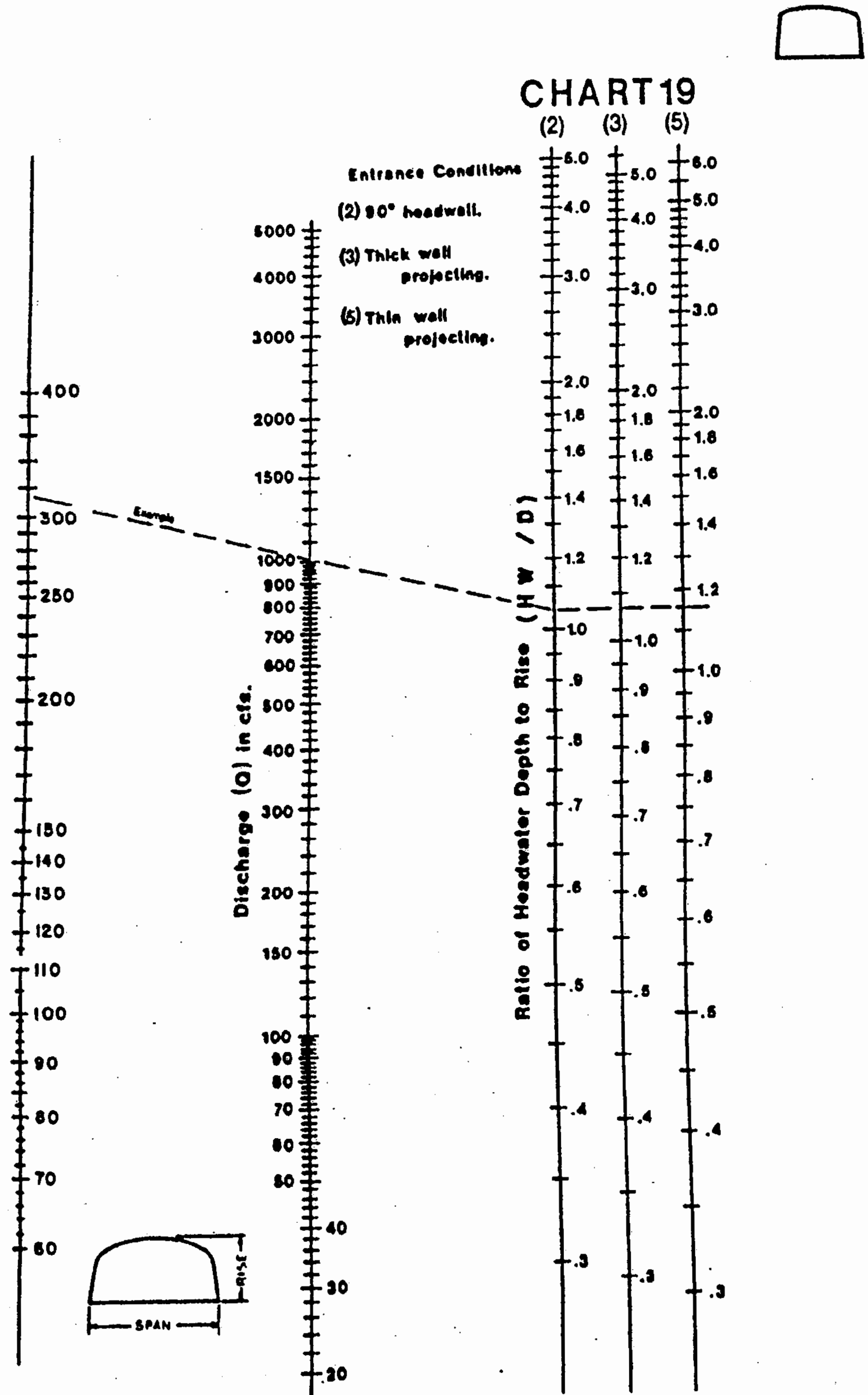
Entrance Type	HW/D	HW ft
(2)	0.88	8.51
(3)	0.90	8.70
(5)	0.97	9.38

Duplication of this nomograph may distort scale

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.4 \le$ RISE / SPAN < 0.5 WITH INLET CONTROL

CHART 19



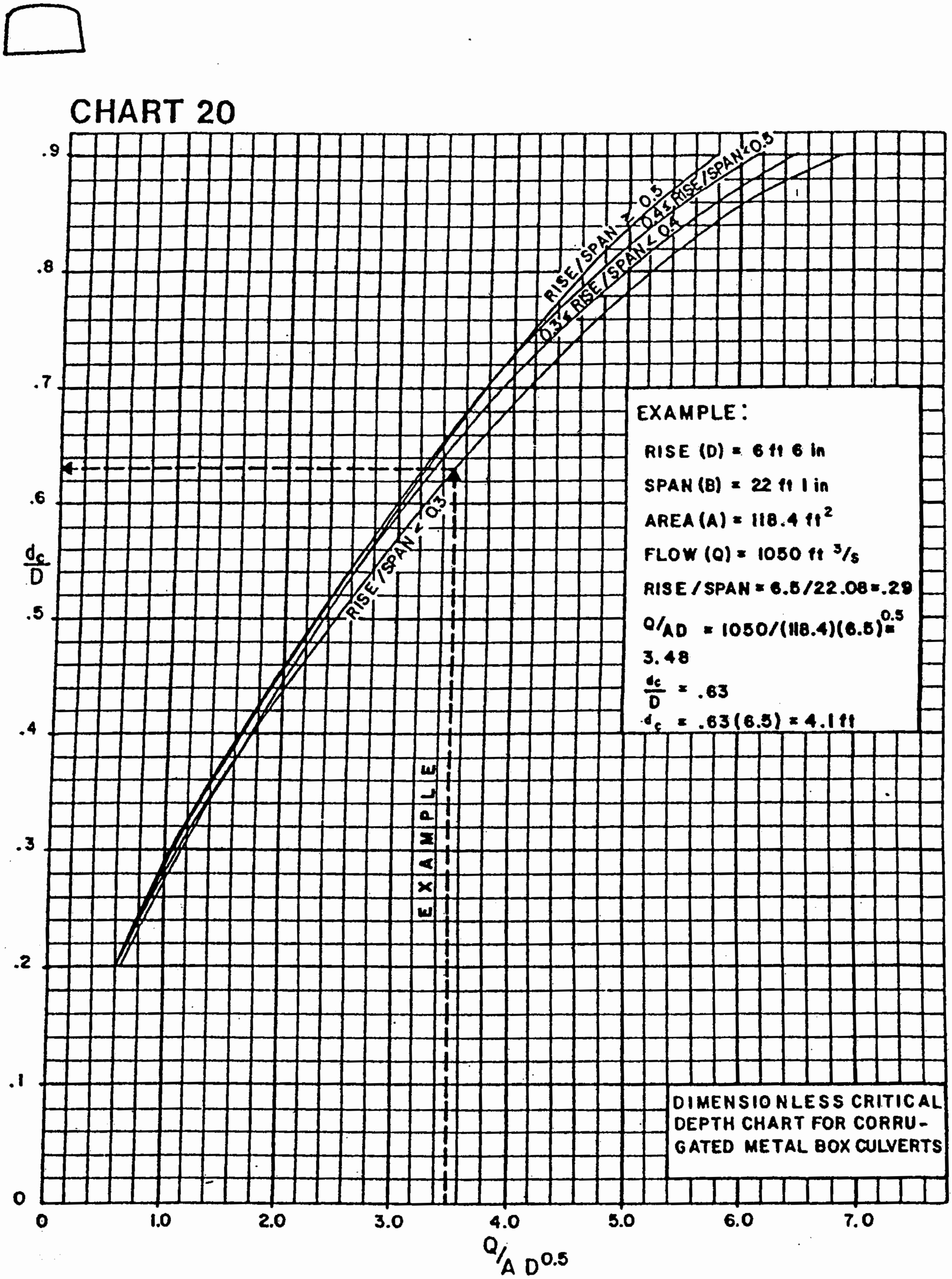
Example:
D=8.0 ft
Q=1004 cfs

Entrance Type	HW/D	HW ft
(2)	1.04	8.32
(3)	1.07	8.56
(5)	1.15	9.20

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

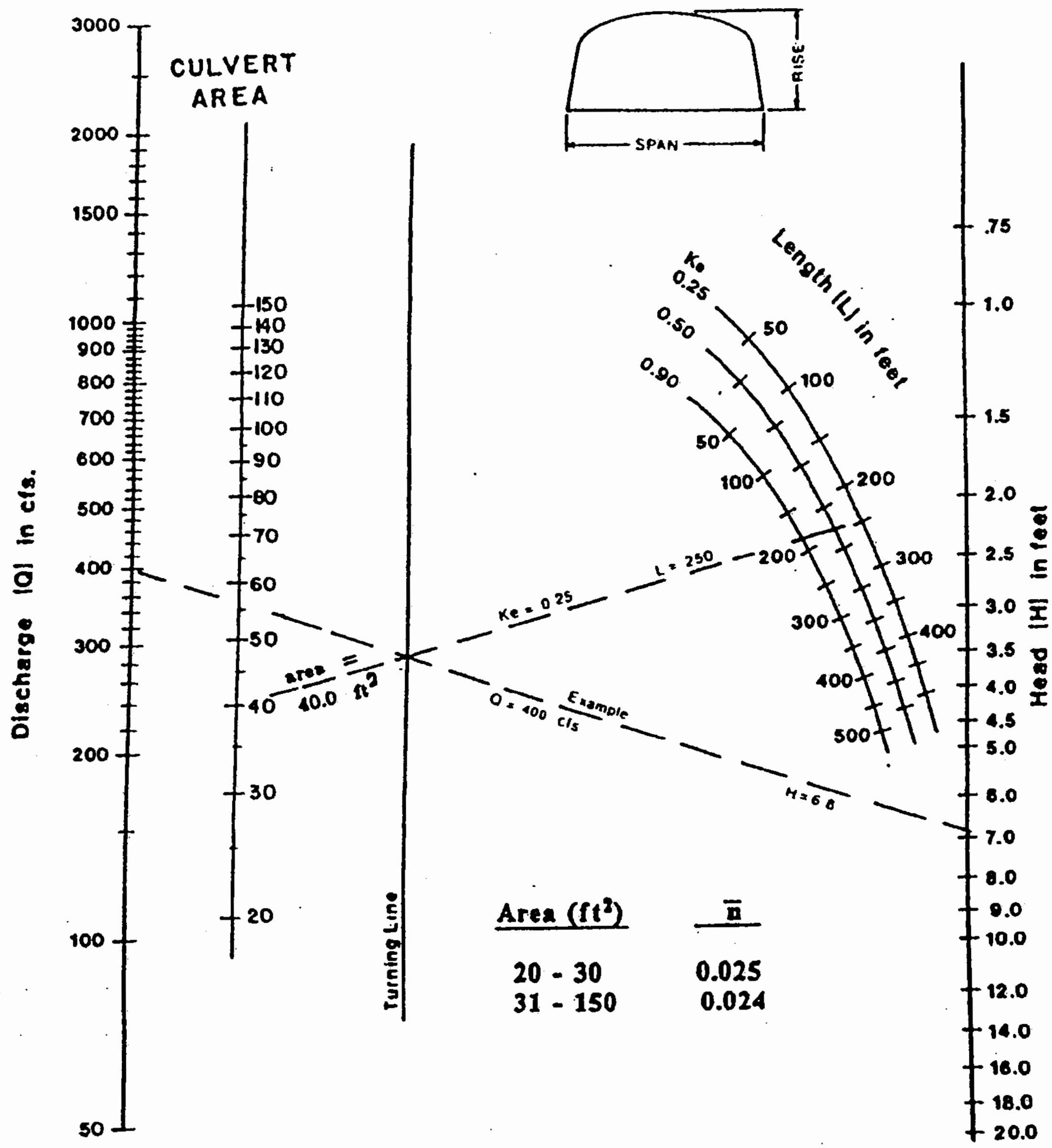
HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.5 \leq$ RISE / SPAN WITH INLET CONTROL

CHART 20

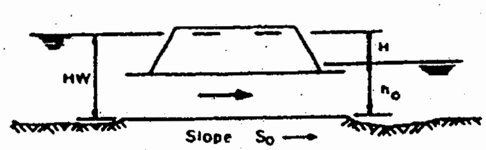


.9
.8
.7
.6
.5
.4
.3
.2
.1
0
d_c/D
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Q/A D0.5
RISE / SPAN ≥ 0.5
0.4 ≤ RISE / SPAN < 0.5
0.3 ≤ RISE / SPAN < 0.4
RISE / SPAN < 0.3
EXAMPLE
EXAMPLE:
RISE (D) = 6 ft 6 in
SPAN (B) = 22 ft 1 in
AREA (A) = 118.4 ft²
FLOW (Q) = 1050 ft ³/s
RISE / SPAN = 6.5/22.08 = .29
Q/AD = 1050/(118.4)(6.5)^0.5 = 3.48
dc/D = .63
dc = .63 (6.5) = 4.1 ft
DIMENSIONLESS CRITICAL DEPTH CHART FOR CORRUGATED METAL BOX CULVERTS

CHART 21



Area (ft^2)	n
20 - 30	0.025
31 - 150	0.024



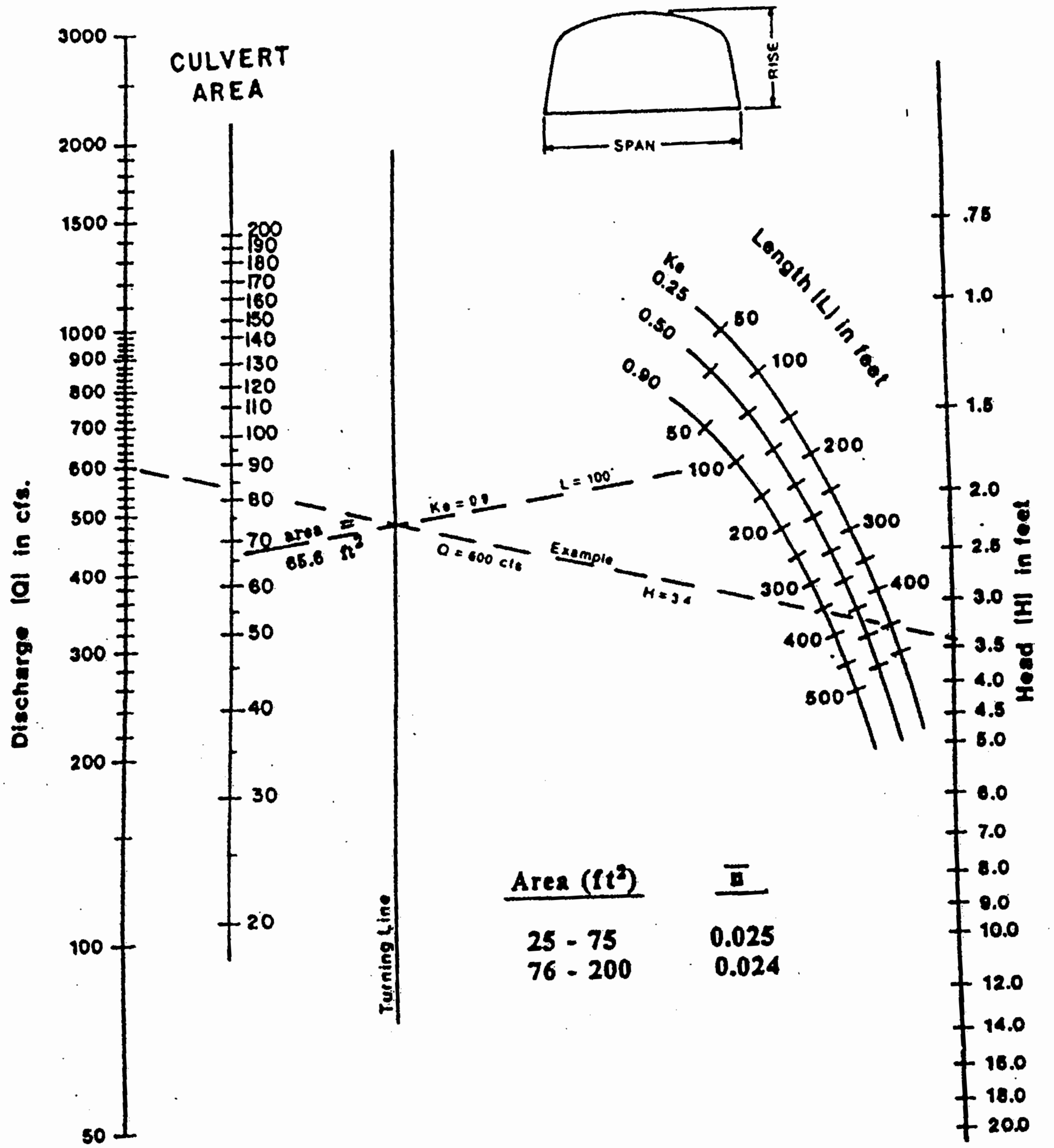
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C. M. BOX CULVERTS
FLOWING FULL
CONCRETE BOTTOM
RISE / SPAN < 0.3

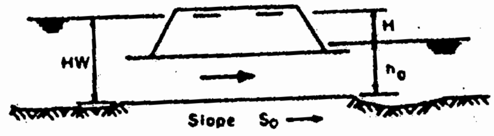
Nomographs adapted from material furnished by
Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 22



Area (ft²)	n
25 - 75	0.025
76 - 200	0.024



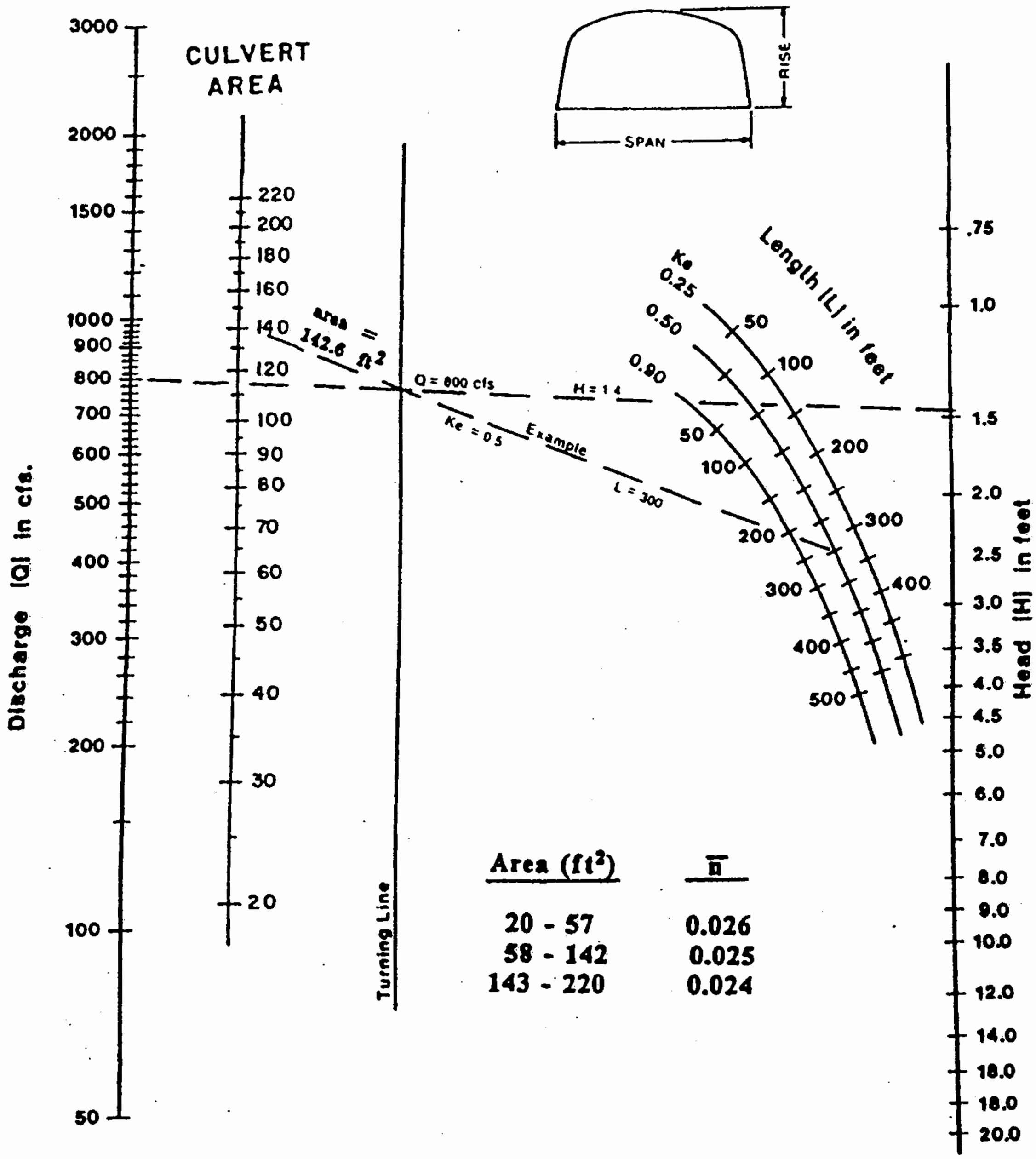
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C. M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM 0.3 ≤ RISE / SPAN < 0.4

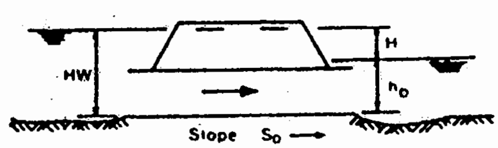
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 23



Area (ft²)	n
20 - 57	0.026
58 - 142	0.025
143 - 220	0.024

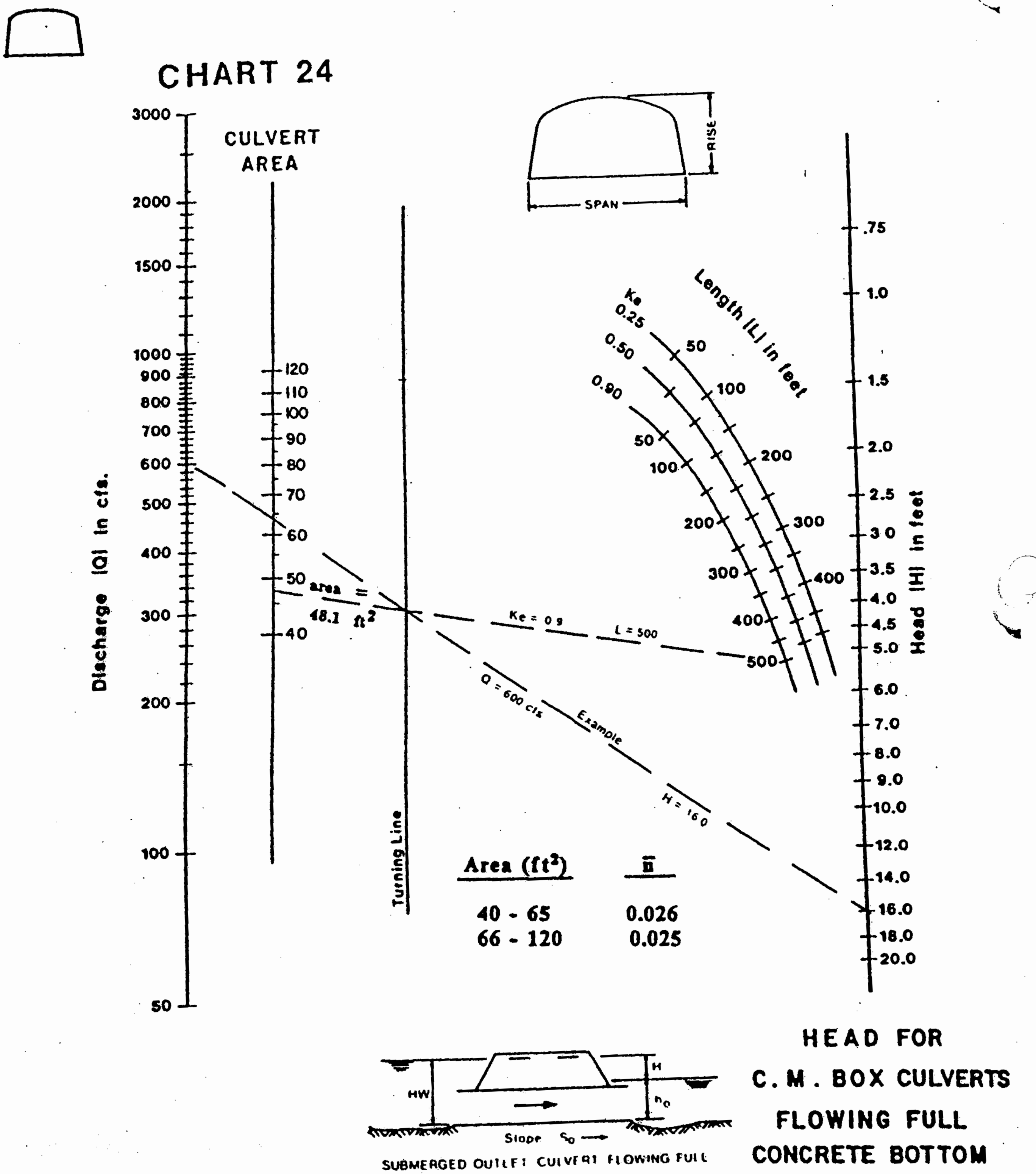


SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C.M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM $0.4 \le$ RISE/SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale



Area (ft²)	n
40 - 65	0.026
66 - 120	0.025

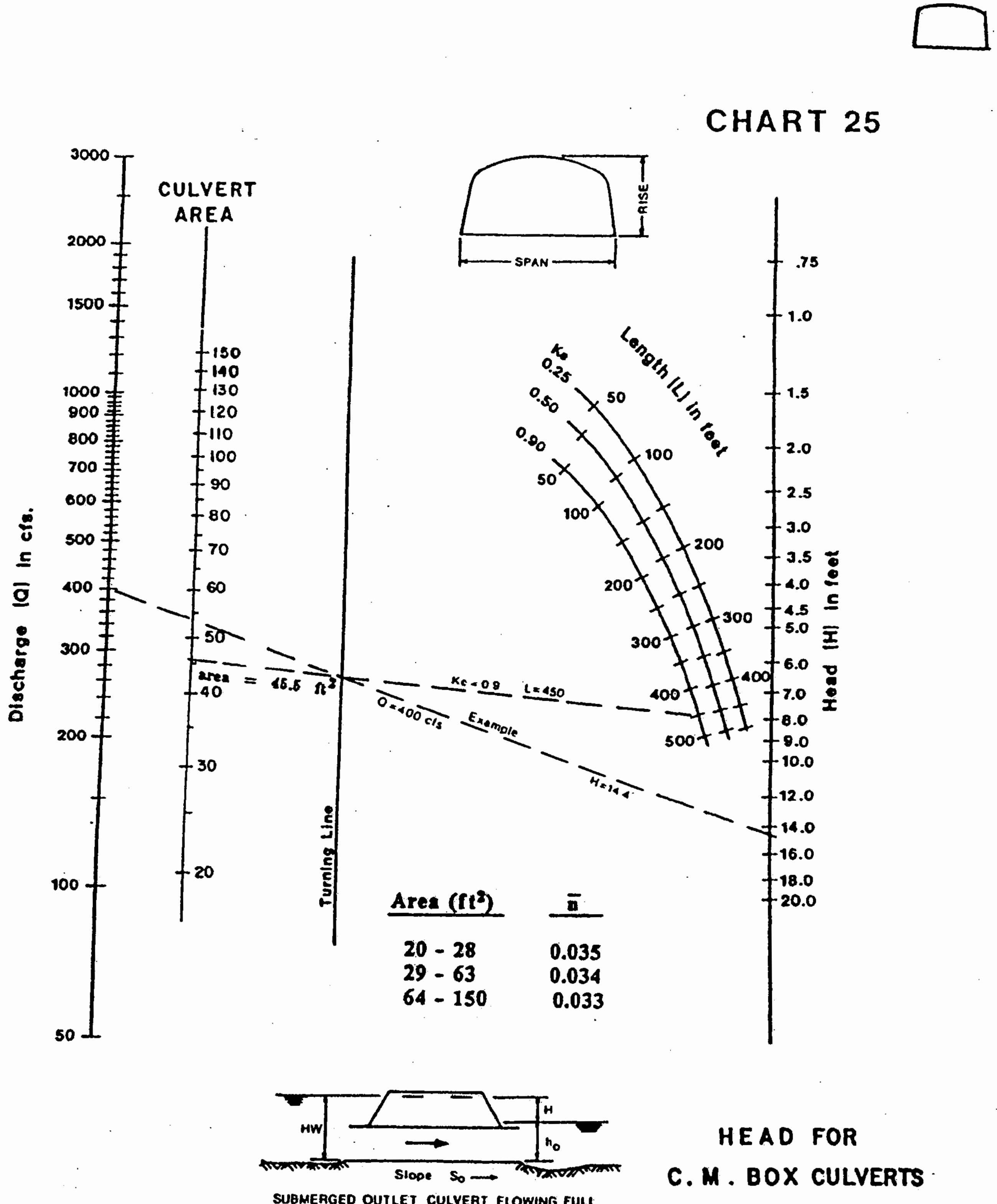
HEAD FOR C. M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM

0.5 ≤ RISE / SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 25



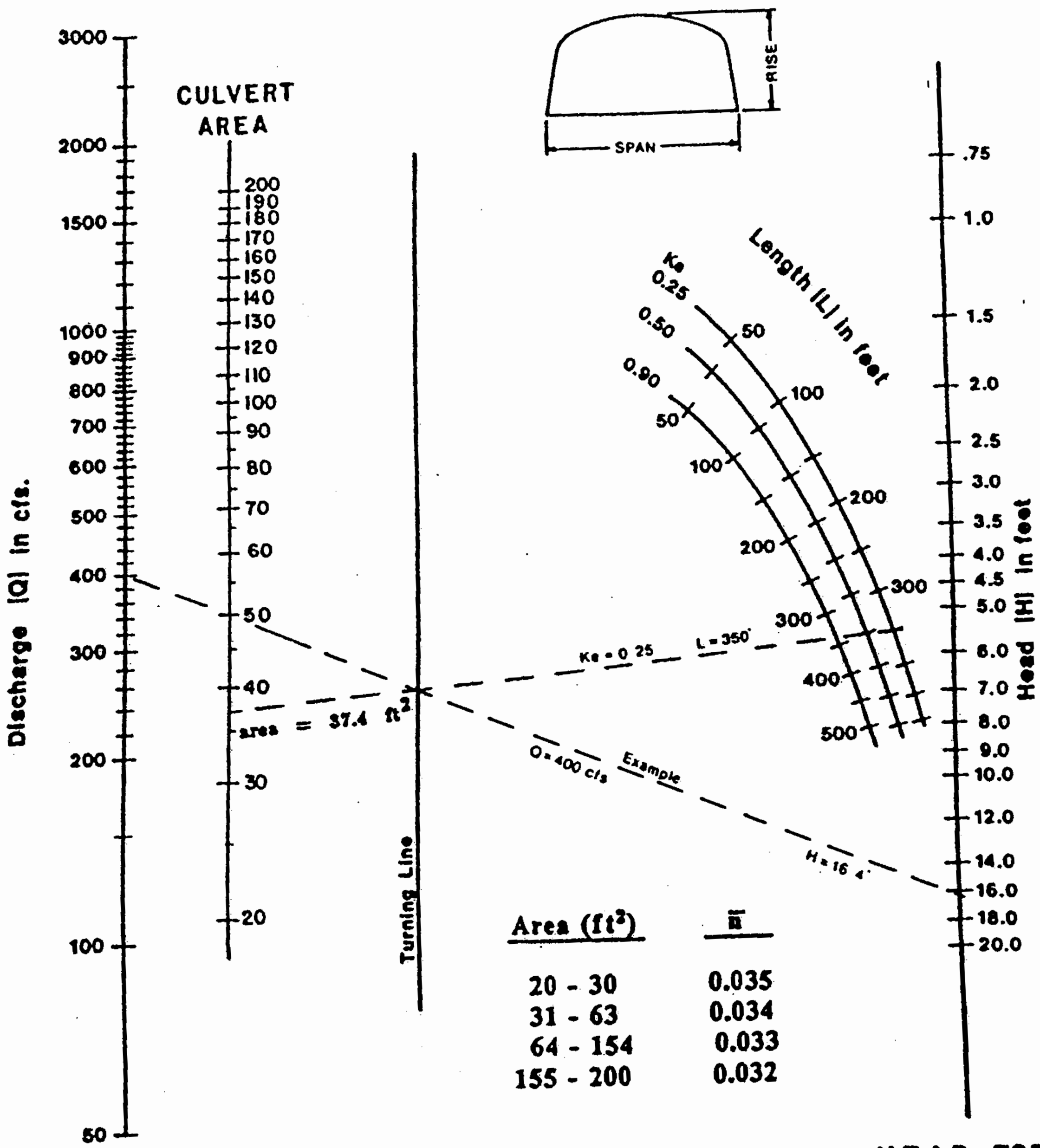
Area (ft²)	n
20 - 28	0.035
29 - 63	0.034
64 - 150	0.033

HEAD FOR
C. M. BOX CULVERTS
FLOWING FULL
CORRUGATED METAL BOTTOM
RISE / SPAN < 0.3

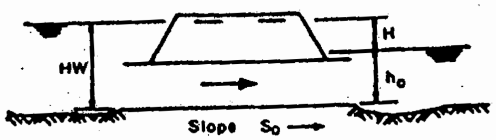
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 26



Area (ft²)	n
20 - 30	0.035
31 - 63	0.034
64 - 154	0.033
155 - 200	0.032



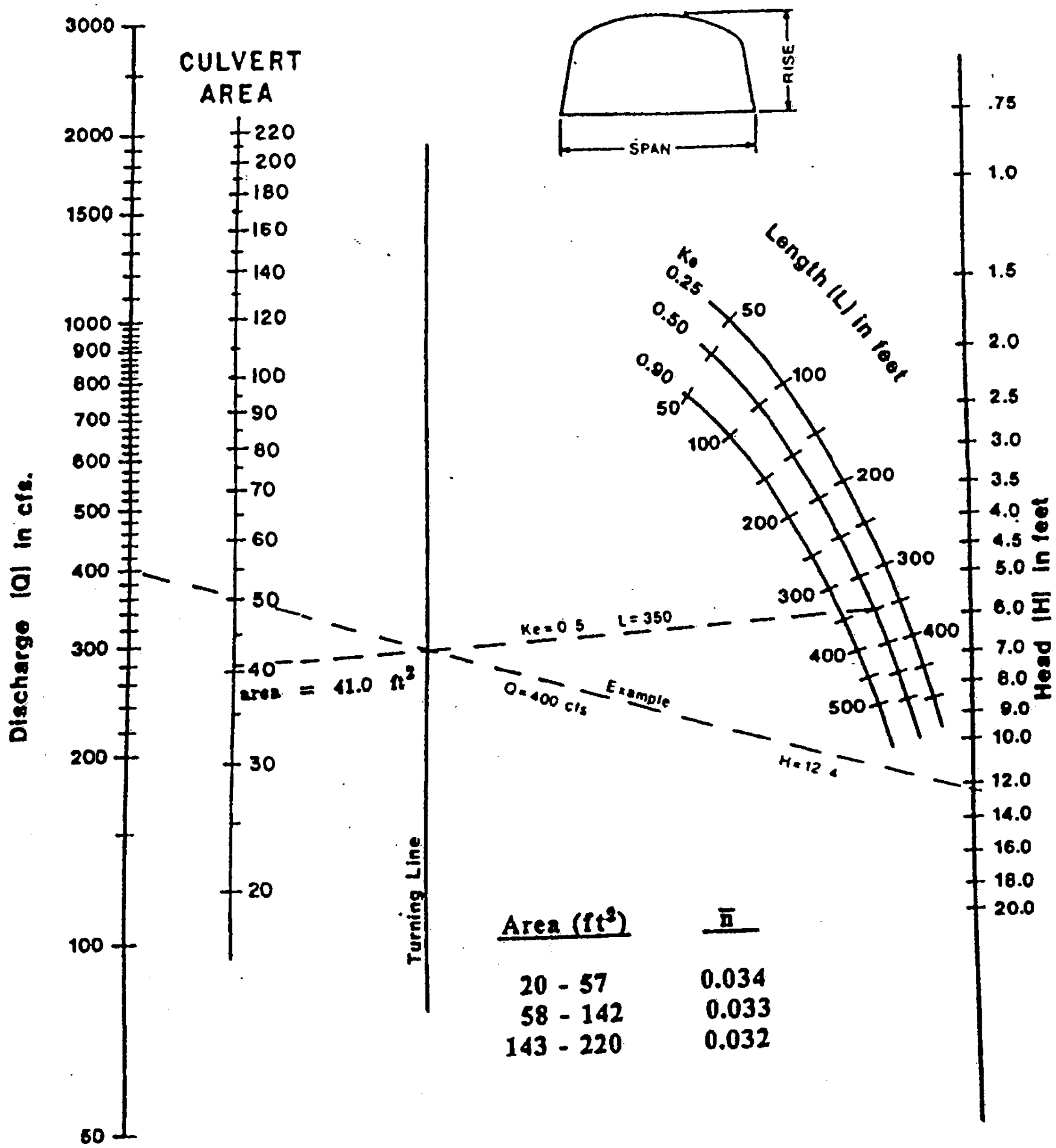
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C. M. BOX CULVERTS FLOWING FULL . CORRUGATED METAL BOTTOM 0.3 ≤ RISE / SPAN < 0.4

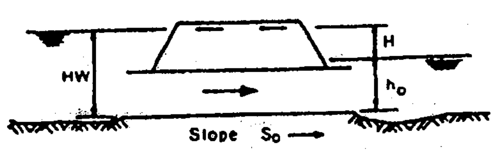
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 27



Area (ft^2)	$\overline{n}$
20 - 57	0.034
58 - 142	0.033
143 - 220	0.032



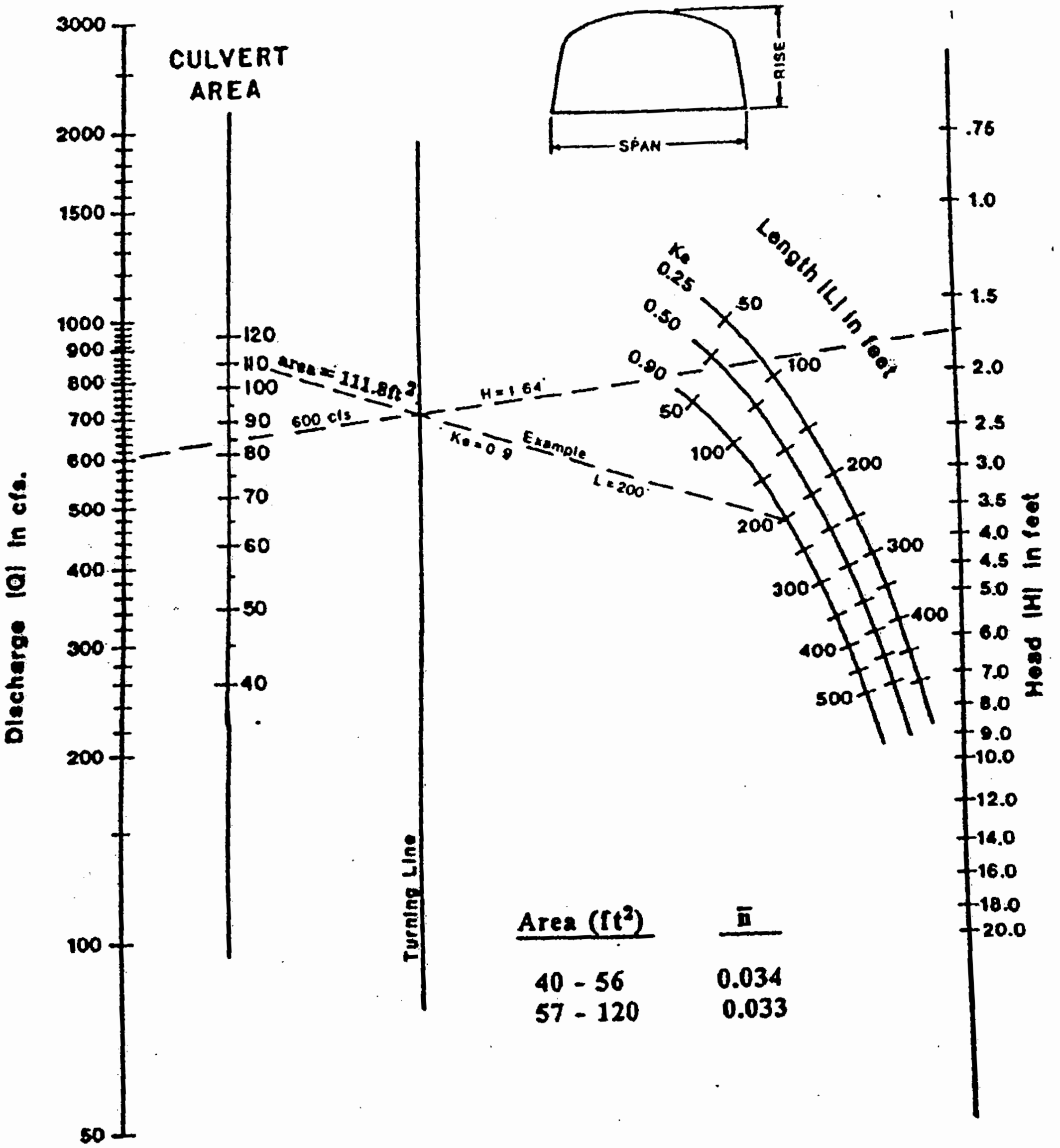
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C. M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM $0.4 \leq$ RISE/SPAN < 0.5

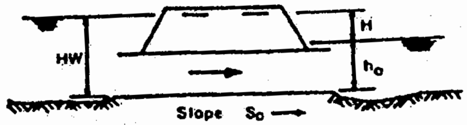
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 28



Area (ft²)	n̄
40 - 56	0.034
57 - 120	0.033



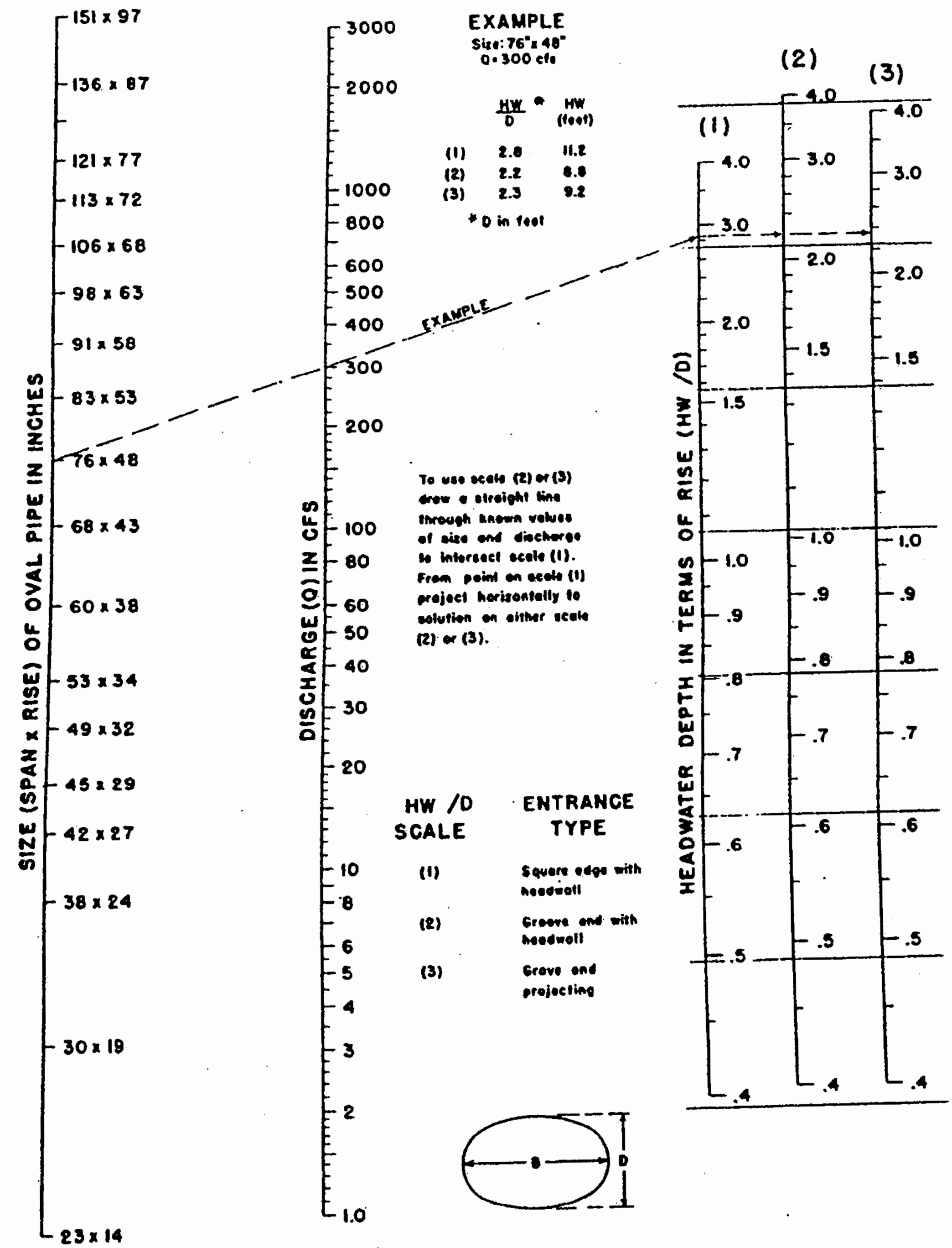
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C. M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM $0.5 \leq$ RISE/SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

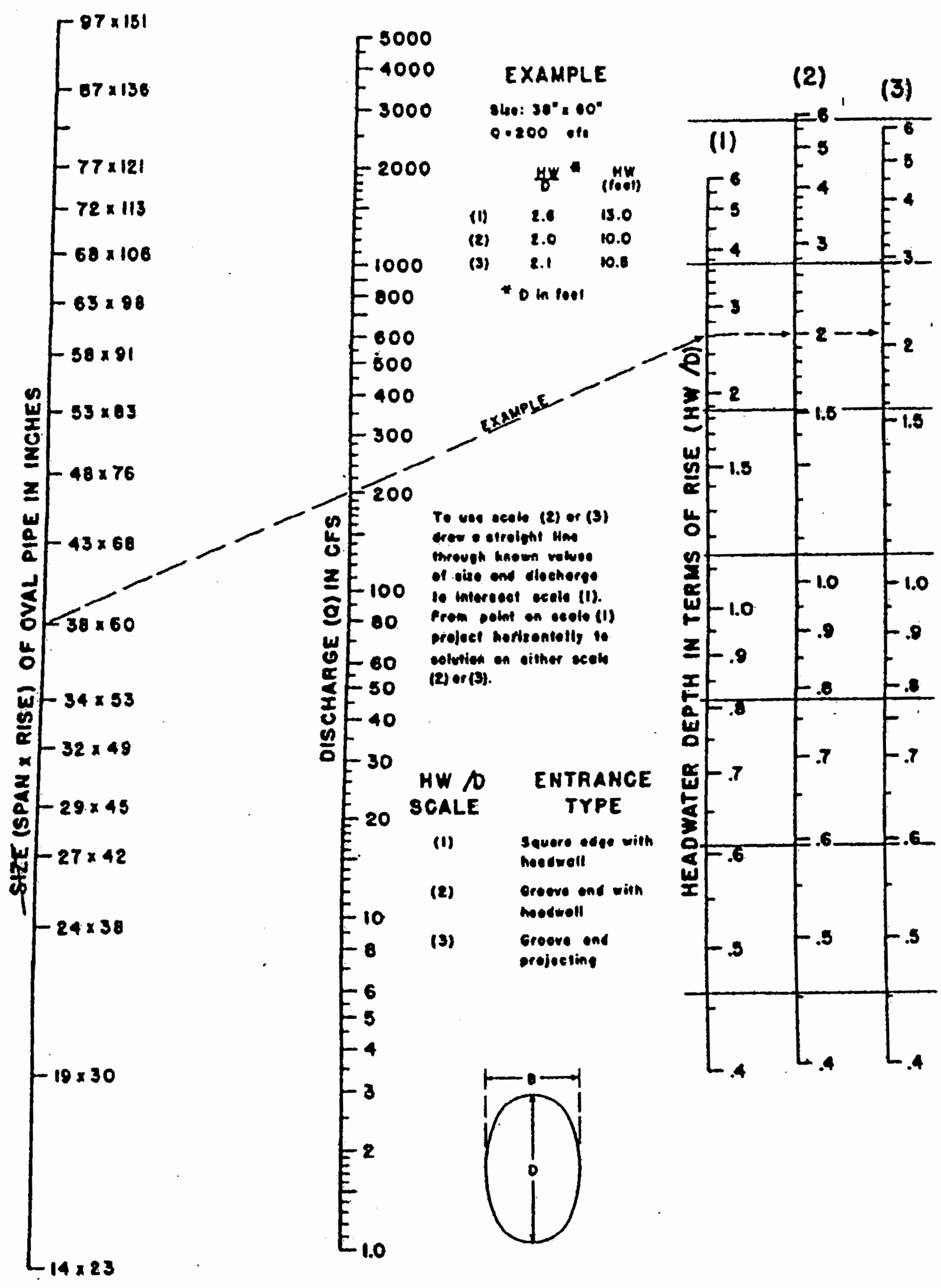
CHART 29



HEADWATER DEPTH FOR OVAL CONCRETE PIPE CULVERTS LONG AXIS HORIZONTAL WITH INLET CONTROL

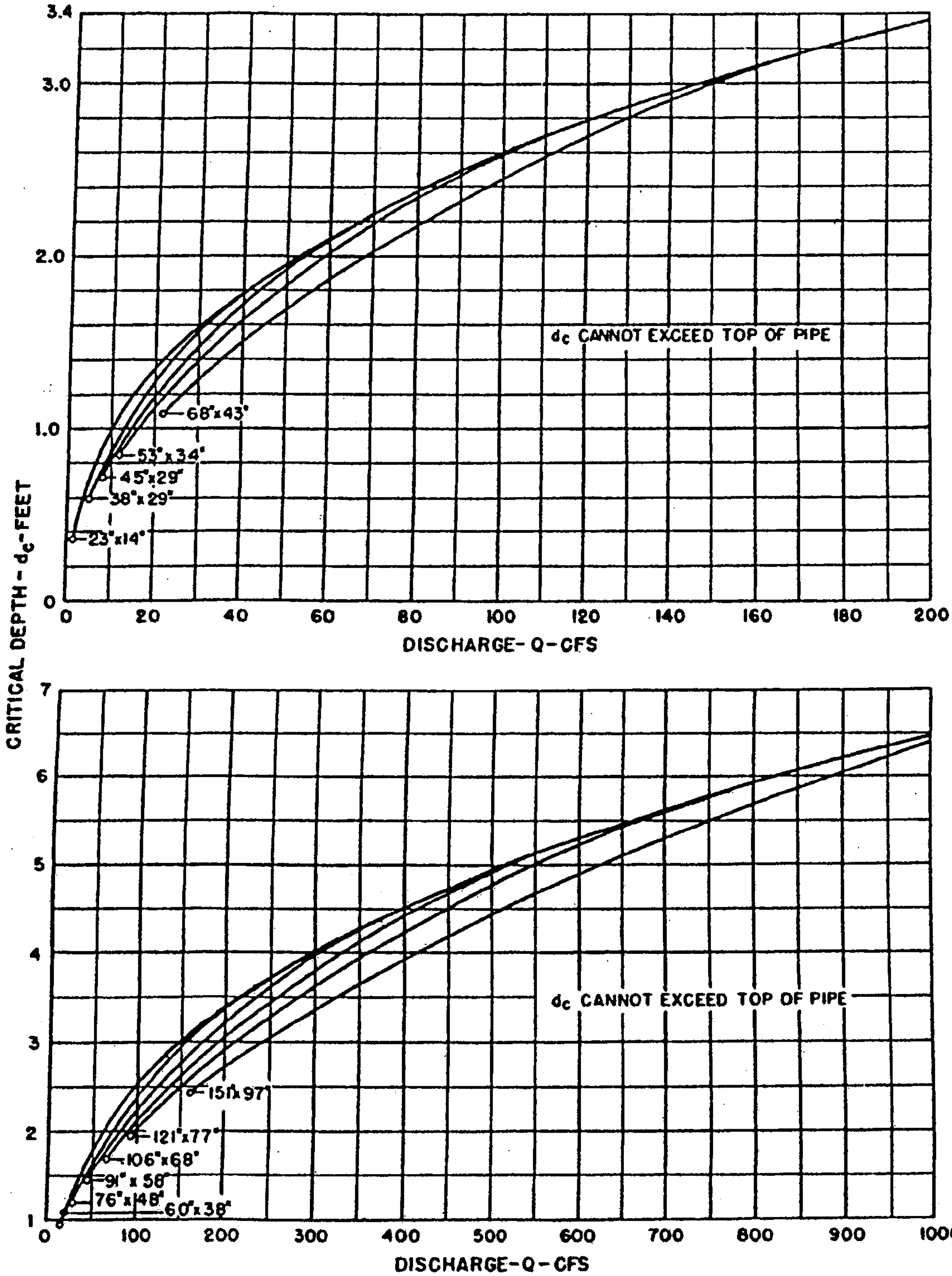
BUREAU OF PUBLIC ROADS JAN. 1963

CHART 30



HEADWATER DEPTH FOR OVAL CONCRETE PIPE CULVERTS LONG AXIS VERTICAL WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

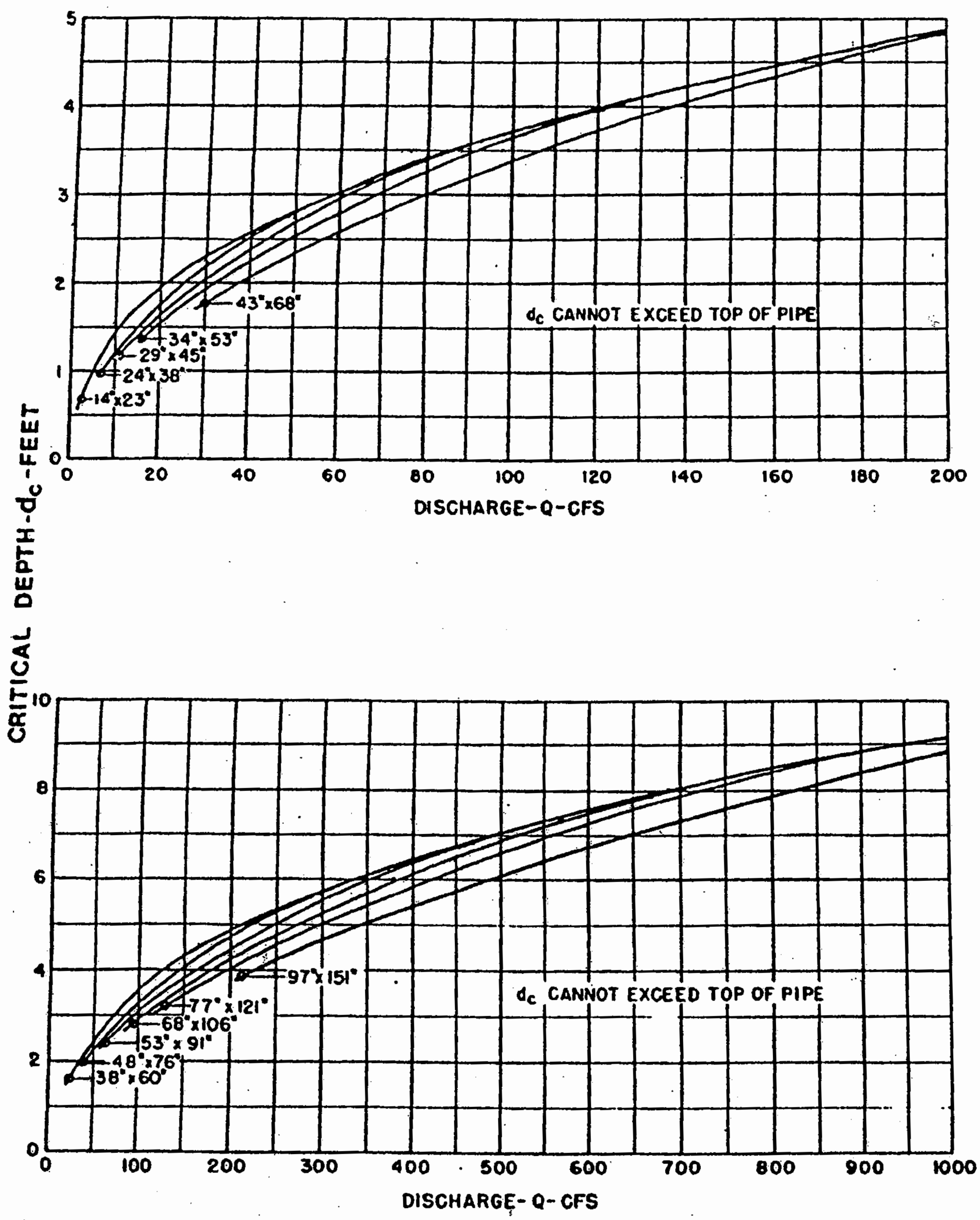


BUREAU OF PUBLIC ROADS

JAN. 1964

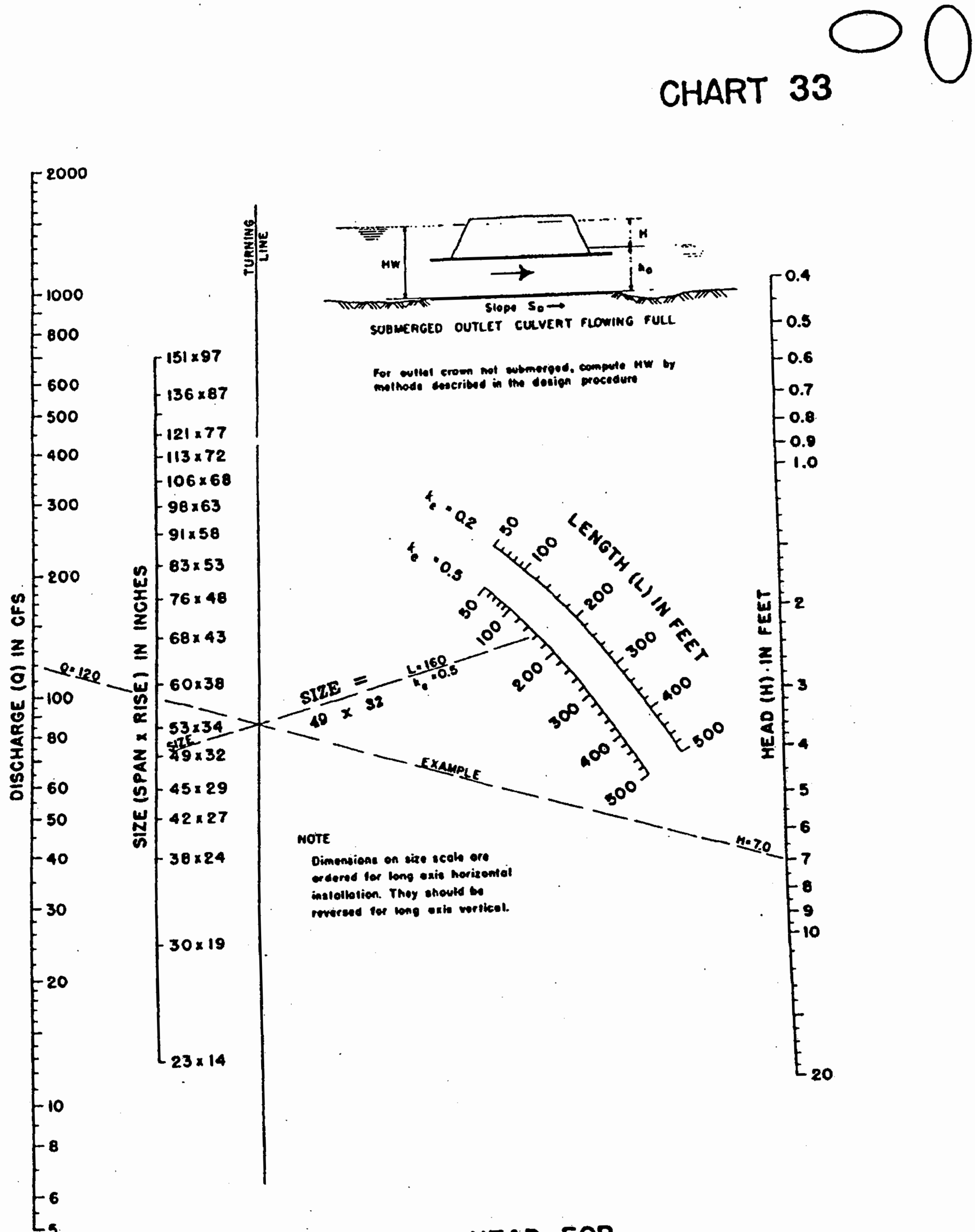
CRITICAL DEPTH
OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL

CHART 32



BUREAU OF PUBLIC ROADS
JAN. 1964

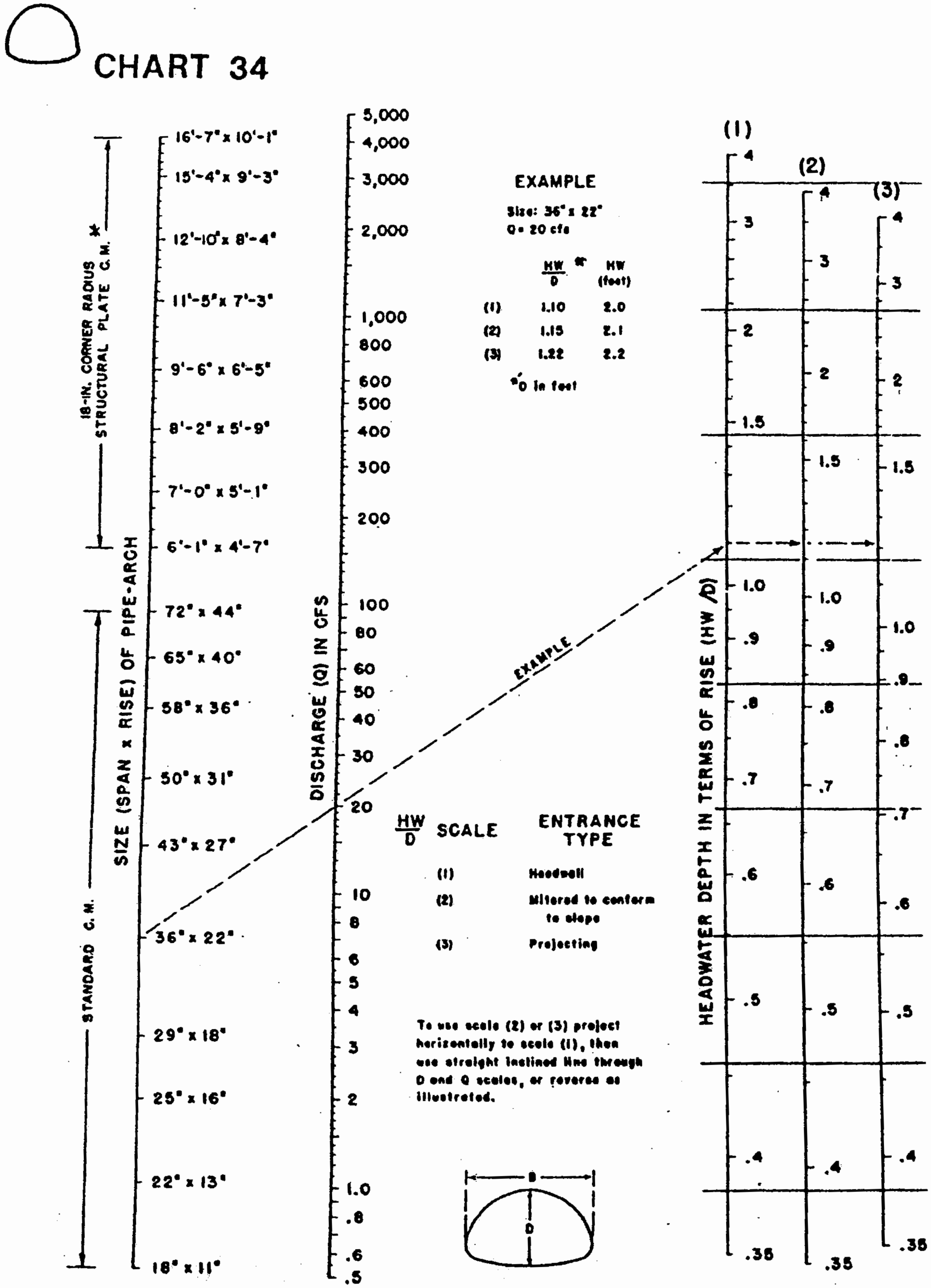
CRITICAL DEPTH
OVAL CONCRETE PIPE
LONG AXIS VERTICAL



HEAD FOR
OVAL CONCRETE PIPE CULVERTS
LONG AXIS HORIZONTAL OR VERTICAL
FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 34



*ADDITIONAL SIZES NOT DIMENSIONED ARE LISTED IN FABRICATOR'S CATALOG

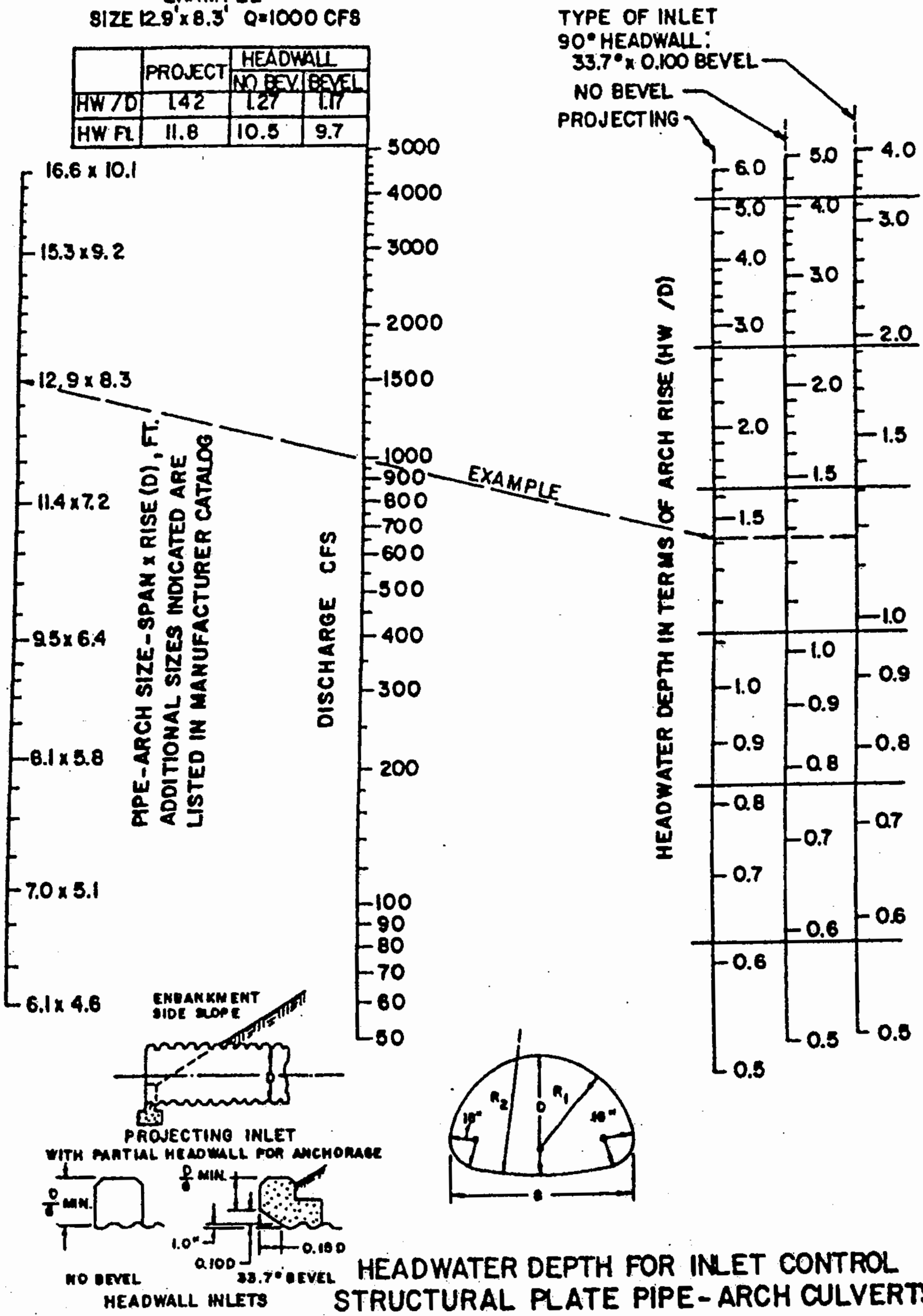
BUREAU OF PUBLIC ROADS JAN. 1963

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

CHART 35

EXAMPLE
SIZE 12.9'x 8.3' Q=1000 CFS

	PROJECT	HEADWALL NO BEV.	HEADWALL BEVEL
HW/D	1.42	1.27	1.17
HW Ft.	11.8	10.5	9.7



HEADWATER DEPTH FOR INLET CONTROL STRUCTURAL PLATE PIPE-ARCH CULVERTS

18-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

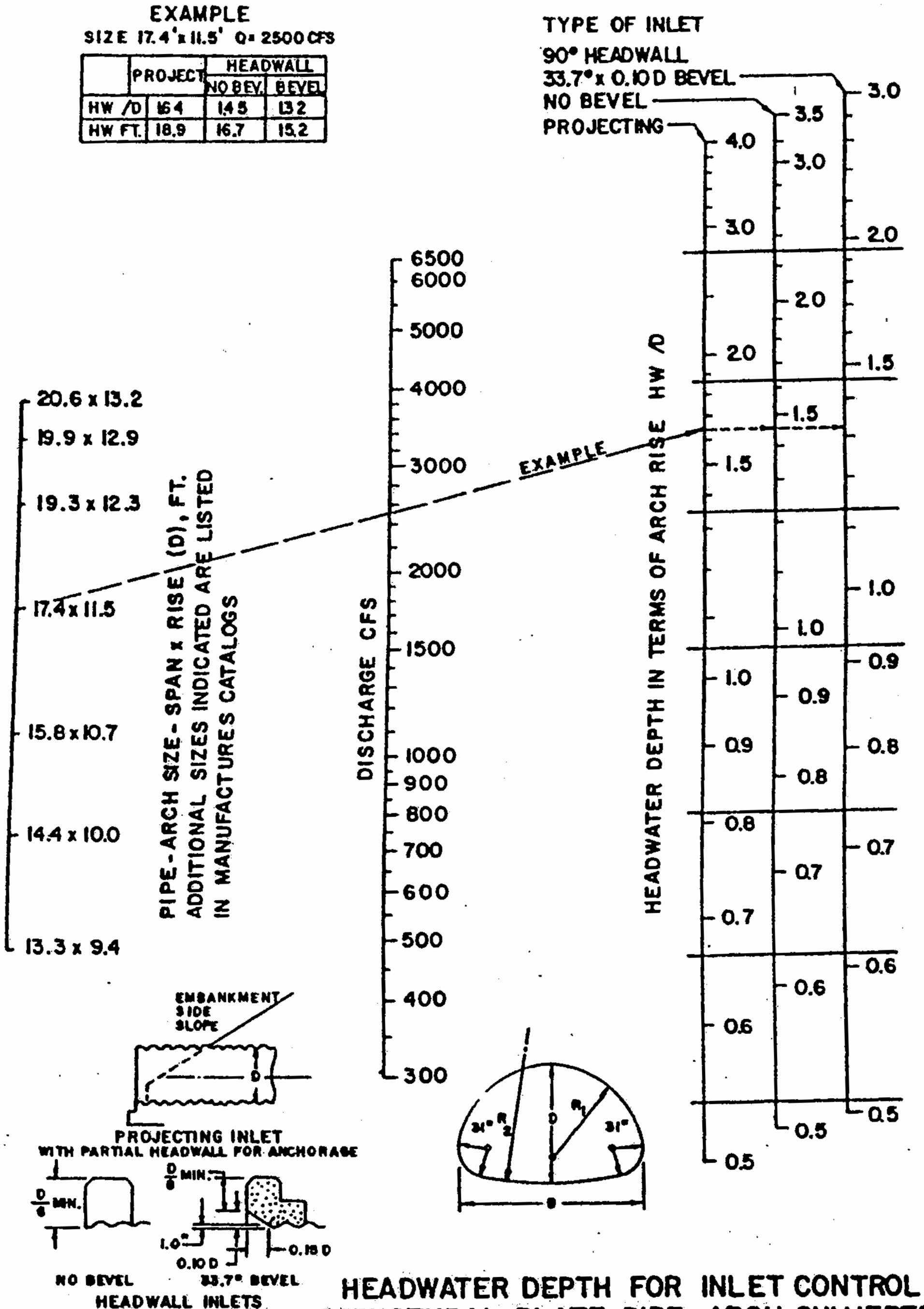
BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1968

CHART 36

EXAMPLE

SIZE 17.4'x 11.5' Q= 2500 CFS

	PROJECT	HEADWALL	
		NO BEV.	BEVEL
HW / D	1.64	1.45	1.32
HW FT.	18.9	16.7	15.2

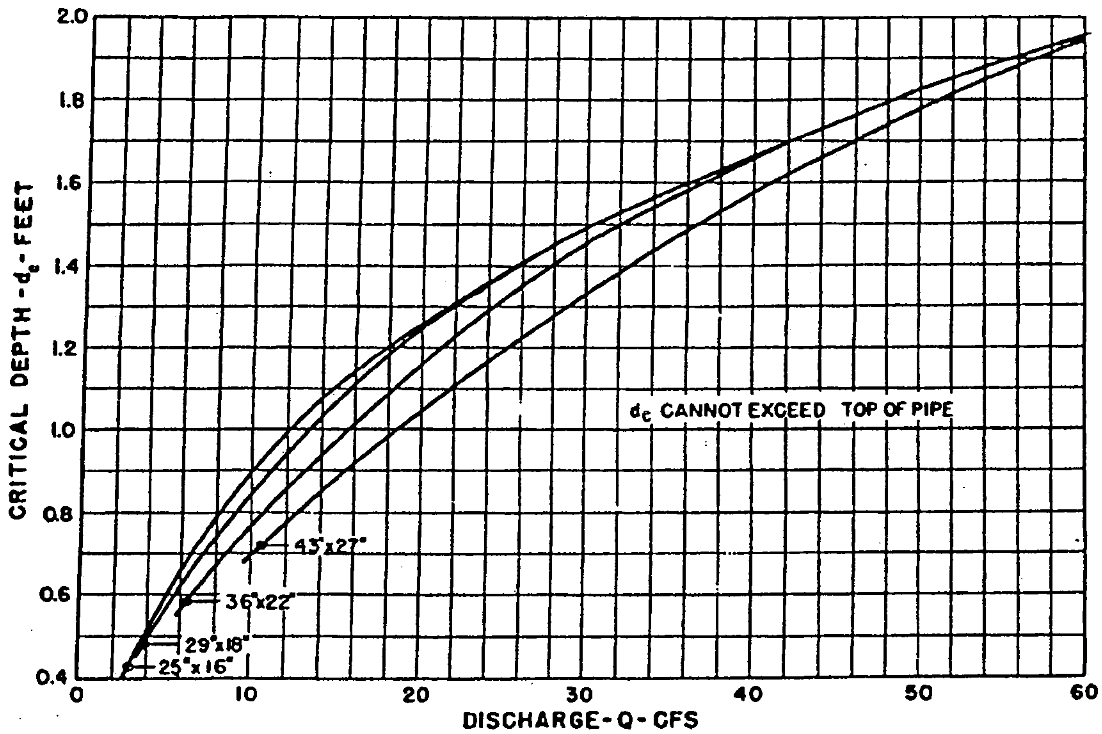


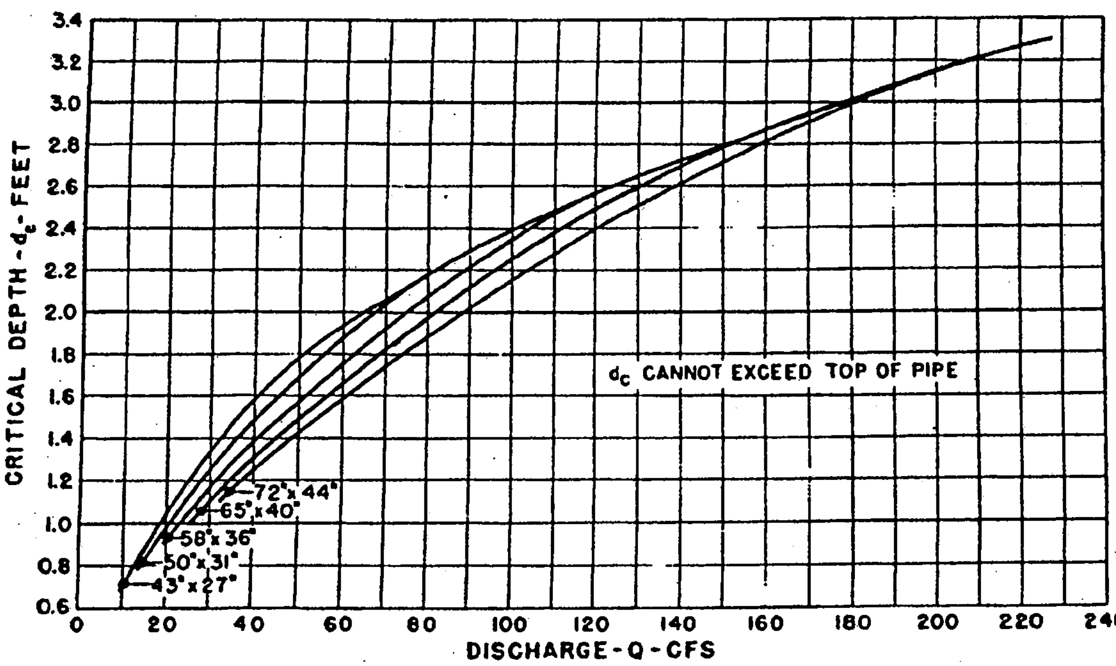
BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1968

HEADWATER DEPTH FOR INLET CONTROL
STRUCTURAL PLATE PIPE-ARCH CULVERTS

31-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

CHART 37

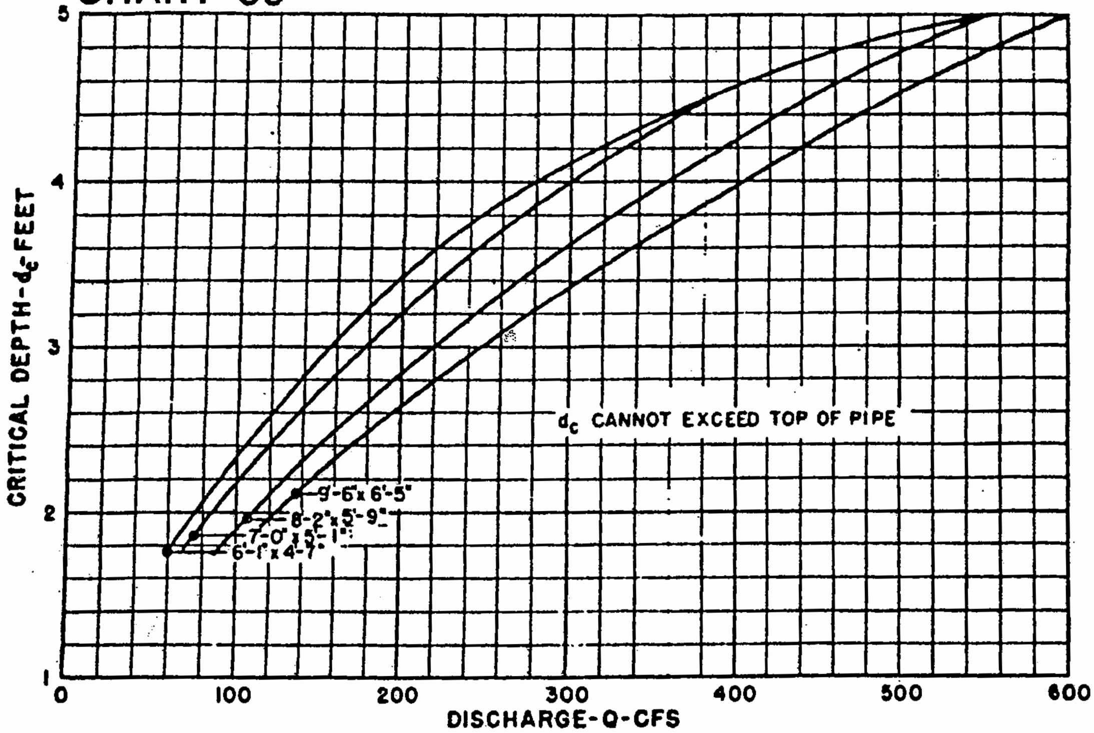


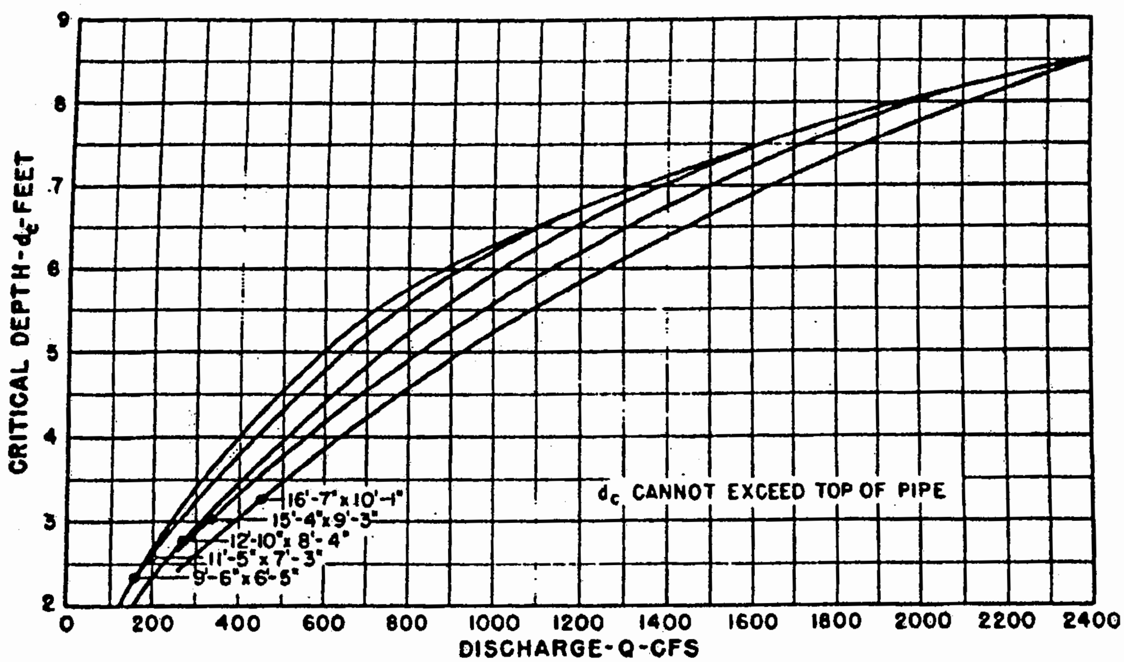


BUREAU OF PUBLIC ROADS
JAN. 1964

CRITICAL DEPTH
STANDARD C.M. PIPE-ARCH

CHART 38



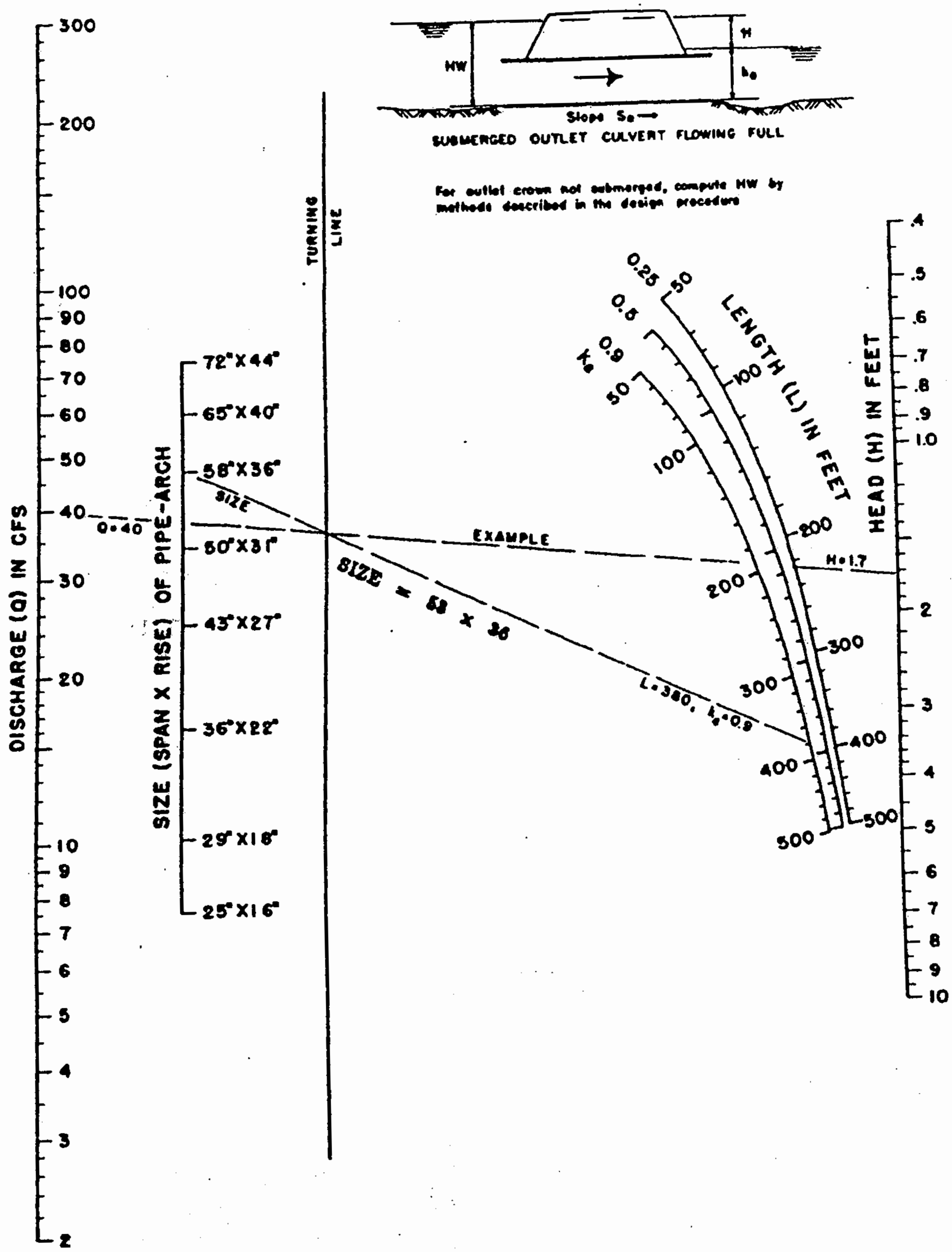


BUREAU OF PUBLIC ROADS

JAN. 1964

CRITICAL DEPTH
STRUCTURAL PLATE
C. M. PIPE-ARCH
18 INCH CORNER RADIUS

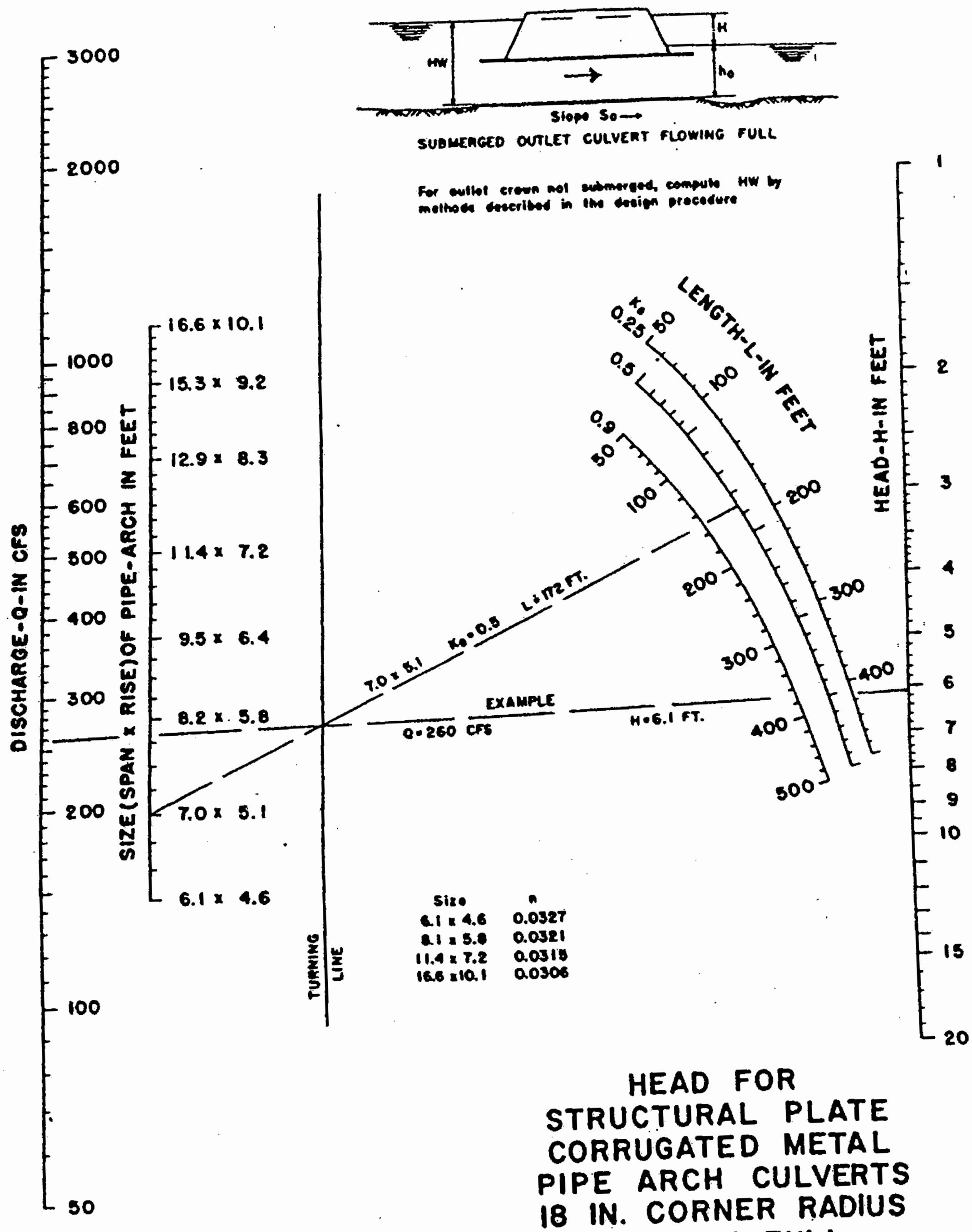
CHART 39



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

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 40

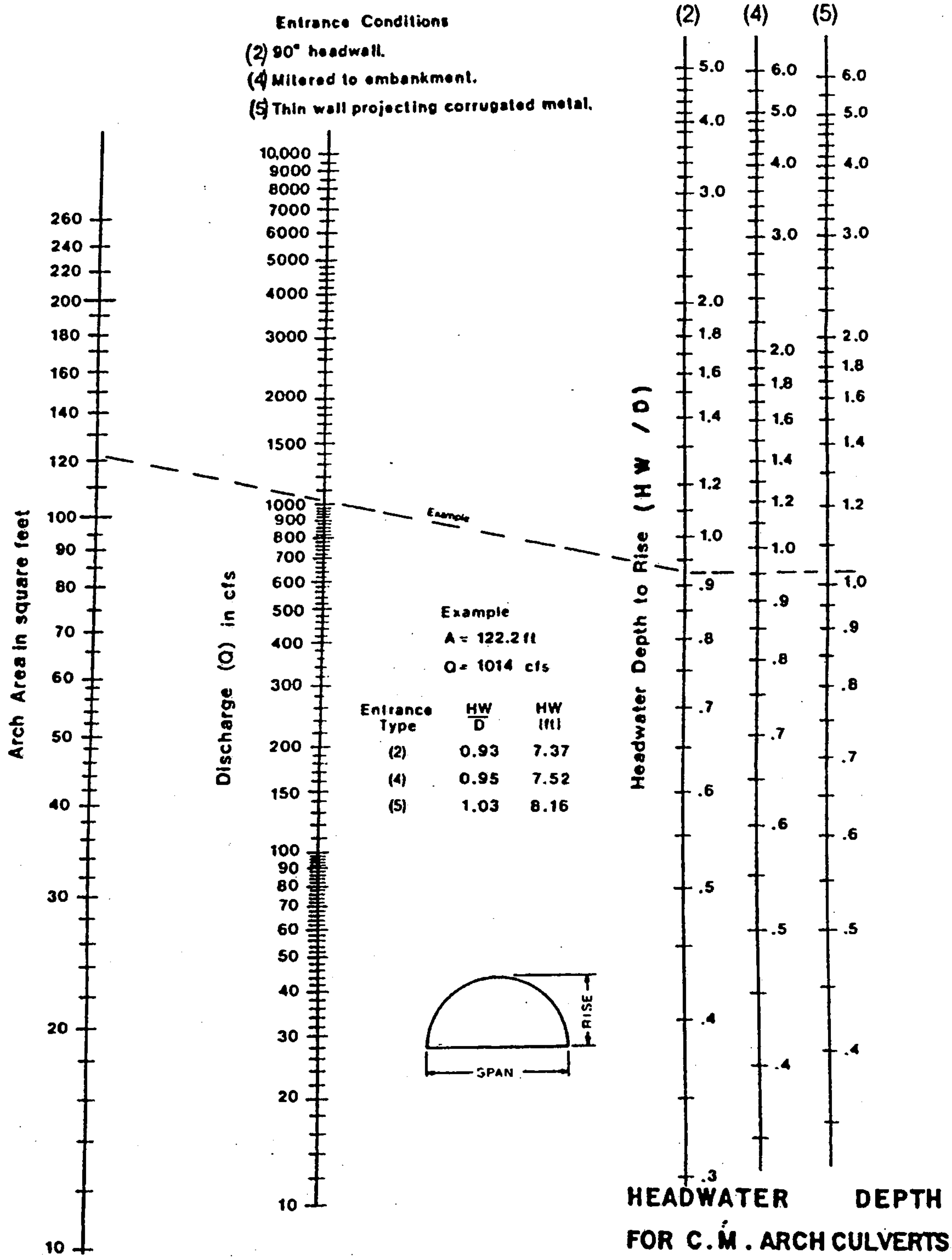


Size	n
6.1 x 4.6	0.0327
8.1 x 5.8	0.0321
11.4 x 7.2	0.0315
16.6 x 10.1	0.0306

HEAD FOR STRUCTURAL PLATE CORRUGATED METAL PIPE ARCH CULVERTS 18 IN. CORNER RADIUS FLOWING FULL n=0.0327 TO 0.0306

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 41

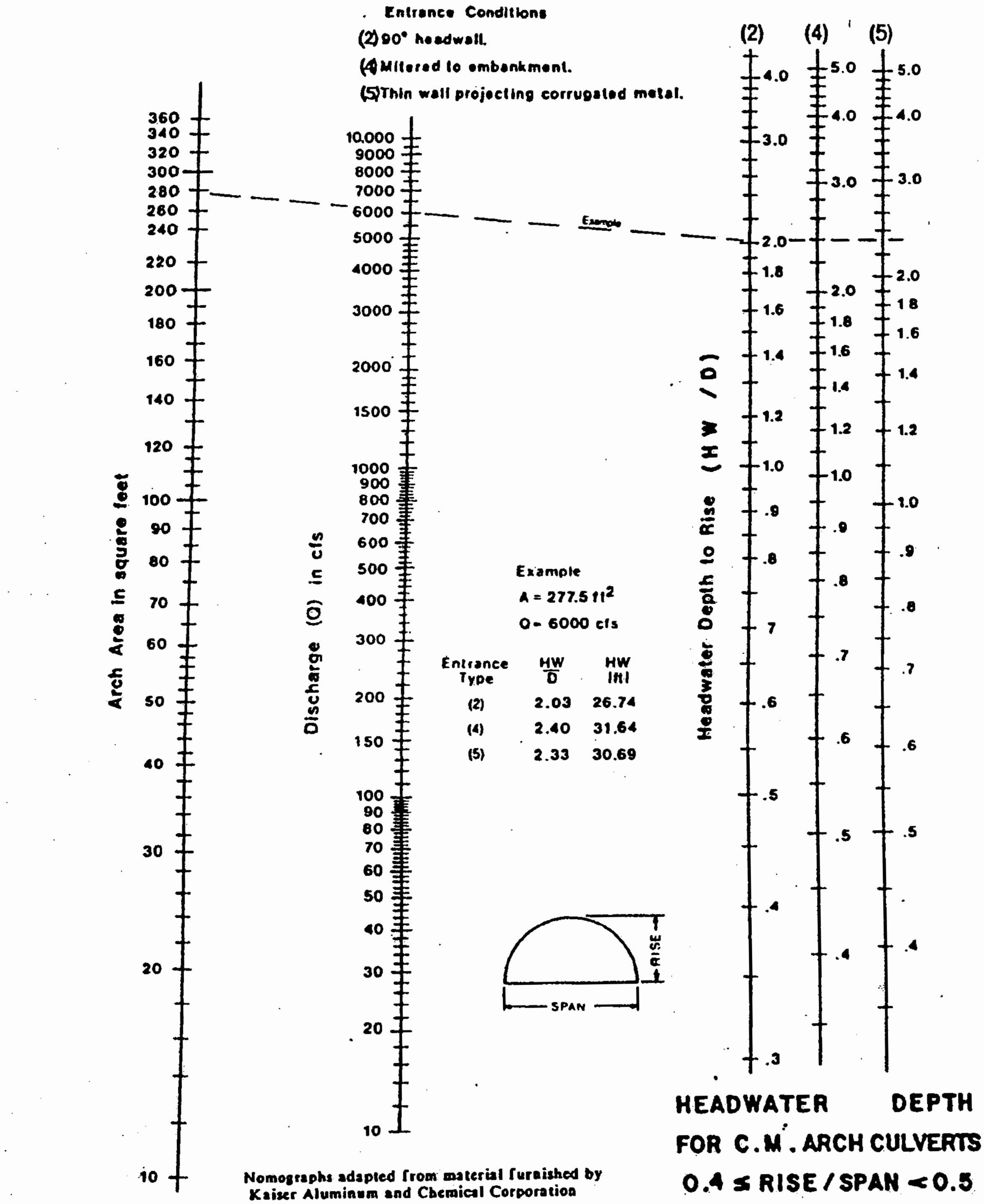


HEADWATER DEPTH FOR C.M. ARCH CULVERTS $0.3 \leq$ RISE / SPAN < 0.4 WITH INLET CONTROL

Duplication of this nomograph may distort scale

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

CHART 42

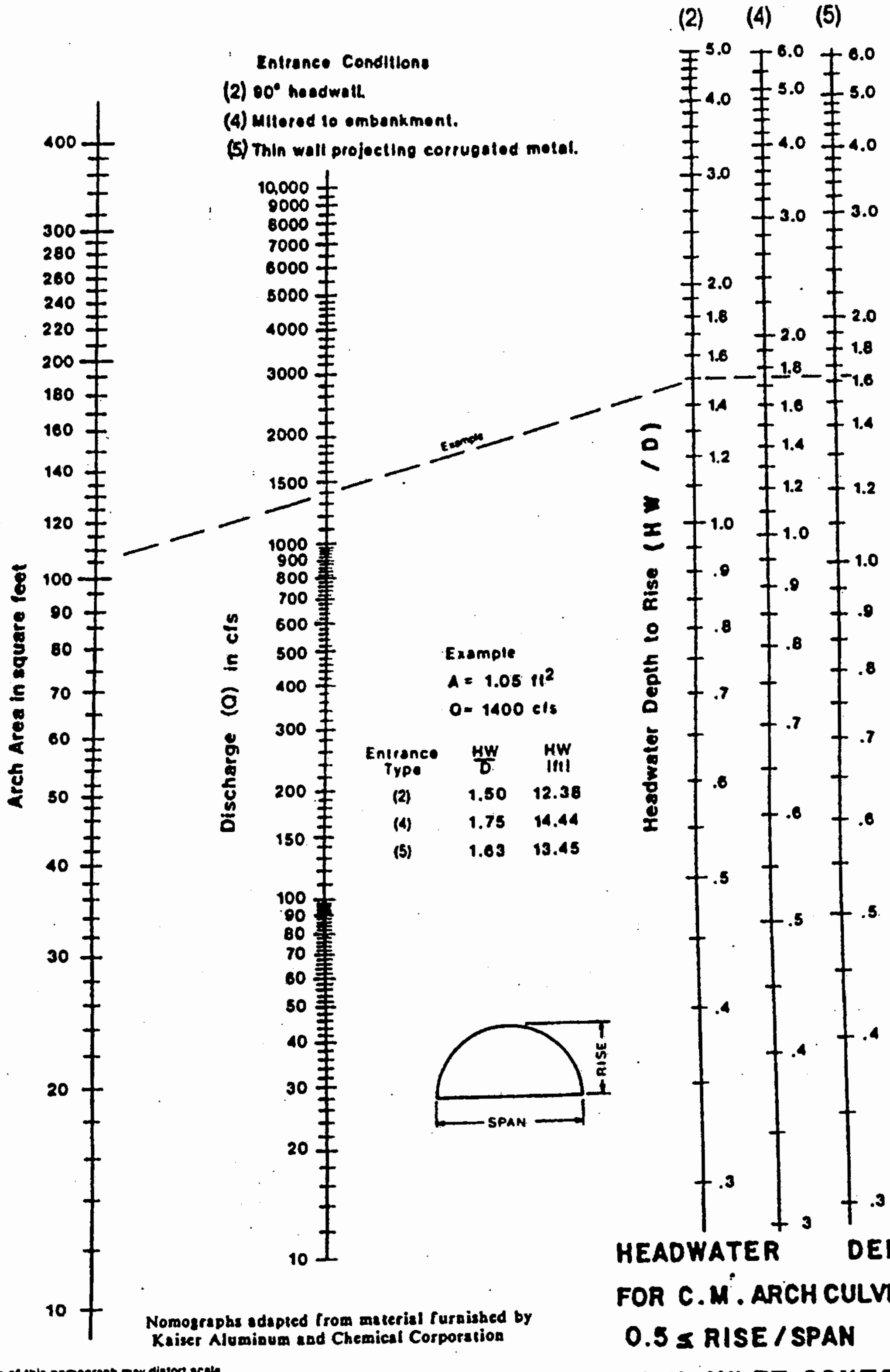


Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

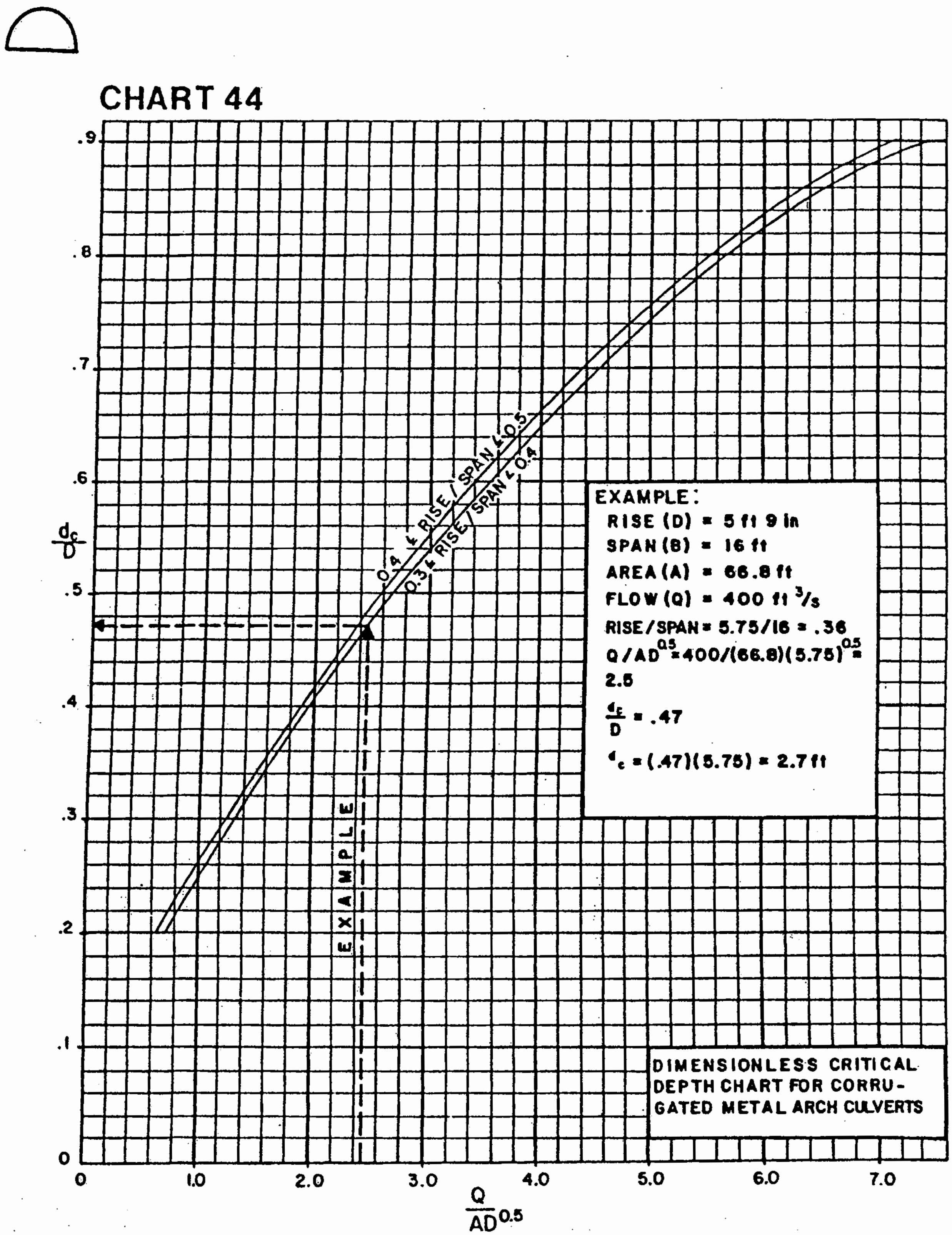
HEADWATER DEPTH FOR C.M. ARCH CULVERTS $0.4 \leq$ RISE / SPAN < 0.5 WITH INLET CONTROL

CHART 43



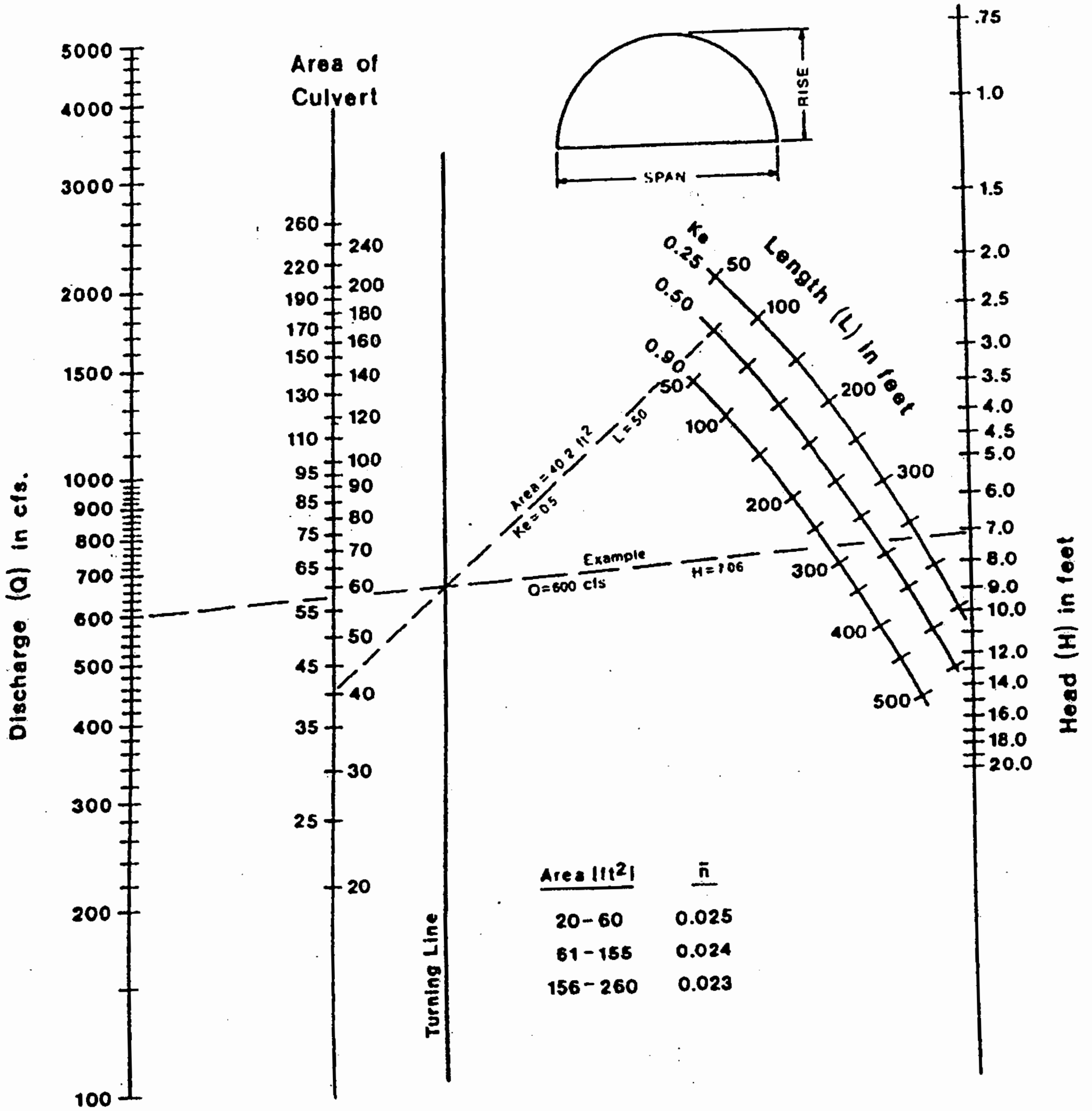
HEADWATER DEPTH FOR C.M. ARCH CULVERTS 0.5 ≤ RISE / SPAN WITH INLET CONTROL

CHART 44

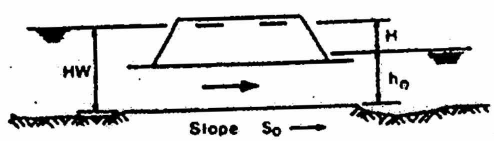


.9
.8
.7
.6
.5
.4
.3
.2
.1
0
$\frac{d_c}{D}$
0.4 ≤ RISE / SPAN ≤ 0.5
0.3 ≤ RISE / SPAN ≤ 0.4
EXAMPLE
EXAMPLE:
RISE (D) = 5 ft 9 in
SPAN (B) = 16 ft
AREA (A) = 66.8 ft
FLOW (Q) = 400 ft ³/s
RISE/SPAN = 5.75/16 = .36
Q / AD^0.5 = 400/(66.8)(5.75)^0.5 = 2.5
dc/D = .47
dc = (.47)(5.75) = 2.7 ft
DIMENSIONLESS CRITICAL DEPTH CHART FOR CORRUGATED METAL ARCH CULVERTS
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
$\frac{Q}{AD^{0.5}}$

CHART 45



Area (ft²)	n̄
20 – 60	0.025
61 – 155	0.024
156 – 260	0.023



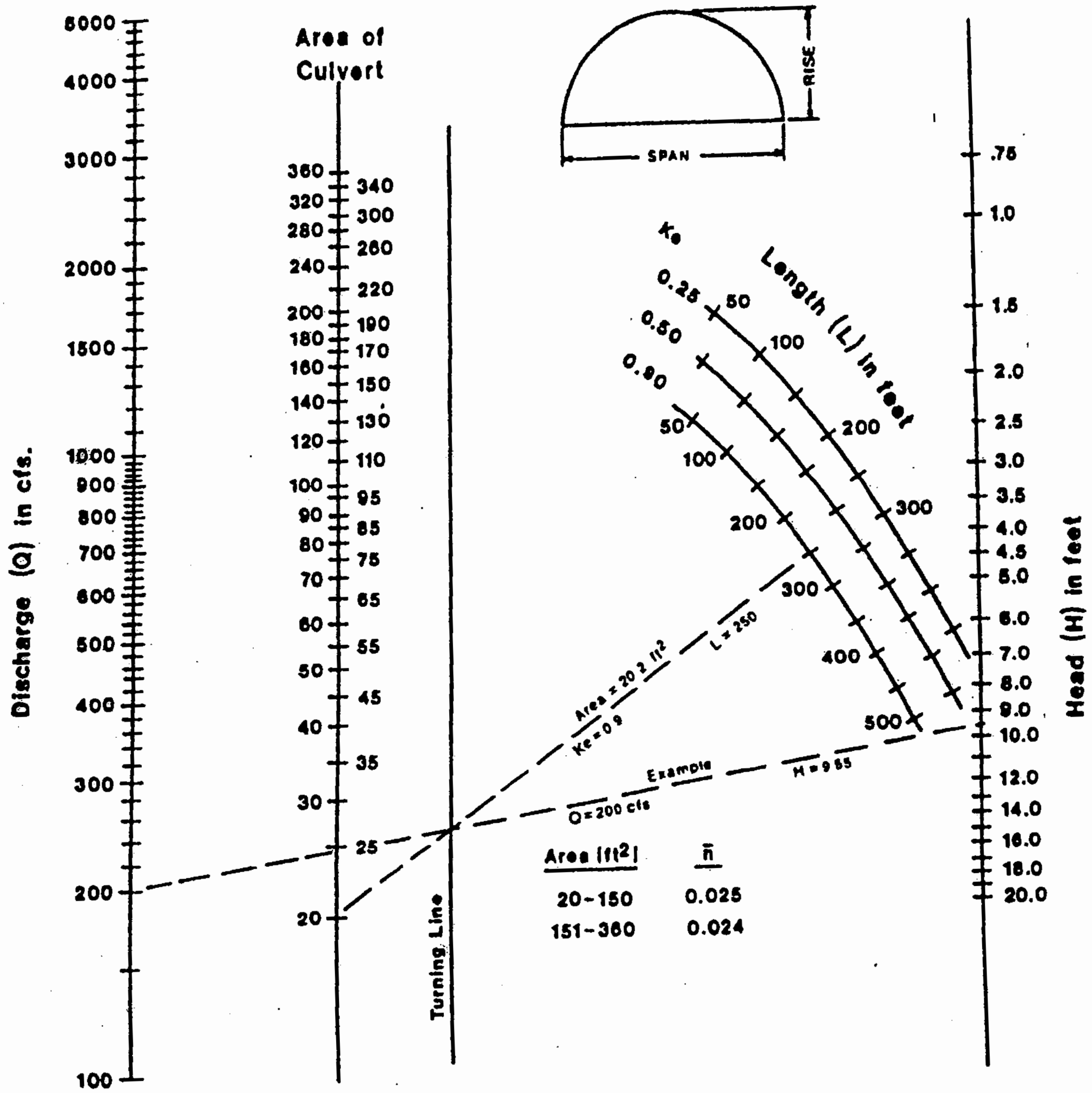
SUBMERGED OUTLET CULVERT FLOWING FULL

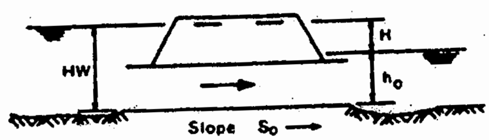
HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
CONCRETE BOTTOM
0.3 ≤ RISE / SPAN < 0.4

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 46





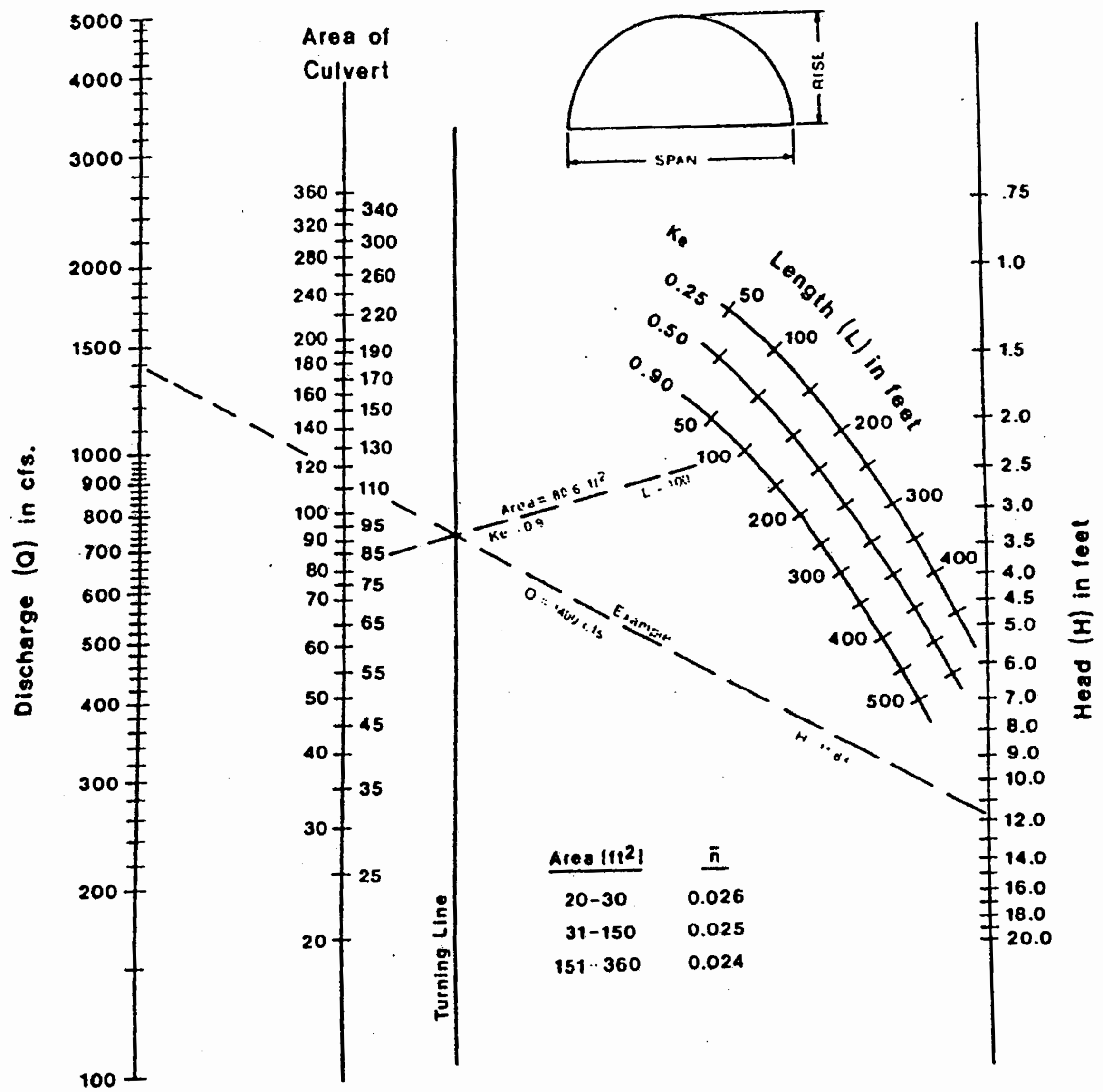
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL CONCRETE BOTTOM $0.4 \leq$ RISE / SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

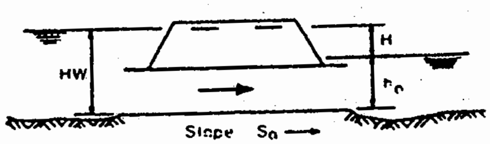
Duplication of this nomograph may distort scale

CHART 47



Area (ft²)	$\bar{n}$
20-30	0.026
31-150	0.025
151-360	0.024

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL CONCRETE BOTTOM $0.5 \leq$ RISE / SPAN

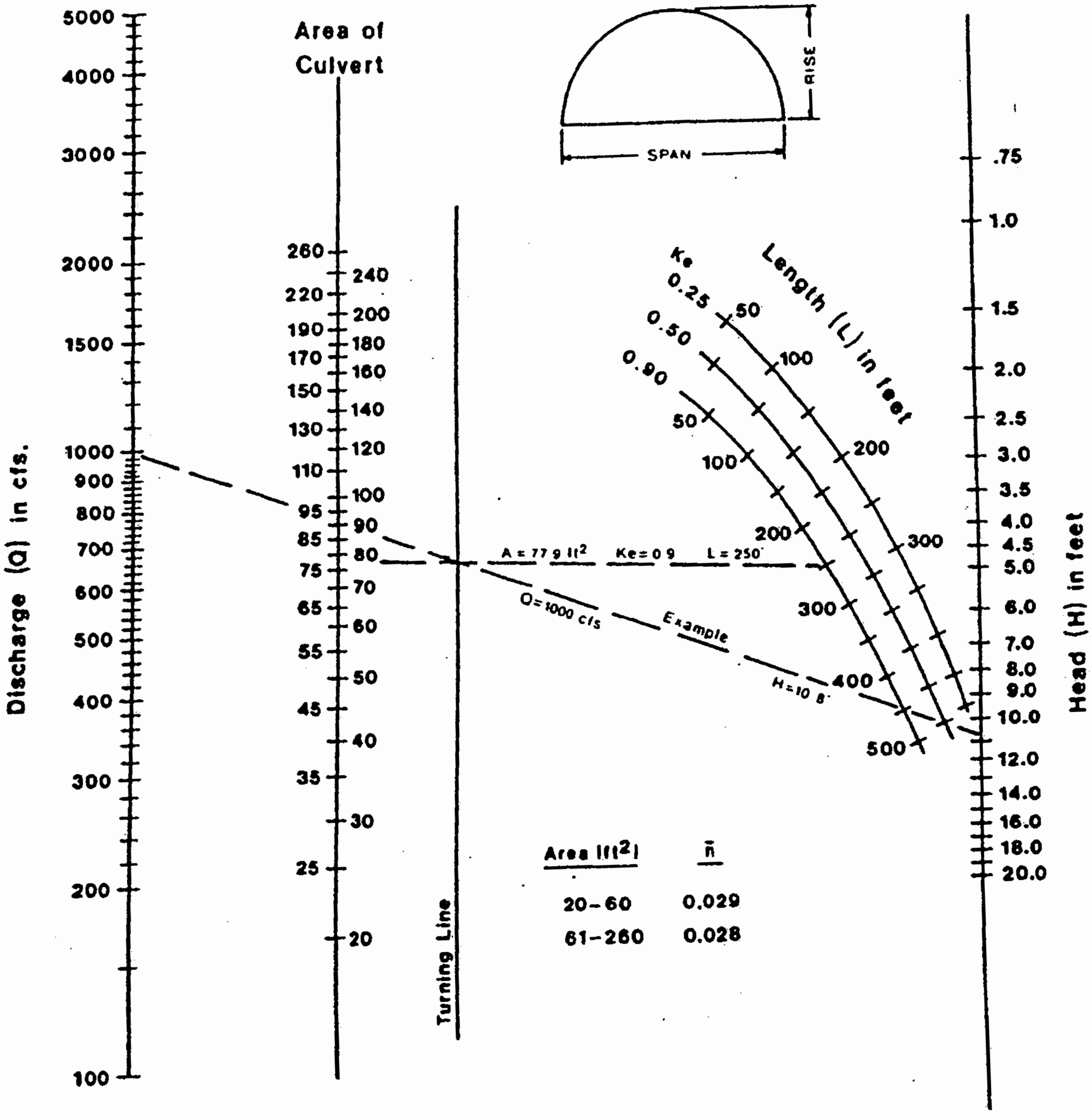


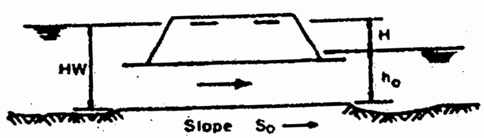
SUBMERGED OUTLET CULVERT FLOWING FULL

Nomographs adapted from material furnished by
Kaiser Aluminum and Chemical Corporation

uplication of this nomograph may distort scale

CHART 48





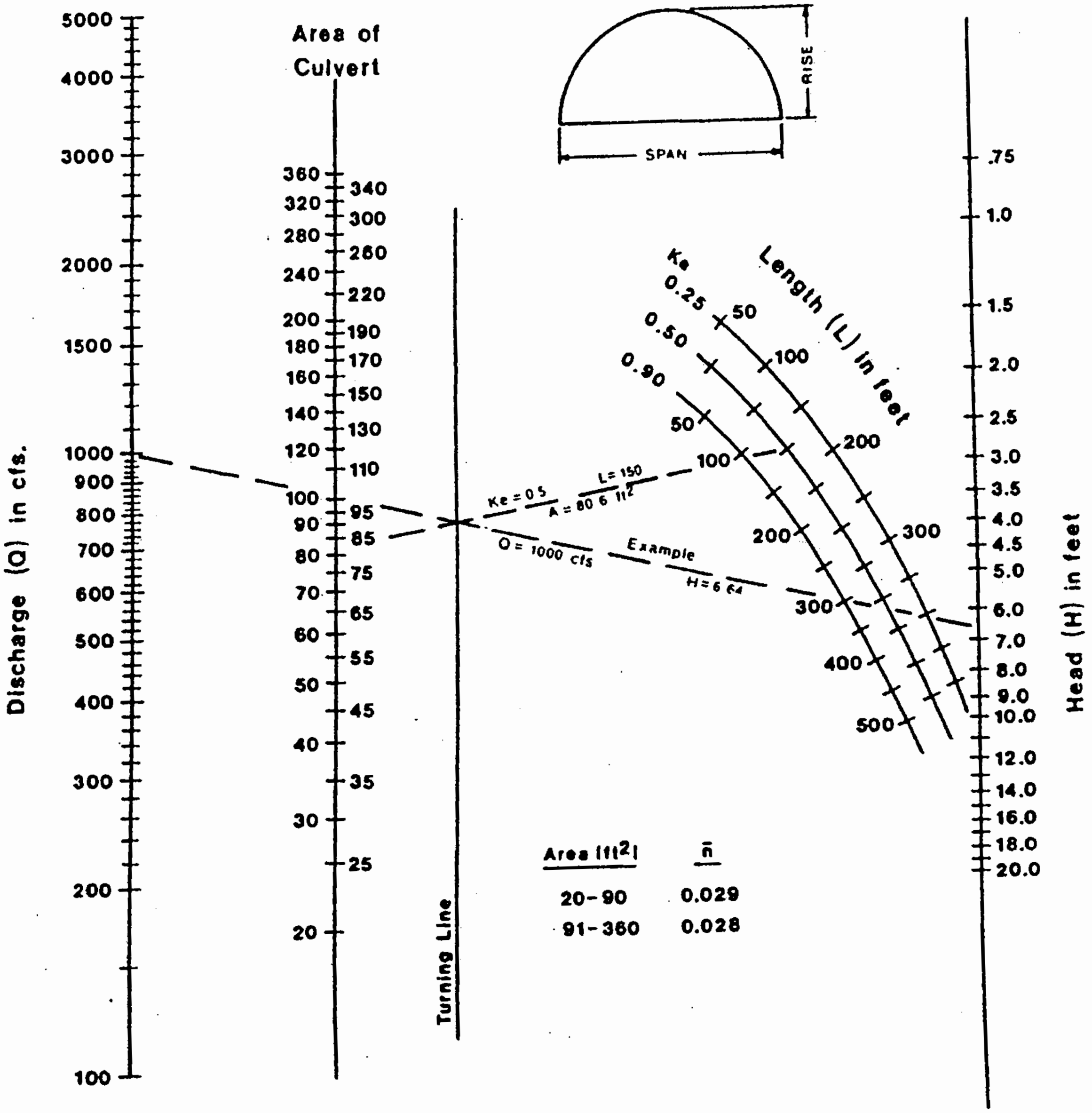
SUBMERGED OUTLET CULVERT FLOWING FULL

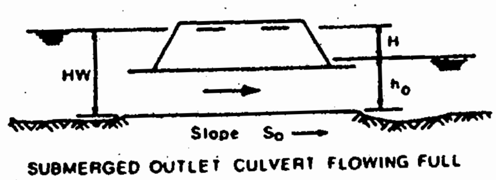
HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
EARTH BOTTOM (n_b = 0.022)
0.3 ≤ RISE / SPAN < 0.4

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 49



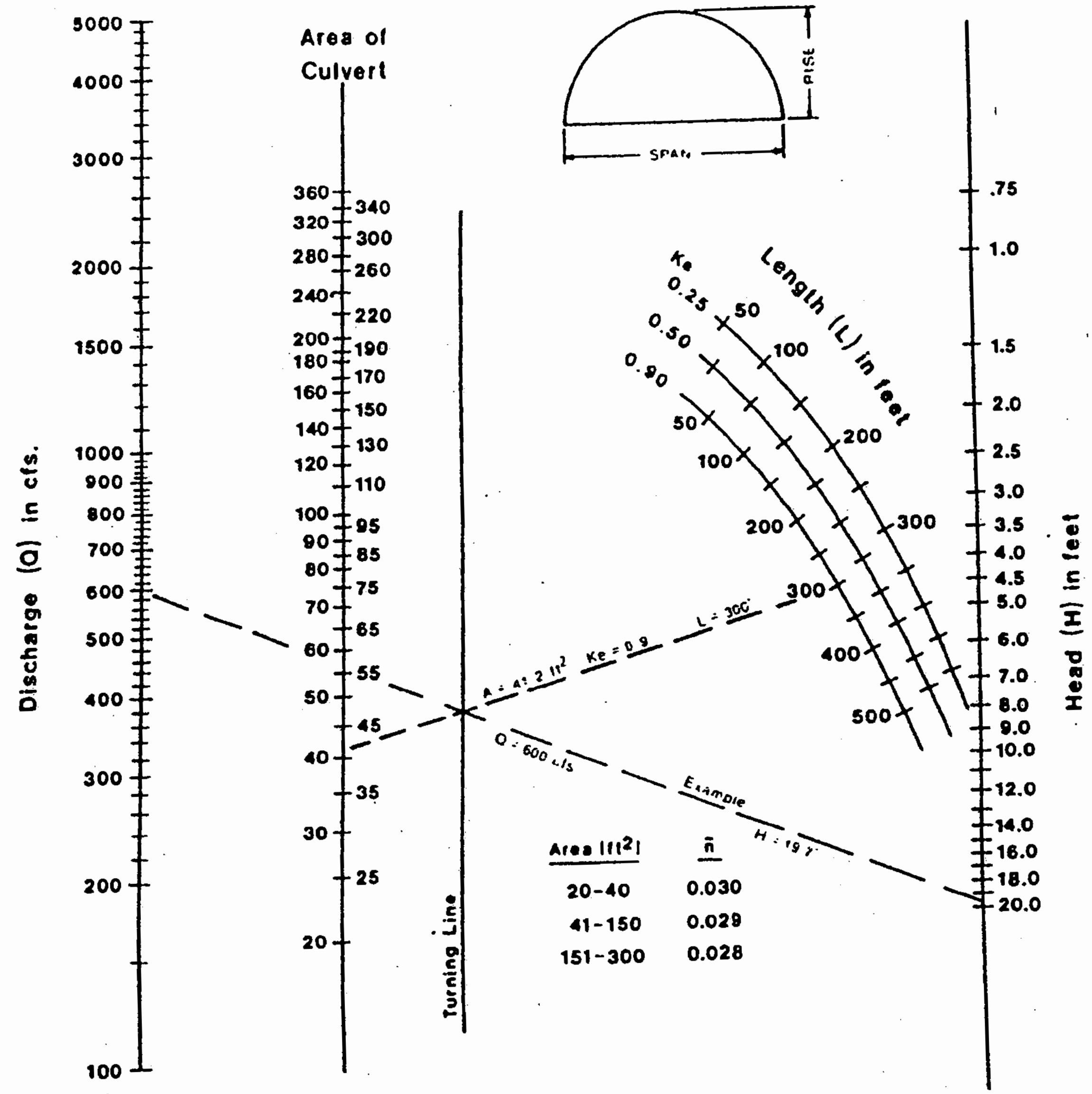


HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
EARTH BOTTOM (n_b = 0.022)
0.4 ≤ RISE / SPAN < 0.5

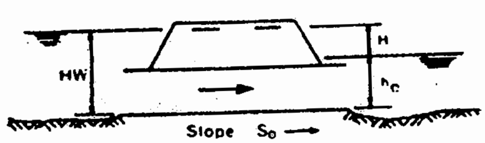
Nomographs adapted from material furnished by
Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

CHART 50



Area (ft²)	$\bar{n}$
20-40	0.030
41-150	0.029
151-300	0.028



SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
EARTH BOTTOM (n_b = 0.022)
0.5 ≤ RISE / SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale