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COMPUTATION OF PEAK DISCHARGE AT CULVERTS

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By R. W. Carter

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COMPUTATION OF PEAK DISCHARGE AT CULVERTS

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ABSTRACT

Methods for computing peak flood flow through culverts on the basis of a field survey of high-water marks and culvert geometry are presented. These methods are derived from investigations of culvert flow as reported in the literature and on extensive laboratory studies of culvert flow. For convenience in computation, culvert flow has been classified into six types, according to the location of the control section and the relative heights of the head-water and tail-water levels. The type of flow which occurred at any site can be determined from the field data and the criteria given in this report. A discharge equation has been developed for each flow type by combining the energy and continuity equations for the distance between an approach section upstream from the culvert and a terminal section within the culvert barrel. The discharge coefficient applicable to each flow type is listed for the more common entrance geometries. Procedures for computing peak discharge through culverts are outlined in detail for each of the six flow types.

INTRODUCTION

The culvert is frequently used as an indirect means of determining peak discharge from small drainage areas. Computation of discharge based on high-water marks is used in lieu of a direct measurement by the current-meter method because the short time interval between rainfall and runoff does not permit the engineer to reach the site with the equipment necessary for a direct measurement. Also, the short duration of the flood and poor measuring conditions would often result in a current-meter measurement of questionable accuracy.

The purpose of this report is to set forth procedures for computation of peak discharge through culverts. This report supersedes the manual Computation of Peak Discharge Through Culverts by S. E. Rantz, M. A. Benson, and J. S. Cragwall, Jr., which is presently used in the Survey. The methods outlined represent no radical departure from those presently used. Rather, they feature simplified methods of computation by use of formulas instead of flow routing, better definition of the discharge coefficient by laboratory investigation, and extension of the methods to include culverts that are under a high head.

Geological Survey Circular 284 (Kindsvater, Carter, and Tracy, 1953) defined procedures for computing peak discharge through bridge openings. It differs from the present report primarily in the range of variables involved: a culvert may generally be distinguished from a bridge waterway by a length-to-width ratio greater than one.

This manual was prepared as part of the research program of the Surface Water Branch, Water Resources Division, U. S. Geological Survey. The author was aided in the laboratory investigation by Harry H. Barnes and Jacob Davidian. C. E. Kindsvater, Professor of Civil Engineering, Georgia Institute of Technology, served as a consultant to the research program.

RECENT INVESTIGATIONS OF CULVERT HYDRAULICS

In preparing this manual full use has been made of previously published investigations on the discharge characteristics of culverts. Since 1920, the U. S. Bureau of Public Roads has sponsored many laboratory investigations at colleges and universities throughout the country. Notable among them is the report by Yarnell, Nagler, and Woodward (1926) which contains the result of more than 3, 000 tests on flow through pipe and box culverts. These tests included a range of pipe diameters from 12 to 30 inches and a range of box sizes from 2 to 4 feet. Various entrance geometries were tested, but only flow with the culvert barrel submerged on both ends was investigated.

F. T. Mavis (1942) reported on a laboratory investigation on round smooth pipes. His tests included a comprehensive range of head-water and tail-water elevations, but only an entrance form with a sharp edge set flush in a headwall was tested.

Straub and Morris (1950a-c) reported on full-scale tests on corrugated and concrete-pipe culverts. This work was extended in a later report by Straub, Anderson, and Bowers (1954).

Other investigations to develop culvert geometries of greater hydraulic efficiency are listed in the bibliography. These reports have also been used in defining coefficients for certain entrance geometries.

In addition to the reports cited, the procedures given in this manual are based on a laboratory investigation conducted by the U. S. Geological Survey at the Georgia Institute of Technology. The tests included all conditions of flow through round, rectangular, and square barrels with various entrance geometries. Sand-grain roughness was used to obtain a range in the friction factor (Darcy $\underline{f}$) of from 0. 017 to 0. 085 for barrel diameters ranging from 4 to 6 inches. The tests were run in a flume 2 feet wide, the bed slope of which was varied from 0 to 8 percent.

CLASSIFICATION OF PRINCIPAL FLOW TYPES

In defining the discharge characteristics of culverts, the energy equation is written for a reach that begins at an approach section upstream from the culvert and ends at a terminal section within the culvert barrel. Whether the terminal section is at the upstream or downstream end of the culvert depends upon the type of flow in the barrel. If critical or rapid flow occurs at the culvert entrance, the height of the head-water surface is not a function of either the barrel friction loss or the height of the tail-water surface, and the terminal section is thus located at the upstream end of the culvert. For all other types of flow the terminal section is located at the downstream end of the culvert.

Information obtained in the field survey includes the peak elevation of the water surface upstream and downstream from the culvert and the geometry of the culvert and approach channel. Reliable high-water marks can rarely be found in the culvert barrel; therefore, the type of flow that occurred during the peak flow cannot always be determined directly from field data, and classification becomes a trial-and-error procedure.

General Classification

For convenience in computation, culvert flow has been classified into six types on the basis of the location of the control section and the relative heights of the head-water and tail-water surfaces. Table 1 lists the characteristics of

TABLE 1. --Characteristics of flow types

[D = maximum vertical height of barrel and diameter of circular culverts; see also plate 1]

Flow type	Barrel flow	Location of terminal section	Kind of control	Culvert slope	$\frac{h_1 - z}{D}$	$\frac{h_4}{h_c}$	$\frac{h_4}{D}$
I............	Partly full	Inlet	Critical depth	Steep	<1.5	<1.0	≤ 1.0
II............	- - do - -	Outlet	- - do - -	Mild	<1.5	<1.0	≤ 1.0
III............	- - do - -	- - do - -	Tailwater	- - do - -	<1.5	>1.0	≤ 1.0
IV............	Full	- - do - -	- - do - -	Any	>1.0	---	>1.0
V............	Partly full	Inlet	Entrance geometry	Any	≥ 1.5	---	≤ 1.0
VI............	Full	Outlet	Entrance and barrel geometry	Any	≥ 1.5	---	≤ 1.0

the six types, and plate 1 illustrates the types of flow. From these the following general classification can be made.

1. If h_4/D is equal to or less than 1.0 and $(h_1 - z)/D$ is less than 1.5, only types I, II, and III flow are possible.

2. If h_4/D is greater than 1.0, only type IV flow is possible.

3. If h_4/D is equal to or less than 1.0 and $(h_1 - z)/D$ is equal to or greater than 1.5, only types V and VI flow are possible.

The type of flow may thus be narrowed to 1 of 3 groups, as shown by figure 1. Outlined on this figure are the steps necessary for identifying the type of flow that occurred. The following sections of this report are organized in the same manner as the illustration so that the procedure may be followed in computing the discharge for any culvert.

One exception to the general classification must be noted. Type I flow can occur with h_4 slightly greater than h_c or with h_4/D greater than 1.0 if the bed slope is very steep. When these conditions occur, negative results will be obtained from the formulas given for the general classification, and methods outlined under Unusual Conditions should be used.

Computation of Types I, II, and III Flow

Flow types I, II, and III are identified by the ratio of the bed slope of the culvert to the critical slope and the ratio of the critical depth to the tail-water depth. As shown by plate 1, type III flow will occur if the elevation of the downstream water surface is higher than the water-surface elevation at critical depth. If the tail-water elevation is lower than the water-surface elevation at critical depth, type I flow will occur if the bed slope of the culvert is greater than the critical slope, or type II flow will occur if the bed slope is less than the critical slope.

To determine which type of flow occurred, (1) assume that type I flow occurred, (2) compute the elevation of the water surface at critical depth and the critical slope, and (3) compare the critical slope with the bed slope and the water-surface elevation at critical depth with the

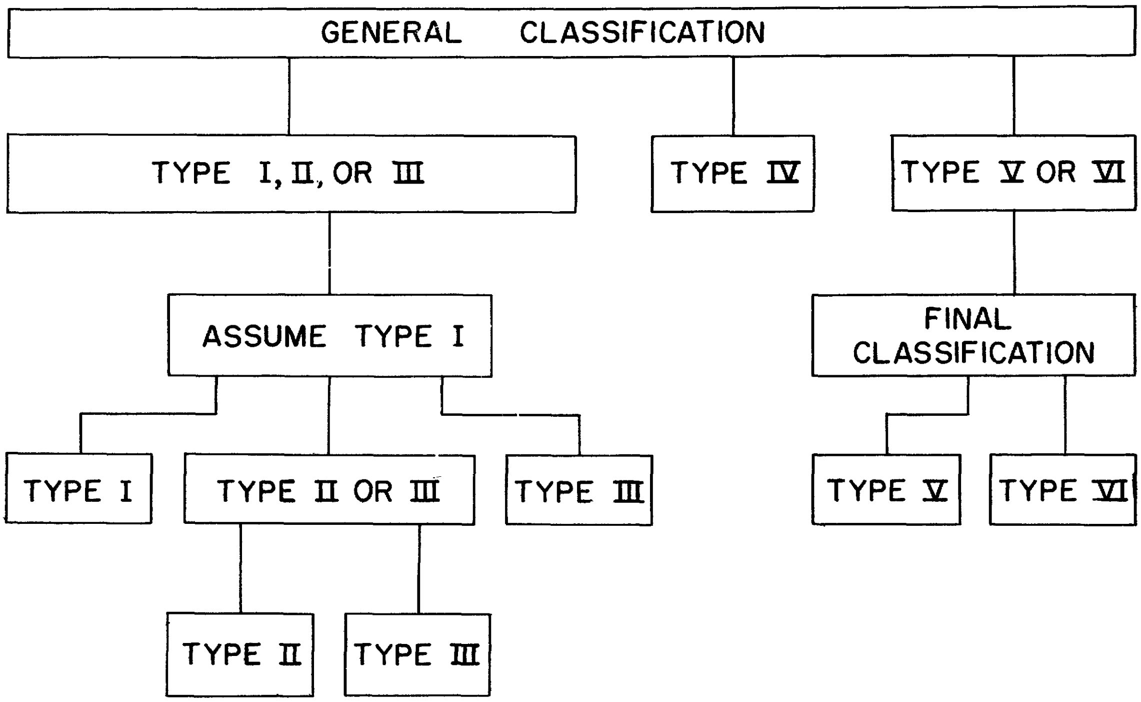


Figure 1.--Procedure for classification and computation of culvert flow.

tail-water elevation. This will result in positive identification of types I or III flow or narrow the possible flow types to types II or III.

Type I Flow

If type I flow is assumed, the critical depth should be at the inlet. Critical depth, d_c, is the depth at the point of minimum specific energy for a given discharge and cross section. The relation between specific energy and depth is illustrated in figure 2. The specific energy, H_o, is the height of the energy grade line above the lowest point in the cross section. Thus,

$$H_o = d + \frac{V^2}{2g}$$

where

H_o = specific energy,

d = maximum depth in the section,

V = mean velocity in the section, and

g = acceleration of gravity.

It can be shown that at the point of minimum specific energy and critical depth, d_c,

$$\frac{Q^2}{g} = \frac{A^3}{T}$$

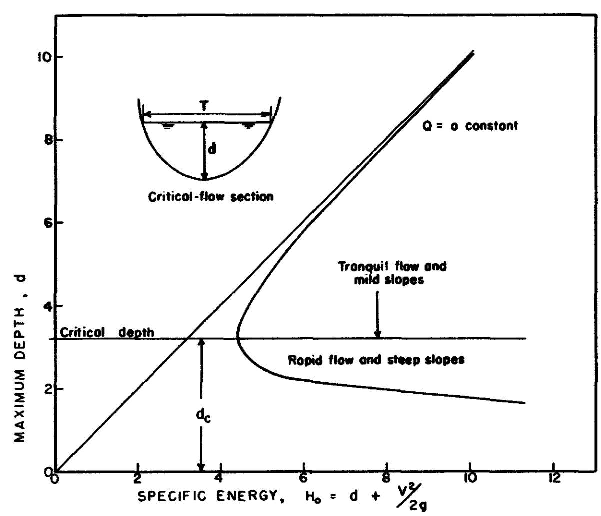


Figure 2.--Relation between specific energy and depth.

and

$$\frac{V^2}{g} = d_m = \frac{A}{T}$$

where

Q = discharge in cfs,

A = area of section below the water surface,

T = width of the section at the water surface,

d_c = maximum depth of water in the critical-flow section, and

d_m = mean depth in section = A/T.

For the condition of minimum specific energy and critical depth, the discharge equation for a section of any shape can be written

$$Q = A_c^{3/2}\sqrt{\frac{g}{T}} \tag{1a}$$

or

$$Q = A_c\sqrt{g\, d_m}. \tag{1b}$$

The discharge equation can be simplified according to the shape of the sections.

Thus, for rectangular sections,

$$Q = 5.67\, b\, d_c^{3/2} \tag{2}$$

and, for circular sections,

$$Q = c_q\, D^{5/2} \tag{3}$$

where

b = width of section,

c_q = function of d_c/D as given in table 2 (column 5), and

d_c = maximum depth of water in the critical-flow section.

If critical depth occurs at the inlet, the discharge may be computed with the applicable critical-depth equations 1, 2, or 3, and the energy equation 4 as written for the distance from an approach section to the inlet,

$$Q = C\, A_c\, \sqrt{2g\left(h_1 - z + \frac{V_1^{\,2}}{2g} - d_c - h_{f_{1.2}}\right)} \tag{4}$$

where

C = the discharge coefficient,

V_1 = the mean velocity in the approach section,

$h_{f_{1.2}}$ = the head loss due to friction between the approach section and the inlet =

$$L_w\,(Q^2/K_1K_c),$$

K = conveyance = $(1.486\, R^{2/3}\, A)/n$, and

L_w = distance from the approach section to the inlet.

Normally a critical depth is assumed which fixes the value of the remaining unknown terms. A good first approximation is $d_c = 0.66(h_1 - z)$. Successive approximations of d_c will quickly converge toward the solution.

In order to check the assumption of type I flow, the critical slope for the culvert is computed as $S_c = (Q/K_c)^2$. Here, S_c is the critical slope and K_c is the conveyance of the section of critical depth at the inlet. If $S_c < S_o$ and $h_4 < h_c$ the assumption of type I flow has been proved and the correct discharge has been computed. If $h_4 > h_c$, type III flow has been identified and the discharge may be computed as outlined on page 10. If $h_4 < h_c$ and $S_c > S_o$, type II flow is assumed and the analysis is continued as outlined on page 7.

For circular and rectangular sections, the identification of flow type is simplified by figures 3, 4, and 5. The procedure is outlined below.

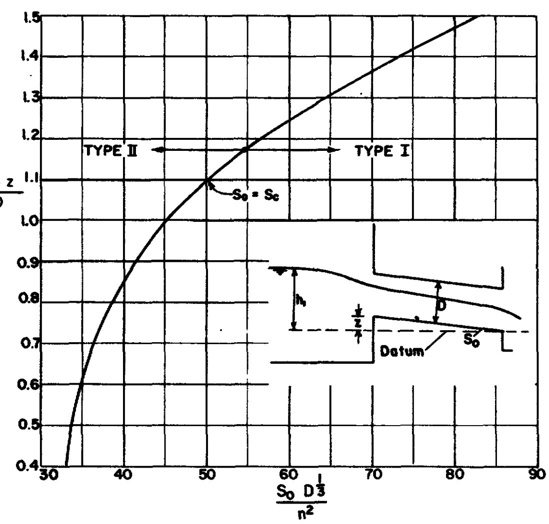


Figure 3.--Critical slope as a function of head for culverts of circular section, with free outfall.

<u>Circular sections</u>

1. Compute $(h_1 - z)/D$ and $(S_o\, D^{1/3})/n^2$

   and plot the point on figure 3.

A point to the right of the curve indicates type I flow and a point to the left type II flow.

2. Determine d_c from figure 4.

3. Compare $(d_c + z)$ with h_4 .

TABLE 2.--Coefficients of area (A_c), hydraulic radius (R_c), conveyance (K_c), and discharge (q_c) for critical-depth flow in pipes of circular section and with part-full flow

[d_c = maximum depth of water, in feet; D = diameter of pipe, in feet]

$\frac{d_c}{D}$	C_a	C_r	C_k	C_q
	$A_c = C_a D^2$	$R_c = C_r D$	$K_c = C_k \frac{D^{8/3}}{n}$	$Q_c = C_q D^{5/2}$
0.01	0.0013	0.0066	0.000068	0.0006
.02	.0037	.0132	.000307	.0025
.03	.0069	.0197	.000747	.0055
.04	.0105	.0262	.001376	.0098
.05	.0147	.0325	.002228	.0153
.06	.0192	.0389	.00328	.0220
.07	.0242	.0451	.00457	.0298
.08	.0294	.0513	.00601	.0389
.09	.0350	.0575	.00775	.0491
.10	.0409	.0635	.00966	.0605
.11	.0470	.0695	.0118	.0731
.12	.0534	.0755	.0142	.0868
.13	.0600	.0813	.0168	.1016
.14	.0668	.0871	.0195	.1176
.15	.0739	.0929	.0225	.1347
.16	.0811	.0985	.0257	.1530
.17	.0885	.1042	.0291	.1724
.18	.0961	.1097	.0327	.1928
.19	.1039	.1152	.0366	.2144
.20	.1118	.1206	.0405	.2371
.21	.1199	.1259	.0446	.2609
.22	.1281	.1312	.0491	.2857
.23	.1365	.1364	.0537	.3116
.24	.1449	.1416	.0586	.3386
.25	.1535	.1466	.0634	.3666
.26	.1623	.1516	.0685	.3957
.27	.1711	.1566	.0740	.4259
.28	.1800	.1614	.0792	.4571
.29	.1890	.1662	.0848	.4893
.30	.1982	.1709	.0907	.523
.31	.2074	.1756	.0968	.557
.32	.2167	.1802	.1027	.592
.33	.2260	.1847	.1088	.628
.34	.2355	.1891	.1155	.666
.35	.2450	.1935	.1220	.704
.36	.2546	.1978	.1283	.743
.37	.2642	.2020	.1350	.784
.38	.2739	.2062	.1421	.825
.39	.2836	.2102	.1488	.867
.40	.2934	.2142	.1561	.910
.41	.3032	.2182	.1631	.955
.42	.3130	.2220	.1702	1.000
.43	.3229	.2258	.1780	1.046
.44	.3328	.2295	.1854	1.093
.45	.3428	.2331	.1931	1.141
.46	.3527	.2366	.2002	1.190
.47	.3627	.2401	.2080	1.240
.48	.3727	.2435	.2160	1.291
.49	.3827	.2468	.2235	1.343
.50	.3927	.2500	.2317	1.396

TABLE 2.--Coefficients of area (A_c) hydraulic radius (R_c) conveyance (K_c) and discharge for (q_c) critical-depth flow in pipes of circular section and with part-full flow--Continued

[d_c = maximum depth of water, in feet; D = diameter of pipe, in feet]

$\frac{d_c}{D}$	C_a	C_r	C_k	C_q
	$A_c = C_a D^2$	$R_c = C_r D$	$K_c = C_k \frac{D^{8/3}}{n}$	$Q_c = C_q D^{5/2}$
0.51	0.4027	0.2531	0.2394	1.449
.52	.4127	.2562	.2472	1.504
.53	.4227	.2592	.2556	1.560
.54	.4327	.2621	.2630	1.616
.55	.4426	.2649	.2710	1.674
.56	.4526	.2676	.2791	1.733
.57	.4625	.2703	.2873	1.792
.58	.4724	.2728	.2955	1.853
.59	.4822	.2753	.3031	1.915
.60	.4920	.2776	.3115	1.977
.61	.5018	.2799	.3192	2.041
.62	.5115	.2821	.3268	2.106
.63	.5212	.2842	.3346	2.172
.64	.5308	.2862	.3423	2.239
.65	.5404	.2882	.3501	2.307
.66	.5499	.2900	.3579	2.376
.67	.5594	.2917	.3658	2.446
.68	.5687	.2933	.3727	2.518
.69	.5780	.2948	.3805	2.591
.70	.5872	.2962	.3874	2.666
.71	.5964	.2975	.3953	2.741
.72	.6054	.2987	.4021	2.819
.73	.6143	.2998	.4090	2.898
.74	.6231	.3008	.4157	2.978
.75	.6319	.3017	.4226	3.061
.76	.6405	.3024	.4283	3.145
.77	.6489	.3031	.4349	3.231
.78	.6573	.3036	.4415	3.320
.79	.6655	.3039	.4470	3.411
.80	.6736	.3042	.4524	3.505
.81	.6815	.3043	.4578	3.602
.82	.6893	.3043	.4630	3.702
.83	.6969	.3041	.4681	3.806
.84	.7043	.3038	.4731	3.914
.85	.7115	.3033	.4768	4.028
.86	.7186	.3026	.4816	4.147
.87	.7254	.3018	.4851	4.272
.88	.7320	.3007	.4884	4.406
.89	.7384	.2995	.4916	4.549
.90	.7445	.2980	.4935	4.70
.91	.7504	.2963	.4951	4.87
.92	.7560	.2944	.4966	5.06
.93	.7612	.2921	.4977	5.27
.94	.7662	.2895	.4979	5.52
.95	.7707	.2865	.4970	5.81
.96	.7749	.2829	.4963	6.18
.97	.7785	.2787	.4940	6.67
.98	.7817	.2735	.4902	7.41
.99	.7841	.2666	.4824	8.83
1.00	.7854	.2500	.4633	--

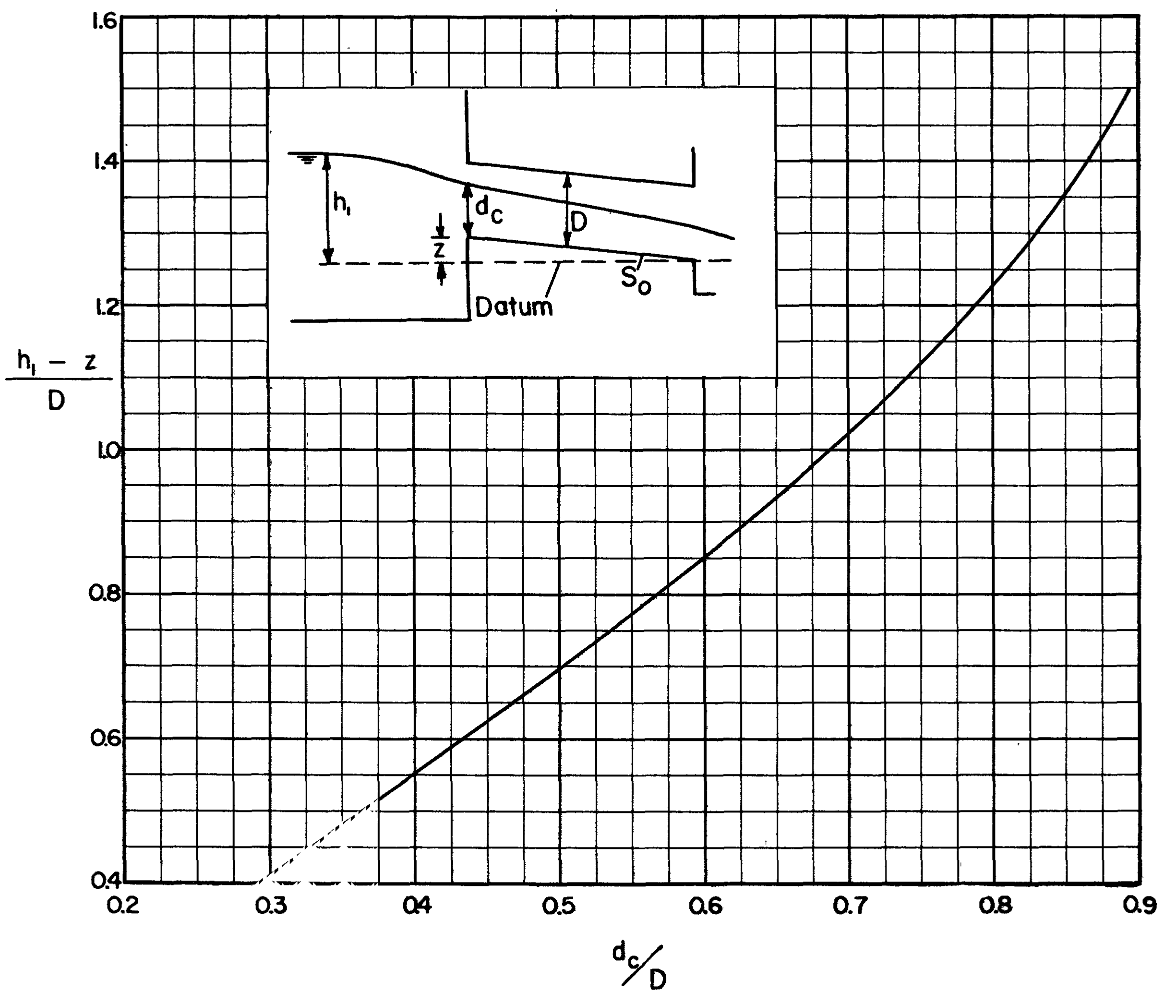


Figure 4. --Relation between head and critical depth in culverts of circular section.

4. Type I flow can occur only if the criterion of step 1 is met and $h_4 < (d_c + z)$. If type I flow is identified, compute the discharge with equations 1 or 3 and 4 as outlined on page 4.

Rectangular sections

1. Compute the parameters of figure 5 for the culvert, assuming that $d_c = 0.66\ (h_1 - z)$, and plot the point. A point to the right of the line indicates type I flow, and a point to the left indicates type II flow.

2. Compare $(d_c + z)$ with h_4.

3. Type I flow can occur only if the criterion of step 1 is met and $h_4 < (d_c + z)$. If type I flow is identified, compute the discharge with equations 1 or 2 and 4 as outlined above.

Type II Flow

If type II flow is assumed, the critical depth should occur at the outlet. The flow equations

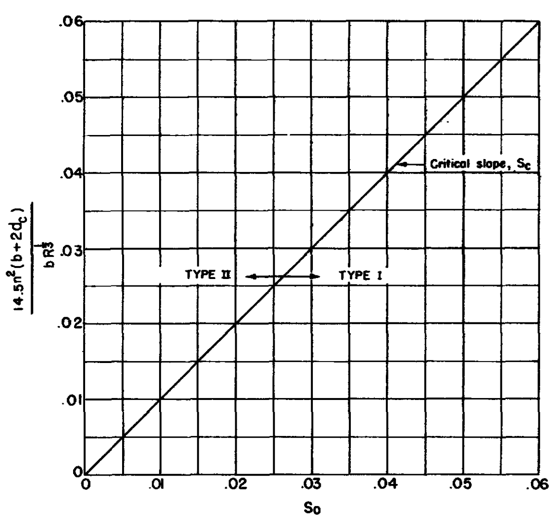


Figure 5. --Critical slope for culverts of rectangular section, with free outfall.

TABLE 3.--Properties of circular pipes

Diameter (inches)	Diameter, D (feet)	Area, A_o (square feet)	D^2	$D^{5/2}$	$D^{8/3}$
6	0.500	0.196	0.250	0.177	0.157
8	.667	.349	.444	.363	.339
10	.833	.545	.694	.634	.614
12	1.00	.785	1.00	1.00	1.00
15	1.25	1.23	1.56	1.75	1.81
18	1.50	1.77	2.25	2.76	2.95
21	1.75	2.41	3.06	4.05	4.44
24	2.00	3.14	4.00	5.66	6.34
30	2.50	4.91	6.25	9.88	11.5
36	3.00	7.07	9.00	15.6	18.7
42	3.50	9.62	12.2	22.9	28.1
48	4.00	12.6	16.0	32.0	40.3
54	4.50	15.9	20.2	43.0	55.1
60	5.00	19.6	25.0	55.9	73.0
66	5.50	23.8	30.2	71.0	94.1
72	6.00	28.3	36.0	88.2	119
78	6.50	33.2	42.2	108	147
84	7.00	38.5	49.0	130	179
96	8.00	50.3	64.0	181	256
108	9.00	63.6	81.0	243	351
120	10	78.5	100	316	464
132	11	95.0	121	401	599
144	12	113	144	499	755
156	13	133	169	609	935
168	14	154	196	733	1140
180	15	177	225	871	1370

used for the computation of type I flow are also applicable here, with the further provision that the barrel-friction loss must be accounted for in the energy equation since the control section has shifted to the outlet.

Thus,

$$Q = C A_c \sqrt{2g\left(h_1 + \frac{V_1^2}{2g} - d_c - h_{f_{1.2}} - h_{f_{2.3}}\right)} \qquad (5)$$

The discharge and the critical depth must be computed by solution of equation 5 and the applicable critical-depth equations 1 and 2 or 3. The solution is tedious, because in order to compute the barrel-friction loss, $h_{f_{2.3}}$, the height of the water surface at the inlet must be established. Therefore, the procedure for computation of discharge outlined below is recommended.

1. Assume the critical depth at the outlet; a good first assumption is $d_c = 0.66\ h_1$.

2. Compute the corresponding discharge with the applicable critical-depth equations 1 and 2 or 3.

3. Compute the depth of water, d_2, at the inlet with the energy equation.

$$d_2 + \frac{V_2^2}{2g\ C^2} = h_1 - z \qquad (6)$$

for the distance from the approach section to the inlet, neglecting the approach velocity head and the friction loss between the approach section and the inlet. Here the depth, d_2, is measured from the lowest point in the section. The equation may be solved by successive approximation. Graphical solutions of equation 6 for circular and rectangular sections are presented in figures 6 and 7, respectively. The depth at the inlet may be computed directly from these graphs.

4. Compute the conveyance of the section at the approach, the inlet, and the outlet.

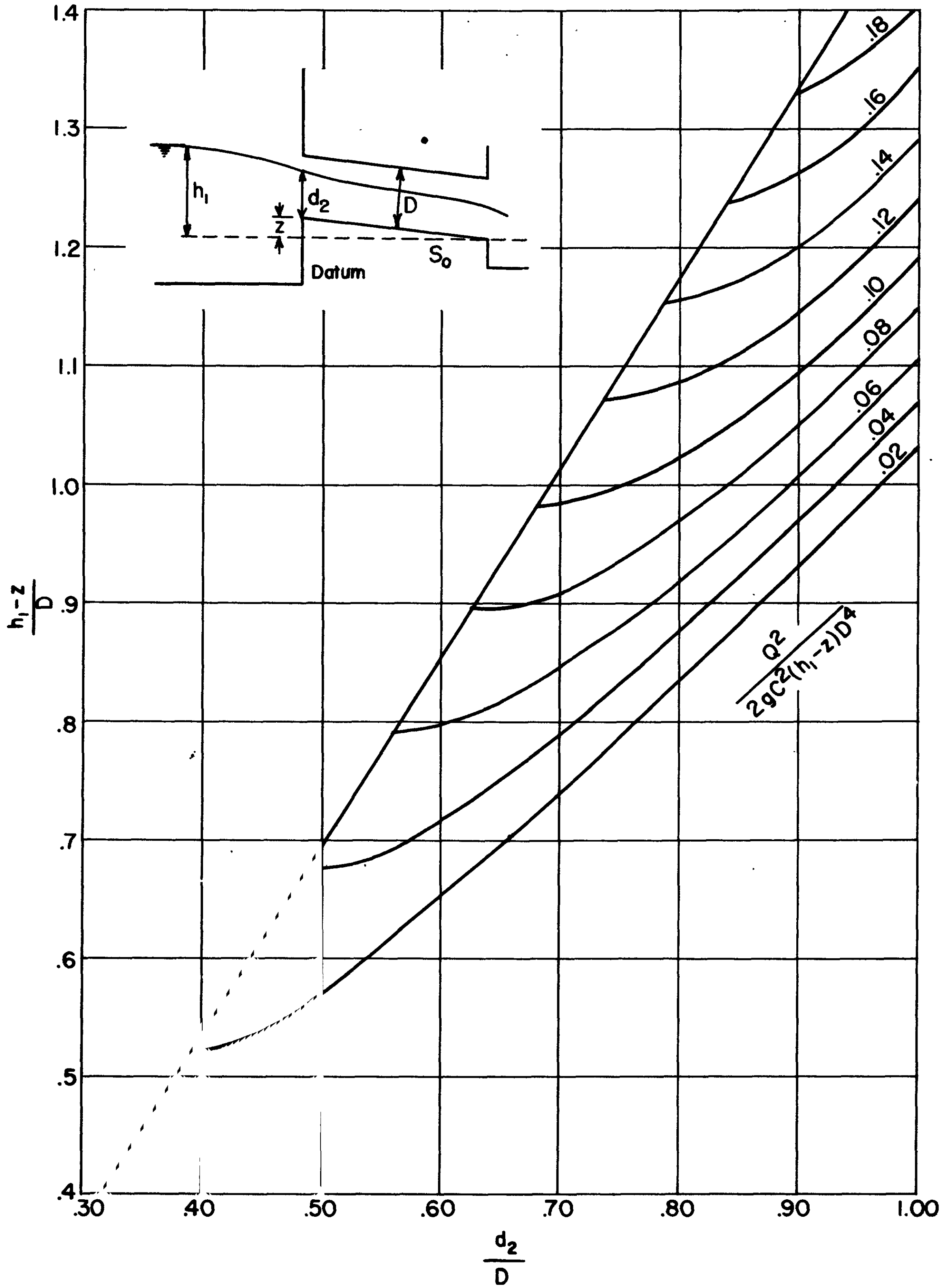


Figure 6.--Relation between height of head-water surface and height of water surface at culvert inlet for culverts of circular section.

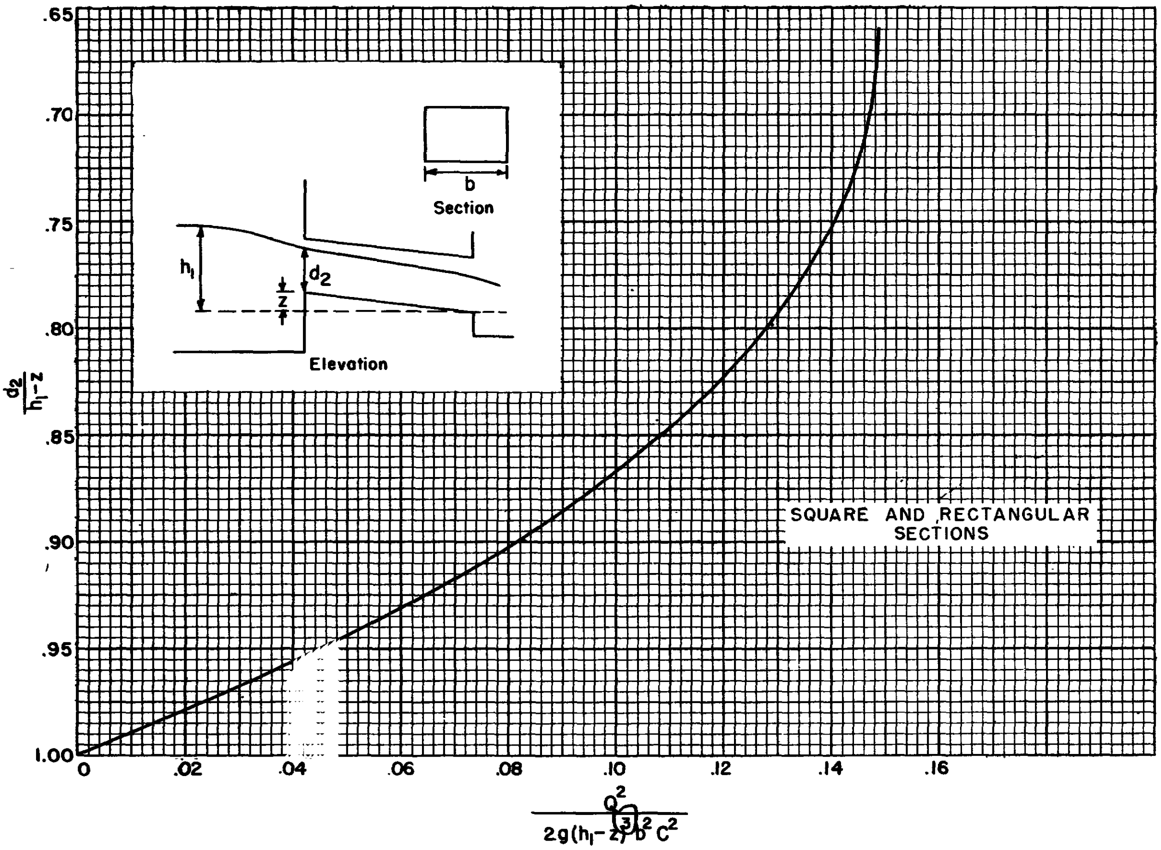


Figure 7.--Relation between height of head-water surface and height of water surface at culvert inlet for culverts of rectangular section.

5. Compute the friction loss between the approach and the inlet,

$$h_{f_{1.2}} = L_w \ (Q^2 / K_1 K_2),$$

and between the inlet and the outlet,

$$h_{f_{2.3}} = L \ (Q^2 / K_2 K_3).$$

6. Compute the velocity head, $V_1{}^2/2g$.

7. Compute the discharge with equation 5.

8. If the discharge computed with equation 5 is not equal to the discharge computed in step 2, the assumed value of d_c is incorrect. The correct value of d_c must be determined by successive approximation, repeating the procedure outlined above.

After the discharge and the elevation of the water surface at critical depth are established, the assumption of type II flow is checked by comparing the elevation of critical depth with the tail-water elevation. If $h_c > h_4$, type II flow occurred. If $h_c < h_4$, type III flow occurred and the discharge may be computed as outlined in the next section.

Type III Flow

In type III flow, critical depth does not occur in the culvert, and the upstream elevation of the water surface for a given discharge is a function of the surface elevation of the tail water. Water-surface elevations h_1 and h_4 can normally be established from high-water marks, and it is assumed that $h_3 = h_4$. The discharge can be computed from the energy equation

$$Q = C A_3 \sqrt{2g(h_1 + \frac{V_1{}^2}{2g} - h_3 - h_{f_{1.2}} - h_{f_{2.3}})}. \quad (7)$$

The following procedure is recommended in computing discharge:

1. Assume a discharge.

2. Determine the depth at the inlet, d_2, by trial solution of equation 6, or directly from figures 6 or 7 if the culvert is circular or rectangular in section.

3. Compute the conveyance of the sections at the approach, the inlet, and the outlet.

4. Compute the friction loss between the approach section and the inlet,

$$h_{f_{1.2}} = L_w\left(\frac{Q^2}{K_1 K_2}\right),$$

and between the inlet and the outlet,

$$h_{f_{2.3}} = L\left(\frac{Q^2}{K_2 K_3}\right),$$

5. Compute the velocity head, $V_1^2/2g$.

6. Compute the discharge with equation 7.

7. If the discharge computed with equation 7 is not equal to the assumed discharge, then another discharge should be assumed and the procedure outlined above repeated.

Computation of Type IV Flow

In type IV flow, both the entrance and the outlet are submerged. The discharge may be computed directly from the energy equation for the distance between section 1 and section 4. In deriving the discharge formula shown below, the velocity head at section 1 and the friction loss between sections 1 and 2 have been neglected, and the energy loss between sections 3 and 4 is assumed to be $V^2_3/2g$. The velocity head at section 4 is also assumed to be zero. Thus,

$$h_1 = h_4 + h_e + h_{f_{2.3}} + \frac{V^2_3}{2g}$$

or

$$Q = CA_o\sqrt{\frac{2g(h_1 - h_4)}{1 + \frac{29C^2n^2L}{R_o^{4/3}}}} \quad (8)$$

Classification of Types V and VI Flow

Type V or VI flow will occur if the tail water is below the crown at the outlet, and $(h_1 - z)/D$ is equal to or greater than 1.5.

As shown in plate 1, part-full flow under a high head is classified as type V. The flow pattern is similar to that downstream from a sluice gate with supercritical flow near the entrance. The occurrence of type V flow requires a relatively square entrance that will cause contraction of the area of live flow to less than the area of the culvert barrel. In addition, the combination of barrel length, roughness, and bed slope must be such that the contracted jet will not expand to the full area of the barrel. If the water surface of the expanding flow comes in contact with the top of the culvert, type VI flow will occur because the passage of air to the culvert will be sealed off, causing the culvert to flow full throughout its length; under these conditions, the head-water surface drops, indicating a more efficient use of the culvert barrel.

Within a certain range either type V or type VI flow may occur, depending upon factors that are very difficult to evaluate. For example, the wave pattern superimposed on the water-surface profile through the culvert can be important in determining full or part-full flow. For these and other reasons the criteria for identifying type V or type VI flow must be considered approximate.

Concrete Culverts

Figure 8 may be used to classify type V or VI flow in concrete culvert barrels by the procedure outlined below.

1. Compute the parameters L/D, r/D, or w/D, and S_o.

2. Select the curve of figure 8 corresponding to r/D or w/D for the culvert. Sketch in an interpolated curve for the given r/D or w/D, if necessary.

3. Plot the point defined by S_o and L/D for the culvert.

4. If the point plots to the right of the curve selected in step 2, the flow was type VI; if the point plots to the left of the curve, the flow was type V.

The use of figure 8 is restricted to square, rounded, or beveled flush entrances from a vertical headwall, either with or without wingwalls. Wingwalls do not affect the flow classification, as the rounding effect they provide is offset by a tendency to produce vortices that supply air to the culvert entrance. For culverts with wingwalls use the geometry of only the top side of the entrance in computing the effective radius of rounding, r, or the effective bevel, w, in using figure 8.

Corrugated-Pipe Culverts

Figure 9 may be used to classify type V or VI flow in rough pipes mounted flush with a vertical headwall, either with or without wingwalls, as outlined below.

1. Determine the ratio r/D for the pipe.

2. From figure 9 select the graph corresponding to the value of r/D for the culvert.

3. Compute the ratio $29n^2\,(h_1 - z)/R_o^{4/3}$

and select the corresponding curve on the graph selected in step 2. Sketch in an interpolated curve for the computed ratio, if necessary.

4. Plot the point defined by S_o and L/D for the culvert.

5. If the point plots to the right of the curve selected in step 3, the flow was type VI; if the point plots to the left of the curve, the flow was type V.

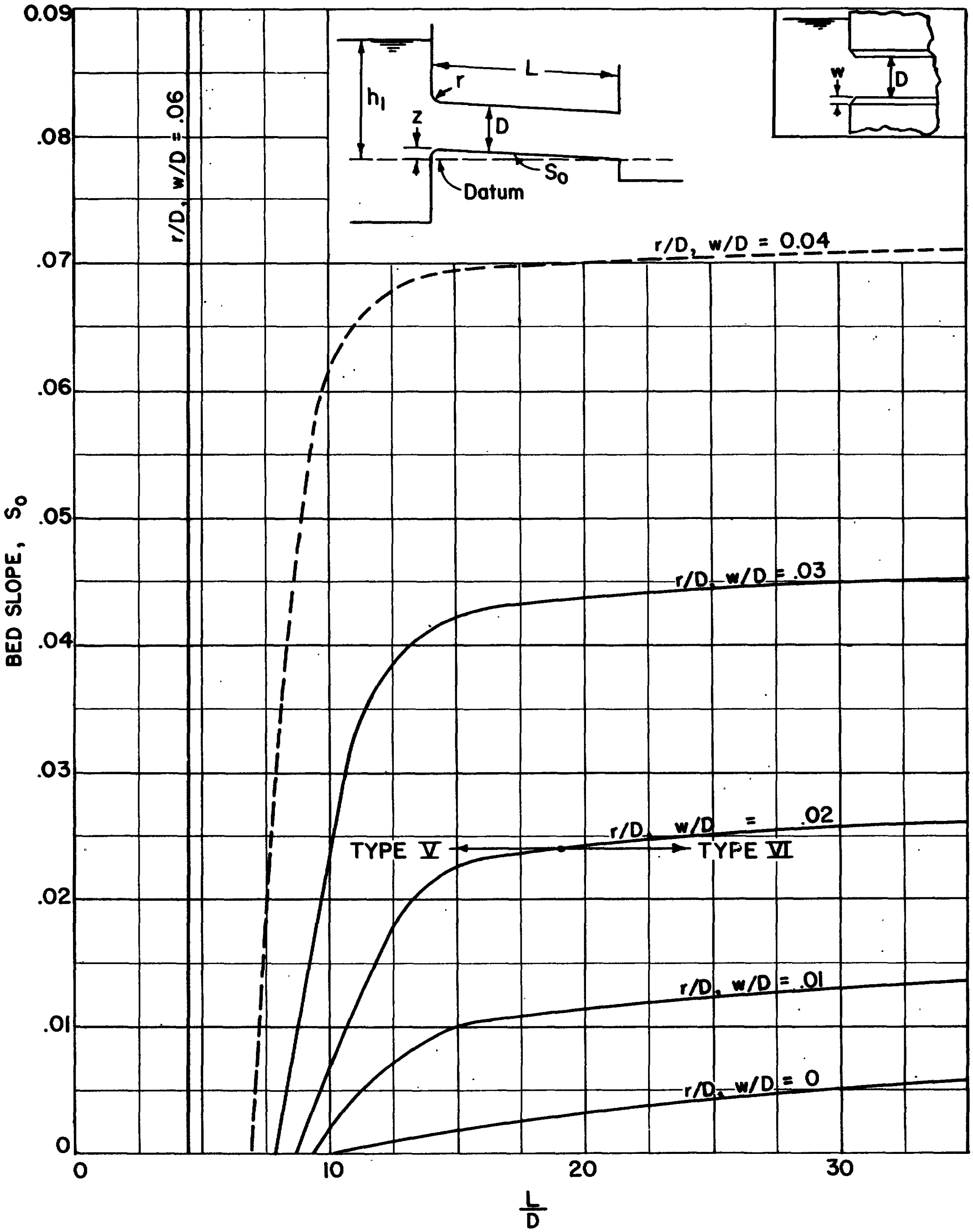


Figure 8.--Criteria for types V and VI flow in box or pipe culverts with concrete barrels and square, rounded, or beveled flush entrances from a vertical headwall, either with or without wingwalls.

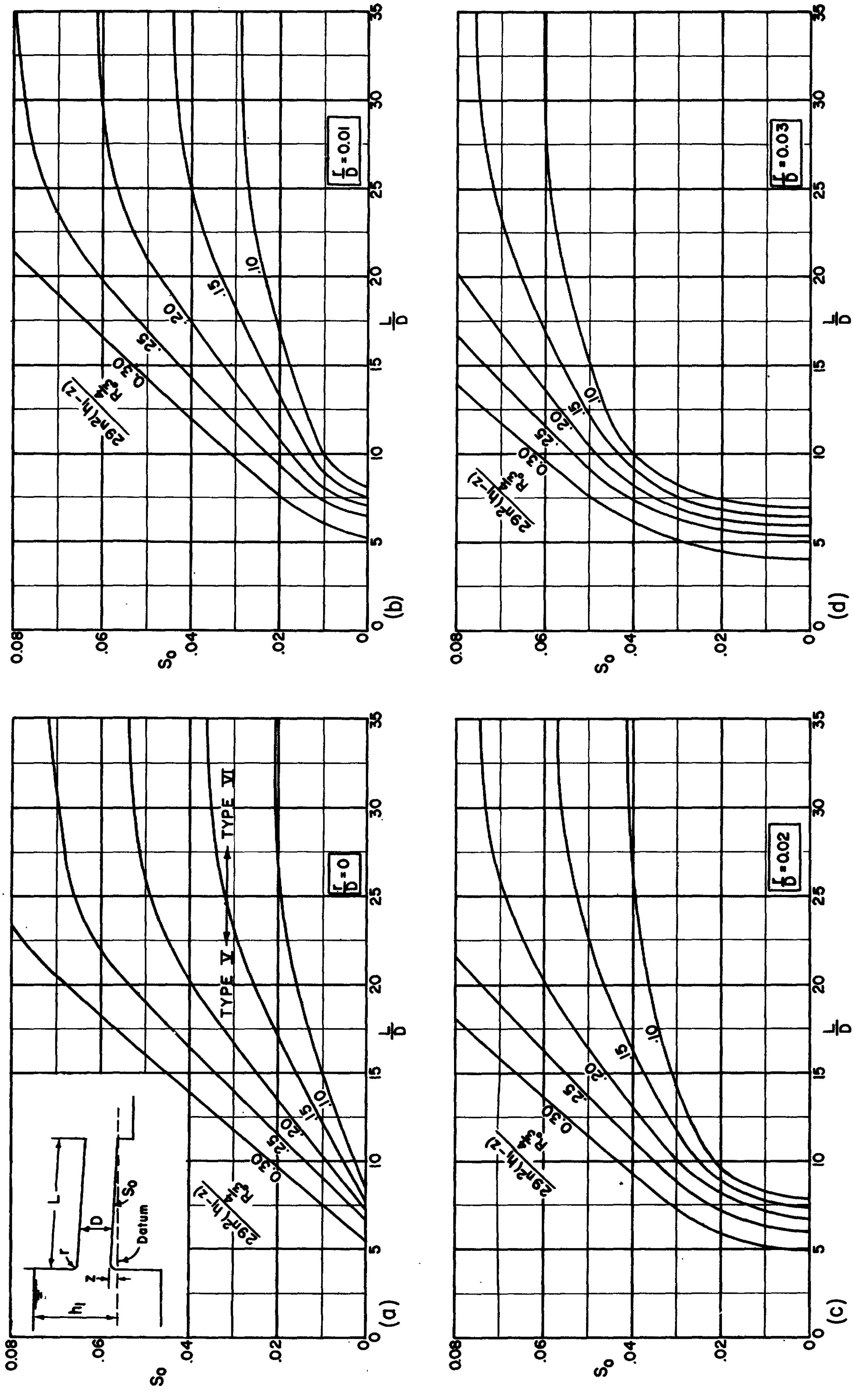


Figure 9.--Criteria for types V and VI flow in pipe culverts with rough barrels.

For a pipe projecting from a headwall or embankment, figure 9a should be used in classifying the flow.

Computation of Type V Flow

In type V flow the culvert entrance is submerged, and the tail water is below the crown at the outlet. The flow is supercritical near the entrance to the culvert. The discharge may be computed directly from the equation

$$Q = CA_o \sqrt{2g(h_1 - z)} \ . \qquad (9)$$

Computation of Type VI Flow

In type VI flow both the inlet and the outlet are submerged. The discharge equation for the distance between sections 1 and 3, neglecting $V_1^2/2g$ and $h_{f_{1.2}}$, is

$$Q = CA_o \sqrt{2g(h_1 - h_3 - hf_{2.3})} \ . \qquad (10)$$

A straightforward application of discharge-equation 10 is hampered by the necessity of determining h_3, which varies from a point below the center of the outlet to its top, even though the water surface is at the top of the culvert. This variation in piezometric head is a function of the Froude number. This difficulty has been circumvented by basing the data analysis upon dimensionless ratios,

$$\frac{Q}{\sqrt{g}\, A_o \sqrt{D}} = \theta\left(\frac{h_1}{D},\ C^2,\ \frac{fL}{4R_o},\ \text{or}\ \frac{29n^2L}{R_o^{4/3}}\right)$$

where h_1/D is proportional to the Froude number.

The functional relation expressed above has been defined by laboratory experiment and is presented in figure 10. The term $\sqrt{g}$ has been deleted from the discharge ratio for convenience. The following procedure may be used to compute discharge.

1. Compute the ratio h_1/D. Select the discharge coefficient, C, applicable to the culvert geometry.

2. From figure 10 determine the value of $Q/A_o \sqrt{D}$ corresponding to $29n^2L/R_o^{4/3} = 1$.

3. Compute the ratio $29n^2L/R_o^{4/3}$ for the culvert under study.

4. From figure 10, using the computed ratio $29n^2L/R_o^{4/3}$ and the coefficient C, find the correction factor k_f.

5. Multiply the value of $Q/A_o \sqrt{D}$ from step 2 by the value of k_f from step 4, thus determining an adjusted ratio $Q/A_o \sqrt{D}$. Determine the value of Q from the adjusted ratio.

UNUSUAL CONDITIONS

One exception to the general flow classification, already noted, is that type I flow can occur with h_4 slightly greater than h_c or with h_4 greater than D. This condition will be recognized when negative results are obtained from the formulas given for the general flow classification. The discharge for this flow condition may be solved by trial computation of the backwater curve that extends from the known tail-water surface to the head-water surface. A unique solution is obtained when the computed head-water surface is the same as that observed from high-water marks, or,

$$h_1 + \frac{V_1^2}{2g} = h_3 + \frac{V_3^2}{2g} + h_{f_{2.3}} + h_e + h_{f_{1.2}}$$

There will be, of course, occasional culvert-flow problems of unusual complexity, examples of which have not been covered in detail here. In most of these, results may be computed by going back to the fundamentals of the subject or to literature covering the special conditions. Undoubtedly there will be occasional problems incapable of reliable solution.

Examples of unusual conditions that might be experienced are culverts of nonuniform barrel geometry, culverts with changes in bottom slope within the barrel, submerged culverts (type IV flow) with flared outlets, culverts with drop inlets, rapid flow (mean depth less than critical depth) in the approach section, and culverts on an adverse slope.

COEFFICIENTS OF DISCHARGE

Coefficients of discharge, C, for flow types I to VI have been defined by laboratory study. The coefficients vary from 0.40 to 0.98 and have been found to be a function of the degree of channel contraction and the geometry of the culvert entrance. In dimensionless notation,

$$C = f(m,\ r/D,\ w/b,\ \theta,\ etc.)$$

where m is a measure of the degree of channel contraction, and the other terms within the parentheses describe the entrance geometry.

For culverts, the percentage of channel contraction, m, is defined as $(1 - A/A_1)\ 100$ where A is the area of flow at the terminal section and A_1 is the area of the approach section. Because the value of m is usually large for flood flows, the laboratory tests placed emphasis on this condition. However, tests on flow through bridge openings as reported by Kindsvater, Carter, and Tracy (1953) demonstrate that the discharge coefficient varies almost linearly between values of m of 0 and 80, and that the coefficient reaches a minimum value at $m = 80$. All coefficients given here are for an m of 80. If the contraction ratio is smaller than 80, the value of C may be computed by interpolating between the value of C listed for an m of 80 and a value of C of 0.98 for an m of 0. The following formula may be used in lieu of interpolation: C(adjusted) = 0.98 - (0.98 - C) $m/80$.

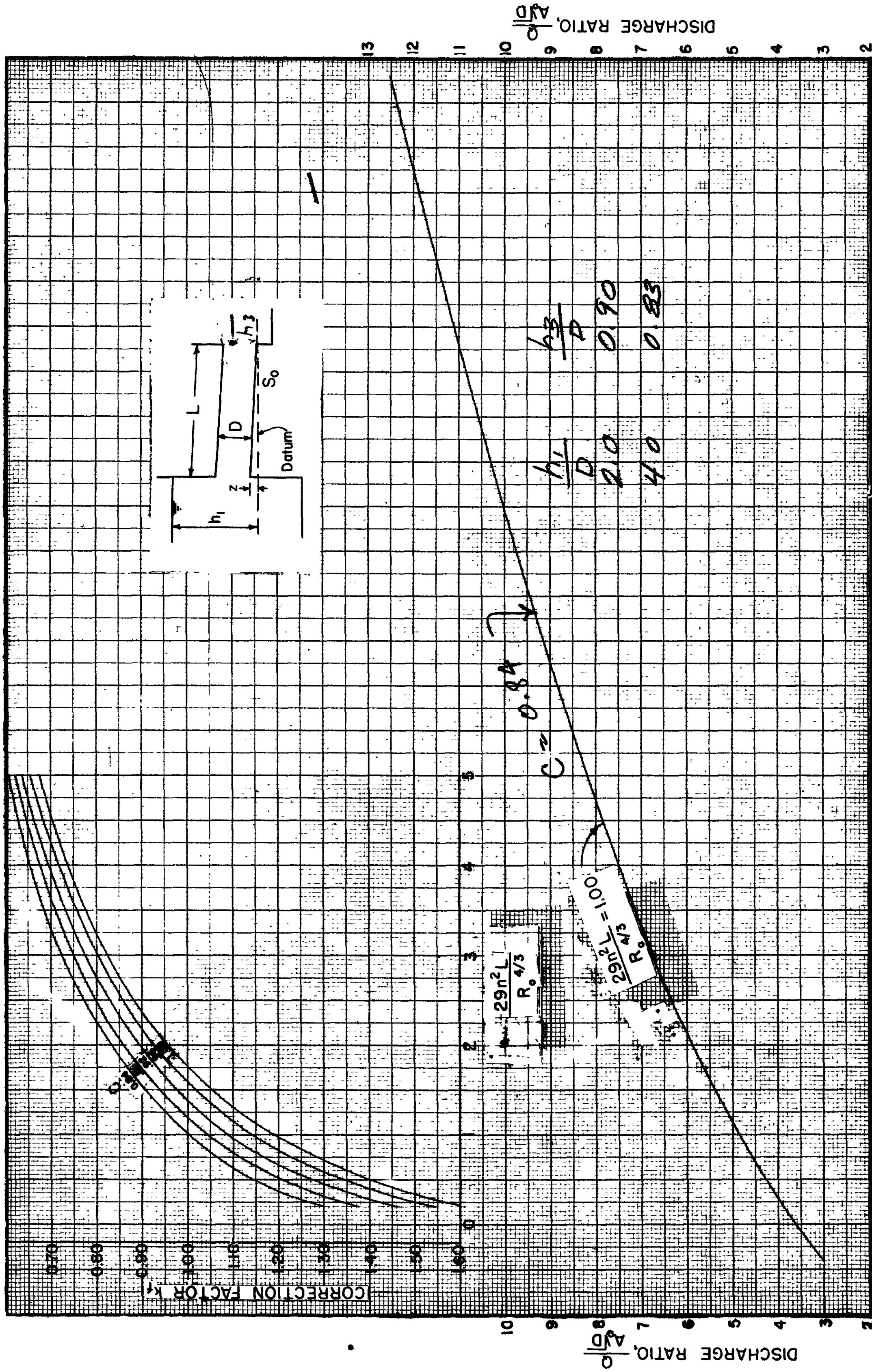


Figure 10.--Relation between head and discharge for type VI flow.

For certain entrance geometries the discharge coefficient is obtained by multiplying a base coefficient by an adjustment factor such as k_r or k_w. If this procedure results in a discharge coefficient greater than 0.98, a coefficient of 0.98 should be used in computing the discharge through the culvert.

The coefficients are applicable to both single- and multiple-culvert installations. If the distance between barrels is less than 0.1 the width of a single barrel, its effect should not be considered in determining the effect of the entrance geometry.

Laboratory tests also indicate that the discharge coefficient does not vary with the proximity of the culvert floor to the ground level at the entrance. Thus in types I, II, and III flow, the geometry of the sides determines the value of C; similarly, in types IV, V, and VI flow the value of C varies with the geometry of the top and sides. If the degree of rounding or beveling is not the same on both sides, or on the sides and the top, the effect of r or w must be obtained by averaging the coefficients determined for each of the sides. One exception is noted: if the vertical sides of the culvert are rounded or beveled and the top entrance is square, multiply the average coefficient determined by the procedure just described by 0.90 for type V flow, and by 0.95 for types IV and VI flow, using the coefficient for the square entrance as the lower limiting value.

In listing the discharge coefficients, it is convenient to divide the 6 flow types into 3 groups, each group having a discharge equation of the same general form. Thus, flow types I, II, and III form one group, types IV and VI another, and type V a third. The coefficient C is descriptive of the live-stream contraction at the inlet and its subsequent expansion in the barrel of the culvert. Hence, coefficients for types I, II, and III flow should be identical for identical geometries, as should coefficients for types IV and VI.

In a systematic presentation of the coefficients, the entrance geometries have been classified in four general categories, with necessary subdivision. The 4 classes are common to all 3 flow-type groups.

In general, coefficients for flow types I, II, III and V are based on tests conducted by the Survey at Georgia Institute of Technology, and coefficients for flow types IV and VI are based primarily on tests by Yarnell and Straub.

Types I, II, and III Flow

Flush Setting in Vertical Headwall

Pipe culverts

The discharge coefficient for square-ended pipes set flush in a vertical headwall is a function of the ratio of the head-water height to the pipe diameter, $(h_1 - z)/D$. The coefficient for flow types I II, and III can be determined from figure 11.

If the entrance to the pipe is rounded or beveled, the discharge coefficient is computed by

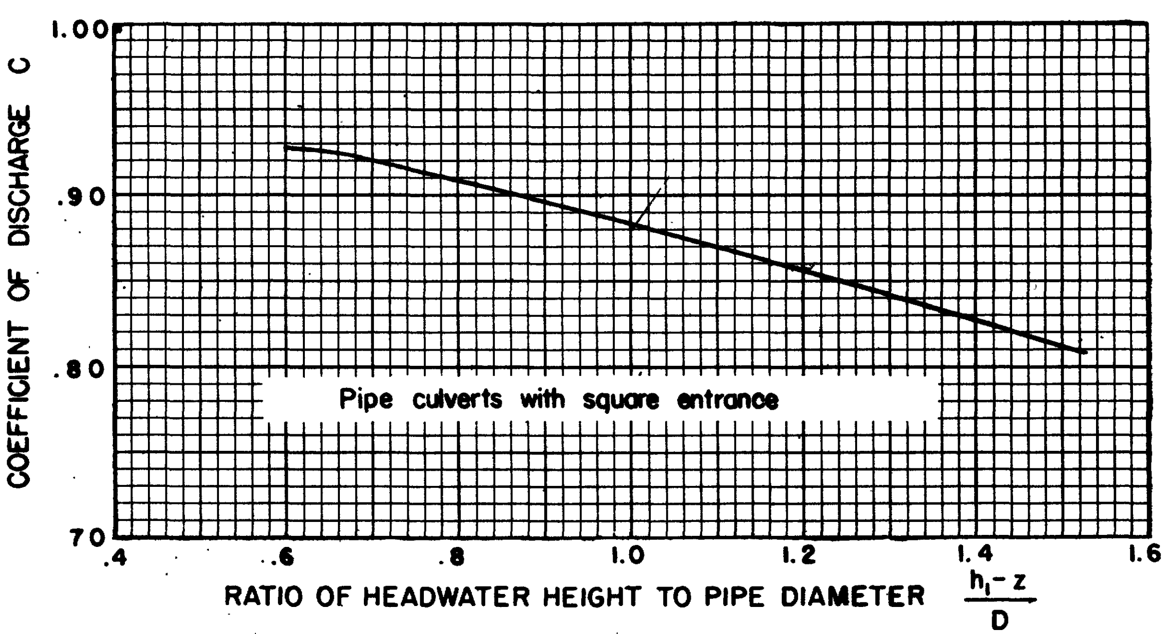


Figure 11.--Base coefficient of discharge for types I, II, and III flow in pipe culverts with square entrance mounted flush with vertical headwall.

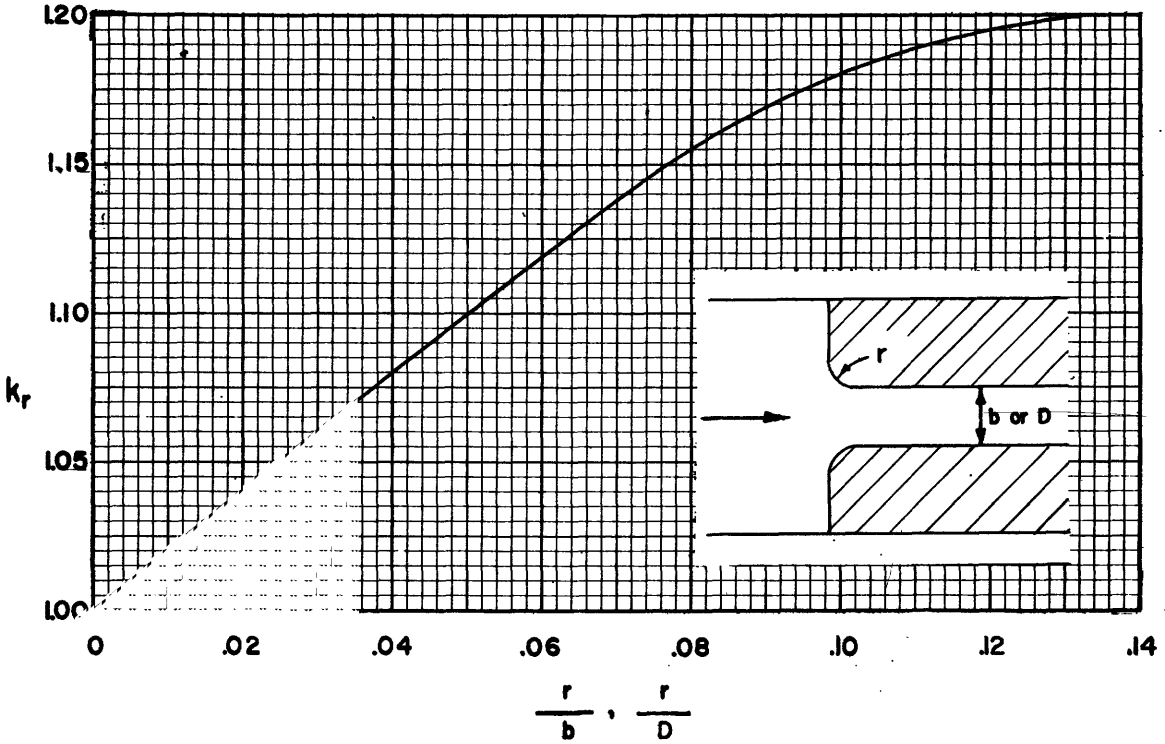


Figure 12.--Variation of the discharge coefficient with entrance rounding, types I, II, and III flow in box or pipe culverts set flush with vertical headwall.

multiplying the coefficient for the square-ended pipe by an adjustment factor, k_r or k_w. These adjustment factors are a function of the degree of entrance rounding or beveling, and these relations as applicable to flow types I, II, and III are defined in figures 12 and 13.

The radius of rounding of corrugated metal pipes and pipe arches is about three-eighths inch. The bevel, w, on all types of concrete pipe, including the bellmouthed pipe, is measured as $(D_m - D)/2$ where D_m is the maximum inside diameter at the entrance (see figure 13) and D is the diameter of the barrel.

Box culverts

The discharge coefficient for box culverts set flush in a vertical headwall is a function of the Froude number. The Froude number for flow types I and II is always 1.0 and the corresponding discharge coefficient is 0.95. The discharge coefficient for type III flow can be determined from figure 14 after computing the Froude number, $V/\sqrt{gd}$, at the downstream end of the culvert.

If the entrance to the box is rounded or beveled, the discharge coefficient is computed by multiplying the coefficient for the square-ended box by an adjustment factor, k_r or k_w. These adjustment factors as applicable to flow types I, II, and III can be determined from figure 12 or 13, respectively.

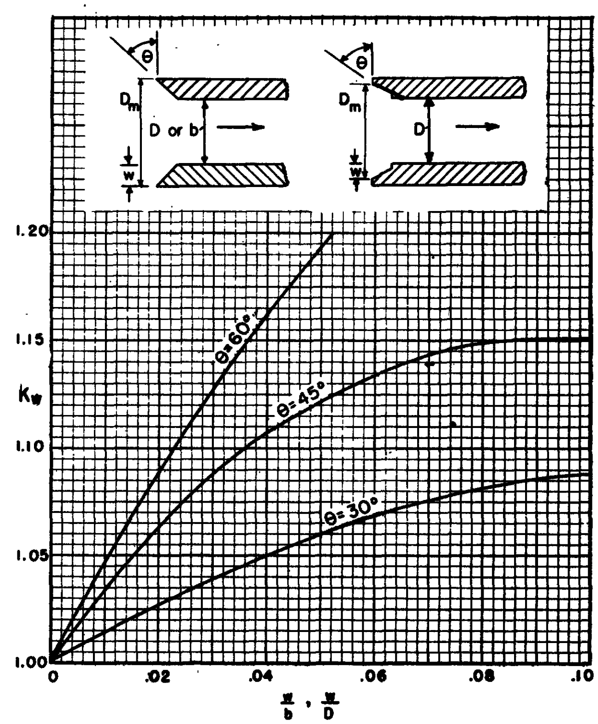


Figure 13.--Variation of the discharge coefficient with entrance beveling, types I, II, and III flow in box or pipe culverts set flush with vertical headwall.

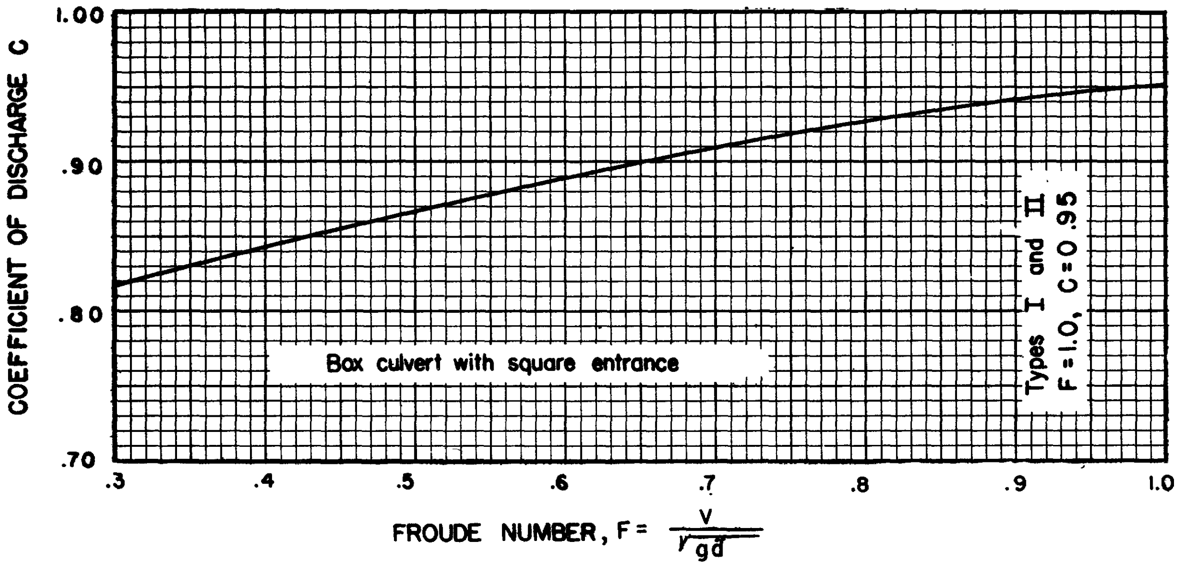


Figure 14.--Base coefficient of discharge for types I, II, and III flow in box culverts with square entrance mounted flush in vertical headwall.

Wingwall Entrance

Pipe culverts set flush with vertical headwall

The addition of wingwalls to the entrance of pipes set flush in a vertical headwall does not affect the discharge coefficient, which can be determined from pages 16 and 17.

Box culverts

The discharge coefficient for box culverts with a wingwall entrance is computed by first selecting a coefficient from figure 14 and then multiplying this coefficient by an adjustment factor, $K\theta$, which can be determined from figure 15 on the basis of the angle θ of the wingwall. For the special condition of $\theta = 90^{\circ}$, use $K\theta = 1.06$. If the angle of the wingwall is not the same on each side, the value of C for each side should be determined independently, and the results averaged.

Projecting Entrance

Corrugated-metal pipes and arches

The discharge coefficient for pipes and pipe arches that extend beyond a headwall or embankment may be determined by first computing a coefficient as outlined for pipes set flush in a vertical headwall and then multiplying this coefficient by an adjustment factor, k_L. The adjustment factor is a function of L_p/D where L_p is the length by which the culvert projects beyond the headwall or embankment.

L_p/D	k_L
0	1.0
.1	.92
$\geq$ 1.0	.90

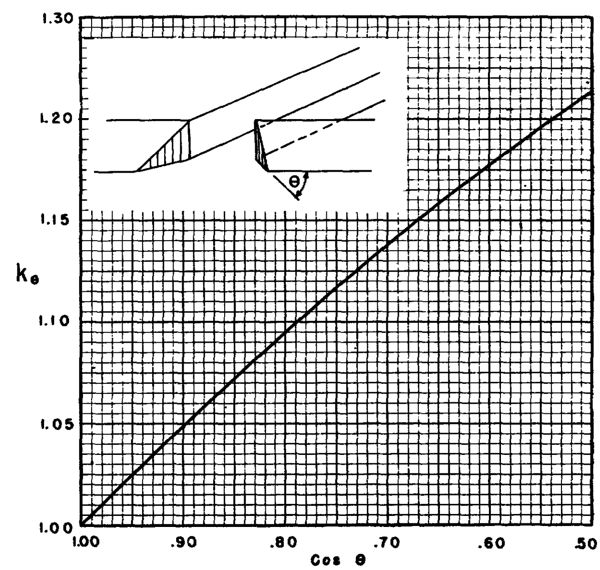


Figure 15.--Variation of discharge coefficient with wingwall angle, types I, II, and III flow in box culverts with wingwall set flush with sloping embankment.

Concrete pipes with beveled end

The discharge coefficient for projecting entrances is the same as for flush entrances for concrete pipes with a beveled end (p. 16).

Mitered Pipe Set Flush With Sloping Embankment

The discharge coefficient for mitered pipes set flush with a sloping embankment is a function

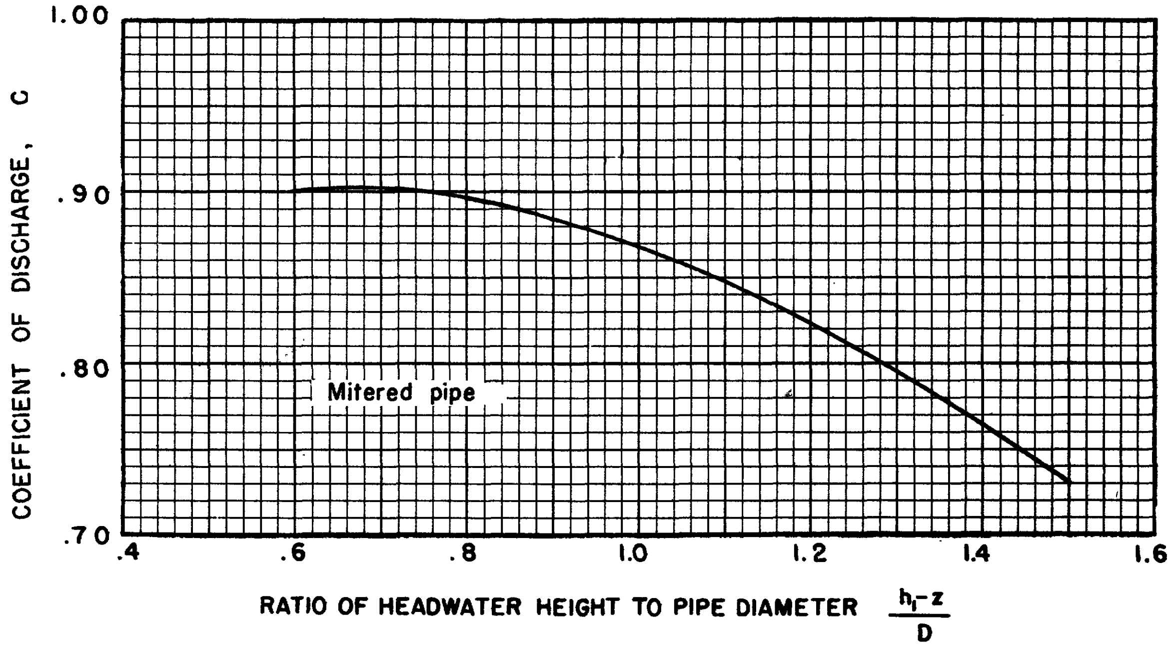


Figure 16.--Variation of discharge coefficient with ratio of head-water height to pipe diameter, types I, II, and III flow in mitered pipe set flush with sloping embankment.

of the ratio of head-water height to pipe diameter and can be determined from figure 16.

Types IV and VI Flow

Flush Setting in Vertical Headwall

Box or pipe culverts

The discharge coefficient for box or pipe culverts set flush in a vertical headwall may be selected from table 4. This includes square-ended pipes or boxes, corrugated pipes, corrugated-pipe arches, corrugated pipes with a standard conical entrance, concrete pipes with a beveled or bellmouthed end, and box culverts with rounded or beveled sides.

Table 4.--Discharge coefficients for box or pipe culverts set flush in a vertical headwall; types IV and VI flow

r/b, w/b, w/D, or r/D	C
0	0.84
.02	.88
.04	.91
.06	.94
.08	.96
.10	.97
.12	.98

Wingwall Entrance

Pipe culverts set flush with vertical headwall

The addition of wingwalls to the entrance of pipes set flush with a vertical headwall does not affect the discharge coefficient, which can be determined from table 4.

Box culverts

For box culverts with wingwalls and a square top entrance the discharge coefficient = 0.87. If the top entrance is rounded or beveled, select a coefficient from table 4 on the basis of the value of w/D or r/D for the top entrance but using 0.87 as a lower limiting value.

Projecting Entrance

Corrugated-metal pipes and arches

The discharge coefficient for corrugated-metal pipes and arches that extend past a headwall or embankment may be determined by first selecting the coefficient from table 4 that corresponds to the particular value of r/D and then multiplying this coefficient by an adjustment factor k_L (p. 18).

Concrete pipes with beveled end

The discharge coefficient for concrete pipes with a beveled end that have a projecting entrance is the same as for those with a flush entrance and can be determined from table 4.

Mitered Pipe Set Flush With Sloping Embankment

The discharge coefficient for pipes mitered and set flush with a sloping embankment is 0.74.

Type V Flow

Flush Setting in Vertical Headwall

Pipe or box culverts

The discharge coefficient for box or pipe culverts set flush in a vertical headwall can be determined from table 5. This includes the square-ended pipe or box, corrugated pipe, the corrugated-pipe arch, concrete pipe with a beveled end, and the box culvert with rounded or beveled sides.

TABLE 5.--Discharge coefficients for box or pipe culverts set flush in a vertical headwall; type V flow

$(h_1 - z)/D$	Value of C when r/b, w/b, r/D, or w/D equals-						
	0	0.02	0.04	0.06	0.08	0.10	0.14
1.4	0.44	0.46	0.49	0.50	0.50	0.51	0.51
1.5	.46	.49	.52	.53	.53	.54	.54
1.6	.47	.51	.54	.55	.55	.56	.56
1.7	.48	.52	.55	.57	.57	.57	.57
1.8	.49	.54	.57	.58	.58	.58	.58
1.9	.50	.55	.58	.59	.60	.60	.60
2.0	.51	.56	.59	.60	.61	.61	.62
2.5	.54	.59	.62	.64	.64	.65	.66
3.0	.55	.61	.64	.66	.67	.69	.70
3.5	.57	.62	.65	.67	.69	.70	.71
4.0	.58	.63	.66	.68	.70	.71	.72
5.0	.59	.64	.67	.69	.71	.72	.73

Wingwall Entrance

Pipe culverts set flush with vertical headwall

For pipes set flush with a vertical headwall, the addition of wingwalls to the entrance does not affect the discharge coefficient, which can be determined from table 5.

Box culverts

The discharge coefficient for box culverts with wingwalls and a square top entrance can be determined from table 6. If the top entrance is rounded or beveled, the coefficient should be selected from table 5 on the basis of w/D or r/D for the top entrance, but using the coefficient from table 6 as a lower limiting value.

TABLE 6.--Discharge coefficients for box culverts with wingwalls; type V flow

$(h_1 - z)/D$	Value of C when the angle of θ of wingwall is----				
	30°	45°	60°	75°	90°
1.3	0.44	0.44	0.43	0.42	0.39
1.4	.46	.46	.45	.43	.41
1.5	.47	.47	.46	.45	.42
1.6	.49	.49	.48	.46	.43
1.7	.50	.50	.48	.47	.44
1.8	.51	.51	.50	.48	.45
1.9	.52	.52	.51	.49	.46
2.0	.53	.53	.52	.49	.46
2.5	.56	.56	.54	.52	.49
3.0	.58	.58	.56	.54	.50
3.5	.60	.60	.58	.55	.52
4.0	.61	.61	.59	.56	.53
5.0	.62	.62	.60	.58	.54

Projecting Entrance

Corrugated-metal pipes and arches

The discharge coefficient for pipes and pipe arches that extend past a headwall or embankment is determined by first selecting a coefficient from table 5 and then multiplying by an adjustment factor k_L (p. 18).

Concrete pipes with beveled end

The discharge coefficient for concrete pipe with a beveled end can be determined from table 5.

Mitered Pipe Set Flush With Sloping Embankment

The discharge coefficient for mitered pipes set flush with a sloping embankment can be determined by first selecting a coefficient from table 5 for a square-ended pipe and then multiplying this coefficient by 0.92.

ROUGHNESS COEFFICIENTS

The following values of Manning's coefficient, *n*, are recommended for use in computing the conveyance of culvert sections.

Material	*n*
Concrete:	
Very smooth	0.012
Ordinary field construction	.015
Badly spalled	.020
Corrugated metal	.024
Cement rubble	.020- .030
Cast iron	.013
Vitrified pipe	.013

The composite value of *n* for corrugated-metal pipe with paved invert may be computed by the formula

$$n = \frac{P_p \times 0.012 + (P - P_p \times 0.024)}{P}$$

where

P_p = length of wetted perimeter that is paved, and

P = total length of wetted perimeter.

COLLECTION OF FIELD DATA

A transit survey of floodmarks and culvert geometry should be made as soon after the flood as possible, and the following information should be obtained.

Culvert Geometry

A complete survey is necessary to determine the dimensions and elevation of the barrel, headwalls, bed slope, and alinement of the culvert. The material used in the culvert should be noted, as well as the condition of the material. Values of *n* for the culvert barrel and the approach reach to the culvert should be recorded. Stereographs of the culvert showing all pertinent conditions upstream and downstream from the culvert should be obtained.

Head Water

The location and elevation of floodmarks along the embankment and upstream from the culvert should be obtained.

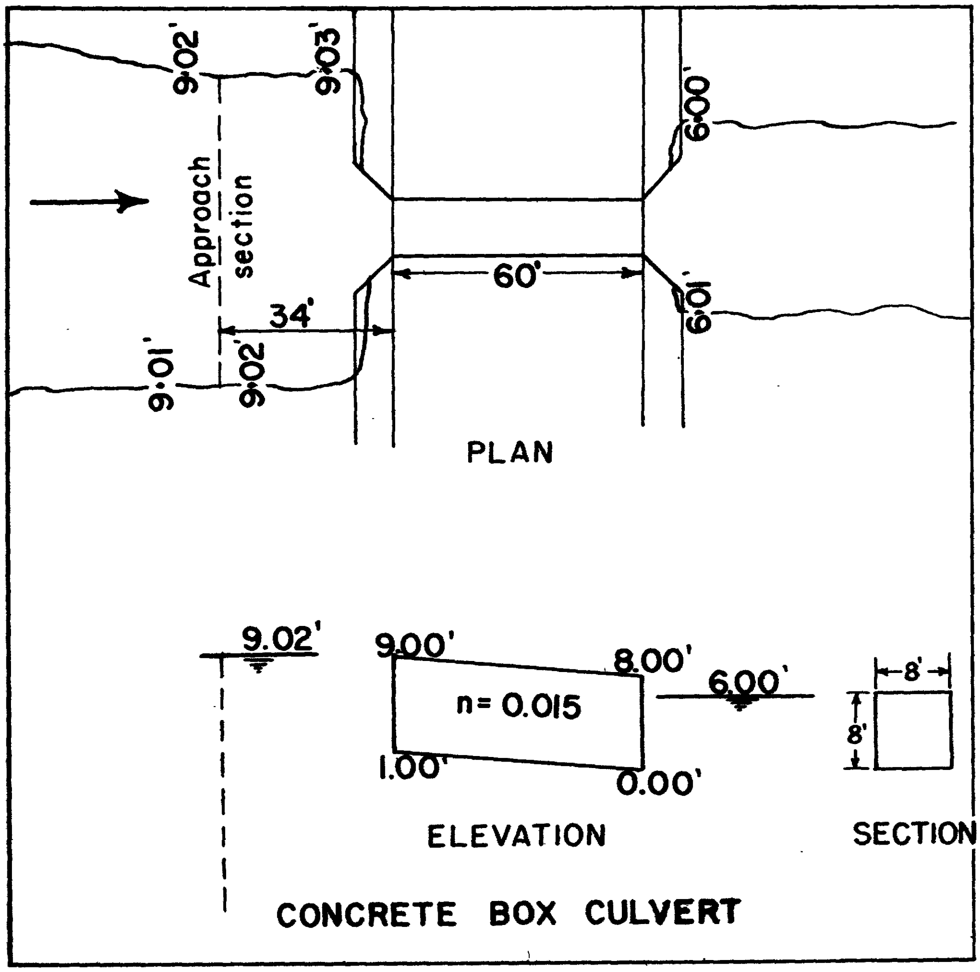
If the area of the approach channel to the culvert is estimated as equal to or greater than five times the area of the culvert barrel, a zero approach velocity in the approach section may be assumed, and no approach section is necessary. Otherwise a cross section of the channel should be at a distance upstream from the toe of the wingwall equal to the width of the entrance to the culvert at the toe of the wingwall. The cross section should be taken at right angles to the channel. If high-water marks cannot be found at the location specified for the approach section, the approach section should be taken where high-water marks can be found.

Tail Water

Floodmarks that represent the elevation of the water surface downstream from the culvert outlet, and not necessarily the elevation of the issuing jet, should be obtained close to the outlet. They should preferably be obtained along the embankment close to the culvert exit.

APPLICATIONS TO FIELD PROBLEMS

EXAMPLE NUMBER 1



Given:

$\theta = 45^{o}$

$h_1 = 1.02$ ft

$z = 1.00$ ft

$D = 8.00$ ft

Computed elsewhere:

$A_1 = 330$ sq ft

$K_1 = 38,900$

Procedure:

1. Compute $(h_1 - z)/D = 1.00$.
2. Compute $h_4/D = 0.75$.
3. From steps 1 and 2 the flow is either type I, II, or III (see table 1).
4. Compute $C = 0.95 \times 1.13 = 1.07$, assuming type I or II flow.

5. Use $C = 0.98$.

6. Assume type I flow.

7. Assume $d_c = 0.66\ (h_1 - z) = 0.66(8.02) = 5.39$.

8. Compute $\frac{14.5\ n^2\ (b + 2_{d_c})}{b\ R^{1/3}} = \frac{14.5 \times 0.015^2\ (8 + 10.78)}{8(2.30)^{1/3}} = 0.0058$.

9. Compute $S_o = \frac{1.00}{60} = 0.017$.

10. From steps 3 and 4 plot point on figure 5. As the point plots to the right of the line, $S_o > S_c$, the control is at the inlet, and the flow is type I. Note that h_c, 6.39 ft, is greater than h_4, 6.00 ft.

11. Compute $K_c = \frac{1.486}{0.015} \times 2.18^{2/3} \times 43.1 = 7130$.

12. Compute $Q = 5.67\ b\ d_c^{3/2} = 5.67 \times 8 \times 5.39^{3/2} = 569$ cfs.

13. Compute $h_{f_{1.2}} = L_w \left(\frac{Q^2}{K_1\ K_c} \right) = 34\ \left(\frac{569^2}{38,900 \times 7130} \right) = 0.04$ ft.

14. Compute $\frac{V_1^2}{2g} = \left(\frac{569}{330} \right)^2 \times \frac{1}{64.3} = 0.05$ ft.

15. Compute $Q = C\ A_c \sqrt{2g\left(h_1 - z + \frac{V_1^2}{2g} - d_c - h_{f_{1.2}}\right)}$

$$Q = 0.98 \times 8 \times 5.39 \sqrt{2g(8.02 + .05 - 5.39 - .04)} = 552 \text{ cfs.}$$

16. As the discharge computed in step 12 is greater than that computed in step 15, the assumed value of d_c is too large.

17. Assume $d_c = 5.28$ ft.

18. Compute $Q = 5.67 \times 8 \times 5.28^{3/2} = 551$ cfs.

19. Compute $h_{f_{1.2}} = 34\ \left(\frac{551^2}{38,900 \times 7230} \right) = 0.04$ ft.

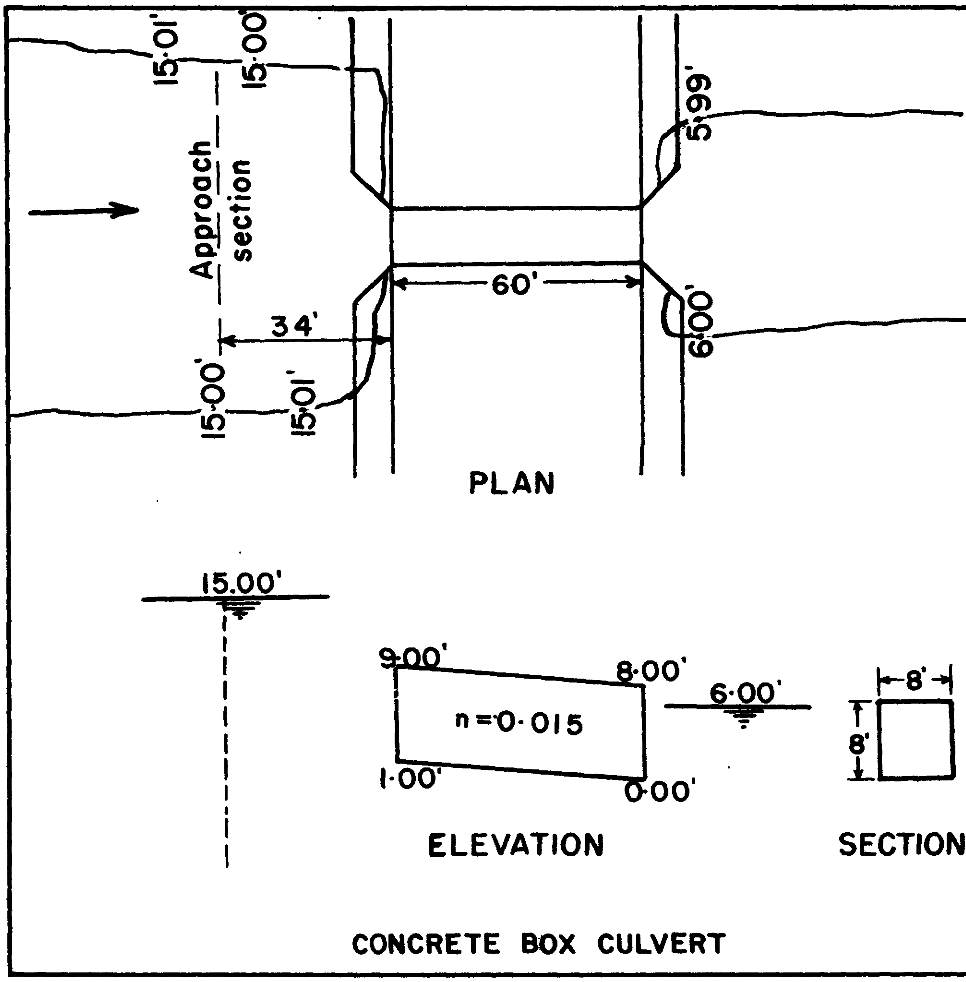
20. Compute $\frac{V_1^2}{2g} = \left(\frac{551}{330} \right)^2 \times \frac{1}{64.3} = 0.04$ ft.

21. Compute $Q = 0.98 \times 8 \times 5.28\ \sqrt{2g(8.02 + .04 - 5.28 - .04)} = 550$ cfs.

22. As the discharge computed in step 18 is virtually the same as that computed in step 21, the correct discharge is 550 cfs.

23. As a final check that this is type I flow, repeat steps 8 to 10.

EXAMPLE NUMBER 2



Given:

θ	= 45°	z	= 1.00 ft.
h_1	= 15.00 ft	h_4	= 6.00 ft.
D	= 8.00 ft.	L	= 60.0 ft.
w	= 0	n	= 0.015

Procedure:

1. Compute $(h_1 - z)/D = 1.75$.
2. Compute $h_4/D = 0.75$.
3. From table 1 the flow is type V or VI.
4. Compute $L/D = 7.5$; $S_o = 0.017$; $w/D = 0$.
5. Use the curve of figure 8 marked $w/D = 0$ as the base curve.
6. Plot the point on figure 8 defined by the value of L/D and S_o. As this point is to the left of the curve marked $w/D = 0$, type V flow occurred.
7. Select the value of C from table 6; 0.50.
8. Compute $Q = CA_o \sqrt{2g(h_1 - z)}$

$$Q = 0.50 \times 8 \times 8 \sqrt{2g(14.00)}$$

$$Q = 962 \text{ cfs.}$$

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SYMBOLS

A = area of flow at section designated by subscript

A_o = area of culvert barrel; the area between barrels is excluded in multiple box culverts

A_c = area of section of flow at critical depth

b = width of box culvert measured at right angles to axis of culvert

C = coefficient of discharge

D = maximum inside vertical dimension of culvert barrel, or the inside diameter of circular section. For corrugated pipes, D is measured as the minimum inside diameter of the pipe

D_m = maximum inside diameter, in feet, of culvert at entrance

d = depth of flow, in feet, as measured to the lowest point in the cross section

d_c = critical depth, in feet

d_m = mean depth = A/T

f = Darcy friction factor

F = Froude number; for rectangular section $= V/\sqrt{gd}$

g = acceleration of gravity = 32.2 ft per sec per sec

h = height, in feet, of average piezometric head at any section above the invert of the culvert at the downstream end. Piezometric head or height, in general, is equivalent to pressure head plus elevation; for uniform flow in open channels, it is equivalent to the elevation of the water surface. In zones of rapid acceleration, the average piezometric height may not be equivalent to the water surface

h_c = $d_c + z$

h_e = head loss, in feet, due to entrance contraction

h_f = head loss, in feet, due to friction; $h_{f_{1.2}}$ is the head loss due to friction between section 1 and section 2 and equals $L_w(Q^2/K_1K_2)$

H_o = specific energy

k = adjustment factor

K = conveyance of a section = $(1.486/n)R^{2/3}A$

L = length, in feet, of the culvert barrel. For mitered pipe, the shortest length is used

L_p = distance, in feet, a culvert barrel projects beyond a headwall or embankment

L_w = distance, in feet, from approach section to the entrance of the culvert. The top of the pipe is used as the entrance point for mitered pipe

m = percent of the channel contraction; for culverts, m is approximated by $(1 - A/A_1)\ 100$, where A is the area of flow at the terminal section

n = Manning's roughness coefficient

P = wetted perimeter, in feet, of cross section of flow

Q = discharge, in cubic feet per second

r = radius, in feet, of entrance rounding

R = hydraulic radius of section of flow; equal to A/P

R_o = hydraulic radius of culvert barrel

S = slope of energy grade line

S_o = bed slope of culvert barrel, ft per ft

S_c = bed slope of culvert for which the normal depth and the critical depth are equal

T = width, in feet, of the section at the water surface

w = distance, in feet, from point of beginning of bevel to line of projection of culvert barrel; pipe or box (see fig. 13)

z = $S_o L$

θ = the acute angle (theta) at which the wingwall and headwall join

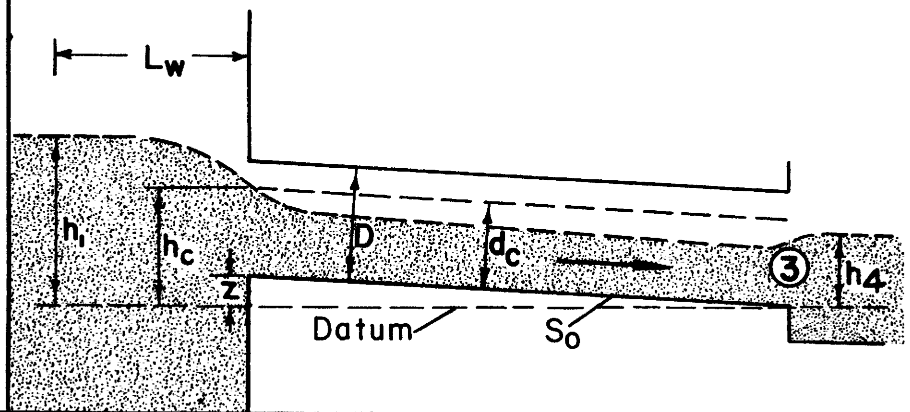
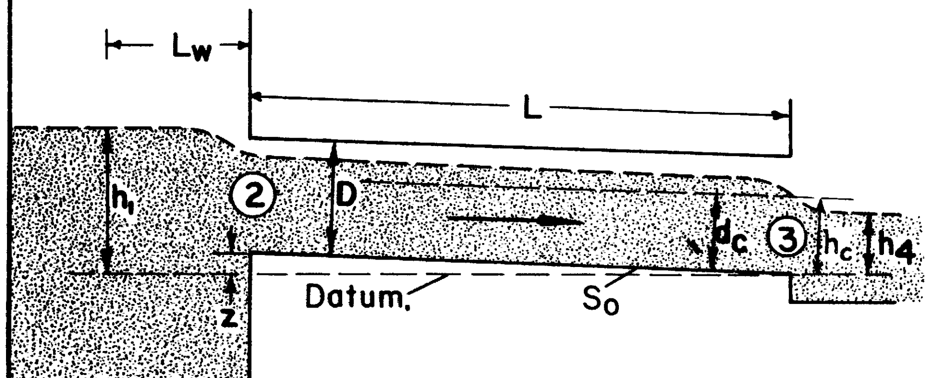
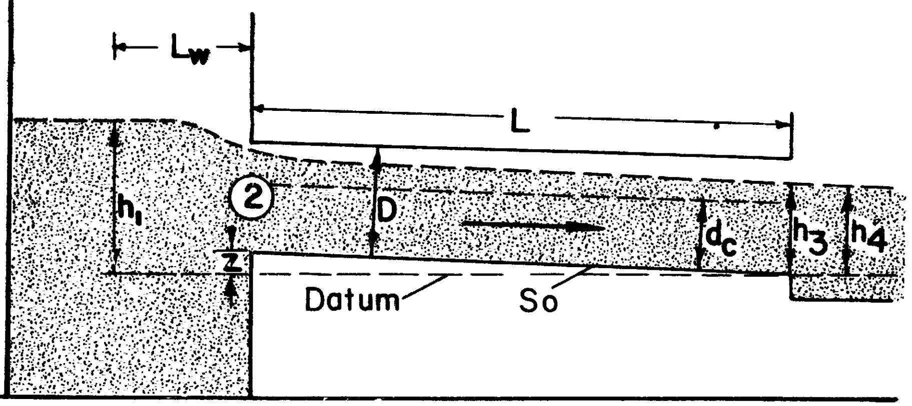
$<$ = less than

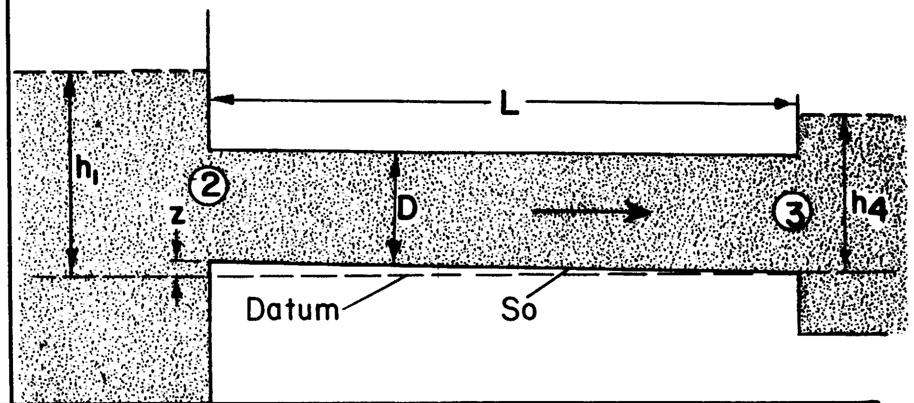
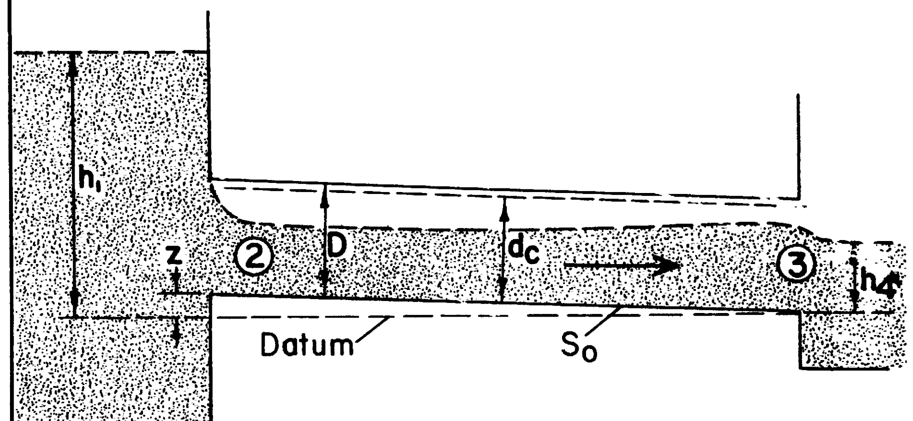
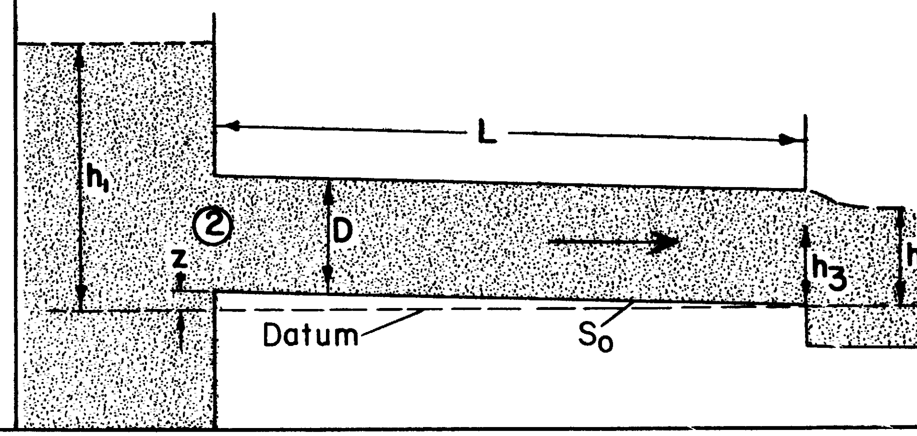
$\not<$ = not less than

$>$ = greater than

$\not>$ = not greater than

Subscripts 1, 2, 3 denote location of section. Section 1 is the approach section, section 2 is in the culvert barrel at the entrance, and section 3 is in the culvert barrel at the outlet.

TYPE	EXAMPLE
I CRITICAL DEPTH AT INLET $\frac{h_1 - z}{D} < 1.5$ $h_4/h_c < 1.0$ $S_o > S_c$	
II CRITICAL DEPTH AT OUTLET $\frac{h_1 - z}{D} < 1.5$ $h_4/h_c < 1.0$ $S_o < S_c$	
III TRANQUIL FLOW THROUGHOUT $\frac{h_1 - z}{D} < 1.5$ $h_4/D \leq 1.0$ $h_4/h_c > 1.0$	

TYPE	EXAMPLE
IV SUBMERGED OUTLET $\frac{h_1 - z}{D} > 1.0$ $h_4/D > 1.0$	
V RAPID FLOW AT INLET $\frac{h_1 - z}{D} \geq 1.5$ $h_4/D \leq 1.0$	
VI FULL FLOW FREE OUTFALL $\frac{h_1 - z}{D} \geq 1.5$ $h_4/D \leq 1.0$	

CLASSIFICATION OF CULVERT FLOW