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Technical Paper No. 7, Series B

Capacity of Box Inlet Drop Spillways Under Free and Submerged Flow Conditions

by

Fred W. Blaisdell and Charles A. Donnelly
Hydraulic Engineers, USDA, SCS

January, 1951

Study conducted by
UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE—RESEARCH
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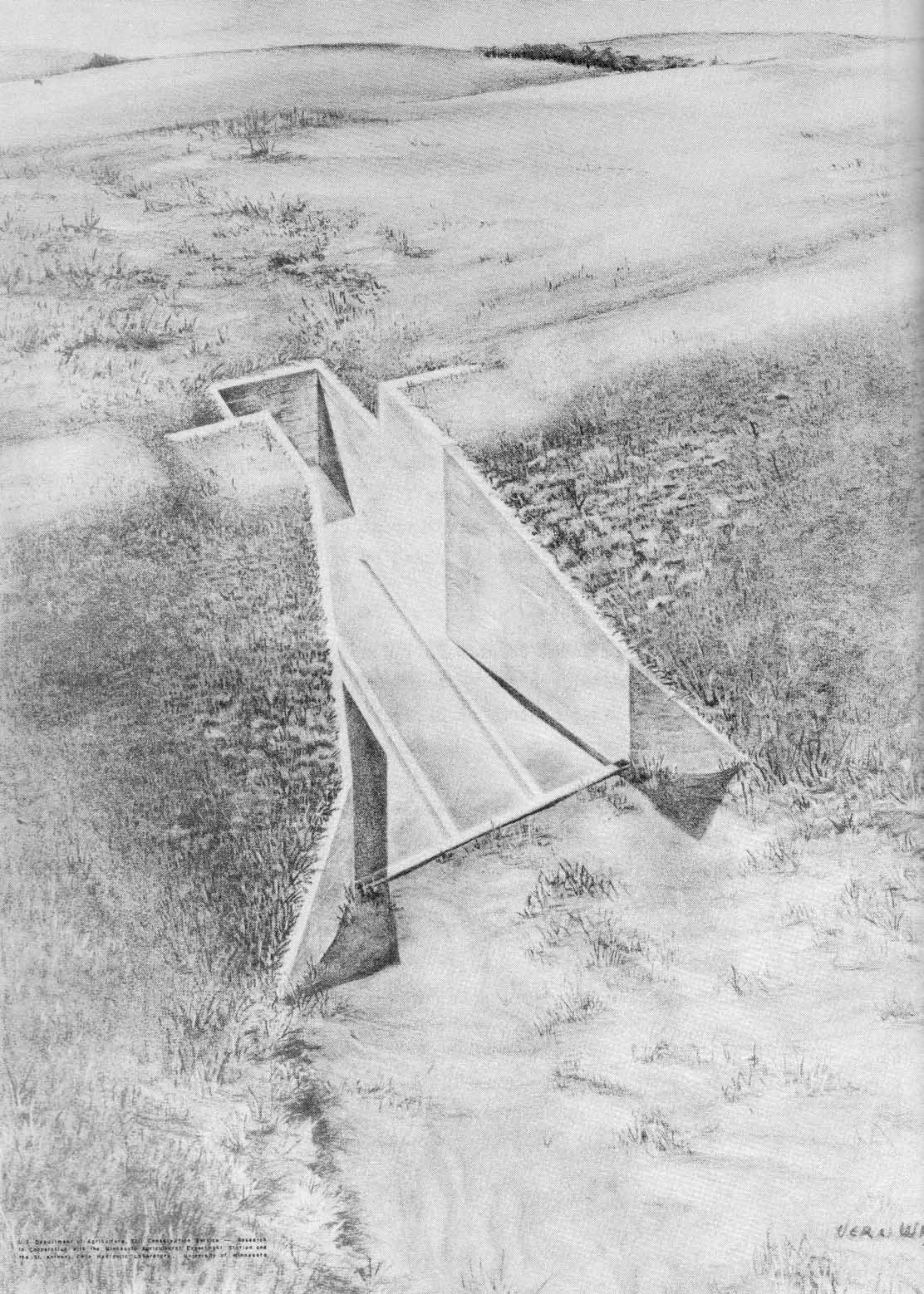
NOMENCLATURE

A	cross-sectional area of flow
B	length of box inlet
c	coefficient of discharge
D	depth of box inlet
g	acceleration due to gravity
H	specific head; depth of flow plus velocity head = $h + h_v$
H_o	apparent specific head at zero flow
H_t	level of tailwater referred to crest of box inlet
$\triangle H$	increase in free flow head caused by submergence
h	piezometric head
h_v	velocity head = $V^2/2g$
L	length of box inlet crest = $2B + W$
N_L	number of tests; control at box inlet crest
N_W	number of tests; control at headwall opening
n	exponent
Q	discharge
Q_o	apparent discharge at zero head
S	standard error of estimate
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



U.S. Department of Agriculture, Soil Conservation Service — Research in Cooperation with the Minnesota Agricultural Experiment Station and the St. Anthony Falls Hydraulic Laboratory, University of Minnesota

CAPACITY OF
BOX INLET DROP SPILLWAYS*

under

Free and Submerged Flow Conditions

INTRODUCTION

The box inlet drop spillway is defined 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.

The drop spillway has been extensively used as a gully control structure where it is necessary to drop water from as short a distance as 2 feet to as much as 12 feet. In more recent years it has also been used in drainage ditches where it functions as a tile outlet and a means of dropping excess surface water into the ditch.

For the sake of economy, auxiliary vegetated spillways are sometimes provided to pass part of the runoff from the larger storms and to permit the use of a smaller mechanical spillway. In order to prevent scour of the drainage ditch banks the elevations of the vegetated spillways are adjusted so no water will pass over them until the downstream drainage ditch flows bank full. In other words, the mechanical spillway must have sufficient capacity to fill the ditch completely before any flow passes over the vegetated spillway. Under these conditions the high downstream water level will likely submerge the spillway and reduce its flow. After the vegetated spillways come into operation, the downstream level rises still further and submergence of the mechanical spillway becomes greater. Spillways designed in this manner are known as the "island dam" type because they can be completely surrounded by water during flood periods. The necessity for these studies to determine the capacity of box inlet drop spillways under submerged flow conditions thus becomes apparent.

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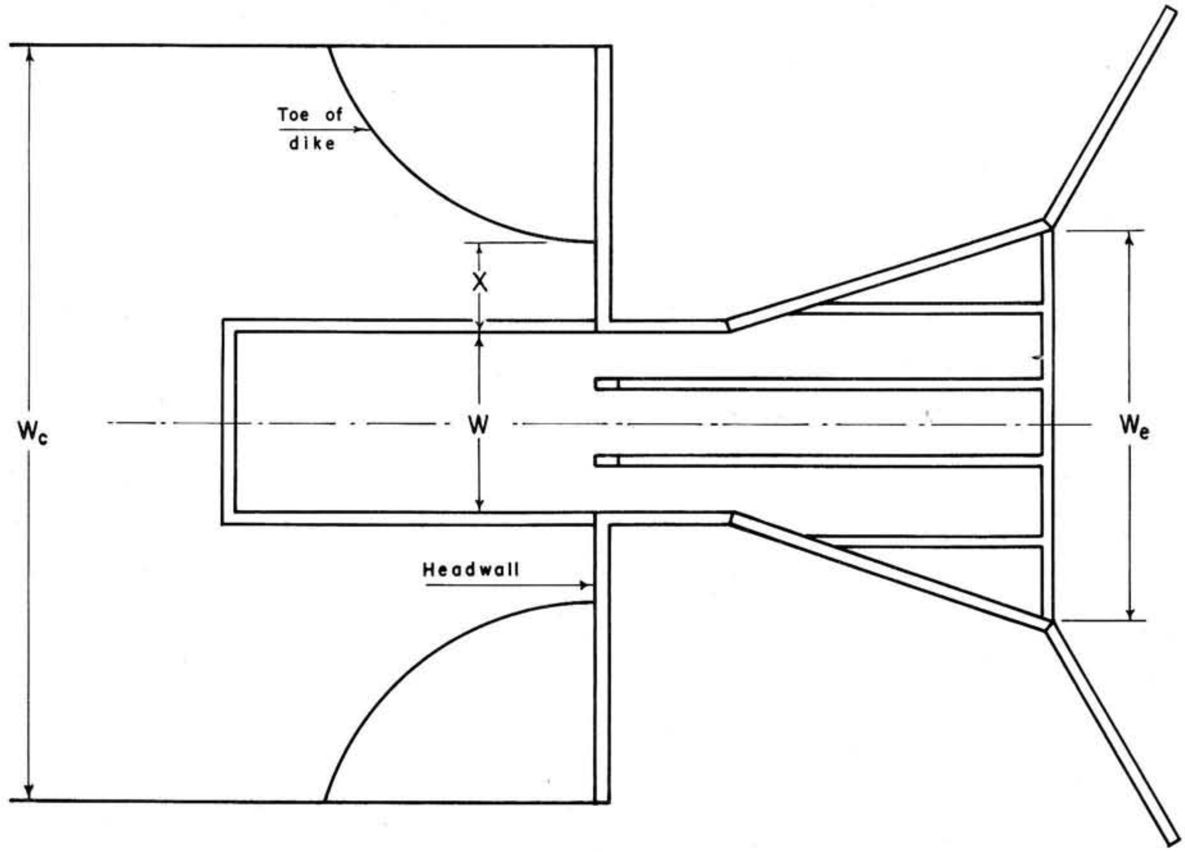
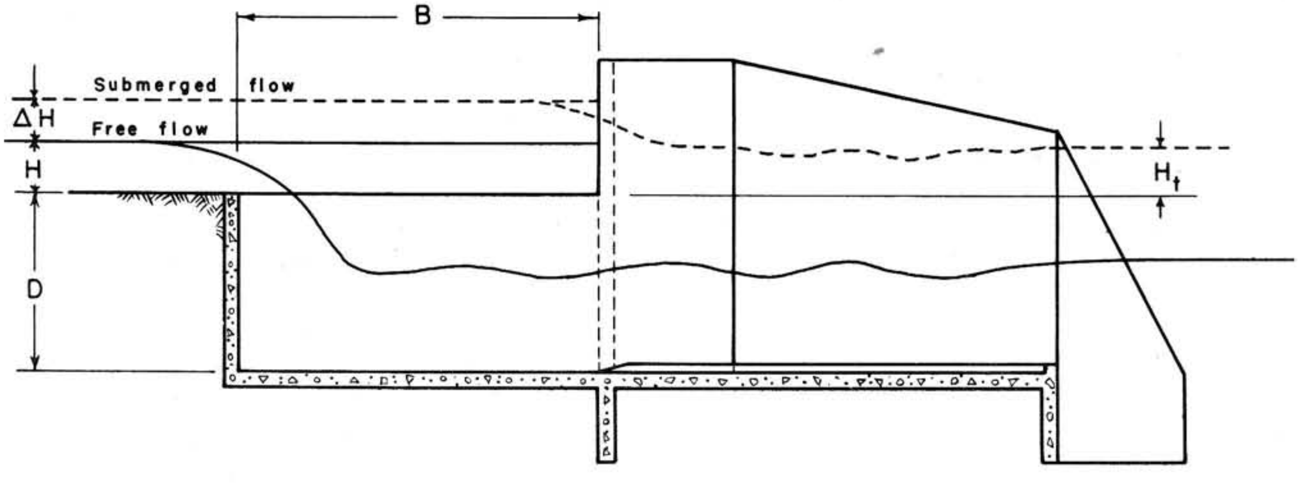
*Soil Conservation Service Report No. MN-R-3-45.



PLAN



SECTION AT CENTER LINE

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Figure 1—Box Inlet Drop Spillway

No tests to determine the free flow capacity of box inlet drop spillways had been made since the development of an outlet for this structure. Free flow calibration tests were made a part of the test program since it seemed probable that the outlet would affect the capacity of the spillway at high flows.

The study resulted in the development of a generalized method for determining the free flow capacity of box inlet drop spillways. The procedure is outlined in the report. No practical generalized method for the determination of the submerged flow capacity of this structure was found; it seemed simpler to determine the submerged flow capacity by a process of interpolation utilizing submergence curves obtained for a wide range of pertinent variables for this purpose.

This experimental determination of the capacity of box inlet drop spillways was begun in 1946 at the initial request of the Region 3 Engineering Division, Soil Conservation Service, United States Department of Agriculture. Although it was interrupted a number of times by special studies, it was completed late in 1950. The study was made by the staff of the Soil Conservation Service located at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis. There the Soil Conservation Service, the Minnesota Agricultural Experiment Station, and the St. Anthony Falls Hydraulic Laboratory cooperate in the solution of problems concerning conservation hydraulics. The experimental work and the analysis of the submergence data were performed by Charles A. Donnelly, hydraulic engineer. The study was directed by Fred W. Blaisdell, project supervisor, who analyzed the greater part of the rating curve data, with the assistance of Miss E. C. Gosslin and Mrs. V. C. Schoumaker. Acknowledgement is also made of the contribution of the Laboratory staff members who assisted in the preparation of this report.

This report is broken down into a number of sections. Introductory sections describe previous work, the test program, and the apparatus and procedure used in conducting the tests. The results of the tests are described in considerable detail and sufficient information is presented to permit the reader to make his own evaluation of the findings. Although adequate information is presented here to permit the design of box inlet drop spillways under free flow conditions, only typical submergence curves are included in this report. A companion report[1] has been prepared for the use of designers and the submergence curves for a wide variety of conditions, as well as the free flow design curves, are included therein. In that report the experimental background has been omitted and only sufficient information included to permit the design to be prepared properly. This report on the experimental work thus provides the support for the design report.

PREVIOUS WORK

The earliest work on box inlet drop spillways to come to the attention of the authors is that reported by Kessler[2] in 1934. Kessler's design was used in some early structures but is now obsolete as far as the Soil Conservation Service program is concerned.

A more complete series of experiments was reported by Huff[3] in 1944. The results apply particularly to entrances to chute spillways although they are applicable to drop spillways if the box inlets are sufficiently deep to insure that the outlet has no backwater effect on the flow over the crest. As the capacity of the spillway is approached the discharges tabulated by Huff will be larger than those obtained with a horizontal outlet floor such as is used with the box inlet drop spillway. The effect of the sloping floor in the box inlet was reported by Huff to be negligible; he agrees with Kessler in this respect. Huff and Kessler also agree with respect to the effect of depth of the approach channel, both showing that a level approach serves to lower the capacity as compared to a deeper approach. Huff gives a little data indicating the great effect of approach channel width on the flow capacity and also briefly touches on the effect of submergence. These latter points are discussed fully in the present report.

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[1] Blaisdell, F. W., and Donnelly, C. A., "Hydraulic Design of the Box Inlet Drop Spillway," University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Paper No. 8, Series B, 1951.

[2] Kessler, L. H., "Experimental Investigation of the Hydraulics of Drop Inlets and Spillways for Erosion Control Structures," Bulletin of the University of Wisconsin, Engineering Experiment Station Series No. 80, 1934, pp. 56-66.

[3] Huff, A. N., "The Hydraulic Design of Rectangular Spillways," U. S. Department of Agriculture, Soil Conservation Service, Washington, D. C., SCS-TP-71, February, 1944.

A new outlet for box inlet drop spillways was reported by Donnelly[4] in 1947. A glance at this design shows that there will be a backwater effect on the flow over the box inlet crest if the drop in the box inlet is low or if the flows are so high as to drown out the box inlet crest. This means that the discharge tables presented by Huff are invalid for many box inlet drop spillway flows. The necessity for additional calibration studies is readily apparent. The submergence data presented by Huff also become invalid as a result of the new outlet design.

An analysis of these reports shows that additional information needs to be obtained to make it possible to compute both the free flow capacity and the effect of submergence on the capacity of box inlet drop spillways when the outlet developed by Donnelly is used.

TEST PROGRAM

A test program was planned as a result of the above considerations to produce data which could be used to design box inlet drop spillways for almost any field condition that might be experienced. The experiences of Huff were drawn on heavily in determining the factors requiring consideration. The test program has been broken down into sections dealing with the free flow tests and the submerged flow tests, the details being outlined in the following sections. Roughly 12,000 individual runs were made to complete the test program. The data obtained during these runs serve as the background for the design equations and curves.

Free Flow Tests

An analysis of the dimensions of a number of box inlets constructed by the Soil Conservation Service was made as an aid in planning the test program. In this analysis the dimensions were expressed in terms of the box width W.

The analysis and correspondence with field engineers indicated that box depths D ranging from W/8 to W would cover the anticipated

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[4] Donnelly, C. A., "Design of an Outlet for Box Inlet Drop Spillway," U. S. Department of Agriculture, Soil Conservation Service, Washington, D. C., SCS-TP-63, November, 1947.

range of field conditions. The length of the box inlet B necessary to cover anticipated field conditions ranged from about W/4 to 2W. Tests were run with boxes as short as 0W (overfall with no box inlet) and as long as 4W. This was done to extend the calibration curves beyond the maximum anticipated limits in order to increase their reliability.

The width of the approach channel W_c greatly affects the flow over the box inlet crest, as Huff has shown. Since Huff's results indicated little effect of channel width when the channel was equal to or greater than 3L wide, this length was adopted as standard. Here L is the inside crest length of the spillway or 2B + W. To evaluate the effects, tests were made with approach channels as narrow as 0.4L and as wide as 10L.

It was anticipated that the weir crest would control the head-discharge relationship for the low relative heads (low H/W) and relatively deep box inlets. However, the box inlet crest will be flooded out when the relative head is high or the box inlet relatively shallow, the headwall opening controlling the discharge under these conditions. The range of flows used during the tests reported here was sufficient to evaluate the head-discharge relationship for both the box inlet crest and the headwall opening control sections and to determine at what stage the control shifted from one to the other.

The free flow test program is given in Table I. Before the test program was considered firm nearly 50 preliminary tests were made to determine the effects of minor factors. Only the free flow tests made subsequent to the preliminary tests are listed in Table I.

Submerged Flow Tests

Prior to commencement of the tests reported here very little was known regarding the effect of submergence on the flow through box inlet drop spillways and the effects of the various spillway elements on the submergence. Most of the nearly 50 preliminary tests were therefore devoted to exploratory submergence tests. The preliminary tests showed that the submergence effect varies with the rate of flow and that the width of the outlet also greatly influences the effect of submergence. The shape of the box inlet and its depth were considered as additional fundamental variables.

TABLE I

TEST PROGRAM - FREE FLOW TESTS

Values of D/W

$\frac{B}{W}$	W_c/L										
	0.4	0.6	0.8	1.0	1.15	1.3	1.5	2.0	3.0	5.0	10.0
0								1	1		
									1/2		
									1/4		
									1/8		
1/4								1	1		
									1/2		
									1/4		
									1/8		
1/2		1	1	1	1	1	1	1	1	1	1
									1/2		
									1/4		
		1/8		1/8			1/8		1/8		
1	1	1	1	1	1	1	1	1	1	1	
									1/2		
									1/4		
	1/8	1/8		1/8			1/8		1/8		
2	1	1	1	1	1	1	1	1	1		
									1/2		
									1/4		
	1/8	1/8		1/8			1/8		1/8		
3								1			
4								1			

Indications were that a very large number of tests would be required to define properly the submergence effect. Considerable thought was given to this phase of the test program so as to reduce the number of tests to a minimum yet to cover adequately the range of conditions anticipated in the field. The variables and their values utilized during the test program are given in Table II.

TABLE II

TEST PROGRAM - SUBMERGED FLOW TESTS

Variable	Values of variable tested
B/W	1/2, 1, 2
D/W	1/4, 1/2, 1
W_e/W	1.0, 1.25, 1.5, 2.0
$Q/W^{5/2}$	0.6, 1.0, 1.5, 2.0, 3.0, 4.0, 6.0

APPARATUS AND PROCEDURE

The experimental setup used for the box inlet drop spillway study was especially designed for making submergence tests. The special features incorporated into it also facilitated the rating tests. A general view of the test setup is shown in Figure 2 and the important features are described in the following paragraphs.

Water for the experiments was obtained from the main Laboratory supply channel through a 4-inch supply line. Since submergence tests require an absolutely constant rate of flow over long periods of time, a constant-level tank was incorporated into the system. The benefits obtained with this device were even greater than had been anticipated. Flow from the constant-level tank was controlled by a 4-inch gate valve and was measured by means of a 1.0-foot type H flume located just upstream from the test channel.

The upstream test channel was made of steel stair—stringer channels bolted together and was 10 feet wide, 10 feet long and 1 foot deep.

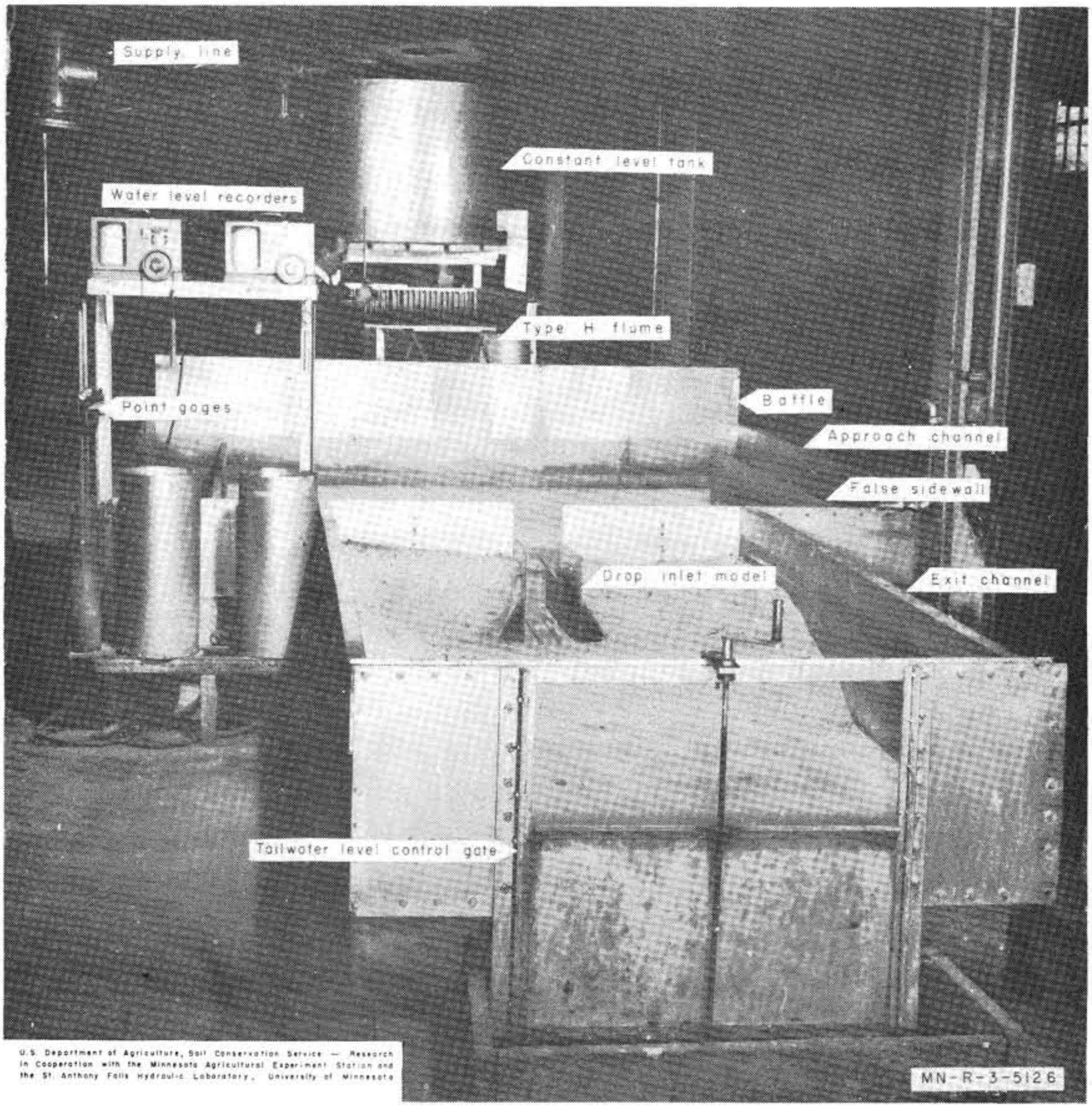

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Figure 2—Test Apparatus

Water from the type H flume dropped into a stilling pool and passed under a solid baffle which served to quiet and distribute the flow. Vertical, movable, false sidewalls were used to simulate approach channels narrower than the test channel. The floor of the approach channel was made absolutely level by means of cement mortar. A pit 24 inches wide, 30 inches long and 6 inches deep was provided in the center of the downstream side of the approach channel. The drop inlets were located in this pit.

The exit channel was made 5 feet wide, 10 feet long and 18 inches deep. The floor of this channel was set 6 inches below the floor of the approach channel. The headwall separating the two channels was provided with an opening for insertion of the models. An adjustable gate at the downstream end of the exit channel controlled the tailwater level.

A headwater piezometer opening was located at the center of the channel 3 feet 6 inches upstream from the headwall. The tailwater piezometer was located 5 feet 0 inches downstream from the headwall. Each piezometer was connected to two stilling wells. Point gages were located over one set of wells for use in determining the water levels. The other set of wells was for water-level recorder floats. No readings were taken from the recorders, the records being used simply for control purposes. Through their use it was possible to tell when the water levels had reached a constant elevation after some change and the time required to make a run was reduced by about 50 per cent thereby. With a little experience it was also possible to tell by glancing at the recorder charts if the connections to the stilling wells were plugged by dirt or air. The recorders thus served to increase the reliability of the readings as well as to save time.

The box inlet drop spillway models were made of Lucite. In general, the box inlet was installed and left in place while a number of different outlets were attached and tested.

The method of conducting an experimental run was much the same for both the free flow and the submerged flow tests. For the free flow tests, the constant-level tank valve was opened to give a low flow, the stage in the channel was allowed to become constant, and readings of discharge and head were obtained and recorded. The valve opening was then changed slightly and the procedure was repeated until a complete range of heads and discharges had been obtained. During the submerged flow tests the control valve was adjusted to give the desired flow, which remained constant throughout each test. For the initial and final runs the tailwater was so low that there was no submergence effect. For the intermediate runs the tailwater was raised and lowered in steps to cover the range from zero submergence to complete submergence. At each step readings of the steady headwater and tailwater elevations were obtained and recorded.

TEST RESULTS

In presenting the results of the box inlet drop spillway tests it is convenient to make a primary distinction between the free flow tests and the submerged flow tests. Therefore, a separate section will be devoted to each portion of this study.

Free Flow Tests

The box inlet weir crest is the control section at the lower flows while at the higher flows the control section shifts to the headwall opening. Since different methods for computing the discharge are employed, the flow past each control will be treated in separate subsections. However, the method used in the initial analysis of the data is the same for both control sections.

Analysis of Data

A number of formulas were investigated before deciding on the method to be used in analyzing the data. The method adopted will be described first; the results obtained with other formulas will be presented in a second subsection.

Method Adopted: Both the flow over the box inlet crest and through the headwall opening are theoretically proportional to the three-halves power of the head or

$$Q \propto H^{3/2} \tag{1}$$

(In this report H is the piezometric head plus the velocity head.) Use was made of this fact to plot all the data for each test on a single sheet. This has the advantage that the point where the flow control section shifts from the box inlet crest to the headwall opening can be readily determined. Also, if the data points fall on a straight line it is an indication that the theoretical exponent is correct.

A typical plot of data is shown in Figure 3. To simplify the analysis, both sides of Equation (1) were raised, before plotting, to the two-thirds power so the ordinate becomes $Q^{2/3}$ and the abscissa becomes H. The lower or steeper section of the rating curve applies to the box inlet crest and the upper or flatter portion to the headwall opening. A number of points fall on neither curve in the vicinity of their intersection. These points, which are probably influenced by both the weir crest and the

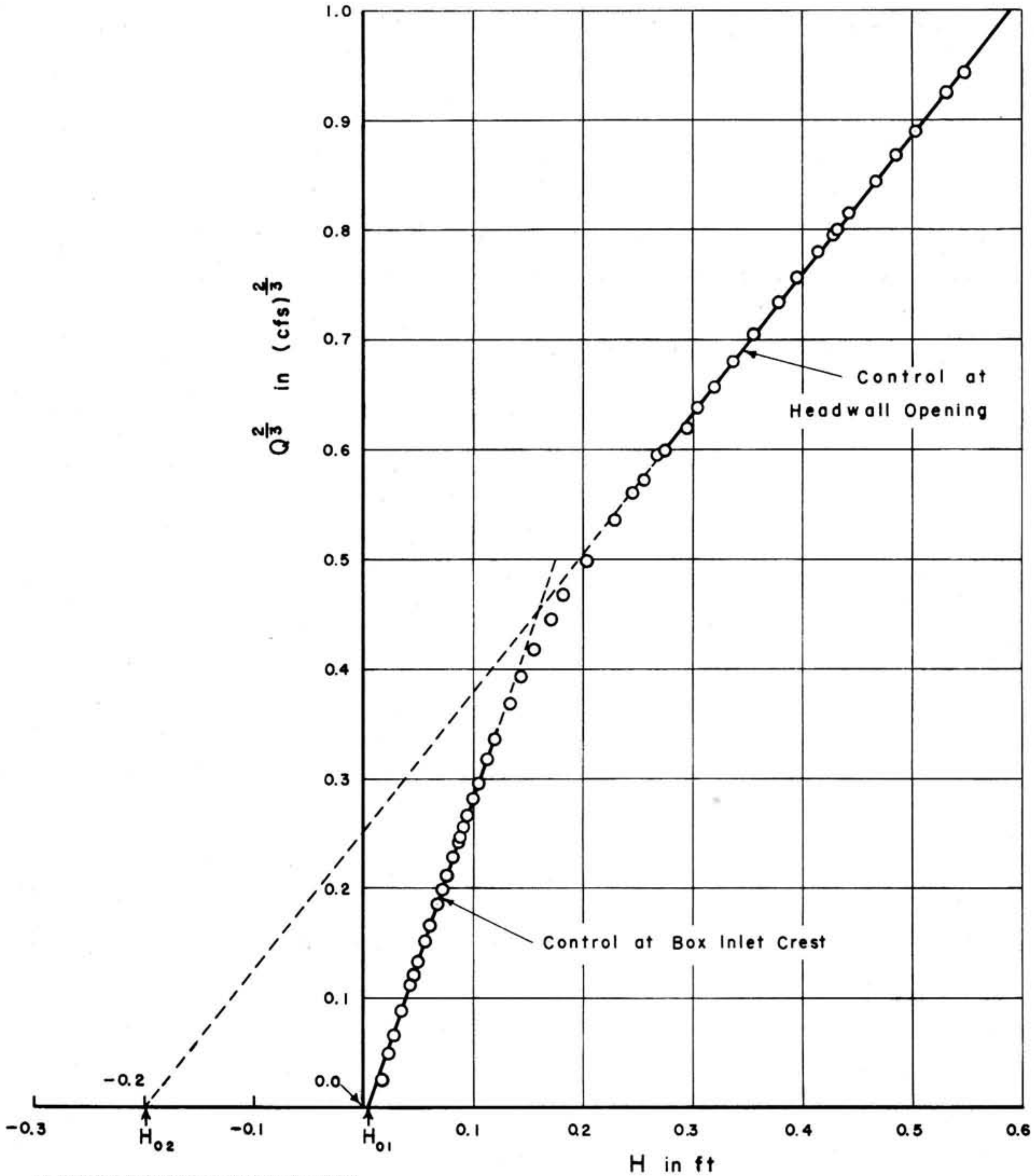

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Figure 3—Typical Plot of Data

headwall opening, were not used in computing the rating curves. In addition, a few of the lowest points were discarded when they fell off the curve, probably as a result of surface tension.

The constants in the equations for the discharge were determined by the method of least squares after it was found that fitting the curves by eye resulted in intolerable personal errors. The equations used had the form

$$Q = c_1 \, L \, \sqrt{2g} \, (H - H_{01})^{3/2} \tag{2}$$

for the box inlet crest portion of the rating curve, and

$$Q = c_2 \, \mathbf{W} \, \sqrt{2g} \, (H - H_{02})^{3/2} \tag{3}$$

for the headwall opening portion of the rating curve. Referring to Figure 3, it will be noticed that the data points fall on straight lines except for those near the intersection of the two curves and for one or two of the lowest flows. This observation, with minor exceptions, is characteristic of all the data obtained during the tests. The deduction from this observation is that the theoretical exponent is correct.

It will be noticed that neither of the curves shown in Figure 3 pass through the origin of coordinates. This had been anticipated for the headwall opening portion of the rating curve because the assumption of the origin of heads at the crest of the box inlet is obviously incorrect and the form of the equation was adopted, for one reason, so the correction H_{02} could be obtained. However, there was no reason to believe that H_{01} in Equation (2) would be other than zero. The fact remains that H_{01} was consistently found to be greater than zero to a degree that left no doubt as to its statistical significance. Much study was devoted to this point in an attempt to arrive at a satisfactory explanation for the head correction. All efforts in this direction proved to be of no avail. Practical means to surmount this difficulty are presented in a following section of this report.

The head-discharge curve coefficients, zero-flow head corrections, and number of runs used in determining the constants are listed in Table III for reference purposes.

TABLE III

SUMMARY OF HEAD-DISCHARGE CURVE DATA

Test Number	$\frac{B}{W}$	$\frac{B}{D}$	$\frac{D}{W}$	$\frac{W_c}{L}$	$\frac{W_e}{W}$	Equation 2			Equation 3			
						c_1	H_{01}	N_L	c_2	H_{02}	$\frac{H_{02}}{D}$	N_V
49	2.0	2.0	1.0	3.0	2.0	0.416	0.006	9	0.414	-0.370	-0.740	8
77				2.0		0.399	0.007	23	0.449	-0.335	-0.670	10
78				1.5		0.390	0.008	24	0.439	-0.340	-0.680	11
79				1.3		0.378	0.008	29	0.461	-0.318	-0.636	10
80				1.15		0.366	0.008	16	0.445	-0.332	-0.664	12
81				1.0		0.346	0.010	22	0.414	-0.364	-0.728	9
82a				0.8		0.307	0.007	20	0.560	-0.236	-0.472	5
83				0.6		0.234	0.005	13	- - - - No data obtainable - - - - -			
83a				0.6		0.235	0.007	9	"	"	"	
84				0.4		0.157	0.006	24	"	"	"	
85	1.0	1.0	1.0	3.0		0.429	0.004	14	0.432	-0.253	-0.506	9
114				2.0		0.416	0.004	16	0.423	-0.263	-0.526	10
115 & 115a				1.5		0.407	0.005	13	0.433	-0.252	-0.504	21
116				1.3		0.400	0.006	11	0.446	-0.239	-0.478	7
117				1.0		0.364	0.006	13	0.468	-0.213	-0.426	8
118				0.8		0.304	0.005	16	- - - - Insufficient data - - - - -			
119				0.6		0.228	0.007	23	- - - - No data obtainable - - - -			
120				0.4		0.153	0.006	13	"	"	"	
121				1.15		0.385	0.006	12	0.434	-0.249	-0.498	8
122				5.0		0.431	0.005	11	0.410	-0.280	-0.560	6
123	0.5	0.5	1.0	10.0		0.436	0.005	9	0.402	-0.152	-0.304	6
124				0.6		0.234	0.008	23	- - - - No data obtainable - - - -			
125				0.8		0.302	0.004	25	"	"	"	
126				1.0		0.364	0.006	10	0.457	-0.119	-0.238	11
127				1.15		0.396	0.006	8	0.430	-0.142	-0.284	11
128				1.3		0.410	0.006	6	0.377	-0.197	-0.394	7
129				1.5		0.421	0.006	11	0.384	-0.183	-0.366	13
130				2.0		0.439	0.007	7	0.393	-0.169	-0.338	11
131				5.0		0.433	0.004	6	0.394	-0.160	-0.320	11
132				3.0		0.445	0.006	13	0.398	-0.158	-0.316	13
165	0.25	0.25	1.0	3.0		0.405	0.000	7	0.424	-0.059	-0.118	15
166				2.0		0.397	-0.003	8	0.434	-0.060	-0.120	17
167	0.0	0.0	1.0	3.0		0.423	0.002	24	0.423	0.002	0.004	25
168				2.0		0.446	0.007	25	0.446	0.007	0.014	25
169 & 169a	2.0	4.0	0.5	3.0		0.392	0.004	18	0.351	-0.227	-0.908	17
226	1.0	2.0				0.419	0.004	17	0.356	-0.199	-0.796	19
227	0.5	1.0				0.447	0.005	15	0.351	-0.136	-0.544	28
252	0.25	0.5				0.429	0.001	11	0.361	-0.079	-0.316	33
253	0.0	0.0				0.420	0.002	36	0.420^{a} 0.386^{b}	0.002^{a} -0.014^{b}	0.008^{a} -0.056^{b}	36^{a} 34^{b}
254	2.0	8.0	0.25			0.411	0.005	11	0.334	-0.116	-0.928	37
285	1.0	4.0				0.388	0.002	10	0.340	-0.113	-0.904	30
324	0.5	2.0				0.467	0.007	12	0.352	-0.085	-0.680	26
330	0.25	1.0				0.476	0.005	6	0.354	-0.060	-0.480	22
331	0.0	0.0				0.456	0.006	13	0.368	-0.014	-0.112	27
332			0.125			0.417^{c} 0.406	0.003^{c} 0.007	4 7	0.349	-0.007	-0.112	31
333	0.25	2.0		3.0		0.459	0.010	10	0.341	-0.032	-0.512	29
334	0.5	4.0		0.6		0.208	0.011	56	0.415	0.011	0.176	56
335				1.0		0.337	0.011	10	0.356	-0.036	-0.576	28
336				1.5		0.334	0.012	7	0.346	-0.038	-0.608	30
337				3.0		0.347	0.012	6	0.341	-0.039	-0.624	32
338	1.0	8.0		0.6		0.235	0.013	12	0.349	-0.042	-0.672	25
339				1.0		0.239	0.011	10	0.340	-0.046	-0.736	28
340				1.5		0.252	0.012	8	0.345	-0.042	-0.672	31
341				3.0		0.235	0.010	12	0.343	-0.042	-0.672	33
342				0.4		0.167	0.011	10	- - - - No data obtainable - - - - -			
343	2.0	16.0		0.4		0.158	0.014	7	0.346	-0.045	-0.720	29
344				0.6		0.143	0.011	11	0.346	-0.044	-0.704	33
345				1.0		0.139	0.009	11	0.343	-0.044	-0.704	29
346				1.5		0.140	0.011	10	0.343	-0.043	-0.688	38
347				3.0		0.142	0.011	9	0.338	-0.047	-0.752	30
348	4.0	4.0	1.0	2.0		0.389	0.002	24	0.361	-0.459	-0.918	23
349	3.0	3.0	1.0	2.0		0.396	0.004	18	0.399	-0.463	-0.806	21

[a] Free nappe [b] No air under nappe [c] No end sill

Other Formulas: A number of additional formulas were carefully considered before abandoning them in favor of Equations (2) and (3). These equations will be discussed briefly. The comparisons of results are based on a least squares analysis of the data obtained from the nine tests numbered 49 and 77 to 84, inclusive, listed in Table III. The same model was used for each of these tests but the approach channel was different in width for each test.

An equation which is frequently used has the form

$$Q = c_3 \, L \, H^n \tag{4}$$

The theoretical value of the exponent n is 1.5. For the nine tests n varied from 1.57 to 1.70. The coefficient c_3 also varied. The variations of both c_3 and n were quite erratic and no relationship between either of them and any other variable was discovered.

It was thought the interference to the flow at the upstream corners of the box inlet might possibly have some influence on the flow over the crest. This influence was presumably a function of the head which could be taken into account by using an equation having the form

$$Q = c_4 \, L \, g^{1/2} \, H^{3/2} + c_5 \, g^{1/2} \, H^{5/2} \tag{5}$$

No trend could be discovered for the coefficients of Equation (5) nor for those of Equation (6), which is the same as Equation (5) except for the addition of a zero correction.

$$Q = c_6 \, L \, g^{1/2} \, H^{3/2} + c_7 \, g^{1/2} \, H^{5/2} + Q_o \tag{6}$$

The standard error of estimate S was computed for each of these equations and for Equation (2). The value of S, averaged for the nine tests is

Equation (2)	0.0031,
Equation (4)	0.0046,
Equation (5)	0.0056,
and	
Equation (6)	0.0052.

The standard error of estimate for Fquation (2) is the lowest of those computed for the four equations and is one significant reason this equation is used herein. Another equally important consideration is that the coefficient in Equation (2) varies consistently with approach channel width. It is noted above that no reliable trend was observed for the coefficients of Equations (4), (5) and (6).

Control at Crest of Box Inlet

Four factors are discussed below which affect the flow through box inlet drop spillways when the control section is the crest of the box inlet. A separate subsection is devoted to each factor and to the method of correcting for its effect. In the concluding subsection corrections to the discharge coefficient are made to demonstrate the precision of the corrections adopted. Although it was shown by Kessler and Huff that the level of the approach channel will affect the discharge, no tests were made to evaluate this effect. The approach channel was made level with the box inlet crest to simulate a natural approach channel silted level full.

Effect of Position of Dike: As the dike is moved closer to the crest of the box inlet free access to part of the box inlet crest is cut off. Although very little data were obtained, information which can be utilized to evaluate the dike effect will be presented for its qualitative value.

The closest position of the dike to the box inlet is the point at which the toe of the dike just touches the crest. At this point $X = 0$. Tests were made with $X/H = 0, 0.7, 1.4, 2.9, 5.7$, and ∞ (no dike) where H is the head for which the spillway is designed. The relative head H/W for which tests were made was 0.35. Since the dike slope was 1 on 3, the toe of the dike also projected upstream by $3H$. The tests were conducted for only a single box inlet having a relative length $B/W = 2$.

When plotting the results it was discovered that the dike position did not affect the discharge when the control was at the headwall opening. Therefore, the comments in this section apply only to the box inlet crest control portion of the rating curve. The ratio of the discharges at identical heads with a dike to that with no dike was computed for each of the dike positions with the following results:

X/H	0.0	0.7	1.4	2.9	5.7	∞
Relative discharge . .	0.84	0.85	0.93	0.97	0.99	1.00

The reduction in discharge resulting when the toe of the dike is located close to the crest is quite large--and this is for one of the longer box inlets tested. Apparently the toe of the dike should be located from 3H to 5H from the box inlet crest in order to minimize the dike effect.

If the effect of the dike for other box inlets can be assumed to be inversely proportional to the length of the crest, then for a box inlet shape of $B/W = 1$, where the crest length is 3W as compared to 5W when $B/W = 2$, the decrease in the relative discharge obtained above will be 5W/3W or 1.7 times as great. The corresponding figure for $B/W = 0.5$ is 5W/2W or 2.5. The importance of keeping the toe of the dike well away from the box inlet crest is quite apparent from these figures.

In using the above values to determine the dike effect it should be kept in mind that the data are too few to permit the determination of any completely reliable figures. The data are presented here in the absence of any better information primarily for their qualitative value.

Effect of Approach Channel Width: It was shown by Huff[5] that the width of the approach channel has a large effect on the discharge. One phase of the present test program was designed to determine this effect quantitatively and accurately. The results are presented in Figure 4 in dimensionless form. The discharge coefficient c_1 was divided by the average discharge coefficient for channel widths equal to or greater than three crest lengths $c_{1,W_c/L \geq 3}$ before plotting. This was so the plotted values would be proportional to the coefficients obtained for the wider channels and would directly indicate the throttling effect of the narrower approach channel. The tests with the deeper box inlets (larger D/W) are the most reliable since they cover a larger range of discharges than did

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[5] Huff, op. cit.

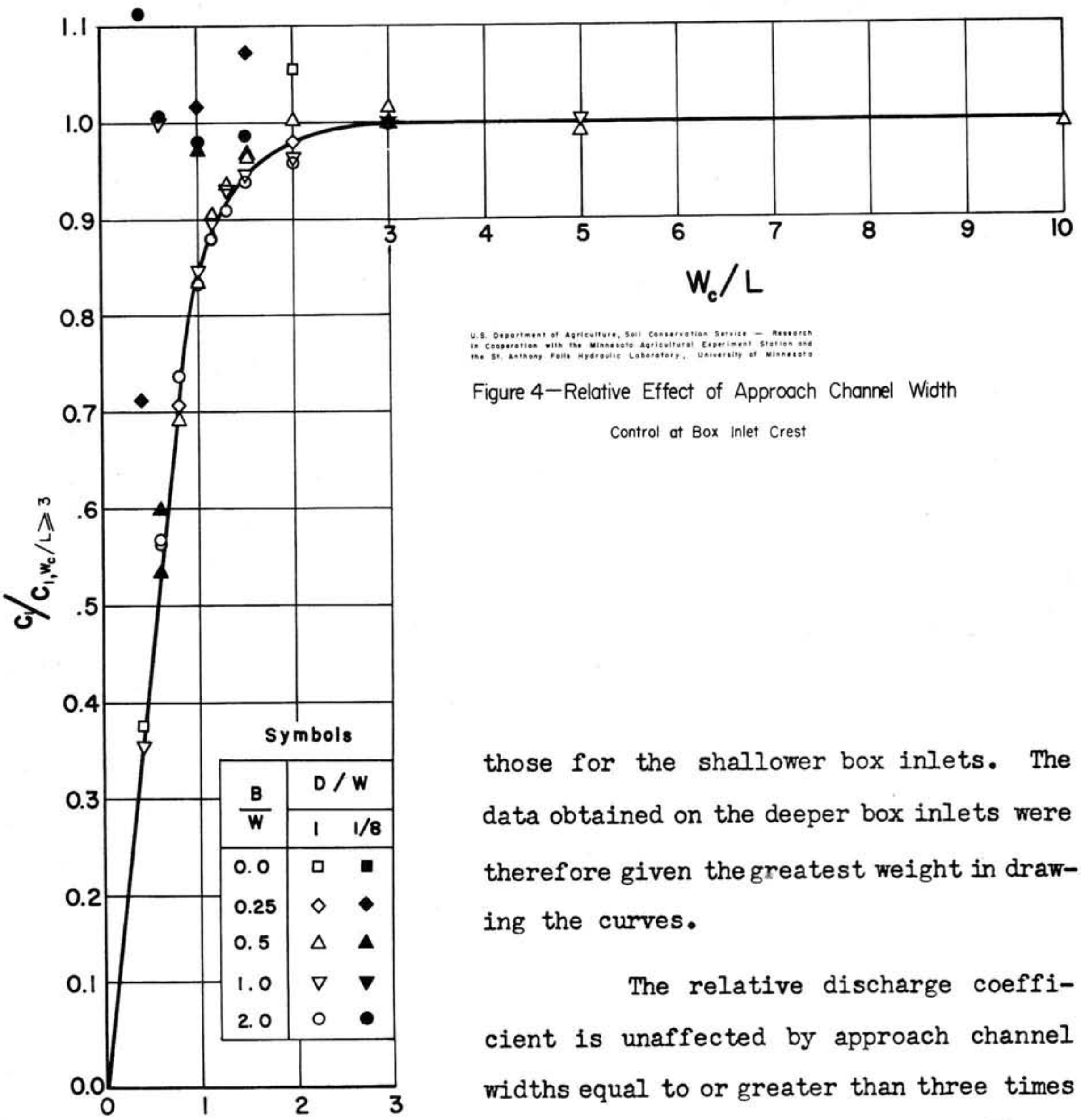

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Figure 4—Relative Effect of Approach Channel Width

Control at Box Inlet Crest

those for the shallower box inlets. The data obtained on the deeper box inlets were therefore given the greatest weight in drawing the curves.

The relative discharge coefficient is unaffected by approach channel widths equal to or greater than three times the length of the box inlet crest. Therefore, all design criteria are based on wide approach channels and the curve of Figure 4 or the factors listed in Table IV, which are taken from the curve, are suggested for use in correcting for the effect of narrow channels. The very rapid reduction in relative discharge as W_c/L decreases below 1 is readily apparent. It appears that under these conditions the longer box inlets become uneconomical and a shorter box inlet, which would operate under a slightly greater head and a much higher discharge coefficient, should be investigated.

TABLE IV

CORRECTION FOR APPROACH CHANNEL WIDTH

Control at Box Inlet Crest

Multiply c_1 or c_8 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	0.84	0.87	0.90	0.92	0.93	0.94	0.95	0.96	0.97	0.97
2	0.98	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00
3	1.00									

Correction is constant when W_c/L exceeds 3.0.

Effect of Shape of Box Inlet: When analyzing the results it was observed that the coefficient of discharge c_1 in Equation (2) was a function of the shape of the box inlet B/W. The discharge coefficients are plotted in Figure 5. In preparing Figure 5 open circles were used when the relative channel width was equal to or greater than 3. Tests made with a relative approach channel width of 2 were corrected for the effect of approach channel width and used to locate the curve for the longer boxes. The corrected coefficients are plotted as crosses in Figure 5. The data obtained for the shallowest box inlets (B/W = 1/8) were not plotted because the end sill caused submergence of the weir crest at all flows.

It is intended that the curve drawn in Figure 5 or the corrections given in Table V be used for design purposes. Because of the scatter in data there is some question as to the correct position of the curve, particularly for the short box inlets (low B/W). However, it is felt that values taken from the curve are valid to within ± 10 per cent. A correction scale has been added at the right side of Figure 5. This scale is based on the assumption that no correction is required to the discharge coefficient of 0.4275 when B/W = 1 but that a correction is required for other box inlet shapes. The use of this correction curve will be discussed in the following subsection.

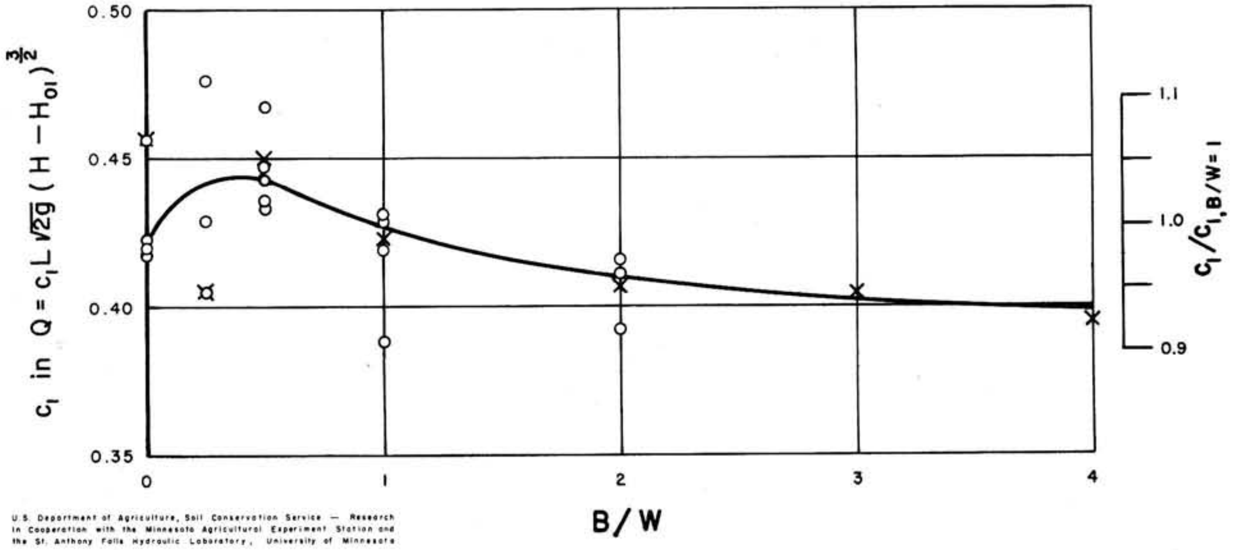

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Figure 5—Effect of Box Inlet Shape on Discharge Coefficient

Control at Box Inlet Crest

$\frac{W_c}{L} \geqslant 3$

TABLE V

CORRECTION FOR BOX INLET SHAPE

Control at Box Inlet Crest

Multiply c_1 or c_8 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	0.99	0.99	0.98	0.98	0.98	0.97	0.97	0.96	0.96
2	0.96	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.94
3	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.93	0.93
4	0.93									

Elimination of Zero-Flow Head Correction: The use of Equation (2) with its zero-flow head correction is open to some objection. Accordingly, a means was sought to eliminate the zero-flow head correction altogether.

It was found possible to do this. The resulting equation for discharge over the box inlet crest has the form

$$Q = c_8 \; L \; \sqrt{2g} \; H^{3/2} \tag{7}$$

where c_8 now varies with the head. To the coefficient in Equation (7) must be applied the corrections for approach channel width and box inlet shape.

To determine the coefficient of discharge and the reliability of Equation (7), c_8 was computed for each run of all pertinent tests. The coefficient c_8 was then corrected for the effect of approach channel width and box inlet shape. The corrected discharge coefficients are plotted in Figure 6 against relative head H/W. The only data not appearing in Figure 6 are those obtained for the shallow boxes where submergence from the end sill affects the discharge even at very low flows. Some shallow box data have been included for runs where the end sill was removed. Data from 51 of the 62 tests listed in Table III appear in Figure 6.

A mean curve has been drawn as a solid line in Figure 6. The coefficient of discharge for a given relative head may be taken from this curve, multiplied by the approach channel width correction and the box inlet shape correction, and substituted in Equation (7) to determine the capacity of the box inlet drop spillway when the box inlet crest controls the discharge. A second method for determining the discharge is outlined in the following paragraph using the correction scale at the right of Figure 6 or the corrections given in Table VI.

It will be noticed that the discharge coefficient is constant in Figure 6 when H/W is greater than 0.6. Therefore, Equation (7) can be written

$$Q = 0.4275 \; L \; \sqrt{2g} \; H^{3/2} \tag{8}$$

or, in English units,

$$Q = 3.43 \; L \; H^{3/2} \tag{9}$$

Equations (8) and (9) are valid when $B/W = 1$, $W_c/L \geq 3$, and $H/W \geq 0.6$. For other box inlet lengths, narrower approach channels and lower heads,

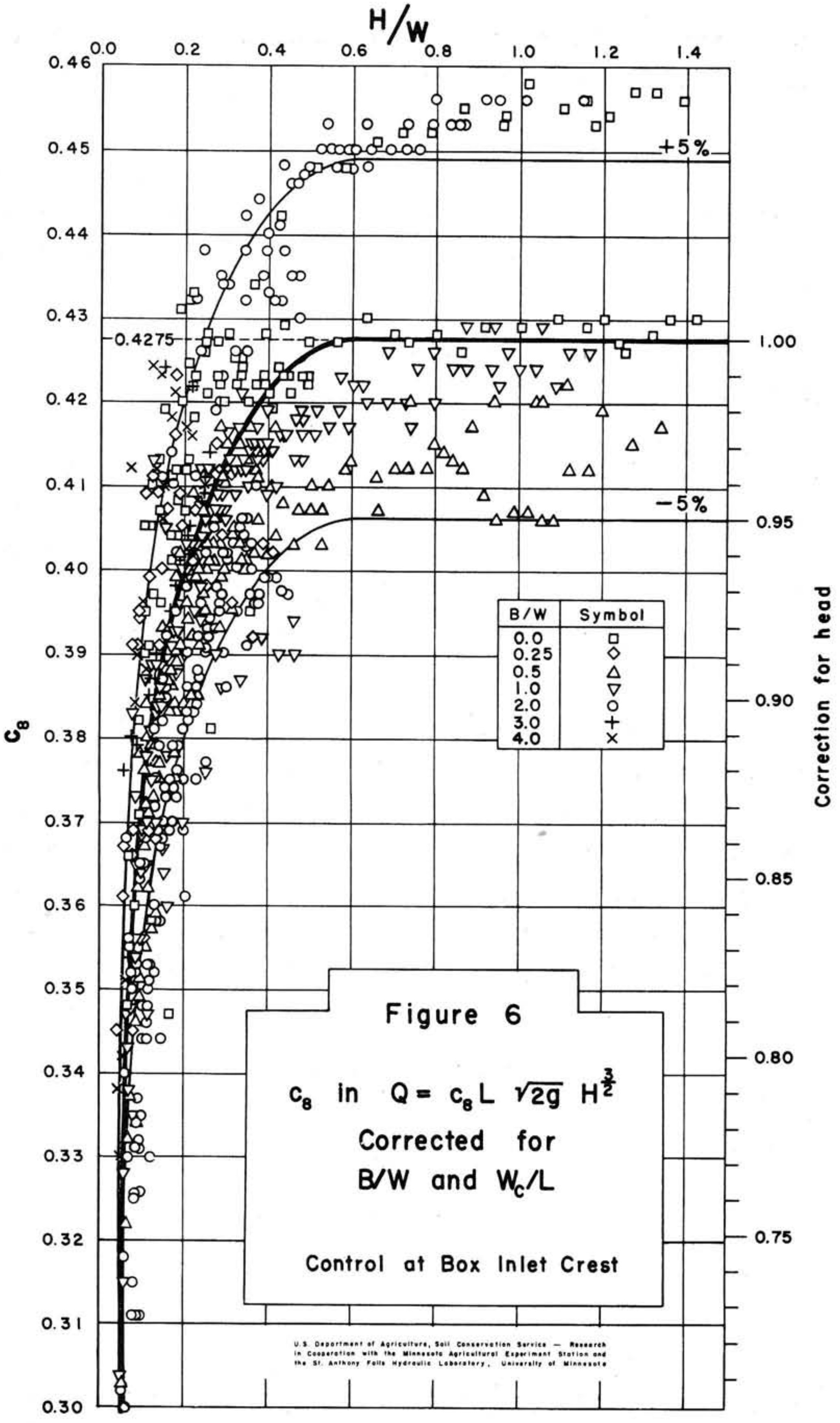

Figure 6

c_8 in $Q = c_8 L \sqrt{2g}\, H^{\frac{3}{2}}$

Corrected for B/W and W_c/L

Control at Box Inlet Crest

U.S. Department of Agriculture, Soil Conservation Service — Research in Cooperation with the Minnesota Agricultural Experiment Station and the St. Anthony Falls Hydraulic Laboratory, University of Minnesota the corrections given by the curves of Figures 4, 5 and 6 or the figures listed in Tables IV, V and VI must be applied.

TABLE VI

CORRECTION FOR HEAD

Control at Box Inlet Crest

Multiply c_8 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
0.1	0.87	0.88	0.89	0.90	0.91	0.91	0.92	0.92	0.93	0.93
0.2	0.93	0.94	0.94	0.95	0.95	0.95	0.95	0.96	0.96	0.96
0.3	0.97	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98
0.4	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00
0.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.6	1.00									

Correction is constant when H/W exceeds 0.6.

Precision of Results: Figure 6 has been prepared to a very large scale in order to facilitate plotting the data. Therefore, the scatter is not as great as might be assumed at first glance. Lightweight lines have been drawn 5 per cent above and below the mean line to permit an evaluation of the reliability of the methods. It can be seen that most of the observed data fall within ± 5 per cent of the mean line. Therefore, Figure 6 may be considered as verifying Equation (7) when c_8 is taken from Figure 6 and corrected by means of Figures 4 and 5 or Tables IV and V. Similar comments apply to Equations (8) and (9) when corrected by means of Figures 4, 5 and 6 or Tables IV, V and VI.

Control at Headwall Opening

At the higher flows the box inlet becomes flooded out and the section controlling the flow shifts from the box inlet crest to the opening in the headwall. The change from one control section to the other is fairly quick, as can be seen by referring to the typical plot presented in Figure 3. Equation (3) is used to define that portion of the rating curve which represents the head-discharge relationship when the headwall opening controls the flow.

A detailed analytical study was made to determine the factors which affect the discharge coefficient and the zero-flow head correction in Equation (3). It was discovered that the dike position, the box inlet shape, and the approach channel width had no effect on the discharge coefficient c_2 but that the coefficient was a function of the depth of the box inlet. With regard to the zero-flow head correction H_{02}, it was discovered that H_{02} was independent of the approach channel width and the dike position but was a function of both the relative length B/W and the relative depth D/W of the box inlet. Separate subsections of the report are devoted to the effect of the relative depth of the box inlet on the discharge coefficient and on the head correction.

Effect of Depth of Box Inlet on Discharge Coefficient: When the discharge coefficient c_2 in Equation (3) is plotted against the relative depth of the box inlet D/W it is found that c_2 increases with D/W. This is shown in Figure 7. The individual points plotted at each of four values of D/W represent different box shapes B/W and different approach channel widths W_c/L. While there is considerable spread to the data, other plots not presented here show that c_2 is independent of both B/W and W_c/L and it seems unlikely that the spread can be decreased.

For design purposes the solid curve drawn in Figure 7 is suggested for use in determining the coefficient of discharge in Equation (3). The discharge coefficients are also listed in Table VII for those who prefer to use tables.

Head Correction: It was anticipated that the zero-flow head correction H_{02} in Equation (3) would be quite large relative to the box inlet depth because the head H was measured from the crest of the box inlet while the effective headwall opening had a depth on the order of $H + D$. It was realized that the upstream crest of the box inlet would affect H_{02}, the effect varying with the ratio B/D of box inlet length B to box inlet depth D. It was anticipated that H_{02} would vary from possibly zero,

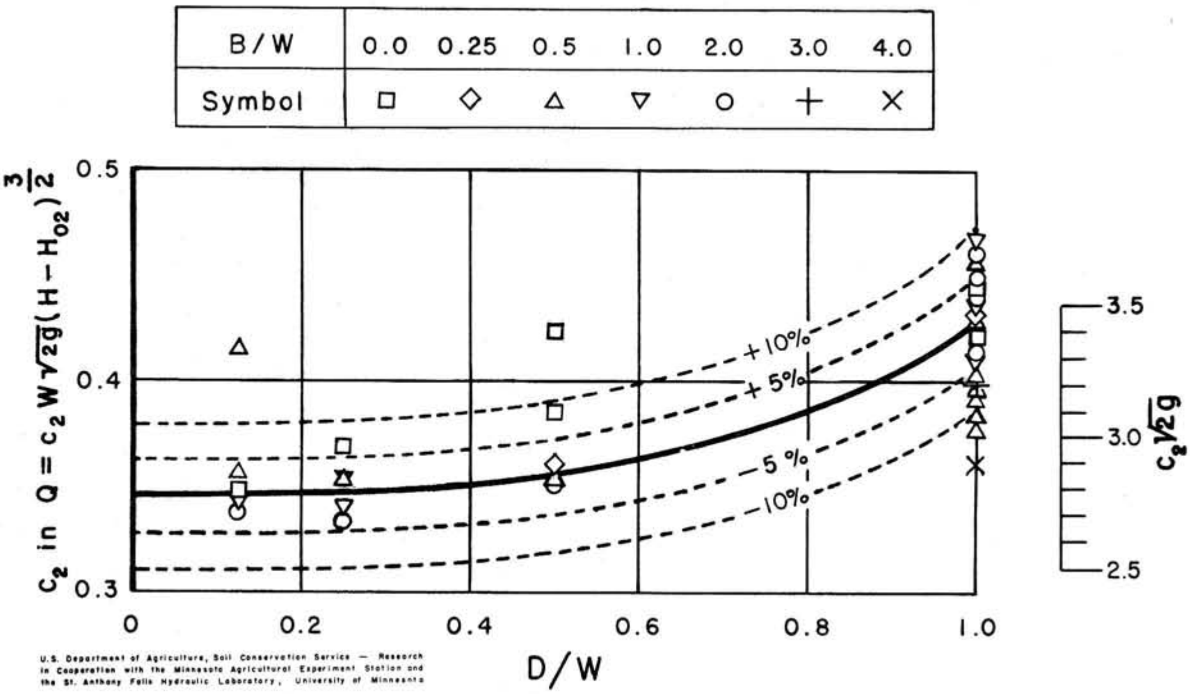

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Figure 7—Coefficient of Discharge

Control at Headwall Opening

TABLE VII

COEFFICIENT OF DISCHARGE

Control at Headwall Opening

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

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

as the box inlet length approached zero, to a minimum of $-D$ for relatively long, shallow box inlets. Furthermore, since the contraction of the jet at the headwall opening would be suppressed by the sides of the box below the level of the box inlet crest, it seemed reasonable to expect that this latter effect would be reflected in the value of H_{02}. Therefore, some means would have to be found to rationalize H_{02} and to devise a method whereby its value could be determined in the design office.

An analysis of the data showed that the head correction is independent of the approach channel width and of the width of the box inlet but that it is a function of the ratio of the box inlet length to its depth B/D. In Figure 8 the ratio H_{02}/D has been plotted against B/D. There it will be noticed that the data for box inlets having relative depths D/W of 1, 1/2 and 1/4 fall on a single curve but that for a relative box inlet depth of 1/8 the data fall on a separate well-defined curve. The reason for this has not been discovered.

In view of the fact that shallow boxes will be uneconomical in most cases for the higher flows where the headwall opening controls the discharge, the solid curve of Figure 8 is presented for design purposes for box inlets equal to or greater in depth than $W/4$. The curve of Figure 8 is also presented in tabular form in Table VIII. In order to cover the relative box inlet depths between 1/4 and 1/8, as well as the deeper box inlets, the data has been plotted in a different form in Figure 9. Although Figure 8 and Table VIII are simpler to use than Figure 9, Figure 9 may be used in place of Figure 8 or Table VIII for design purposes and must be used for the shallower boxes.

Precision of Results: Dashed curves have been added to Figure 7 parallel to the solid curve and 5 per cent and 10 per cent above and below it to indicate the spread of the data. It will be noticed that most of the data fall within a range of about 5 per cent from the design curve. Although occasional data points fall outside the 10 per cent limits, sufficient data fall inside this range to indicate that the coefficient of discharge reasonably can be expected to be within about 10 per cent of the value given by the design curve.

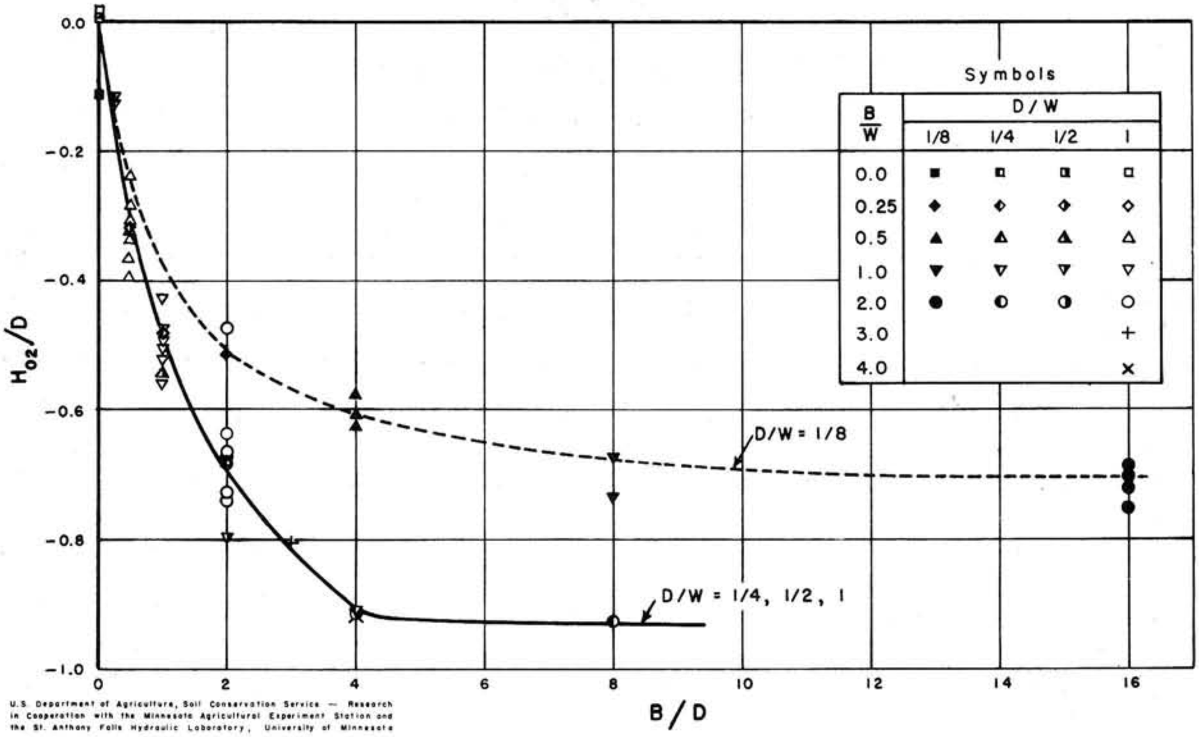

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Figure 8—Relative Head Correction for D/W ≥ 1/4

Control at Headwall Opening

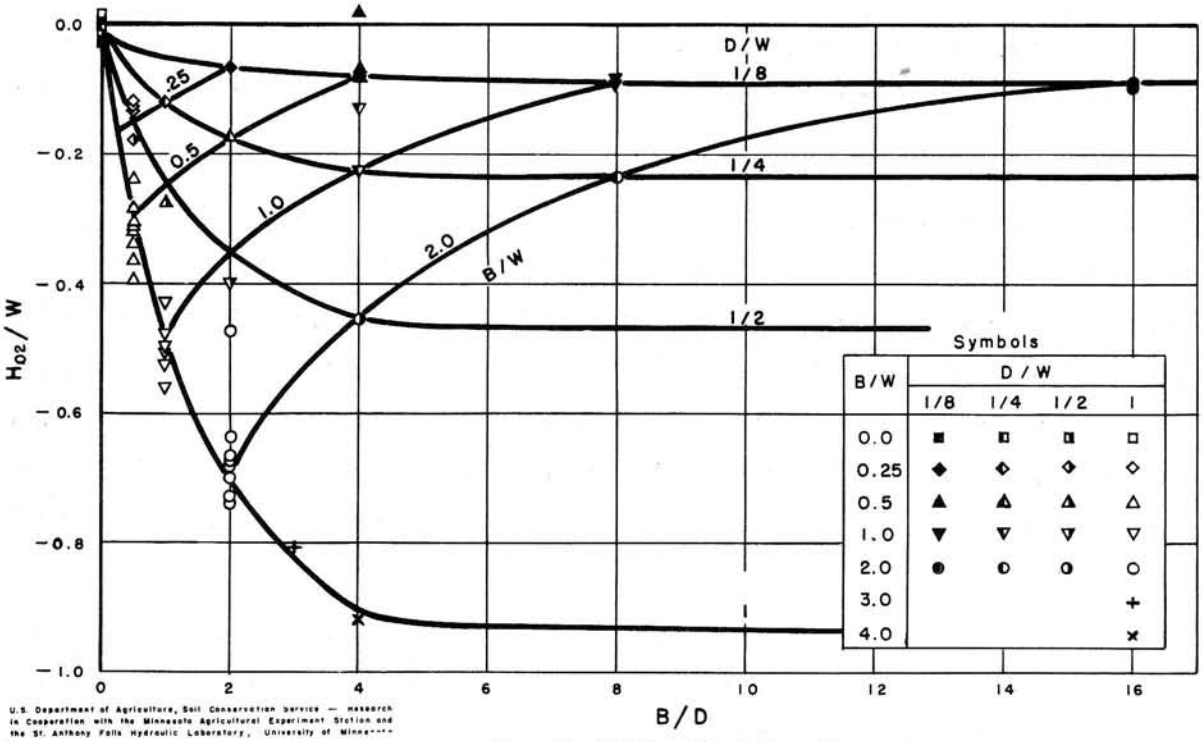

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Figure 9— Relative Head Correction

Control at Headwall Opening

TABLE VIII

HEAD CORRECTION H_{02}/D FOR $D/W \geq 1/4$

Control at Headwall Opening

H_{02}/D is negative

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	0.49	0.52	0.54	0.56	0.59	0.61	0.63	0.65	0.67	0.68
2	0.70	0.71	0.72	0.74	0.75	0.76	0.77	0.79	0.80	0.81
3	0.82	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.89	0.90
4	0.90	0.91	0.91	0.92	0.92	0.92	0.92	0.92	0.92	0.92
5	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93	0.93
6	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
7	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
8	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93

With regard to the head correction, it appears that the curve of Figure 8 can be expected to give this correction to within about 10 per cent, in general. At the low values of B/D the curve is steep and it seems likely that there the head correction may vary by as much as 20 per cent from the curve. These accuracies also apply to Table VIII. Little can be said regarding the accuracies obtainable through the use of Figure 9 but it seems likely that the comments made regarding Figure 8 also apply to Figure 9.

It was noted during the tests that the coefficient of discharge and the head correction vary in such a manner as to indicate that a deviation of one from the curve was at least partially corrected by a compensating deviation of the other. To some degree at least the variations from the design curves of Figures 7 and 8 are therefore quite likely compensating.

One other point needs mentioning. After plotting the rating curves (as in Figure 3) it was noticed that for a few of the curves the data points at the highest heads fell slightly above the straight line. These points were discarded when computing the discharge coefficient c_2 and the head correction H_{02}. They deviated from the rating curves at a relative head H/W in excess of about 1.2. The deviation was not observed for the deeper boxes when D/W exceeded 0.25 and for only about half the tests where D/W equaled 0.25. One reason this deviation was not noticed was that the heads seldom reached that high a value of H/W. The deviation was particularly noticeable when D/W equaled 0.125, although it did not exceed 3 per cent in discharge. Since the higher heads probably are outside the practical range of use of this type of spillway, no attempt was made to correct for the deviation from the curves. The deviation is in a direction to give a capacity greater than was computed for the spillway and in this respect is on the safe side. In any case, the deviation is so small when compared to other uncertainties as to be unimportant, at least over the range in heads covered by the tests. The test setup did not permit the use of heads greater than $H/W = 1.4$.

Submerged Flow Tests

At many field locations it is possible to have a downstream water level so high as to submerge the box inlet crest. This is particularly true of the "island dam" type of design. Since the high tailwater level lowers the capacity of the box inlet drop spillway, tests were made to evaluate the effect of submergence.

It was suspected that a number of factors would require investigation. Because the relative importance of the various factors was unknown, preliminary tests were run to determine the effect of each factor. The following section of the report is devoted to a discussion of the preliminary tests. A second section discusses the submergence calibration tests, which were voluminous because no simple method was discovered by which the results could be systematized.

Preliminary Tests

The preliminary tests and analyses cover the effect of banks in the exit channel, the effect of varying the length of the straight section in the outlet, the effect of the width of the outlet, the effect of varying the rate of flow, and attempts to systematize and condense the results. A separate subsection is devoted to each of these effects.

Effect of Banks in Exit Channel: Ditches and natural streams of course have banks which may or may not affect the flow through the box inlet drop spillway at high tailwater levels. In conducting submerged flow studies it is more convenient if it is not necessary to shape the exit channel. A test was therefore made to determine if the submergence curve was affected by the presence or absence of the shaped downstream channel.

In Figure 10 the data points shown as triangles were obtained with a downstream channel filled with sand, the shape being formed by water running over it with the tailwater at about its normal level. The data points shown as circles were obtained with no sand in the downstream channel. From this figure it can be seen that the presence or absence of the bed and banks in the downstream channel had no effect on the submergence curve. As a result, all subsequent submergence curves were obtained without stream banks in the downstream channel. This greatly facilitated the study without detracting from its value.

Effect of Length of Straight Section: The outlet for the box inlet drop spillway has a straight or parallel sided section between the box inlet and the stilling basin, which may have flaring walls. The length of this straight section may be varied to fit the site conditions and it was thought that the varying lengths might modify the submergence effect. Tests were therefore made to determine if the different lengths of straight section had an effect on the submergence curve.

Data obtained with straight sections having lengths equal to three and five times the minimum lengths given by the design equations are plotted in Figure 11. There it may be seen that the points fall on a single curve within the limits of experimental precision. No comparable data are available for the minimum length of straight section but all available data indicate no effect of straight section length. It is concluded that the length of the straight section does not affect the submergence curve.

Effect of Width of Outlet: The stilling basin proper can be constructed with either parallel sidewalls constructed as extensions of the straight section walls or with flaring sidewalls. The choice depends largely in the outlet, the effect of the width of the outlet, the effect of varying the rate of flow, and attempts to systematize and condense the results. A separate subsection is devoted to each of these effects.

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Data obtained with straight sections having lengths equal to three and five times the minimum lengths given by the design equations are plotted in Figure 11. There it may be seen that the points fall on a single curve within the limits of experimental precision. No comparable data are available for the minimum length of straight section but all available data indicate no effect of straight section length. It is concluded that the length of the straight section does not affect the submergence curve.

Effect of Width of Outlet: The stilling basin proper can be constructed with either parallel sidewalls constructed as extensions of the straight section walls or with flaring sidewalls. The choice depends largely

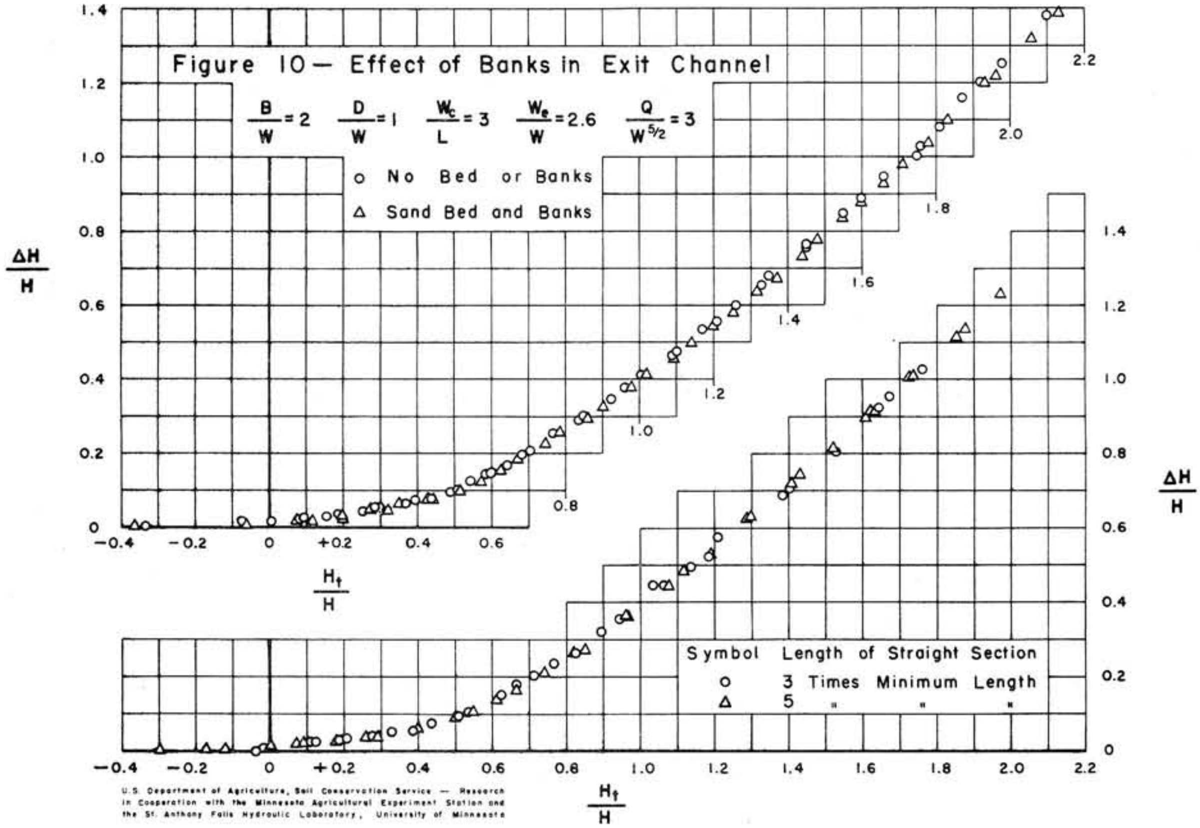

Figure 10 — Effect of Banks in Exit Channel

$\frac{B}{W}=2 \quad \frac{D}{W}=1 \quad \frac{W_c}{L}=3 \quad \frac{W_e}{W}=2.6 \quad \frac{Q}{W^{5/2}}=3$

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Figure 11 — Effect of Length of Straight Section

$\frac{B}{W}=2 \quad \frac{D}{W}=1 \quad \frac{W_c}{L}=3 \quad \frac{W_e}{W}=1.8 \quad \frac{Q}{W^{5/2}}=3$

on the site selected for the structure. If flaring sidewalls are used it is likely there will be a recovery of velocity head in the outlet that may mitigate the submergence effect. Therefore, the influence of flaring outlet sidewalls was investigated.

A study of the data indicates that the rate of flare of the outlet sidewalls, within reasonable limits, does not affect the submergence curves. Flares tested varied from 1 in ∞ to 1 in 2.

It is apparently the width of the outlet at its downstream end W_e that determines the amount of energy recovered in the outlet. This is shown in Figure 12, where it can be readily seen that the increase in upstream head ΔH due to a given tailwater level H_t diminishes rapidly as the outlet is widened. As would be anticipated, the effect of width decreases as the width increases until, in the case cited in Figure 12, there is no benefit in using outlets wider than about 1.5W.

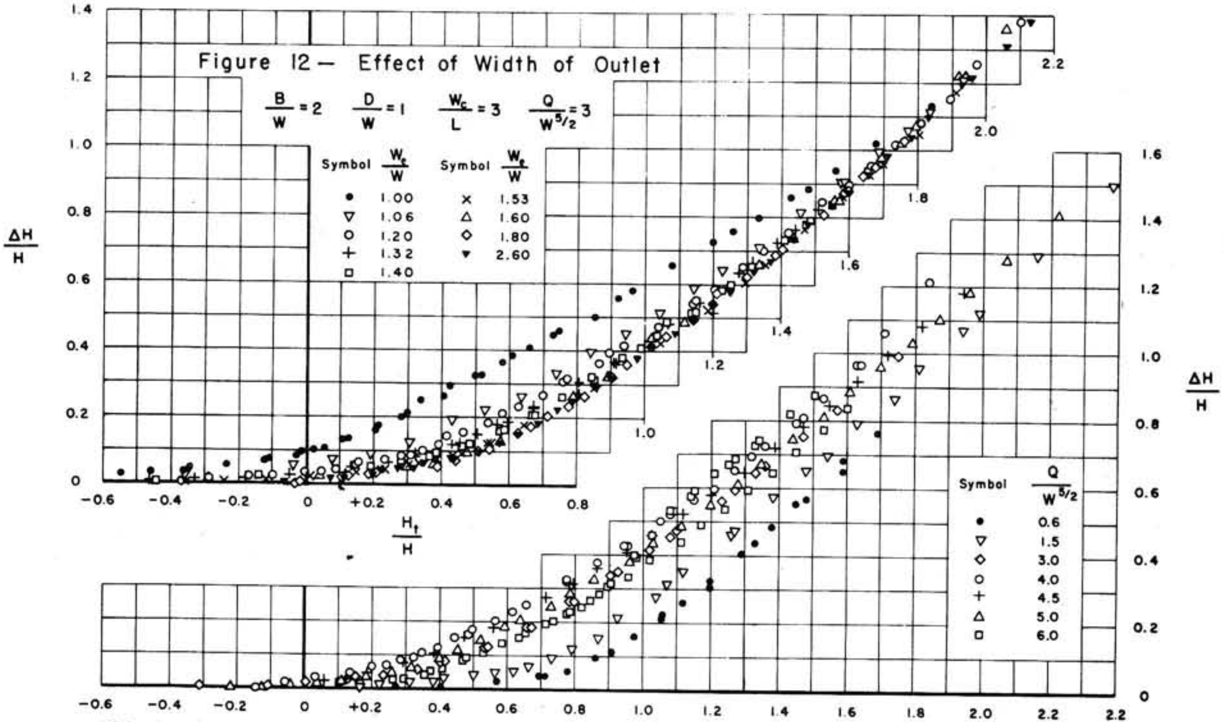

Figure 12 — Effect of Width of Outlet

$\frac{B}{W} = 2 \quad \frac{D}{W} = 1 \quad \frac{W_c}{L} = 3 \quad \frac{Q}{W^{5/2}} = 3$

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Figure 13 — Effect of Discharge

$\frac{B}{W} = 2 \quad \frac{D}{W} = 1 \quad \frac{W_c}{L} = 3 \quad \frac{W_e}{W} = 1.64$

The results of this investigation show the great effect of width of outlet and indicate the necessity of considering outlet width as one of the variables in a study of submergence effects on flow through box inlet drop spillways.

Effect of Varying Discharge: Because the effect of submergence sometimes varies with the discharge, several submergence curves were obtained with discharge as the only controlled variable. The results of this study are shown in Figure 13, where it can be seen that the submergence effect increases with the discharge up to the point where $Q/W^{5/2} = 4$. At still higher discharges the submergence effect decreases.

An excellent correlation was obtained showing that the discharge which produced the greatest submergence effect corresponds to the discharge on the free flow rating curve where the control changes from the box inlet crest to the headwall opening. This discharge is apparently independent of the width of the outlet but varies greatly with the depth of the box inlet and apparently to a minor degree with the length of the box inlet.

As a result of this phase of the study it can be seen that the submergence effect is a function of the discharge.

Attempts to Systematize Results: It has been pointed out that a large number of significant variables are involved in this submergence study. If the results of these tests could be systematized in some manner, it would not only be possible to reduce the number of tests required but would also simplify the presentation of the results and facilitate their use.

A great deal of time and thought was devoted to this study. The results were discouraging. While a little progress was made in reducing some of the variables to a single curve, the complications and reduction in accuracy resulting from multiple corrections indicated that it would be simpler and more accurate if the designer made his own interpolations from the original submergence curves. Therefore, all attempts to systematize the data were abandoned and efforts were directed toward obtaining sufficient submergence data to cover the anticipated range of field conditions.

Submergence Calibration Tests

The preliminary tests discussed in the foregoing paragraphs bear out the comments made by King when commenting on the submerged weir experiments made by Bazin. King[6] says, "Each type of weir is a problem in itself and if the laws governing [submerged] flow over it are to be determined, each requires an extensive experimental investigation, covering a wide range of conditions."

The test program was designed to provide the "extensive experimental investigation" which King says is required. The range of variables covered is given in Table II. The data for each of the 36 models or variations were plotted on separate sheets, each of the six constant discharges recorded on each sheet being represented by a different curve. Figure 13 is representative of these plots. There seemed insufficient justification to go to the time and expense required to plot each of the approximately 7500 points and prepare 36 figures for this report. However, the 216 submergence curves minus the data points have been prepared for design use

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[6] King, Horace Williams, "Handbook of Hydraulics," (Second Edition). New York: McGraw-Hill Book Company, 1929, p. 162.

and are presented in a companion report[7] prepared especially for use by those who have occasion to determine the flow through box inlet drop spillways under submerged flow conditions.

SUMMARY OF RESULTS

The results of the tests made on box inlet drop spillways are summarized in the following outline:

I. Free Flow Tests

A. Control at Crest of Box Inlet

1. The toe of the dike should be located a minimum distance of 3H to 5H from the box inlet crest to minimize its effect on the flow over the crest. Indications are that locating the dike close to the crest may reduce the capacity by as much as 15 per cent when $B/W = 2$, 25 per cent when $B/W = 1$, and 40 per cent when $B/W = 0.5$.

2. The width of the approach channel has a very large effect on the discharge coefficient when W_c/L is less than 3.0. Corrections for the effect of approach channel width may be taken from the curve of Figure 4 or from Table IV.

3. The coefficient of discharge varies with the box inlet shape B/W as shown in Figure 5. Corrections for the effect of box inlet shape may be obtained either from Figure 5 or from Table V.

4. It is possible to eliminate the zero-flow head correction in Equation (2) if the coefficient of discharge is varied with the head. Coefficients of discharge c_8 for use in the equation

$$Q = c_8 \; L \; \sqrt{2g} \; H^{3/2} \tag{7}$$

can be obtained from the curve of Figure 6.

5. The discharge over the box inlet crest can be computed from the equation

$$Q = 0.4275 \; L \; \sqrt{2g} \; H^{3/2} \tag{8}$$

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[7] Blaisdell and Donnelly, op. cit.

or, in English units,

$$Q = 3.43\ L\ H^{3/2} \tag{9}$$

when $B/W = 1$, $W_c/L \geq 3$, and $H/W \geq 0.6$. For other box lengths, narrower approach channels and lower heads, the corrections obtained from the curves of Figures 4, 5 and 6 or from Tables IV, V and VI must be applied.

6. The discharge over the box inlet crest can be determined within about 7 per cent of the true value if the specified limits of applicability of results are recognized and the foregoing corrections are applied.

B. Control at Headwall Opening

1. The position of the dike, the shape of the box inlet, and the width of the approach channel do not affect the discharge coefficient.

2. The discharge coefficient c_2 in the equation

$$Q = c_2\ W\ \sqrt{2g}\ (H - H_{02})^{3/2} \tag{3}$$

is a function of the relative depth of the box inlet D/W. The coefficient may be obtained from the curve of Figure 7 or from Table VII.

3. The zero-flow head correction is independent of the approach channel width, the width of the box inlet, and the dike position.

4. The ratio of the zero-flow head correction H_{02} in Equation (3) to the box inlet depth D is a function of the ratio B/D of box inlet length B to its depth D for box inlets having relative depths D/W of 1, 1/2 and 1/4. Zero-flow head corrections may be obtained from Figure 8 or from Table VIII when D/W lies within the specified limits.

5. For shallow box inlets the relationships of Figure 8 and Table VIII become invalid. Figure 9 may be used to obtain the zero-flow head correction for any box inlet proportions within the experimental limits.

6. The discharge through the headwall opening can be determined to within about 10 per cent of the true value if the above coefficients and corrections are applied and the limits covered by the experiments are not exceeded.

II. Submerged Flow Tests

A. Conditions Affecting Submergence

1. The location of the banks or even the complete absence of a downstream channel does not affect the submergence.

2. The length of the straight section between the box inlet and the outlet does not affect the submergence.

3. The width of the stilling basin at its exit has a very important effect on the submergence--the wider outlets, within certain limits, contributing to a reduction in the effect of submergence.

4. The submergence effect is a function of the discharge. Apparently the greatest submergence effect occurs at that free flow discharge where the control changes from the box inlet crest to the headwall opening.

B. Attempts to systematize and condense the test results proved unprofitable, making it necessary to run tests on each variable for the full range of anticipated field conditions.