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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PROGRESS REPORT
RESEARCH STUDY ON
STILLING BASINS AND BUCKET DISSIPATORS

Laboratory Report Hyd-380

ENGINEERING LABORATORIES BRANCH

OFFICE OF THE ASSISTANT COMMISSIONER AND CHIEF ENGINEER
DENVER, COLORADO

June 11, 1954

TO THE READER:

This report is a preliminary copy of part of a larger proposed volume dealing with stilling basin design. The contents of the entire proposed report are described under "Scope" and the portion presented here is given in the "Contents." It was decided to distribute this tentative issue because of the reaction of the designers who saw portions of the manuscript in draft form. Without exception, they expressed their desires to have it made available even in tentative form.

Various members of the Hydraulic Laboratory Staff have contributed critical comments to this issue. It is requested that you read this portion of the report critically and apply the data and methods to your problems. Any inconsistencies or incomplete sections should be noted and your comments and criticisms forwarded to the Hydraulic Laboratory.

It is hoped that with your help, this volume will become a usable source of information in the design of stilling basins for all types of structures. Your frank criticisms and comments are desired.

J. N. Bradley

CONTENTS

CONTENTS--Continued

FIGURES

TABLES

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Office of the Assistant Commissioner and Chief Engineer
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June 11, 1954

Laboratory Report No. Hyd-380
Hydraulic Laboratory
Compiled by: J. N. Bradley

Subject: Progress report, research study on stilling basins and bucket dissipators

INTRODUCTION

Although the Bureau of Reclamation has designed and constructed hundreds of stilling basins and energy dissipation devices in conjunction with spillways, outlet works, and canal structures, it has been necessary in many cases to make model studies of individual structures to be assured that these will operate as anticipated. The reason for this procedure in many cases can be linked to the fact that a factor of uncertainty exists which in retrospect is related to an incomplete understanding of the over-all characteristics of the hydraulic jump. This is especially understandable to the author, in that extensive library research has failed to reveal the information desired. Past experiments on the hydraulic jump have been made in a piecemeal manner; the connecting links are vague or nonexistent.

Purpose

Due to numerous requests for up-to-date hydraulic design information on stilling basin and bucket dissipators, the laboratory initiated a general research program on the hydraulic jump in 1952. It was planned to begin the program with a rather academic study of the hydraulic jump, observing all phases as it occurs in open channel flow. Then with a supposedly broader understanding of this phenomenon, proceed to the more practical aspect of stilling basin and bucket dissipator design.

Stilling basins will be defined as structures in which all or part of a hydraulic jump is confined. Other structures, such as buckets, which do not operate on the hydraulic jump principle, will be designated as energy dissipators. No single stilling basin or bucket design performs best for all types of installations encountered in practice as the various stilling basins and buckets have physical limitations. For example the capacity of a stilling basin having blocks or baffles on the floor is limited by the ability of these appurtenances to remain intact under the most adverse conditions imposed upon them. It will be possible to consider only a few of the many facets in the design of these structures.

The practical aspect of the investigations will be an attempt to generalize the hydraulic design of existing structures, develop new or improved designs where needed, and determine tentative limitations as to size and capacity of the various structures.

Scope

The program as planned deals with the hydraulic design of the following structures which will appear in the order shown:

1. General investigation of the hydraulic jump on horizontal apron

2. Stilling basin, with horizontal apron utilizing chute blocks at upstream end and dentated sill at downstream end, such as are often used on earth dam spillways. The appurtenances modify the jump causing it to form in a shorter than normal length

3. Unusually short type of stilling basin suitable for canal structures, small outlet works, and small spillways where additional baffle blocks result in a further shortening of the jump

4. Wave suppressors for small canal structures and diversion dams where the hydraulic jump is unstable

5. Stilling basin with sloping apron for large capacities and high velocities, where appurtenances in basin are undesirable

6. The overchute type of dissipator where baffle blocks distributed over the entire length and width of the chute dissipate the energy in the water as it falls

7. A stilling basin for diversion dams where temporary retrogression is expected

8. A stilling basin for diversion dams which can accommodate both free and submerged flow

9. The slotted bucket for medium and low overfall dams

10. The solid bucket for overfall dams at which an excess of tail water exists, and

11. The flip bucket which discharges above the tail water.

A large portion of the information for the designs to be considered was collected from Hydraulic Laboratory records and experience over a 23-year period, interspersed with tests on some of the same structures in the field. Also advantage was taken of available literature on the subject. In spite of the fact that existing literature and data would fill volumes, the information is far from complete from an over-all standpoint. It was therefore necessary to supply the missing information from current experiments.

Experimental Equipment

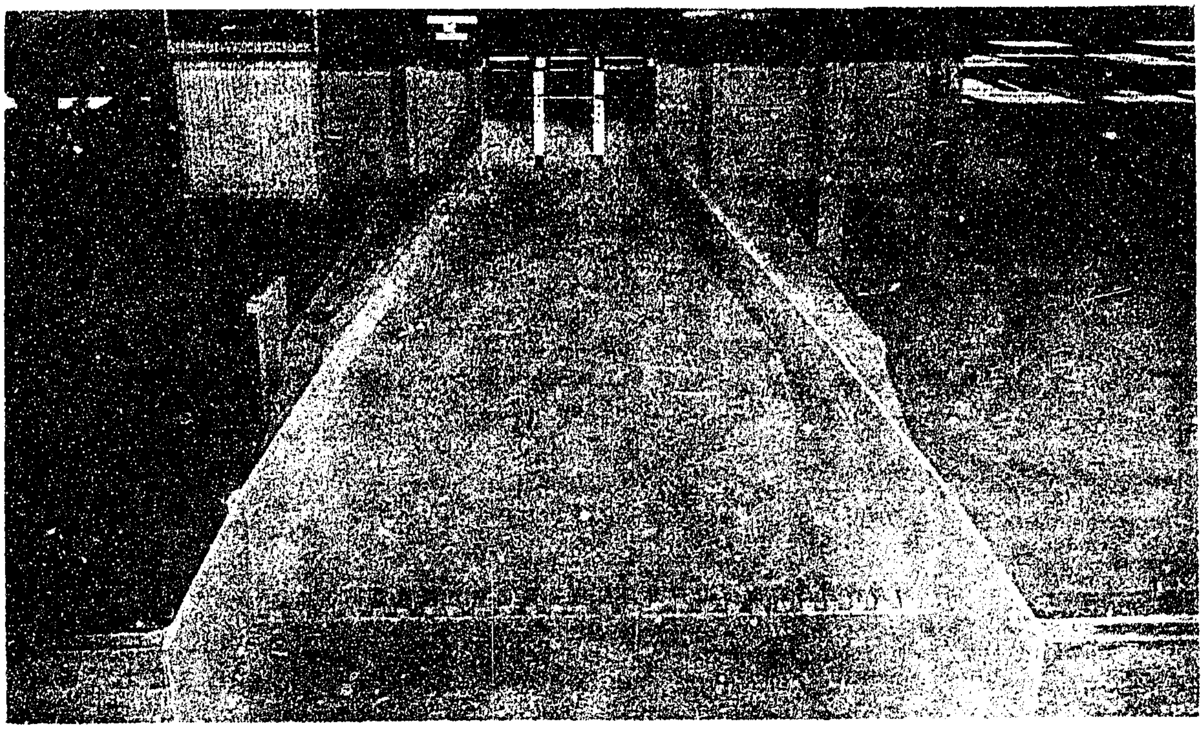
Five test flumes were used at one time or another to obtain the experimental data required in the present test program, Flumes A and B, Figure 1; Flumes B and D, Figure 2; and Flume F, Figure 3. The arrangement shown as Flume E, Figure 3, actually occupied a portion of Flume D during one stage of the testing but it will be designated as a separate flume for ease of reference. Each flume served a useful purpose either in verifying similarity or extending the range of the experiments. Flumes A, B, C, D, and E contained overflow sections so that the entering jets fell into the stilling basins at a vertical angle. The degree of the angle varied in each case. In Flume F, the entering jet emerged from under a vertical slide gate so the initial velocity was horizontal.

The experiments were started in a model of the Trenton Dam spillway, Figure 1A, having a small discharge and low velocity. This was not an ideal piece of equipment for general experiments as the training walls on the chute were diverging. This caused the distribution of flow entering the stilling basin to shift with each change in discharge, nonetheless, this piece of equipment served a purpose in that it aided in getting the research program underway.

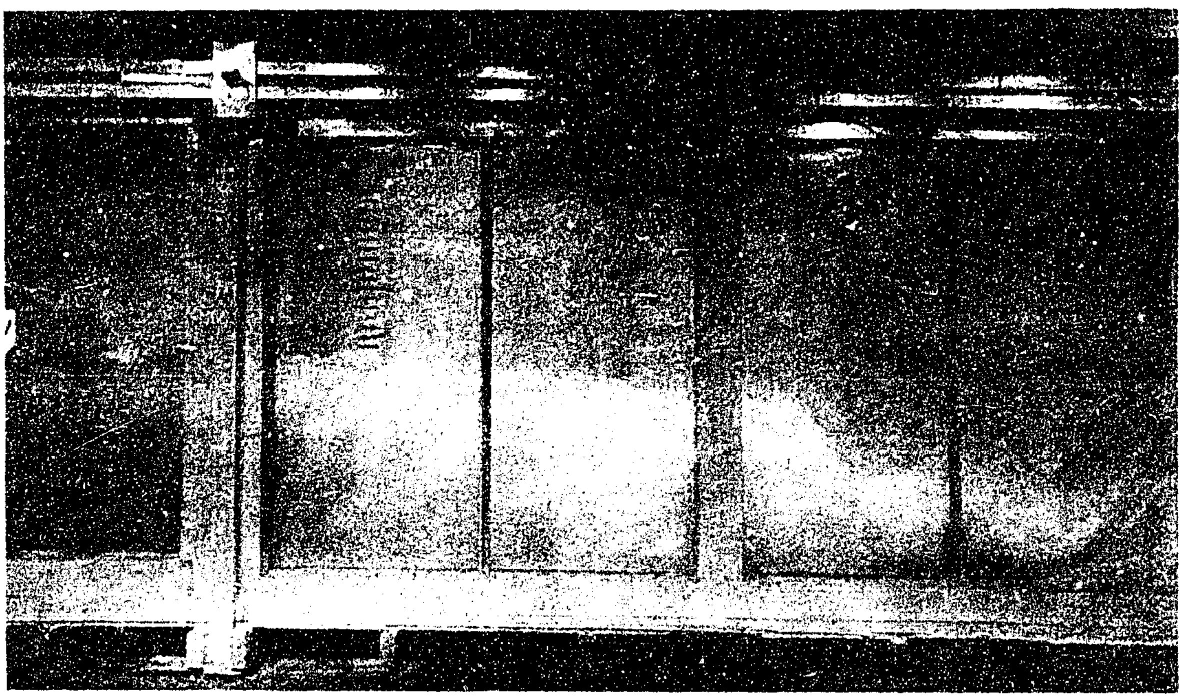
Tests were then continued in a glass-sided laboratory flume 2 feet wide and 40 feet long in which an overflow section was installed, Flume B, Figure 1. The crest of the overflow section was 5.5 feet above the floor, while the downstream face was on a slope of 0.7:1. The capacity was about 10 cfs.

Later, the work was carried on at the base of a chute 18 inches wide having a slope of 2 horizontal to 1 vertical and a drop of approximately 10 feet, Flume C, Figure 2. The stilling basin had a glass wall on one side. The discharge capacity was 5 cfs.

FIGURE 1

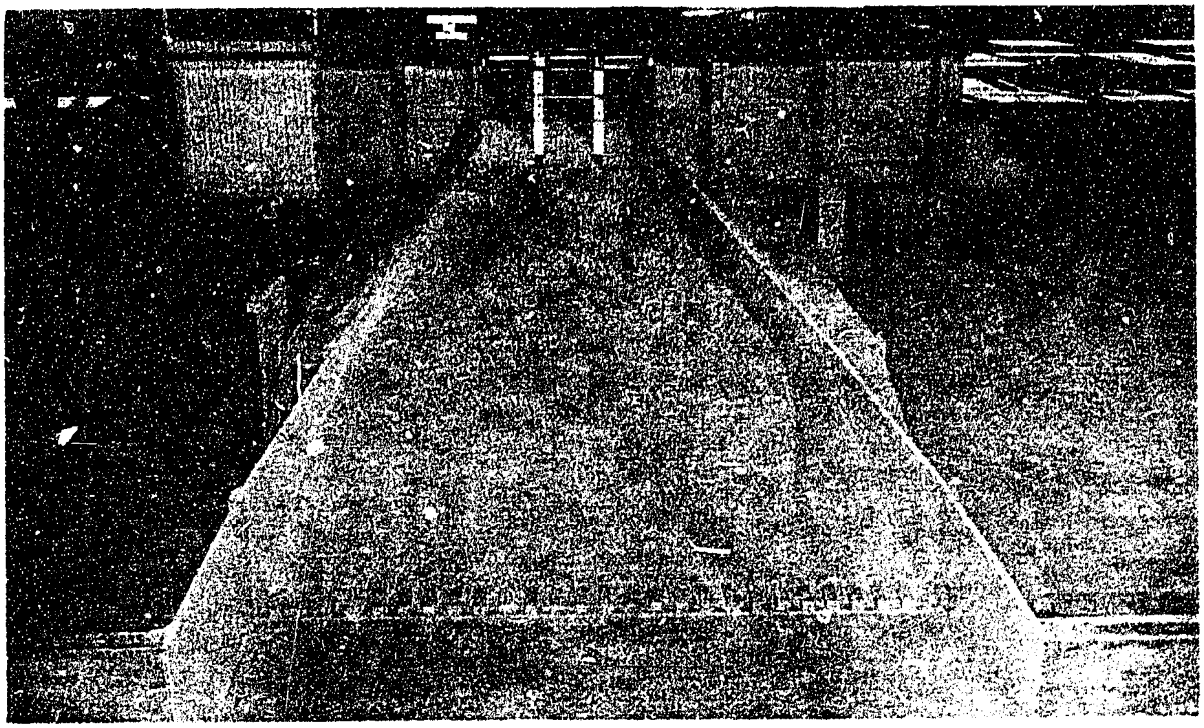


TEST FLUME A
Width of basin 5 feet, drop 3 feet, discharge 6 cfs

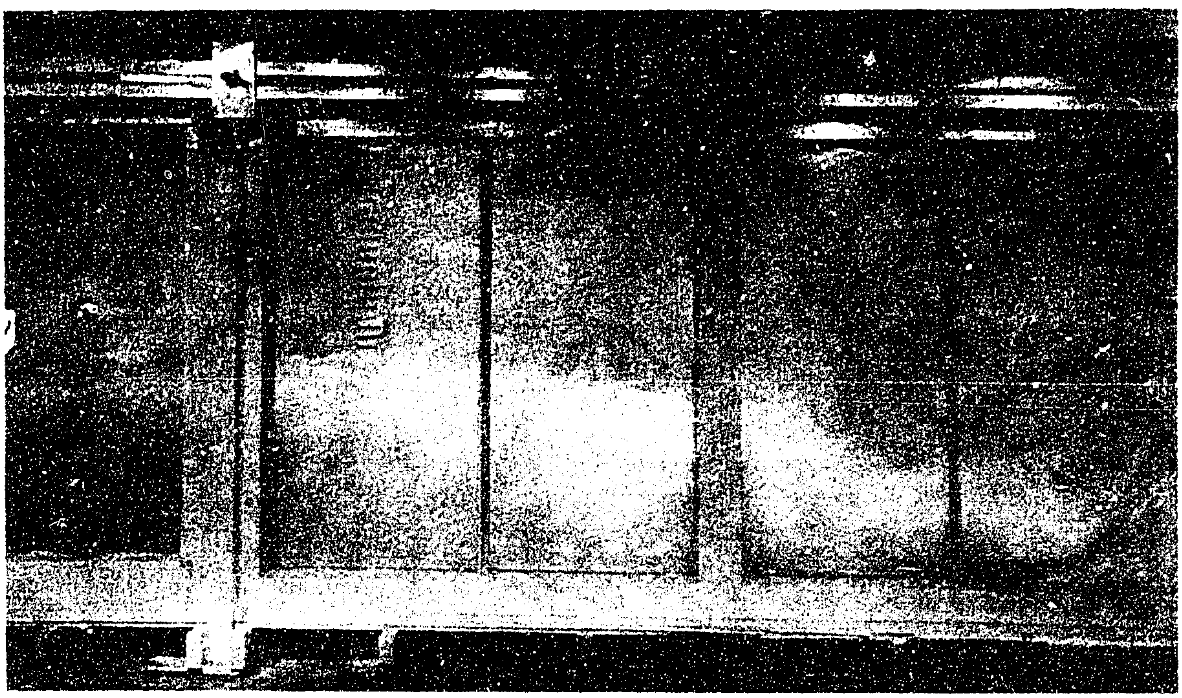


TEST FLUME B
Width 2 feet, drop 5.5 feet, discharge 10 cfs

FIGURE 1

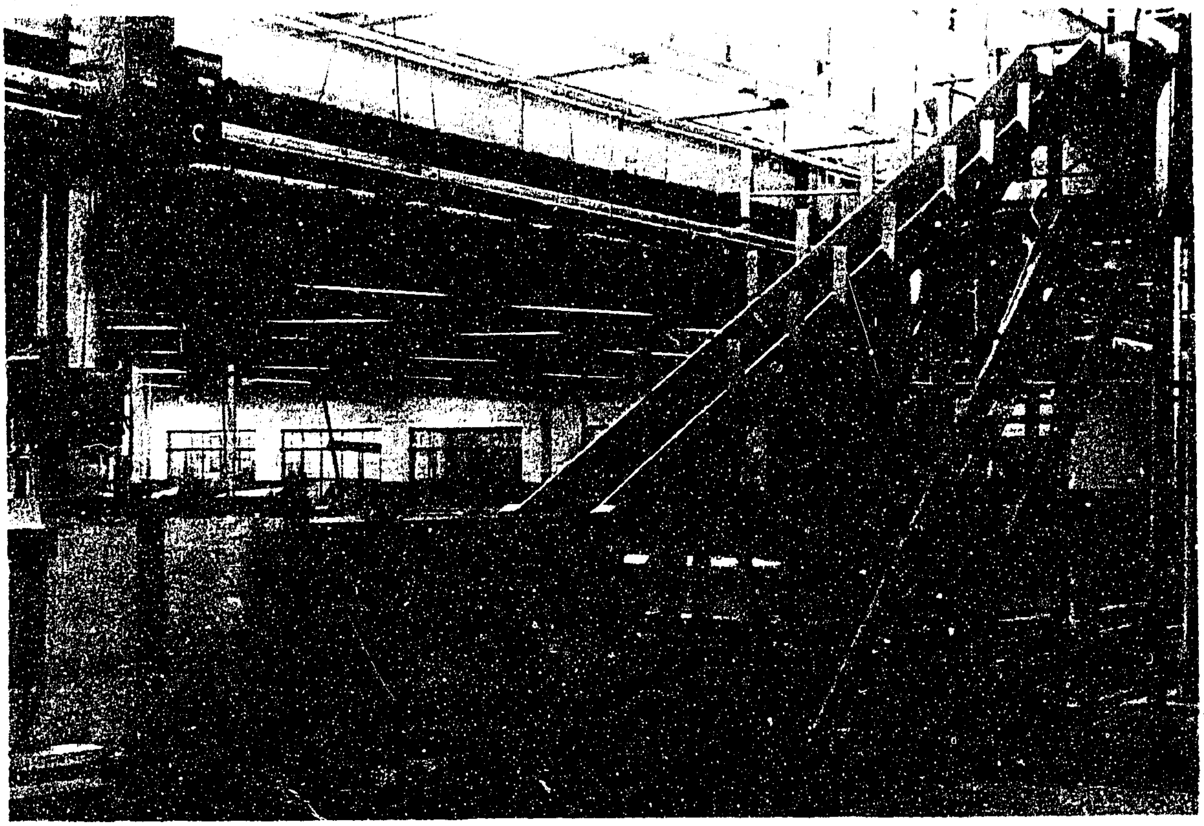


TEST FLUME A
Width of basin 5 feet, drop 3 feet, discharge 6 cfs

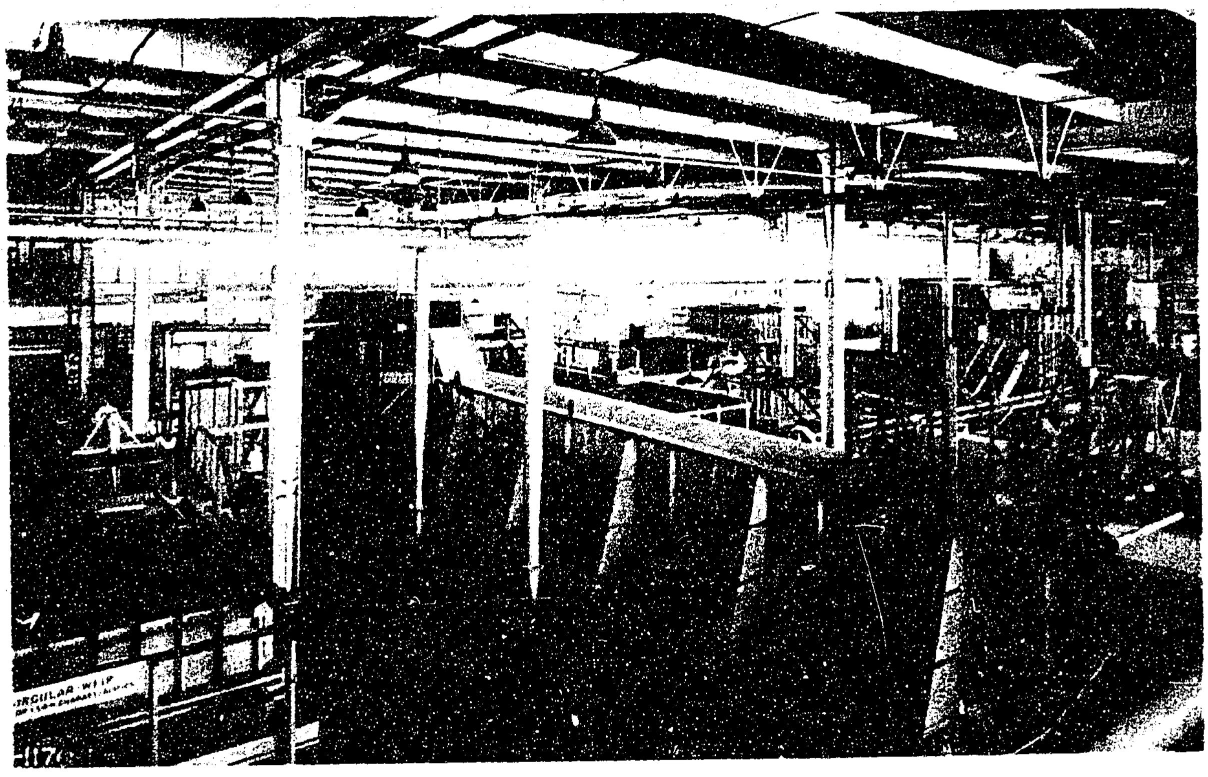


TEST FLUME B
Width 2 feet, drop 5.5 feet, discharge 10 cfs

FIGURE 2

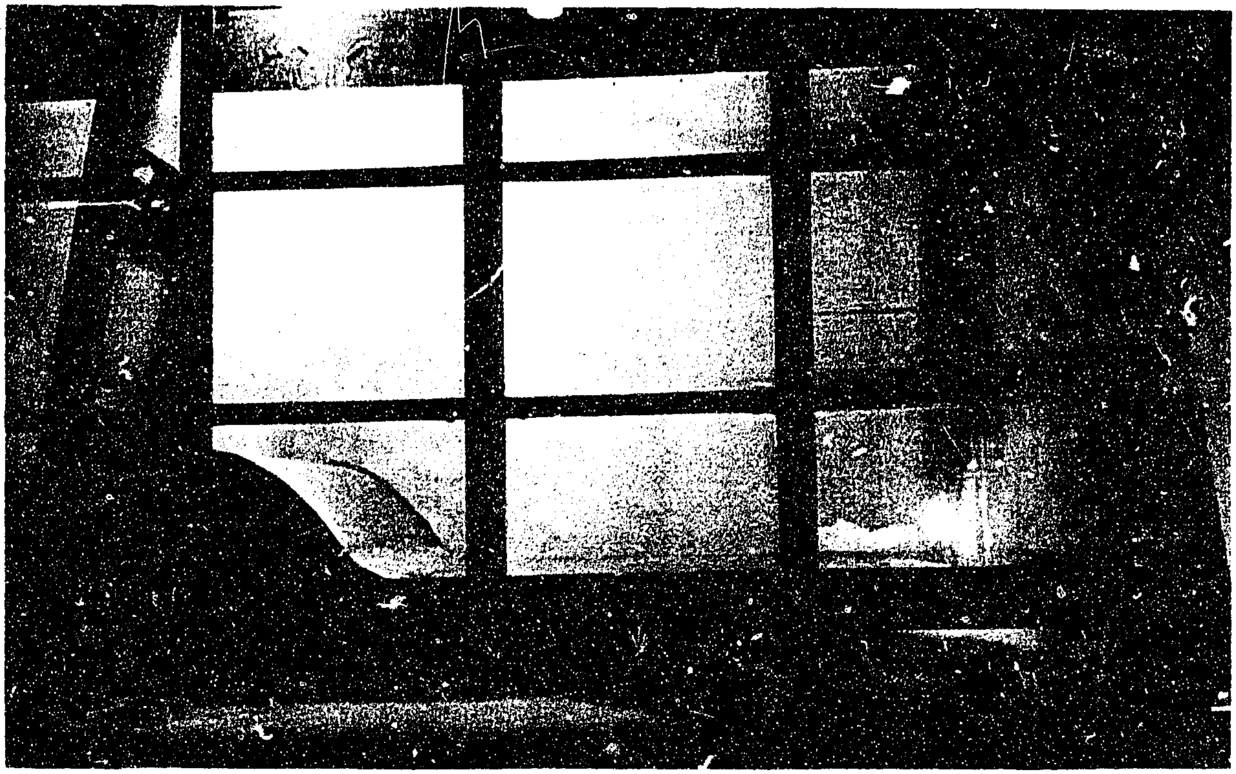


TEST FLUME C
Width 1.5 feet, drop 10 feet, discharge 5 cfs, slope 2:1

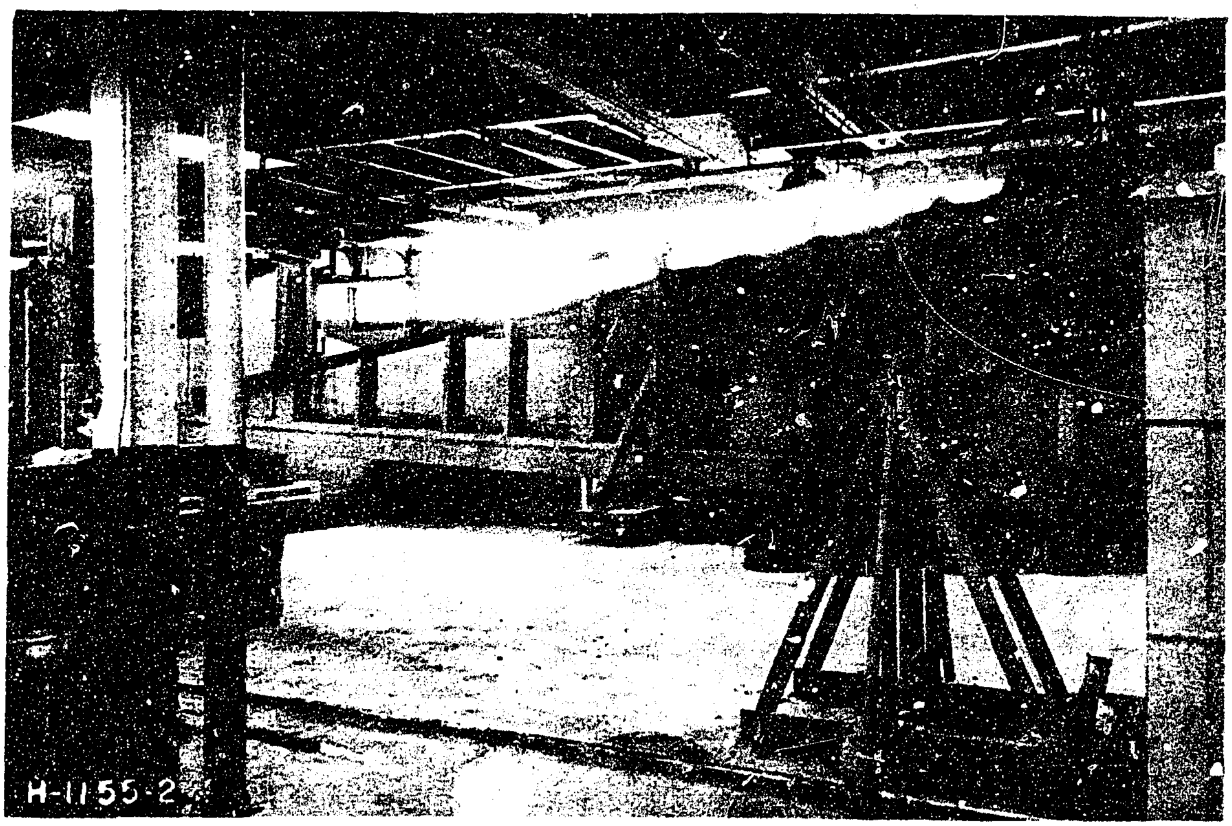


TEST FLUME D
Width 4 feet, drop 12 feet, discharge 28 cfs, slope 0.8:1

FIGURE 3



TEST FLUME E
Width 4 feet, drop 0.5 to 1.5 feet, discharge 10 cfs



TEST FLUME F
Adjustable tilting type, maximum slope 12 degrees, width 12 inches,
Discharge 5 cfs

The largest scale experiments were made on a glass-sided laboratory flume 4 feet wide and 80 feet long, in which an overfall crest with a slope of 0.8:1 was installed, Flume D, Figure 2. The drop from headwater to tail water in this case was approximately 12 feet, and the maximum discharge was 28 cfs.

The downstream end of the above flume was also utilized for testing small overflow sections 0.5 to 1.5 feet in height. The maximum discharge used was 10 cfs. As stated above, this piece of equipment will be designated as Flume E, and is shown on Figure 3.

The sixth piece of equipment was a tilting flume which could be adjusted for slopes up to 12°, Flume F, Figure 3. This flume was 1 foot wide by 20 feet long; the head available was 2.5 feet, and the flow was controlled by a slide gate. The discharge capacity was about 3 cfs.

Each piece of equipment contained a head gage, a tail gage, a scale for measuring the length of the jump, a point gage for measuring the average depth of flow entering the jump, and a means of regulating the tail water depth. The discharge in all cases was measured through the laboratory venturi meters or portable venturi-orifice meters. The tail water depth was measured by a point gage operating in a stilling-well in most of the cases. The tail water depth was regulated by an adjustable weir at the end of each flume.

Remarks

It is felt that the design information to be presented will be found economical as well as effective, yet an effort was made to lean toward the conservative side. In other words, a moderate factor of safety has been included throughout. Thus the information is considered suitable for general use with the following provision:

> It should be made clear at the outset that the information herein is based upon symmetrical and uniform action in the stilling basins and buckets. Should entrance conditions or appurtenances near the head of any of these structures tend to produce unsymmetry of flow down the chute and in the stilling basin, these generalized designs may not be adequate. In this case it may be advisable to make the basin in question of a more symmetrical nature, more conservative, or it may be wise to invest in a model study. Also, should greater economy be desired than these generalized designs indicate, a model study is recommended.

SECTION 1

GENERAL INVESTIGATION OF THE HYDRAULIC JUMP ON HORIZONTAL APRON (BASIN I)

Introduction

A tremendous amount of experimental, as well as theoretical, work has been performed in connection with the hydraulic jump on a horizontal apron. To mention a few of the experimenters who contributed basic information, there are: Bakhmeteff and Matzke 1/ 9/, Safranez 3/, Woycicki 4/, Chertonosov 10/, Einwachter 11/, Elms 12/, Hinds 14/, Forcheimer 21/, Kennison 22/, Kozeny 23/, Rehbock 24/, Schoklitsch 25/, Woodward 26/, and others. There is probably no phase of hydraulics that has received more attention, yet, from a practical viewpoint there is still much to be learned.

As mentioned previously, the first phase of the present study was academic in nature consisting of correlating the results of others and observing the hydraulic jump throughout its various phases; the primary purpose being to become better acquainted with the over-all jump phenomenon. The objectives in mind were: (1) to determine the applicability of the hydraulic jump formula for the entire range of conditions experienced in design; (2) as only a limited amount of information exists on the length of jump, it was desired to correlate existing data and extend the range of these determinations; and (3) it was desired to observe the various forms of the jump and to catalog and evaluate them.

Current Experimentation

To satisfactorily observe the hydraulic jump throughout its entire range required a testing program in all of the six flumes shown on Figures 1, 2, and 3. This involved about 125 tests, Table 1, at discharges from 1 to 28 cfs. The number of flumes used enhanced the value of the results in that it was possible to observe the degree of similitude obtained for the various scales. Greatest reliance was naturally placed on the results from the larger scales, or larger flumes, as it is well known that the jump action in small models occurs too rapidly for the eye to follow details. Incidentally, the length of jump obtained from the two smaller flumes, A and F, was consistently shorter than that observed for the larger flumes. This was the result of out-of-scale frictional resistance on the floor and side walls. As testing advanced and this deficiency became better understood, some allowance was made for this effect in the observations.

Table 1

NATURAL STILLING BASIN WITH HORIZONTAL FLOOR
(Stilling Basin 1)

Test flume (1)	θ = tan-1 Slope of floor (2)	Q Total discharge cfs (3)	W Width of stilling basin ft (4)	q Discharge per ft of basin width (5)	TW/ = D_2 Tail water depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	$\frac{D_2}{D_1}$ (9)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (10)	L Length of jump ft (11)	$\frac{L}{D_2}$ (12)	$\frac{L}{D_1}$ (13)	$E_1 = d_1 + \frac{V_1^2}{2g}$ ft (14)	$E_2 = d_2 + \frac{V_2^2}{2g}$ ft (15)	$E_L = E_1 - E_2$ ft (16)	$\frac{E_L}{D_1}$ (17)	$\frac{E_L}{E_1}$ % (18)	Gate opening ft (19)
	0	3.000	4.925	0.610	0.564	8.47	0.072	7.83	5.56	3.0	5.32	42	1.187	0.532	0.605	8.40	51.0	
		3.500		0.712	0.612	8.79	.081	7.56	5.44	3.3	5.39	41	1.282	0.633	0.649	8.01	50.6	
		4.000		0.814	0.651	8.95	.091	7.15	5.23	3.5	5.38	38	1.336	0.675	0.661	7.26	49.5	
		4.500		0.916	0.694	8.96	.102	6.80	4.96	3.8	5.48	37	1.354	0.721	0.633	6.21	46.8	
		5.000		1.017	0.730	9.08	.112	6.52	4.78	4.1	5.62	37	1.392	0.760	0.632	5.64	45.4	
	0	4.300	2.000	2.150	1.450	17.48	.123	12.03	8.78	9.0	6.08	73	4.868	1.513	3.355	27.23	58.9	
		5.000		2.500	1.600	17.48	.143	11.19	8.15	10.1	6.31	71	4.888	1.638	3.250	22.73	66.5	
		3.000		1.500	1.236	17.24	.087	14.20	10.30	7.5	6.07	86	4.702	1.259	3.443	39.57	73.2	
		6.000		3.000	1.754	17.54	.171	10.26	7.47	10.6	6.04	62	4.948	1.799	3.149	18.42	63.6	
		7.000		3.500	1.908	17.59	.199	9.59	6.95	11.5	6.03	58	5.003	1.960	3.043	15.29	60.8	
		8.000		4.000	2.016	17.47	.229	8.80	6.43	12.3	6.10	54	4.968	2.077	2.891	12.62	58.2	
		7.000		3.500	1.900	17.41	.201	9.45	6.84	11.5	6.05	57	4.908	1.953	2.955	14.70	60.2	
		3.110		1.550	1.240	17.61	.088	14.09	10.46	7.9	6.37	90	4.903	1.264	3.639	41.35	74.2	
		4.100		2.050	1.440	17.52	.117	12.31	9.03	8.7	6.04	74	4.883	1.471	3.412	29.16	69.9	
		5.975		2.988	1.760	17.58	.170	10.35	7.51	10.2	5.80	60	4.969	1.805	3.164	18.61	63.7	
		7.010		3.505	1.900	17.52	.200	9.50	6.90	11.3	5.95	56	4.967	1.953	3.014	15.07	60.7	
		8.000		4.000	2.030	17.54	.228	8.90	6.48	12.6	6.21	55	5.006	2.090	2.915	12.79	58.3	
		4.150		2.075	1.450	17.44	.119	12.18	8.91	8.8	6.07	74	4.842	1.432	3.360	28.24	59.4	
		5.500		2.750	1.691	17.40	.158	10.70	7.72	10.7	6.33	68	4.850	1.732	3.128	19.50	64.4	
		6.000		3.000	1.764	17.44	.172	10.26	7.41	11.0	6.24	64	4.895	1.809	3.086	17.94	63.0	
		6.500		3.250	1.827	17.38	.187	9.77	7.08	11.3	6.18	60	4.878	1.875	3.002	16.05	61.5	
		2.000		1.000	1.000	17.24	.058	17.24	12.62	6.4	6.40	110	4.674	1.016	3.658	63.07	78.3	
		2.500		1.250	1.104	17.35	.072	15.33	11.40	6.7	6.07	93	4.752	1.124	3.628	50.39	76.3	
		3.000		1.500	1.235	17.44	.086	14.36	10.48	7.4	5.99	86	4.809	1.258	3.551	41.29	73.8	
		3.500		1.750	1.325	17.50	.100	13.25	9.75	7.8	5.89	78	4.856	1.352	3.504	35.04	72.2	
		4.000		2.000	1.433	17.39	.115	12.46	9.04	8.5	5.93	74	4.811	1.463	3.348	29.11	69.6	
		4.500		2.250	1.517	17.44	.129	11.76	8.56	9.4	6.20	73	4.852	1.551	3.301	25.59	68.0	
		5.000		2.500	1.599	17.24	.145	11.03	7.98	10.0	6.25	69	4.761	1.637	3.124	21.54	65.6	
		5.500		2.750	1.691	17.40	.158	10.70	7.72	10.7	6.33	68	4.860	1.732	3.128	19.80	64.4	
C	0	1.000	1.500	0.667	0.910	20.21	.033	27.58	19.55	5.0	5.49	152	5.375	0.918	5.457	165.36	85.6	
		1.500		1.000	1.125	20.43	.048	23.44	16.76	6.4	5.69	133	5.785	1.137	5.648	117.07	83.2	
		2.000		1.333	1.300	21.16	.063	20.63	14.86	7.7	5.92	122	7.016	1.316	5.700	90.48	81.2	
		2.500		1.667	1.465	21.39	.078	18.78	13.48	8.9	6.08	114	7.169	1.485	5.684	72.87	79.3	
		3.000		2.000	1.615	21.74	.092	17.55	12.63	9.7	6.01	105	7.431	1.639	5.792	62.96	77.9	
		3.380		2.253	1.730	22.09	.102	16.96	12.19	10.8	6.24	106	7.679	1.756	5.923	58.07	77.1	
		4.000		2.667	1.890	22.79	.117	16.15	11.74	11.1	5.87	95	8.152	1.921	6.261	53.51	76.5	
		4.440		2.960	2.010	23.13	.128	15.70	11.39	12.3	6.11	96	8.435	2.044	6.391	49.93	75.8	
		1.250		0.833	0.914	17.35	.048	19.04	13.96	5.4	5.91	112	4.723	0.927	3.796	79.08	80.4	
		1.750		1.167	1.135	18.82	.062	18.30	13.32	6.5	5.73	105	5.563	1.151	4.412	71.15	79.3	
		2.250		1.500	1.320	19.48	.077	17.14	12.37	7.8	5.91	101	5.969	1.340	4.629	50.12	77.6	
		2.750		1.833	1.458	20.37	.090	16.31	11.97	9.1	6.20	101	6.533	1.492	5.041	56.01	77.1	
		3.250		2.167	1.616	20.84	.104	15.54	11.39	10.0	6.19	96	6.849	1.644	5.205	50.05	76.0	
		3.750		2.500	1.736	21.19	.118	14.71	10.87	11.0	6.34	93	7.091	1.768	5.323	45.11	75.1	
		4.250		2.833	1.870	21.14	.134	13.96	10.18	11.6	6.20	87	7.074	1.905	5.169	38.57	73.1	
D	0	4.000	3.970	1.006	1.110	20.16	.050	22.20	15.89	6.5	5.86	130	6.361	1.123	5.238	104.76	82.3	
		5.000		1.259	1.220	20.31	.062	19.68	14.37	7.5	6.15	121	6.467	1.236	5.231	84.37	80.9	
		6.000		1.511	1.376	20.42	.074	18.19	13.23	8.4	6.24	114	6.549	1.365	5.184	70.05	79.2	
		7.000		1.763	1.460	20.50	.086	16.98	12.32	9.0	6.16	105	6.612	1.483	5.129	59.64	77.6	
		8.000		2.015	1.570	20.56	.098	16.02	11.55	9.7	6.18	99	6.662	1.595	5.067	51.70	76.1	
		9.000		2.267	1.670	20.80	.109	15.32	11.11	10.0	5.99	92	6.827	1.699	5.128	47.05	75.1	
		8.080		2.035	1.600	20.56	.099	16.16	11.52	9.5	5.94	96	6.663	1.625	5.038	50.89	75.6	
		11.730		2.955	1.962	21.41	.138	14.22	10.16	12.4	6.32	90	7.256	1.997	5.259	38.11	72.5	
		10.000		2.519	1.752	20.99	.120	14.60	10.68	10.4	5.94	87	6.961	1.784	5.177	43.14	74.4	
		3.000		0.756	0.954	19.69	.038	25.11	12.98	5.4	5.66	142	6.181	0.964	5.217	137.29	84.4	
		5.000		1.259	1.250	20.31	.062	20.16	14.37	7.4	5.92	119	6.457	1.266	5.201	83.89	80.4	
		7.000		1.763	1.452	20.50	.086	16.88	12.12	8.7	5.99	101	6.612	1.475	5.137	59.73	77.7	
		9.000		2.257	1.693	20.80	.109	15.53	11.11	10.5	6.20	96	6.827	1.721	5.106	46.84	74.8	
		11.720		2.952	1.922	21.39	.138	13.93	10.15	11.4	5.93	83	7.243	1.959	5.284	38.29	73.0	
		10.000		2.519	1.780	20.99	.120	14.83	10.68	11.2	6.29	93	6.961	1.811	5.150	42.92	74.0	
		12.000		3.023	1.953	21.29	.142	13.75	9.96	12.3	6.30	87	7.180	1.990	5.190	36.55	72.3	
		14.000		3.526	2.163	21.63	.163	13.27	9.44	13.0	6.01	80	7.428	2.204	5.224	32.05	70.3	
		16.000		4.030	2.330	22.02	.183	12.73	9.07	13.8	5.92	75	7.712	2.376	5.336	29.16	69.2	
		18.000		4.534	2.495	22.56	.201	12.41	8.87	15.4	6.17	77	8.104	2.545	5.553	27.65	68.6	

Table [illegible]—Continued

NATURAL STILLING BASIN WITH HORIZONTAL FLOOR
(Stilling Basin I)

Test flume (1)	Tan of slope of floor (2)	[illegible] (3)	Width of stilling basin ft (4)	q Discharge per ft of basin width (5)	D_2 = TW Tail water depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	$\frac{D_2}{D_1}$ (9)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (10)	L Length of jump ft (11)	$\frac{L}{D_2}$ (12)	$\frac{L}{D_1}$ (13)	$E_1 = d_1 + \frac{V_1^2}{2g}$ ft (14)	$E_2 = d_2 + \frac{V_2^2}{2g}$ ft (15)	$E_L = E_1 - E_2$ ft (16)	$\frac{E_L}{D_1}$ (17)	$\frac{E_L}{E_1}$ % (18)	Gate opening ft (19)
D	0	4.980	3.970	1.254	1.220	20.23	.062	19.68	14.32	7.0	5.74	113	6.417	1.236	5.181	83.56	80.7	
		10.000		2.519	1.792	20.99	.120	14.93	10.60	11.0	6.14	92	6.961	1.823	5.138	42.82	73.8	
		11.000		2.771	1.867	21.15	.131	14.25	10.30	11.3	6.05	86	7.077	1.901	5.176	39.51	73.1	
		13.000		3.275	2.009	21.55	.152	13.22	9.74	12.4	6.17	82	7.363	2.050	5.313	34.95	72.2	
		15.000		3.778	2.180	21.84	.173	12.60	9.25	13.3	6.10	77	7.580	2.226	5.354	30.95	[illegible]	
		6.500		1.637	1.412	20.46	.080	17.65	12.75	8.9	6.30	111	6.580	1.433	5.147	64.34	78.2	
		4.980		1.254	1.220	20.23	.062	19.68	14.32	7.0	5.74	113	6.417	1.236	5.181	83.56	80.7	
		17.000		4.282	2.410	22.30	.192	12.56	8.77	14.6	6.05	76	7.914	2.461	5.453	28.40	68.9	
		19.000		4.786	2.560	22.79	.210	12.19	8.77	15.3	5.98	73	8.275	2.614	5.661	26.96	68.4	
		21.000		5.290	2.656	23.20	.228	11.65	8.56	16.0	6.02	70	8.586	2.717	5.869	25.74	68.4	
		26.160		6.589	3.060	24.22	.272	11.25	8.19	19.4	6.34	71	9.381	3.132	6.249	22.97	66.6	
		22.960		5.786	2.842	24.12	.240	11.84	8.68	18.7	6.59	78	9.274	2.907	6.367	26.53	68.7	
		23.930		6.028	2.845	23.73	.254	11.20	8.30	18.1	6.43	72	8.998	2.925	6.083	23.95	67.6	
		28.370		7.147	3.202	24.55	.291	11.00	8.02	21.0	6.56	72	9.657	3.279	6.378	21.92	66.0	
F	0	0.960	1.000	0.960	0.792	12.15	.079	10.03	7.62	4.0	5.05	51	2.371	0.815	1.556	19.70	65.6	0.125
		0.815		0.815	0.653	9.59	.085	7.68	5.80	3.0	4.59	35	1.513	0.677	0.836	9.84	55.3	
		0.680		0.680	0.540	8.61	.079	6.84	5.40	2.4	4.44	30	1.230	0.565	0.665	8.42	54.1	
		1.580		1.580	0.992	11.70	.135	7.35	5.61	6.2	6.25	46	2.261	1.031	1.230	9.11	54.4	.208
		1.200		1.200	0.740	8.89	.135	5.48	4.26	4.3	5.81	32	1.362	0.781	0.581	4.30	42.7	
		1.400		1.400	0.880	10.37	.135	6.52	4.97	5.4	6.14	40	1.805	0.919	0.886	6.56	49.1	
		2.230		2.230	1.220	12.89	.173	7.05	5.45	7.3	5.98	42	2.753	1.272	1.481	8.56	53.8	.291
		1.730		1.730	0.927	10.00	.173	5.36	4.24	5.2	5.61	30	1.726	0.981	0.745	4.31	43.2	
		1.250		1.250	0.644	7.23	.173	3.72	3.06	3.4	5.28	20	0.985	0.702	0.283	1.64	28.7	
		1.150		1.150	0.581	6.65	.173	3.36	2.82	3.1	5.34	18	0.860	0.642	0.218	1.26	25.3	
		1.400		1.400	0.638	6.69	.210	3.04	2.57	3.3	5.17	16	0.901	0.712	0.189	0.90	21.0	.333
		1.850		1.850	0.882	8.81	.210	4.20	3.39	5.0	5.67	24	1.415	0.950	0.465	2.21	32.9	
		2.200		2.200	1.075	10.48	.210	5.12	4.03	6.2	5.77	30	1.915	1.140	0.775	3.69	40.5	
		2.740		2.740	1.345	13.05	.210	6.40	5.02	8.2	6.10	39	2.854	1.410	1.444	6.88	50.6	
		1.830		1.830	0.753	7.29	.251	3.00	2.56	3.5	4.65	14	1.076	0.845	0.231	0.92	21.5	.396
		2.350		2.350	1.023	9.36	.251	4.08	3.29	5.6	5.47	22	1.611	1.105	0.506	2.02	31.4	
		2.780		2.780	1.235	11.08	.251	4.92	3.90	7.2	5.83	29	2.157	1.314	0.843	3.36	39.1	
		3.165		3.165	1.427	12.61	.251	5.69	3.44	8.4	5.89	33	2.720	1.504	1.216	4.84	44.7	
		1.900		1.900	0.704	6.67	.285	2.47	2.20	3.2	4.55	11	0.976	0.817	0.159	0.55	16.3	.458
		2.540		2.540	1.016	8.91	.285	3.56	2.94	5.3	5.22	19	1.518	1.113	0.405	1.42	25.7	
		3.000		3.000	1.219	10.53	.285	4.28	3.48	7.0	5.74	25	2.007	1.313	0.694	2.44	34.6	
		3.460		3.460	1.435	12.14	.285	5.04	4.01	8.3	5.78	29	2.574	1.525	1.049	3.68	40.8	
E	0	5.000	3.970	1.259	0.840	10.49	0.120	7.00	5.34	5.0	5.95	42	1.831	0.875	0.956	7.97	52.2	Dam 1.5'
		6.000		1.511	0.940	10.57	.143	6.57	4.92	5.6	5.96	39	1.880	0.980	.900	6.29	47.9	high
		7.000		1.763	0.990	10.75	.164	6.04	4.67	5.9	5.96	36	1.960	1.039	.921	5.62	47.0	
		8.000		2.014	1.080	10.89	.185	5.84	4.46	6.3	5.83	34	2.029	1.134	.895	4.84	44.1	
		9.000		2.266	1.160	11.05	.205	5.66	4.30	6.6	5.69	28	2.104	1.219	.885	4.32	42.1	
		11.000		2.770	1.260	11.17	.248	5.08	3.95	7.1	5.63	32	2.188	1.335	.853	3.44	39.0	
		4.000		1.008	0.770	10.28	.098	7.86	5.79	4.7	6.10	48	1.742	0.796	.946	9.65	54.3	
		10.000		2.518	1.220	11.09	.227	5.37	4.10	6.9	5.66	30	2.139	1.286	.853	3.76	39.9	
	0	10.002	3.970	2.518	1.080	8.99	.280	3.86	3.00	6.0	5.56	21	1.536	1.164	.372	1.33	24.2	Dam 10"
		9.000		2.266	1.000	8.78	.258	3.88	3.05	5.5	5.50	21	1.457	1.080	.377	1.46	25.9	high
		8.000		2.014	0.960	8.76	.230	4.17	3.22	5.0	5.21	22	1.413	1.029	.384	1.67	27.2	
		7.000		1.763	0.900	8.24	.214	4.21	3.13	4.7	5.22	22	1.269	0.961	.308	1.44	24.3	
		6.000		1.511	0.820	8.39	.180	4.56	3.48	4.3	5.24	24	1.274	0.873	.401	2.23	31.5	
		5.000		1.259	0.760	7.77	.162	4.69	3.40	4.1	5.39	25	1.102	0.803	.299	1.85	27.2	
		4.000		1.007	0.660	7.75	.130	5.08	3.79	3.7	5.61	28	1.064	0.697	.367	2.82	34.5	
		3.000		0.755	0.570	7.95	.100	5.70	4.21	3.3	5.79	33	1.082	0.597	.485	4.85	44.8	
	0	5.084	3.970	1.281	0.620	5.80	.221	2.81	2.17	2.6	4.19	12	0.744	0.686	.058	0.26	7.80	
		3.675		0.926	0.510	5.12	.168	3.04	2.20	2.5	4.90	15	0.576	0.561	.015	0.09	2.60	Dam 6"
		2.440		0.615	0.410	5.44	.113	3.63	2.85	2.2	5.36	19	0.573	0.445	.128	1.13	22.30	high
		7.680		1.934	0.770	5.69	.340	2.26	1.72	3.0	3.90	9	0.874	0.866	.008	0.02	0.92	
		6.000		1.511	0.690	5.68	.266	2.59	1.93	2.8	4.06	10	0.768	0.765	.003	0.01	0.39	

Experimental Results

Definitions of the symbols used in connection with the hydraulic jump on a horizontal floor are shown on Figure 4. The procedure followed in each test of this series was to first establish a flow. The tail water depth was then gradually increased until the front of the jump moved upstream to Section 1, indicated on Figure 4. The tail water was then measured, the length of the jump recorded, and the depth of flow entering the jump, D_1, was obtained by averaging a generous number of point gage measurements taken immediately upstream from Section 1, Figure 4. The results of the measurements and succeeding computations are tabulated in Table 1. The measured quantities are tabulated as follows: total discharge (Column 3), tail water depth, which should be the conjugate depth in this case (Column 6), length of jump (Column 11), and depth of flow entering jump (Column 8).

Column 1 indicates the test flumes in which the experiments were performed, and Column 4 shows the width of each flume. All computations are based on discharge per foot width of flume, or q, and unit discharges are shown in Column 5.

The velocity entering the jump V_1, Column 7, was computed by dividing q (Column 5) by D_1 (Column 8).

The Froude Number

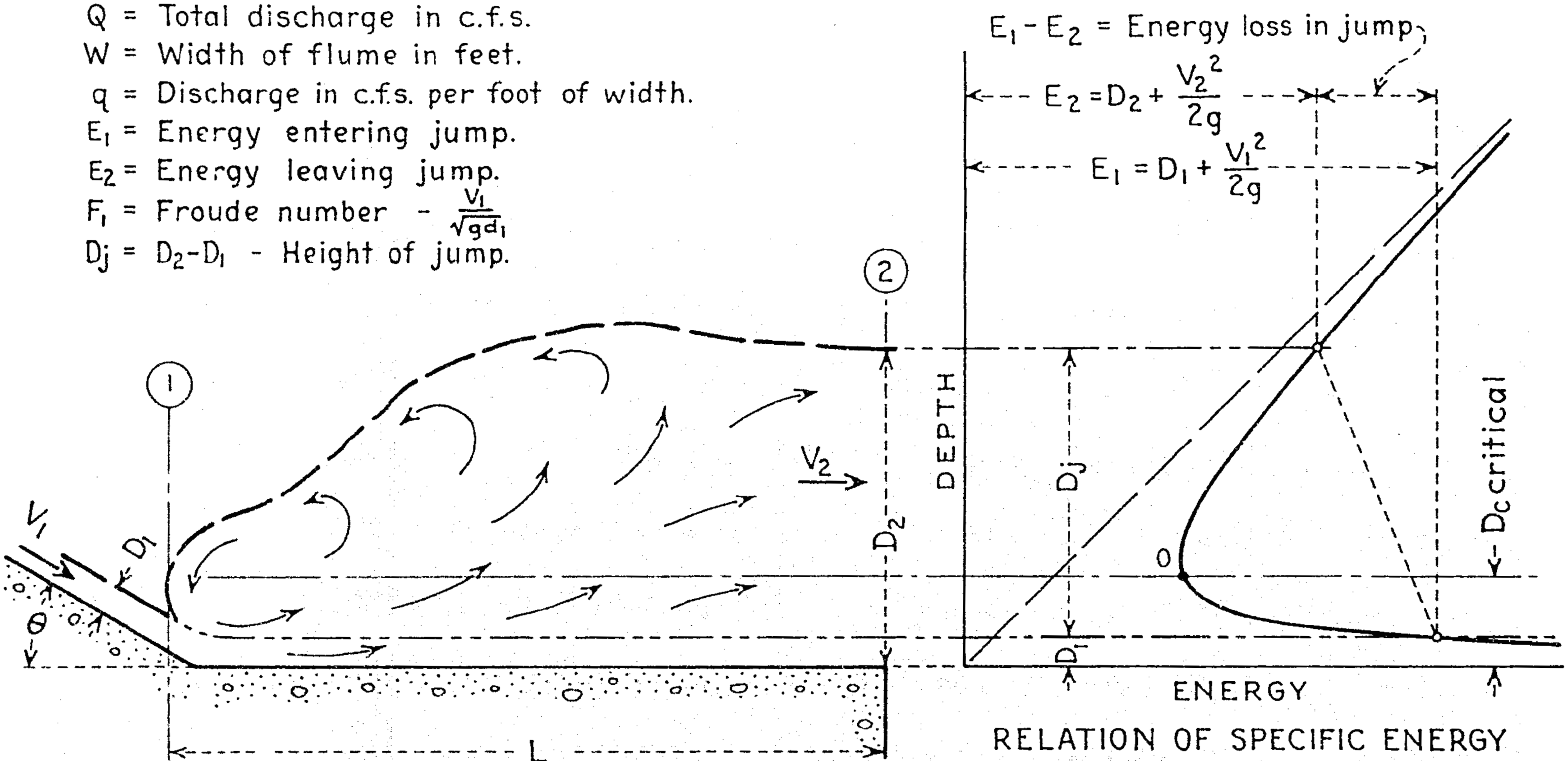
The Froude number, Column 10, Table 1, is simply:

$$F_1 = \frac{V_1}{\sqrt{gD_1}} \tag{1}$$

where F_1 is a dimensionless parameter, V_1 and D_1 are velocity and depth of flow, respectively, entering the jump, and g is the acceleration of gravity. The law of similitude states that where gravitational forces predominate, as they do in open channel phenomenon, the Froude number should be the same value in model and prototype. Although energy conversions in a hydraulic jump bear some relation to the Reynolds number, gravity forces predominate and, the Froude number is very useful for plotting stilling basin characteristics. Bahkmeteff and Matzke 1/ demonstrated this application in 1936 when they related stilling basin characteristics to the square of the Froude number of $\frac{V^2}{gD_1}$. They termed this expression the kinetic flow factor.

The Froude number will be used throughout this presentation. As the acceleration of gravity is a constant, the term g could be omitted. Its inclusion makes the expression dimensionless, however, and the form shown as (1) is preferred.

Q = Total discharge in c.f.s.
W = Width of flume in feet.
q = Discharge in c.f.s. per foot of width.
E_1 = Energy entering jump.
E_2 = Energy leaving jump.
F_1 = Froude number - $\frac{V_1}{\sqrt{gd_1}}$
$D_j = D_2 - D_1$ - Height of jump.



HYDRAULIC JUMP - ON HORIZONTAL FLOOR

RELATION OF SPECIFIC ENERGY TO DEPTH OF FLOW

HYDRAULIC JUMP STUDIES

STILLING BASIN I

DEFINITION OF SYMBOLS

437

Applicability of Hydraulic Jump Formula

The theory of the hydraulic jump in horizontal channels has been treated thoroughly by others (see Bibliography), and will not be repeated here. The expression for the hydraulic jump, based on pressure-momentum, occurs in many forms. The following form is most commonly used in the Bureau 15/.

$$D_2 = -\frac{D_1}{2} + \sqrt{\frac{D_1^2}{4} + \frac{2V_1^2 D_1}{g}} \qquad (2)$$

This may also be written:

$$D_2 = -\frac{D_1}{2} + \sqrt{\frac{D_1^2}{4} + \frac{2V_1^2 D_1^2}{gD_1}}$$

Carrying D_1 over to the left side of the equation and substituting F_1^2 for $\frac{V_1^2}{gD_1}$,

$$\frac{D_2}{D_1} = -1/2 + \sqrt{1/4 + 2F_1^2}$$

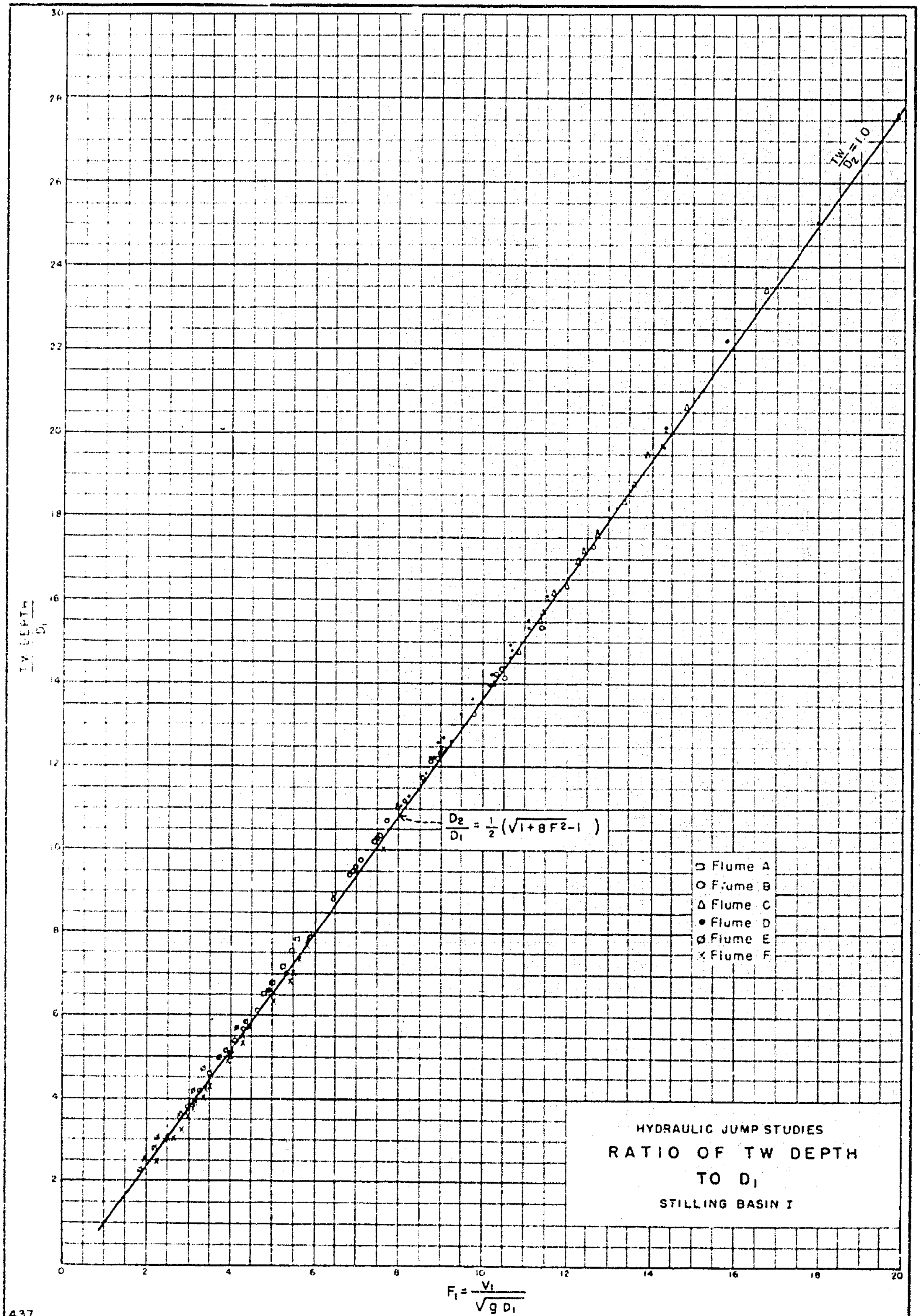
or

$$\frac{D_2}{D_1} = 1/2\left(\sqrt{1 + 8F_1^2} - 1\right) \qquad (3)$$

Expression (3) shows that the ratio of conjugate depths is strictly a function of the Froude number. The ratio $\frac{D_2}{D_1}$ is plotted with respect to the Froude number on Figure 5. The line, which is virtually straight except for the lower end, represents the above expression for the hydraulic jump; while the points which are experimental are from Columns 9 and 10, Table 1. The agreement is quite good for the entire range. There is an unsuspected characteristic, however, which should be mentioned here but will be enlarged on later.

Although the tail water depth, recorded in Column 6 of Table 1, was sufficient to bring the front of the jump to Section 1 (Figure 4) in each test, the ability of the jump to remain at Section 1 for a slight lowering of tail water depth became more difficult for the higher and lower values of the Froude number. The jump was least sensitive to variation in tail water depth in the middle range, or values of F_1 from 4.5 to 9.

FIGURE 5



HYDRAULIC JUMP STUDIES

RATIO OF TW DEPTH TO D_1

STILLING BASIN I

437

Length of Jump

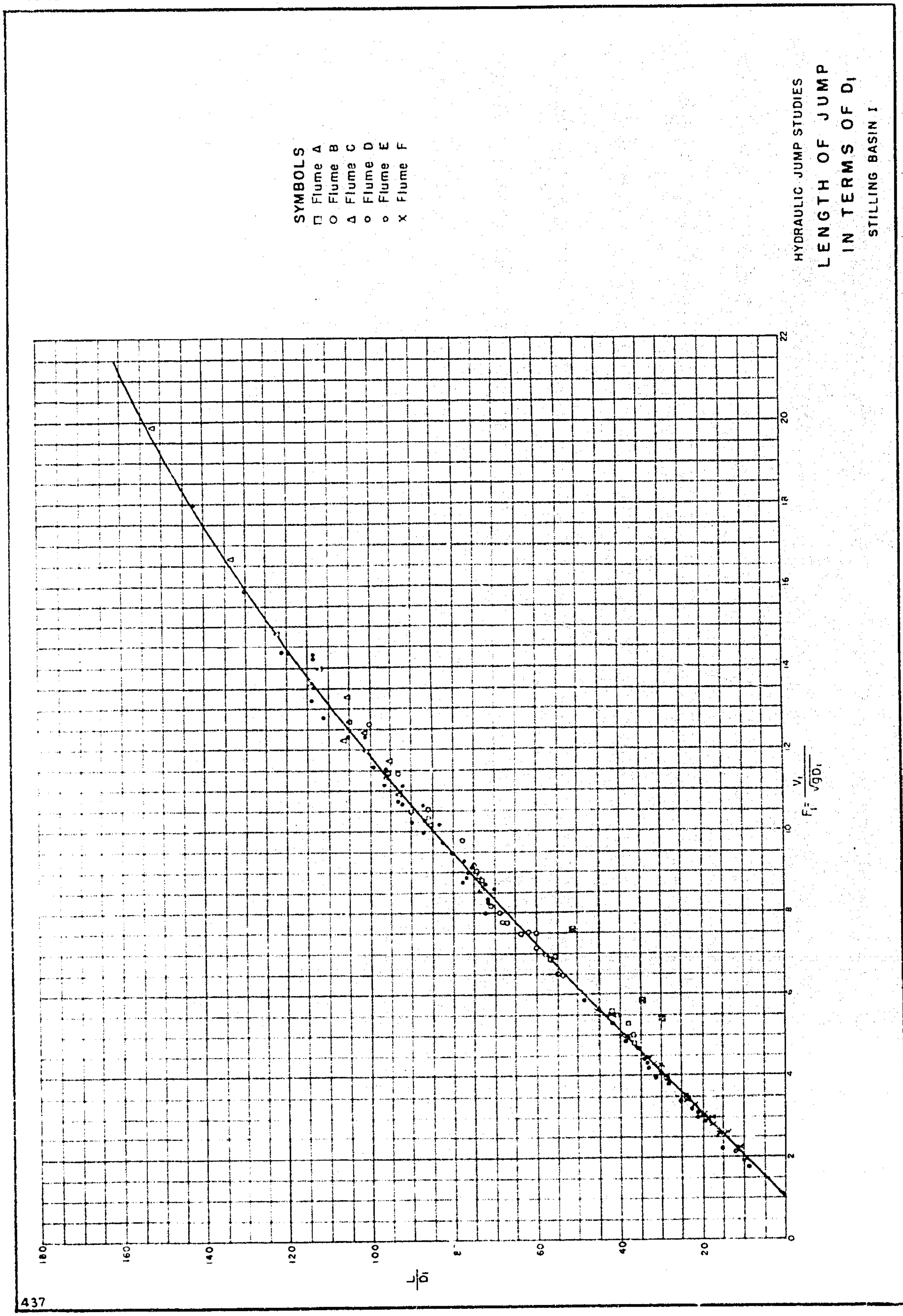
The length of the jump, Column 11, Table 1, was the most difficult measurement to determine. In cases where chutes or overfalls were used, the front of the jump was held near the intersection of the chute and the horizontal floor, as shown on Figure 4. The length of jump was measured from this point to a point downstream where either the high-velocity jet began to leave the floor or to a point on the surface immediately downstream from the roller, whichever was the longer. In the case of Flume F, where the flow discharged from a gate onto a horizontal floor, the front of the jump was maintained just downstream from the completed contraction of the entering jet. The point at which the high-velocity jet begins to rise from the floor is not fixed, but tends to shift upstream and downstream. This is also true of the roller on the surface. It was at first difficult to repeat length observations within 5 to 10 percent by either criterion, but with practice satisfactory measurements became possible.

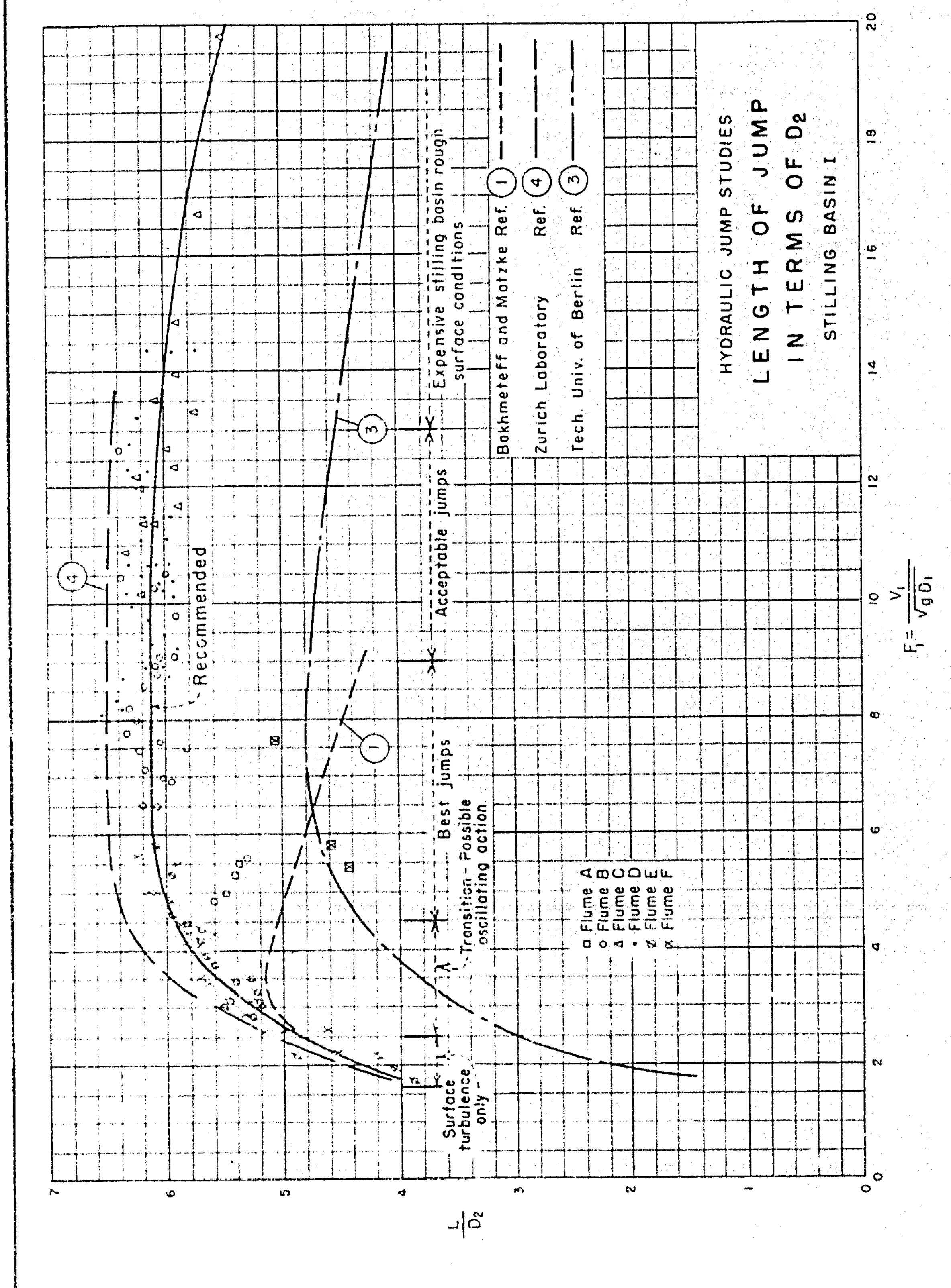
A system devised to measure velocities on the bottom, to aid in determining the length of jump, proved inadequate and too laborious to allow completion of the program planned. Visual observations, therefore, proved to be the most satisfactory as well as the most rapid method for determining the length measurement. It was the intention to judge the length of the jump from a practical standpoint; in other words, the end of the jump, as chosen, would represent the end of the concrete floor and side walls of a conventional stilling basin.

The length of jump has been plotted in two ways. The first is perhaps the better method while the second is the more common. The first method is shown on Figure 6 where the ratio length of jump to D_1 (Column 13, Table 1) is plotted with respect to the Froude number, (Column 10) for results from the six test flumes. The resulting curve is fairly flat, which is the principal advantage gained by the use of these coordinates. The second method of plotting, where the ratio of length of jump to the conjugate tail water depth D_2 (Column 12) is plotted with respect to the Froude number, is presented on Figure 7. This latter method of plotting will be used throughout the study. The points represent the experimental values.

In addition to the curve established by the test points, curves representing the results of three other experimenters are shown on Figure 7. The best known and most widely accepted curve for length of jump is that of Bakhmeteff and Matzke 1/ which was determined from experiments made at Columbia University. The greater portion of this curve, labelled 1, is at variance with the present experimental results. Because of the wide use this curve has experienced, a rather complete explanation is presented regarding the disagreement.

FIGURE 6


HYDRAULIC JUMP STUDIES
LENGTH OF JUMP IN TERMS OF D_1
STILLING BASIN I
SYMBOLS
□ Flume A
○ Flume B
△ Flume C
○ Flume D
○ Flume E
x Flume F
$F_1 = \frac{V_1}{\sqrt{gD_1}}$
$\frac{L}{D_1}$
0
2
4
6
8
10
12
14
16
18
20
22
20
40
60
80
100
120
140
160
180
437



HYDRAULIC JUMP STUDIES
LENGTH OF JUMP IN TERMS OF D2
STILLING BASIN I
Bakhmeteff and Matzke Ref. 1
Zurich Laboratory Ref. 4
Tech. Univ. of Berlin Ref. 3
Expensive stilling basin rough surface conditions
Acceptable jumps
Best jumps
Transition - Possible oscillating action
Surface turbulence only
Recommended
Flume A
Flume B
Flume C
Flume D
Flume E
Flume F
L/D2
F1 = V1/√(gD1)

437

The experiments of Bakhmeteff and Matzke were performed in a flume 6 inches wide, with limited head. The depth of flow entering the jump was adjusted by a vertical slide gate. The maximum discharge was approximately 0.7 cfs, and the thickness of the jet entering the jump, D_1, was 0.25 foot for a Froude number of 1.94. The results up to a Froude number of 2.5 are in agreement with the present experiments. To increase the Froude number, it was necessary for Bakhmeteff and Matzke to decrease the gate opening. The extreme case involved a discharge of 0.14 cfs and a value of D_1 of 0.032 foot, for $F_1 = 8.9$, which is much smaller than any discharge or value of D_1 used in the present experiments. Thus, it is reasoned that as the gate opening decreased, in the 6-inch-wide flume, frictional resistance in the channel downstream increased out of proportion to that which would have occurred in a larger flume or a prototype structure. Thus, the jump formed in a shorter length than it should. In laboratory language, this is known as "scale effect," and is construed to mean that prototype action is not faithfully reproduced. It is quite certain that this was the case for the major portion of the Bahkmeteff-Matzke curve. In fact, they were somewhat dubious concerning the small scale experiments.

To confirm the above conclusion, it was found that results from Flume F, which was 1 foot wide, became erratic when the value of D_1 approached 0.10. Figures 6 and 7 show three points obtained with a value of D_1 of approximately 0.085. The three points are given the symbol ⊠ and fall short of the recommended curve.

The two remaining curves, labelled 3 and 4, on Figure 7, portray the same trend as the curve obtained from the current experiments. The criterion used by each experimenter for judging the length of the jump is undoubtedly responsible for the displacement. The curve labelled 3 was obtained at the Technical University of Berlin on a flume 1/2-meter wide by 10 meters long. The curve labelled 4 was determined from experiments performed at the Federal Institute of Technology, Zurich, Switzerland, on a flume 0.6 of a meter wide and 7 meters long. The curve numbers are the same as the reference numbers in the bibliography which refer to the work.

As can be observed from Figure 7, the test results from Flumes B, C, D, E, and F plot sufficiently well to establish a single curve. The five points from Flume A, denoted by squares, appear somewhat erratic and plot to the right of the general curve. Henceforth, reference to Figure 7 will concern only the recommended curve which is considered applicable for general use.

Energy Absorption in Jump

With the experimental information available, it is only a matter of computation to determine the energy absorbed in the jump. Columns 14 through 18, Table 1, list the computations, and the symbols may be defined by consulting the specific energy diagram on Figure 4. Column 14 lists the total energy, E_1, entering the jump at Section 1 for each test. This is simply the depth of flow, D_1, plus the velocity head computed at the point of measurement. The energy leaving the jump, which is the depth of flow plus the velocity head at Section 2, is tabulated in Column 15. The differences in the values of Columns 14 and 15 constitute the loss of energy, in feet of water, attributed to the conversion, Column 16. Column 18 lists the percentage of energy lost in the jump E_L, to total energy entering jump, E_1. This percentage is plotted with respect to the Froude number and is shown as the curve to the left on Figure 8. For a Froude number of 2.0, which would correspond to a relatively thick jet entering the jump at low velocity, the curve shows the energy absorbed in the jump to be about 7 percent of the total energy entering. Considering the other extreme, for a Froude number of 19, which would be produced by a relatively thin jet entering the jump at very high velocity, the absorption by the jump would amount to 85 percent of the energy entering. Thus the hydraulic jump can perform over a wide range of conditions. There are poor jumps and good jumps, with the most satisfactory occurring over the center portion of the curve.

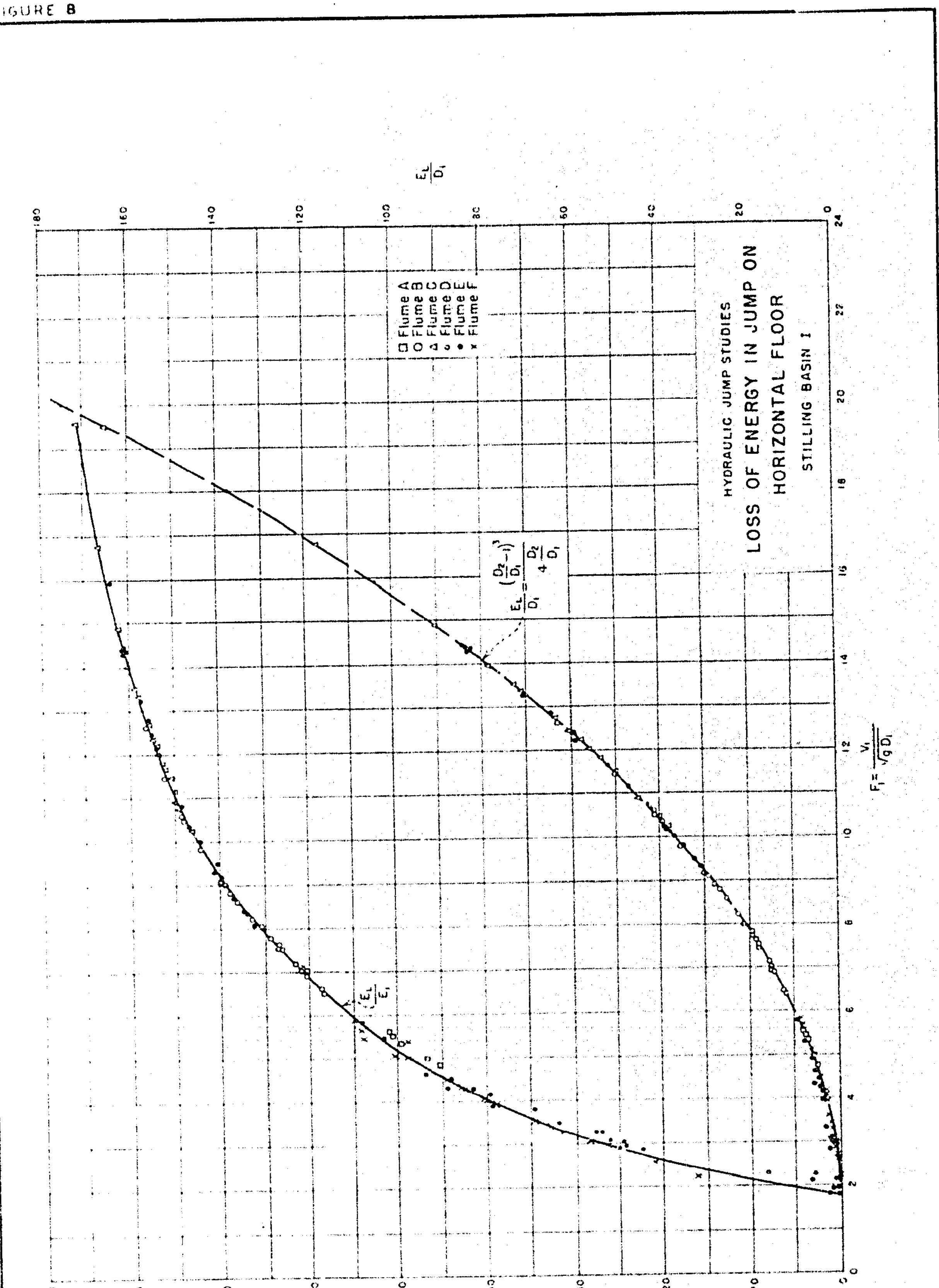
Another method of expressing the energy absorption in a jump is to express the loss E_L, in terms of D_1. The curve to the right on Figure 8, shows the ratio $\frac{E_L}{D_1}$ (Column 17, Table 1) plotted against the Froude number. As there are those who prefer this method of plotting, the latter curve has been included.

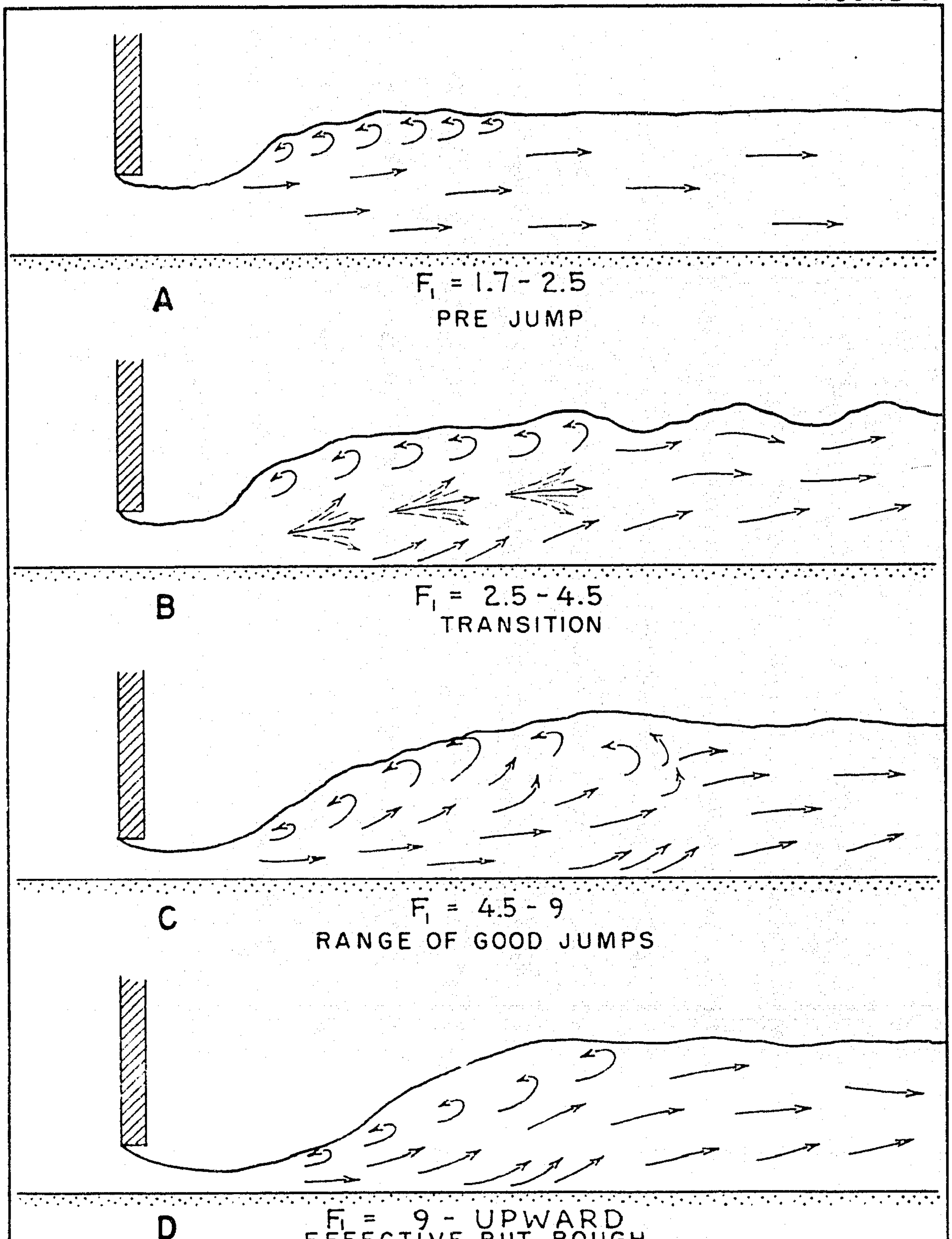
Forms of the Hydraulic Jump

The hydraulic jump may occur in at least four different distinct forms on a horizontal apron, as shown on Figure 9. Incidentally, all of these forms are encountered in design. The internal characteristics of the jump and the energy absorption in the jump vary with each form. Fortunately these forms, some of which are desirable and some undesirable, can be cataloged conveniently with respect to the Froude number.

The form shown in Figure 9A can be expected when the Froude number ranges for 1.7 to 2.5. When the Froude number is unity, the water would be flowing at critical depth; thus a jump could not form. This would correspond to Point O on the specific energy diagram of Figure 4.

FIGURE 8


HYDRAULIC JUMP STUDIES
LOSS OF ENERGY IN JUMP ON HORIZONTAL FLOOR
STILLING BASIN I
□ Flume A
○ Flume B
△ Flume C
◇ Flume D
● Flume E
× Flume F
$\frac{E_L}{D_1} = \frac{\left(\frac{D_2}{D_1}-1\right)^3}{4\frac{D_2}{D_1}}$
$\frac{E_L}{E_1}$
$\frac{E_L}{D_1}$
$F_1 = \frac{V_1}{\sqrt{gD_1}}$
LOSS IN ENERGY IN PERCENT $\frac{E_L}{E_1}$
437



HYDRAULIC JUMP STUDIES

STILLING BASIN I

JUMP FORMS

437

For the values of Froude number between 1.0 and 1.7 there is only a slight difference in the conjugate depths D_1 and D_2. A slight ruffle on the water surface is the only apparent feature that differentiates this from flow with uniform velocity distribution. As the Froude number approaches 1.7, a series of small rollers develop on the surface as indicated in Figure 9A, and this action remains much the same but with further intensification up to a value of about 2.5. Actually there is no particular stilling basin problem involved; the water surface is quite smooth, the velocity throughout is fairly uniform, and the energy loss is low.

Figure 9B indicates the type of jump that may be encountered at values of the Froude number from 2.5 to 4.5. This is an oscillating type of action, so common in canal structures, where the entering jet oscillates from bottom to surface and back again with no regular period. Turbulence occurs near the bottom one instant and entirely on the surface the next. Each oscillation produces a large wave of irregular period which, in the case of canals, can travel for miles doing unlimited damage to earth banks and riprap. The case is of sufficient importance that a separate section, Section 4, has been devoted to the practical aspects of design.

A well stabilized jump can be expected for the range of Froude numbers between 4.5 and 9 (Figure 9C). In this range, the downstream extremity of the surface roller, and the point at which the high-velocity jet tends to leave the floor practically occur in the same vertical plane. The jump is well balanced and the action is thus at its best. The energy absorption in the jump for Froude numbers from 4.5 to 9 ranges from 45 to 70 percent (Figure 8).

As the Froude number increases above 9, the form of the jump gradually changes to that shown in Figure 9D. This is the case where V_1 is very high, D_1 is comparatively small, and the difference in conjugate depths is large. The high-velocity jet no longer carries through for the full length of the jump. In other words, the downstream extremity of the surface roller now becomes the determining factor in judging the length of the jump. Slugs of water rolling down the front face of the jump intermittently fall into the high-velocity jet generating additional waves downstream, and a rough surface can prevail. Figure 8 shows that the energy dissipation for this case may reach 85 percent.

The limits of the Froude number given above for the various forms of jump are not definite values, but overlap somewhat depending on local factors. Returning to Figure 7, it is found that the length curve catalogs the various phases of the jump quite well. The flat portion of the curve indicates the range of best operation. The steep portion of the curve to the left definitely indicates an internal change in the form of the jump. In fact, two changes are manifest, the form shown in Figure 9A and the form, which might better be called a transition stage, shown in Figure 9B. The right end of the curve on Figure 7 also indicates a change in form, but to less extent.

Practical Considerations

As stated previously, it was the intention to stress the academic rather than the practical viewpoint in this section. An exception has been made, as this is the logical place to point out a few of the practical aspects of stilling basin design using horizontal aprons. Viewing the four forms of jump just discussed, the following is pertinent:

1. All forms are encountered in stilling basin design.

2. The form in Figure 9A requires no baffles or special consideration. The only requirement necessary is to provide the proper length of pool, which is relatively short. This can be obtained from Figure 7.

3. The form in Figure 9B is one of the most difficult to handle and is frequently encountered in the design of canal structures, diversion dams, and even outlet works. Baffle blocks or appurtenances in the basin are of little value. Waves are the main source of difficulty and methods for coping with them are discussed in Section 4. Although all four forms of jump have occurred in design in the past, the present information can be used to restrict the use of the form which is really objectionable. In many cases its use cannot be avoided, but in other cases, altering of dimensions may bring it out of the undesirable range.

4. No particular difficulty is encountered in the form shown on Figure 9C. Arrangements of baffles and sills will be found a valuable means of shortening the length of basin.

5. As the Froude number increases, the jump becomes more sensitive to tail water depth. For numbers as low as 8, a tail water depth greater than the conjugate depth is advisable to be certain that the jump will stay on the apron. This phase will be discussed in more detail in the following sections.

6. When the Froude number is greater than 10, a stilling basin may no longer be the most economical or satisfactory dissipation device. The difference in conjugate depths is great, and, generally speaking, a very deep basin and high training walls are required. As the hydraulic jump does not perform at its best in

this range, the cost of the stilling basin may not be commensurate with the results obtained. A bucket type of dissipator may give comparable results at less cost.

Water-surface Profiles and Pressures

Water-surface profiles for the jump on a horizontal floor were not measured as these have already been determined by Bakhmeteff and Matzke 1/, Newman and LaBoon 19/, and Moore 26/ 18/. It has been shown by several experimenters that the vertical pressures on the floor of the stilling basin are virtually the same as the water-surface profile would indicate. Although there will be more bulking in the prototype and the freeboard of training walls will be less than for the model due to entrainment of air, pressures obtained from models are sufficiently accurate for design purposes.

Conclusions

The foregoing experiments and discussion serve to associate the Froude number with stilling basin design where it offers many advantages. The ratio of conjugate depths, the length of jump, the type of jump to be expected, and the losses involved have all been related to this number. The principal advantage of this form of presentation is that one may see the entire picture at a glance. The foregoing information is basic to the understanding of the hydraulic jump. The following sections will deal with the more practical aspects, such as modifying the jump by baffles and sills to increase stability and shorten the length.

An example follows which may help clarify the information so far presented:

Application of Results (Example 1)

Water flowing under a sluice gate discharges into a rectangular stilling basin the same width as the gate. The average velocity and the depth of flow after contraction of the jet is complete are: $V_1 = 85$ ft/sec and $D_1 = 5.6$ feet. Determine the conjugate tail water depth, the length of basin required to confine the jump, the effectiveness of the basin to dissipate energy, and the type of jump to be expected.

$$F_1 = \frac{V_1}{\sqrt{gD_1}} = \frac{85}{\sqrt{32.2 \times 5.6}} = 6.34$$

Entering Figure 5 with this value

$$\frac{D_2}{D_1} = 8.5$$

The conjugate tail water depth

$$D_2 = 8.5 \times 5.6 = 47.6 \text{ feet}$$

Entering the recommended curve on Figure 7 with a Froude number of 6.34

$$\frac{L}{D_2} = 6.13$$

Length of basin necessary to confine the jump

$$L = 6.13 \times 47.6 = 292 \text{ feet}$$

Entering Figure 8 with the above value of the Froude number, it is found that the energy absorbed in the jump is 58 percent of the energy entering.

By consulting Figure 9 it is apparent that a very satisfactory jump can be expected.

SECTION 2

STILLING BASIN FOR EARTH DAM SPILLWAYS AND LARGE CANAL STRUCTURES (BASIN II)

Introduction

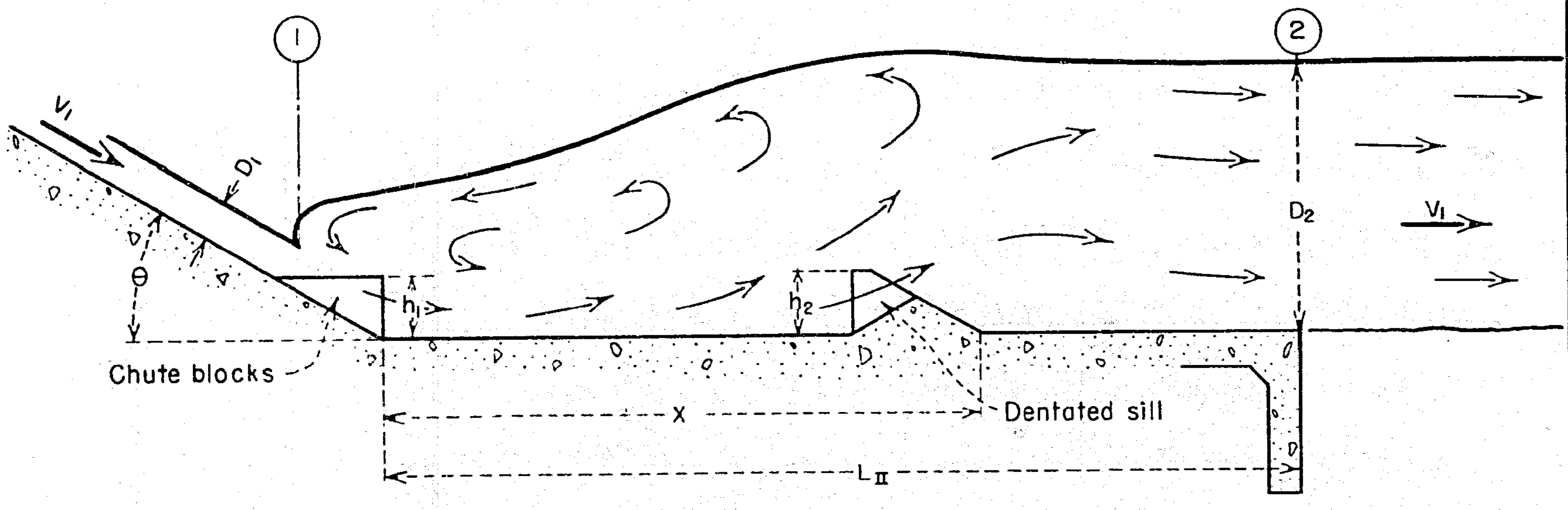
Stilling basins are seldom designed to confine the entire hydraulic jump, as was assumed in the foregoing section; first, for economic reasons and secondly, because there are means of obtaining comparable or better performance in shorter lengths. It is possible to shorten the length of jump by the installation of accessories such as blocks, baffles, and sills in the stilling basin. In addition to shortening the jump, the accessories exert a stabilizing effect and in some cases increase the factor of safety. This section and those following will deal with the more practical aspects of stilling basin design.

The present section will concern a stilling basin which has been in common use on earth dam spillways and large canal structures, and will be denoted as Basin II (Figure 10). The basin contains chute blocks at the upstream end and a dentated sill near the downstream end. The principal aim was to generalize the design and determine the range of operating conditions for which this basin is best suited. The first objective was not difficult as the Bureau has designed and constructed many of these basins, some of which were checked with models. The principal task consisted of consulting laboratory records and tabulating the results. To accomplish the second objective required additional laboratory experiments.

Beginning with the first phase, the capacities and dimensions of 36 stilling basins for earth dams, small overflow dams and large canal structures, which have been tested by models, are listed in Table 2. The model studies were made in several laboratories by many individuals over a 23-year period. Each individual was more or less free to experiment with models of these structures as he saw fit. The final designs, tabulated in Table 2, represent an agreement between designer and experimenter for each case. Thus, the tabulation should be ideal for selecting a generalized design for Basin II.

Results of Compilation

With the aid of Figure 10, most of the symbols used in Table 2 are self-explanatory. Column 1 lists the reference material used in compiling the table. Column 2 lists the maximum reservoir elevation, Column 3 the maximum tail water elevation, Column 5 the elevation of the



HYDRAULIC JUMP STUDIES

STILLING BASIN II

DEFINITION OF SYMBOLS

FIGURE 10
REPORT HYD. 380

437

Table 2

MODEL RESULTS OF EXISTING TYPE II STILLING BASINS

Dam	Report No. (1)	Max reservoir el (2)	Tailwater el (3)	Fall headwater to tailwater ft (4)	Basin floor el (5)	Max discharge cfs (6)	W Width of basin ft (7)	q Discharge per ft of basin cfs (8)	V_1 (Actual) velocity ft/sec (9)	D_1 ft (10)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (11)	[illegible] (12)	[illegible] (13)	D_2 (Conjugate) ft (14)	[illegible] (15)	L Length of basin ft (16)	L/[illegible] (17)	Slope entering basin degrees with horizontal (18)
Rye Patch	Hyd-3.16	4123	4065.5	57.5	4062	20,000	110	182	44	4.14	3.81	23.5	5.67	25	1.16	46	[illegible]	33
Unity	Hyd-211	3820	3771	49	3769	10,000	55.5	180	49	3.67	4.50	22	5.90	21.5	1.12	53	[illegible]	26.7
Alcova	Hyd-5.1	5500	5354	146	5309	55,000	150	367	62	4.68	6.82	45	10.04	37	1.22	125	3.37	25.0
Shadow Mountain	Hyd-162	8367	8332	35	8313	10,000	70	143	42	3.40	4.01	19	5.59	21	0.90	56	[illegible]	28
Boysen (Final)	Hyd-212	4752	4625	126	4594	20,000	66	303	80	3.79	7.33	34	8.97	37	0.92	151	[illegible]	34
Boysen (Prelim)	Hyd-212	4752	4646.5	105.5	4600	62,000	125	496	70	7.06	4.63	46.5	6.56	43	1.08	146	[illegible]	33.7
Scofield	Hyd-160	7630	7583.6	46.4	7564	6,200	40	155	48	3.23	4.70	19.6	6.06	20	0.98	60	[illegible]	33.7
Boca	Hyd-225	5605	5508	97	5497	8,000	75	107	68	1.57	9.56	21	13.37	21	1.00	58.6	[illegible]	26.7
Fresno	Hyd-177	2591	2528	63	2499.5	51,000	190	268	58	4.62	4.75	26.5	6.16	29	0.96	85	[illegible]	33.7
Bull Lake	Hyd-26.1	5805	5743.5	61.5	5725	10,000	100	100	55	1.82	7.17	18.5	10.16	17.5	1.06	75	[illegible]	14
Caballo	Hyd-72	4182	4118	64	4086	33,000	108	306	56	5.46	4.21	32	5.96	30	1.07	78.2	2.71	26.7
Moon Lake	Hyd-156	8137	8028.2	108.8	8005	10,000	75	133	67	1.98	8.38	23.2	11.71	22	1.05	60	[illegible]	26.7
Deer Creek	Hyd-215	5417	5285	132	5260	12,000	75	160	78	2.05	9.59	25	12.19	26.5	0.94	75	[illegible]	26.7
Alamogordo	Hyd-243	4275	4163	112	4118	56,000	110	509	76	6.70	5.17	45	6.71	46	0.96	125	[illegible]	26.7
Enders	Hyd-252	3129.5	3057	73	3016	200,000	400	500	59	6.47	3.57	41	4.86	39	1.05	115	[illegible]	26.7
Medicine Creek	Hyd-279	2406.9	2328	81	2287	97,800	262	373	63	5.92	4.56	41	6.92	35	1.17	125	[illegible]	26.7
Cedar Bluff	Hyd-330	2192	2074.3	118	2035.5	87,400	200	437	76	5.75	5.58	39	6.79	42.5	0.92	141	[illegible]	18.5
Falcon	Hyd-278	314.2	235	79	175	456,000	600	760	57	13.33	2.75	60	4.50	45	1.33	180	[illegible]	26.7
Trenton	Hyd-301	2785	2700.6	84	2653	133,000	266	500	60	8.33	3.66	48	5.78	39	1.23	125	[illegible]	18.5
Cachuma	Hyd-354	757.6	578.8	179	523	161,000	322	500	85	5.88	6.17	56	9.52	49	1.14	153	[illegible]	26.7
Tiber	Hyd-268	3014.9	2835.8	179	2797	54,250	200	271	85	3.19	8.38	39	12.22	36	1.05	117	[illegible]	18
Imperial Spillway	TM-516	191	168	25	150	150,000	1197.5	125	34	3.68	3.12	16	4.34	14.5	1.10	41	[illegible]	14
Imperial Sluiceway	TM-516	181	155	26	140	24,000	248.3	97	37	2.62	4.02	15	5.72	13.5	1.11	64	[illegible]	14
Grassy Lake	Hyd-226	7210	7100	110	7086	1,200	20	60	69	0.87	13.02	14	16.0	15.5	0.90	45	[illegible]	26.7
Box Butte	Hyd-44	4014	3961	53	3946.5	2,500	40	62	47	1.32	7.20	13	11.36	[illegible]	1.15	50	3.85	22
Siphon Drop Turnout	PVI-84-RC	169.7	150.7	19	136	2,000	33.5	60	31	1.94	3.92	15	7.73	10	1.50	36	[illegible]	22
Pilot Knob Wasteway	Hyd-164	170.26	124	46	94.5	13,155	140	94	46	2.04	5.66	30	14.70	15.5	1.94	60	[illegible]	18.5
AA Canal Drop 1	PVI-84-RC	43.6	29.2	14	13.3	8,700	118	74	27	2.74	2.87	16	5.83	10	1.60	27	2.7	22
Wasteway No. 2	Hyd-108	1185.75	1027.4	159	1014.9	2,100	40	52	85	0.61	19.14	12	19.60	16	0.75	45	2.81	24.7
Big Sandy No. 2	Hyd-121	6761.3	6702	59	6679	7,500	50	150	51	2.94	5.24	23	7.80	20.5	1.12	72	[illegible]	33.7
Cherry Creek	Hyd-146	5632.4	5556	74	5515	45,000	115	388	60	6.47	4.15	40	5.10	35	1.14	120	[illegible]	25
Pine View	Hyd-3.06	4870	4827	43	4785	9,000	40	225	46	4.89	3.67	32	6.54	23	1.39	96	[illegible]	33.7
Agency Valley	TM-506	3340	3266.5	74	3234	10,700	50	200	55	3.64	5.07	32	8.79	24	1.33	116	[illegible]	33.7
Davis		647	515.5	132	490	175,000	246	711	78	9.12	4.55	56	6.14	54	1.04	100	[illegible]	14
Senty	Hyd-331	3717.6	3603	114.6	3559	64,700	215	301	70	4.30	5.94	34	7.92	34	1.0	102	[illegible]	20
Cle Elum	TM-590	2240	2130	110	2097	40,000	200	200	70	2.76	7.30	33	11.52	28	1.15	107	[illegible]	33.7
Maximum				179			1197.5	760	85	13.33	19.14	60	19.60	49	1.94	180	[illegible]	34
Minimum				14			20	52	27	0.61	2.75	12	4.34	10	0.75	27	[illegible]	14
Average				95				265							1.13		[illegible]	

Dam	Chute blocks: Type (19)	h_1 Height ft (20)	$\frac{h_1}{D_1}$ (21)	w_1 Width ft (22)	$\frac{w_1}{h_1}$ (23)	$\frac{w_1}{s_1}$ (24)	Main baffle blocks: Type (25)	Position on apron $\frac{X}{L_r}$ (26)	h_2 Height ft (27)	$\frac{h_2}{D_2}$ (28)	w_2 Width ft (29)	$\frac{w_2}{h_2}$ (30)	$\frac{w_2}{s_2}$ (31)	Intermediate baffle blocks: Type (32)	Position on apron $\frac{X}{L_s}$ (33)	Height ft (34)	Height/D_2 (35)	Width ft (36)	Width/Height (37)	Width/Spacing (38)	Type of basin (39)	Wing walls at end of basin (40)
Rye Patch	Solid	4.0	0.97	--	--	--	Solid	1.0	2.0	0.08	--	--	--	--	--	--	--	--	--	--	Rectangular	45° warped
Unity	Teeth	3.5	0.95	1.83	0.52	1.0	Teeth	0.93	5.5	.25	2.17	0.39	1.0	--	--	--	--	--	--	--	R	Normal
Alcova	Solid	4.3	0.96	--	--	--	T	1.0	10.0	.22	5.0	0.50	1.0	--	--	--	--	--	--	--	R	None
Shadow Mountain	T	3.0	0.88	4.5	1.33	1.78	T	1.0	3.5	.18	4.0	1.14	1.78	--	--	--	--	--	--	--	R	Normal
Boysen (Final)	T	4.0	1.06	5.25	1.31	1.75	T	0.68	8.75	.26	5.25	0.60	1.75	--	--	--	--	--	--	--	R	None
Boysen (Prelim)	T	6.0	0.85	7.5	1.25	1.5	T	1.0	8.0	.17	7.5	0.94	1.8	--	--	--	--	--	--	--	R	None
Scofield	T	3.5	1.08	3.5	1.0	1.91	T	1.0	4.0	.20	3.5	0.88	1.91	--	--	--	--	--	--	--	R	Normal
Boca	T	4.0	2.55	3.0	0.75	1.0	T	1.0	4.0	.19	3.0	0.75	1.0	--	--	--	--	--	--	--	R	Normal
Fresno	T	4.0	0.86	4.0	1.0	1.0	T	1.0	6.0	.21	4.0	0.67	1.0	--	--	--	--	--	--	--	R	45° warped
Bull Lake	None	--	--	--	--	--	T	1.0	4.0	.22	5.0	1.25	1.0	--	--	--	--	--	--	--	R	Normal
Caballo	T	4.5	0.82	4.0	0.89	1.0	T	0.90	6.5	.20	4.0	0.62	1.0	--	--	--	--	--	--	--	R	Normal
Moon Lake	T	2.6	1.31	1.875	0.72	1.0	T	0.85	5.0	.22	3.75	0.75	1.0	--	--	--	--	--	--	--	R	Normal
Deer Creek	T	3.0	1.46	3.0	1.0	1.0	T	1.0	5.0	.20	3.0	0.60	1.0	--	--	--	--	--	--	--	R	Normal
Alamogordo	T	8.0	1.19	3.5	0.44	1.0	T	1.0	9.0	.20	4.0	0.44	1.0	--	--	--	--	--	--	--	R	Normal
Enders	T	6.0	0.71	5.0	0.83	1.0	T	1.0	12.0	.29	5.0	0.42	1.0	--	--	--	--	--	--	--	R	Normal
Medicine Creek	T	6.75	1.14	6.0	0.89	1.0	T	1.0	8.0	.20	6.0	0.75	1.0	--	--	--	--	--	--	--	R	Normal
Cedar Bluff	T	7.0	1.22	6.0	0.86	1.0	T	1.0	9.4	.23	6.0	0.67	1.0	--	--	--	--	--	--	--	R	Normal
Falcon	T	8.0	0.60	10.0	1.25	1.0	T	1.0	12.0	.20	10.0	0.83	1.0	--	--	--	--	--	--	--	R	45° vertical
Trenton	T	5.0	0.60	5.0	1.0	1.0	T	1.0	9.0	.19	5.0	0.56	1.0	--	--	--	--	--	--	--	R	Normal
Cachuma	T	5.5	0.94	5.08	0.92	1.0	T	1.0	12.0	.21	5.08	0.42	1.0	--	--	--	--	--	--	--	R	Normal
Tiber	T	7.0	2.19	5.0	0.71	1.0	T	1.0	8.0	.21	5.0	0.62	1.0	--	--	--	--	--	--	--	R	Normal
Imperial Spillway	T	2.33	0.63	2.49	1.02	1.03	T	1.0	3.75	.23	3.27	1.01	1.0	--	--	--	--	--	--	--	R	20° warped
Imperial Sluiceway	T	3.33	1.27	3.0	0.90	0.95	T	0.65	5.0	.33	5.67	1.13	1.1	--	--	--	--	--	--	--	R	20° warped
Grassy Lake	T	1.0	1.14	1.67	1.67	1.0	T	1.0	2.0	.14	1.33	0.66	1.0	--	--	--	--	--	--	--	R	Normal
Box Butte	T	3.3	2.56	3.0	0.91	1.0	T	1.0	3.0	.20	3.0	1.0	1.0	--	--	--	--	--	--	--	R	Normal
Siphon Drop Turnout	T	2.25	1.16	2.25	1.0	1.0	T	1.0	3.25	.22	2.25	0.69	1.0	T	0.72	3.25	0.22	2.25	1.44	1.0	R	45° warped
Pilot Knob Wasteway	T	2.5	1.22	2.5	1.0	1.0	T	1.0	5.0	.17	5.0	1.0	1.0	--	--	--	--	--	--	--	R	45° warped
AA Canal Drop 1	T	1.75	0.64	1.75	1.0	1.0	Solid	1.0	1.0	.06	--	--	--	--	--	--	--	--	--	--	R	30° warped
Wasteway No. 2	Vanes	--	--	--	--	--	Solid	1.0	2.0	.17	--	--	--	T	.71	2.41	.20	2.41	1.0	1.0	R	30° warped
Big Sandy No. 2	T	2.5	0.85	3.25	1.30	1.0	T	1.0	3.0	.13	3.25	1.08	1.0	--	--	--	--	--	--	--	Trapezoidal	Normal
Cherry Creek	None	--	--	--	--	--	Solid	1.0	5.0	.12	--	--	--	T	.73	5.0	.12	3.75	0.75	1.0	T	None
Pine View	None	--	--	--	--	--	T	1.0	5.0	.16	6.0	1.20	1.0	--	--	--	--	--	--	--	T	Warped curve
Agency Valley	Solid	2.5	0.69	--	--	--	T	0.91	10.0	.31	3.33	0.33	1.0	--	--	--	--	--	--	--	T	50° warped
Davis	T	14.3	1.56	13.0	0.91	1.06	T	1.0	14.3	.26	13.0	0.91	1.06	--	--	--	--	--	--	--	R	Normal
Senty	T	7.0	1.63	5.0	0.72	1.0	T	1.0	8.0	.24	5.0	0.62	1.0	--	--	--	--	--	--	--	R	Normal
Cle Elum	None	--	--	--	--	--	T	1.0	10.0	.30	10.0	1.0	1.0	--	--	--	--	--	--	--	R	None
Maximum			2.55		1.67	1.91		1.0		.33		1.25	1.91		.73		.22		1.44	1.0		
Minimum			0.60		0.44	0.95		0.65		.06		0.33	1.00		.71		.12		0.75	1.0		
Average			1.15		0.97	1.15		0.97		.20		0.76	1.13							1.0		

437

stilling basin floor, and Column 6 the maximum discharge for each spillway. Column 4 indicates the height of the structure studied, showing a maximum fall from headwater to tail water of 179 feet, a minimum of 14 feet, and an average of 85 feet. Column 7 shows that the width of the stilling basins varied from 1,197.5 to 20 feet. The discharge per foot of basin width, Column 8, varied from 760 to 52 cfs, with 265 as an average. The computed velocity, V_1, entering the stilling basin (Column 9) varied from 85 to 27 feet per second, and the depth of flow, D_1, entering the basin (Column 10) varied from 13.33 feet to 0.61 of a foot. The value of the Froude number (Column 11) varied from 19.14 to 2.75. Column 12 shows the actual depth of tail water above the stilling basin floor, which varied from 60 to 12 feet, while Column 14 lists the computed, or conjugate, tail water depth for each stilling basin. The conjugate depths, D_2, were obtained from Figure 5. The ratio of the actual tail water depth to the conjugate depth is listed for each basin in Column 15. This shows a maximum of 1.94, a minimum of 0.75, and an average of 1.13.

Chute Blocks

The chute blocks, or spreading device, used at the entrance to the stilling basin varied. Some contained nothing at this point, others a solid step, but in the majority of cases a serrated device was utilized, known as chute blocks. The chute blocks at the upstream end of the basin tend to corrugate the jet, lifting a portion of it from the floor, resulting in a shorter length of jump than would be possible without them. These blocks also tend to improve the action in the jump. The proportioning of chute blocks has always been subject to question, but the tabulation in Columns 19 through 24 of Table 2 should serve to set these figures quite definitely. Column 20 shows the height of the chute blocks, while Column 21 gives the ratio of height of block to the depth D_1. The ratios of height of block to D_1 indicate a maximum of 2.55, a minimum of 0.6, and an average of 1.15.

The width of the blocks is shown in Column 22. Column 23 gives the ratio of width of the block to height, with a maximum of 1.67, a minimum of 0.44, and an average of 0.97. The ratio of width of block to spacing, tabulated in Column 24, shows a maximum of 1.91, a minimum of 0.95, and an average of 1.15. The three ratios indicate that the proportion: height equals width, equals spacing, equals D_1 should be a satisfactory standard for chute block design. The wide variation shows that these dimensions are not critical.

Dentated Sill

The sill in or at the end of the basin was either solid or some form of dentated arrangement, as designated in Column 25. The shape of the dentates and the angle of the sills varied considerably in the spillways tested, Columns 26 through 31. The position of the dentated sill also varied and this is indicated by the ratio $\frac{X}{L_{II}}$ in Column 26. The distance, X, is measured to the downstream edge of the sill, as illustrated in Figure 10. The ratio $\frac{X}{L_{II}}$ varied from 1 to 0.65, with an average of 0.97.

The heights of the dentates are given in Column 27. The ratio of height of block to the conj tail water depth is shown in Column 28. These ratios show a maximum of 0.33, a minimum of 0.06, and an average of 0.20. The width to height ratio, Column 30, shows a maximum of 1.25, a minimum of 0.33, and an average of 0.76. The ratio of width of block to spacing, Column 31, shows a maximum of 1.91, a minimum of 1.0, and an average of 1.13. For the sake of generalization, the following proportions are recommended: (1) height of dentated sill = $0.2D_2$, (2) width of blocks = $0.15D_2$, and (3) spacing of blocks = $0.15D_2$, where D_2 is the conjugate tail water depth. It is recommended that the dentated sill be placed at the downstream end of the apron.

Column 32 through 38 show the proportions of additional baffle blocks used on three of the stilling basins. These are not necessary and are not recommended for this type of basin.

Additional Details

Column 18 indicates the angle, with the horizontal, at which the high-velocity jet enters the stilling basin for each of the spillways. The maximum angle was 34° and the minimum 14°. The effect of the vertical angle of the chute on the action of the hydraulic jump could not be evaluated from the information available. This factor will be considered, however, in Section 5 in connection with sloping apron design.

Column 39 designates the cross section of the basin. In all but three cases the basins were rectangular. The three cross sections that were trapezoidal had side slopes varying from 1/4:1 to 1/2:1. The generalized designs presented in this report are for stilling basins with rectangular cross sections. Where trapezoidal basins are used, a model study is strongly recommended.

Designers have been concerned over the type of wing wall which should be used at the end of stilling basins. Column 40, Table 2, indicates that in the majority of basins constructed for earth dam spillways the wing walls were normal to the training walls. Five basins were constructed without wing walls using a rock blanket for protection. The remainder utilized angling wing walls or warped transitions downstream from the basin. The latter are common on canal structures. The object, of course, is to build the cheapest wing wall that will afford the necessary protection. The type of wing wall is usually dictated by local conditions such as, width of the channel downstream, depth to foundation rock, degree of protection needed, etc., thus wing walls are not amenable to generalization.

Verification Tests

It was early learned that the information on Table 2 did not cover the entire range of operating conditions desired. There was insufficient information to determine the length of basin for the larger values of the Froude number; there was little or no information on the tail water depth at which sweepout occurs, and the information available was of little value for generalizing water surface profiles. It was, therefore, necessary to perform a set of experiments to extend the range and to supply the missing data. The experiments were made on 17 Type II basins, proportioned according to the above rules, and installed in Flumes B, C, D, and E (see Columns 1 and 2, Table 3). Each basin was judged at the discharge for which it was designed; the length was adjusted to the minimum that would produce satisfactory operation, and the absolute minimum tail water depth for acceptable operation was measured. The basin operation was also observed for flows less than the designed discharge and found to be satisfactory in each case.

Table 3 is quite similar to Table 2 with the exception that the length of basin L_{II} (Column 11) was determined by experiment, and the tail water depth at which the jump just began to sweepout of the basin was recorded (Column 13).

Tail Water Depth

The solid line on Figure 11 was obtained from the hydraulic jump formula $\frac{D2}{D1} = 1/2 \left(\sqrt{1+8F^2}-1\right)$ and represents conjugate tail water depth. It is the same as the line shown on Figure 5. The dash lines on Figure 11 are merely guides drawn for tail water depths other than conjugate depth. The points shown as dots were obtained from Column 13 of Table 2, and constitute the ratio of actual tail water depth to D_1 for each basin listed. It can be observed that the majority of the basins were designed for full conjugate tail water depth or greater.

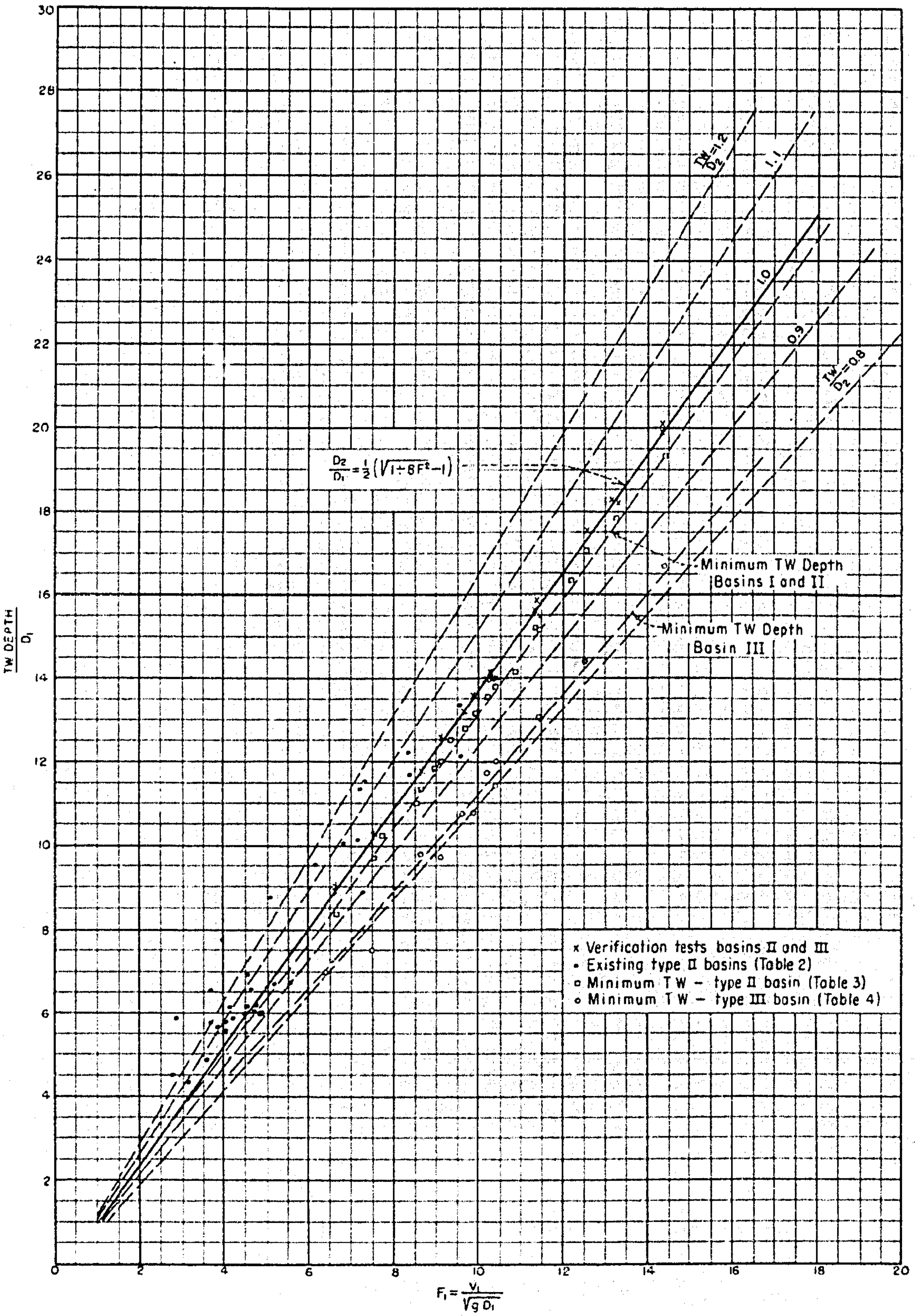
A previous design chart in Bureau use suggests that, where baffles and sills are utilized, the stilling basin floor be positioned to use a tail water depth of 0.85 of the conjugate depth. This practice is definitely discouraged as it will lead to questionable designs. To confirm the erroneous nature of this statement, a dotted line showing minimum tail water depth for Basins I and II, obtained from Column 14 of

Table 3

VERIFICATION TESTS ON TYPE II STILLING BASIN

Flume (1)	Test (2)	Q Total discharge cfs (3)	W Width of basin ft (4)	q Discharge per foot of basin width cfs (5)	TW Tailwater depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	D_2/D_1 (9)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (10)	L_{II} Length of jump ft (11)	$\frac{L_{II}}{D_2}$ (12)	T_{so} Tailwater at sweep out ft (13)	$\frac{T_{so}}{D_1}$ (14)	$\frac{T_{so}}{D_2}$ (15)
B	1	2.500	2.000	1.250	1.120	17.36	0.072	15.60	11.39	4.95	4.42	1.09	15.13	0.97
	2	4.000		2.000	1.430	17.54	0.114	12.54	9.16	6.10	4.27	1.37	12.02	0.96
	3	6.000		3.000	1.750	17.65	0.170	10.29	7.54	7.30	4.17	1.65	9.70	0.94
	4	8.000		4.000	2.030	17.86	0.224	9.06	6.64	8.00	3.94	1.88	8.39	0.93
C	5	1.600	1.500	1.067	1.070	17.49	0.061	17.54	12.48	4.60	4.30	1.04	17.04	0.97
	6	2.100		1.400	1.240	17.94	0.078	15.89	11.32	5.40	4.35	1.18	15.12	0.95
	7	2.630		1.753	1.355	18.26	0.096	14.11	10.39	5.70	4.21	1.32	13.75	0.97
	8	2.750		1.833	1.400	18.33	0.100	14.00	10.21	6.23	4.45	1.36	13.60	0.97
	9	4.000		2.667	1.785	20.36	0.131	13.62	9.91	7.40	4.15	1.73	13.21	0.97
D	10	5.000	3.970	1.259	1.235	20.30	0.062	19.91	14.38	5.10	4.13	1.20	19.35	0.97
	11	6.000		1.511	1.350	20.41	0.074	18.24	13.21	5.80	4.30	1.32	17.83	0.98
	12	9.800		2.468	1.750	21.84	0.113	15.50	11.45	7.80	4.46	1.73	15.31	0.99
	13	11.000		2.770	1.855	21.15	0.131	14.16	10.29	8.10	4.37	1.82	13.89	0.98
	14	13.000		3.273	2.020	21.39	0.153	13.20	9.64	8.70	4.31	1.95	12.75	0.97
	15	20.000		5.036	2.585	23.00	0.219	11.80	8.66	10.60	4.10	2.48	11.32	0.96
E	16	5.000	3.970	1.259	0.840	10.49	0.[illegible]20	7.00	5.33	3.36	4.00	0.79	6.58	0.94
	17	10.000		2.518	1.220	11.09	0.227	5.37	4.10	4.51	3.70	1.10	9.02	0.90

Flume	Test	h_1 Height chute blocks ft (16)	$\frac{h_1}{D_1}$ (17)	$\frac{w_1}{h_1}$ (18)	$\frac{s_1}{h_1}$ (19)	h_2 Height dentated sill ft (20)	$\frac{h_2}{D_2}$ (21)	$\frac{w_2}{h_2}$ (22)	$\frac{s_2}{h_2}$ (23)	α Slope water surface degrees (24)	ϕ Slope of Chute (25)
B	1	0.073	1.01	1.0	1.0	0.219	0.196	0.75	0.75	10.5	0.7:1
	2	0.114	1.00	1.0	1.0	0.286	0.200	0.75	0.75	10.0	
	3	0.170	1.00	1.0	1.0	0.352	0.201	0.75	0.75	9.6	
	4	0.229	1.02	1.0	1.0	0.406	0.200	0.75	0.75	9.0	
C	5	0.062	1.02	1.0	1.0	0.320	0.300	0.75	0.75	11.3	2:1
	6	0.078	1.00	1.0	1.0	0.260	0.210	0.75	0.75	10.8	
	7	0.105	1.09	1.0	1.0	0.250	0.185	0.75	0.75	10.5	
	8	0.100	1.00	1.0	1.0	0.310	0.221	0.75	0.75	10.0	
	9	0.131	1.00	1.0	1.0	0.446	0.250	0.75	0.75	10.4	
D	10	0.062	1.00	1.0	1.0	0.250	0.203	1.00	1.00	12.0	0.6:1
	11	0.074	1.00	1.0	1.0	0.270	0.200	1.00	1.00	11.2	
	12	0.153	1.35	1.0	1.0	0.400	0.229	1.00	1.00	10.0	
	13	0.131	1.00	1.0	1.0	0.396	0.214	0.75	0.75	10.2	
	14	0.153	1.00	1.0	1.0	0.400	0.198	0.75	0.75	8.3	
	15	0.219	1.00	1.0	1.0	0.517	0.200	0.75	0.75	9.5	
E	16	0.122	1.02	1.0	1.0	0.200	0.238	0.75	0.75	6.5	Varied
	17	0.235	1.04	1.0	1.0	0.270	0.221	0.75	0.75	5.3	



HYDRAULIC JUMP STUDIES
STILLING BASINS I, II AND III
MINIMUM TAILWATER DEPTHS

437

Table 3, is shown on Figure 11. The line indicates the point at which the front of the jump moves away from the chute blocks. In other words, any additional lowering of the tail water would cause the jump to leave the basin. Consulting Figure 11 it can be observed that the margin of safety for a Froude number of 2 is 2 percent; while for a number of 6 it increases to 6 percent, for a number of 10 it diminishes to 4 percent, and for a number of 16 it is 2.5 percent. To be certain that this is understood, it will be stated another way. The jump will no longer operate properly when the tail water depth approaches $0.98D_2$ for a Froude number of 2 or $0.94D_2$ for a number of 6 or $0.96D_2$ for a number of 10, or $0.975D_2$ for a number of 16. In other words, the margin of safety is largest in the middle range where the more desirable jumps are obtainable. A minimum safety factor of 5 percent of D_2 is recommended for the average Type II basin. For the two extremes of the curve it is advisable to provide a tail water greater than conjugate depth to be safe. Incidentally, the line showing the minimum tail water depth for Basin II (Figure 11) also applies for Basin I described in Section 1. This evidence should be sufficient to justify the retirement of the previous design chart.

There are several other thoughts with regard to tail water considerations which are mentioned as a reminder. First, tail water curves are usually extrapolated for the discharges encountered in design, so they can be in error. Secondly, the actual tail water depth usually lags in a temporal sense that of the tail water curve for rising flow and leads the curve for a falling discharge. Thirdly, a tail water curve may be such that the most adverse condition occurs at less than the maximum designed discharge; and fourthly, temporary or permanent retrogression to the river bed downstream may be a factor needing consideration. These factors, some of which are difficult to evaluate, are all important in stilling basin design, and suggest that an adequate factor of safety is essential. It is advisable to construct a jump height curve, superimposed on the tail water curve, for each basin to determine the most adverse operating condition. This procedure will be illustrated later.

The experiments repeatedly demonstrated that there is no simple remedy for a deficiency in tail water depth. Increasing the length of basin, which is the remedy often attempted in the field, will not compensate for deficiency in tail water depth. For these reasons, care should be taken to consider all factors that may affect the tail water at a future date. A stilling basin that does not perform properly cannot be justified in the light of money saved by skimping, regardless of the amount.

Length of Basin

The length of the Type II basin is shown as the intermediate curve on Figure 12. The points shown as dots are for the existing basins listed in Table 2. The ratio of length of basin to conjugate depth is plotted with respect to the Froude number (Columns 17 and 11, Table 2). The conjugate depth has been used rather than the actual tail water depth, as the former is a definite value which can be computed in each case. The points, indicated by dots, scatter considerably, and practically 50 percent of these are for values of the Froude number less than 5. These stilling basins were all tested by means of models, and the length in most cases was reduced to a minimum. This is one of the advantages of a model study.

The points denoted as squares on the same curve represent the results of verification tests made to extend the range. The points were obtained from Columns 12 and 10 of Table 3. The curve has been arbitrarily terminated at a Froude number of 4 as there is no assurance that the jump will be stable. A limit of 4.5 was given in Section 1 for Basin I without appurtenances; however, the chute blocks in Basin II had a tendency to extend the lower limit slightly. For stilling basin design involving values of the Froude number under 4.5, reference is made to Section 5. There is always a possibility of reducing the length of basin, over that shown on Figure 13, by a model study.

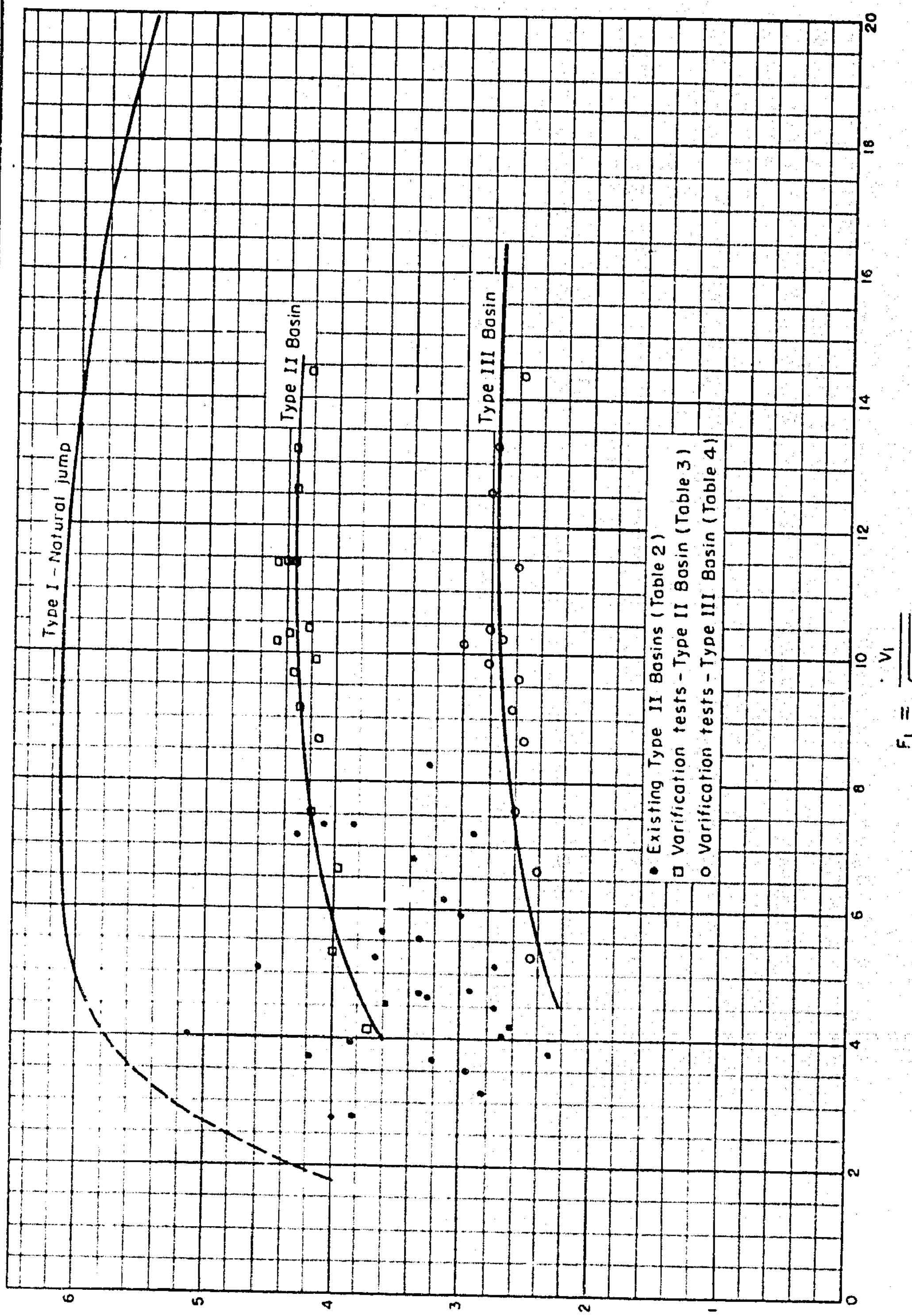
Water Surface Profiles

Water surface profiles were determined from the tests for the purpose of computing uplift pressures under the basin apron. As the water surface in the stilling basin tests fluctuated rapidly, and as air bulking in a prototype structure will expand the volume of its contents, over that indicated by its model, it was felt that there was no point in maintaining a high degree of accuracy in measurement. Therefore, approximate profiles are presented which can also be considered pressure profiles.

The method of procedure is illustrated on Figure 13. A horizontal line is drawn at conjugate depth. A vertical line is also drawn from the upstream face of the dentated sill. Beginning at the point of intersection, a sloping line is constructed as shown. The angle α, that this sloping line makes with the horizontal, is related to the Froude number.

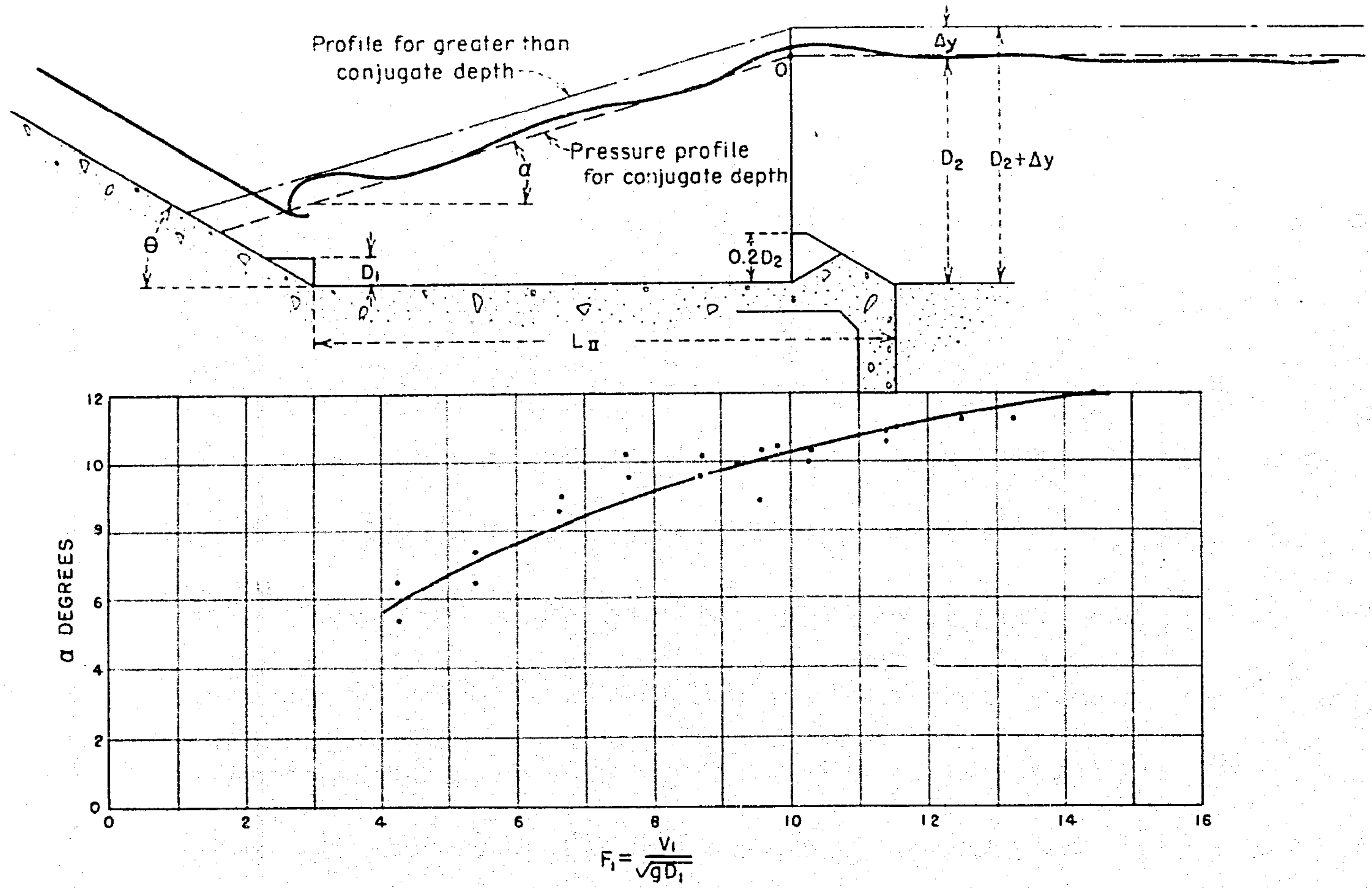
The angle α (Column 24, Table 3) observed in each of the verification tests has been plotted with respect to the Froude number on Figure 13. The slope increases with the Froude number. The above procedure gives the approximate water surface and pressure profile for

FIGURE 12
REPORT HYD 380



HYDRAULIC JUMP STUDIES
STILLING BASINS I, II, AND III
LENGTH OF JUMP ON HORIZONTAL FLOOR

437



HYDRAULIC JUMP STUDIES
STILLING BASIN II
APPROXIMATE WATER SURFACE AND PRESSURE PROFILES

437

conjugate tail water depth. Should the tail water depth be greater than D_2, the profile will resemble the uppermost line on Figure 13; the angle remains unchanged. This information applies only for the Type II basin, constructed as recommended in this section.

Conclusions

The following rules are recommended for generalization of Basin II, Figure 14:

1. Set basin apron to utilize full conjugate tail water depth, plus added factor of safety if needed. An additional factor of safety is advisable for both low and high values of the Froude number (see Figure 11). A minimum margin of safety of 5 percent of D_2 is recommended.

2. Basin II may be effective down to a Froude number of 4 but this should not be taken for granted (see Section 4 for values less than 4.5).

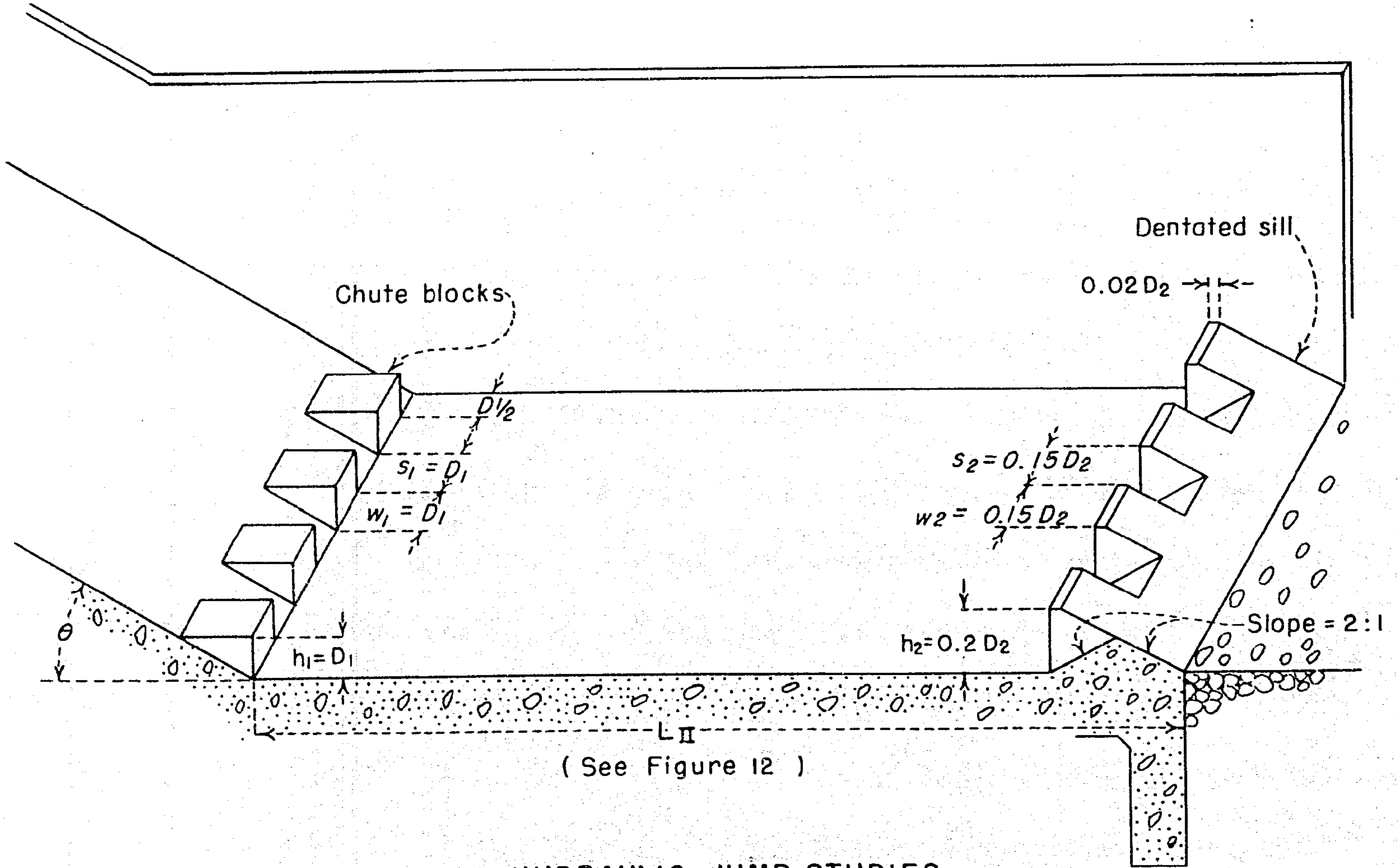
3. The length of basin can be obtained from the intermediate curve on Figure 12.

4. The height of chute blocks is equal to the depth of flow entering the basin, or D_1, Figure 14. The width and spacing should be equal to approximately D_1; however, this may be varied to eliminate the need of fractional blocks. A space equal to $\frac{D_1}{2}$ is preferable along each wall to reduce spray and maintain desirable pressures.

5. The height of the dentated sill is equal to $0.2D_2$, while the maximum width and spacing recommended is approximately $0.15D_2$. In this case a block is recommended adjacent to each side wall, Figure 14. The slope of the continuous portion of the end sill is 2:1. In the case of narrow basins, which would involve only a few dentates according to the above rule, it is advisable to reduce the width and the spacing so long as this is done proportionately. Reducing the width and spacing actually improves the performance in narrow basins, thus, the minimum width and spacing of the dentates is governed only by structural considerations.

6. It is not necessary to stagger the chute blocks and the sill dentates. In fact this practice is usually inadvisable from a construction standpoint.

7. The verification tests on Basin II indicated no perceptible change in the stilling basin action with respect to the slope of the chute preceding the basin. The slope of chute varied from 0.6:1 to



HYDRAULIC JUMP STUDIES

STILLING BASIN II

RECOMMENDED PROPORTIONS

437

FIGURE 14
REPORT HYD. 380

2:1 in these tests, Column 25, Table 3. Actually, the slope of the chute does have an effect on the hydraulic jump in some cases. This subject will be discussed in more detail in Section 5 with regard to sloping aprons. It is recommended that the sharp intersection between chute and basin apron, Figure 14, be replaced with a curve of reasonable radius when the slope of the chute is 1:1 or greater. Chute blocks can be incorporated on the curved face as readily as on the plane surfaces.

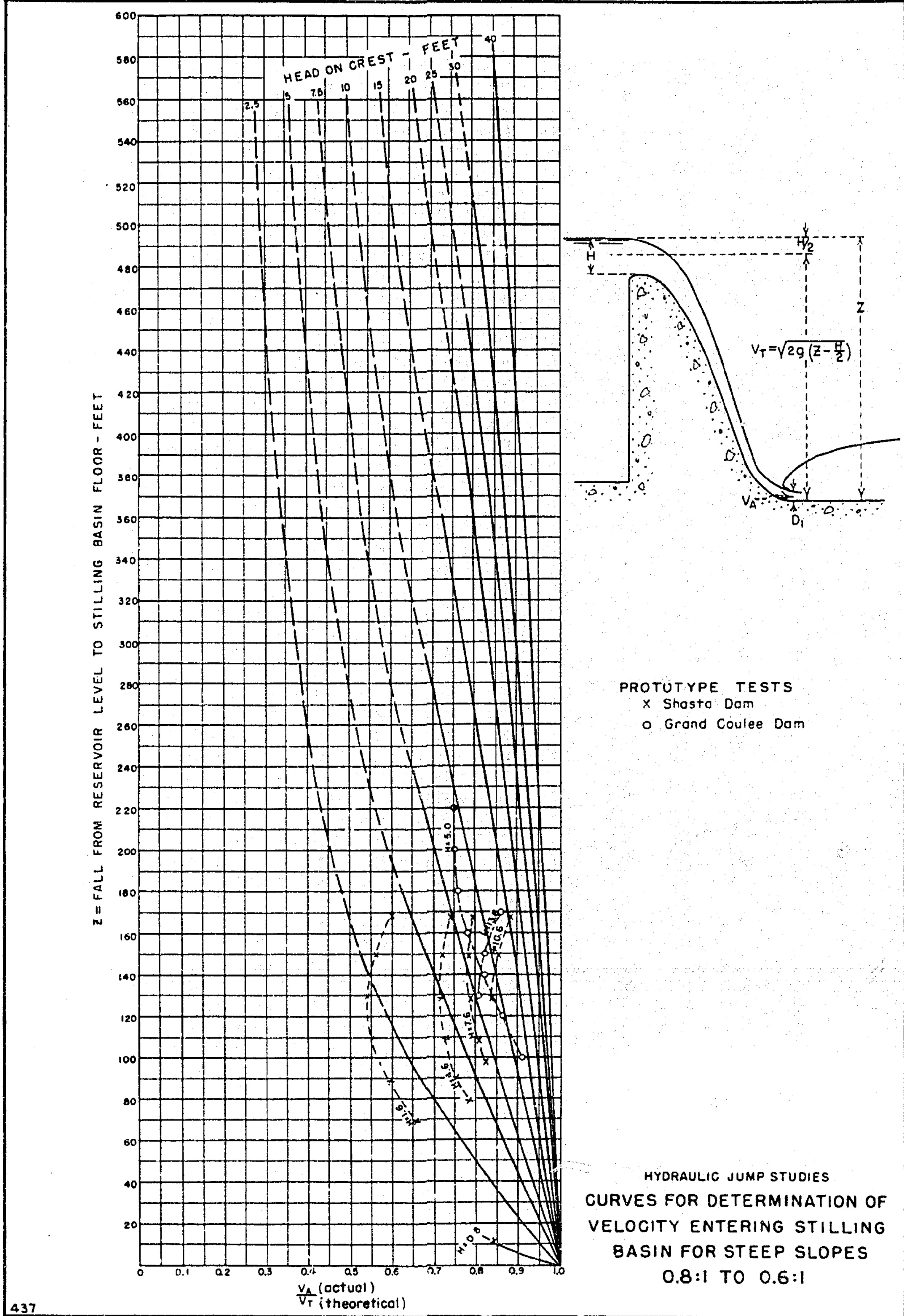
Following the above rules will result in a safe, conservative stilling basin for spillways with fall up to 200 feet and for flows up to 500 cfs per foot of basin width, providing the jet entering the basin is reasonably uniform both as to velocity and depth. For greater falls, larger unit discharges, or possible unsymmetry, a model study of the specific design is recommended.

Aids in Computation

Previous to presenting an example illustrating the method of proportioning Basin II, a chart will be presented which should be of special value for preliminary computations. The chart makes it possible to determine V_1 and D_1 with a fair degree of accuracy, for chutes having slopes of 0.8:1 or steeper, where computation is a difficult and arduous procedure. The chart presented as Figure 15 represents a composite of experience, computation, and a limited amount of experimental information obtained from prototype tests on Shasta and Grand Coulee Dams. There is much to be desired in the way of experimental confirmation; however, it is felt that this chart is sufficiently accurate for preliminary design. A concerted effort will be made to obtain additional experimental information whenever possible.

The ordinate on Figure 15 is fall from reservoir level to stilling basin floor, while the abscissa is the ratio of actual to theoretical velocity at entrance to the stilling basin. The theoretical velocity $V_T = \sqrt{2g(Z-H/2)}$ (see Figure 15). The actual velocity is the term desired. The curves represent different heads, H, on the crest of the spillway. As is reasonable, the larger the head on the crest, the more nearly the actual velocity at the base of the spillway will approach the theoretical. For example, with H = 40 feet and Z = 230 feet, the actual velocity at the base of the dam would be 0.95 of the computed theoretical velocity; while with a head of 10 feet on the crest, the actual velocity would be 0.75 V_T. The value of D_1 is computed by dividing the unit discharge by the actual velocity obtained from Figure 15.

The chart is not applicable for chutes flatter than 0.6:1 as frictional resistance assumes added importance in this range. Therefore, it will be necessary to compute the draw-down curve as usual starting at the gate section where critical depth is known.



HYDRAULIC JUMP STUDIES

CURVES FOR DETERMINATION OF VELOCITY ENTERING STILLING BASIN FOR STEEP SLOPES 0.8:1 TO 0.6:1

Insufflation, produced by air from the atmosphere mixing with the sheet of water during the fall, need not be considered in the hydraulic jump computations. Insufflation need be considered principally in the design of chute and stilling basin walls. It is not possible to construct walls sufficiently high to confine all spray and splash; thus, the best that can be hoped for is a height that is reasonable and commensurate with the material and terrain to be protected.

Application of Results (Example 2)

The crest of an overfall dam, having a downstream slope of 0.7:1, is 200 feet above the horizontal floor of the stilling basin. The head on the crest is 30 feet and the maximum discharge is 480 cfs per foot of stilling basin width. Proportion a Type II stilling basin for these conditions.

Entering Figure 15 with a head of 30 feet over the crest and a total fall of 230 feet,

$$\frac{V_A}{V_T} = 0.92$$

The theoretical velocity $V_T = \sqrt{2g(230-\frac{30}{2})} = 117.6$ ft/sec.

The actual velocity $V_A = V_1 = 117.6 \times 0.92 = 108.2$ ft/sec.

$$D_1 = \frac{q}{V_1} = \frac{480}{108.2} = 4.44 \text{ feet}$$

The Froude number

$$F_1 = \frac{V_1}{\sqrt{gD_1}} = \frac{108.2}{\sqrt{32.2 \times 4.44}} = 9.04$$

Entering Figure 11 with a Froude number of 9.04, the solid line gives,

$$\frac{TW}{D_1} = 12.3$$

As TW and D_2 are synonomous in this case, the conjugate tail water depth,

$$D_2 = 12.3 \times 4.44 = 54.6 \text{ feet}$$

The minimum tail water line for the Type II basin on Figure 11 shows that a factor of safety of about 4 percent can be expected for the above Froude number.

Should it be desired to provide a margin of safety of 7 percent, the following procedure may be followed: Consulting the line for minimum TW depth for the Type II basin, Figure 11,

$$\frac{TW}{D_1} = 11.85 \text{ for a Froude number of } 9.04$$

The tail water depth at which sweepout is incipient:

$$TW_{SO} = 11.85 \times 4.44 = 52.6 \text{ feet}$$

Adding 7 percent to this figure, the stilling basin apron should be positioned for a tail water depth of

$$52.6+3.7 = 56.3 \text{ feet or } 1.03D_2$$

The length of basin can be obtained by entering the intermediate curve on Figure 12 with the Froude number of 9.04.

$$\frac{L_{II}}{D_2} = 4.28$$

$$L_{II} = 4.28 \times 54.6 = 234 \text{ feet (see Figure 14)}$$

The height, width, and spacing of the chute blocks as recommended is D_1, thus the dimension can be 4 feet 6 inches.

The height of the dentated sill is $0.2D_2$ or 11 feet, while the width and spacing of the dentates can be $0.15D_2$ or 8 feet 3 inches.

SECTION 3

SHORT STILLING BASIN FOR CANAL STRUCTURES, SMALL OUTLET WORKS, AND SMALL SPILLWAYS (BASIN III)

Introduction

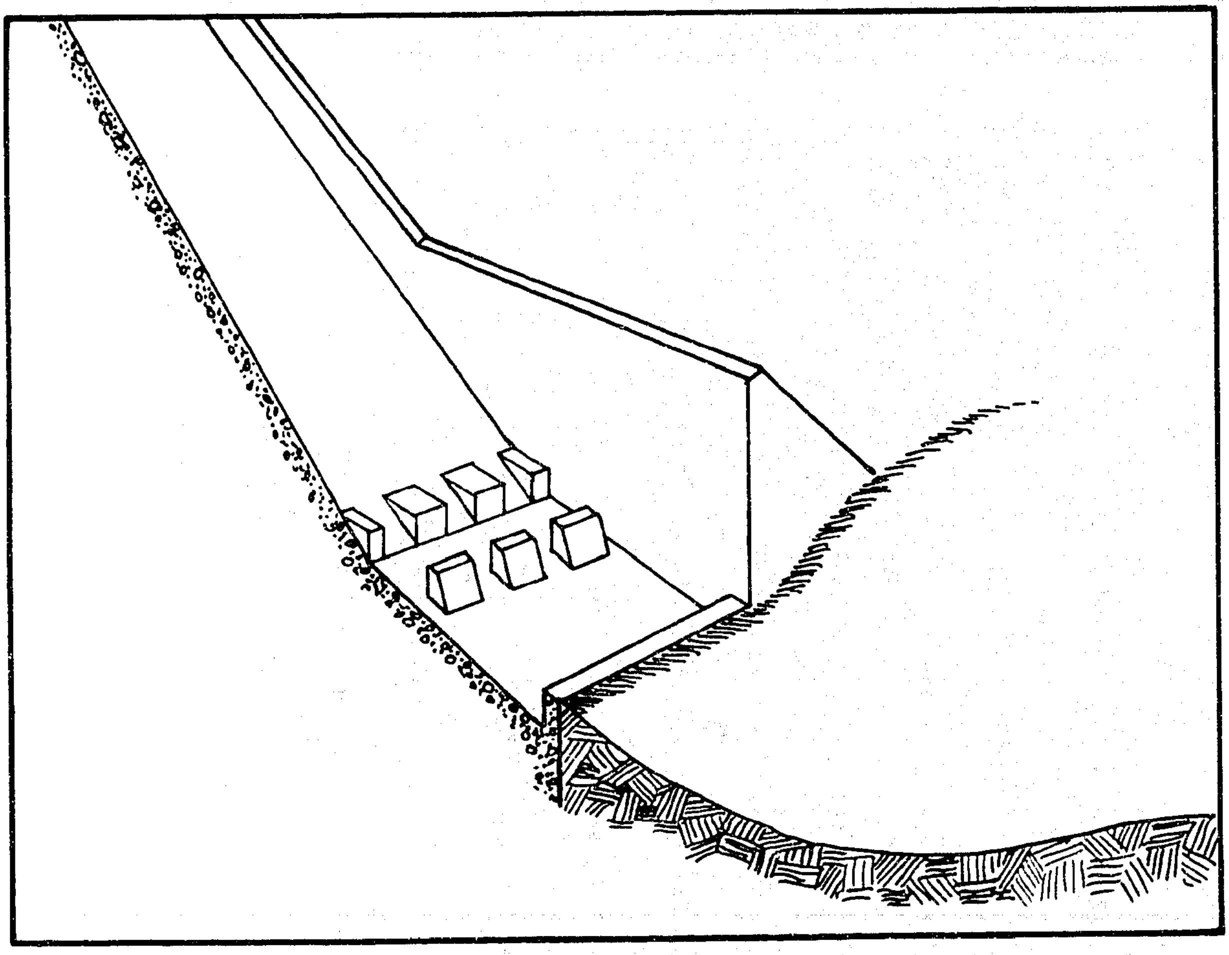
Basin II often is considered too conservative and consequently over-costly for structures carrying small discharges at moderate velocities. This can be especially true in the case of canal chutes, drops, wasteways, and other structures which are constructed by the dozen on canal systems. Any saving that can be effected in decreasing the size of these structures can amount to a sizable sum when multiplied by the number of structures involved. There is, of course, another consideration which should be kept in mind. If the dimensions of a particular structure are reduced to the point where it no longer operates satisfactorily, this mistake will be repeated many times over. A generalized design will be developed here for smaller structures where a more economical stilling basin is justified.

Development

The most effective way to shorten a stilling basin is to modify the jump by the addition of appurtenances in the basin. One restriction was imposed on these appurtenances, however; they must be self cleaning or nonclogging. This restriction thus limited the appurtenances to blocks or sills which could be incorporated on the stilling basin apron.

The Department of Agriculture 8/ 16/ developed a very short stilling basin designated "The SAF Basin," for use on drainage structures such as the Soil Conservation Service constructs, fits this specification and was very desirable from the standpoint of economy. This basin, shown in Figure 16, is actually a modification of Basin II just described. It was the intention to first check this design to determine its adequacy so far as Bureau requirements were concerned. Several stilling basins were set up in the laboratory according to the SAF rules, and they all demonstrated that the factor of safety was not sufficient for Bureau use. It was discovered, however, that the arrangement of this basin had excellent possibilities, and that by changing dimensions, such as the length, the tail water depth, the height and location of the baffle blocks, etc., the desired degree of conservatism could be obtained.

In addition to the foregoing tests, numerous experiments were performed using various types and arrangements of baffle blocks on the



HYDRAULIC JUMP STUDIES

SAF STILLING BASIN

apron in an effort to obtain the best possible solution. Some of the baffle blocks tried are shown on Figure 17. The experimentation consisted of varying the height, width and spacing of the blocks and their position on the apron. The blocks were positioned in both single and double rows with the second row staggered with respect to the first. Arrangement "a" on Figure 17 consisted of a solid bucket sill which was tried in several positions on the apron. This sill required an excessive tail water depth to be effective. Arrangement "b" was approximately the same shape as "a" except blocks and spaces replaced the solid sill. For certain heights, widths, and spacing these blocks performed quite well resulting in a water surface similar to that shown on Figure 20. Block "c" was ineffective for any height. The velocity passed over the block at about a 45 degree angle, thus was not impeded, and the water surface downstream was very turbulent with waves. The stepped Block "d" was also ineffective both for a single row and a double row. The action was much the same as for "c". The cube "e" was effective when the best height, width, spacing and position on the apron were found. The front of the jump was almost vertical and the water surface downstream was quite flat and smooth, much like the water surface shown on Figure 20. Block "f", which is the same shape used in the SAF basin, performed identically with the cubical block "e". The important feature as to shape appeared to be the vertical upstream face. The foregoing blocks were arranged in single and double rows. The second row in each case was of little value, Sketch "h", Figure 17.

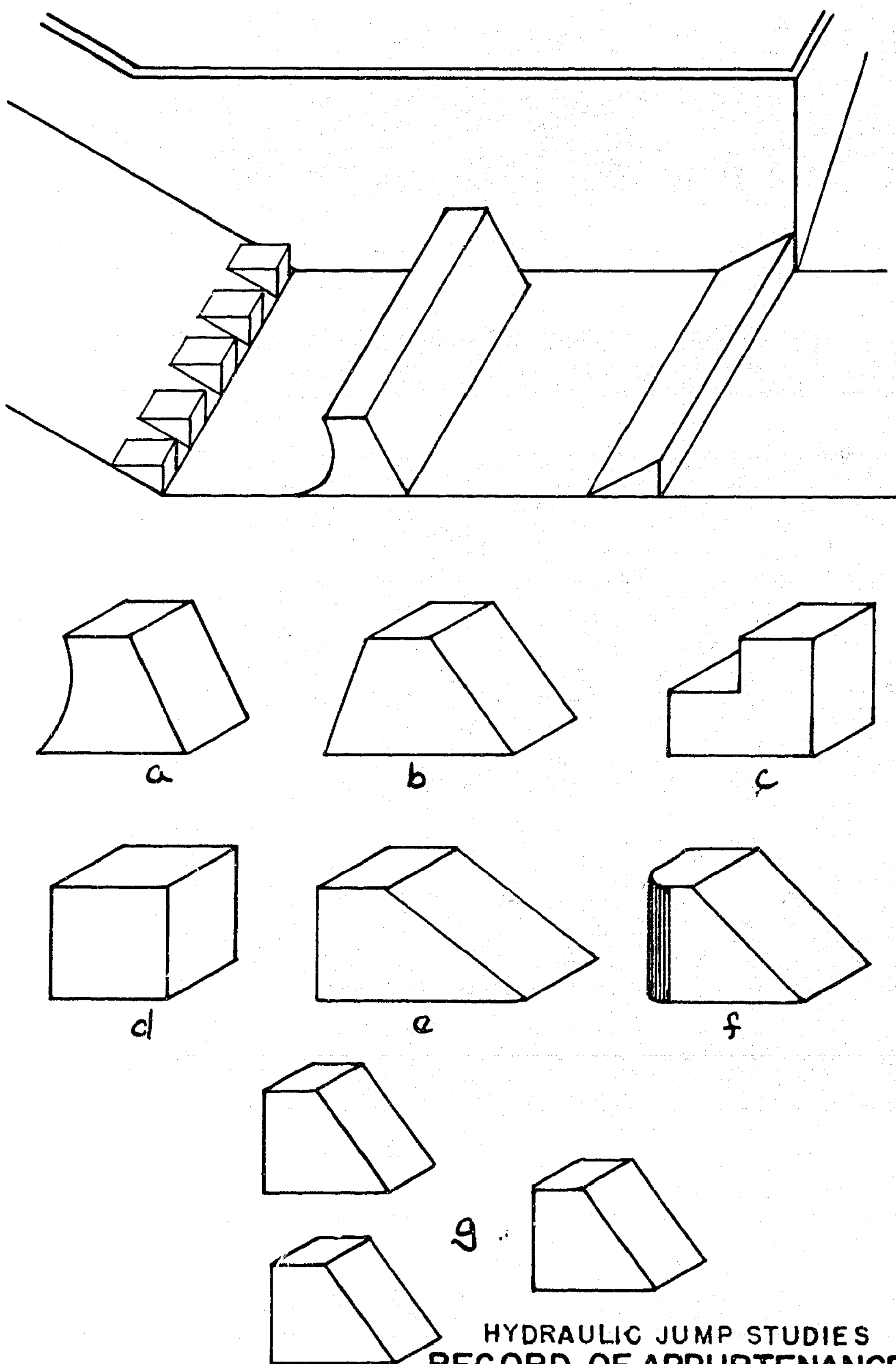
Block "g" is the same as Block "f" with the corners rounded. It was found that rounding the corners greatly reduced the effectiveness of the blocks. It fact a double row of blocks with rounded corners did not perform as well as a single row of Blocks "b", "e", or "f". As Block "f" is usually preferable from a construction standpoint, it was used throughout the remaining tests to determine a general design with respect to height, width, spacing and position on the apron.

In addition to experimenting with the baffle blocks, variations were tried with respect to the size and shape of the chute blocks and the end sill. It was found that the chute blocks should be kept small, no larger than D_1 if possible. The end sill had little or no effect on the jump proper. The basin as finally developed is shown on Figure 18. This is principally an impact dissipation device whereby the baffle blocks are called upon to do most of the work. The chute blocks aid in stabilization of the jump and the end sill is for scour control.

Verification Tests

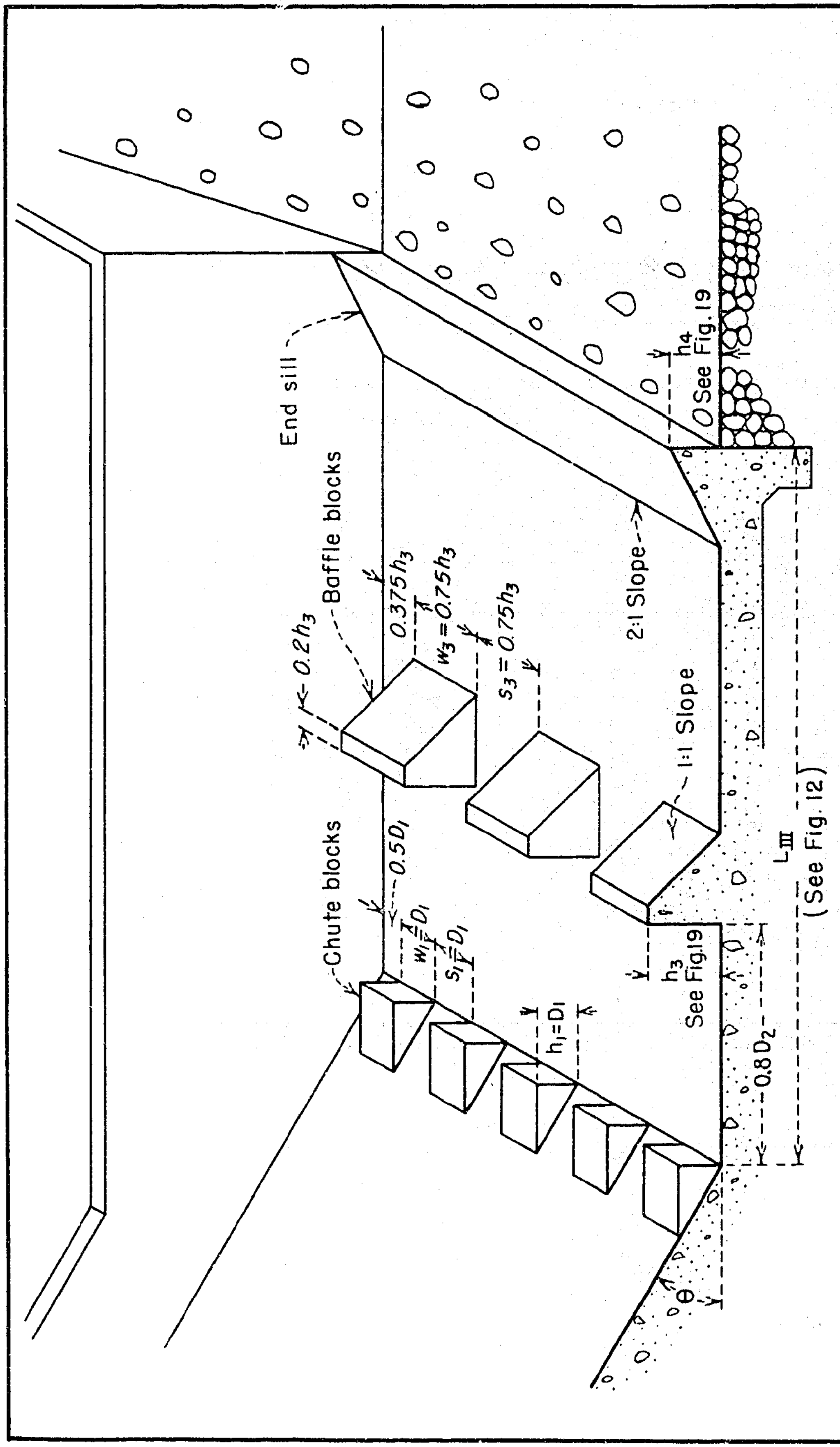
At the conclusion of the development work, a set of verification tests was made to examine and record the performance of this basin, which will be designated as Basin III, over the entire range of operating

FIGURE 17



HYDRAULIC JUMP STUDIES
RECORD OF APPURTENANCES
BASIN III.

FIGURE 18
REPORT HYD. 380



HYDRAULIC JUMP STUDIES
STILLING BASIN III
RECOMMENDED PROPORTIONS

conditions that may be met in practice. The tests were made on a total of 14 basins constructed in Flumes B, C, D, and E. The conditions under which the tests were run, the dimensions of the basin, and the results are recorded on Table 4. The headings are identical with those of Table 3 except for the dimensions of the baffle blocks and end sills. The additional symbols can be identified from Figure 18. Stilling basin action was quite stable for this design; in fact, more so than for either Basins I or II. The front of the jump was steep and there was less wave action to contend with downstream than in either of the former basins. In addition, Basin III has a large factor of safety and operates equally well for all values of the Froude number above 4.0. The former basins have neither of these attributes. The verification tests served to show that, with a few revisions, Basin III as developed was very satisfactory.

Chute Blocks

The recommended proportions for Basin III are shown on Figure 18. The height, width, and spacing of the chute blocks are equal to D_1, the same as was recommended for Basin II. Larger heights were tried, as can be observed from Column 18, Table 4, but are not recommended. The larger chute blocks tend to throw a portion of the high-velocity jet over the baffle blocks. Some cases will be encountered in design, however, where D_1 is less than 8 inches. In such cases the blocks may be made 8 inches high, which is considered by some designers as the minimum size from a construction standpoint. The width and spacing are the same as the height, but this may be varied so long as the aggregate width of spaces approximately equals the total width of the blocks.

Baffle Blocks

The height of the baffle blocks increase with the Froude number as can be observed from Columns 22 and 10, Table 4. The height, in terms of D_1, can be obtained from the upper line on Figure 19. The width and spacing can vary so long as the total spacing is equal to the total width of blocks. The most satisfactory width and spacing were found to be three-fourths of the height. It is not necessary to stagger the baffl clocks with the chute blocks as this is often difficult and there is little to be gained from a hydraulic standpoint.

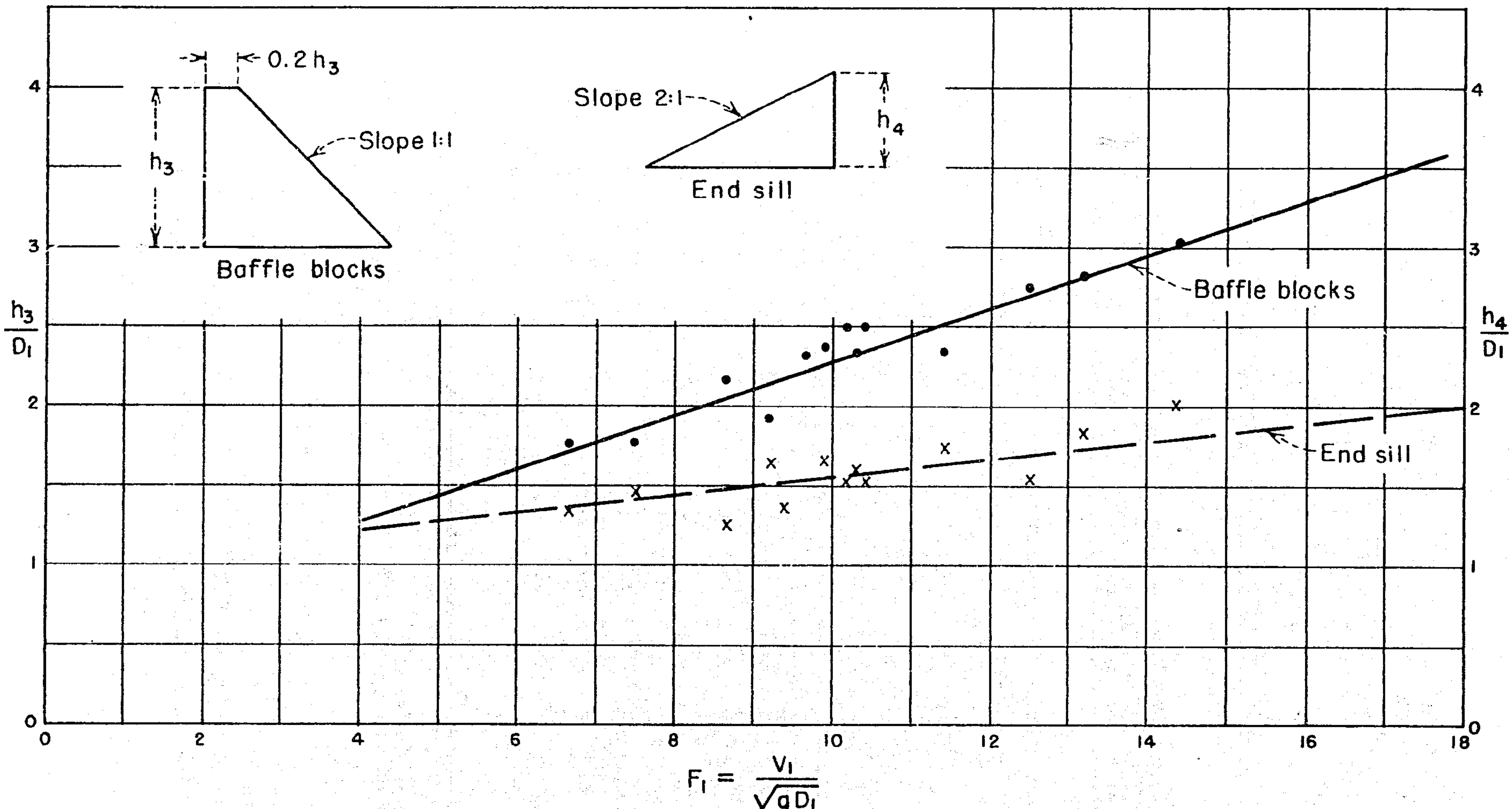
The baffle blocks are located $0.8D_2$ downstream from the chute blocks as shown in Figure 18. The actual positions used in the verification tests are shown in Column 25, Table 4. The position, height and spacing of the baffle blocks on the apron should be adhered to carefully, as these dimensions are important. For example, if the blocks are set appreciably upstream from the position shown, they will produce a cascade with resulting wave action. On the contrary, if the blocks are set

Table 4

VERIFICATION TESTS ON TYPE III STILLING BASIN

Flume (1)	Test (2)	Q Total discharge cfs (3)	W (4)	q Discharge per foot of Basin width (5)	TW Tailwater depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	D_2/D_1 (9)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (10)	L_{III} Length of jump ft (11)	$\frac{L_{III}}{D_2}$ (12)	T_{so} Tailwater at sweep out ft (13)	$\frac{T_{so}}{D_1}$ (14)	$\frac{T_{so}}{D_2}$ (15)	ϕ Slope of Chute (16)
B	1	2,500	2.000	1.250	1.120	17.36	0.072	15.56	11.41	2.90	2.59	0.94	13.05	0.84	0.7:1
	2	4.000		2.000	1.430	17.54	0.114	12.54	9.16	3.70	2.59	1.11	9.73	0.78	
	3	6.000		3.000	1.750	17.65	0.170	10.29	7.54	4.50	2.57	1.29	7.58	0.74	
	4	8.000		4.000	2.030	17.86	0.224	9.06	6.64	4.90	2.41	1.57	7.00	0.77	
C	5	1.600	1.500	1.067	1.070	17.49	0.061	17.54	12.48	3.00	2.80	0.88	14.42	0.82	2:1
	6	2.630		1.753	1.350	18.26	0.096	14.06	10.39	3.80	2.81	1.16	12.08	0.86	
	7	2.750		1.833	1.400	18.33	0.100	14.00	10.21	4.20	3.00	1.17	11.70	0.84	
	8	4.000		2.667	1.785	20.36	0.131	13.62	9.91	5.00	2.80	1.42	10.84	0.80	
D	9	5.000	3.970	1.259	1.250	20.30	0.062	20.16	14.38	3.20	2.56	1.04	16.77	0.83	0.6:1
	10	6.000		1.511	1.350	20.41	0.074	18.24	13.21	3.70	2.74	1.12	15.13	0.83	
	11	11.00		2.771	1.860	21.15	0.131	14.20	10.29	5.00	2.69	1.50	11.45	0.81	
	12	13.00		3.274	2.020	21.40	0.153	13.20	9.64	5.20	2.57	1.65	10.78	0.82	
	13	20.00		5.038	2.585	23.00	0.219	11.80	8.66	6.46	2.50	2.15	9.82	0.83	
E	14	5.000	3.970	1.259	0.840	10.49	0.120	7.00	5.33	2.10	2.50	0.70	5.83	0.83	Varied

Flume	Test	h_1 Height of chute blocks ft (17)	$\frac{h_1}{D_1}$ (18)	$\frac{w_1}{h_1}$ (19)	$\frac{s_1}{h_1}$ (20)	h_3 Height of baffle blocks ft (21)	$\frac{h_3}{D_1}$ (22)	$\frac{w_3}{h_3}$ (23)	$\frac{s_3}{h_3}$ (24)	Distance to baffles ft (25)	$\frac{L_{III}}{3D_2}$ (26)	h_4 Height of end sill ft (27)	$\frac{h_4}{D_1}$ (28)	Z Depth upstream from baffles ft (29)	$\frac{Z}{D_2}$ (30)
B	1	0.073	1.01	1.0	1.0	0.167	2.32	1.0	1.0	0.800	0.714	0.125	1.74	0.60	0.54
	2	0.114	1.00	1.0	1.0	0.218	1.91	1.0	1.0	0.920	0.643	0.187	1.64	0.80	0.56
	3	0.333	1.96	0.6	0.6	0.302	1.78	1.0	1.0	1.200	0.686	0.250	1.47	0.95	0.54
	4	0.229	1.02	1.0	1.0	0.396	1.77	1.0	1.0	1.340	0.660	0.302	1.35	1.20	0.59
C	5	0.052	1.02	1.0	1.0	0.167	2.74	0.75	0.75	0.850	0.794	0.092	1.51	0.60	0.56
	6	0.100	1.04	1.0	1.0	0.240	2.50	0.75	0.75	1.000	0.741	0.146	1.52	0.65	0.48
	7	0.146	1.46	1.0	1.0	0.250	2.50	0.75	0.75	1.210	0.864	0.156	1.56	0.70	0.50
	8	0.187	1.43	0.75	0.75	0.312	2.38	0.75	0.75	1.430	0.801	0.219	1.67	0.90	0.50
D	9	0.062	1.00	1.0	1.0	0.188	3.03	1.0	1.0	1.000	0.800	0.125	2.02	0.60	0.48
	10	0.083	1.12	1.0	1.0	0.208	2.81	1.0	1.0	1.120	0.830	0.135	1.82	0.65	0.48
	11	0.135	1.03	1.0	1.0	0.302	2.31	1.0	1.0	1.250	0.672	0.208	1.59	0.95	0.51
	12	0.156	1.02	1.0	1.0	0.354	2.31	1.0	1.0	1.680	0.832	0.208	1.36	1.05	0.52
	13	0.219	1.00	1.0	1.0	0.479	2.19	0.75	0.75	2.153	0.833	0.271	1.24	1.30	0.50
E	14	0.122	1.02	1.0	1.0	0.215	1.79	0.75	0.75	0.672	0.833	0.150	1.25	0.55	0.65



HYDRAULIC JUMP STUDIES

STILLING BASIN III

HEIGHT OF BAFFLE BLOCKS AND END SILL

437

farther downstream than shown, a longer basin will be required. Likewise, if the baffle blocks are too high, they can produce a cascade, while if too low a rough water surface will result. It is not the intention to give the impression that the position or height of the baffle blocks are critical. Their position or height are not critical so long as the above proportions are followed. There exists a reasonable amount of leeway in all directions; however, one cannot place the baffle blocks on the pool floor at random and expect anything like the excellent action associated with the Type III basin.

The baffle blocks may be in the form shown on Figure 18, or they may be cubes; either shape is effective. The corners of the baffle blocks are not rounded, as the sharp edges are effective in producing eddies which in turn aid in the dissipation of energy. It is advisable to place reinforcing steel back at least 6 inches from the block surfaces when possible, as there is some evidence that steel placed close to the surface aids spalling.

End Sill

The height of the solid end sill is also shown to vary with the Froude number although there is nothing critical about this dimension. The heights of the sills used in the verification tests are shown in Columns 27 and 28 of Table 4. The height of the end sill in terms of D_1 is plotted with respect to the Froude number and shown as the lower line on Figure 19. A slope of 2:1 was used throughout the tests.

Tail Water Depth

The SAF rules suggest the use of a tail water depth less than full conjugate depth, D_2. As in the case of Basin II, full conjugate depth, measured above the apron, is also recommended for Basin III. There are several reasons for this statement: First, the best operation for this stilling basin occurs at full conjugate tail water depth; secondly, if less than the conjugate depth is used, the surface velocities leaving the pool are high, the jump action is impaired, and there is a greater chance for scour downstream; and thirdly, if the baffle clocks erode with time, the additional tail water depth will serve to lengthen the interval between repairs. On the other hand, there is no particular advantage to using greater than the conjugate depth, as the action in the pool will show little or no improvement.

The margin of safety for Basin III varies from 15 to 18 percent depending on the value of the Froude number, as can be observed by the dotted line labelled, "Minimum Tail Water Depth--Basin III," on Figure 11. The points, from which the line was drawn, were obtained from the verification tests, Columns 10 and 14, Table 4. Again, this line does not represent complete sweepout, but the point at which the front of the jump moves away from the chute blocks and the basin no longer functions properly. In special cases it may be advisable to encroach on this wide margin of safety, however, it is not advisable as a general rule for the reasons stated above.

Length of Basin

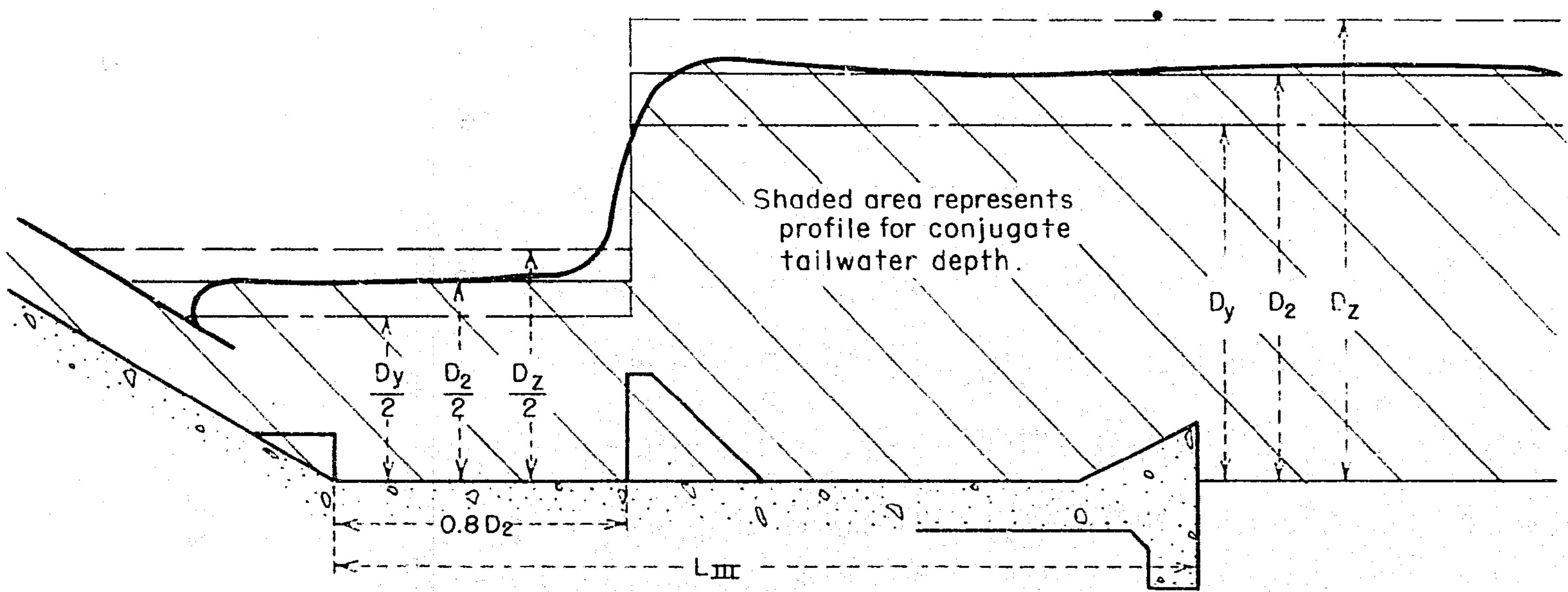
The length of Basin III, which is related to the Froude number, can be obtained by consulting the lower curve on Figure 12. The points, indicated by circles, were obtained from Columns 10 and 12, Table 4, and indicate the extent of the verification tests. The length is measured from the downstream side of the chute blocks to the downstream edge of the end sill, Figure 18. Although this curve was determined conservatively it will be found that the length of Basin III is less than one half the length needed for a basin without appurtenances. Basin III, as was true of Basin II, may be effective for values of the Froude number as low as 4.0, thus the length curve was terminated at this value.

Water Surface and Pressure Profiles

Approximate water surface profiles were obtained for Basin III during the verification tests. The front of the jump was so steep, Figure 20, that only two measurements were necessary--the tail water depth and the depth upstream from the baffle blocks. The tail water depth is shown in Column 6 and the upstream depth is recorded in Column 29 of Table 4. The ratio of the upstream depth to conjugate depth is shown in Column 30. As can be observed, the ratio is much the same regardless of the value of the Froude number. The average of the ratios in Column 30 is 0.52. Thus it will be assumed that the depth upstream from the baffle blocks is one half the tail water depth.

The profile represented by the cross hatched area, Figure 20, is for conjugate tail water depth. For a greater tail water depth D_z, the upstream depth would be $\frac{D_z}{2}$. For a tail water depth less than conjugate, D_y, the upstream depth would be approximately $\frac{D_y}{2}$. There appears to be no particular significance to the fact that this ratio is one half.

The information on Figure 20 applies only to Basin III, proportioned according to the rules set forth. It can be assumed that for all practical purposes the pressure and water surface profiles are the same. There will be a localized increase in pressure on the apron immediately upstream from each baffle block but this has been taken into account, more or less, by extending the diagram to full tail water depth beginning at the upstream face of the baffle blocks.



HYDRAULIC JUMP STUDIES

STILLING BASIN III

APPROXIMATE WATER SURFACE AND PRESSURE PROFILES

437

Recommendations

The following rules pertain to the design of the Type III basin, Figure 18.

1. The stilling basin operates best at full conjugate tail water depth, D_2. A reasonable factor of safety is involved at conjugate depth for all values of the Froude number (Figure 11), but it is recommended that the designer not make a general practice of encroaching on this margin of safety.

2. The length of pool, which is less than one half the length of the natural jump, can be obtained by consulting the curve for Basin III on Figure 12.

3. Stilling Basin III may be effective for values of the Froude number as low as 4.0 but this cannot be stated for certain (consult Section 4 for values under 4.5).

4. Height, width, and spacing of chute blocks should equal the average depth of flow entering the basin, or D_1. Width of blocks may be decreased, providing spacing is reduced a like amount. Should D_1 prove to be less than 8 inches, make the blocks 8 inches high.

5. The height of the baffle blocks varies with the Froude number and is given on Figure 19. The blocks may be cubes or they may be constructed as shown on Figure 18 so long as the upstream face is vertical and in one plane. This feature is important. The width and spacing of baffle blocks are also shown on Figure 18. In narrow structures where the specified width and spacing of blocks do not appear practical, block width and spacing may be reduced, providing they are reduced a like amount. A half space is recommended adjacent to the walls.

6. The upstream face of the baffle blocks should be set at a distance of $0.8D_2$ from the downstream face of the chute blocks (Figure 18). This dimension is also important.

7. The height of the solid sill at the end of the basin can be obtained from Figure 19. The slope is 2:1 upward in the direction of flow.

8. As a reminder, a condition of excess tail water depth does not justify shortening of the basin length.

9. It is recommended that a radius of reasonable length be used at the intersection of the chute and basin apron for slopes of 45 degrees or greater.

10. As a general rule the slope of the chute has little effect on the jump unless long flat slopes are involved. This phase will be considered in Section 5 on sloping aprons.

As the Type III basin is short coupled, the above rules should be followed closely for its proportioning. If the proportioning is to be varied from that recommended, a model study is advisable. Arbitrary limits for the Type III basin are set at 200 cfs per foot of basin width, or 100 feet of fall, until experience demonstrates otherwise.

Application of Results (Example 3)

Given the following computed values for a small overflow dam

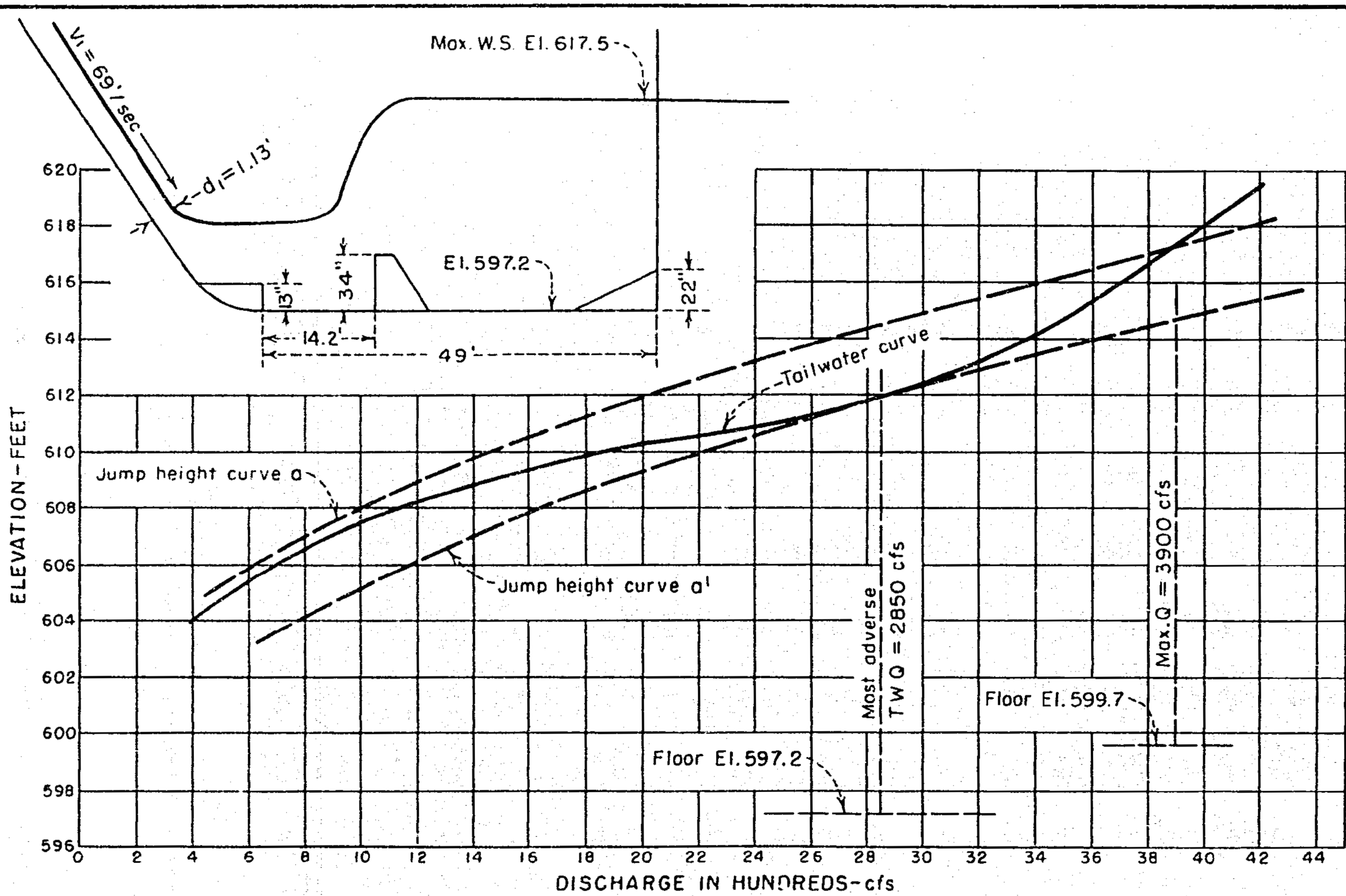
Q cfs	q cfs	V_1 ft/sec	D_1 ft
3900	78.0	69	1.130
3090	61.8	66	0.936
2022	40.45	63	0.642
662	13.25	51	0.260

and the tail water curve for the river, identified by the solid line on Figure 21: Proportion a Type III basin for the most adverse condition utilizing full conjugate tail water depth. The flow is symmetrical and the width of the basin is 50 feet. (The purpose of this example is to demonstrate the use of the jump height curve.)

The first step is to compute the jump height curve. As V_1 and D_1 are given, the Froude number is computed and tabulated in Column 2, Table 5.

Table 5

Q cfs (1)	F_1 (2)	$\frac{D_2}{D_1}$ (3)	D_1 ft (4)	D_2 ft (5)	Jump height elevation Curve A (6)	Jump height elevation Curve B (7)
3900	11.42	15.75	1.130	17.80	617.5	615.0
3090	12.02	16.60	0.936	15.54	615.2	612.7
2022	13.85	19.20	0.642	12.33	612.0	609.5
662	17.62	24.5	0.260	6.37	606.1	603.6



HYDRAULIC JUMP STUDIES

STILLING BASIN III - EXAMPLE 3

TAILWATER AND JUMP HEIGHT CURVE

FIGURE 21
REPORT HYD. 380

Entering Figure 11 with these values of the Froude number values of $\frac{TW}{D_1}$ are obtained for conjugate tail water depth from the solid line. These values are $\frac{D_2}{D_1}$ and are shown listed in Column 3. The conjugate tail water depths for the various discharges, Column 5, were obtained by multiplying the values in Column 3 by those in Column 4.

If it were assumed that the most adverse operating condition occurs at the maximum discharge of 3,900 cfs, the stilling basin apron would be located at elevation 617.5-17.8 or elevation 599.7.

With the apron at elevation 599.7 the tail water required for conjugate tail water depth for each discharge would follow the elevations listed in Column 6. Plotting Columns 1 and 6 on Figure 21 results in Curve A, which shows that the tail water depth is inadequate for all but the maximum discharge.

The tail water curve is unusual in that the most adverse tail water condition occurs at a discharge of approximately 2,850 cfs rather than maximum. As full conjugate tail water depth is desired for the most adverse tail water condition, it is necessary to shift the jump height curve downward to match the tail water curve for a discharge of 2,850 cfs (see Curve B, Figure 21). The coordinates for Curve B are given in Columns 1 and 7, Table 5. This will place the basin floor 2.5 feet lower, or elevation 597.2 feet, as shown in sketch on Figure 21.

Although the position of the basin floor was set for a discharge of 2,850 cfs, the remaining details are proportioned for the maximum discharge of 3,900 cfs.

Entering Figure 12 with a Froude number of 11.42,

$$\frac{L_{III}}{D_2} = 2.75, \text{ and the length of}$$

basin required $L_{III} = 2.75 \times 17.80 = \underline{48.95}$ feet.

(Notice that conjugate depth was used, not tail water depth.)

The height, width, and spacing of chute blocks are equal to D_1 or 1.130 feet (use <u>13</u> or <u>14</u> inches).

The height of the baffle blocks for a Froude number of 11.42 (Figure 19) is $2.5D_1$.

$h_3 = 2.5 \times 1.130 = 2.825$ feet (use <u>34</u> inches).

The width and spacing of the baffle blocks are preferably three-fourths of the height or

$0.75 \times 34 = \underline{25.5}$ inches.

From Figure 18, the upstream face of the baffle blocks should be $0.8D_2$ from the downstream face of the chute blocks, or

$0.8 \times 17.80 = \underline{14.24}$ feet.

The height of the solid end sill, Figure 19, is $1.60D_1$, or

$h_4 = 1.60 \times 1.130 = 1.81$ feet (use $\underline{22}$ inches).

The final dimensions of the basin are shown on Figure 21.

SECTION 4

WAVE SUPPRESSORS FOR CANAL STRUCTURES, OUTLET WORKS, AND DIVERSION DAMS (BASIN IV)

Introduction

This section will be devoted to discussing the characteristics of the hydraulic jump in stilling basins for values of the Froude number between 2.5 and 4.5. The jump is not completely developed in this range and the former methods of design do not apply. This range is encountered principally in the design of canal structures, but occasionally diversion dams and outlet works fall in this category. Three devices, developed from laboratory tests, are presented for combating wave action which is so persistent for values of the Froude number between 2.5 and 4.5.

Jump Characteristics

For values of the Froude number between 2.5 and 4.5, the entering jet oscillates intermittently from bottom to surface, as indicated in Figure 9B, with no particular period. Each oscillation generates a wave which is very difficult to dampen. In narrow structures, such as canals, these waves persist in varying degrees for miles. As they encounter obstructions in the canal, such as bridge piers, turnouts, checks and transitions, reflected waves may be generated which tend to dampen the original wave, or the period could be such that the reflected wave actually accentuates the original wave. Waves are destructive to earth-lined canals and riprap and produce undesirable surges at gaging stations and in measuring devices. Incidentally, structures falling in this range are the ones that require the most maintenance. In fact, it has been necessary to replace or rebuild a number of existing structures in this category.

On wide structures, such as diversion dams, wave action is not as pronounced as the waves can travel laterally as well as parallel to the direction of flow. The combined action produces a dampening effect but a choppy water surface. The resulting waves are usually dissipated in a short distance.

Where outlet works, operating under heads of 50 feet or greater, fall within the range of Froude number between 2.5 and 4.5 a model study of the stilling basin is imperative. A model study is the only means of being assured that a design of this nature will be satisfactory.

Wave Suppressors

Years of experience with models and field structures operating at Froude numbers from 2.5 to 4.5, yield only a few remedies for effectively reducing the amplitude of waves. The first is applicable for stilling pools preceded by an overfall or chute structure, a second is for small canal drops, and a third is for a gate structure discharging onto a horizontal floor. These three types will be discussed here.

Overfall or Chute Structure

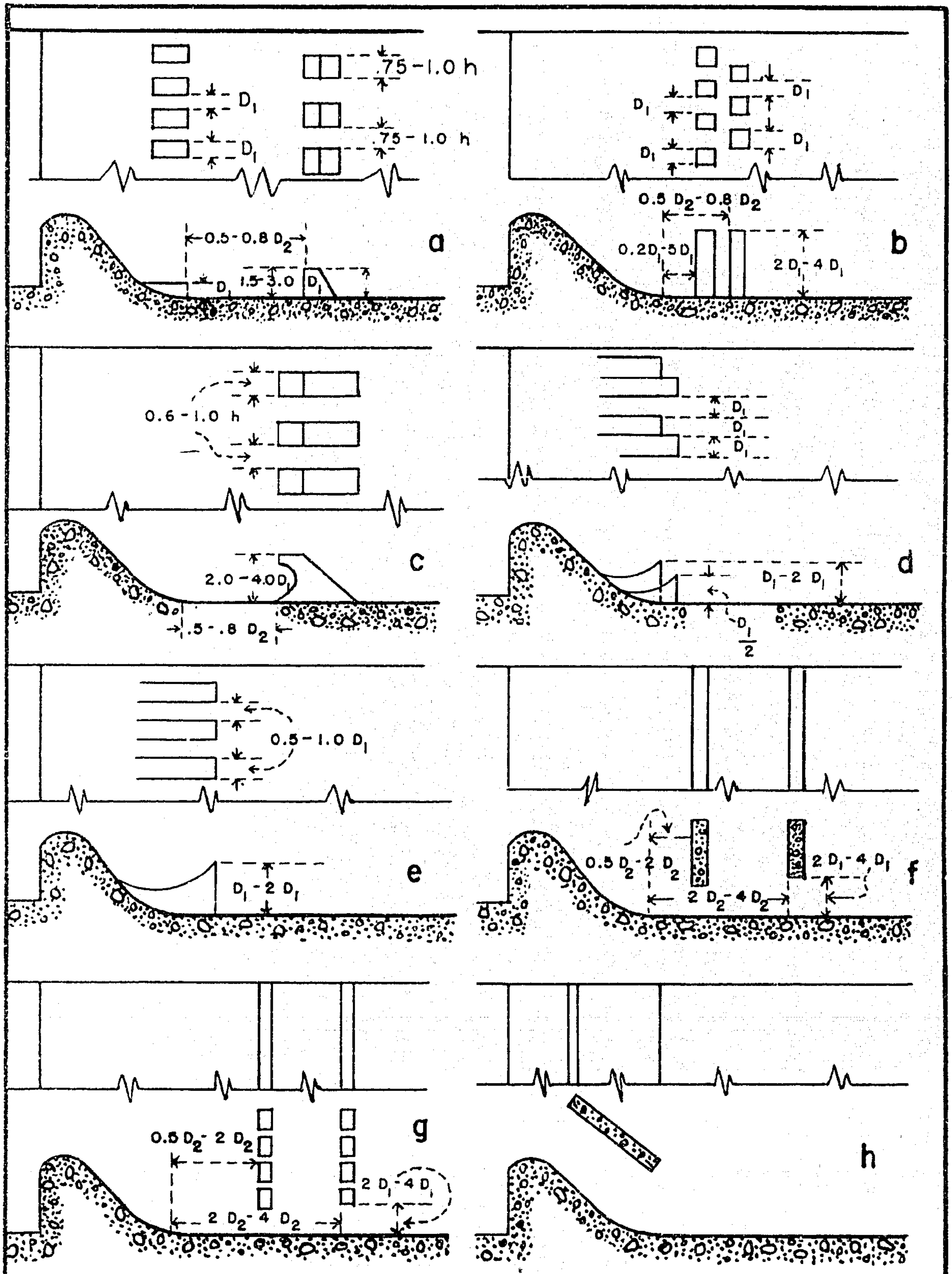
The best way to combat a wave problem is to eliminate the wave at its source; in other words, concentrate on altering the condition which generates the wave. In the case of the stilling basin preceded by an overfall or chute, two schemes were apparent for eliminating waves at their source. The first was to break up or eliminate the roller, shown on Figure 9B, by opposing it with directional jets. The second was to bolster or intensify the roller by directional jets in anticipation that it would stabilize.

The first method was unsuccessful in that the number and size of appurtenances necessary to break up the roller occupied so much volume that these in themselves posed an obstruction to the flow. This testing consisted of systematically placing numerous shaped baffle blocks and guide blocks in the stilling basin in combination with various types of spreader teeth and deflectors in the chute. The program involved dozens of tests, and not until all conceivable ideas were tried was this approach abandoned. A few of the basic ideas tested are shown on Figure 22.

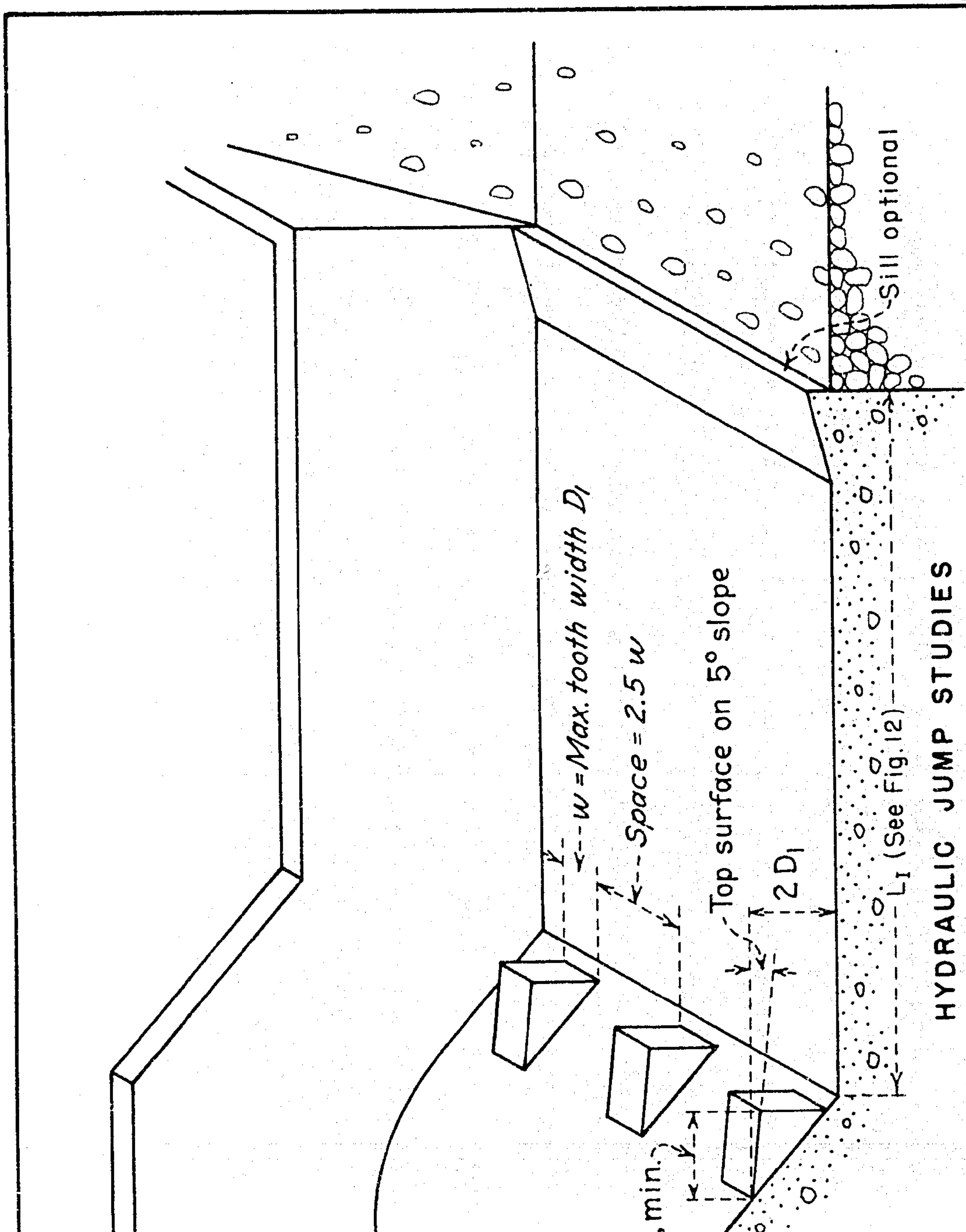
The second approach, that of attempting to intensify the roller, yielded better results. In this case, large blocks were placed well up on the chute while nothing was installed in the stilling basin proper. The object in this case was to direct a jet at the base of the roller in an attempt to strengthen it. After a number of trials, the roller was actually intensified which did improve the stability of the jump. Sketches d and e on Figure 22 indicate just two schemes that showed promise, although many variations were tried. After finding an arrangement that was effective, it was then attempted to make this as simple a matter of construction as possible. The dimensions and proportions of the deflector blocks as finally adopted are shown on Figure 23.

The object in the latter scheme was to place as few appurtenances as possible in the path of the flow, as volume occupied by appurtenances merely creates a backwater problem, thus requiring higher training walls. The number of deflector blocks shown on Figure 23 is a minimum requirement to accomplish the purpose set forth. The width of the blocks is shown equal to D_1 and this is the maximum width recommended.

FIGURE 22



HYDRAULIC JUMP STUDIES
RECORD OF APPURTENANCES
BASIN IV.



HYDRAULIC JUMP STUDIES

STILLING BASIN IV

FOR F_1 2.5 - 4.5

From a hydraulic standpoint it is desirable that the blocks be constructed narrower than indicated, preferably $0.75D_1$. The ratio of block width to spacing is 1:2.5. The blocks are rather high and, in some cases, extremely long but this is essential as the jet must play at the base of the roller to be effective. The extreme top of the blocks are $2D_1$ above the floor of the stilling basin. To accommodate the various slopes of chutes and ogee shapes encountered, a rule has been established that the horizontal length of the blocks should be at least $2D_1$. The upper surface of each block is sloped at 5 degrees in a downstream direction as it was found that this feature resulted in better operation, especially at the lower discharges.

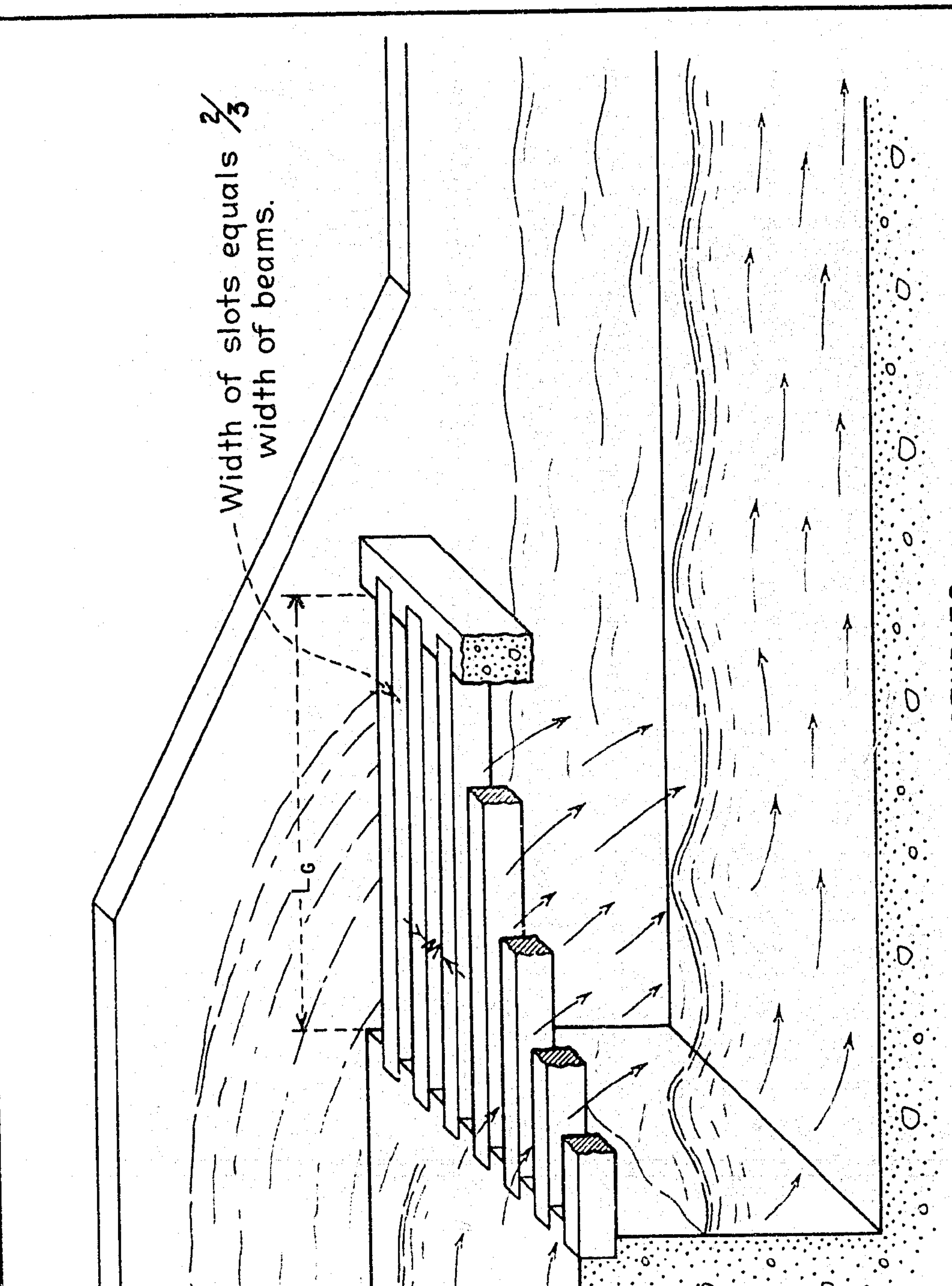
A tail water depth 5 to 10 percent greater than the conjugate depth is recommended for the above basin. The jump is very sensitive to tail water depth at these low values of the Froude number; a slight deficiency in tail water depth may allow the jump to sweep completely out of the basin. Many of the difficulties that have been encountered in small field structures in the past can be attributed to this aspect of the jump for low numbers. In addition, the jump performs much better and wave action is diminished if the tail water depth is increased to approximately $1.1D_2$.

The length of this basin, which is relatively short, can be obtained from the upper curve on Figure 12. No additional blocks or appurtenances are needed in the basin, as these will prove a greater detriment than aid. The addition of a small triangular sill placed at the end of the apron for scour control is optional. If designed for the maximum discharge, this stilling basin will perform satisfactorily for all flows. This design is applicable for rectangular cross sections only.

Small Canal Drop

A second scheme for reducing wave action at the source, for values of the Froude number between 2.5 and 4.5, is applicable to small drops in canals. The Froude number in this case would be computed the same as though the drop were an overflow crest. A series of steel rails, channel irons or timbers in the form of a grizzly are installed at the drop, as shown on Figure 24. The over falling jet is separated into a number of long, thin sheets of water which fall nearly vertical into the canal below. Dissipation is excellent and the usual wave problem is avoided. If the rails are tilted downward at an angle of 3 degrees or more the grid is self cleaning.

Two spacing arrangements were tested in the laboratory: In the first, the spacing was equal to the width of the beams, and in the second the spacing was two thirds of the beam width. The latter was



HYDRAULIC JUMP STUDIES
DROP ENERGY DISSIPATOR (TYPE IV)
FOR F 2.5–4.5

437

the more effective. In the first, the length of grizzly required was about 2.9 times the depth of flow in the canal upstream, while in the second, it was necessary to increase the length to approximately 3.6y. The following expression can be used for computing the length of grizzly.

$$L_G = \frac{Q}{CWN\sqrt{2gy}} \tag{4}$$

where Q is total discharge, C is an experimental coefficient, W is the width of spacing in feet, N is the number of spaces, g is the acceleration of gravity and y is the depth of flow in the canal upstream (see Figure 24). The value of C for the two arrangements tested was 0.245.

In this case the grizzly makes it possible to avoid the hydraulic jump. Should it be desired to maintain a certain level in the canal upstream, the grid may be tilted upward to act as a check, however, this arrangement may pose a cleaning problem.

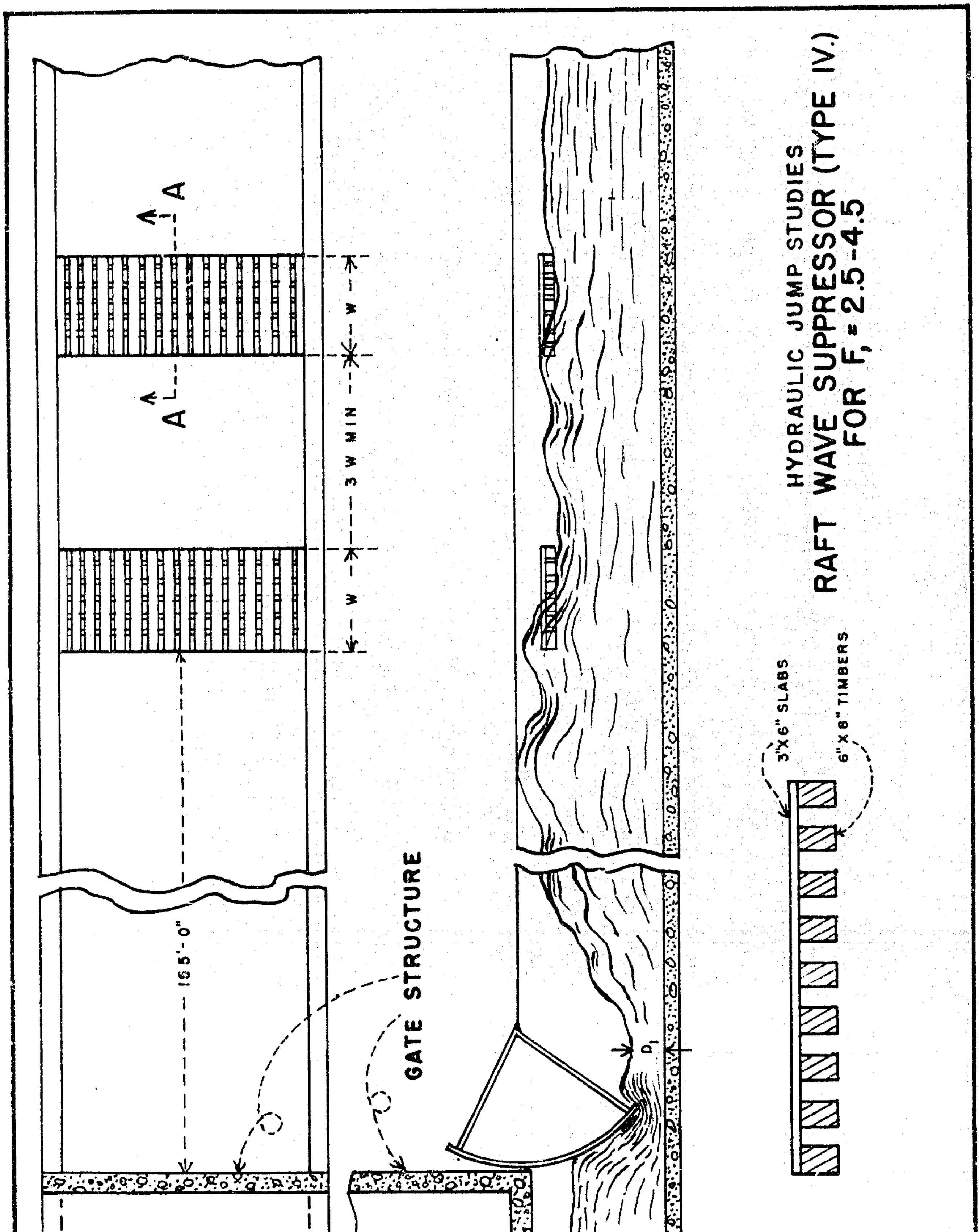
Gate Controlled Structures Discharging Horizontally into Stilling Basin

A glance at Figures 23 and 24 will indicate that the preceding treatments can in no way apply to a gate controlled structure discharging horizontally into a stilling basin. The gate controlled structure, Figure 25, operating in the range of Froude numbers from 2.5 to 4.5, poses a separate problem. In this case there appears no means of eliminating waves at their source. Appurtenances in the stilling basin merely produced severe splashing and created a backwater effect, resulting in submerged flow at the gate for the larger flows. Submerged flow would reduce the effective head on the structure and in turn, the capacity.

The remedy in this case may not be the most desirable but it was the only scheme found satisfactory for coping with existing waves. The method is the result of a model study on a specific field structure. The general arrangement of the structure is shown in Figure 25. The Froude number varied from 3 to 7, depending on the head behind the gate and the gate opening. Velocities in the canal ranged from 5 to 10 feet per second. Waves generated reached a height of as much as 1.5 feet, measured from trough to crest.

The most effective solution consisted of placing two stationary rafts 20 feet long by 8 feet wide, made from 6- by 8-inch timbers, in the canal downstream from the stilling basin (Figure 25). A space was left between each timber and lighter cross pieces were placed on the rafts parallel to the flow, giving the appearance of many rectangular holes (Figure 26).

FIGURE 25



HYDRAULIC JUMP STUDIES
RAFT WAVE SUPPRESSOR (TYPE IV.)
FOR $F_1 = 2.5-4.5$

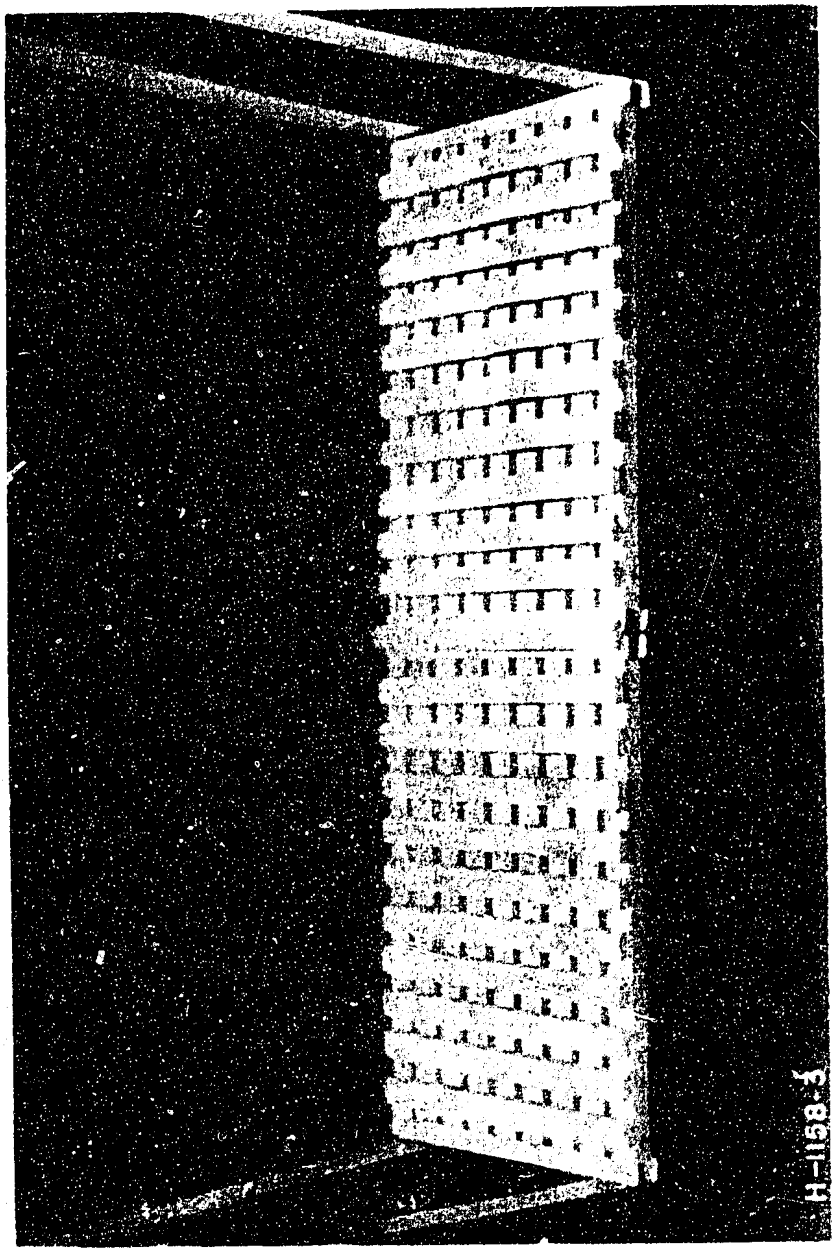
During the course of the experiments a number of schemes were tested such as rafts having only longitudinal slots, steel plates with punched holes anchored at the surface, and vertical curtain walls (Sketches f and g, Figure 22) with and without holes. None of these approached the performance of the raft shown on Figure 26. Several essential requirements were apparent, but there may be others: (1) that the rafts be punctured with a series of holes; (2) that there must be some depth to these holes; (3) that at least two rafts are necessary; and (4) that the rafts must be held stationary. It was found that the ratio of hole area to total area of raft could be from 1:6 to 1:8. The raft shown in Figure 26 is 20 feet long by 8 feet wide. The width is a minimum dimension. The rafts must have sufficient thickness so that the troughs of the waves do not break free from the underside. The top surfaces of the rafts are set at the mean water surface in a fixed position so that they cannot move. Spacing between rafts should be at least three times the raft dimension, measured parallel to the flow. The first raft decreases the wave height at least 50 percent, while the second raft effects a further reduction. Surges over the raft dissipate themselves by flow downward through the holes, while surges from under the raft flow upward through the holes. The effect is amazing, especially when the difficulty of the problem is considered. For this specific case the waves were reduced from 18 inches to 3 inches in height.

In the majority of cases, wave action is only serious at the maximum discharge when freeboard is endangered, so the rafts can be a permanent installation. For this application the rafts should perform equally well in trapezoidal as well as rectangular channels. The rafts can be made adjustable for rectangular channels should it be desired to suppress the waves at partial flows. In the case of trapezoidal channels, a second set of rafts may be placed under the first set for partial flows. Collection of trash at the racks could actually improve their performance.

The same raft arrangement is also applicable for suppressing waves with a regular period such as wind waves, waves produced by the starting and stopping of pumps, etc. In this case, the position of the downstream raft is important. The second raft should be positioned at some fraction of the wave length downstream. Placing it at a full wave length could cause both rafts to be ineffective. Thus, for narrow canals it may be advisable to make the second raft portable.

Conclusions

The most difficult problems encountered in stilling basin design occur for values of the Froude number between 2.5 and 4.5. Waves are produced by an unstable condition of the jump. Once the waves are suppressed there is no particular dissipation problem. Three schemes for wave suppression have been discussed.



PERFORATED RAFT WAVE SUPPRESSOR
20 feet long by 8 feet wide

The first arrangement, involving deflected jets which intensify the roller in the jump, is applicable to rectangular channels only. Its use is limited to small overflow sections and small canal drops.

The second device, which employs a grizzly or grating, is merely a means of avoiding the hydraulic jump. Its use is limited to small canal drops. This scheme is shown applicable for rectangular channels but with modifications it may be effective in other sections.

The third arrangement is strictly a device to suppress wave action. It consists of two fixed rafts, which perform best in a rectangular channel, but are also quite effective in trapezoidal sections. It is important that these rafts be fixed in position so they cannot move, otherwise additional waves may be produced.

SECTION 5

STILLING BASIN WITH SLOPING APRON
(BASIN V)

Introduction

Much has been argued, pro and con, concerning the advantages and disadvantages of stilling basins with sloping aprons. The discussion had never been settled satisfactorily, simply because there was not sufficient supporting data available to draw conclusions. It was decided in this study, therefore, to investigate the sloping apron type of basin sufficiently to answer the various questions and also to provide more definite design data.

Four flumes, A, B, D, and F, Figures 1, 2, and 3, were used to obtain the range of Froude numbers desired. In the case of Flumes A, B, and D, floors were installed to the slope desired, while Flume F could be tilted to obtain slopes from 0 to 12 degrees. The slope, as referred to here, is the tangent of the angle between the floor and with the horizontal, and will be designated as "ϕ." Five principal measurements were made in these tests, namely: the discharge, the average depth of flow entering the jump, the length of the jump, the tail water depth, and the slope of the apron. The tail water was adjusted so that the front of the jump formed either at the intersection of the spillway face and the sloping apron or, in the case of the tilting flume, at a selected point.

The jump that occurs on the sloping apron takes many forms depending on the slope and arrangement of the apron, the value of the Froude number, and the concentration of flow or discharge per foot of width; but from all appearances, the dissipation is as effective as occurs in the true hydraulic jump on a horizontal apron.

Previous Experimental Work

Previous experimental work on the sloping apron has been carried on by several experimenters. In 1934, the late C. L. Yarnell of the United States Department of Agriculture supervised a series of experiments on the hydraulic jump on sloping aprons. Carl Kindsvater 5/ later compiled these data and presented a rather complete picture, both experimentally and theoretically, for one slope, namely: 1:6 ($\tan \phi = 0.167$). G. H. Hickox 5/ presented data for a series of experiments on a slope of 1:3 ($\tan \phi = 0.333$). Bakhmeteff 1/ and Matzke 6/ performed experiments on slopes of 0 to 0.07 made in a flume 6 inches wide.

From an academic standpoint, the jump may occur in several ways on a sloping apron, as outlined by Kindsvater, presenting separate and distinct problems, Figure 27. Case A is a jump on a horizontal apron. In Case B, the toe of the jump forms on the slope, while the end occurs over the horizontal apron. In Case C, the toe of the jump is on the slope, and the end is at the junction of the slope and the horizontal apron; while in Case D, the entire jump forms on the slope. With so many possibilities, it is easily understood why experimental data have been lacking on the sloping apron. Messrs. Yarnell, Kindsvater, Bakhmeteff, and Matzke limited their experiments to Case D. B. D. Rindlaub 7/ of the University of California concentrated on the solution of Case B, but his experimental results are complete for only one slope, that of 12.33° ($\tan \phi = 0.217$).

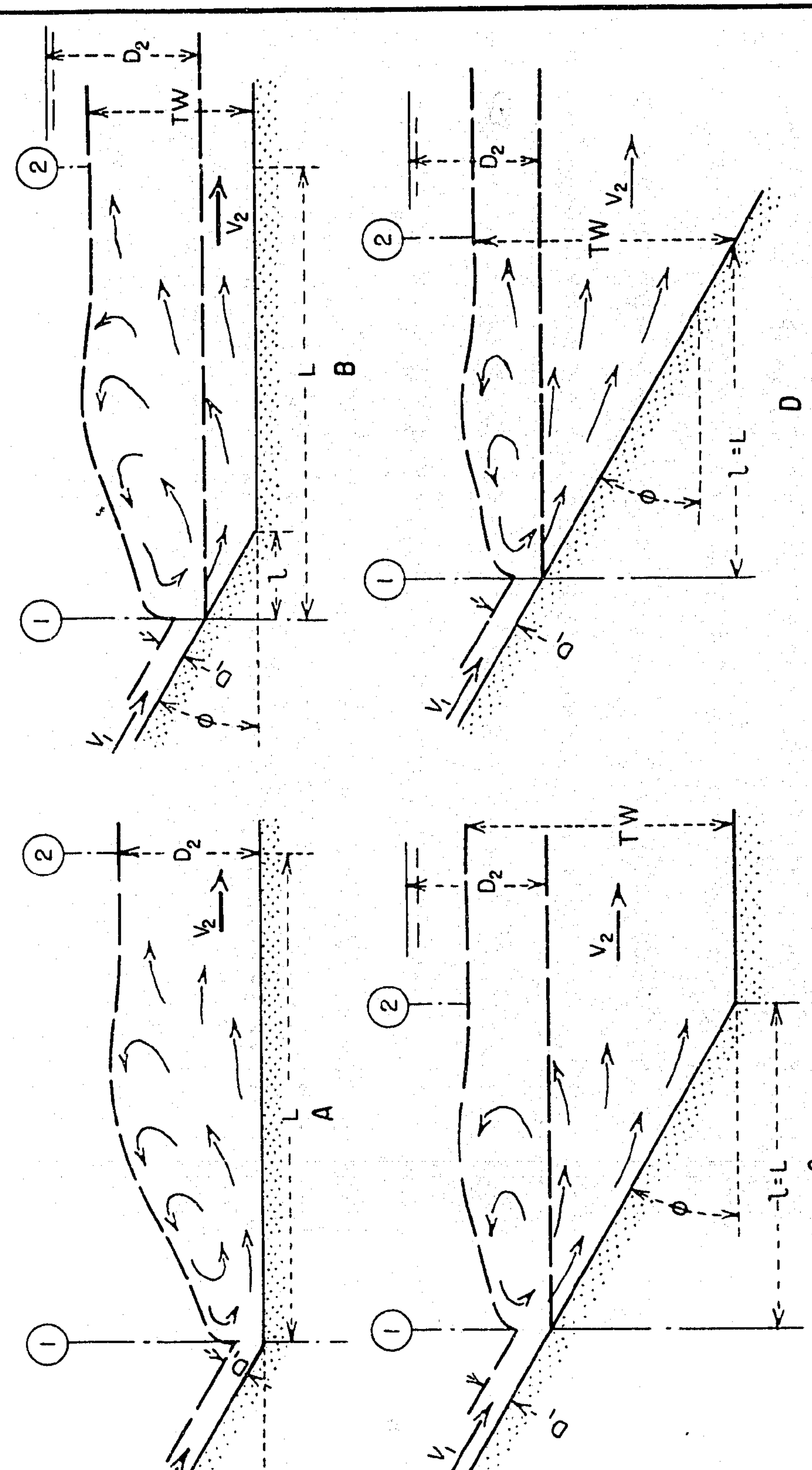
Present Considerations

From a practical standpoint, the scope of the present test program need not be so broad as outlined in Figure 27. For example, the action in Cases C and D is for all practical purposes the same, if it is assumed that a horizontal floor begins at the end of the jump for Case D. The first of the current experiments to be described in this chapter involves Case D. However, sufficient tests were made on Case C to verify the above statement that Cases C and D can be considered as one. The second set of tests will deal with Case B. Case B is virtually Case A operating with excessive tail water depth. As the tail water depth is further increased, Case B approaches Case C. The results of Case A have already been discussed in the preceding chapters, and Cases D and B will be considered here in order.

Experimental Results (Case D)

Data obtained from the four flumes used in the sloping apron tests (Case D experiments) are tabulated on Table 6. The headings are very much the same as those in previous tables, but will need some explanation. Column 2 lists the tangents of the angles of the slopes tested. The depth of flow entering the jump, D_1, Column 8, was measured at the beginning of the jump in each case, corresponding to Section 1, Figure 27D. It represents the average of a generous number of point gage measurements. The velocity at this same point, V_1, Column 7, was computed by dividing the unit discharge, q, (Column 5) by D_1. The length of jump, Column 11, was measured in the flume, bearing in mind that the object of the test was to obtain practical data for stilling basin design. The end of the jump was chosen as the point where the high velocity jet began to lift from the floor, or a point on the level tail water surface immediately downstream from the surface roller, whichever occurred farthest downstream. The length of the jump, as tabulated in Column 11, is the horizontal distance from Sections 1 to 2, Figure 27D. The tail

FIGURE 27



HYDRAULIC JUMP STUDIES
STILLING BASIN V
SLOPING APRONS

Table 6

STILLING BASINS WITH SLOPING APRON
Case D, Basin V

Test flume (1)	Slope of apron tan ∅ (2)	Q Total discharge cfs (3)	W Width of basin ft (4)	q Discharge per foot of basin cfs (5)	TW Tail-water depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	$\frac{TW}{D_1}$ (9)	$F_1 = \frac{V_1}{gD_1}$ (10)	L Length of jump ft (11)	$\frac{L}{TW}$ (12)	$\frac{D_2}{D_1}$ (13)	D_2 Conjugate TW depth ft (14)	$\frac{TW}{D_2}$ (15)	$\frac{L}{D_2}$ (16)	K Shape factor (17)
A	0.067	2.000	4.830	0.410	0.520	7.35	0.052	10.00	6.09	2.60	5.00	8.20	0.426	1.22	6.11	2.50
		2.250		0.461	0.560	8.09	0.057	9.82	5.97	2.90	5.18	7.90	0.450	1.24	6.45	2.50
		2.500		0.512	0.589	8.26	0.062	9.50	5.85	3.10	5.26	7.85	0.486	1.21	6.38	2.40
		2.750		0.564	0.629	8.42	0.067	9.39	5.73	3.30	5.25	7.70	0.516	1.22	6.40	2.45
		3.000		0.615	0.660	8.54	0.072	9.17	5.61	3.40	5.15	7.55	0.544	1.21	6.25	2.45
		3.250		0.666	0.694	8.65	0.077	9.01	5.49	3.45	4.97	7.40	0.570	1.22	6.05	2.50
		3.500		0.717	0.744	8.74	0.082	9.07	5.38	3.60	4.84	7.20	0.590	1.26	6.10	2.80
		1.500	4.350	0.345	0.474	7.67	0.045	10.53	6.37	2.40	5.06	8.60	0.387	1.22	6.20	2.50
		2.500		0.575	0.642	8.46	0.068	9.44	5.72	3.20	4.98	7.70	0.523	1.23	6.12	2.50
		3.500		0.805	0.792	8.85	0.091	8.70	5.17	4.00	5.05	6.90	0.628	1.26	6.37	2.75
	0.096	2.000	4.830	0.414	0.560	7.96	0.052	10.77	6.15	2.50	4.47	8.20	0.426	1.31	5.87	2.04
		2.500		0.518	0.652	7.97	0.065	10.03	5.51	3.60	5.52	7.45	0.484	1.35	7.44	2.28
		3.000		0.621	0.745	8.26	0.075	9.93	5.33	3.20	4.30	7.10	0.532	1.40	6.01	2.40
		3.500		0.725	0.835	8.53	0.085	9.82	5.15	3.60	4.31	6.90	0.586	1.42	6.15	2.50
		4.000		0.828	0.940	8.63	0.096	9.79	4.90	4.00	4.26	6.50	0.624	1.51	6.41	2.75
	0.135	2.000	4.810	0.416	0.620	6.93	0.060	10.33	4.99	2.50	4.06	6.60	0.396	1.56	6.32	2.15
		2.500		0.520	0.710	7.54	0.069	10.29	5.06	3.00	4.23	6.75	0.466	1.52	6.44	2.07
		3.000		0.624	0.895	7.80	0.080	10.06	4.86	3.20	3.97	6.40	0.512	1.57	6.25	2.15
		3.500		0.728	0.905	8.09	0.090	10.06	4.75	3.60	3.98	6.30	0.567	1.60	6.34	2.22
		4.000		0.832	0.985	8.58	0.097	10.15	4.85	3.90	3.96	6.40	0.621	1.59	6.28	2.19
	0.152	1.500	4.350	0.345	0.540	6.27	0.055	9.82	4.71	2.10	3.89	6.20	0.341	1.58	6.16	1.94
		2.000		0.460	0.663	6.76	0.068	9.75	4.57	2.55	3.85	6.10	0.415	1.60	6.15	2.00
		2.500		0.575	0.790	7.57	0.076	10.39	4.84	3.10	3.92	6.45	0.490	1.61	6.33	2.00
		3.000		0.690	0.900	7.67	0.090	10.00	4.50	3.40	3.78	6.00	0.540	1.67	6.30	2.10
	0.185	1.500	4.350	0.345	0.600	6.05	0.057	10.53	4.47	2.15	3.58	5.90	0.336	1.78	6.40	1.83
		2.000		0.460	0.720	6.57	0.070	10.29	4.38	2.60	3.61	5.80	0.406	1.77	6.40	1.83
		2.500		0.575	0.840	7.01	0.082	10.24	4.31	3.00	3.57	5.70	0.467	1.80	6.42	1.85
	0.218	1.750	4.350	0.402	0.700	6.00	0.067	10.45	4.08	2.30	3.29	5.45	0.365	1.92	6.30	1.70
		2.250		0.517	0.862	6.63	0.078	11.05	4.19	2.70	3.13	5.55	0.433	1.99	6.24	1.73
	0.280	1.250	4.350	0.287	0.620	4.70	0.061	10.16	3.35	1.60	2.58	4.25	0.259	2.39	6.18	1.44
		1.500		0.345	0.675	4.79	0.072	9.38	3.15	1.80	2.67	4.05	0.292	2.31	6.17	1.44
		1.750		0.402	0.752	4.79	0.084	8.95	2.91	1.95	2.59	3.70	0.311	2.42	6.27	1.46
B	0.052	1.000	2.000	0.500	0.855	17.24	0.029	29.48	17.85	4.10	4.79	24.75	0.718	1.19	5.71	2.94
		1.500		0.750	1.010	16.30	0.046	21.96	13.40	5.10	5.05	18.45	0.849	1.19	6.01	2.80
		2.000		1.000	1.160	16.39	0.061	19.02	11.69	6.10	5.26	15.10	0.982	1.18	6.21	2.78
		2.500		1.250	1.300	17.12	0.073	17.81	11.16	6.50	5.00	15.35	1.121	1.16	5.80	2.45
		3.000		1.500	1.426	17.05	0.088	16.20	10.13	7.50	5.26	13.85	1.218	1.17	6.15	2.70
		3.500		1.750	1.570	17.16	0.102	15.39	9.46	8.00	5.10	12.95	1.321	1.19	6.06	2.90
		4.000		2.000	1.693	17.09	0.117	14.47	8.80	8.90	5.26	12.10	1.416	1.20	6.28	2.92
		4.500		2.250	1.813	17.05	0.132	13.73	8.27	9.60	5.29	11.30	1.492	1.22	6.44	3.10
		5.000		2.500	1.920	17.01	0.147	13.06	7.82	9.60	5.10	10.60	1.558	1.23	6.29	3.20
		5.500		2.750	2.020	17.08	0.161	12.55	7.50	10.50	5.20	10.20	1.642	1.23	6.40	3.20
		6.000		3.000	2.110	16.95	0.177	11.92	7.10	11.00	5.21	9.65	1.708	1.24	6.44	3.30
	0.102	1.000		0.500	0.970	15.63	0.032	30.31	15.40	4.20	4.33	21.25	0.680	1.42	6.17	2.51
		1.500		0.750	1.180	15.63	0.048	24.58	12.57	5.20	4.41	17.30	0.830	1.42	6.27	2.50
		2.000		1.000	1.354	15.87	0.063	21.49	11.14	6.10	4.51	15.35	0.967	1.40	6.31	2.44
		2.500		1.250	1.543	16.23	0.077	20.04	10.30	6.80	4.40	14.15	1.088	1.42	6.24	2.50
		3.000		1.500	1.724	16.48	0.091	18.95	9.63	7.60	4.41	13.20	1.200	1.44	6.34	2.56
		3.000		1.500	1.720	16.30	0.092	18.70	9.47	7.50	4.36	12.95	1.191	1.44	6.30	2.58
		3.500		1.750	1.890	16.36	0.107	17.66	8.81	8.20	4.34	12.10	1.293	1.46	6.34	2.75
		4.000		2.000	2.040	16.53	0.121	16.86	8.37	8.80	4.31	11.40	1.379	1.48	6.38	2.72
		4.500		2.250	2.152	16.42	0.137	15.71	7.82	9.40	4.37	10.60	1.452	1.48	6.47	2.70
		5.000		2.500	2.300	16.45	0.152	15.13	7.44	10.00	4.34	10.10	1.536	1.50	6.51	2.75
		5.500		2.750	2.450	16.18	0.170	14.41	6.91	10.60	4.33	9.35	1.590	1.54	6.67	2.85

Table 6--Continued

STILLING BASINS WITH SLOPING APRON
Case D, Basin V

Test flume (1)	Slope of apron tan ø (2)	Q Total discharge cfs (3)	W Width of basin ft (4)	q Discharge per foot of basin cfs (5)	TW Tail-water depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	$\frac{TW}{D_1}$ (9)	$F_1 = \frac{V_1}{gD_1}$ (10)	L Length of jump ft (11)	$\frac{L}{TW}$ (12)	$\frac{D_2}{D_1}$ (13)	D_2 Conjugate TW depth ft (14)	$\frac{TW}{D_2}$ (15)	$\frac{L}{D_2}$ (16)	K Shape factor (17)

Test flume (1)	Slope of apron tan ø (2)	Q Total discharge cfs (3)	W Width of basin ft (4)	q Discharge per foot of basin cfs (5)	TW Tail-water depth ft (6)	V_1 Velocity entering jump ft/sec (7)	D_1 Depth entering jump ft (8)	$\frac{TW}{D_1}$ (9)	$F_1 = \frac{V_1}{gD_1}$ (10)	L Length of jump ft (11)	$\frac{L}{TW}$ (12)	$\frac{D_2}{D_1}$ (13)	D_2 Conjugate TW depth ft (14)	$\frac{TW}{D_2}$ (15)	$\frac{L}{D_2}$ (16)	K Shape factor (17)
B	0.164	2.000	2.000	1.000	1.537	15.38	0.065	23.65	10.64	6.10	3.97	14.65	0.952	1.61	6.41	1.88
		2.500		1.250	1.737	14.88	0.084	20.68	9.05	6.90	3.97	12.40	1.042	1.67	6.62	1.95
		3.000		1.500	1.940	14.71	0.102	19.02	8.11	7.50	3.86	11.05	1.128	1.72	6.64	2.02
		3.500		1.750	2.120	14.83	0.118	17.97	7.61	8.20	3.87	10.30	1.215	1.74	6.75	2.03
		4.000		2.000	2.270	15.04	0.133	17.07	7.27	8.70	3.83	9.85	1.310	1.73	6.64	2.01
		4.500		2.250	2.420	14.90	0.151	16.03	6.75	9.20	3.80	9.10	1.374	1.76	6.70	2.08
		5.000		2.500	2.590	14.88	0.168	15.42	6.39	9.70	3.74	8.65	1.454	1.78	6.67	2.08
		5.500		2.750	2.750	14.86	0.185	14.86	6.09	10.20	3.71	8.20	1.517	1.81	6.73	2.10
	0.213	2.000		1.000	1.750	13.33	0.075	23.33	8.60	6.00	3.43	11.75	0.881	1.99	6.81	1.71
		2.500		1.250	2.000	13.59	0.092	21.74	7.89	6.60	3.30	10.70	0.984	2.03	6.71	1.76
		3.000		1.500	2.150	13.51	0.111	19.37	7.15	7.30	3.40	9.70	1.077	2.00	6.78	1.73
		3.500		1.750	2.370	13.57	0.129	18.37	6.65	8.00	3.38	9.00	1.161	2.04	6.89	1.76
		4.000		2.000	2.600	13.51	0.148	17.57	6.19	8.30	3.19	8.35	1.236	2.10	6.71	1.79
		4.500		2.250	2.720	13.55	0.166	16.39	5.86	9.10	3.34	7.85	1.303	2.09	6.98	1.78
		5.000		2.500	2.890	13.59	0.184	15.71	5.58	9.60	3.32	7.50	1.380	2.09	6.96	1.79
		5.500		2.750	3.100	13.55	0.203	15.27	5.30	10.00	3.22	7.10	1.441	2.15	6.94	1.81
	0.263	2.000		1.000	1.900	11.63	0.086	22.09	6.98	5.60	2.95	9.45	0.813	2.34	6.89	1.55
		3.000		1.500	2.330	11.63	0.129	18.06	5.70	6.90	2.96	7.65	0.987	2.36	6.99	1.56
		4.000		2.000	2.820	12.35	0.162	17.41	5.40	8.10	2.87	7.25	1.174	2.40	6.90	1.57
		5.000		2.500	3.270	12.38	0.202	16.19	4.85	9.20	2.81	6.45	1.303	2.51	7.06	1.59
		6.000		3.000	3.602	12.35	0.243	14.82	4.41	10.00	2.77	5.80	1.409	2.56	7.09	1.59
D	0.100	4.000	3.970	1.007	1.530	18.64	0.054	28.33	14.14	6.60	4.31	19.50	1.053	1.45	6.27	2.65
		6.000		1.511	1.888	19.12	0.079	23.90	11.99	8.20	4.34	16.50	1.303	1.45	6.29	2.65
		8.000		2.015	2.200	19.75	0.102	21.57	10.90	9.70	4.41	14.95	1.525	1.44	6.36	2.65
		10.000		2.518	2.630	20.14	0.125	21.04	10.04	11.50	4.37	13.75	1.719	1.53	6.69	2.85
		2.250		0.567	1.200	18.90	0.030	40.00	19.23	4.75	3.96	26.70	0.801	1.50	5.93	2.75
		4.500		1.134	1.710	18.29	0.062	27.58	12.94	7.80	4.56	17.90	1.109	1.54	7.03	2.90
		6.750		1.700	2.100	19.54	0.087	24.14	11.67	9.10	4.33	16.10	1.400	1.50	6.50	2.78
F	0.174	1.980	1.000	1.980	1.452	7.17	0.276	5.26	2.41	4.30	2.96	3.00	0.828	1.75	5.19	1.88
		2.800		2.800	1.663	7.69	0.364	4.57	2.24	5.00	3.01	2.80	1.018	1.63	4.91	1.76
	0.200	2.960		2.980	2.035	8.32	0.358	5.68	2.45	5.80	2.85	3.05	1.092	1.86	5.31	1.72
		3.850		3.850	2.460	8.48	0.454	5.42	2.22	6.70	2.72	2.75	1.248	1.97	5.37	1.81
	0.150	3.850		3.850	2.095	7.97	0.483	4.33	2.02	5.90	2.82	2.45	1.183	1.77	4.99	2.10
		1.780		1.780	1.260	6.93	0.257	4.90	2.41	4.00	3.17	3.00	0.771	1.63	5.19	2.00
	0.100	1.940		1.940	1.180	6.40	0.303	3.89	2.05	3.70	3.14	2.50	0.757	1.56	4.89	2.91
		3.870		3.870	1.648	7.38	0.524	3.14	1.80	4.80	2.91	2.15	1.126	1.46	4.26	2.55
	0.050	3.620		3.620	1.357	7.62	0.475	2.86	1.95	4.30	3.17	2.35	1.116	1.22	3.85	3.00
		1.820		1.820	1.306	12.38	0.147	8.88	5.69	6.80	5.21	7.65	1.124	1.16	6.05	3.90
		3.910		3.910	1.291	6.66	0.587	2.20	1.53	3.60	2.79	1.80	1.057	1.22	3.41	3.20
		2.300		2.300	0.943	5.87	0.392	2.41	1.65	2.80	2.97	1.95	0.764	1.23	3.67	3.20

water depth, tabulated in Column 6, is the depth measured at the end of the jump, corresponding to the depth at Section 2 on Figure 27D.

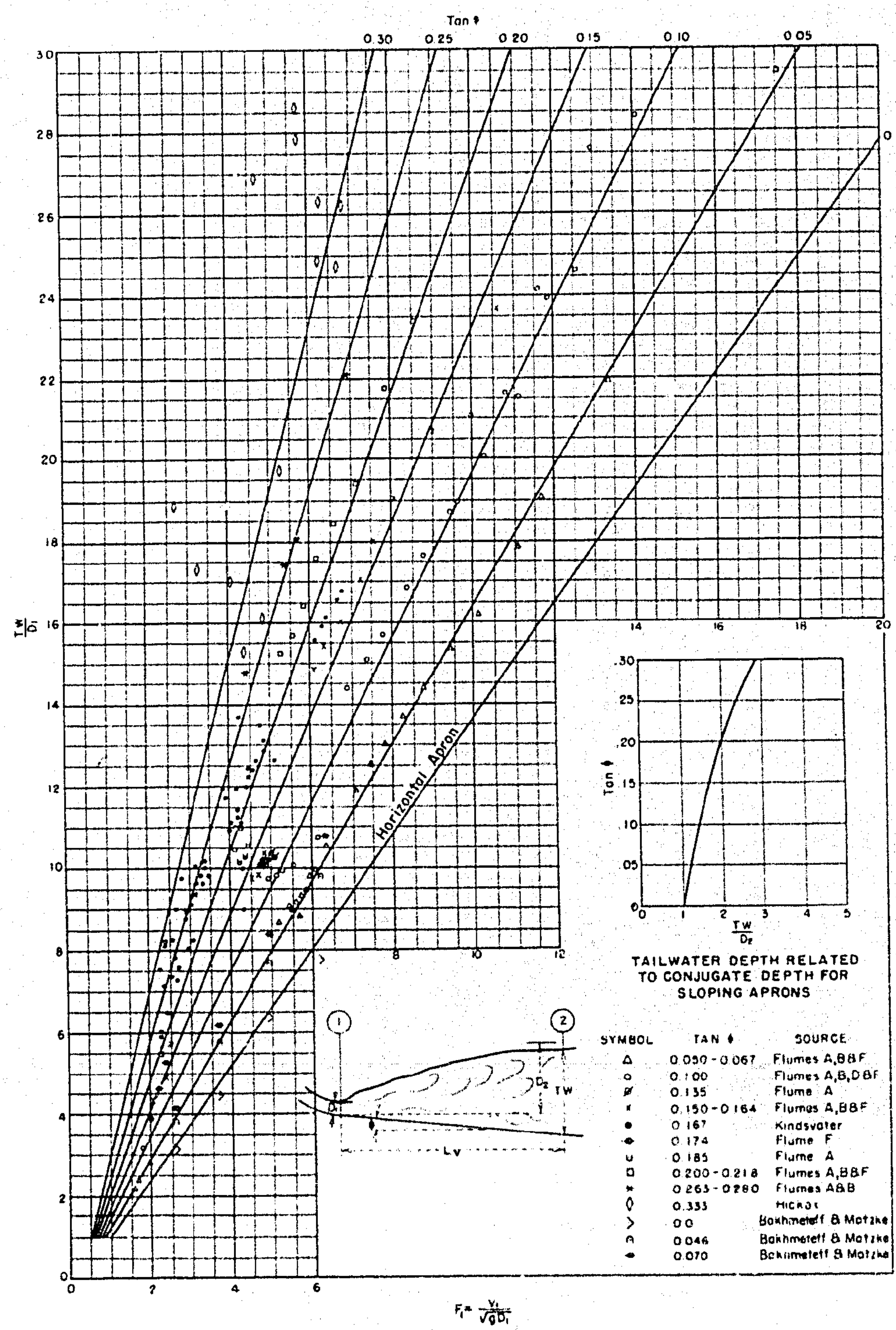
The ratio $\frac{TW}{D1}$ (Column 9, Table 6) is plotted with respect to the Froude number (Column 10) for sloping aprons having tangents of 0 to 0.30 on Figure 28. Superimposed on Figure 28 are data from Kindsvater, 5/ Hickox, 5/ Bahkmeteff, 1/ and Matzke.6/ The agreement is within experimental error. The small chart on the right of Figure 28 shows the ratio of tail water depth, for a continuous sloping apron, to conjugate depth, for a horizontal apron, for various slopes. For example, if the tangent of the slope is 0.10, a tail water depth equal to 1.4 times the conjugate depth will occur at the end of the jump; while if the slope of the floor is 0.30, the tail water depth at the end of the jump will be 2.8 times the conjugate depth required for a horizontal apron. The conjugate depth, D_2, referred to here, is listed in Column 14, Table 6 for each run, and was computed by assuming that the hydraulic jump forms on a horizontal floor which begins at Section 1. The imaginary horizontal floor is indicated by the dash line on Figure 27D. The conjugate depth, D_2, arrived at in this manner, is merely a reference figure which will be used frequently throughout this discussion. It was obtained by entering the curve for zero slope on Figure 28 with the various values of the Froude number listed in Column 10, and reading off values of $\frac{D2}{D1}$ which are tabulated in Column 13. Values of D_2 were then obtained by multiplying the values in Column 13 by the values in Column 8.

Length of Jump (Case D)

The length of jump for the Case D experiments has been presented in two ways. First, the ratio length of jump to tail water depth, Column 12, was plotted with respect to the Froude number on Figure 29 for sloping aprons having tangents from 0 to 0.25. Secondly, the ratio of length of jump to the conjugate tail water depth, Column 16, Table 6, has been plotted with respect to the Froude number for the same range of slopes on Figure 30. Although not evident on Figure 29, it can be seen from Figure 30 that the length of jump on a sloping apron is longer than that which occurs on a horizontal floor. For example, for a Froude number of 8, the ratio $\frac{L}{D_2}$ varies from 6.1, for a horizontal apron, to 7.0, for an apron with a slope of 0.25. Length determinations from Kindsvater 5/ for a slope of 0.167 are also plotted on Figure 29. The points show a wide spread.

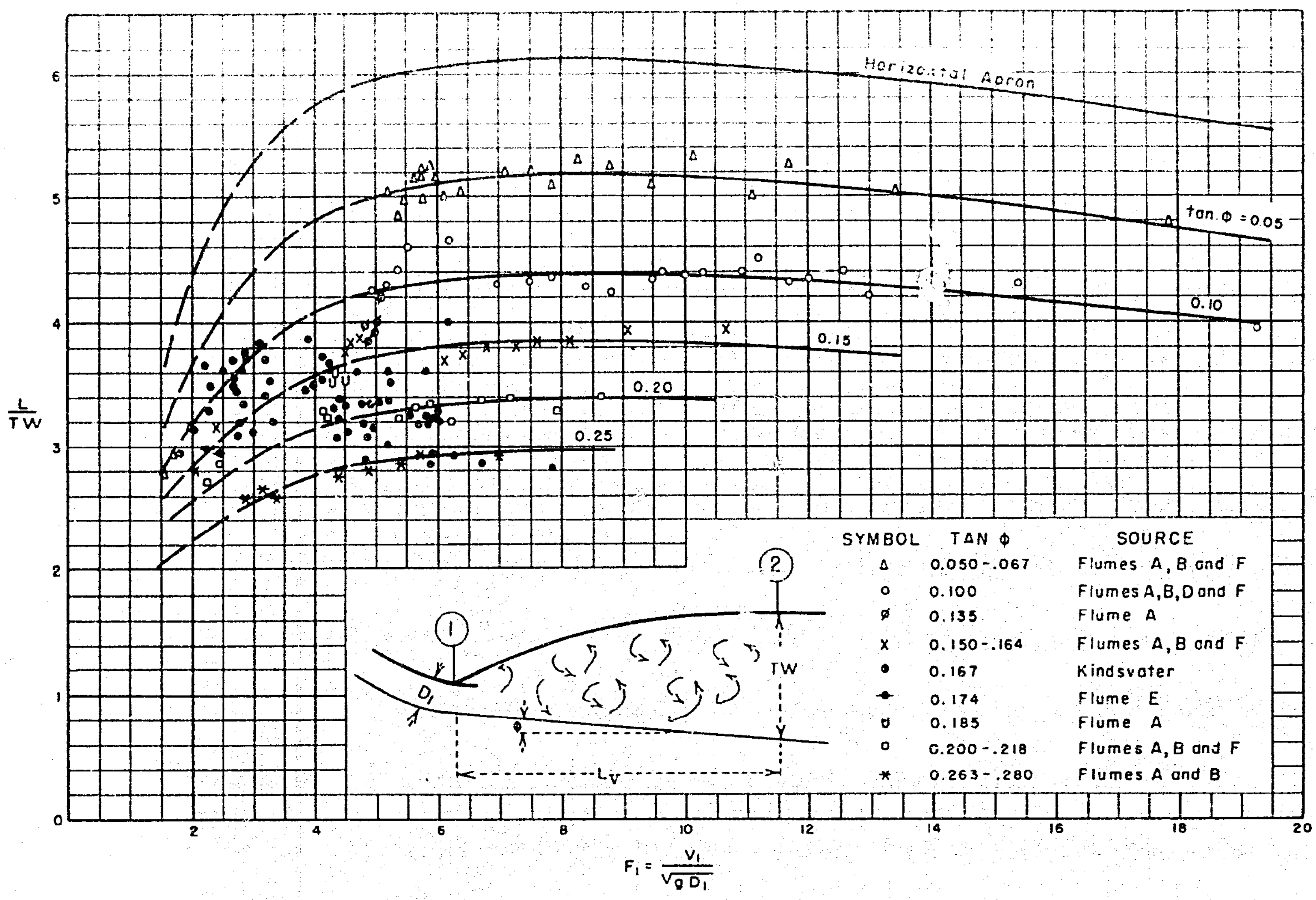
Expression for Jump on Sloping Apron (Case D)

Several mathematicians and experimenters have developed expressions for the hydraulic jump on sloping aprons, 2/ 5/ 6/ 13/ so



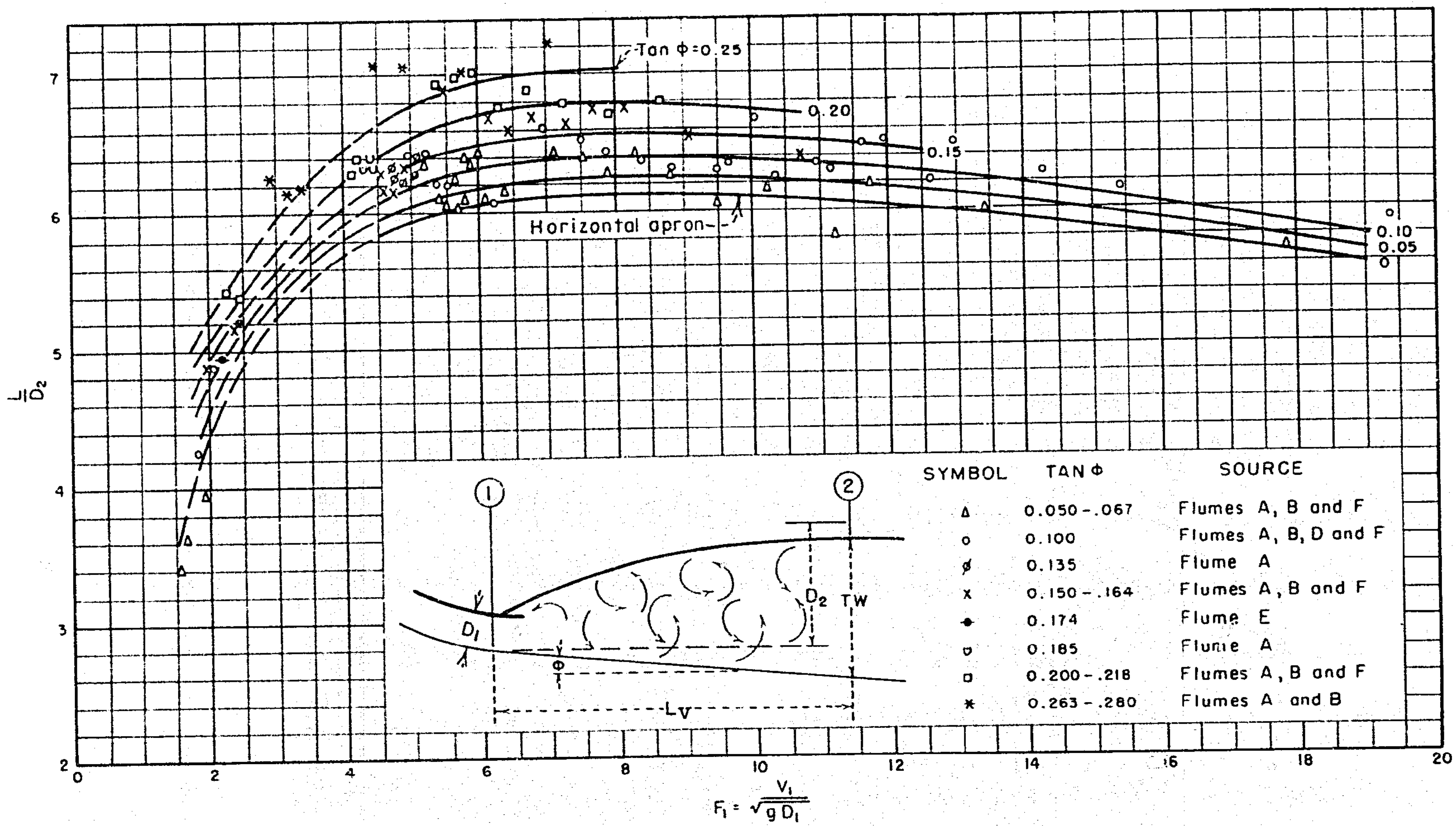
HYDRAULIC JUMP STUDIES
STILLING BASIN V (CASE D)
HYDRAULIC JUMP ON SLOPING APRON
RATIO OF TAILWATER DEPTH TO D_1

437



HYDRAULIC JUMP STUDIES
STILLING BASIN V (CASE D)
LENGTH OF JUMP IN TERMS OF TW DEPTH

FIGURE 29



HYDRAULIC JUMP STUDIES
STILLING BASIN V (CASE D)
LENGTH OF JUMP IN TERMS OF CONJUGATE DEPTH, D_2

there is no need to repeat any of these derivations here. An expression presented by Kindsvater 5/ is the more common and perhaps the more practical to use.

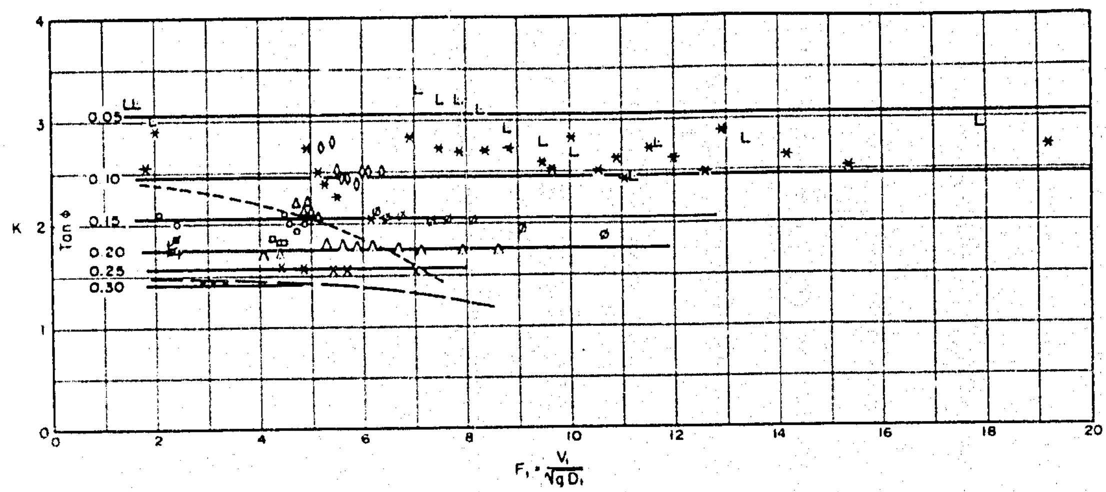
$$\frac{D_2}{D_1} = \frac{1}{2 \cos \phi} \sqrt{\frac{8F_1^2 \cos^3 \phi}{1+2K \tan \phi} + 1} - 1 \quad (5)$$

All symbols have been referred to previously, except for the coefficient K, a dimensionless parameter called the shape factor, which varies with the Froude number and the slope of the apron. Kindsvater and Hickox evaluated this coefficient from the profile of the jump and the measured floor pressures. Surface profiles and pressures were not measured in the current tests but, as a matter of interest, K was computed from Expression 5 by substituting experimental values and solving for K. The resulting values of K are listed in Column 17 of Table 6, and are shown plotted with respect to the Froude number for the various slopes on Figure 31A. Superimposed on Figure 31A are data from Kindsvater for a slope of 0.167, and data from Hickox on a slope of 0.333. The agreement is not particularly striking nor do the point plot well, but it should be remembered that the value K is dependent on the method used for determining the length of jump. The current experiments indicate that the Froude number has little effect on the value of K. Assuming this to be the case values of individual points for each slope were averaged and K is shown plotted with respect to tan ϕ on Figure 31B. This phase is incidental to the study at hand and has been discussed only as a matter of record.

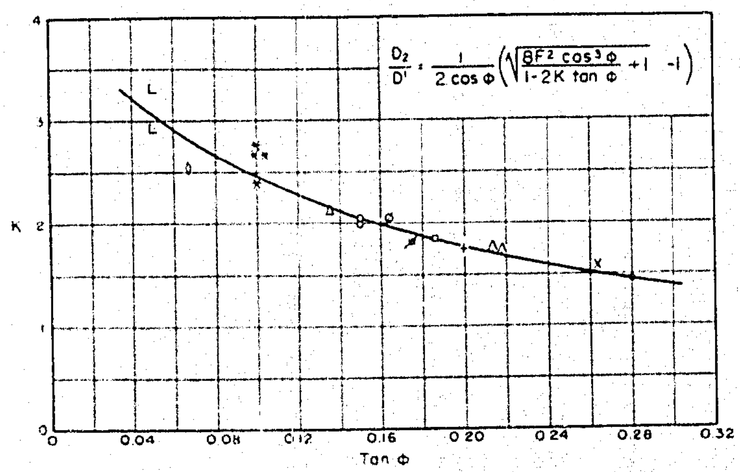
Jump Characteristics (Case B)

Case B is the one usually encountered in sloping apron design where the jump forms both on the slope and over the horizontal portion of the apron (Figure 27B). Although this form of jump may appear quite complicated, it can be readily analyzed when approached from a practical standpoint. The primary concern in sloping apron design is the tail water depth required to move the front of the jump up the slope to Section 1, Figure 27B. There is little to be gained by a sloping apron unless the entire length of the sloping portion is utilized.

Referring to the sketches on Figure 32A, it can be observed that for a tail water equal to the conjugate depth, D_2, the front of the jump will occur at a point O, a short distance up the slope. This distance is noted as l_o and varies with the degree of slope. If the tail water depth is increased a vertical increment, ΔY_1, it would be reasonable to assume that the front of the jump would raise a corresponding increment. This is not true, the jump profile undergoes an immediate change as the slope becomes part of the stilling basin. Thus, for an increase in tail water depth, ΔY_1, the front of the jump moves up the slope to Point 1, or



A



Above curve is based on assumption that K is independent of F_1

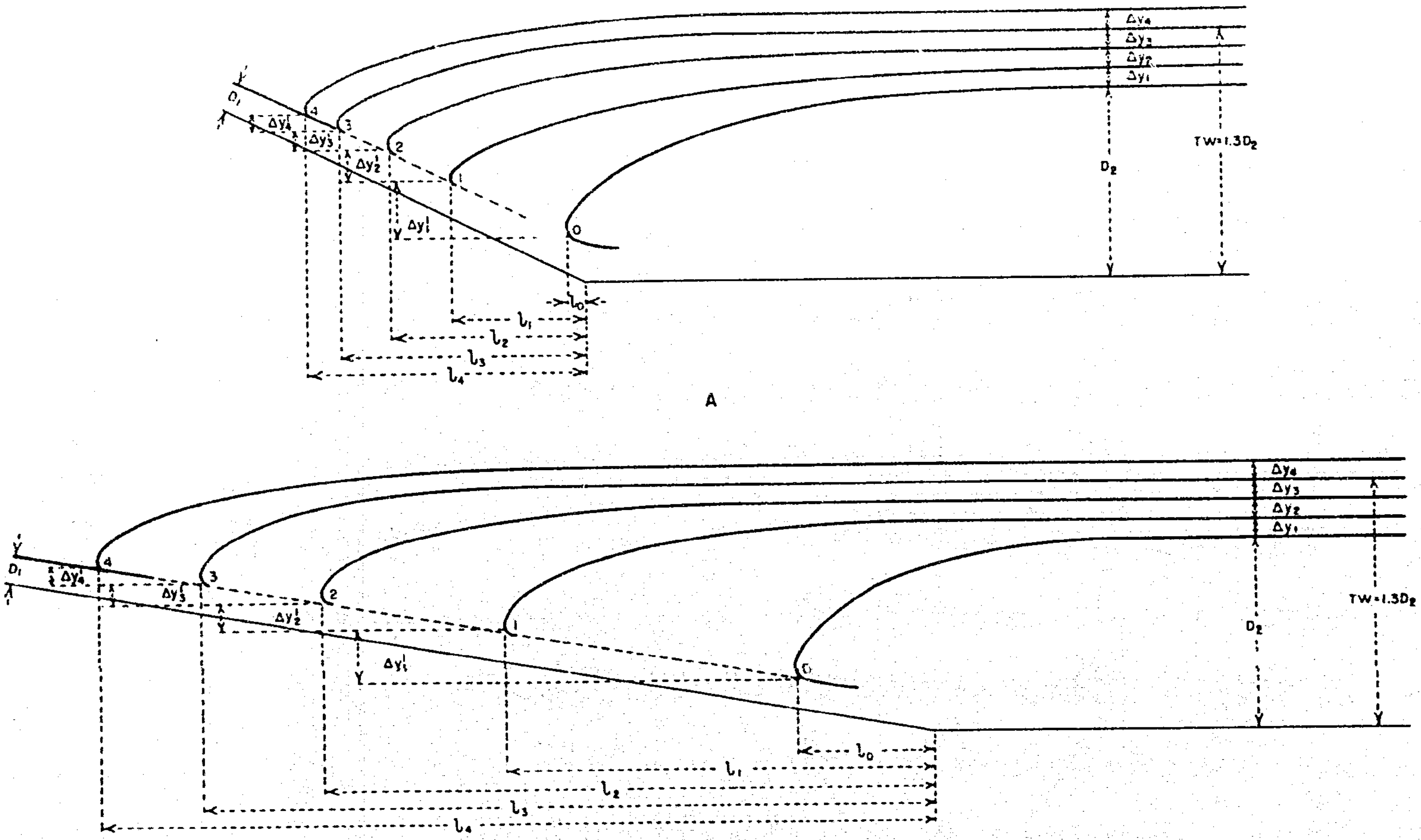
B

SYMBOL	Tan Φ
L	0.052
◊	.067
*	.100
Δ	.135
O	.150
Ø	.164
⌀′	.174
□	.185
+	.200
Λ	.215
X	.263
•	.280
– – – –	.167 Kindsvater
— — —	.333 Hickox

HYDRAULIC JUMP STUDIES

STILLING BASIN V (CASE D)

SHAPE FACTOR K



HYDRAULIC JUMP STUDIES

STILLING BASIN V (CASE B)

PROFILE CHARACTERISTICS

FIGURE 32

moves a vertical distance $\Delta Y_1'$, which is several times ΔY_1. Increasing the tail water depth a second increment, say ΔY_2, the same effect occurs to a lesser degree, moving the front of the jump to Point 2. Additional increments of tail water depth produce the same effect but to a still lesser degree, and this continues until the tail water depth approaches $1.3D_2$. For tail water depths greater than this amount, the relation is geometric; an increase in tail water depth, ΔY_4, moves the front of the jump up the slope an equal vertical distance $\Delta Y_4'$, from Point 3 to 4.

From the above discussion, it is evident that the change in profile produced by allowing the jump to move onto the slope is very much in favor of the designer. Should the slope be very flat, as in Figure 32B, the horizontal movement of the front of the jump is even more pronounced. The following studies were made to definitely tabulate the characteristics described above for conditions encountered in design. It has been necessary in the past to check practically all sloping apron designs by model studies to be certain that the entire sloping portion of the apron was utilized.

Experimental Results (Case B)

The experiments for determining the magnitude of the above mentioned characteristics were carried out on a large scale in Flume D, and the results are recorded in Table 7. A sloping floor was placed in the flume as in Figure 27B. A discharge was established (Column 3, Table 7) and the depth of flow, D_1 (Column 6) was measured immediately upstream from the front of the jump in each instance. The velocity entering the jump, V_1, (Column 7) and the Froude number (Column 8) were computed. Entering Figure 28 with the computed values of F_1, the ratio $\frac{D_2}{D_1}$ (Column 9) was obtained from the line labelled "Horizontal apron." Multiplying this ratio by D_1 results in the conjugate depth for a horizontal apron which is listed in Column 10 of Table 7. The tail water was then set at conjugate depth (Point 0, Figure 32) and the distance, l_o, measured and tabulated. The distance l_o gives the position of the front of the jump on the slope, measured from the break in slope, for conjugate depth. The tail water was then increased, moving the front of the jump up to Point 1, Figure 32. Both the distance l_1 and the tail water depth were measured, and these are recorded in Columns 11 and 12, respectively of Table 7. The tail water was then raised, moving the front of the jump to Point 2 while the length l_2 and the tail water depth were recorded. The same procedure was repeated until the entire apron was utilized by the jump. In each case, D_1 was measured immediately upstream from the front of the jump, thus compensating for frictional resistance on the slope. The velocity, V_1, and the Froude number were computed at the same location. The tests were made for slopes with tangents varying from 0.05 to 0.30, and in some cases, several lengths of floor were used for each slope, as indicated in Column 15 of Table 7.

Table 7

STILLING BASINS WITH SLOPING APRONS
(Case B, Basin V)

Test flume (1)	Slope of apron tan ϕ (2)	Q Total discharge cfs (3)	W Width of basin ft (4)	q Discharge per foot of basin cfs (5)	D_1 Depth entering jump ft (6)	V_1 Velocity entering jump ft/sec (7)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (8)	$\frac{D_2}{D_1}$ (9)	D_2 Conjugate TW depth ft (10)	l Length of jump on slope ft (11)	TW Tail-water depth ft (12)	$\frac{l}{D_2}$ (13)	$\frac{TW}{D_2}$ (14)	L_s Length of sloping floor ft (15)
D	0.05	5.050	3.970	1.272	0.063	20.19	14.18	19.51	1.229	6.00	1.390	4.88	1.13	4.0
		8.070		2.033	.101	20.13	11.16	15.30	1.545	6.00	1.745	3.88	1.13	
		11.555		2.910	.139	20.94	9.90	13.60	1.890	6.00	2.040	3.17	1.08	
	.10	5.255		1.324	.067	19.76	13.46	18.60	1.246	4.80	1.440	3.85	1.16	4.0
		8.090		2.038	.103	19.79	10.87	15.00	1.545	4.80	1.750	3.11	1.13	
		11.560		2.911	.140	20.79	9.80	13.40	1.876	4.80	2.080	2.56	1.11	
		5.000		1.259	.064	19.67	13.70	18.90	1.210	8.10	1.830	6.69	1.51	8.0
					.065	19.37	13.38	18.40	1.196	6.30	1.660	5.26	1.39	
					.067	18.79	12.80	17.65	1.183	4.70	1.510	3.97	1.28	
					.068	18.51	12.50	17.20	1.169	4.00	1.410	3.42	1.21	
					.070	17.98	11.99	16.50	1.155	3.20	1.340	2.77	1.16	
		7.850		1.977	.101	19.57	10.86	15.00	1.515	7.80	2.070	5.15	1.37	
					.102	19.38	10.70	14.70	1.499	6.00	1.940	4.00	1.29	
					.103	19.19	10.54	14.50	1.494	5.30	1.880	3.55	1.26	
					.104	19.01	10.39	14.25	1.482	4.40	1.770	2.96	1.19	
		11.218		2.825	.139	20.32	9.61	13.15	1.828	8.30	2.410	4.54	1.32	
					.141	20.04	9.41	12.88	1.816	6.20	2.260	3.41	1.24	
					.142	19.89	9.30	12.80	1.818	4.80	2.180	2.64	1.20	
		6.000		1.511	.076	19.88	12.70	17.50	1.330	2.20	1.375	1.65	1.03	2.0
								17.50	1.330	1.70	1.340	1.28	1.01	
					.077	19.62	12.46	17.15	1.321	0.80	1.305	0.61	0.99	--
					.078	19.37	12.23	16.80	1.310	0	1.280	0	0.98	
		8.057		2.029	.098	20.70	11.66	16.00	1.568	2.40	1.625	1.53	1.04	
					.099	20.49	11.48	15.80	1.564	1.90	1.600	1.22	1.02	
					.100	20.29	11.31	15.60	1.560	1.60	1.585	1.02	1.02	
					.101	20.09	11.14	15.40	1.555	0.60	1.550	0.39	1.00	
					.102	19.89	10.98	15.15	1.545	0	1.530	0	0.99	
	.15	6.000		1.511	.075	20.15	12.96	17.85	1.339	0.50	1.335	0.37	1.00	1.2
								17.85	1.339	1.10	1.365	0.82	1.02	
		8.057		2.029	.099	20.49	11.48	15.80	1.564	0.60	1.564	0.38	1.00	
								15.80	1.564	1.20	1.600	0.77	1.02	--
		11.535		2.905	.136	21.36	10.21	14.00	1.904	0.50	1.905	0.26	1.00	
								14.00	1.904	1.50	1.970	0.79	1.03	
		5.295		1.333	.069	19.32	12.97	17.85	1.232	4.00	1.530	3.25	1.24	
		8.080		2.035	.104	19.57	10.70	14.70	1.529	4.20	1.810	2.75	1.18	
		11.553		2.910	.141	20.64	9.69	13.25	1.868	4.20	2.150	2.25	1.15	
		4.976		1.253	.064	19.58	13.64	18.75	1.200	5.30	1.660	4.42	1.38	5.3
					.065	19.27	13.32	18.35	1.193	5.10	1.590	4.27	1.33	
					.066	18.98	13.02	18.00	1.188	4.00	1.505	3.37	1.27	
					.067	18.70	12.74	17.55	1.176	3.10	1.420	2.64	1.21	
								17.55	1.176	2.60	1.375	2.21	1.17	
					.068	18.42	12.45	17.15	1.166	2.20	1.305	1.89	1.12	
								17.15	1.166	1.80	1.230	1.54	1.05	
		8.025		2.021	.103	19.62	10.77	14.85	1.530	5.30	1.940	3.46	1.27	
								14.85	1.530	4.30	1.875	2.81	1.23	
								14.85	1.530	3.80	1.800	2.48	1.18	
					.104	19.43	10.62	14.60	1.518	2.80	1.705	1.84	1.12	
								14.60	1.518	2.20	1.640	1.45	1.08	
					.105	19.25	10.47	14.40	1.512	1.20	1.580	0.79	1.05	
		11.530		2.904	.142	20.45	9.57	13.10	1.860	5.30	2.260	2.85	1.22	
								13.10	1.860	4.30	2.190	2.31	1.18	
								13.10	1.860	3.60	2.120	1.94	1.14	

Table 7--Continued

STILLING BASINS WITH SLOPING APRONS
(Case B, Basin V)

Test flume (1)	Slope of apron: tan ϕ (2)	Q Total discharge cfs (3)	W Width of basin ft (4)	q Discharge per foot of basin cfs (5)	D_1 Depth entering jump ft (6)	V_1 Velocity entering jump ft/sec (7)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (8)	$\frac{D_2}{D_1}$ (9)	D_2 Conjugate TW depth ft (10)	l Length of jump on slope ft (11)	TW Tail-water depth ft (12)	$\frac{l}{D_2}$ (13)	$\frac{TW}{D_2}$ (14)	L_s Length of sloping floor ft (15)
D	0.20	5.393	3.970	1.358	0.071	19.13	12.65	17.35	1.232	4.60	1.790	3.73	1.45	5.3
								17.35	1.232	4.40	1.720	3.58	1.40	
								17.35	1.232	4.00	1.680	3.25	1.36	
					.072	18.86	12.40	17.05	1.228	3.60	1.605	2.93	1.31	
								17.05	1.228	3.00	1.550	2.44	1.26	
								17.05	1.228	2.60	1.490	2.12	1.21	
					.073	18.60	12.13	16.65	1.212	2.30	1.420	1.90	1.17	
								16.60	1.215	1.50	1.350	1.24	1.11	
								16.60	1.215	1.20	1.280	0.99	1.05	
		8.080		2.035	.105	19.38	10.54	14.50	1.523	4.60	2.010	3.02	1.32	
								14.50	1.523	4.00	1.955	2.63	1.28	
								14.50	1.523	3.30	1.890	2.17	1.24	
					.104	19.57	10.70	14.70	1.529	3.10	1.830	2.03	1.20	
								14.70	1.529	2.50	1.730	1.64	1.13	
								14.70	1.529	1.80	1.670	1.18	1.09	
		11.573		2.915	.145	20.10	9.30	12.80	1.856	4.40	2.310	2.37	1.24	
								12.80	1.856	3.70	2.230	1.99	1.20	
								12.80	1.856	3.30	2.175	1.78	1.17	
		4.820		1.214	.063	19.27	13.53	18.70	1.178	3.70	1.605	3.14	1.36	4.0
		8.089		2.037	.105	19.40	10.55	14.50	1.523	3.90	1.900	2.56	1.25	
		11.565		2.913	.143	20.37	9.50	13.05	1.866	3.90	2.180	2.09	1.17	
	0.25	5.344		1.346	.071	18.96	12.54	17.25	1.225	4.20	1.825	3.43	1.49	5.3
								17.25	1.225	4.10	1.755	3.35	1.43	
								17.25	1.225	3.50	1.680	2.86	1.37	
					.070	19.22	12.81	17.75	1.242	3.00	1.600	2.42	1.29	
								17.75	1.242	2.60	1.525	2.09	1.23	
								17.75	1.242	2.20	1.445	1.77	1.16	
								17.75	1.242	1.60	1.375	1.29	1.11	
								17.75	1.242	0.90	1.290	0.72	1.04	
		8.080		2.035	.107	19.02	10.25	14.05	1.503	4.30	2.100	2.86	1.40	
					.106	19.20	10.40	14.30	1.516	3.40	1.960	2.24	1.29	
								14.30	1.516	2.90	1.860	1.91	1.23	
								14.30	1.516	2.10	1.740	1.38	1.15	
					.105	19.38	10.54	14.50	1.523	1.30	1.650	0.85	1.08	
								14.50	1.523	0.50	1.550	0.33	1.02	
		11.553		2.910	.147	19.80	9.10	12.45	1.830	4.30	2.410	2.35	1.32	
					.146	19.93	9.20	12.60	1.840	4.10	2.320	2.22	1.26	
									1.840	3.20	2.230	1.74	1.21	
					.145	20.07	9.29	12.75	1.849	2.30	2.140	1.24	1.16	
									1.849	1.60	2.090	0.87	1.13	
					.144	20.21	9.39	12.85	1.850	1.20	2.010	0.65	1.09	
									1.850	0.80	1.950	0.43	1.05	
		6.005		1.512	.079	19.14	12.00	16.50	1.306	3.60	1.760	2.76	1.35	4.0
		8.057		2.029	.105	19.32	10.51	14.45	1.517	3.60	1.925	2.37	1.27	
		11.535		2.905	.144	20.17	9.37	12.85	1.850	3.60	2.210	1.95	1.19	
	0.30	8.105		2.041	.110	18.55	9.86	13.50	1.485	4.50	2.300	3.03	1.55	5.3
		5.410		1.362	.074	18.40	11.92	16.40	1.214	4.50	2.070	3.71	1.71	
		11.553		2.910	.150	19.40	8.83	12.05	1.808	4.50	2.570	2.49	1.42	
		5.960		1.506	.079	19.06	11.95	16.45	1.300	3.40	1.840	2.62	1.42	4.0
		8.050		2.028	.106	19.13	10.36	14.25	1.510	3.40	2.025	2.25	1.34	
		11.538		2.906	.146	19.90	9.18	12.55	1.832	3.40	2.300	1.85	1.26	

The resulting lengths and tail water depths, divided by the conjugate depth, are shown in Columns 13 and 14 of Table 7, and these values have been plotted on Figure 33. The horizontal length has been used rather than the vertical distance, ΔY, as the former dimension is more convenient for use. Figure 33 shows that the straight lines for the geometric portion of the graph tend to intersect at a common point, $\frac{l}{D_2} = 1$ and $\frac{TW}{D_2} = 0.92$. The change in the profile of the jump as it moves from a horizontal floor to the slope is evidenced by the curved portion of the lines.

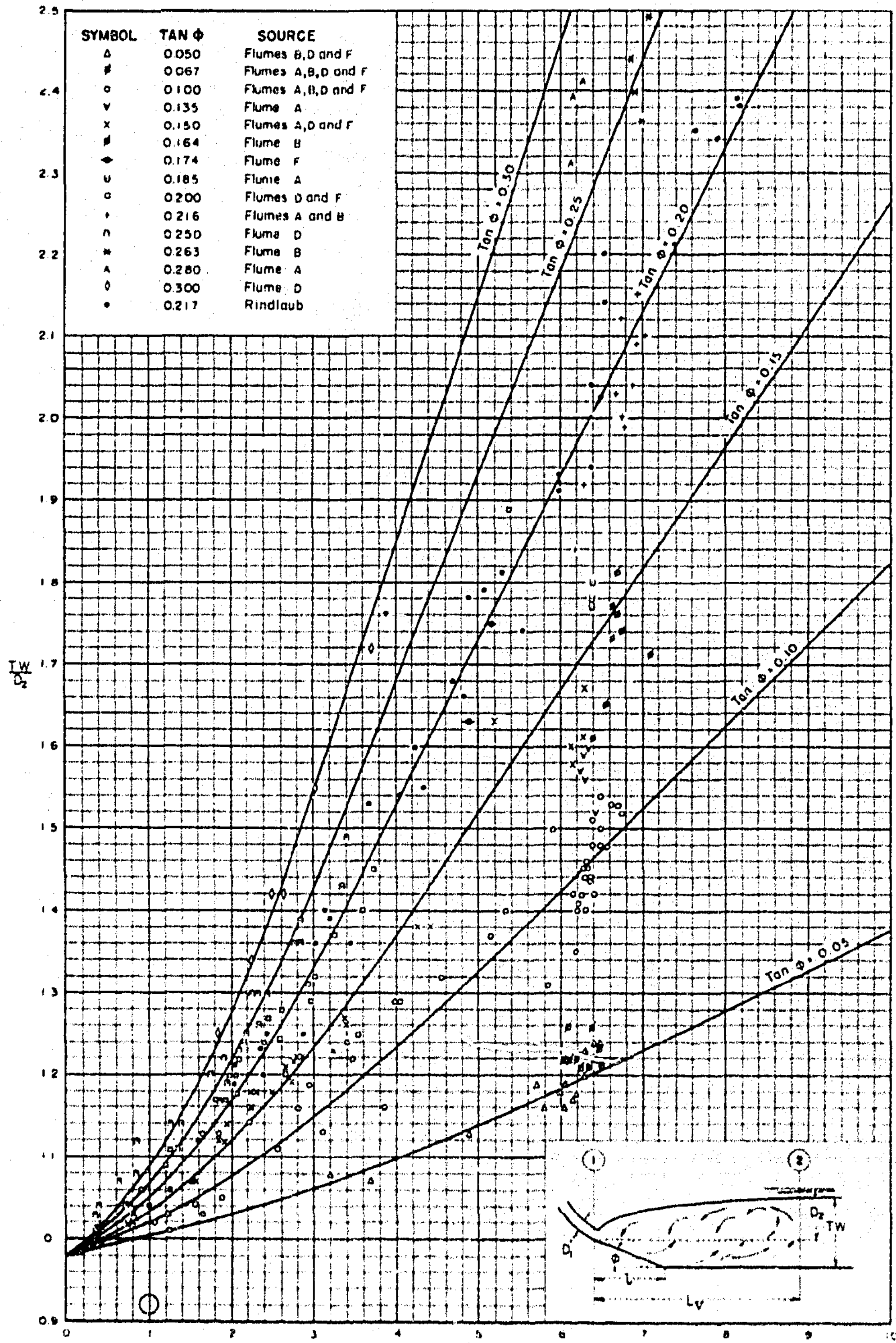
Case C, Figure 27, is the upper extreme of Case B; and as there is practically no difference in the performance for Cases D and C, data for Case D (Table 6) can again be utilized. By assuming that a horizontal floor begins at the end of the jump in Case D, Columns 15 and 16 of Table 6 can be plotted on Figure 33. In addition, data from experiments by D. D. Rindlaub of the University of California, for a slope of 0.217, have been plotted on Figure 33. The agreement of the information from the three sources is very satisfactory.

Length of Jump (Case B)

It is suggested that the length of jump for Case B be obtained from Figure 30. Actually, Figure 30 is for continuous sloping aprons, but these lengths can be applied to Case B with but negligible error. In some cases the length of jump is not of particular concern because it may not be economically possible to design the basin to confine the entire jump. This is especially true when sloping aprons are used in conjunction with medium or high concrete overfall dams where the rock in the river bed is in fairly good condition. When sloping aprons are designed shorter than the length indicated on Figure 30, the rock in the river downstream must act as part of the stilling basin. On the other hand, when the quality of foundation material is questionable, it is advisable to make the apron sufficiently long to confine the entire jump, Figure 30.

Existing Structures

To determine the practical value of the methods given for the design of sloping aprons, existing basins employing sloping aprons were, in effect, redesigned using the current experimental information. Pertinent data for 13 existing spillways are tabulated in Table 8. The slope of the spillway face is listed in Column 3; the tangent of the sloping stilling basin apron is listed in Column 4; the elevation of the upstream end of the apron, or front of the jump, is listed in Column 7; the elevation of the end of the apron is listed in Column 8; the fall from headwater to upstream end of apron is tabulated in Column 9; and the total discharge is shown in Column 11. Where outlets discharge into the spillway stilling basin, that discharge has also been included



HYDRAULIC JUMP STUDIES

STILLING BASIN V (CASE B)

TAILWATER REQUIREMENT FOR SLOPING APRONS

Table 8

EXISTING STILLING BASINS WITH SLOPING APRONS

Dam (1)	Location (2)	Slope of dam face (3)	Slope of stilling basin apron tan ø (4)	Reservoir elevation ft (5)	Crest elevation ft (6)	Elevation upstream end of apron ft (7)	Elevation downstream end of apron ft (8)	Fall headwater to U.S. end of apron ft (9)	Head on crest of spillway ft (10)	Q Max discharge cfs (11)	Max tail-water elevation ft (12)	TW depth ft (13)	l Length of sloping apron ft (14)	h Length of horizontal apron ft (15)	l + h Total length of apron ft (16)
Shasta	California	0.8:1	0.083	1065	1037	570.6	549.5	494.4	28.0	250,000	631.0	81.5	256.7	51.9	308.6
Norris	Tennessee	0.7:1	.250	1047	1020	826.0	805.5	221.0	27.0	197,600	872.0	66.5	81.5	142.5	224
Bhakra (prelim)	India	0.8:1	.100	1580	1552	1139.4	1112.2	440.6	28.0	189,500	1196.0	83.8	257	15	272
Canyon Ferry	Montana	Varies	.167	3800	3766	3625.0	3600.0	175.0	34.0	200,000	3670.0	70.0	137	57	194
Bhakra (final)	India	0.8:1	.100	1685	1645	1117.5	1095.0	567.5	40.0	290,000	1205.0	110.0	224.5	165	389.5
Madden	Canal Zone	0.75:1	.250	250	232	98.0	64.5	152.0	18.0	280,000	141.5	77.0	142	8	150
Folsom	California	0.67:1	.125	466	418	137.0	115.0	329.0	48.0	250,000	205.5	90.5	177	147	324
Olympus	Colorado	Varies	.250	7475	7460	7417.0	7405.0	58.0	15.0	20,000	7431.0	26.0	48.5	43.6	92.1
Capilano	British Colombia	0.65:1	.222	570	547	274.0	246.0	296.0	23.0	43,000	320.0	74.0	128	106	234
Rihand	India	0.7:1	.077	888	852	647.6	604.0	240.4	36.0	455,000	679.0	75.0	325	10	335
Friant	California	0.7:1	.143	578	560	296.0	282.5	282.0	18.0	90,000	330.0	47.5	97	125	222
Keswick	California	Varies	.062	587	537	488.6	483.8	98.4	50.0	250,000	541.0	57.2	105	23	128
Dickinson	North Dakota	0.5:1	.125	2428	2416	2388.0	2380.0	40.9	12.4	33,200	2403.0	23.0	61.5	9.5	71

Dam	V_{th} Theoretical velocity entering basin ft/sec (17)	$\frac{V_A}{V_{th}}$ (18)	$V_A = V_1$ Actual velocity entering basin ft/sec (19)	W Width of basin ft (20)	q Discharge per foot of basin cfs (21)	D_1 Depth entering basin ft (22)	$F_1 = \frac{V_1}{\sqrt{gD_1}}$ (23)	$\frac{D_2}{D_1}$ (24)	D_2 Conjugate TW depth ft (25)	$\frac{l}{D_2}$ (26)	$\frac{TW}{D_2}$ (27)	$\frac{L}{D_2}$ (28)	L Actual length of jump ft (29)	$\frac{l + h}{L}$ (30)
Shasta	176	0.81	141	375	667	4.73	11.42	15.75	74.5	3.44	1.09	6.30	469	0.66
Norris	116	0.91	106	332	595	5.61	7.88	10.70	60.0	1.36	1.11	7.03	422	.53
Bhakra (prelim)	166	0.82	136	300	632	4.65	11.11	15.25	70.9	3.63	1.18	6.35	450	.60
Canyon Ferry	101	0.95	96	271	738	7.69	6.10	8.20	63.1	2.17	1.11	6.55	413	.47
Bhakra (final)	188	0.85	156	260	1115	7.15	10.27	14.20	101.5	2.21	1.08	6.36	646	.60
Madden	96	0.91	87	448	625	7.18	5.72	7.70	55.3	2.57	1.39	6.90	382	.39
Folsom	140	0.95	133	242	1033	7.76	8.41	11.45	88.9	1.99	1.02	6.50	578	.56
Olympus	57	0.95	54	120	167	3.09	5.41	7.30	22.6	2.15	1.15	6.86	155	.59
Capilano	135	0.87	117	80	538	4.60	9.62	13.10	60.3	2.12	1.23	6.85	384	.61
Rihand	117	0.92	108	664	685	6.34	7.56	10.25	65.0	5.00	1.15	6.30	413	.82
Friant	133	0.81	108	330	273	2.53	11.97	16.45	41.6	2.33	1.14	6.40	266	.83
Keswick	69	1.00	69	240	1042	15.15	3.12	4.00	60.6	1.73	0.94	5.45	330	.39
Dickinson	47	--	34	200	166	4.86	2.71	3.45	16.8	3.66	1.37	5.36	90	.79

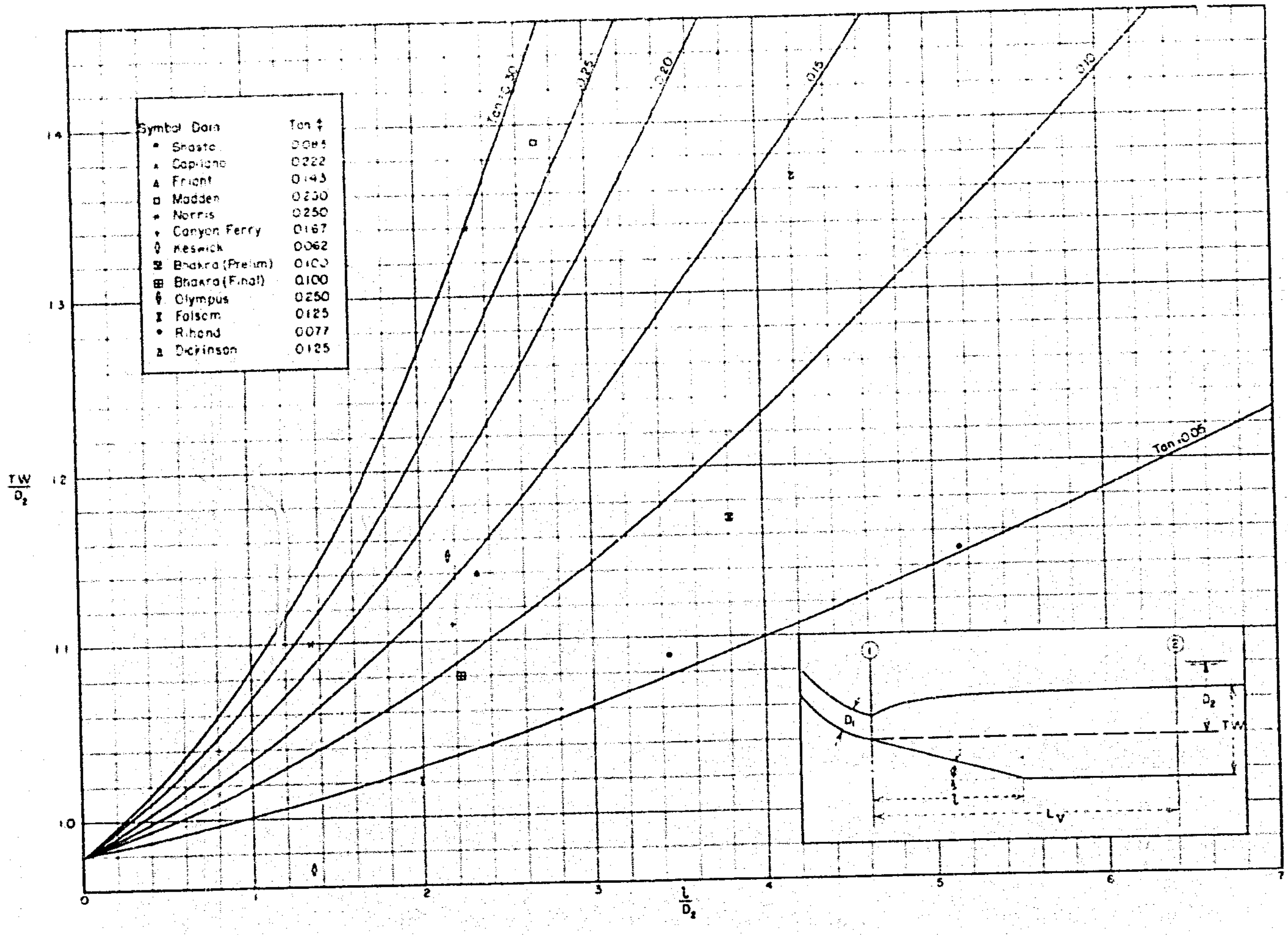
Average 0.60

in the total. The length of the sloping portion of the apron is given in Column 14; the length of the horizontal portion of the apron is given in Column 15; and the over-all length is given in Column 16. Columns 17 through 27 are computations similar to those performed in the previous table.

The lower portion of the curves of Figure 33 have been reproduced to a larger scale on Figure 34. The coordinates from Columns 26 and 27 of Table 8 have been plotted on Figure 34 for each of the 13 spillways. Cross sections of the basins are shown on Figures 35 and 36. Taking the stilling basins in the order shown on Figure 34, we find that the basin apron is not completely utilized for the maximum discharge condition at the Shasta Dam. This discharge includes both spillway and outlet works. The tail water depth is more than sufficient for the jump to utilize the entire stilling basin apron at Capilano Dam; and the full apron length is utilized at Friant, Madden and Norris Dam spillways. The entire apron length will not be utilized for the maximum discharge at Canyon Ferry Dam. In this case the apron was designed for a discharge of 200,000 cfs but the stilling basin will operate at 250,000 cfs without sweeping out. Keswick shows a deficiency in tail water depth for utilization of the entire apron, but this is compensated for, to some extent, by large spreader teeth at the upstream end of the apron. For the preliminary and final basin designs for the Bhakra Dam spillway, both utilize practically the full length of apron. The jump will not occupy the full length of apron for maximum discharge on Olympus, Folsom, or Rihand Dam spillways. The models of the latter two structures actually showed this to be true. The full length of apron will be utilized by the jump for the stilling basin at Dickinson Dam. This was an earth dam spillway in which appurtenances were used in the basin.

All of the structures listed in Table 8 and shown on Figures 35 and 36 were designed with the aid of model studies. The degree of conservatism used in each case was dependent on local conditions and the individual designer.

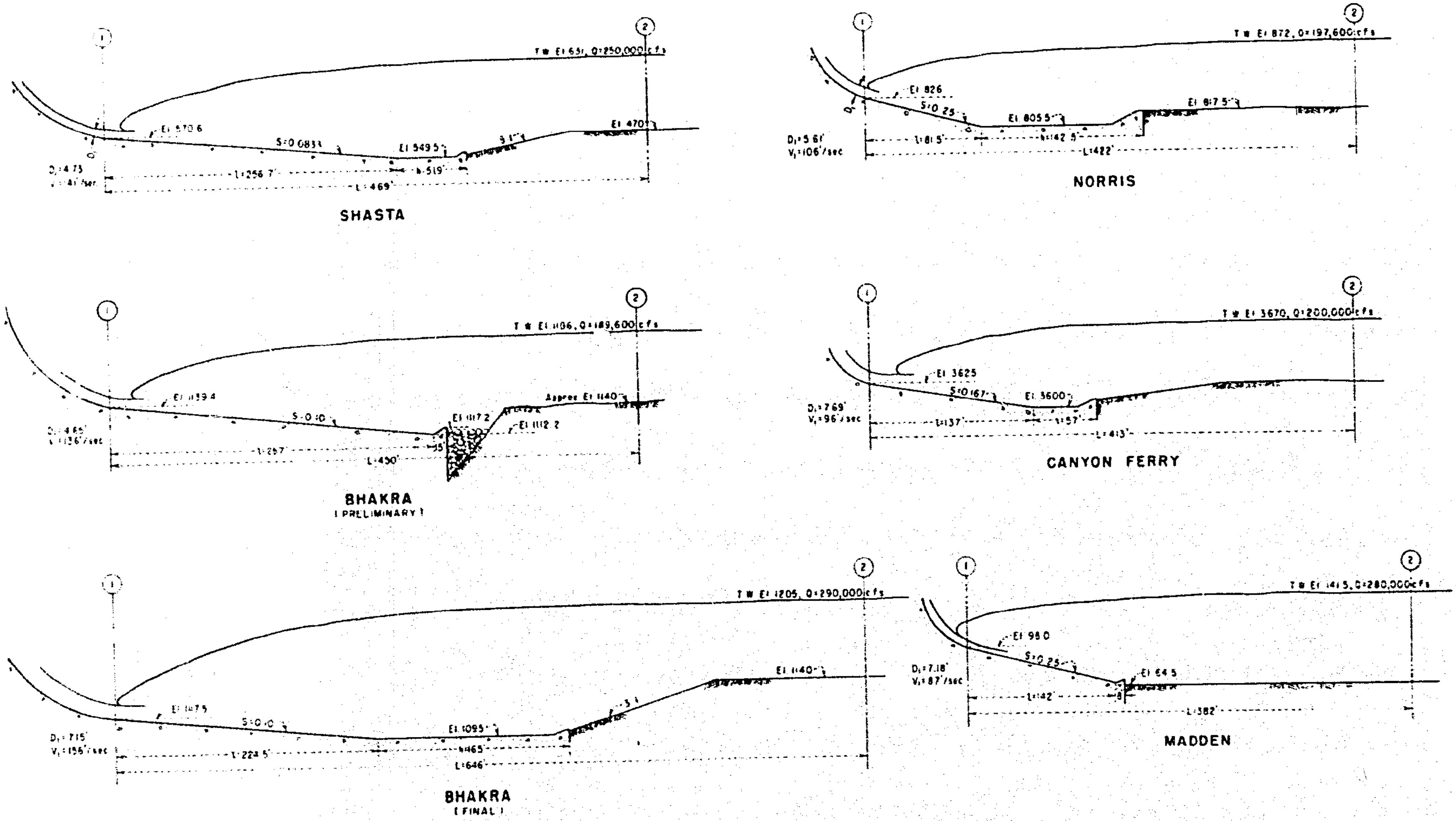
The total lengths of apron provided for the above 13 existing structures are shown in Column 16 of Table 8. The length of jump for the maximum discharge condition for each case is tabulated in Column 29 of the same table. The ratio of total length of apron to length of jump is shown in Column 30. The total apron length ranges from 39 to 83 percent of the length of jump; or considering the 13 structures collectively, the average total length of apron is 60 percent of the length of the jump.



HYDRAULIC JUMP STUDIES

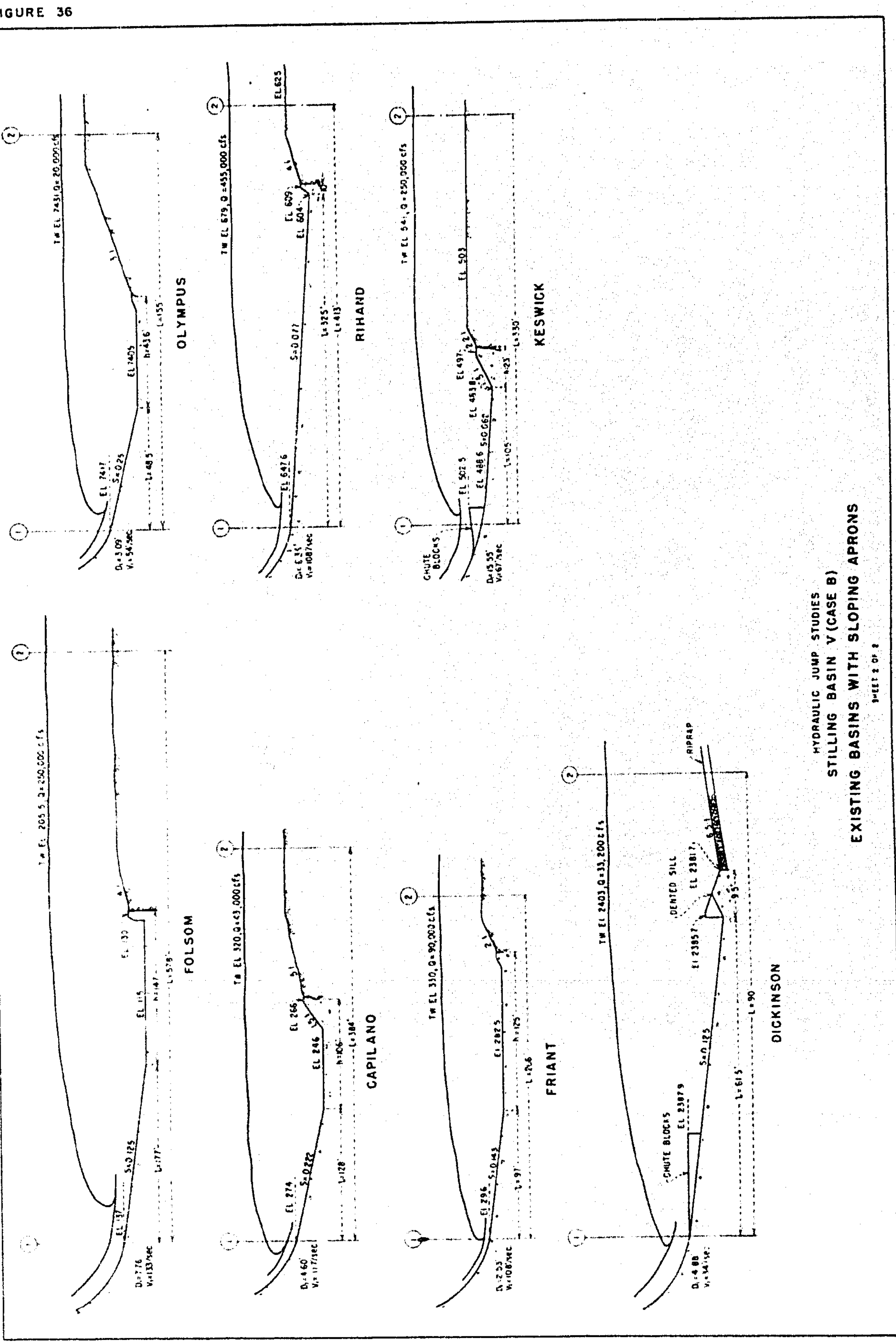
STILLING BASIN V (CASE B)

COMPARISON OF EXISTING SLOPING APRON DESIGNS WITH CURRENT EXPERIMENTAL RESULTS



HYDRAULIC JUMP STUDIES
STILLING BASIN V (CASE B)
EXISTING BASINS WITH SLOPING APRONS
SHEET 1 OF 2

FIGURE 36



HYDRAULIC JUMP STUDIES
STILLING BASIN V (CASE B)
EXISTING BASINS WITH SLOPING APRONS
SHEET 2 OF 2

Evaluation of Sloping Aprons

A convincing argument, quoted by the laboratory in the past, has been that sloping aprons should be constructed in such a way that the jump height curve matches the tail water curve for all discharge conditions. This procedure results in what has been designated a tailor-made basin. Some of the existing basins shown on Figures 35 and 36 were designed in this manner. In light of the current experiments, it was discovered that this course is not the most desirable approach. Instead, matching the jump height curve with the tail water curve should be a secondary consideration, except for the maximum discharge condition.

Thus the first consideration in design is to determine the apron slope that will involve the minimum amount of excavation, the minimum amount of concrete, or both, for the maximum discharge and tail water condition. It is felt that this is the prime consideration. Only then is the jump height checked to determine whether the tail water depth is adequate for the intermediate discharges. It will be found that the tail water depth usually exceeds the required jump height for the intermediate discharges. This may result in a slightly submerged condition for intermediate discharges, but this is usually very acceptable operation. Should the reverse be true, the tail water depth is insufficient for intermediate flows, it may be necessary to drop the sloping portion of the apron, change the slope, use a horizontal basin, or no change may be necessary so long as the basin is adequate for the most adverse intermediate flow. In other words, it is not necessary for the front of the jump to form at the upstream end of the sloping apron for intermediate discharges provided the tail water depth and length of basin are considered adequate. This method of attack leaves the designer free to choose any reasonable slope he desires, as the tests showed that the slope of the apron had little effect on the effectiveness of the stilling basin action.

It is not possible to standardize on sloping apron design nearly as much as for the horizontal aprons, as much more individual judgment is required. The slope and over-all shape of the apron must be determined from economic reasoning, while the length must be judged by the type and soundness of the rock of the river bed downstream. The existing structures shown on Figures 35 and 36 should serve as a guide in proportioning future sloping apron designs.

Sloping Apron Versus Horizontal Apron

A point, which it is felt has been misunderstood in the past with regard to horizontal aprons for high dams, can now be clarified. The Bureau has constructed very few stilling basins with horizontal aprons for its larger dams. It has been the consensus that the hydraulic jump on a horizontal apron is very sensitive to slight changes in tail water depth. This is very true for the larger values of the Froude number, but this characteristic can be remedied. Suppose a horizontal apron is designed for a Froude number of 10. The basin will operate satisfactorily for conjugate tail water depth, but as the tail water is lowered to $0.98D_2$ the front of the jump will begin to move. By the time the tail water is dropped to $0.96D_2$, the jump will probably be completely out of the basin. Thus to design a stilling basin in this range the tail water depth must be known with certainty or a factor of safety should be provided in the design. To guard against a deficiency in tail water depth, the same procedure is suggested here as for Basins I and II. Referring to the minimum tail water curve for Basins I and II on Figure 11, the margin of safety can be observed for any value of the Froude number. It is recommended that the tail water depth for maximum discharge be at least 5 percent larger than the minimum shown on Figure 11. For values of the Froude number greater than 9, a 10 percent factor of safety may be advisable as this will not only stabilize the jump but will improve the performance. With the additional tail water depth, the horizontal apron will perform on a par with the sloping apron. Thus the primary consideration in design need not be hydraulic but structural. The basin, with either horizontal or sloping apron, which can be constructed at the least cost is the most desirable.

Effect of Slope of Chute

A factor which occasionally affects stilling basin operation is the slope of chute entering the basin. The foregoing experimentation was sufficiently extensive to shed some light on this factor. The tests showed that the slope of chute upstream from the stilling basin was unimportant, as far as jump performance was concerned, so long as the velocity distribution in the jet entering the jump was reasonably uniform. In the case of steep chutes or flat short chutes, the velocity distribution can be considered normal. The principal difficulty is experienced with long flat chutes where frictional resistance on bottom and side walls is sufficient to produce a center velocity greatly exceeding that on the bottom or sides. When this happens, greater activity results in the center of the stilling basin than on the sides producing an assymetrical jump with strong side eddies. This same effect is also witnessed when the angle of divergence of a chute is too great for the water to follow properly. In either case the surface of the jump is unusually rough and choppy and the position of the front of the jump is not always predictable.

In the case of earth dam spillways the practice has been to make the upstream portion unusually flat, then steepen the slope to 2:1, or that corresponding to the natural trajectory of the jet, immediately preceding the stilling basin. Figure 1A, which shows the model spillway for Trenton Dam, illustrates this practice. Bringing an unsymmetrical jet into the stilling basin at a steep angle usually does aid in stabilizing the jump. This is not effective, however, where very long flat slopes are involved and the velocity distribution is completely out of balance.

The most adverse condition has been observed where long canal chutes terminate in stilling basins. A typical example is the chute and basin at Station 25+19 on the South Canal, Uncompahgre Project, Colorado° Figure 37. The operation of this stilling basin is not particularly objectionable, but it will serve as an illustration. The above chute is approximately 700 feet long with a slope of 0.0892. The stilling basin at the end is also shown on Figure 37. A photograph of the prototype basin operating at normal capacity is shown on Figure 38. The action is a surging type, the jump is unusually rough, with a great amount of splash and spray. Two factors contribute to the rough operation: the unbalanced velocity distribution in the entering jet, and excessive divergence of the chute in the steepest portion.

A definite improvement can be accomplished in future designs, where long flat chutes are involved by utilizing the Type III basin described in Section 3. The baffle blocks on the floor tend to alter the unsymmetrical jet, resulting in an over-all improvement in operation. This is the only corrective measure that can be suggested at this time.

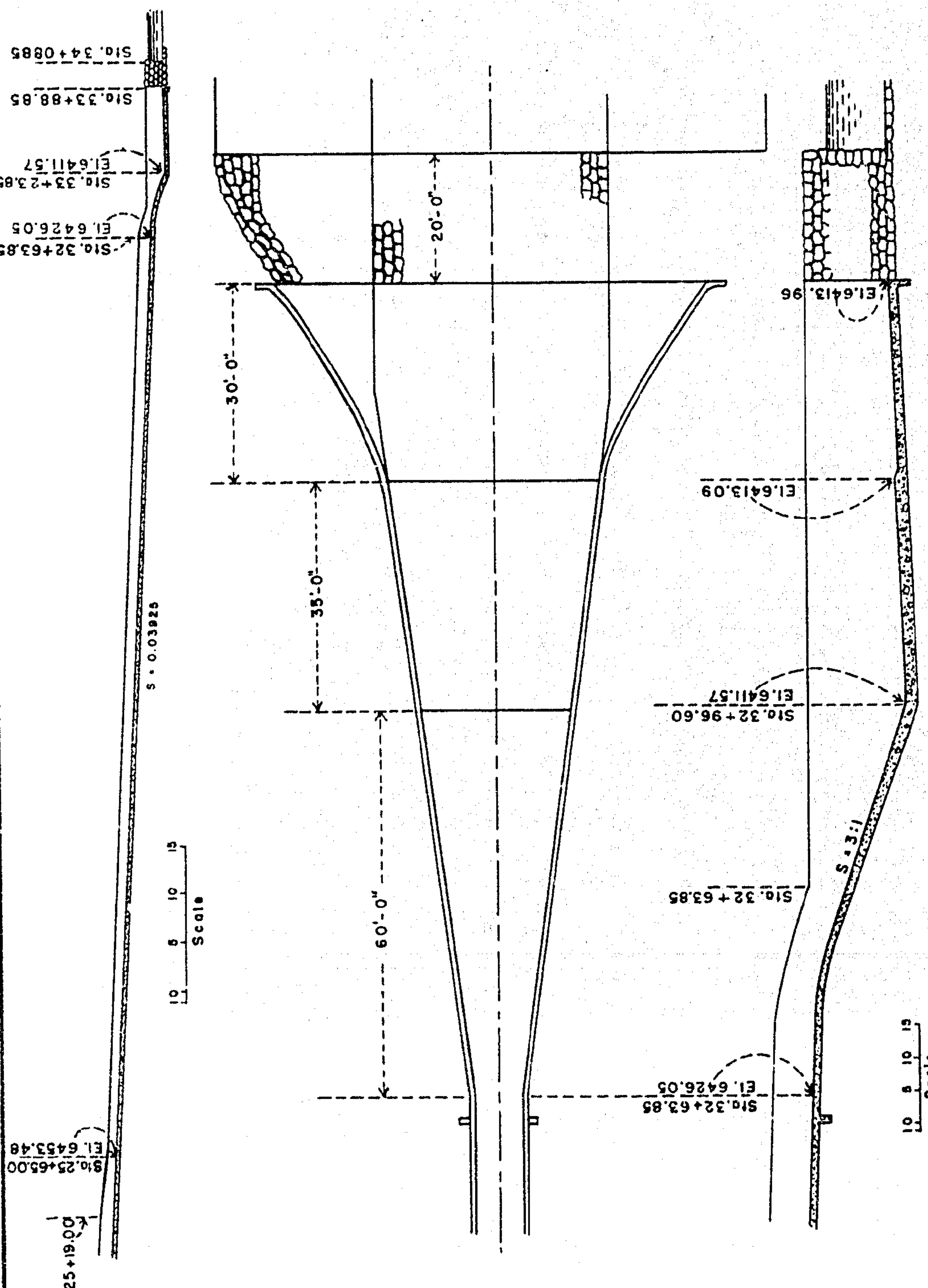
Recommendations

The following rules have been devised for the design of sloping aprons as developed from the foregoing experiments:

1. Determine an apron arrangement which will give the greatest economy for the maximum discharge condition. This is the governing factor and the only justification for using a sloping apron.

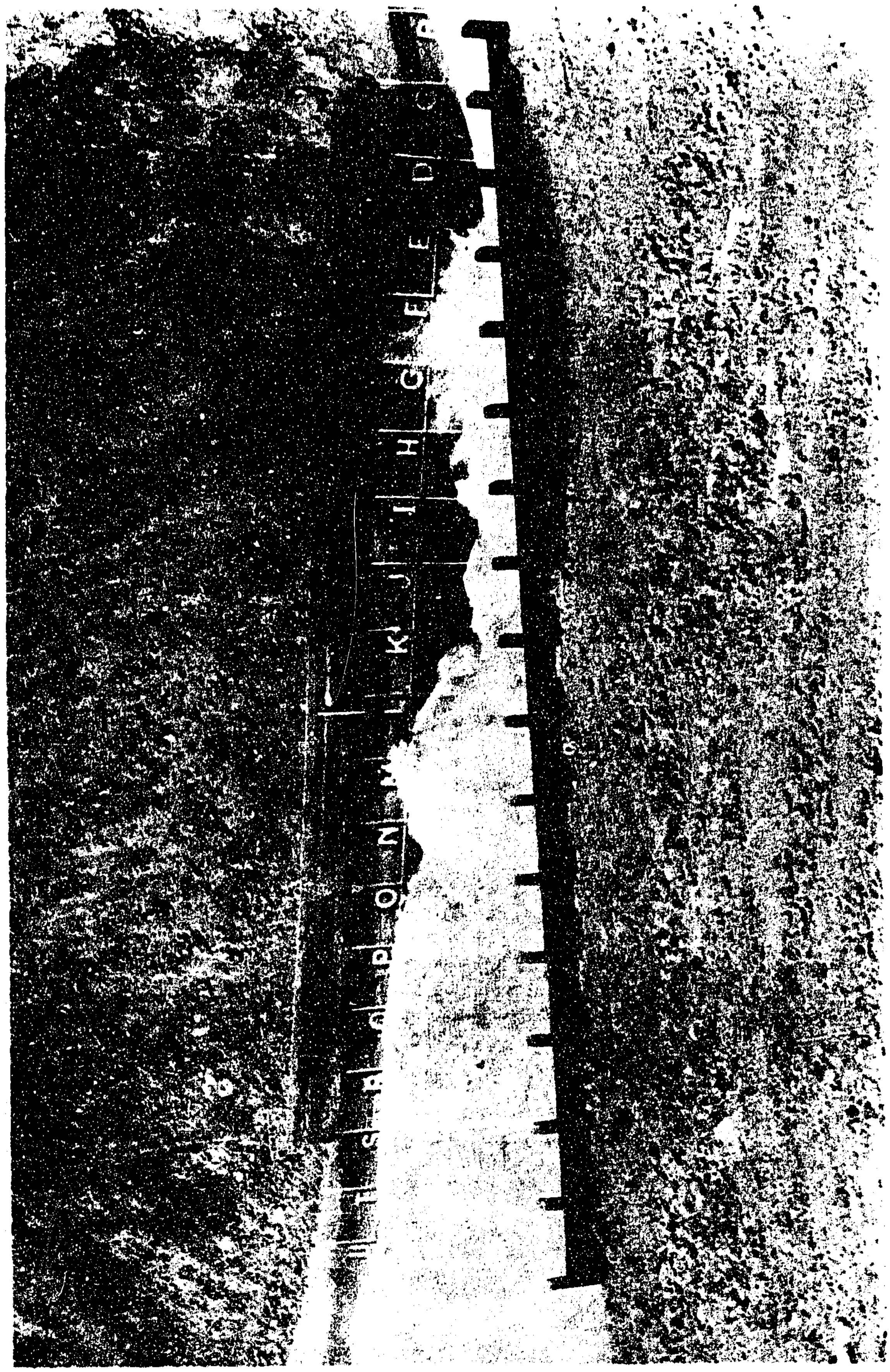
2. Position the apron so that the front of the jump will form at the upstream end of the slope for the maximum discharge and tail water condition by means of the information on Figure 34. Several trials will usually be required before the slope and location of the apron are compatible with the hydraulic requirement. It may be necessary to raise or lower the apron, or change the original slope entirely.

3. The length of the jump for maximum or partial flows can be obtained from Figure 30. The portion of the jump to be confined on the stilling basin apron is a decision for the designer. In making this decision, Figures 35 and 36 may be helpful. The average over-all apron in Figures 35 and 36 averages 60 percent of the length of jump for the maximum discharge condition. The apron may be lengthened or shortened, depending upon the quality of the rock in the river bed and



HYDRAULIC JUMP STUDIES
SOUTH CANAL CHUTE STA. 25+19
UNCOMPAGHRE PROJECT, COLO.

FIGURE 38



CHUTE STILLING BASIN ON SOUTH CANAL
UNCOMPAHGRE PROJECT

other local conditions. If the apron is set upon loose material and the rock downstream is in poor condition, it may be advisable to make the total length of apron the same as the length of jump.

4. With the apron designed properly for the maximum discharge condition, the next step is to be certain that the tail water depth and length of basin are sufficient for, say, 1/4, 1/2, and 3/4 capacity. If the tail water depth is sufficient or in excess of the jump height for the intermediate discharges, this design is acceptable. If the tail water depth is deficient, it may then be necessary to try a flatter slope or reposition the sloping portion of the apron. It is not necessary that the front of the jump form at the upstream end of the sloping apron for partial flows. In other words, the front of the jump may remain at Section 1 (Figure 27B), move upstream from Section 1, or move down the slope for partial flows, providing the tail water depth and length of the apron are considered sufficient for these flows.

5. A horizontal apron will perform on a par with the sloping apron, for high values of the Froude number, if the proper tail water depth is provided.

6. The slope of the chute upstream from a stilling basin has little effect on the hydraulic jump so long as the velocity distribution and depth of flow are reasonably uniform on entering the jump.

7. A small solid triangular sill, placed at the end of the apron, is the only appurtenance needed in conjunction with the sloping apron. It serves to lift the flow as it leaves the apron and thus acts to control scour. Its dimensions are not critical; the most effective height is between $0.05D_2$ and $0.10D_2$ and a slope of 3:1 to 2:1 (see Figures 35 and 36).

A spillway should be operated to produce as nearly symmetrical flow in the stilling basin as possible. (This applies to all stilling basins.) Unsymmetry produces large horizontal eddies that can carry river bed material onto the apron. This material, motivated by the energy in the eddies, can abrade the apron and appurtenances in the basin at a very surprising rate. These eddies can also undermine wing walls and settle riprap. Unsymmetrical operation is expensive operation, and operators should be continuously reminded of this fact.

Where the discharge over high spillways exceed 500 cfs per foot of apron width, or where there is any form of unsymmetry involved, a model study is advisable. For the higher values of the Froude number, stilling basins become increasingly expensive, and the performance less acceptable. Thus, where practical, a bucket type of dissipator may serve the purpose better and more economically than a stilling basin.

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