HYDRAULIC DESIGN of the BOX-INLET DROP SPILLWAY

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PREFACE

This publication is a manual for the design of box-inlet drop spillways. Criteria, curves, and tables are presented for (1) determining the discharge capacity of the box-inlet crest; (2) determining the discharge capacity of the headwall opening; (3) the design of the outlet; and (4) determining the effect of tailwater submergence on the spillway capacity. An example shows the application to the design of a box-inlet drop spillway.

This design manual was first published as St. Anthony Falls Hydraulic Laboratory Technical Paper 8, Ser. B, in January 1951. It was reprinted without material change by the U.S. Department of Agriculture, Soil Conservation Service, as SCS–TP–106 in July 1951. The present manual supersedes SCS–TP–106 and includes the trapezoidal weir and dike effect information obtained by Neal E. Minshall from studies at the University of Wisconsin.

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SYMBOLS

A	cross-sectional area of approach channel
B	length of box inlet
c	coefficient of discharge
c_t	coefficient of discharge for a triangular weir
D	depth of box inlet
d_2	height of tailwater above basin floor
d_3	height of tailwater above top of end sill
d_c	critical depth in straight section
d_{ce}	critical depth at stilling-basin exit
F	difference in elevation of box-inlet crest and top of end sill
f	height of end and longitudinal sills
g	acceleration due to gravity
H	specific head; depth of flow plus velocity head $=h+h_v$
H_0	apparent specific head at zero flow; zero-flow head correction
H_t	level of tailwater referred to crest of box inlet
$\triangle H$	increase over free-flow head caused by high tailwater level
h	piezometric head
h_v	velocity head $=V^2/2g$
L	length of box-inlet crest $=2B+W$
L_S	minimum length of straight section of outlet
L_B	minimum length of stilling-basin section of outlet
p	spacing of center pair of longitudinal sills either side of outlet centerline
Q	discharge
r	spacing of outer pair of longitudinal sills
t	minimum height of sidewall at basin exit above tailwater elevation
V	mean velocity $=Q/A$
W	width of box inlet
W_c	width of approach channel
W_e	width of stilling-basin exit
X	distance from box-inlet crest to toe of dike
Y	distance upstream from headwall to toe of dike
α	included angle of triangular weir
θ	angle wingwall makes with outlet centerline

Subscript 1 applies when control section is at box-inlet crest
Subscript 2 applies when control section is at headwall opening

HYDRAULIC DESIGN OF THE BOX-INLET DROP SPILLWAY

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INTRODUCTION

This handbook contains sufficient information to permit the complete hydraulic design of a box-inlet drop spillway and explains briefly the various factors that influence the design. Its four major sections deal with the free-flow capacity, the outlet design, the submerged-flow capacity, and the utilization of the preceding information in the design of box-inlet drop spillways.

The box-inlet drop spillway may be described as a rectangular box open at the top and at the downstream end. The spillway is shown in figure 1. Storm runoff is directed to the box by dikes and headwalls, enters over the upstream end and two sides, and leaves through the open downstream end. An outlet structure is attached to the downstream end of the box. The long crest of the box inlet permits large flows to pass over it with relatively low heads, yet the width of the spillway need be no greater than that of the exit channel.

EXPERIMENTAL BACKGROUND

The design information presented here is based on an extensive experimental program. The free and submerged flow tests were conducted, with interruptions, between 1946 and 1950. They consist of 361 tests, each test differing in some respect from the others and requiring approximately 35 observations made with differing flow conditions. Thus, over 12,000 observations form the background for the discharge design procedure. Similarly, the outlet design is based on 386 tests representing (1) the exploratory tests used to determine the general form of the outlet and (2) the tests made to determine and verify the general design rules for each element of the outlet. These tests were made between 1944 and 1946. The outlet wingwall design was modified slightly as a result of special studies made in 1950. The dike effect in this revision is based on a 1965 analysis of data obtained in 1953 under the direction of Neal E. Minshall at the University of Wisconsin. A further addition is the information published by Minshall [1] on the trapezoidal weir box inlet shown in figure 2. Detailed descriptions of the flow tests and the outlet tests may be found in the reports by Donnelly [2] and by Blaisdell and Donnelly.[3,4]

The test programs in general are adequate to define accurately the values of the variables involved in the design of box-inlet drop spillways. The tests were conducted and analyzed by laboratory personnel experienced in the conduct and interpretation of hydraulic model tests. Every feasible effort has been made to insure the reliability of the final results. The results are generally expressed in dimensionless form. This is to allow as much condensation as possible, yet to permit the widest possible application to structures similar in geometrical form to the box-inlet drop spillway and outlet discussed here.

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[1] Minshall, N. E. Discussion of THE BOX INLET DROP SPILLWAY AND ITS OUTLET. Amer. Soc. Civil Engin. Trans. 121: 987–992. 1956.

[2] Donnelly, C. A. DESIGN OF AN OUTLET FOR BOX INLET DROP SPILLWAY. U.S. Dept. Agr., Soil Conserv. Serv. SCS–TP–63, 31 pp. 1947.

[3] Blaisdell, F. W., and Donnelly, C. A. CAPACITY OF BOX INLET DROP SPILLWAYS UNDER FREE AND SUBMERGED FLOW CONDITIONS. Minn. Univ. St. Anthony Falls Hydraul. Lab. Tech. Paper 7, Ser. B, 36 pp. 1951.

[4] Blaisdell, F. W., and Donnelly, C. A. THE BOX INLET DROP SPILLWAY AND ITS OUTLET. Amer. Soc. Civil Engin. Trans. 121: 955–994. 1956.

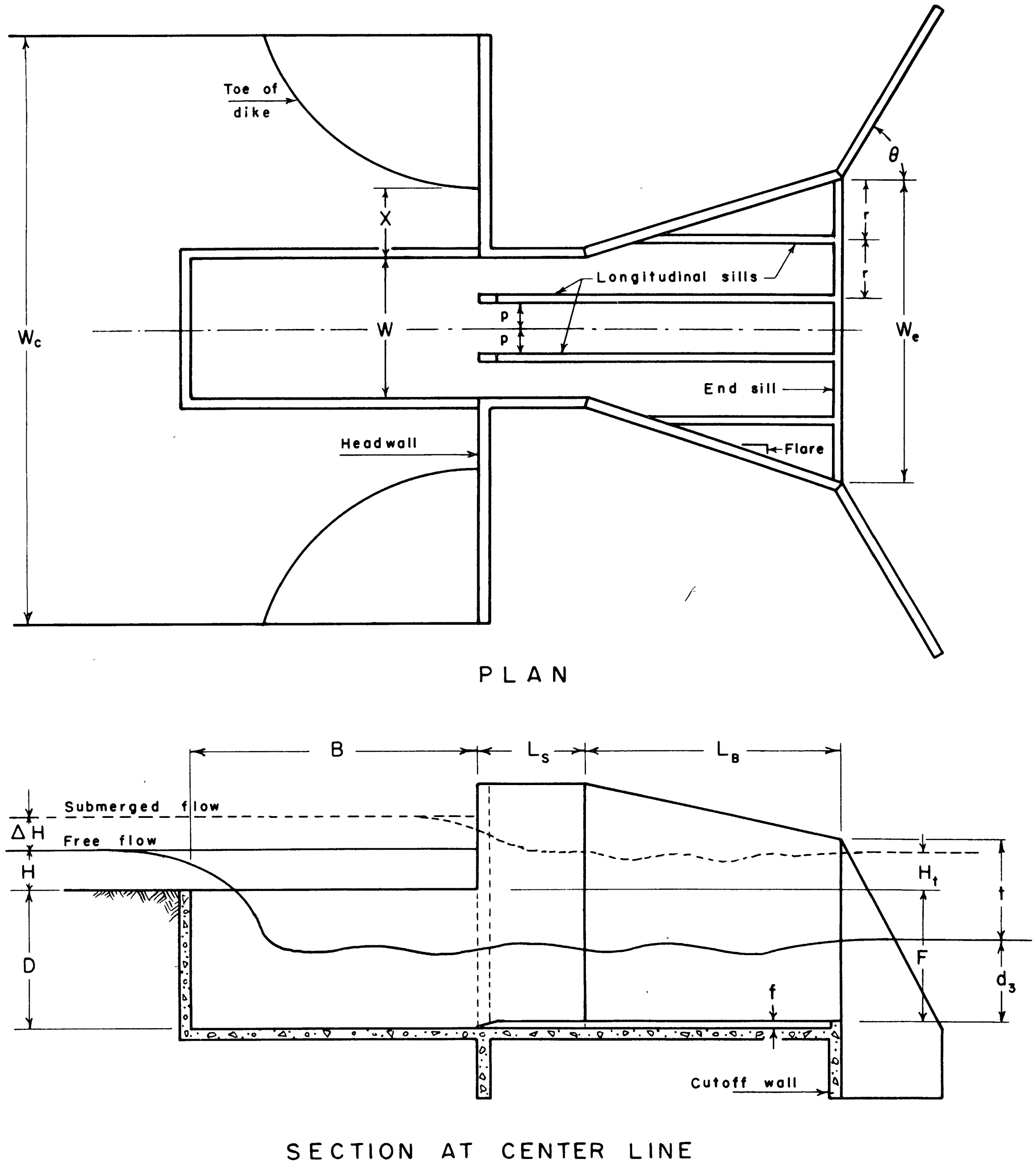

FIGURE 1.—Box-inlet drop spillway.

FREE-FLOW CAPACITY

Free flow exists in the box-inlet drop spillway whenever the downstream or tailwater level is so low that it has no effect on the amount of water that will pass the spillway. The problem then is to determine what parts of the spillway affect the flow and to evaluate these effects. Two different sections are effective in controlling the flow: the crest of the box inlet controls the flow up to that point where the box inlet is flooded out; the opening in the headwall controls at higher flows. The flow at which the control changes from one point to the other is dependent upon a number of factors, the principal ones being the box-inlet depth and its length.

Since the primary factors that influence the free flow past box-inlet drop spillways are dif-

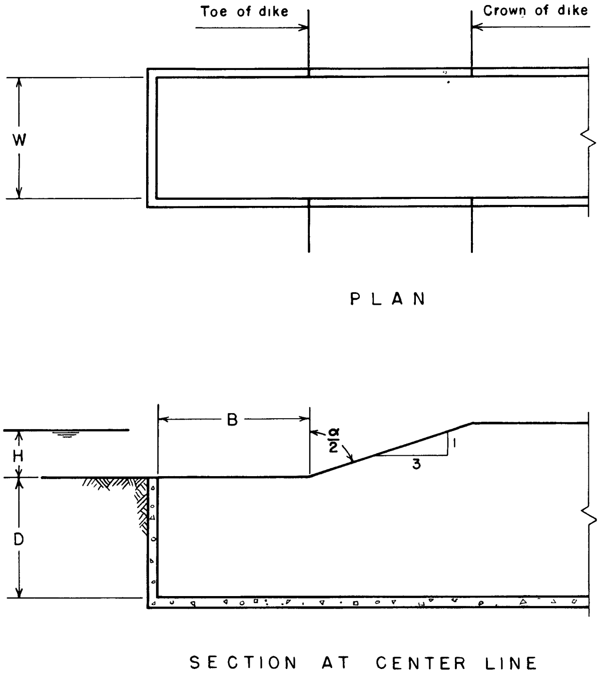

FIGURE 2.—Trapezoidal weir box inlet.

ferent when the control is at the box-inlet crest from what they are when the control is at the headwall opening, the descriptions and the design information for each control will be discussed in separate sections. For convenience in use, the design charts and tables are grouped together following the descriptive material concerning them.

Control at Box-Inlet Crest

Water enters the box inlet over the upstream end and two sides when the section controlling the flow is the box-inlet crest. The common rectangular weir formula

$$Q=c_1L\sqrt{2g}H^{3/2} \qquad (1a)$$

is used to determine the head under these conditions. The equation is easier to use for some problems if it is solved for the head

$$H=\left(\frac{Q}{c_1L\sqrt{2g}}\right)^{2/3} \qquad (1b)$$

King's *table 5-1*[5] gives the three-halves powers of numbers and his *table 7-18* gives the two-thirds powers of numbers, which may prove helpful in solving these equations. In equations 1a and 1b, Q is the discharge in cubic feet per second; c_1 is a dimensionless discharge coefficient; L is the crest length, $2B+W$, in feet; B is the inside length of the box inlet in feet; W is the width of the box inlet in feet; g is the acceleration due to gravity and is equal to 32.2 feet per second per second; and H is the head over the spillway crest in feet. The head H is here assumed to be the depth of flow plus the velocity head. Most of these symbols are illustrated in figure 1.

The discharge coefficient c_1 in equations 1a and 1b has the value 0.4275 and $c_1\sqrt{2g}=3.43$ when $B/W=1.0$, $W_c/L\geq 3.0$, and $H/W\geq 0.6$. Here W_c is the approach-channel width in feet.

Corrections

A number of corrections must be applied to c_1 in equations 1a and 1b to take into account the effects of various factors such as the variation of c_1 with head and the effects of box-inlet shape, approach-channel width, and dike position. These corrections are described in the following paragraphs.

Variation of Discharge Coefficient with Head.—The coefficient of discharge in equations 1a and 1b varies with the head on the spillway when $H/W\leq 0.6$, whereas for $H/W\geq 0.6$, the coefficient is constant.

For design purposes the ratio H/W may be computed, after which the discharge coefficient c_1 in equations 1a and 1b can be read directly from the curve shown in figure 3, using the left-hand ordinate. An alternative way to determine the discharge is to use 0.4275 for c_1, or 3.43 for $c_1\sqrt{2g}$, and multiply by a correction read from the curve of figure 3, using the right-hand ordinate. This correction may also be obtained from table 1. Figure 3 and table 1 are valid when $0<H/W<1.5$; they should be used with caution outside the range covered by the tests.

Variation of Discharge Coefficient with Box-Inlet Shape.—The shape of the box inlet in plan has a considerable effect on the discharge coefficient. This variation is shown in figure 4. Since the discharge coefficient c_1 in equations 1a and 1b has been taken as correct when $B/W=1$, it is necessary to apply a correction to c_1 if B/W is not equal to 1.

The ordinates of figure 4 indicate the correction to be applied to c_1 for each shape of box inlet between $BW=0$ and $B/W=4$—the range in shapes covered by the tests. The corrections may also be obtained from table 2. The discharge coefficient is multiplied by the box-inlet shape correction to correct for this effect.

Variation of Discharge Coefficient with Approach-Channel Width.—The width of the upstream or approach channel has a very great effect on the discharge if the channel is too narrow. For the longer boxes and longer crest lengths, the approach-channel width can easily be so narrow as to make part of the crest inefficient. Under these conditions a change in the proportions of

[5] KING, H. W., and BRATER, E. F. HANDBOOK OF HYDRAULICS. Ed. 5. pp. 5–32 to 5–45 and 7–62 to 7–67. New York. 1963.

the box inlet may prove economical or it may be desirable to consider the use of a different type of spillway.

The correction for approach-channel width shown in figure 5 is a function of the ratio of approach-channel width to crest length, W_c/L. The correction can also be obtained from table 3. When $W_c/L \geq 3$, no correction is required. At lesser relative channel widths the factor by which the discharge coefficient c_1 in equations 1a and 1b is multiplied becomes small. The tests covered a range of relative approach-channel widths W_c/L from 0.4 to 10, and the corrections are valid over this range.

Variation of Discharge Coefficient with Dike Position.—The proximity of the toe of the earth dike to the box-inlet crest has an important effect on the discharge coefficient because the dike toe interferes with the free access of water to the box-inlet crest near the headwall. The toe of the dike should be kept as far from the box inlet as is feasible.

Little data were obtained regarding the effect of dike position on the discharge coefficient. Such data as were obtained were of qualitative rather than quantitative value. For this reason, as mentioned in the section, "Experimental Background," the more extensive data obtained by Minshall during his tests at the University of Wisconsin were borrowed and reanalyzed to develop design information on the dike effect. The effect of the dike is shown in table 4.

The dike-effect data were developed from experiments on box-inlet drop spillways with relative box lengths B/W of 0.5, 1.0, 1.5, and 2.0; dike slopes of 1 on 3; the toe of the dike ranging for relative distances from the box-inlet crest at the headwall X/W from 0 to 0.6, and for no dike in the channel that had a relative width W_c/L of 10; and dike toes that extended upstream from the headwall to relative distances Y/W of 1.0, 1.7, 1.9, and 2.2. No effect of Y/W on the dike effect could be detected. The relative head H/W had an effect on the dike correction factor, but no pattern could be detected for the variation in the correction factor with relative head.

The dike-effect correction factors listed in table 4 were used to compute discharges to test the agreement of the computed and experimentally observed discharges. The ratio of the observed discharge to the computed discharge ranged from 0.90 to 1.15 for most of the available data. Since the dike correction factor includes all the residual differences and unaccounted-for variations, this agreement is felt to be satisfactory for design purposes. However, the agreement is less satisfactory for values of H/W less than 0.2.

Elimination of Dike Effect.—The effect of the dike on the discharge coefficient can be eliminated. This is accomplished by sloping the crest of the box inlet to fit the dike slope. The dike is then extended to the sloping drop-inlet crest. This is shown in figure 2. Minshall[6] has called this inlet a trapezoidal weir box inlet.

An advantage of the trapezoidal weir box inlet is that the dike can be constructed to a definite concrete surface. Field experience has shown that the toe of the dike is frequently built too close to the rectangular weir box inlet. The result is a decrease in the designed capacity of the box inlet. The trapezoidal weir makes it more likely that the dike will be installed as designed.

The capacity of the trapezoidal weir box inlet is given by summing the rectangular and triangular weir formulas

$$Q=c_1L\sqrt{2g}H^{3/2}+c_t\frac{8}{15}\tan\frac{\alpha}{2}\sqrt{2g}H^{5/2} \qquad (2)$$

where c_t is the dimensionless discharge coefficient for a triangular weir and α is the included angle of the weir. King's *table 5–2*[7] gives the five-halves powers of numbers.

In equation 2, the coefficient c_1 is 0.4275 and $c_1\sqrt{2g}$ is 3.43 as for equations 1a and 1b. The same corrections, except for the dike position correction, must be applied. If the dike slope is 1 on 3, Minshall[8] assigns a value of 9 to $c_t\frac{8}{15}\tan\frac{\alpha}{2}\sqrt{2g}$, which means that $c_t=0.70$. The indicated precision of this coefficient is approximately ± 10 percent.

Variation of Discharge Coefficient With Approach-Channel Depth.—It is known from tests performed by others[9,10] that the depth of the approach channel has an effect on the discharge. Both Huff and Kessler indicate a decrease in discharge as the approach channel becomes shallower. All the tests used as the basis for the design curves presented in this report were made with the approach channel level with the box-inlet crest; i.e., the approach channel was silted full. Deeper approaches will increase the discharge, and in this respect the design curves are conservative.

Precision of Results

Equations 1a and 1b, when the discharge coefficient c_1 is corrected for the effects of head, box-inlet shape, and approach-channel width, and when there is no dike effect, can be expected to give the discharge to within ± 7 percent under ideal conditions. With dike effects, the precision is about ± 15 percent. This precision was ob-

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[6] See footnote 1, *p. 987*.

[7] See footnote 5, *pp. 5–42 to 5–45*.

[8] See footnote 1, *p. 991*.

[9] KESSLER, L. H. EXPERIMENTAL INVESTIGATION OF THE HYDRAULICS OF DROP INLETS AND SPILLWAYS FOR EROSION CONTROL STRUCTURES. Wis. Univ. Engin. Expt. Sta. Ser. 80, 66 pp. 1934.

[10] HUFF, A. N. THE HYDRAULIC DESIGN OF RECTANGULAR SPILLWAYS. U.S. Dept. Agr., Soil Conserv. Serv., SCS–TP–71, 67 pp. 1944.

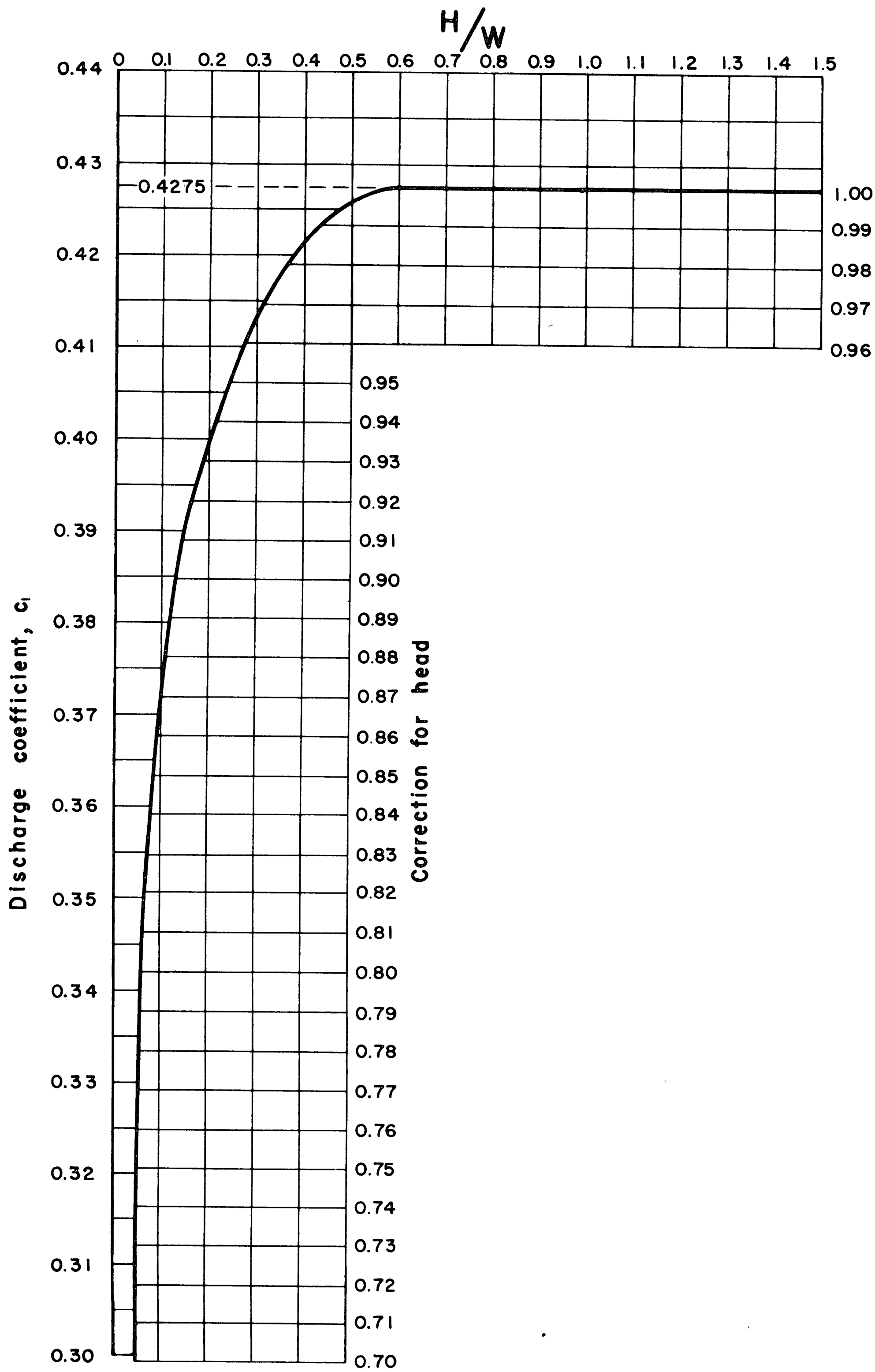

FIGURE 3.—Discharge coefficient and correction for head, with control at box-inlet crest.

tained in the laboratory; under field conditions, somewhat less precision must be anticipated.

Summary (Control at Box-Inlet Crest)

The preceding comments regarding the flow over the box-inlet crest when the discharge is free and the crest of the box inlet controls the discharge may be summarized as follows:

1. The general formula for a rectangular weir is

$$Q=0.4275L\sqrt{2g}H^{3/2} \quad (1a)$$

or, in English units,

$$Q=3.43LH^{3/2} \quad (1c)$$

When solved for H these equations read

$$H=\left(\frac{Q}{0.4275L\sqrt{2g}}\right)^{2/3} \quad (1b)$$

and

$$H=\left(\frac{Q}{3.43L}\right)^{2/3} \quad (1d)$$

The general formula for a trapezoidal weir with a 1-on-3 dike slope is

$$Q=0.4275L\sqrt{2g}H^{3/2}+0.70\frac{8}{15}\tan\frac{\alpha}{2}\sqrt{2g}H^{5/2} \quad (2a)$$

or, in English units,

$$Q=3.43LH^{3/2}+9H^{5/2} \quad (2b)$$

2. The discharge coefficients in equations 1 and 2 must be multiplied by:
   a. The correction for head given in figure 3 or table 1;
   b. The correction for box-inlet shape given in figure 4 or table 2;
   c. The correction for approach-channel width given in figure 5 or table 3; and
   d. The correction for dike proximity to the box-inlet crest given in table 4. This correction does not apply to equation 2.
3. The approach channel is silted level with the crest of the box inlet.
4. The precision of the design curves and tables is within ±7 percent when there is no dike effect and about ±15 percent when dikes are used.

Control at Headwall Opening

The box inlet is flooded out at the higher flows and for the shallower boxes. Under these conditions, the opening in the headwall controls the flow through the spillway. A method for determining whether the control is at the box-inlet crest or at the headwall opening is presented in the section on "Example of Application." When the control is at the headwall opening, the discharge formula is

$$Q=c_2W\sqrt{2g}(H+H_{02})^{3/2} \quad (3a)$$

when solved for Q and

$$H=\left(\frac{Q}{c_2W\sqrt{2g}}\right)^{2/3}-H_{02} \quad (3b)$$

when solved for H. In equations 3a and 3b, H is measured from the box-inlet crest, whereas the effective headwall opening is on the order of $H+D$, D being the depth of the box inlet in feet. The head correction H_{02} is therefore required.

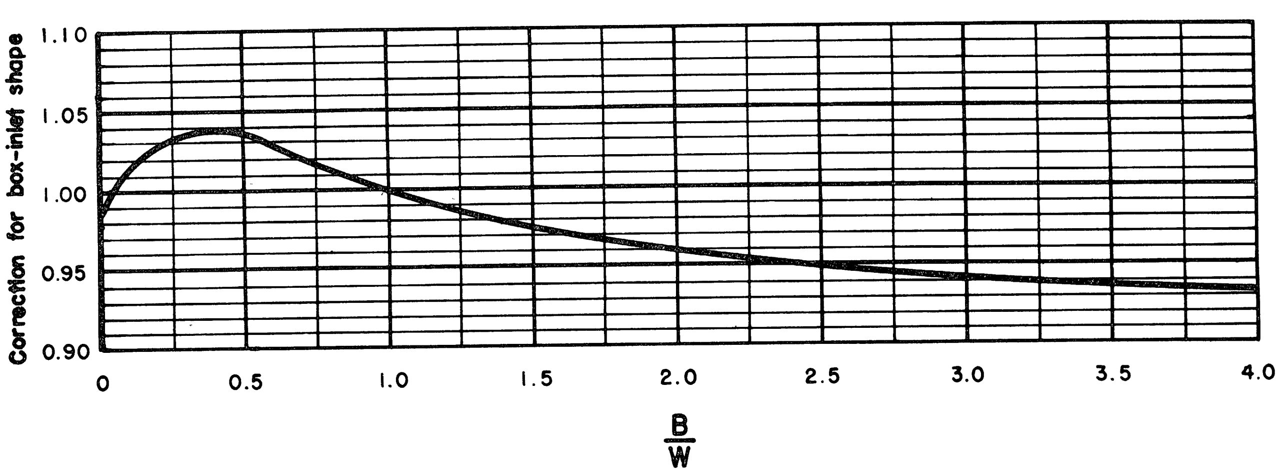

FIGURE 4.—Correction for box-inlet shape, with control at box-inlet crest $\left(\frac{W_e}{L}\geq 3\right)$.

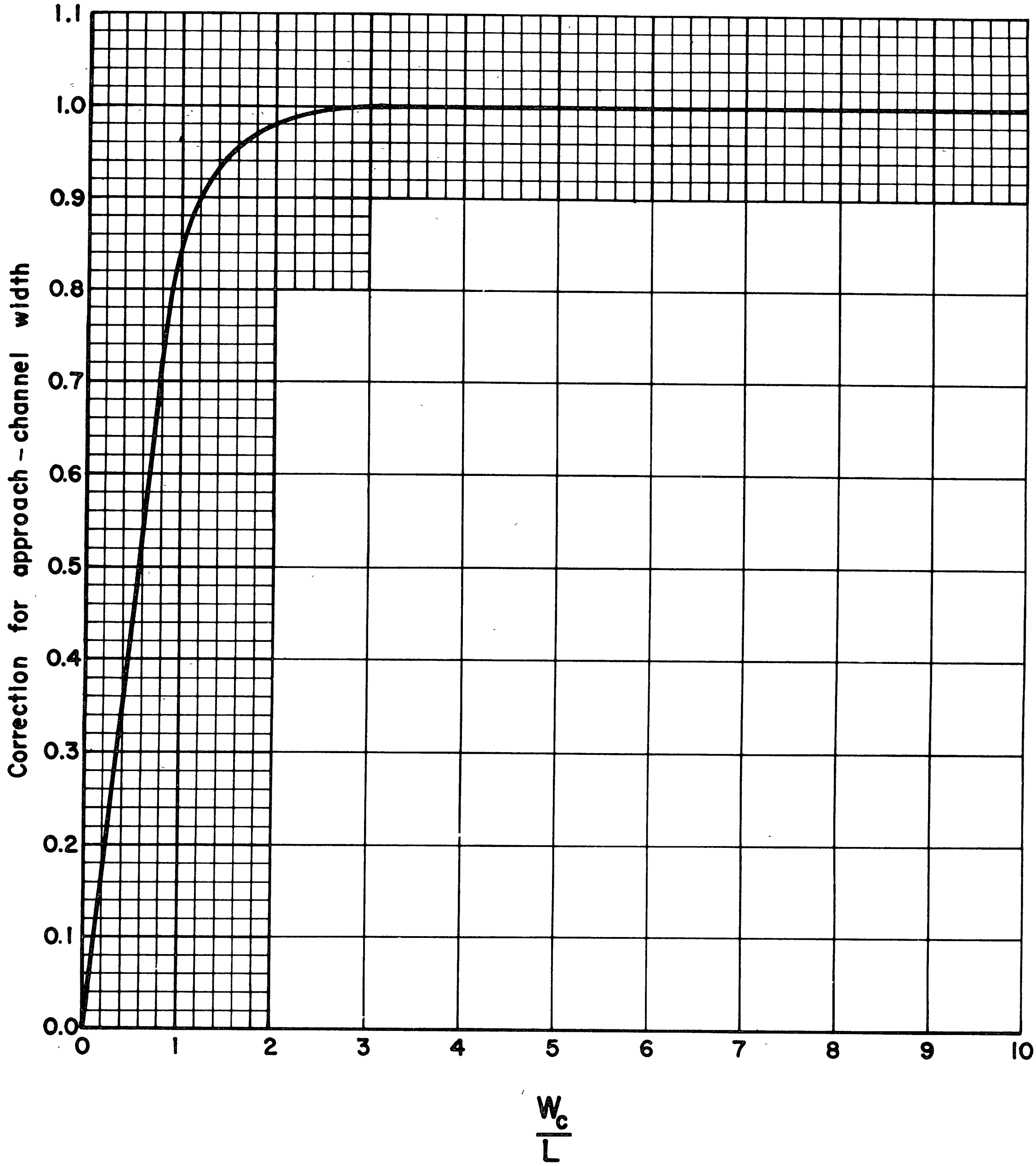

FIGURE 5.—Correction for approach-channel width, with control at box-inlet crest.

A number of factors affect the flow through the headwall opening, and they determine the values of the discharge coefficient c_2 and the head correction H_{02} in equations 3a and 3b. These factors are discussed in the following paragraphs.

Discharge Coefficient

The discharge coefficient c_2 in equations 3a and 3b increases as the relative depth D/W of the box inlet increases. The range of values of D/W covered by the tests is from about 0 to 1.

The discharge coefficient c_2 may be taken from the curve of figure 6 or from table 5.

Head Correction

It is only natural to expect that the magnitude of the head correction H_{02} in equations 3a and 3b will approach the box-inlet depth for the relatively longer and shallower box inlets and that it will decrease toward zero for the relatively shorter and deeper box inlets.

TABLE 1.—*Correction for head (control at box-inlet crest)*

[Multiply c_1 in $Q=c_1L\sqrt{2g}\,H^{3/2}$ by correction]

H/W	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0						0.76	0.80	0.82	0.84	0.86
.1	0.87	0.88	0.89	0.90	0.91	.91	.92	.92	.93	.93
.2	.93	.94	.94	.95	.95	.95	.95	.96	.96	.96
.3	.97	.97	.97	.97	.98	.98	.98	.98	.98	.98
.4	.99	.99	.99	.99	.99	.99	.99	.99	.99	1.00
.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.6 [1]	1.00									

[1] Correction is 1.00 when *H/W* exceeds 0.6.

TABLE 2.—*Correction for box-inlet shape (control at box-inlet crest)*

[Multiply c_1 in $Q=c_1L\sqrt{2g}\,H^{3/2}$ by correction]

B/W	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.98	1.01	1.03	1.03	1.04	1.04	1.03	1.02	1.01	1.01
1	1.00	.99	.99	.98	.98	.98	.97	.97	.96	.96
2	.96	.96	.95	.95	.95	.95	.95	.95	.94	.94
3	.94	.94	.94	.94	.94	.94	.94	.94	.93	.93
4	.93									

TABLE 3.—*Correction for approach-channel width (control at box-inlet crest)*

[Multiply c_1 in $Q=c_1L\sqrt{2g}\,H^{3/2}$ by correction]

W_c/L	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.00	0.09	0.18	0.27	0.35	0.44	0.53	0.62	0.71	0.80
1	.84	.87	.90	.92	.93	.94	.95	.96	.97	.97
2	.98	.98	.99	.99	.99	.99	1.00	1.00	1.00	1.00
3 [1]	1.00									

[1] Correction is 1.00 when W_c/L exceeds 3.0.

TABLE 4.—*Correction for dike effect (control at box-inlet crest)*

[Multiply c_1 in $Q=c_1L\sqrt{2g}\,H^{3/2}$ by correction]

$\frac{B}{W}$	*X/W*						
	0.0	0.1	0.2	0.3	0.4	0.5	0.6
0.5	0.90	0.96	1.00	1.02	1.04	1.05	1.05
1.0	.80	.88	.93	.96	.98	1.00	1.01
1.5	.76	.83	.88	.92	.94	.96	.97
2.0	.76	.83	.88	.92	.94	.96	.97

The relative head correction H_{02}/D is a simple function of *B/D* for box inlets having relative depths *D/W* of 1/4, 1/2, and 1. The relative head correction may be taken from the curve of figure 7 or from table 6 when *D/W* is between 1/4 and 1, inclusive; however the curves of figure 7 and table 6 are not valid when *D/W* = 1/8. Although figure 8 has been prepared to give the head correction for the shallower box inlets, it can be used for any box inlet when *D/W* is between 1/8 and 1. To utilize figure 8 it is necessary to compute, before entering the figure, any two of the three ratios *B/D*, *B/W*, or *D/W*.

Other Factors

A thorough study was made to discover those factors which determine the magnitude of the discharge coefficient c_2 and the head correction H_{02} in equations 3a and 3b.

With regard to the discharge coefficient, c_2 is not affected by the box-inlet shape, the approach-channel width, or the dike position. The only factor that affects the discharge coefficient is the relative depth of the box inlet. This is discussed above.

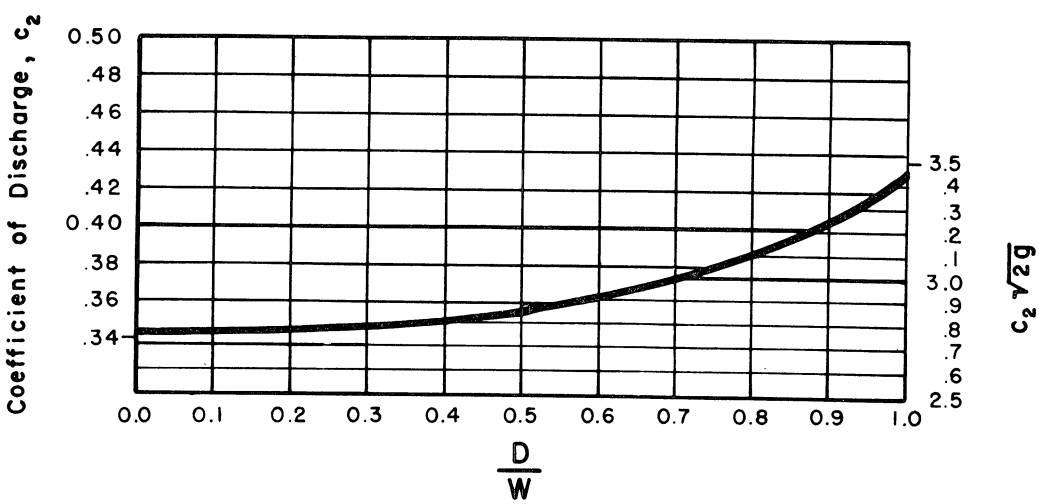

FIGURE 6.—Coefficient of discharge, with control at headwall opening.

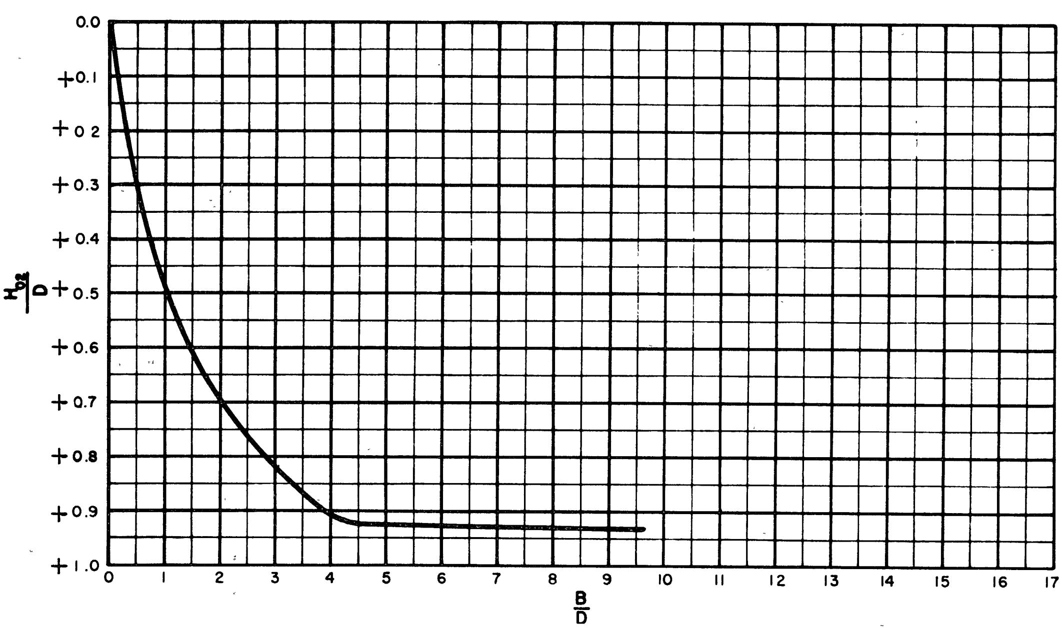

FIGURE 7.—Relative head correction for $D/W \geq 1/4$, with control at headwall opening.

With regard to the head correction, H_{02} is not affected by the approach-channel width or the dike position. The only factors that affect the head correction are the relative length B/W and the relative depth D/W of the box inlet.

Precision of Results

The discharge coefficient c_2 in equations 3a and 3b is reliable to within about ± 10 percent. The head correction H_{02} is also believed to be reliable to within about 10 percent of the indicated value except for the steep portion of the curve of figure 7 where errors of ± 20 percent are possible. These percentages apply up to relative heads H/W of about 1.2.

The discharge coefficient and the head correction apparently vary in such a manner that the errors are at least partially compensating. The two percentages mentioned are therefore not additive but probably partly cancel each other.

Summary (Control at Headwall Opening)

The preceding comments regarding the flow through box-inlet drop spillways when the dis-

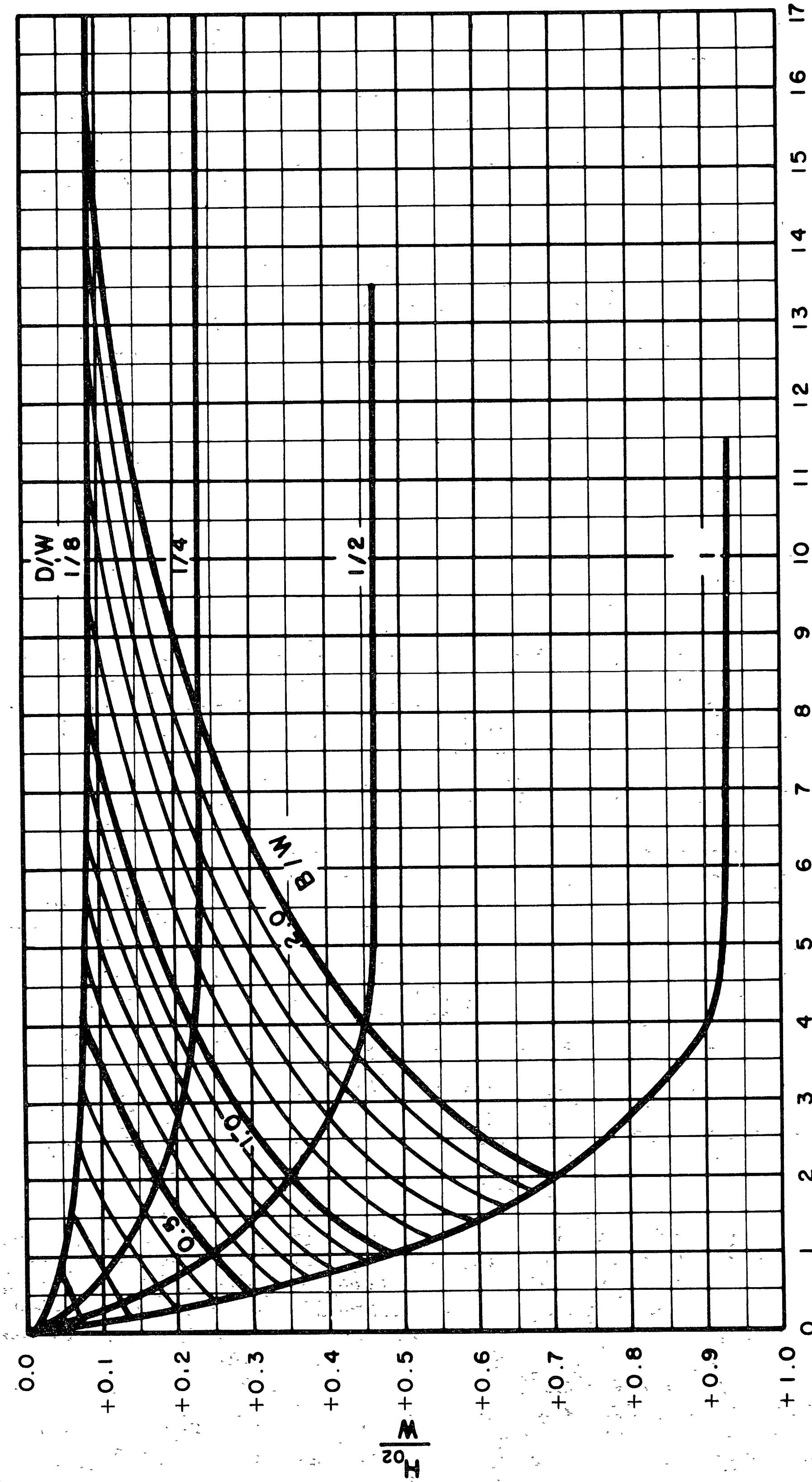

FIGURE 8.—Relative head correction, with control at headwall opening.

TABLE 5.—*Coefficient of discharge (control at headwall opening)*

[c_2 in $Q=c_2 W\sqrt{2g}(H+H_{02})^{3/2}$]

Coefficient of discharge	D/W										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
c_2	0. 34	0. 34	0. 35	0. 35	0. 35	0. 36	0. 36	0. 37	0. 39	0. 40	0. 43
$c_2\sqrt{2g}$	2. 76	2. 76	2. 77	2. 78	2. 81	2. 85	2. 90	2. 99	3. 10	3. 22	3. 43

TABLE 6.—*Head correction H_{02}/D for $D/W \geq 0.25$ (control at headwall opening)*

B/D	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0. 00	0. 07	0. 13	0. 20	0. 25	0. 30	0. 35	0. 39	0. 42	0. 46
1	. 49	. 52	. 54	. 56	. 59	. 61	. 63	. 65	. 67	. 68
2	. 70	. 71	. 72	. 74	. 75	. 76	. 77	. 79	. 80	. 81
3	. 82	. 83	. 84	. 85	. 86	. 87	. 87	. 88	. 89	. 90
4	. 90	. 91	. 91	. 92	. 92	. 92	. 92	. 92	. 92	. 92
5	. 92	. 92	. 92	. 92	. 93	. 93	. 93	. 93	. 93	. 93
6	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93
7	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93
8	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93	. 93

charge is controlled by the headwall opening may be summarized as follows:

1. The general formulas are

$$Q=c_2 W\sqrt{2g}(H+H_{02})^{3/2} \qquad (3a)$$

and

$$H=\left(\frac{Q}{c_2 W\sqrt{2g}}\right)^{2/3}-H_{02} \qquad (3b)$$

2. The discharge coefficient c_2 may be obtained from figure 6 or from table 5.
3. The head correction H_{02} may be obtained from figure 8. If D/W is between ¼ and 1, inclusive, H_{02} may be more readily determined from figure 7 or from table 6.
4. The precision of the design curves and tables is probably within ±10 percent.

OUTLET DESIGN

The outlet is that part of the box inlet drop spillway located downstream from the headwall. Since the form of the outlet is determined largely by the manner in which the flow leaves the box inlet, it is pertinent to describe the outflow briefly. The water passing over the sides of a box inlet springs clear of the sidewalls and creates a space between the nappes and the sidewalls. These spaces are filled with water having a helical motion about a horizontal axis. At the exit of the box inlet the helices from the opposite sides of the spillway enter the outlet along the sidewalls and create a considerable disturbance and uneven distribution of flow across the outlet. It is this poor velocity distribution and attempts to improve it that cause the major problems in the development of the outlet.

Since the critical depth is used when computing the dimensions of the outlet, it will be discussed first. Then the two major parts of the outlet—the straight section and the stilling basin—are discussed.

Critical Depth

The critical depth is the depth at which water flows when its energy content is a minimum. As used here, the critical depth can be most conveniently computed by the equation

$$d_c=\sqrt[3]{\frac{(Q/W)^2}{g}} \qquad (4a)$$

where d_c is the critical depth in feet; Q is the discharge in cubic feet per second; W is the width of the spillway and the straight section of the outlet in feet; and g is the acceleration due to gravity and is equal to 32.2 feet per second per second. Because the exit of the stilling basin may be wider than the straight section, the critical depth at that point is

$$d_{ce}=\sqrt[3]{\frac{(Q/W_e)^2}{g}} \tag{4b}$$

where d_{ce} and W_e are the critical depth and width at the exit of the stilling basin.

Table 7 has been prepared to facilitate the use of equations 4a and 4b. There, the critical depth d_c or d_{ce} in feet is given for various discharges per unit width Q/W or Q/W_e in cubic feet per second per foot of width.

Straight Section

The straight section is used between the box inlet and the stilling basin to assist in breaking up the helical rollers described earlier, to improve the flow distribution, to make better use of the available tailwater, and to improve the scour pattern. The straight section has sidewalls located parallel to the outlet centerline and in line with the sides of the box inlet; that is, the straight-section width W is equal to the box-inlet width W.

If the straight section is too short it will not adequately perform its function of improving the performance of the outlet. The minimum length of the straight section is given by the equation

$$L_S=d_c\left(\frac{0.2}{B/W}+1\right) \tag{5}$$

for values of $B/W \geq 0.25$ where L_S is the minimum length of the straight section in feet, and B and W are the length and width of the box inlet in feet.

Ordinarily equation 5 will give a straight section that is too short for practical use. When this occurs the straight section may be lengthened to suit the site with assurance that it will still function properly. There is no reason that the straight section cannot be lengthened, covered, and used as a highway culvert if desired.

It is not intended that the box-inlet drop spillway be used for a straight-drop spillway where $B/W=0$ and the form of equation 5 requires uneconomically long straight sections for short box inlets. Since the minimum value of B/W used in developing equation 5 was 0.25, the equation should not be used for box inlets shorter than $B/W=0.25$.

Stilling Basin

The flared or stilling-basin section is used to remove destructive energy from the flow and to discharge water into the downstream channel in a manner that will not damage the bed, the banks, or the structure itself. The several features of the stilling-basin design require a number of steps.

Sidewall Flare

It will frequently be desirable and economical to flare the sidewalls of the stilling basin. Benefits achieved thereby may include less required tailwater depth, decrease in excavation for the entire structure, and better flow conditions in the downstream channel.

The sidewalls may be parallel extensions of the straight-section sidewalls or they may flare. Rates of flare of each sidewall up to two longitudinal to one transverse are permissible. If the sidewall flare is greater than two longitudinal to one transverse, the flow does not spread out rapidly enough to follow the sidewalls, the main stream will be concentrated at the center of the stilling basin, and whirls will develop between the stream and the walls. Flares greater than 1 in 2 thus become wasteful of construction materials and at the same time produce poorer flow conditions in the stilling basin and downstream channel. The choice between the limits 1 in ∞ (no flare) and 1 in 2 depends on site conditions; the broad permissible limits allow the adaptation of the outlet to almost any field situation.

Basin Length

For economy in construction the flared or stilling-basin section should be made as short as possible, but it must be long enough to dissipate the energy in the flow. The basin must be proportionately longer for the short box inlets than for the long box inlets because of the manner in which the water leaves the box inlet. The equation for the minimum length of stilling basin L_B is

$$L_B=\frac{L}{2B/W} \tag{6}$$

for values of $B/W \geq 0.25$. Greater stilling-basin lengths may be used, but it will be more economical to lengthen the straight section; lesser stilling-basin lengths should never be used.

Equation 6, like equation 5, should not be used when B/W is less than 0.25.

Tailwater Level

The minimum tailwater depth d_2 above the floor of the stilling basin required for proper energy dissipation is ordinarily a function of the critical depth at the end of the stilling basin d_{ce}. However, when the stilling-basin exit is too wide, still or nearly still water exists along the sidewalls of the basin. That part of the outlet occupied by still water is obviously not being used to dissipate energy and can be eliminated. Still water occurs along the sidewalls when the stilling-basin exit is wider than $11.5d_{ce}$.

Two equations are necessary to determine the required tailwater depth. When the stilling-basin exit width W_e is less than $11.5d_{ce}$, the depth of tailwater above the stilling-basin floor d_2 is given by the equation

$$d_2=1.6d_{ce} \tag{7a}$$

and when W_e is greater than $11.5d_{ce}$ the tailwater depth is

$$d_2=d_{ce}+0.052W_e \tag{7b}$$

If it is desirable to measure the tailwater depth from the top of the end sill d_3 rather than from the floor of the stilling basin d_2, equation 7a should be changed to read

$$d_3=1.33d_{ce} \tag{8a}$$

and equation 7b should read

$$d_3=0.83d_{ce}+0.043W_e \tag{8b}$$

Satisfactory results can be obtained with wide stilling-basin outlets and equations 7b or 8b, but the wider basins make inefficient use of the outlet and will be more expensive than a basin with a narrower outlet width. Tailwater depths greater than that given by equations 7a and 7b or 8a and 8b may be used; lesser depths will result in greater scour in the downstream channel.

End Sill

The end sill deflects upward the stream leaving the stilling basin, prevents scour close to the exit of the stilling basin, and creates a horizontal roller under the deflected stream with the velocity at the bed directed upstream, thus actually bringing material upstream and depositing the larger material at the end of the stilling basin.

The height of the end sill is very important. When the end sill is too high, the jet leaving the basin jumps over the sill and lands some distance out from the end of the basin, causing severe erosion at that particular location. On the other hand, when the end sill is too low, the water leaving the basin causes the same severe erosion but it occurs very near the end of the basin. The most satisfactory height of the end sill f is given by the equation

$$f=d_2/6 \tag{9}$$

Longitudinal Sills

Longitudinal sills are used in the straight section and stilling basin to assist in the distribution of the flow across the stilling basin, to prevent high velocities at the sides of the basin, and to reduce the scour at the end of the basin and the erosion of the stream banks. The sills may also be used for structural purposes.

The following rules should be used to determine the size and arrangement of the longitudinal sills:

1. When the stilling basin sidewalls are parallel, the longitudinal sills may be omitted.
2. The center pair of longitudinal sills should start at the exit of the box inlet and extend through the straight section and stilling basin to the end sill.
3. When W_e is less than $2.5W$, only two sills are needed. These sills should be located on either side of the centerline at a distance p of $W/6$ to $W/4$.
4. When W_e exceeds $2.5W$, an additional pair of sills is required. These sills are located parallel to the outlet centerline and midway between the center sills and the sidewalls at the exit of the stilling basin.
5. The height of the longitudinal sills is the same as the height of the end sill.

Sidewall Height

The sidewalls must extend above the tailwater level at the end of the stilling basin by an amount sufficient to prevent overtopping and the resulting erosion of the dam fill. Rough water in the stilling basin requires a greater freeboard than is frequently used in open ditches. The minimum height of the sidewalls above the water surface at the end of the stilling basin t should be

$$t=d_2/3 \tag{10}$$

or greater. All the rules presented here are based on sidewalls extending above the tailwater level, even where submergence must be considered. Under submerged flow conditions much higher sidewalls may be required; however, the freeboard above the tailwater level may be safely reduced somewhat because the water surface will be smoother.

Wingwalls

The shape and the position of the wingwalls have more effect on the scour of the bed and the dam fill near the end of the stilling basin than has been commonly supposed. Considerable study was given to the shape and location of wingwall that would best protect the dam fill.

A wingwall triangular in elevation is greatly superior to a rectangular wingwall. Its top should slope downward at an angle of 45° with the horizontal. However, if conditions make it desirable to use a flatter slope, the top may have a slope as flat as 30° without changing the anticipated scour significantly.

In plan, the wingwalls should flare at an angle θ of 60° with the outlet centerline, although a flare of 45° would probably make no significant change in the anticipated scour. Wingwalls located parallel to the centerline will cause no deeper scour, but they will cause more extensive bed scour between the wingwalls and are not recommended.

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TABLE 7.—*Critical depths in feet for various discharges per foot of width*

$\frac{Q}{W}$	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0	0.000	0.068	0.107	0.141	0.171	0.198	0.224	0.248	0.271	0.293
1	.314	.335	.355	.374	.393	.412	.430	.448	.465	.482
2	.499	.515	.532	.548	.563	.579	.594	.609	.624	.639
3	.654	.668	.683	.697	.711	.725	.738	.752	.765	.779
4	.792	.805	.818	.831	.844	.857	.869	.882	.894	.907
5	.919	.931	.943	.955	.967	.979	.991	1.003	1.015	1.026
6	1.038	1.049	1.061	1.072	1.084	1.095	1.106	1.117	1.128	1.139
7	1.150	1.161	1.172	1.183	1.194	1.204	1.215	1.226	1.236	1.247
8	1.257	1.268	1.278	1.289	1.299	1.309	1.319	1.330	1.340	1.350
9	1.360	1.370	1.380	1.390	1.400	1.410	1.420	1.430	1.439	1.449
10	1.459	1.469	1.478	1.488	1.498	1.507	1.517	1.526	1.536	1.545
11	1.555	1.564	1.573	1.583	1.592	1.601	1.611	1.620	1.629	1.638
12	1.648	1.657	1.666	1.675	1.684	1.693	1.702	1.711	1.720	1.729
13	1.738	1.747	1.756	1.764	1.773	1.782	1.791	1.800	1.808	1.817
14	1.826	1.835	1.843	1.852	1.860	1.869	1.878	1.886	1.895	1.903
15	1.912	1.920	1.929	1.937	1.946	1.954	1.962	1.971	1.979	1.988
16	1.996	2.004	2.012	2.021	2.029	2.037	2.045	2.054	2.062	2.070
17	2.078	2.086	2.094	2.103	2.111	2.119	2.127	2.135	2.143	2.151
18	2.159	2.167	2.175	2.183	2.191	2.199	2.207	2.215	2.222	2.230
19	2.238	2.346	2.254	2.262	2.269	2.277	2.285	2.293	2.301	2.308
20	2.316	2.324	2.331	2.339	2.347	2.354	2.362	2.370	2.377	2.385
21	2.393	2.400	2.408	2.415	2.423	2.430	2.438	2.445	2.453	2.460
22	2.468	2.475	2.483	2.490	2.498	2.505	2.513	2.520	2.527	2.535
23	2.542	2.549	2.557	2.564	2.572	2.579	2.586	2.593	2.601	2.608
24	2.615	2.623	2.630	2.637	2.644	2.652	2.659	2.666	2.673	2.680
25	2.687	2.695	2.702	2.709	2.716	2.723	2.730	2.737	2.744	2.752
26	2.759	2.766	2.773	2.780	2.787	2.794	2.801	2.808	2.815	2.822
27	2.829	2.836	2.843	2.850	2.857	2.864	2.871	2.878	2.885	2.891
28	2.898	2.905	2.912	2.919	2.926	2.933	2.940	2.946	2.953	2.960
29	2.967	2.974	2.981	2.987	2.994	3.001	3.008	3.015	3.021	3.028
30	3.035	3.042	3.048	3.055	3.062	3.068	3.075	3.082	3.089	3.095
31	3.102	3.109	3.115	3.122	3.129	3.135	3.142	3.148	3.155	3.162
32	3.168	3.175	3.181	3.188	3.195	3.201	3.208	3.214	3.221	3.227
33	3.234	3.240	3.247	3.253	3.260	3.266	3.273	3.279	3.286	3.292
34	3.299	3.305	3.312	3.318	3.325	3.331	3.338	3.344	3.350	3.357
35	3.363	3.370	3.376	3.383	3.389	3.396	3.402	3.408	3.414	3.421
36	3.427	3.433	3.440	3.446	3.452	3.459	3.465	3.471	3.478	3.484
37	3.490	3.496	3.503	3.509	3.515	3.522	3.528	3.534	3.540	3.547
38	3.553	3.559	3.565	3.571	3.578	3.584	3.590	3.596	3.603	3.609
39	3.615	3.621	3.627	3.633	3.640	3.646	3.652	3.658	3.664	3.670
40	3.676	3.683	3.689	3.695	3.701	3.707	3.713	3.719	3.725	3.731
41	3.737	3.743	3.750	3.756	3.762	3.768	3.774	3.780	3.786	3.792
42	3.798	3.804	3.810	3.816	3.822	3.828	3.834	3.840	3.846	3.852
43	3.858	3.864	3.870	3.876	3.882	3.888	3.894	3.900	3.906	3.912
44	3.918	3.924	3.929	3.935	3.941	3.947	3.953	3.959	3.965	3.971
45	3.977	3.983	3.988	3.994	4.000	4.006	4.012	4.018	4.024	4.030
46	4.035	4.041	4.047	4.053	4.059	4.065	4.070	4.076	4.082	4.088
47	4.094	4.099	4.105	4.111	4.117	4.123	4.128	4.134	4.140	4.146
48	4.152	4.157	4.163	4.169	4.175	4.180	4.186	4.192	4.198	4.203
49	4.209	4.215	4.220	4.226	4.232	4.238	4.243	4.249	4.255	4.260
50	4.266									

Summary (Outlet Design)

The preceding rules for the design of the outlet for a box-inlet drop spillway may be summarized as follows:

1. The critical depth in the straight section is

$$d_c=\sqrt[3]{\frac{(Q/W)^2}{g}} \tag{4a}$$

2. The critical depth at the exit of the stilling basin is

$$d_{ce}=\sqrt[3]{\frac{(Q/W_e)^2}{g}} \tag{4b}$$

3. The minimum length of the straight section is

$$L_S=d_c\left(\frac{0.2}{B/W}+1\right) \tag{5}$$

for values of $B/W \geq 0.25$. Greater lengths of straight section may be used.

4. The sidewalls of the stilling basin may flare from 1 in ∞ (parallel extensions of the straight section walls) to 1 in 2.
5. The minimum length of the stilling basin is

$$L_B=\frac{L}{2B/W} \tag{6}$$

for values of $B/W \geq 0.25$. Longer lengths of stilling basin may be used but it will require less material if the straight section is lengthened to obtain the same overall outlet length.

6a. When the stilling basin is less than $11.5d_{ce}$ wide at its exit, the minimum tailwater depth over the basin floor is

$$d_2=1.6d_{ce} \tag{7a}$$

If the tailwater depth is measured from top of the end sill, its depth is

$$d_3=1.33d_{ce} \tag{8a}$$

6b. When the stilling basin is more than $11.5d_{ce}$ wide at its exit, the minimum tailwater depth over the basin floor is

$$d_2=d_{ce}+0.052W_e \tag{7b}$$

If the tailwater depth is measured from the top of the end sill, its depth is

$$d_3=0.83d_{ce}+0.043W_e \tag{8b}$$

However, stilling basins as wide as $11.5d_{ce}$ may make inefficient use of the outlet.

6c. Greater tailwater depths may be used; lesser depths will cause more scour in the downstream channel.

7. The height of the end sill is

$$f=d_2/6 \tag{9}$$

8. Longitudinal sills will improve the flow distribution in the outlet. They should be located as follows:
   a. When the stilling basin sidewalls are parallel, the longitudinal sills may be omitted.
   b. The center pair of longitudinal sills should start at the exit of the box inlet and extend through the straight section and stilling basin to the end sill.
   c. When W_e is less than $2.5W$, only two sills are needed. These sills should be located at a distance p of $W/6$ to $W/4$ each side of the centerline.
   d. When W_e exceeds $2.5W$, two additional sills are required. These sills should be located parallel to the outlet centerline and midway between the center sills and the sidewalls at the exit of the stilling basin.
   e. The height of the longitudinal sills is the same as the height of the end sill.
9. The minimum height of the sidewalls above the water surface at the exit of the stilling basin should be

$$t=d_2/3 \tag{10}$$

or greater. The sidewalls should extend above the tailwater surface under all conditions.

10a. The wingwalls should be triangular in elevation and have a top slope of 45° with the horizonal. Top slopes as flat as 30° are permissible.

10b. The wingwalls should flare in plan at an angle of 60° with the outlet centerline. Flare angles of 45° are permissible. Wingwalls parallel to the outlet centerline are not recommended.

SUBMERGED-FLOW CAPACITY

Submergence decreases the capacity of the box-inlet drop spillway whenever the tailwater level is nearly up to or above the crest of the box inlet. There are many locations where high tailwater levels may affect the flow, particularly in drainage work or where the "island dam" type of design is used. Therefore, an evaluation of the submergence effect is necessary in order to make complete the information required for the design of box-inlet drop spillways.

In this report the submergence effect is measured by the increase in head ΔH over the free-flow head H for the same discharge. The submergence is measured by the height of the tailwater H_t above the crest of the box inlet. The ratios $\Delta H/H$ and H_t/H are used when plotting and analyzing the results.

The factors that affect the flow when the tailwater level is high are discussed in the following paragraphs. Curves for evaluating the effect of submergence on the flow through box-inlet drop spillways are shown.

Factors Influencing Submergence Effect

Several factors that affect the free-flow capacity of the box-inlet drop spillway have no effect on the submerged-flow capacity; on the other hand, some of those factors that have no effect on the free-flow capacity do have a significant effect on the submerged-flow capacity. The two factors having the greatest effect on the submerged-flow capacity are the discharge and the width of the stilling-basin exit. They, as well as several factors that have no effect on the submerged-flow capacity, will be discussed.

Discharge

The fact that the submergence effect varies with the discharge complicates the determination of that effect. Under some conditions the variation is not particularly great, but under other conditions the variation is very large. The submergence effect increases with the discharge up to a certain point, but with further increases in the discharge the submergence effect decreases. These facts may be verified by reference to the submergence curves shown in figures 9 to 44 (pp. 17 to 35). The discharge that produces the greatest submergence effect apparently coincides with that point on the free-flow rating curve where the control section changes from the box-inlet crest to the headwall opening.

Outlet-Exit Width

The flare angle of the sidewalls has no direct effect on the submergence, but the width of the stilling basin at its exit W_e apparently determines the magnitude of the submergence effect. The wider the exit, within certain limits, the less will be the effect of submergence. Apparently, there is little or no advantage in making the outlet wider than $1.5W$, since with wider outlets the decrease in submergence effect is nil. The effect of outlet width can be determined by comparing the submergence curves for different outlet widths when the other variables have identical values.

Other Factors

The length of the straight section of the outlet has no influence on the submergence. Also, since the presence or absence of bed and banks in the experimental test channel had no direct influence on the submergence effect, it is assumed that variations in the locations of the bed and banks will be unimportant under field conditions.

Submergence Curves

The submergence curves shown on pages 17 to 35 may be used to evaluate the effect of high tailwater levels on the capacity of box-inlet drop spillways. All attempts to systematize further or condense the data proved unfruitful, and as a result the curves are more voluminous than is desirable. Even so, it is realized that the curves presented may not completely cover the range of conditions experienced in the application of the results.

Each of the 36 appended figures represents a different combination of B/W, D/W, and W_e/W. Reference to table 8 will give the figure number for any of the various combinations of variables. The several submergence curves in each figure are for different discharges and represent values of the ratio $Q/W^{5/2}$ equal to 0.6, 1.0, 1.5, 2.0, 3.0, 4.0, and sometimes 5.0 and 6.0. (*Table 5–2* in King's "Handbook of Hydraulics" [11] gives the five-halves powers of numbers and may be used to facilitate the computation of this ratio.) Some curves for different values of $Q/W^{5/2}$ coincide; others fall so close together that it was not possible to show them separately in the figures, and these were combined into a single average curve. The differences between the extreme and the mean curves are in no case greater than half the distance to the nearest curve of $0.05\Delta H/H$, whichever is the lesser.

Computation of Submergence Effect

The computation for the effect of submergence requires a prior knowledge of the dimensions B, D, W, and W_e of the box-inlet drop spillway, the discharge Q, and the tailwater level referred to the box-inlet crest H_t. The computation procedure to determine the increase in head caused by submergence is as follows:

1. Compute the ratios B/W, D/W, and W_e/W and select the proper figure from table 8.

[11] See footnote 7.

2. Compute the ratio $Q/W^{5/2}$ and select the proper submergence curve.
3. Compute the head H for free-flow conditions.
4. Compute the ratio H_t/H, enter the figure with this value, and read the value of $\Delta H/H$ corresponding to the intersection of H_t/H and $Q/W^{5/2}$.
5. Multiply $\Delta H/H$ by H to obtain the increase in head ΔH caused by submergence.
6. Add ΔH to H to give the actual head above the spillway under submerged-flow conditions.

Interpolation will be necessary if values other than those given in figures 9 to 44, inclusive, are desired. If the discharge is not known, the submergence effect can be determined only by the process of successive approximations.

TABLE 8.—*Figure numbers for submergence curves*

$\frac{B}{W}$	$\frac{D}{W}$	W_e/W			
		1.0	1.25	1.5	2.0
0. 5	0. 25	9	10	11	12
	. 5	13	14	15	16
	1. 0	17	18	19	20
1. 0	. 25	21	22	23	24
	. 5	25	26	27	28
	1. 0	29	30	31	32
2. 0	. 25	33	34	35	36
	. 5	37	38	39	40
	1. 0	41	42	43	44

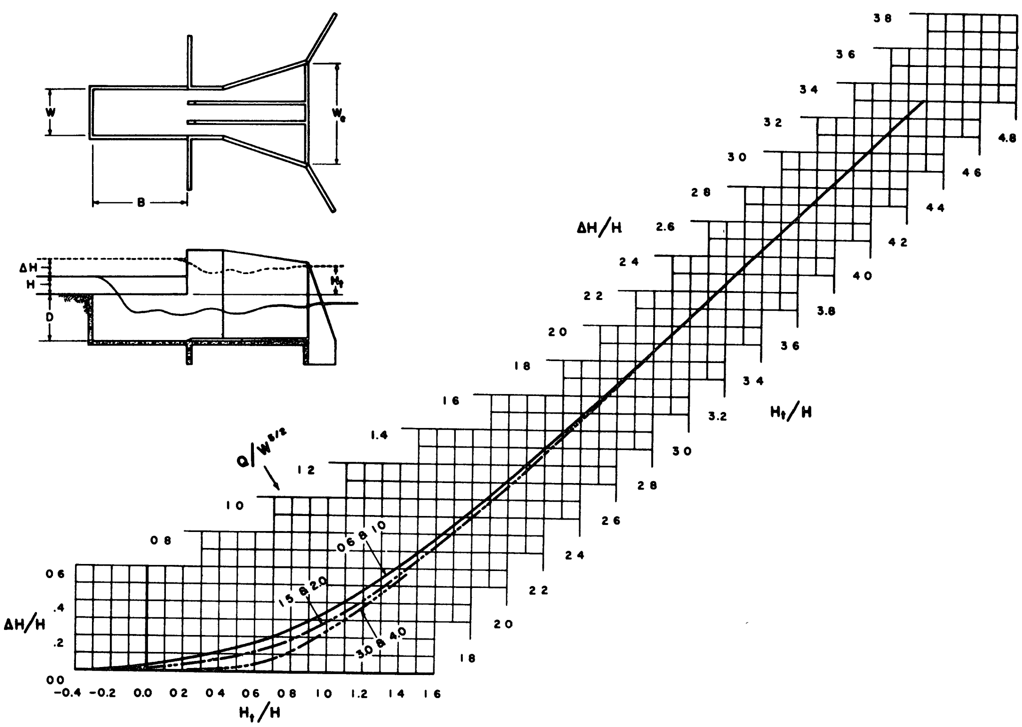

FIGURE 9.—Effect of submergence:

$\frac{B}{W}=0.5;\ \frac{D}{W}=0.25;\ \frac{W_e}{W}=1.0.$

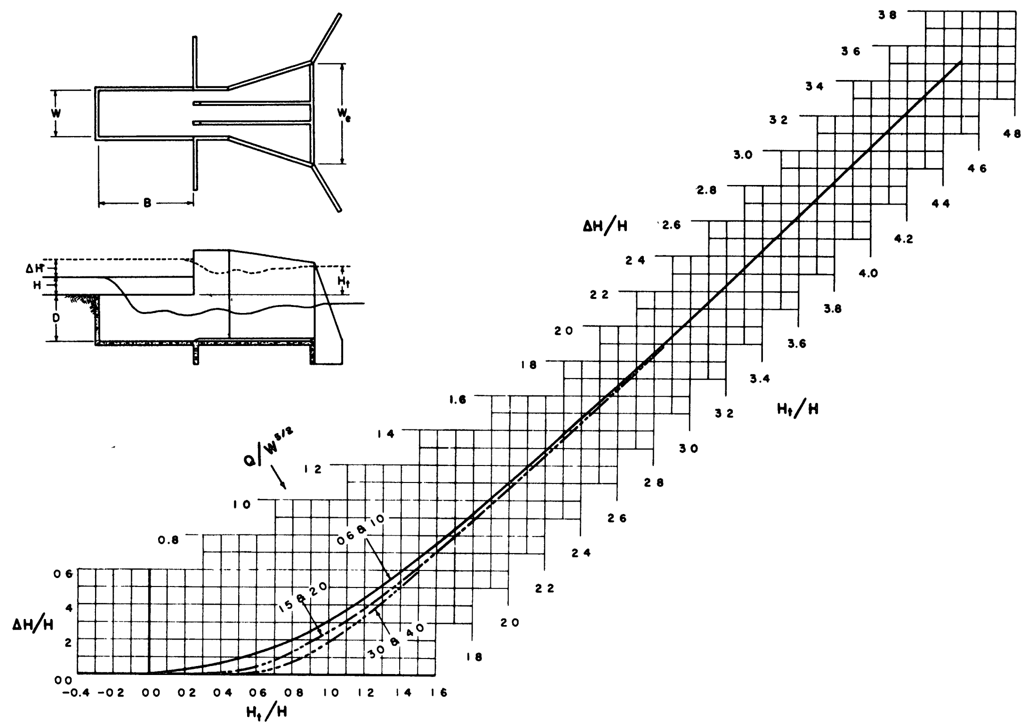

FIGURE 10.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.25$.

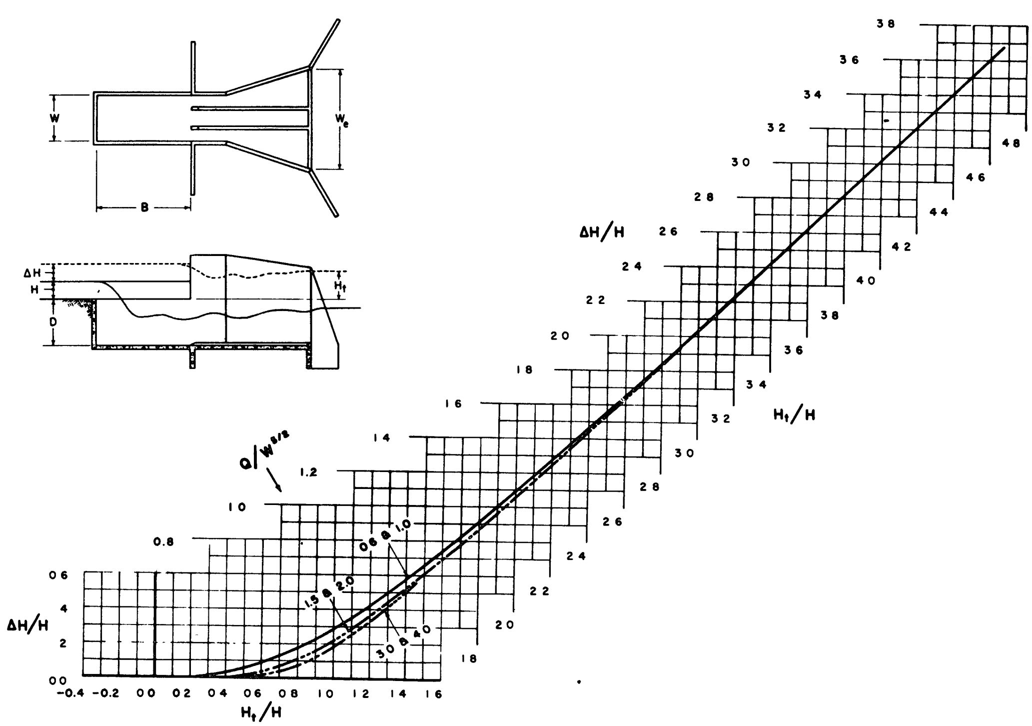

FIGURE 11.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.5$.

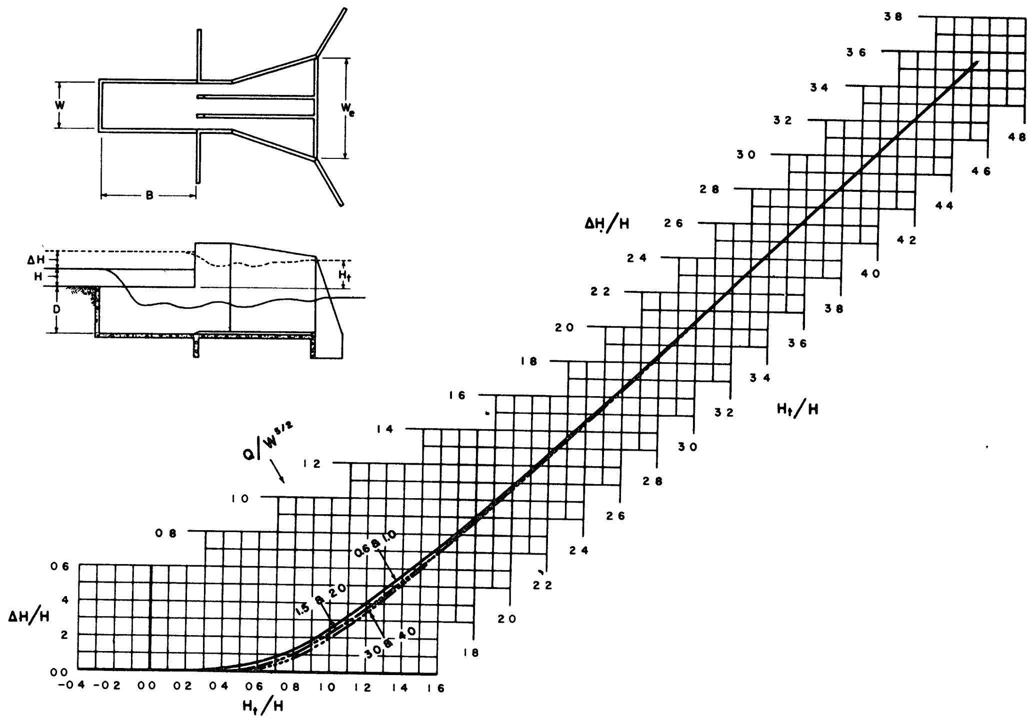

FIGURE 12.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=2.0$.

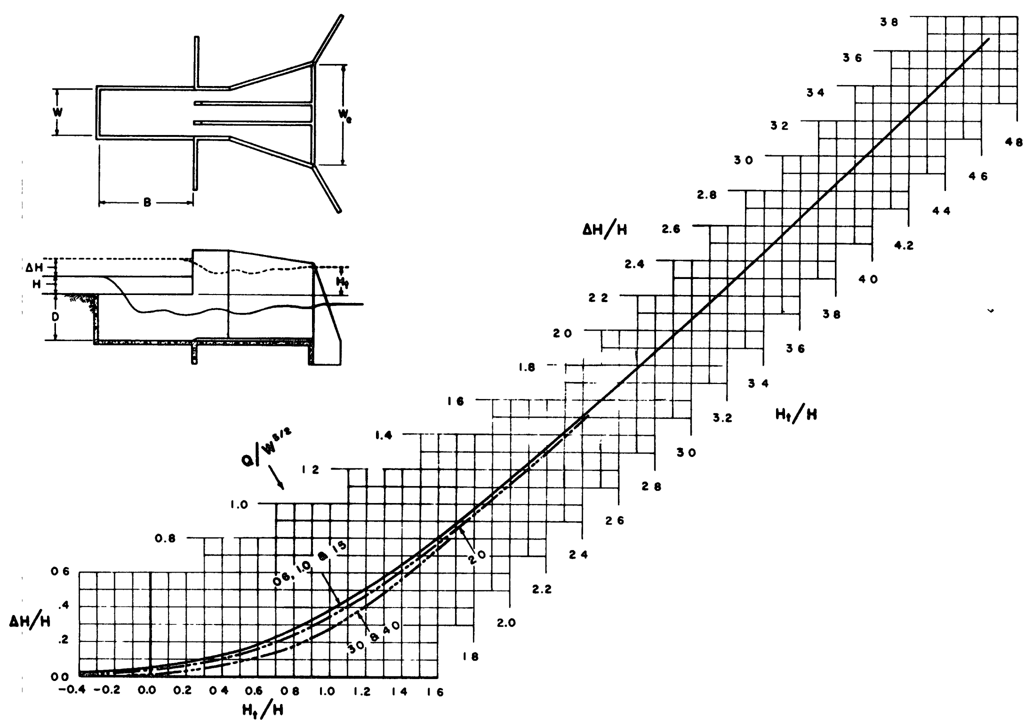

FIGURE 13.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.0$.

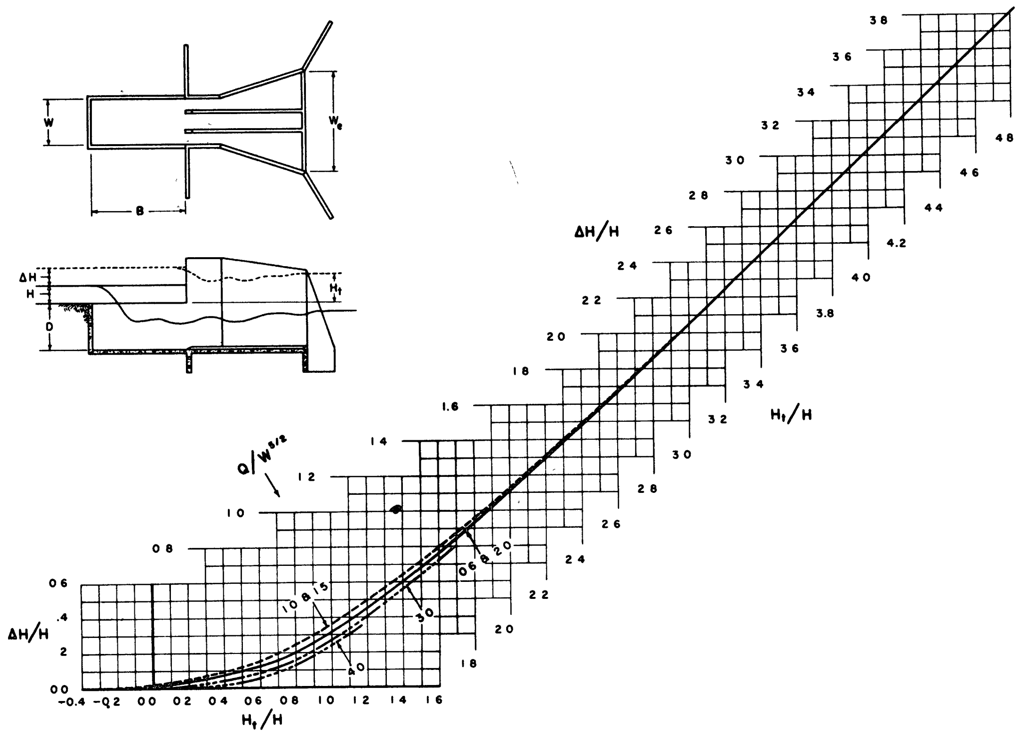

FIGURE 14.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.25$.

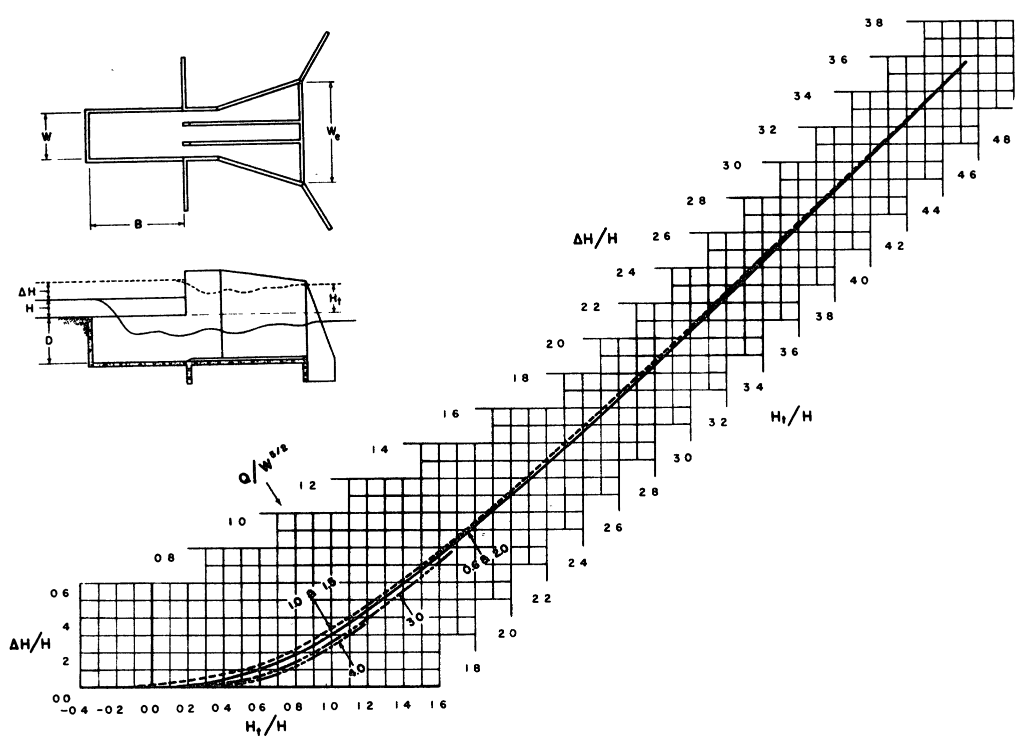

FIGURE 15.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.5$.

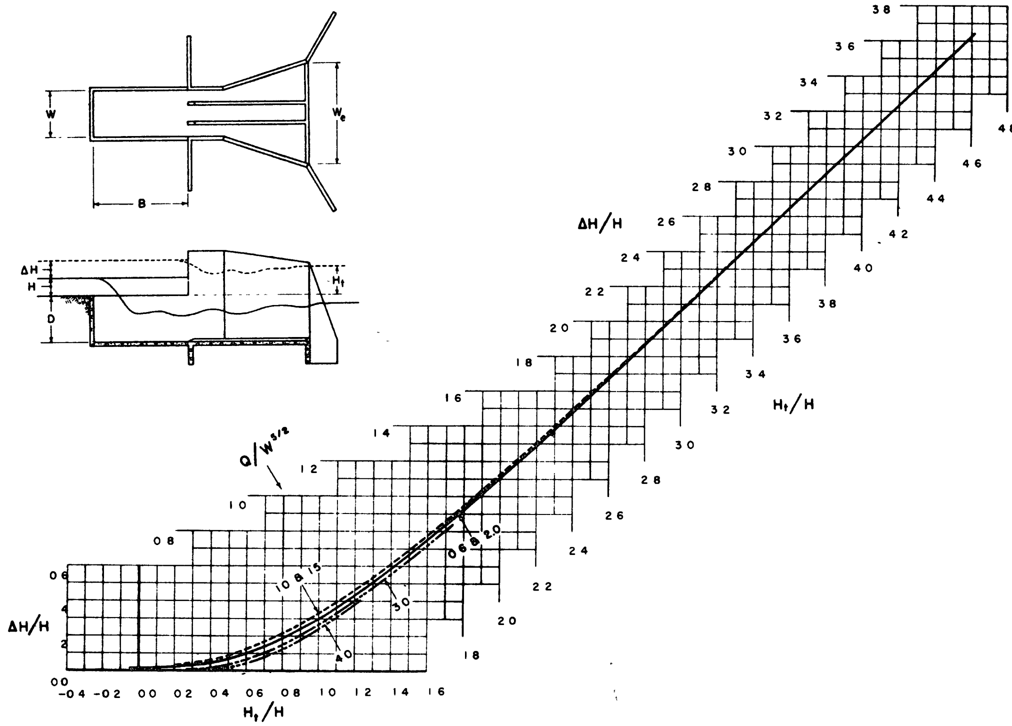

FIGURE 16.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=2.0$.

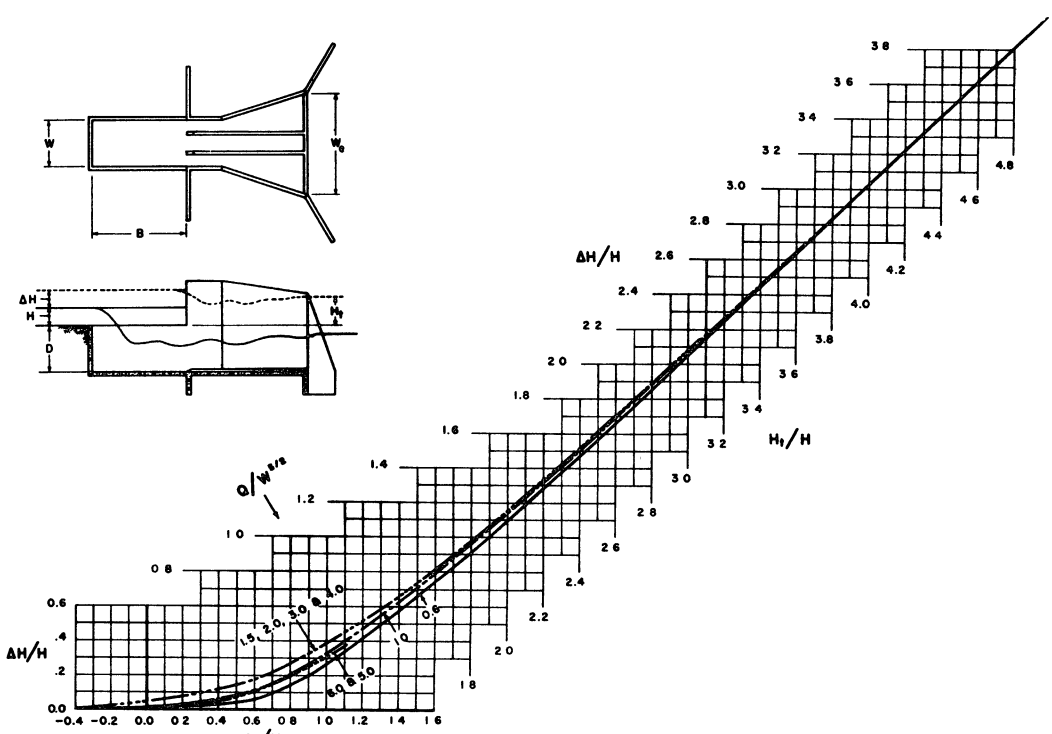

FIGURE 17.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.0$.

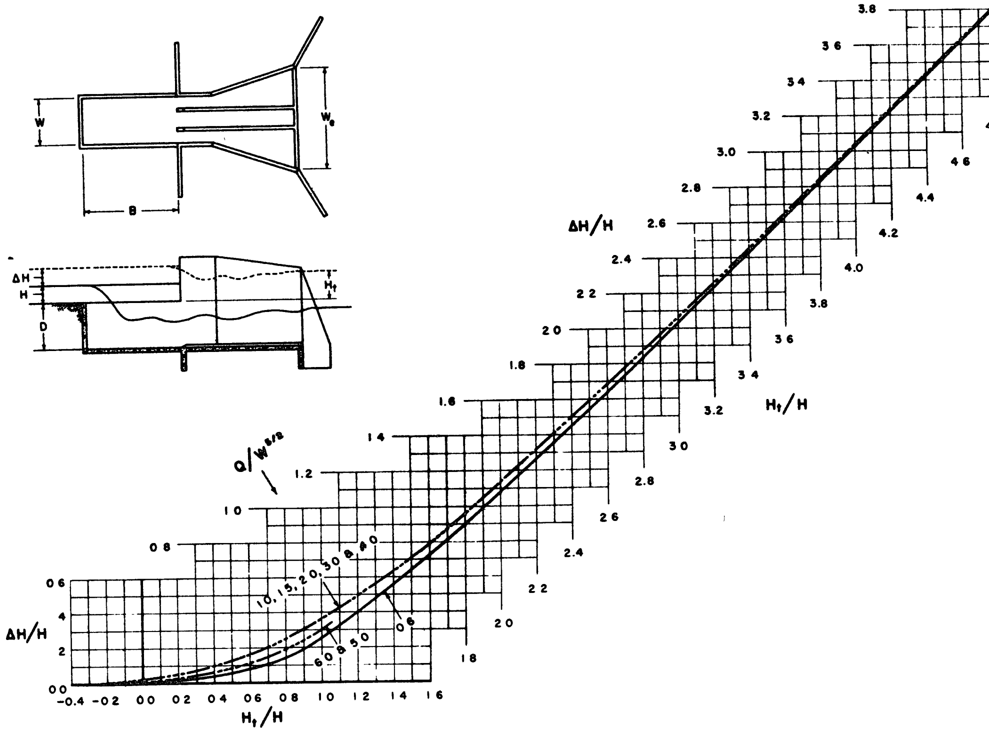

FIGURE 18.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.25$.

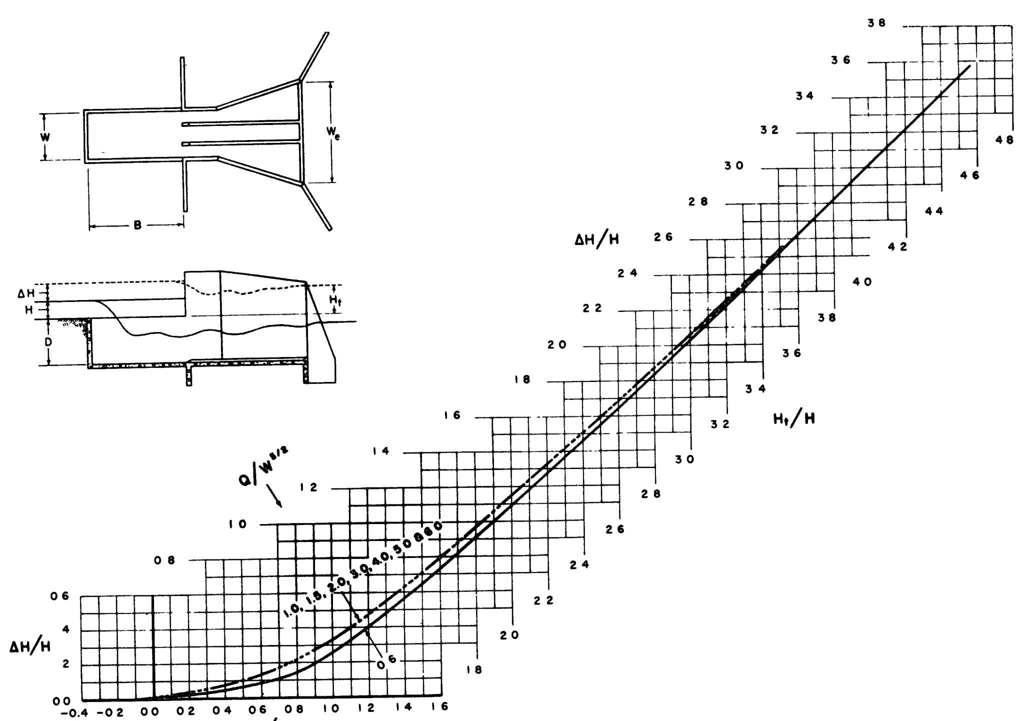

FIGURE 19.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.5$.

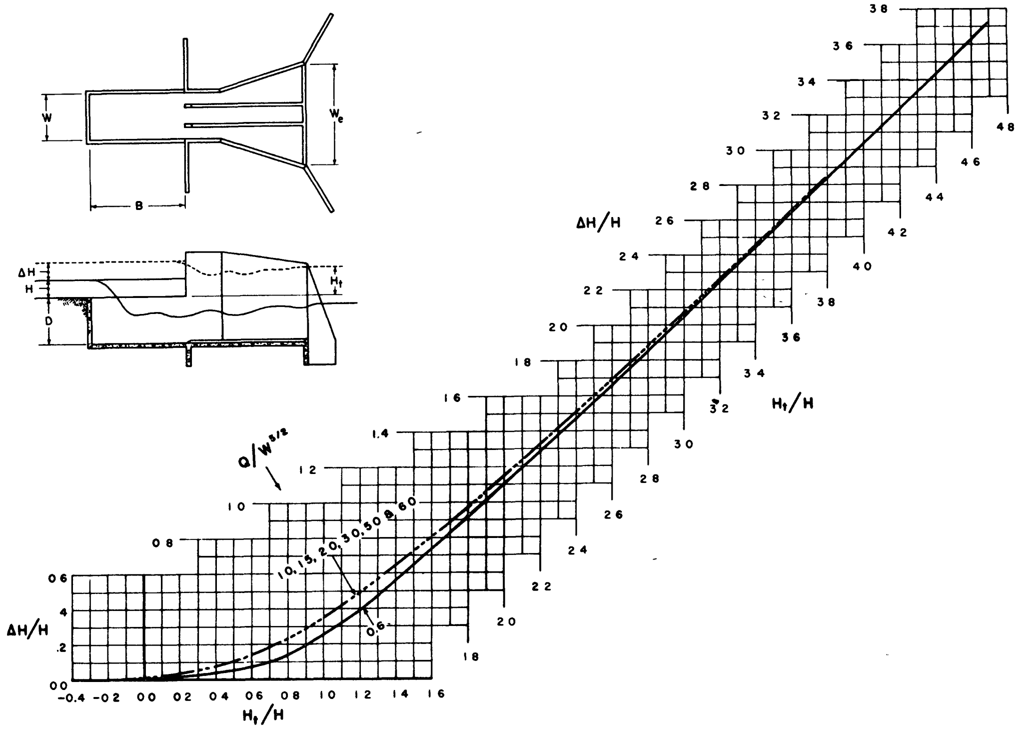

FIGURE 20.—Effect of submergence: $\frac{B}{W}=0.5$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=2.0$.

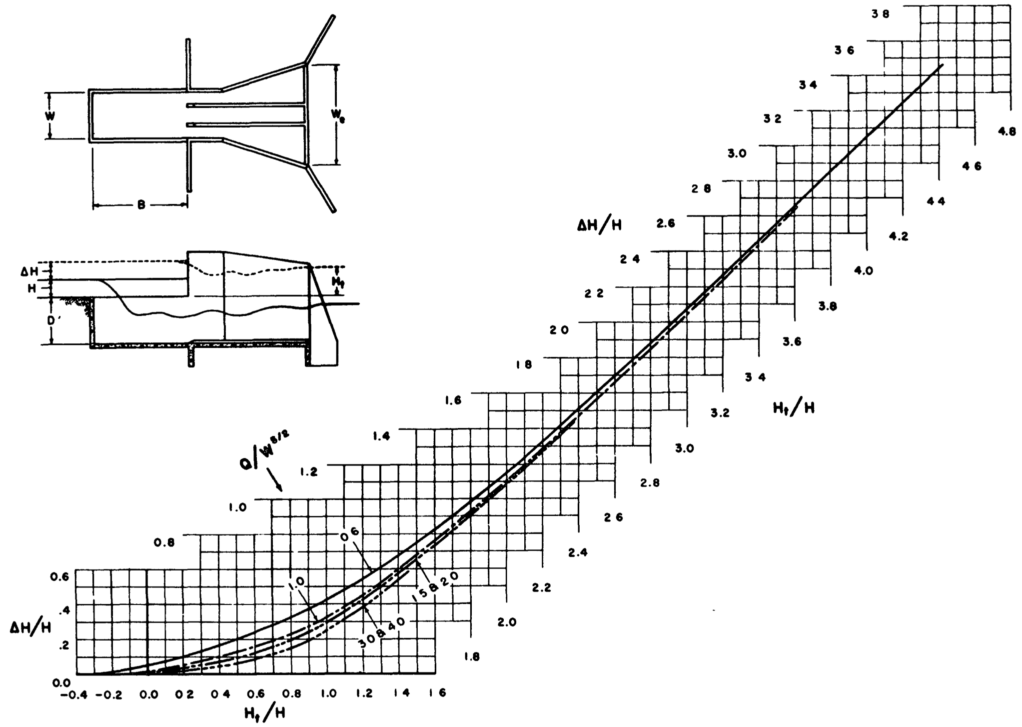

FIGURE 21.—Effect of submergence: $\frac{B}{W}=1.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.0$.

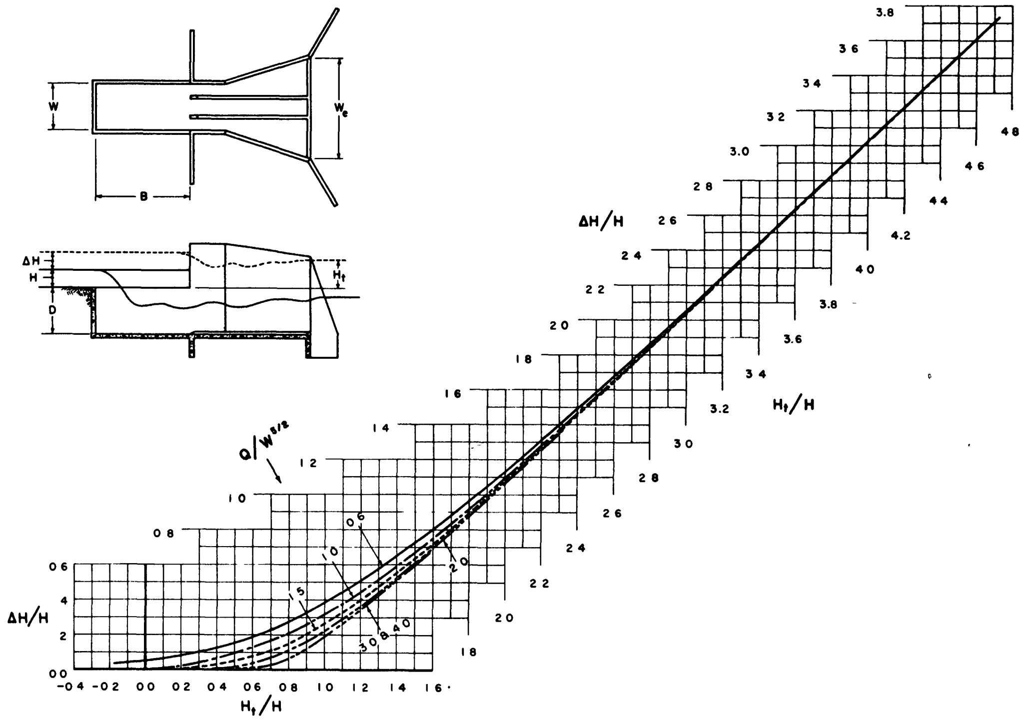

FIGURE 22.—Effect of submergence: $\frac{B}{W}=1.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.25$.

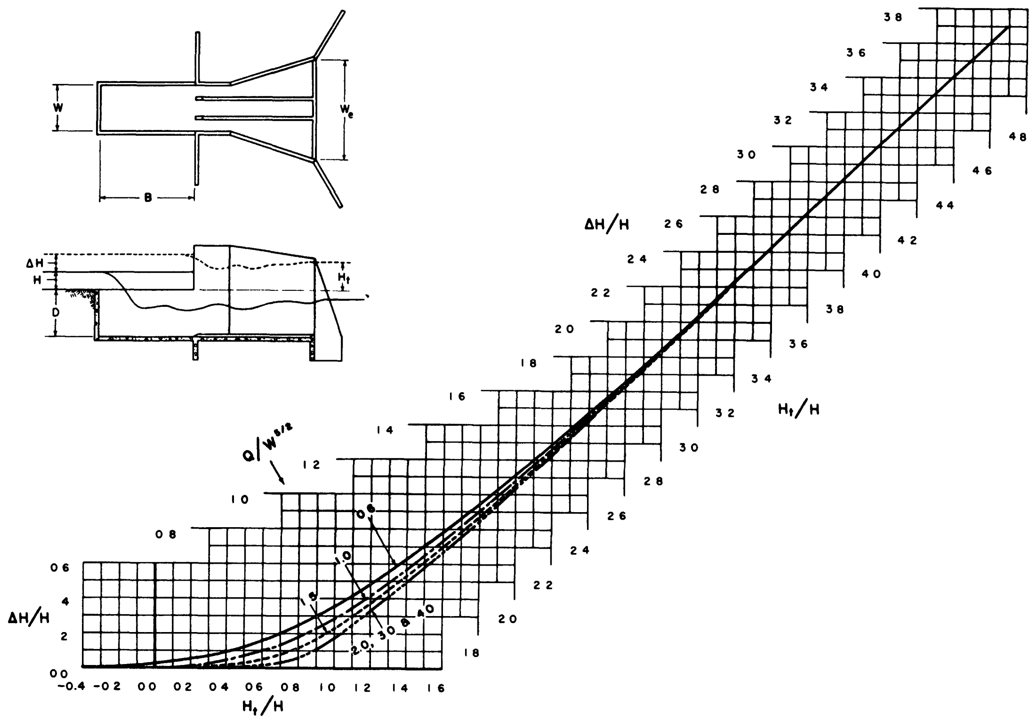

FIGURE 23.—Effect of submergence: $\frac{B}{W}=1.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.5$.

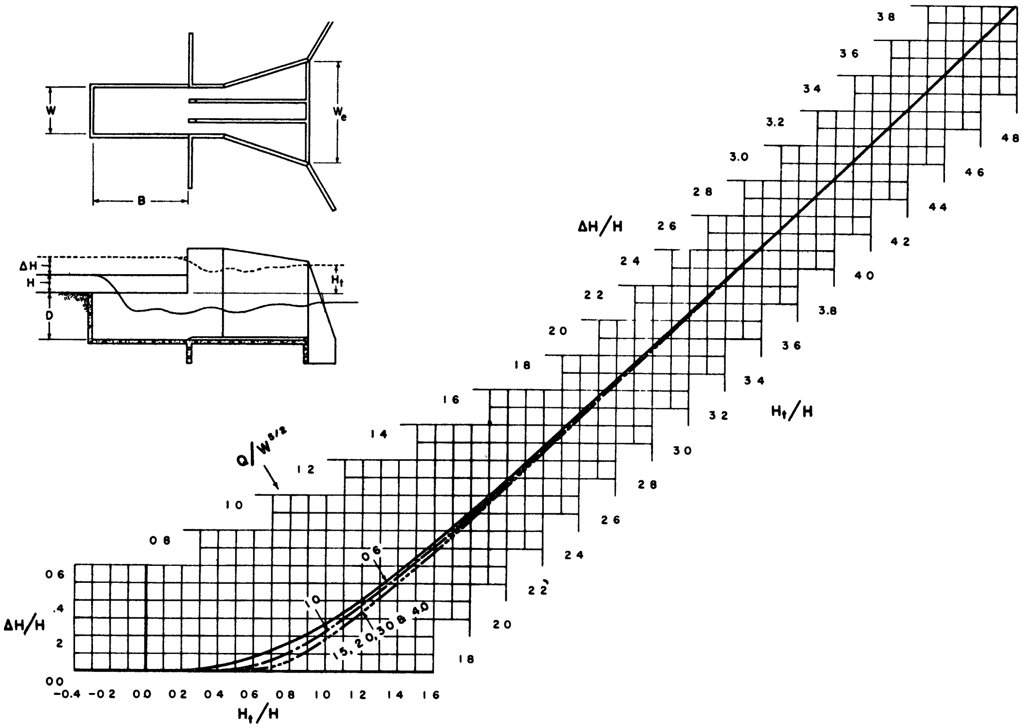

FIGURE 24.—Effect of submergence:

$$\frac{B}{W}=1.0;\ \frac{D}{W}=0.25;\ \frac{W_e}{W}=2.0.$$

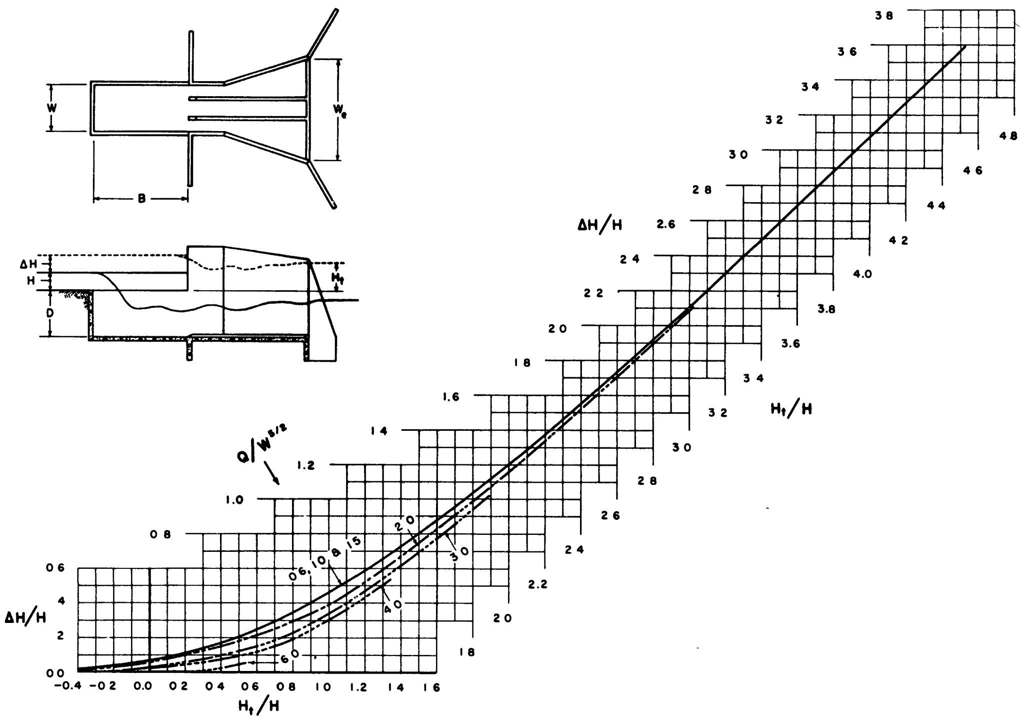

FIGURE 25.—Effect of submergence:

$$\frac{B}{W}=1.0;\ \frac{D}{W}=0.5;\ \frac{W_e}{W}=1.0.$$

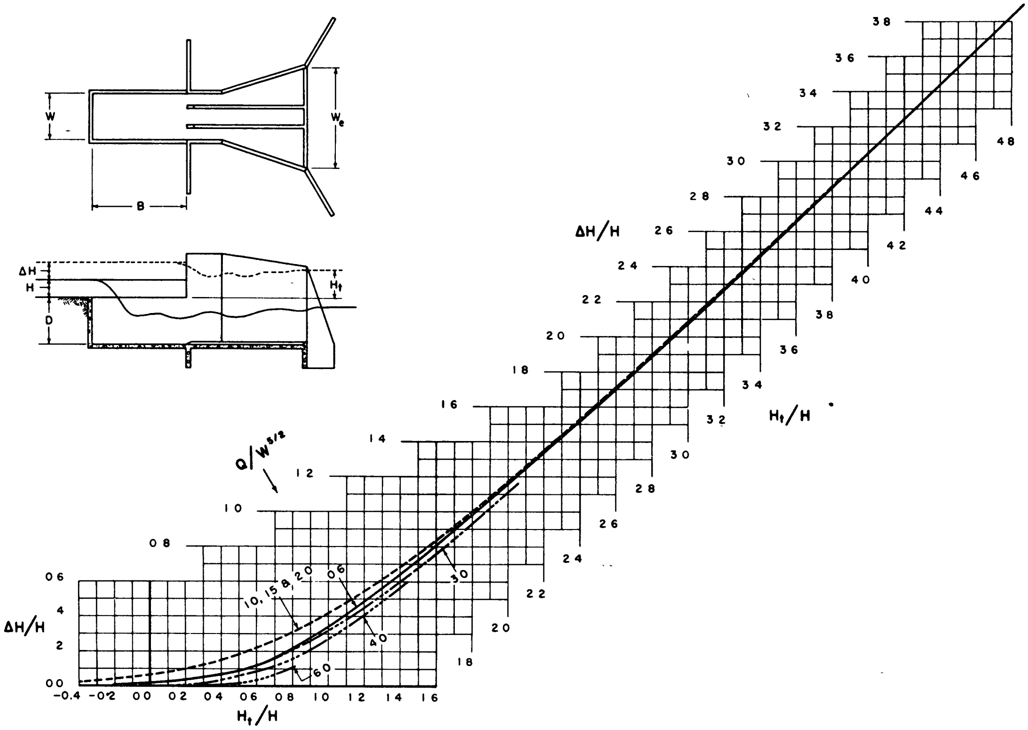

FIGURE 26.—Effect of submergence: $\frac{B}{W}=1.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.25$.

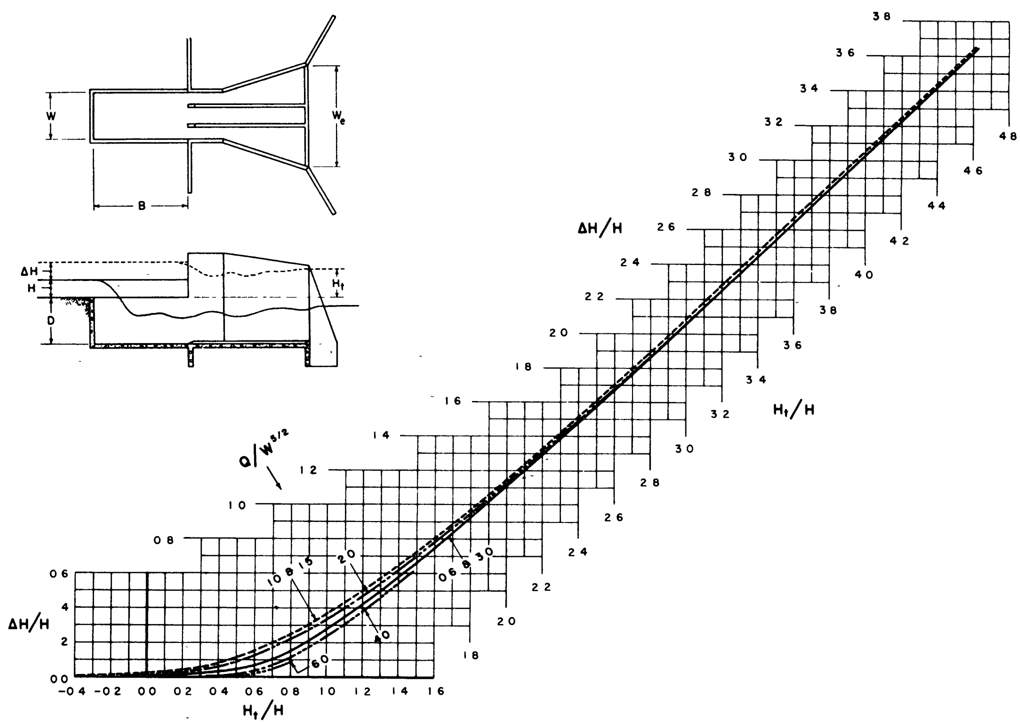

FIGURE 27.—Effect of submergence: $\frac{B}{W}=1.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.5$.

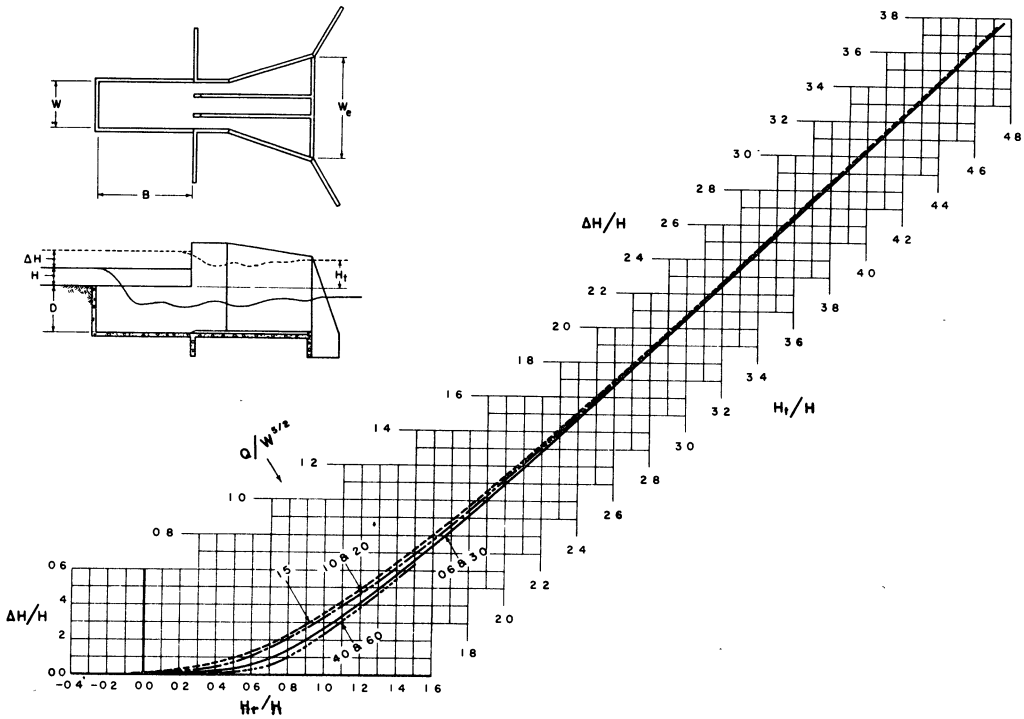

FIGURE 28.—Effect of submergence:
$\frac{B}{W}=1.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=2.0$.

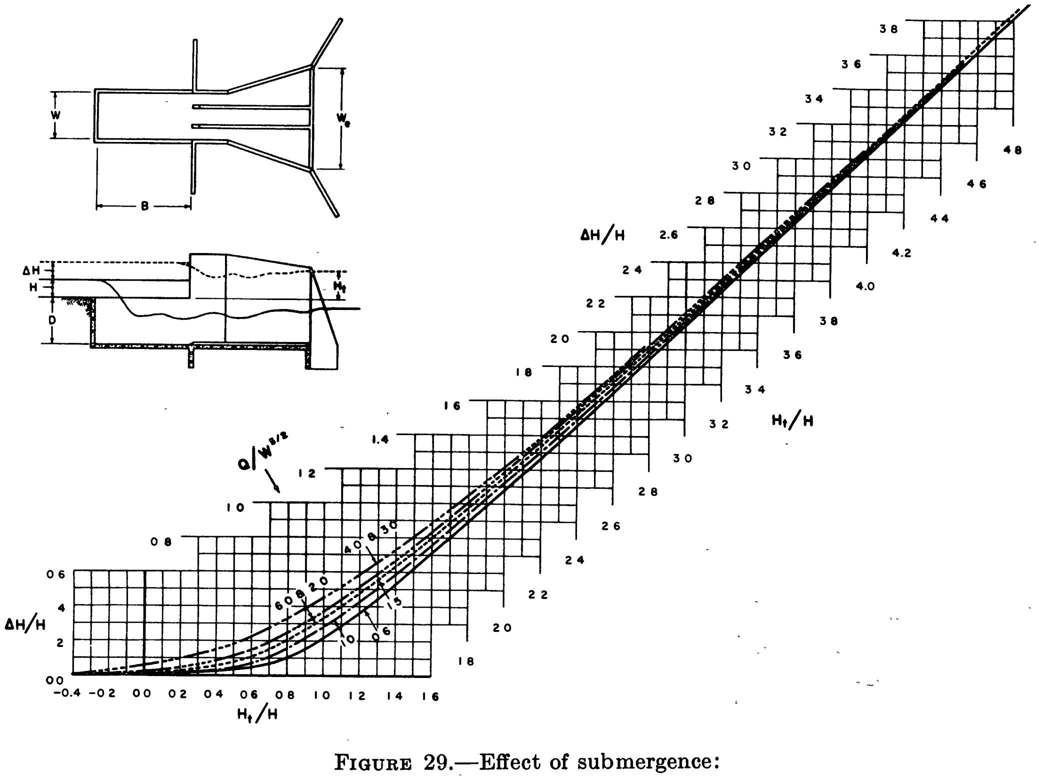

FIGURE 29.—Effect of submergence:
$\frac{B}{W}=1.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.0$.

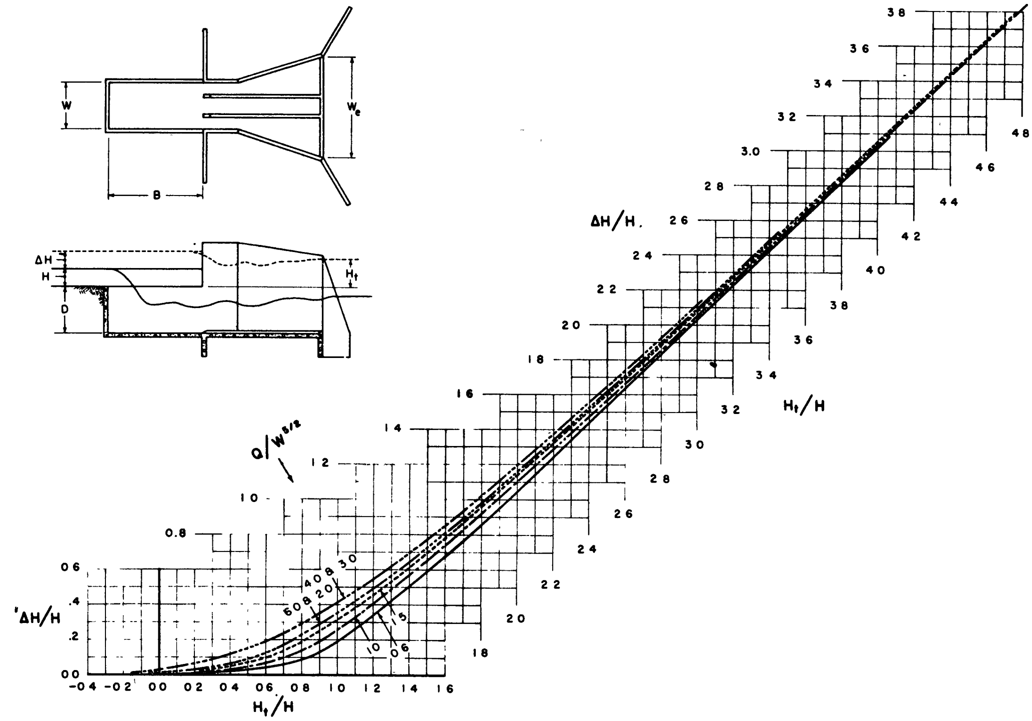

FIGURE 30.—Effect of submergence:
$\frac{B}{W}=1.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.25$.

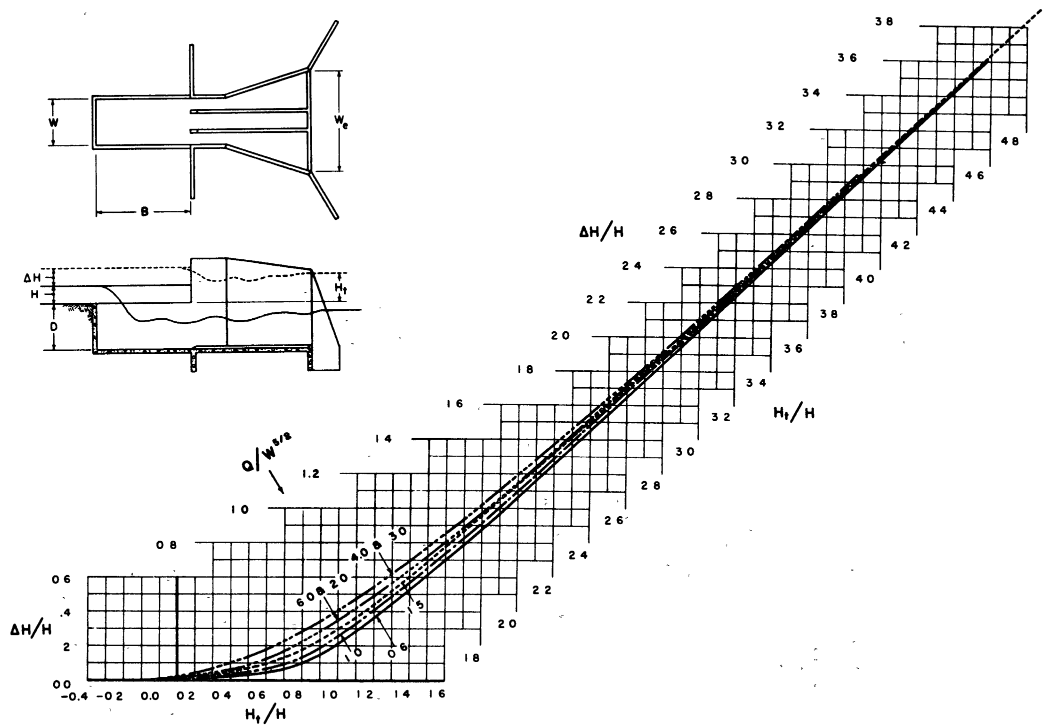

FIGURE 31.—Effect of submergence:
$\frac{B}{W}=1.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.5$.

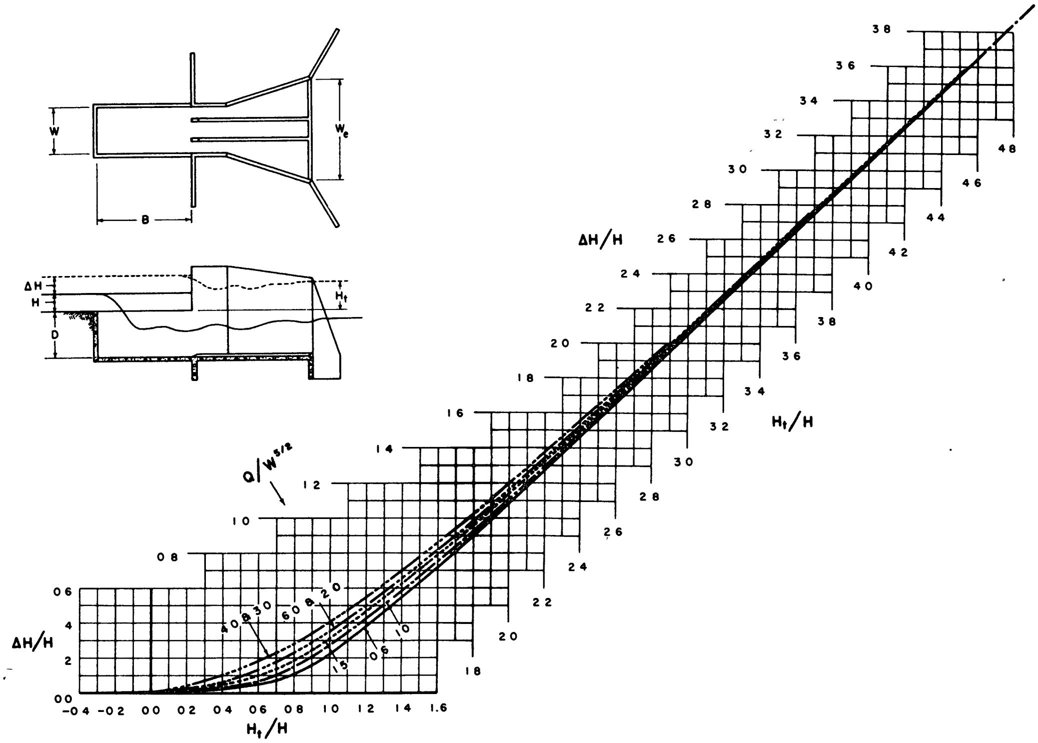

FIGURE 32.—Effect of submergence:
$\frac{B}{W}=1.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=2.0$.

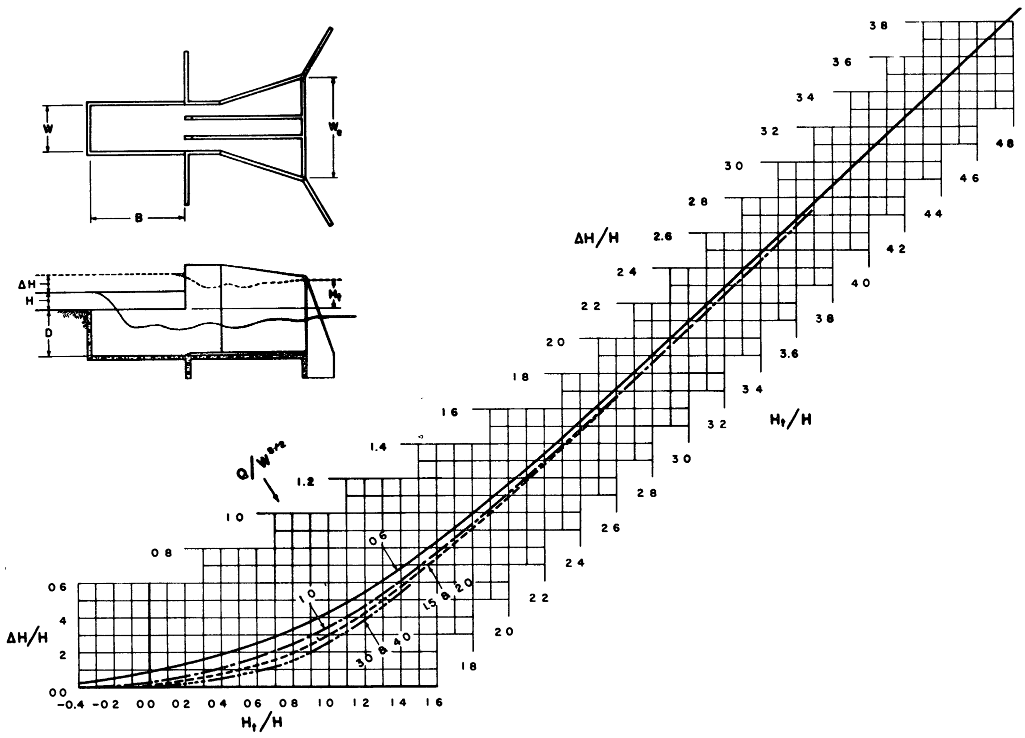

FIGURE 33.—Effect of submergence:
$\frac{B}{W}=2.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.0$.

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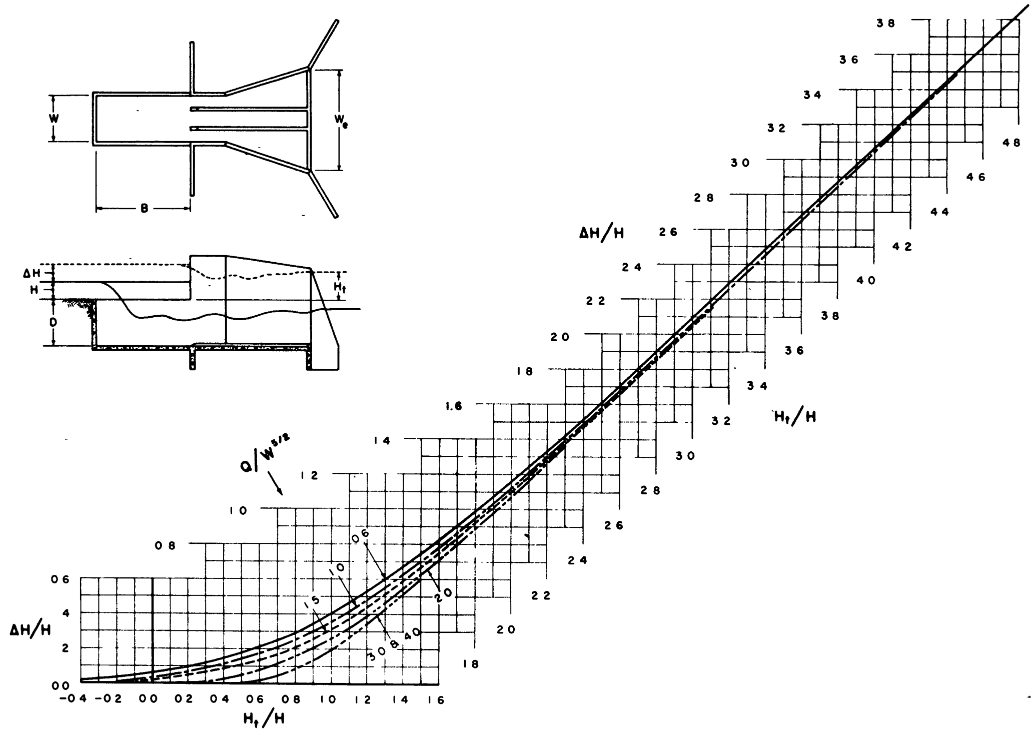

FIGURE 34.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.25$.

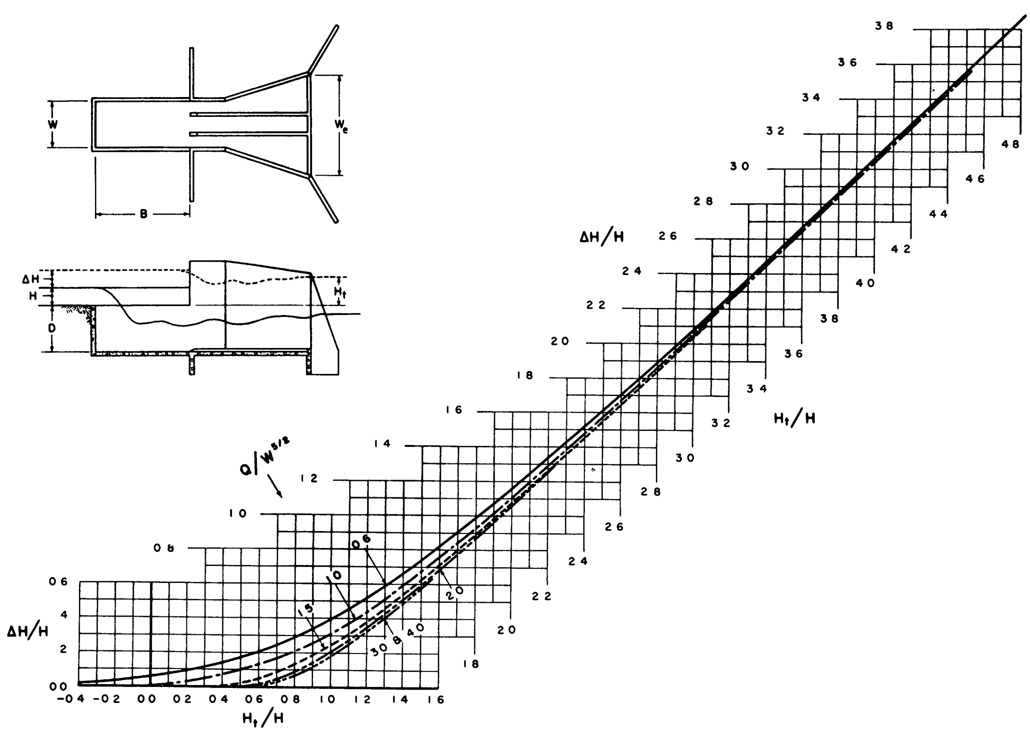

FIGURE 35.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=1.5$.

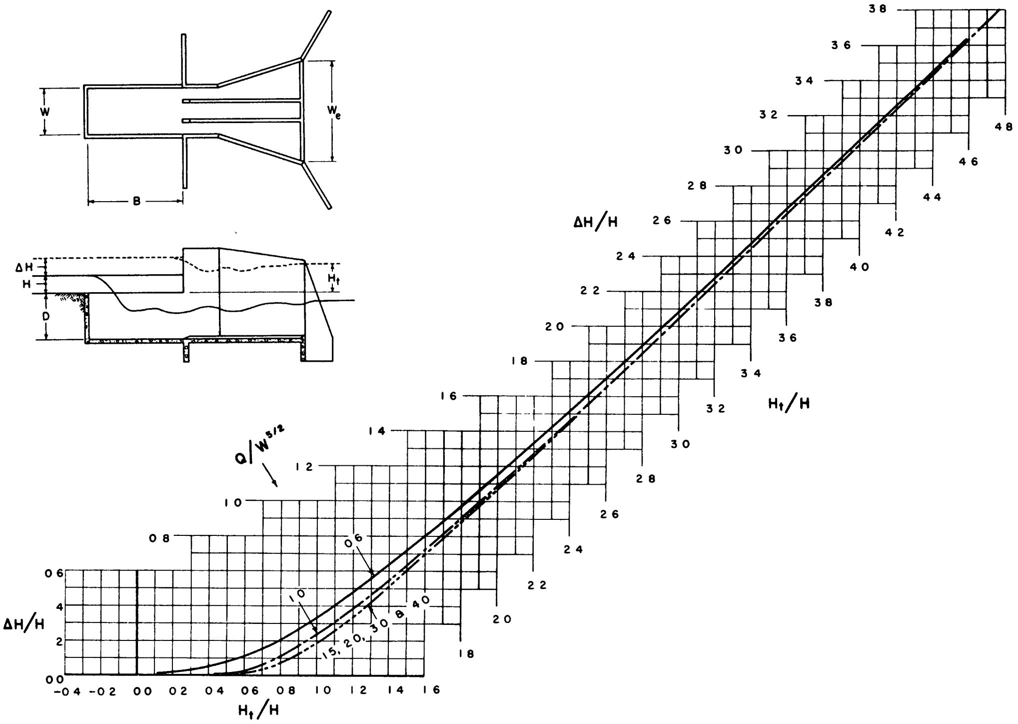

FIGURE 36.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.25$; $\frac{W_e}{W}=2.0$.

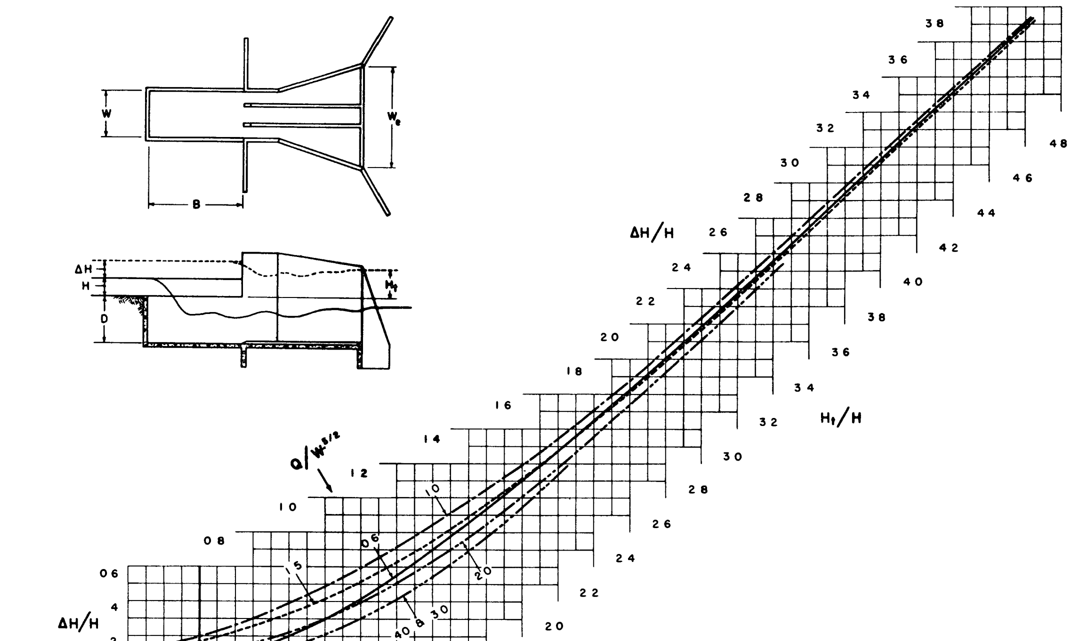

FIGURE 37.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.0$.

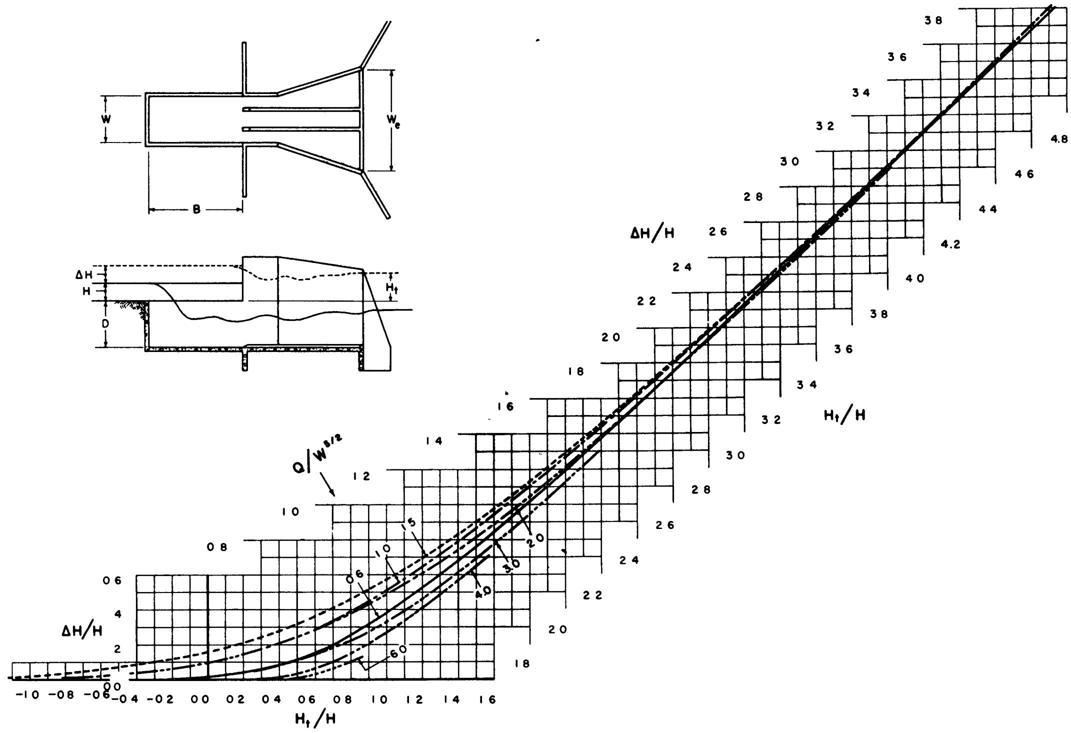

FIGURE 38.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.25$.

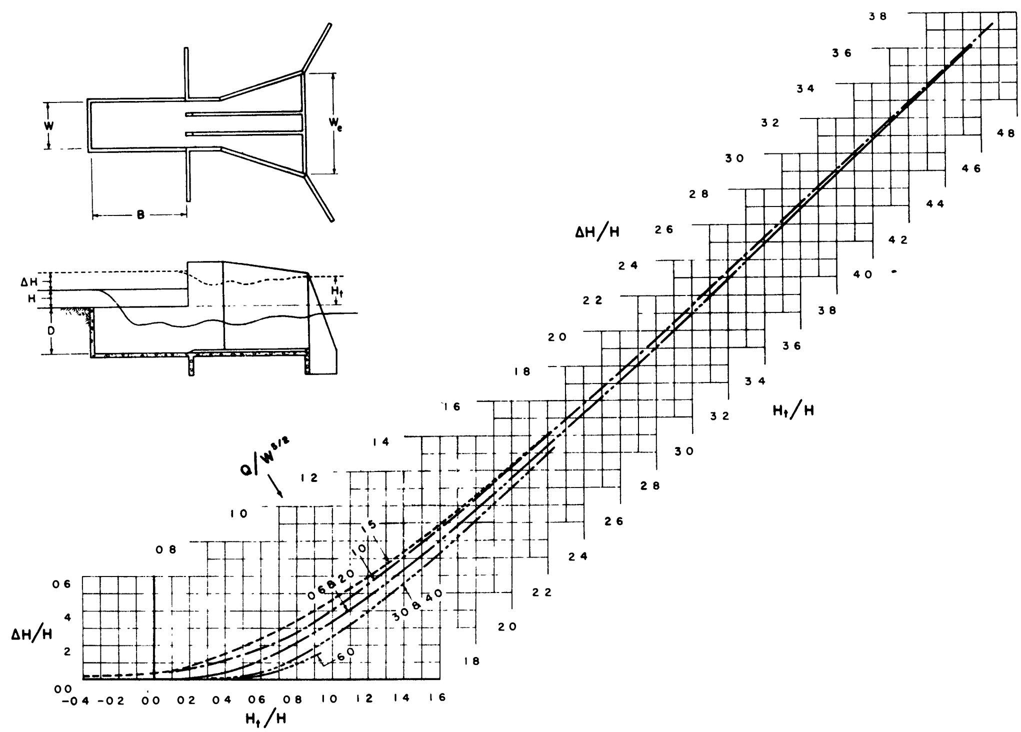

FIGURE 39.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=1.5$.

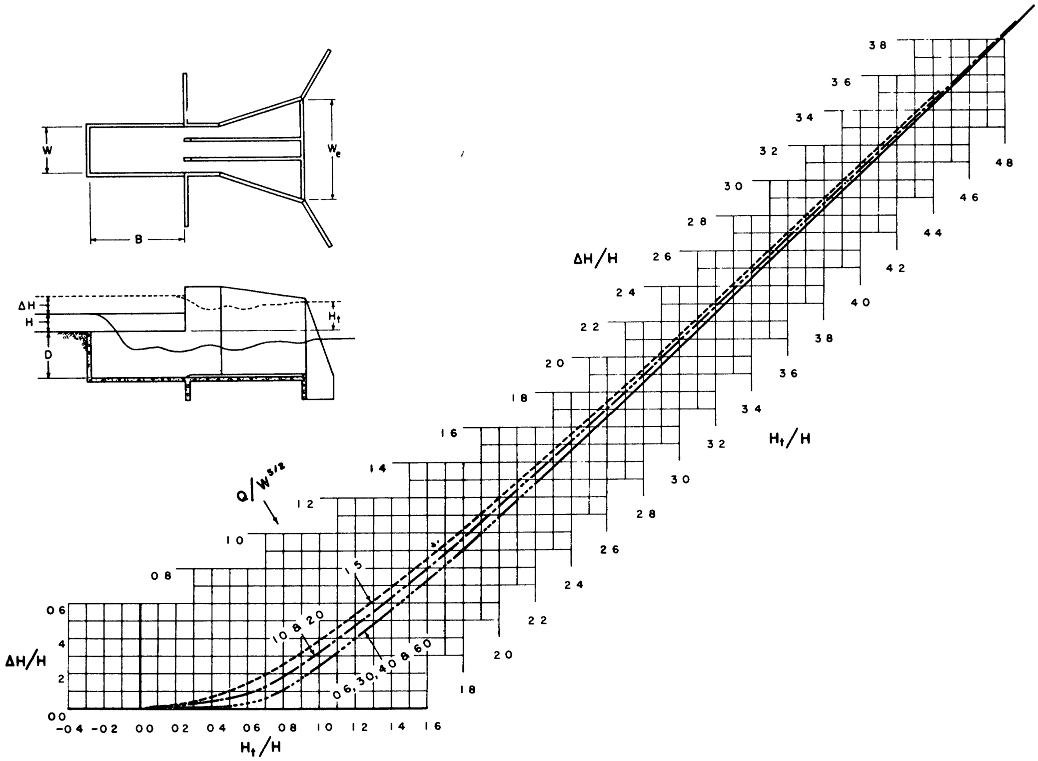

FIGURE 40.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=0.5$; $\frac{W_e}{W}=2.0$.

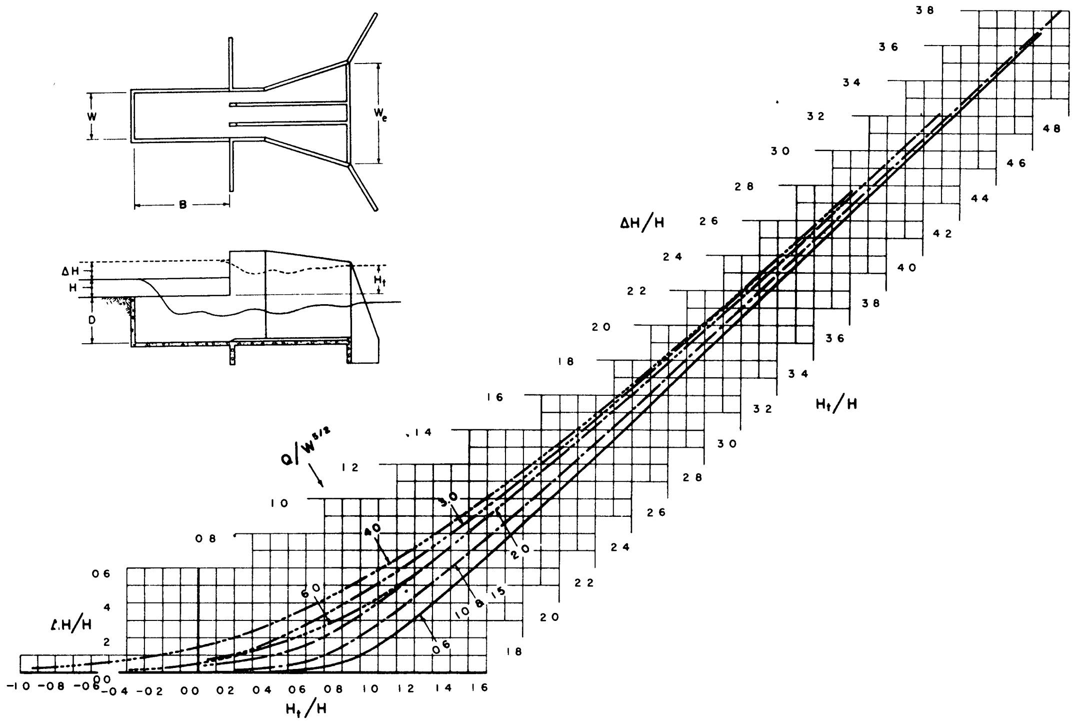

FIGURE 41.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.0$.

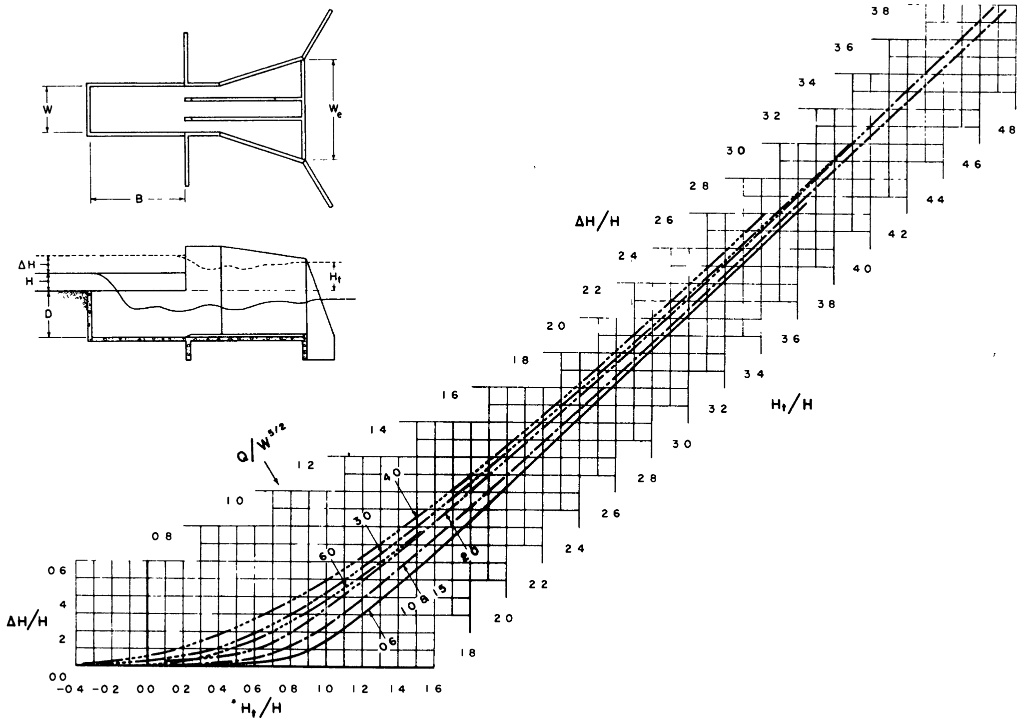

FIGURE 42.—Effect of submergence:
$\frac{B}{W}=2.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.25$.

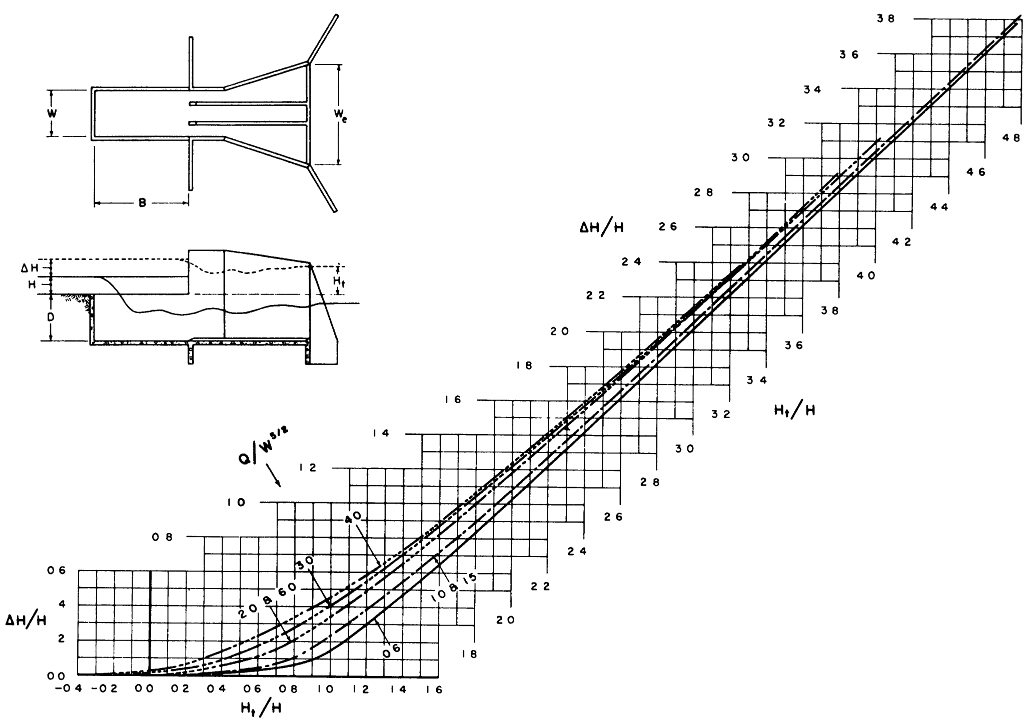

FIGURE 43.—Effect of submergence:
$\frac{B}{W}=2.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=1.5$.

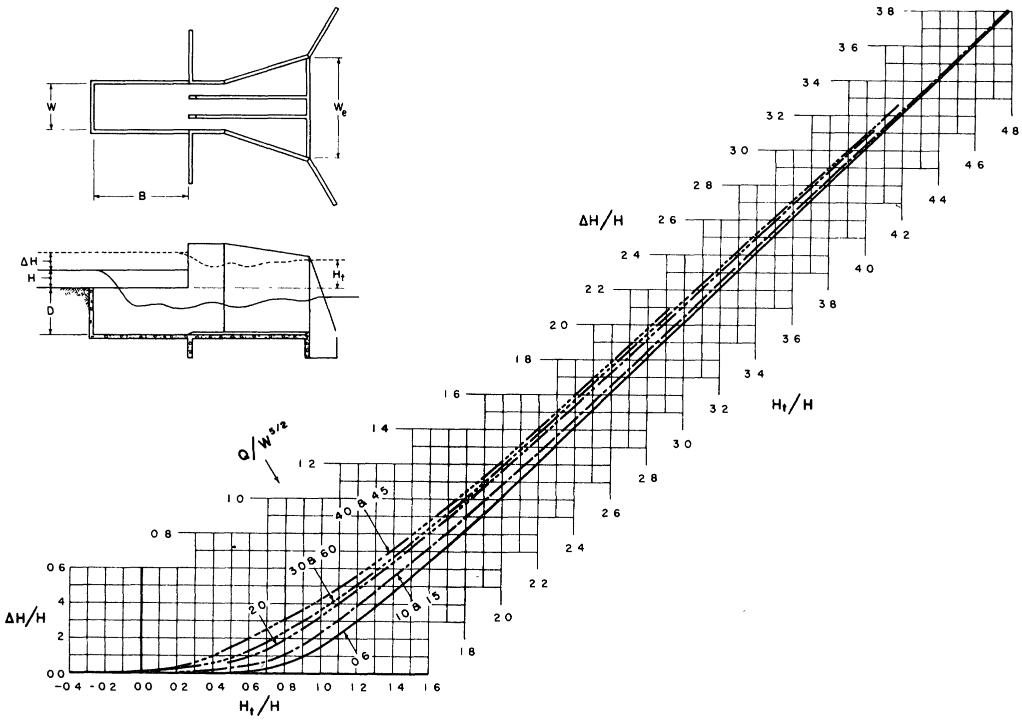

FIGURE 44.—Effect of submergence: $\frac{B}{W}=2.0$; $\frac{D}{W}=1.0$; $\frac{W_e}{W}=2.0$.

EXAMPLE OF APPLICATION

The hydraulic design of a typical box-inlet drop spillway is worked out here to illustrate how the design information presented previously can be applied. A number of factors other than those mentioned must be considered by the designer, and they may require that the proportions of the spillway be altered from those proportions which are determined solely from hydraulic considerations. These factors are outside the scope of this publication and will not be discussed here.

The design discharge, the topography of the site, and the exit channel conditions will be assumed, since their determination is not a part of the spillway design proper.

It is assumed that the design discharge is 200 cubic feet per second. The approach channel approximates a trapezoidal section having a 45-foot bottom width and 1-on-5 side slopes. The controlled drop through the box-inlet drop spillway is 4 feet, the crest of the box inlet being at elevation 100.0 feet and the exit channel at elevation 96.0 feet. The exit channel has a 10-foot bottom width and 1-on-3 side slopes, and a depth of flow of 4.3 feet, making the tailwater elevations 100.3 feet with the design discharge. With this preliminary information at hand it is possible to proceed with the design of the spillway.

The equation

$$H=\left(\frac{Q}{3.43L}\right)^{2/3} \qquad \text{(1d)}$$

will be used in the preliminary analysis to determine tentatively the magnitudes of H and L. This is tantamount to assuming that the box-inlet crest controls the head-discharge relationship. Later it will be determined if this assumption is valid and shown that it is not, in this case; but the computation must be made to make the determination. Substituting 200 for Q and disregarding for the present the corrections to the discharge coefficient, H is as follows for several assumed values of L:

L (feet)	10	15	20
H (feet)	3. 24	2. 47	2. 04

A head of 2.47 feet is satisfactory and the length of the crest will temporarily be taken as 15 feet.

The following combinations of B and W will give the required crest length:

B (feet)	6	5	4	3
W (feet)	3	5	7	9
B/W	2.00	1.00	.57	.33

The box 3 feet wide seems a little narrow so the next wider box will be chosen as giving the best box width. Tentatively, then, the box inlet will be 5 feet long by 5 feet wide.

At this point it is well to compute the head and to assume the control to be at the headwall opening, in order to determine if this head is greater than the head obtained when the control is assumed at the box-inlet crest. The greater value will be the actual head. With $W=5.0$ feet, $B=5.0$ feet, and $D=4.0$ feet, the ratio $D/W=4.0/5.0=0.80$ and $B/D=5.0/4.0=1.25$. If figure 6 is entered with $D/W=0.80$, it is found that $c_2\sqrt{2g}=3.10$; if figure 7 is entered with $B/D=1.25$, it is found that $H_{02}/D=0.55$, from which $H_{02}=0.55$ times $4.0=2.20$ feet. The assumed discharge and width and the values read from figures 6 and 7 are substituted in equation 3b,

$$H=(200/3.10\times5.0)^{2/3}-2.20=(12.9)^{2/3}-2.20=5.50-2.20=3.30 \text{ feet}$$

Since this is greater than the 2.47 obtained with the control at the box-inlet crest, the control section is at the headwall opening. The tentative head of 3.30 feet is satisfactory for the conditions assumed at the site.

Up to this point no attempts have been made to determine the head accurately. Now that the principal dimensions have been tentatively established, it is possible to do this. Because the preliminary computations have shown that the control is at the headwall opening, the head is given by the equation

$$H=\left(\frac{Q}{c_2W\sqrt{2g}}\right)^{2/3}-H_{02} \qquad \text{(3b)}$$

Since the discharge coefficient c_2 depends on the relative depth of the box inlet, this depth must be determined. (The end-sill height was neglected in the preliminary analysis.) In the example the controlled drop is 4 feet. The height of the end sill will be taken as 0.6 foot, this dimension being based on an assumed outlet width of 10 feet, a computed d_c of 2.3 feet (equation 4b or table 7) and a computed d_2 of 3.7 feet (equation 7). The box-inlet depth D is then 4.6 feet and $D/W=4.6/5=0.92$. Reference to figure 6 or table 5 gives $c_2\sqrt{2g}$ equal to 3.26. In order to determine the head correction H_{02} it is necessary to determine D/W and B/D. Because $D/W=0.92>0.25$, H_{02}/D can be obtained from figure 7 or from table 6. Since $B/D=1.1$, H_{02}/D is found to be 0.52. The head correction $H_{02}=0.52\times4.6=2.39$ feet. The equation then becomes

$$H=\left(\frac{200}{3.26\times5}\right)^{2/3}-2.39=12.27^{2/3}-2.39=5.32-2.39=2.93 \text{ feet}$$

This head is not the final head because it must be corrected for the effect of submergence. Also, this head is somewhat below the 3.30 feet computed initially, but in the absence of cost comparisons it will be assumed that the lower dike is economical and the discharge computations will not be repeated with a box inlet having different dimensions.

If a storm is to be routed through the structure, it will be desirable to plot a head-discharge curve. The first step is to determine the corrections when the control is at the box-inlet crest.

The first correction is that for head. Computations of H/W for a number of heads and the corresponding values of the head correction taken from figure 3 or from table 1 are given in table 9.

The second correction is that for box-inlet shape. Since $B/W=1$, the correction for box-inlet shape is 1.00, as can be seen by referring to figure 4 or to table 2. This correction is also noted in table 9.

The third correction is that for approach-channel width. The experiments were conducted with an approach channel having a horizontal floor and vertical sidewalls. Since this is obviously not a typical field condition, some means must be found to express the field-channel dimensions in terms of a channel having a rectangular cross section. It will be arbitrarily assumed that the depth of flow and cross-sectional area of both the field and the rectangular channels are identical. The width of the field channel is therefore taken as $W_c=A/H$. In the example,

$$W_c=\frac{(45+5H)H}{H}=45+5H$$

The width of the approach channel has been computed, together with W_c/L, and both values are given in table 9. The approach-channel width correction is also given in table 9, the correction having been obtained from either figure 5 or from table 3.

The fourth and final correction is for the proximity of the dike to the crest of the box inlet. In order to make the headwall extension as short as possible, the toe of the dike will be located 3 feet from the box-inlet crest. The relative distance of the dike toe from the crest X/W is given in table 9, together with corrections taken from table 4.

TABLE 9.—*Rating curve computations for example*

[Assumed dimensions: B=5.0 feet; W=5.0 feet; L=15.0 feet; D=4.6 feet; X=3.0 feet; dimensionless ratios: B/W=1.0; D/W=0.92; B/D=1.1; X/W=0.6]

Items to be computed	H							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Control at box-inlet crest:								
H/W	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
W_e [1]	47.5	50.0	52.5	55.0	57.5	60.0	62.5	65.0
W_e/L	3.17	3.33	3.50	3.67	3.83	4.00	4.17	4.33
Discharge coefficient—correction for:								
Head (fig. 3 or table 1)	.87	.93	.97	.99	1.00	1.00	1.00	1.00
Shape (fig. 4 or table 2)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Channel (fig. 5 or table 3)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dike (table 4)	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Corrected discharge coefficient [2]	3.01	3.22	3.36	3.43	3.46	3.46	3.46	3.46
Q_{crest} [3]	16	48	93	146	205	270	340	415
Control at headwall opening, $Q_{headwall}$ [4]	80	102	125	150	176	204	233	263

[1] $W_e=45+5H$.
[2] Uncorrected discharge coefficient$=0.4275\sqrt{2g}=3.43$.
[3] Q_{crest}=(corrected discharge coefficient)$LH^{3/2}$.
[4] $Q_{headwall}=16.3\ (H+2.39)^{3/2}$.

The discharge coefficient is corrected by successively multiplying it by the corrections. For example, the computation when H=0.5 foot is

$$\text{Corrected coefficient}=0.87\times1.00\times1.00\times1.01\times3.43=3.01$$

The corrected coefficient is given in table 9 and is used to compute the discharge, which is also listed.

The computations just completed apply when the control is at the box-inlet crest. Because the point at which the control changes from the box-inlet crest to the headwall opening is not known, it is necessary to repeat the computations for the headwall opening in order to determine that point as well as to complete the rating curve. It has been determined previously that $c_2\sqrt{2g}=3.26$ and $H_{02}=2.39$. If these values are substituted in equation 3a, the discharge, when the control is at the headwall opening, is

$$Q=3.26\times5.00(H+2.39)^{3/2}=16.3(H+2.39)^{3/2}$$

The discharge as given by this equation has been computed for the same values of H used for determining the discharge when the control was assumed to be at the box-inlet crest. They are listed in table 9.

It is now possible to plot the head-discharge curve. This is shown in figure 45. The section that controls the discharge is that section which gives the least discharge at a given head. The actual rating curve has been drawn as a solid line, whereas the imaginary parts are dashed lines. The two curves intersect just below the design discharge; so, for the design discharge, the headwall opening controls the head-discharge relation, as was determined previously, and the head, also as determined previously, is 2.93 feet. Although the intersection of the two curves of figure 45 is sharp, the head-discharge relation is actually curved at this location. Nevertheless, the curves as drawn are undoubtedly sufficiently accurate for all practical purposes.

The next step in the design of the structure is to compute the dimensions of the outlet. The critical depths of flow both in the straight section and at the end sill are required and should be computed first. Equations 4a and 4b are used for this purpose. The width of the straight section is 5.0 feet, and the discharge per foot of width Q/W is 200/5=40. From table 7, the critical depth d_c=3.68 feet. The exit of the outlet is assumed to be 10.0 feet wide, or equal to the width of the downstream ditch. There Q/W_e= 200/10=20 and d_{ce}=2.32 feet.

The minimum length of the straight section, computed from equation 5, is

$$L_S=3.68(0.2/1+1)=4.42\text{ feet}$$

It may be necessary to lengthen the straight section in order to permit the dam fill to be put in with the proper cross section, and this is permissible. After the submergence computations have been made, it will be possible to determine the final height of the dike, the dam section, and the length of the straight section.

The maximum permissible flare of the stilling basin sidewalls is 1 in 2. In order to increase the width from 5.0 feet at the end of the straight section to 10.0 feet at the exit of the stilling basin, the basin must be at least

$$\frac{10.0-5.0}{2}\times2=5\text{ feet long}$$

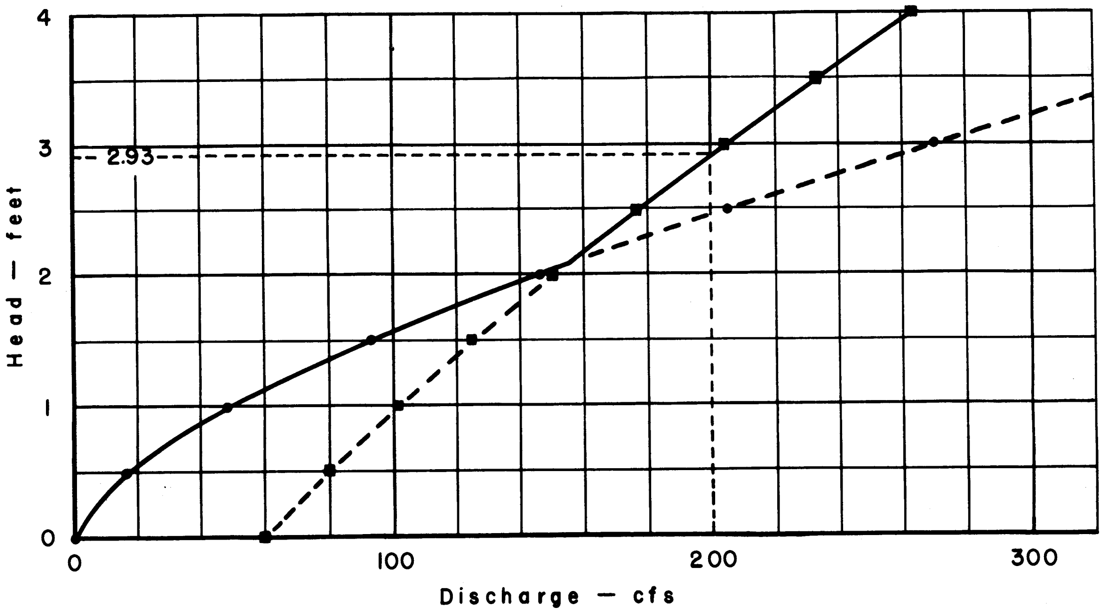

FIGURE 45.—Head-discharge curve for example.

The minimum length of the stilling basin computed from equation 6 is

$$L_B=\frac{15}{2\times 1}=7.5 \text{ feet}$$

Since the latter length is the greater, it governs, and L_B will be made 7.5 feet.

The next step is to determine the required minimum tailwater depth. The width of the stilling basin at its exit, in terms of d_{ce}, is 10/2.32 =4.3. This is less than 11.5, so equations 7a and 8a are used to determine the tailwater depth. The required minimum depth above the stilling-basin floor is

$$d_2=1.6\times 2.32=3.71 \text{ feet}$$

If measured above the top of the end sill, this depth is

$$d_3=1.33\times 2.32=3.09 \text{ feet}$$

The depth in the downstream channel is 4.3 feet, and the depth naturally obtained is therefore adequate, if it is assumed the top of the end sill is located at the channel grade or elevation 96.0. If desired, the stilling-basin exit could be narrowed somewhat so as to obtain a d_3 closer to the depth in the downstream channel. The computation might proceed as follows:

$$d_3=4.3 \text{ feet}$$

and

$$d_{ce}=4.3/1.33=3.23 \text{ feet}$$

From table 7, $Q/W_e=33$. Since $Q=200$ cubic feet per second, $W_e=200/33=6.06$ feet, say 6.0 feet. This would then be the minimum outlet width that could be used with the assumed tailwater depth. Nevertheless, in this example a width of 10 feet will be used. In an actual design the width providing the most economical solution, probably the 6.0-foot width, would be the logical one to choose.

One other point should be made regarding the elevations of the outlet floor and the end sill relative to the available tailwater depth. If d_2 and d_3 had been greater than the available tailwater depth, the outlet would have had to be lowered sufficiently below grade so that the elevation of the top of the end sill plus the required tailwater depth d_3 would have given an elevation not higher than the tailwater depth naturally available. However, if it had proved undesirable to locate the end sill below grade elevation, an alternative would have been to increase the outlet width sufficiently to reduce the required d_3 to the depth naturally obtainable. The procedure for making this latter adjustment has been outlined above.

For the design of the details, the end-sill height, computed from equation 9, will be $f=3.71/6=0.62$ foot, say 7.5 inches. (An end sill 8 inches high could have been used, 7.5 inches being chosen because it is the width of an 8-inch board.) This final end-sill height should be compared with the height assumed when the head-discharge curve was computed with the control at the headwall opening. In this case the difference is 0.62—0.60=0.02 foot and is so small that it can be safely neglected. However, if this difference had been large, it would have been necessary to recompute the head-discharge curve.

The number of longitudinal sills required depends on the ratio $W_e/W=10/5=2$. Since this ratio is less than 2.5, only two sills are required. These may be located from 5/6=0.83 foot to 5/4=1.25 feet either side of the centerline. If the sills are used to strengthen the floor slab, their location within these limits will be determined by structural considerations. Here, the centerlines of the sills will be located 1.0 foot either side of the centerline.

The minimum height of the sidewalls above the tailwater level, computed from equation 10, is

$$t=3.71/3=1.24 \text{ feet}$$

The top of the sidewalls at the stilling basin exit should be 4.3+1.24=5.54, say 5.5 feet, above the top of the end sill.

The angle that the wingwalls make with the outlet centerline will be assumed as 45°. The tops of the wingwalls will be sloped to fit the dam fill, and the walls will be terminated where their tops disappear below the surface of the ground. A better arrangement would be to extend the wingwalls until their tops are at the level of the end sill, but here the risk involved in shortening them is not felt to be worth the extra cost of extending them.

In the example, the tailwater depth for the design discharge was purposely made deep enough to cause submergence, to allow illustration of the method of computing this effect. To determine the proper submergence curve, it is necessary to know the magnitude of the ratios $B/W=1.0$, $D/W=0.92$, and $W_c/W=2.0$. These ratios were computed earlier. Entering table 8, it is apparent that the submergence effect must be interpolated between figure 28 where $D/W=0.5$ and figure 32 where $D/W=1.0$. Because $Q/W^{5/2}=200/55.9=3.6$, it will be necessary to interpolate between the curves for $Q/W^{5/2}=3$ and 4 in figures 28 and 32. The free-flow head is 2.93 feet and the tailwater level is 0.3 foot above the crest of the spillway, making the ratio $H_t/H=0.3/2.93=0.10$. The submergence curves are entered with this figure and values of $\Delta H/H$ read off. The interpolations are made in table 10.

TABLE 10.—*Values of $\Delta H/H$ for $B/W=1.0$, $W_e/W=2.0$, and $H_t/H=0.10$ for example*

$\frac{Q}{W^{5/2}}$	D/W		
	0.5	0.92	0.1
3.0	0.01		0.02
3.6	.00	0.02	.02
4.0	.00		.02

The desired value of $\Delta H/H$ is 0.02, from which

$$\Delta H=0.02\times2.93=0.06 \text{ foot}$$

and the head for submerged flow is 2.93+0.06=2.99 feet. A head of 3.00 feet will be used in the subsequent design.

These computations have determined the submergence effect at only one discharge. In order to route a storm through the structure, it will be necessary to compute and plot a tailwater rating curve and then to determine the effect of submergence at a number of flows so as to be able to plot a rating curve for submerged flow similar to the free-flow curve shown in figure 45.

In accordance with standard practice a freeboard of 6 inches is required to the top of the headwall and a freeboard of 1 foot is required to the top of the dike. The top of the headwall will therefore be at elevation 103.5 feet and the top of the dike at elevation 104.0 feet. The design of the spillway is summarized in the plan and section shown in figure 46. It will be noticed there that it was necessary to increase the length of the straight section from 4.42 feet to 5.0 feet in order to provide an adequate cross section to the dike.

Although field problems will probably differ considerably from the assumptions given for this example, it is felt that most of the conditions that might be obtained have been illustrated. The best design, of course, depends on the skill with which the designer applies the methods to his particular problem. The attempt here has been to provide the information that the designer requires to compute the proportions of box-inlet drop spillways.

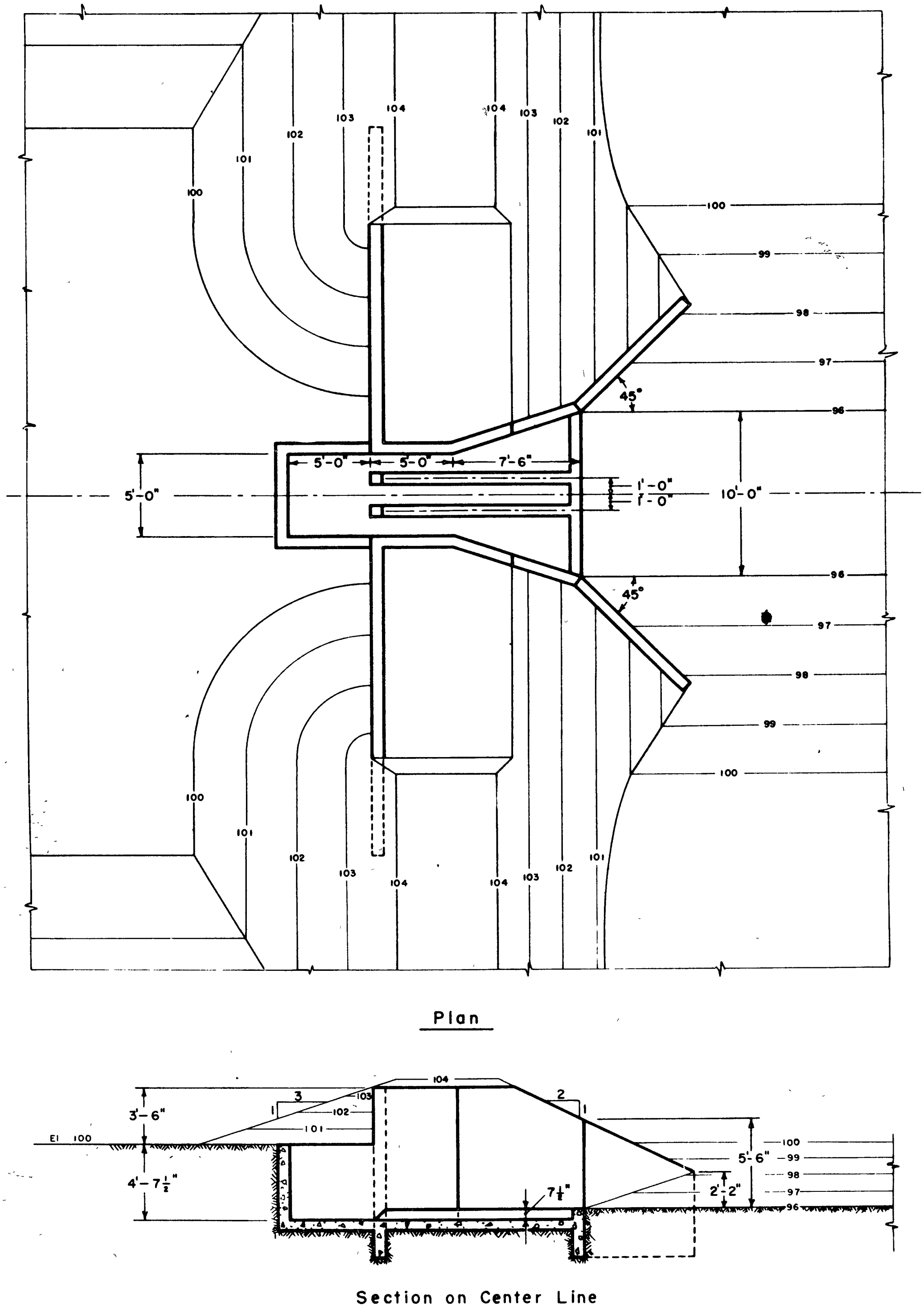

FIGURE 46.—Proportions of box-inlet drop spillway for example.

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