UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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HYDRAULIC LABORATORY REPORT NO. 182

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STUDIES OF FLOW CHARACTERISTICS, DISCHARGE AND PRESSURES RELATIVE TO SUBMERGED DAMS

By

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Denver, Colorado,

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UNITED STATES
DEPARTMENT OF THE INTERIOR
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Hydraulic Laboratory
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Subject: Studies of flow characteristics, discharge and pressures relative to submerged dams.

INTRODUCTION

Many attempts by different individuals have been made to piece together experimental data from various sources on flow over submerged dams. As submerged flow, at its best, is unstable, it is not difficult to understand why these attempts have been only partially successful. A bibliography of the most prominent work on submerged flow over dams is included as an appendix to this report. Even if this material could be pieced together, its scope would not be sufficient to represent the picture as a whole. An attempt was made, therefore, to obtain as complete an account as the time available would permit from one laboratory study. The object of the study was to obtain general information to aid in the design of submerged dams and for this reason the results have been expressed in the most general form, that of dimensionless numbers.

This report supplements Laboratory Reports Nos. HYD-122 and 118 both on "Studies of Crests for Overfall Dams." The former consists of a complete record of the testing and results on a program of experiments for the determination of overfall dam profiles and free flow discharge coefficients, while HYD-118 is an abstract of the former. The present Report No. HYD-182 constitutes a continuation of the former studies, but applies principally to small overfall dams.

SUMMARY

The report is based on experimental results from two small dams which were tested in the Bureau of Reclamation Hydraulic Laboratory. The report deals entirely with submerged flow over these dams. The study included:

1. Investigation of the various types of flow encountered
2. Determination of discharge coefficients
3. The measurement of water surfaces and pressures on the dam and in the stilling basin to aid in stability determinations

Four distinct types of flow were prevalent on the downstream apron:

1. Flow at supercritical velocities
2. Flow involving the hydraulic jump
3. Flow accompanied by a drowned jump
4. Flow approaching complete submergence

Discharge coefficients were first determined for the free flow condition, then redetermined for the various conditions involving submergence. The difference between the two is termed the decrease in the coefficient of discharge due to submergence. This factor expressed in percent of the free flow coefficient has been plotted for practically all combinations of flow which can occur on small dams with horizontal downstream aprons.

Water surface and pressure measurements are included in dimensionless coordinates for a representative number of flow combinations. These plots are intended to aid the designer in picturing the type of flow to be encountered and, at the same time, offer actual values for stability determinations.

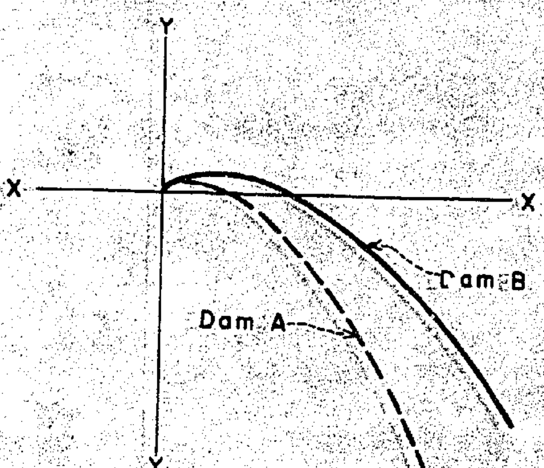
Four examples have been included in the report to demonstrate the possible uses of the enclosed experimental information.

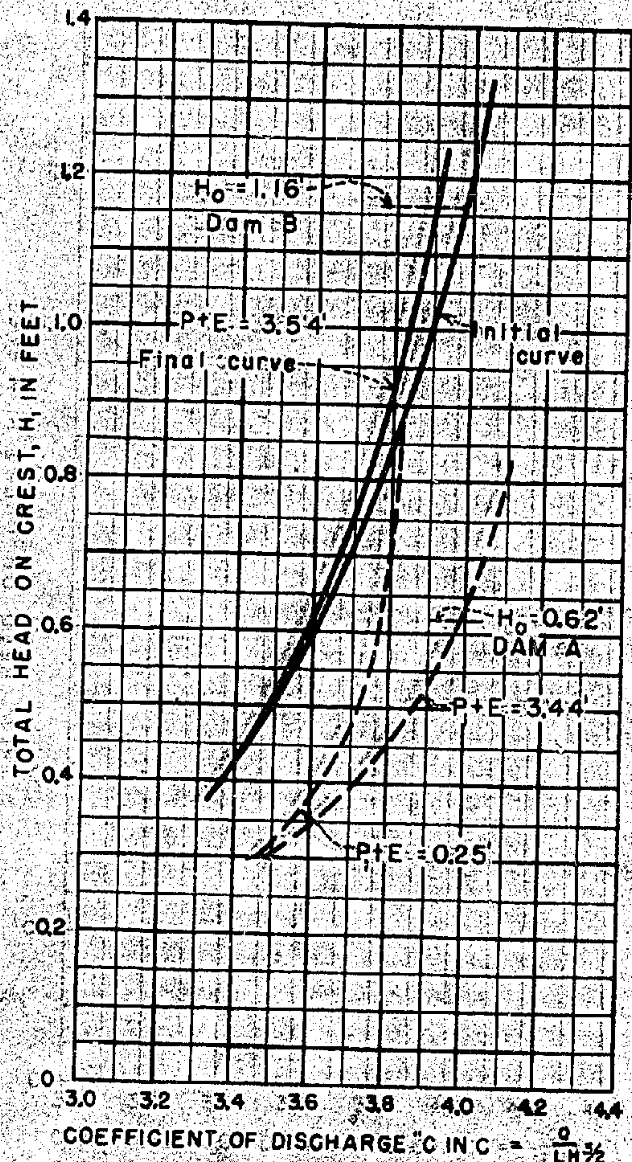
Test Equipment

The experiments were performed on two different pieces of equipment but both were tested in the Bureau of Reclamation Hydraulic Laboratory in Denver, Colorado. The first set of experiments was performed using a sheet metal overflow dam constructed according to the coordinates for Dam A on Figure 1. The dam was installed in a rectangular sheet-metal lined flume 1.52 feet wide and approximately twenty-four feet long. Adjustable floors were provided both upstream

DAM SHAPE COORDINATES

DAM A		DAM B	
X IN	Y FEET	X IN	Y FEET
0	0	0	0
0.034	+0.038	0.052	+0.061
0.067	0.057	0.104	0.096
0.101	0.068	0.156	0.117
0.135	0.074	0.208	0.131
0.168	0.075	0.260	0.138
0.202	0.073	0.312	0.140
0.235	0.073	0.364	0.139
0.270	0.064	0.416	0.135
0.303	0.056	0.468	0.128
0.336	0.046	0.520	0.118
0.404	+0.021	0.572	0.106
0.471	-0.012	0.624	0.091
0.538	0.050	0.702	0.065
0.605	0.094	0.806	+0.022
0.673	0.145	0.910	-0.030
0.807	0.265	1.014	0.088
0.942	0.408	1.118	0.153
1.076	0.572	1.222	0.230
1.211	0.762	1.300	0.286
1.345	0.977	1.560	0.518
1.480	1.210	1.820	0.795
1.614	1.466	2.080	1.113
1.749	-1.751	2.340	-1.478





DAM A — — —

Designed head, H_o = 0.62'
P_1+E = 3.44' and 0.25'
Length of Crest = 1.52'

DAM B ——

Designed Head, H_o = 1.16'
P_1+E = 3.54'
Length of Crest = 1.95'

SUBMERGED DAM STUDIES
DAM COORDINATES AND FREE CREST COEFFICIENT OF DISCHARGE CURVES

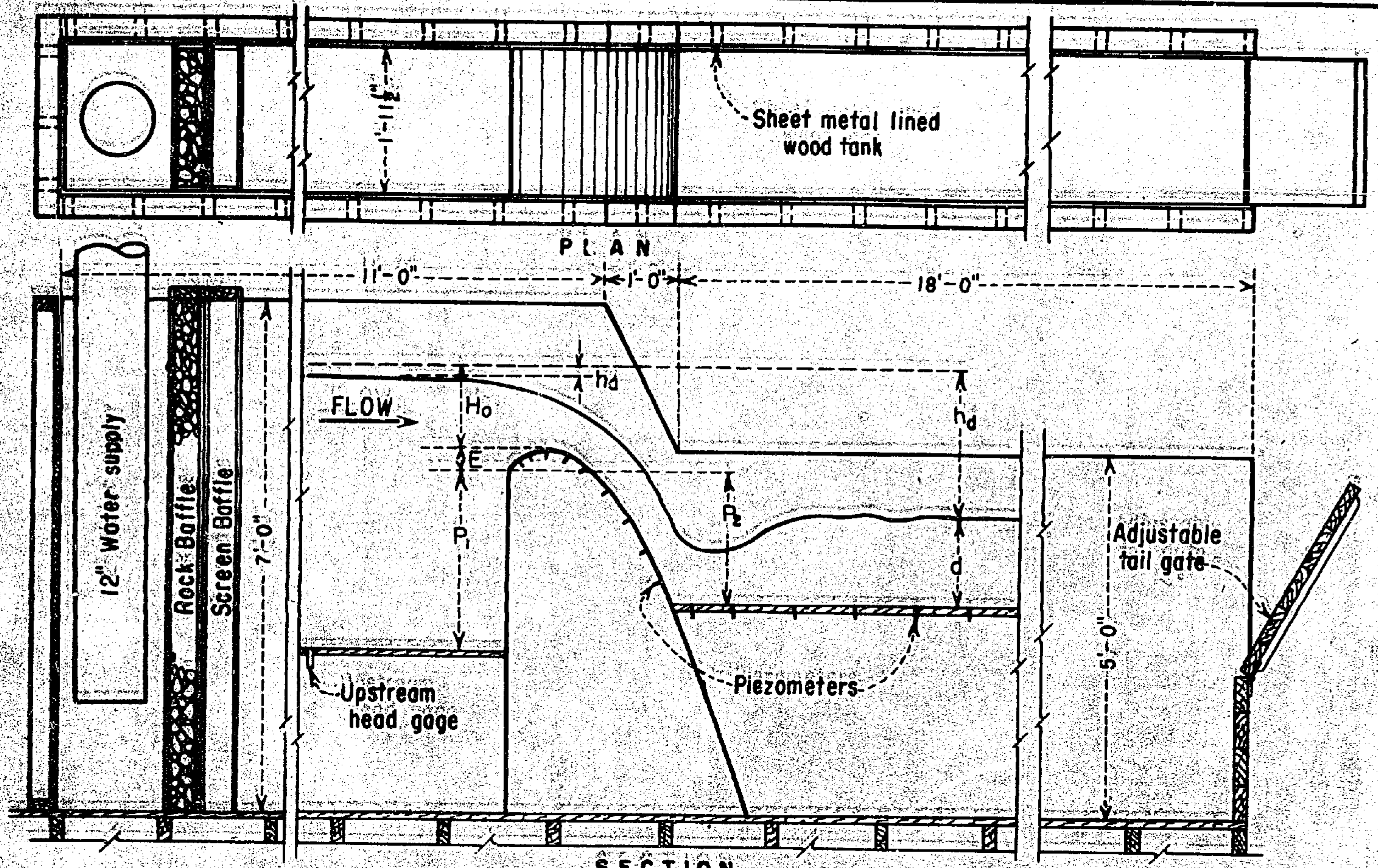
and downstream from the dam in addition to the main floor of the flume, Figure 2. For all positions, the adjustable floors were sealed tightly against the dam and sidewalls to prevent flow around these floors. The second set of experiments was performed in another but similar flume 1.95 feet in width and 30 feet long in which a sheet-metal dam was installed, constructed according to the coordinates for Dam B on Figure 1.

In both cases the movable floors were similarly constructed, the positions of the gages were in similar locations, and the controls on the two flumes were alike in most respects. The upstream head gage connection in each case was located in the movable floor approximately fifteen H_o, or fifteen times the designed head, upstream from the crest of the dam. This was connected to a transparent pot on the outside of the flume from which head readings were measured by a hook gage. The tailwater level was obtained from a point gage located 4 H_o downstream from the crest of the dam. Water-surface profiles along the flume were obtained from a point gage which could be moved along a 4-inch channel iron located over the center of the flume. Pressure measurements on the dam and on the downstream floor were obtained on Dam B fr[illegible] piezometers located normal to these surfaces as shown in Figure 2. The discharge to the model was measured through the accurately calibrated laboratory venturi meter system. Regulation of the tailwater on Dam B was accomplished by means of an adjustable-hinged gate located at the downstream end of the flume.

Test Procedure

The initial tests were made to obtain data required to construct curves for the free discharge condition with the upstream floor set in different positions. By this is meant the downstream floor was removed completely and free flow allowed to prevail for these tests. The curves are shown for two upstream floor positions for Dam A and one floor position for Dam B on Figure 1. The second curve for Dam B was obtained after changes were made in the approach channel to the dam. After the tests on Dam A, it was learned that the effect on the flow produced by the upstream floor position could be segregated from the effect produced by the downstream conditions. In other words, the entire effect of the upstream floor is accounted for in the free flow coefficient curves on Figure 1. For this reason it was not necessary to employ more than one upstream floor position for Dam B.

FIGURE 2



SECTION OF EXPERIMENTAL FLUME
USED FOR SUBMERGED FLOW EXPERIMENTS
FLOW DOWNSTREAM AT OR BELOW CRITICAL DEPTH IN ALL CASES

Upon completion of the free flow coefficient curves, the upstream floor was set in one of the calibrated positions and the downstream floor was fixed in a position approaching the crest of the dam. A constant head was maintained on the dam while readings of the discharge and depth of flow over the downstream floor were made for various tailwater depths. Flow conditions encountered varied from supercritical velocities to flow at practically one hundred percent submergence, the discharge in the latter case approaching zero. This procedure involved from six to eight runs, each made with the tailgate in a different position. The same test was repeated while a second head was maintained on the crest of the dam. After this the downstream floor was lowered to a second position and the twelve to sixteen runs, outlined above, repeated. This entire routine was repeated for floor positions varying from the crest of the dam to the permanent floor of the flume. In the case of Dam A, the upstream floor was shifted to the second calibrated position and certain runs repeated. The testing on Dam A was limited to supercritical velocities on the downstream floor while that on Dam B included four types of flow. The decrease in the coefficient of discharge due to submergence and also due to the presence of the downstream floor was obtained for each run by subtracting the coefficient of discharge, thus obtained, from the free flow coefficient of Figure 1 for a corresponding flow condition. The experimental points, thus obtained, have been tabulated and included as Table 1.

The nomenclature used in the column headings of Table 1 is illustrated by the sketch on Figure 3. Column 1 indicates the discharge per foot of dam for each run; Column 2 shows the total head on the crest of the dam, including velocity head of approach; and Column 3 is the coefficient of discharge obtained by substituting these values in the expression $C = \frac{Q}{LH^{3/2}}$. The tabulation in Column 4 represents the difference between the free discharge coefficient, Figure 1, and the coefficient obtained with submerged flow for the same dam with operation at identical heads. The positions of the upstream and downstream floors, throughout the test, are recorded in Columns 5 and 6, respectively. Columns 7 and 8 involve purely geometrical relationships, namely, the degree of submergence and the position of the downstream floor with respect to the head on the crest. Column 9 indicates the type of flow encountered downstream from the dam for each run (Figure 3A). The symbol, H_o, when encountered, indicates only the total designed head for a given dam while, H, represents any total head applied to the same dam.

TABLE 1

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SUBMERGED DAM STUDIES

COMPILATION OF EXPERIMENTAL DATA

DAM A

(1) q Per foot of width	(2) H Feet	(3) C	(4) Percent decrease in C	(5) P1 + B Feet	(6) P2 + B Feet	(7) hd/H	(8) (hd + d)/H	(9) Type of Flow
1.888	0.398	4.034	0	3.44	0.402	1.575	2.008	1
1.886	0.400	4.012	0		0.475	1.330	1.788	
1.888	0.399	3.949	1.28		0.349	1.084	1.688	
1.798	0.399	3.878	3.05		0.270	0.936	1.461	
1.781	0.400	3.787	5.58		0.209	0.809	1.348	
1.686	0.399	3.683	8.35		0.140	0.688	1.234	
1.580	0.389	3.417	14.63		0.087	0.534	1.082	
1.177	0.318	3.157	18.86		0.058	0.506	1.075	
1.200	0.376	3.237	26.49		0.058	0.576	1.122	
1.259	0.320	3.387	13.40		0.085	0.617	1.155	
1.511	0.320	3.497	9.78		0.109	0.660	1.210	
1.547	0.518	3.608	7.23		0.135	0.715	1.260	
1.586	0.321	3.678	8.15		0.160	0.770	1.307	
1.597	0.320	3.714	4.12		0.195	0.833	1.358	
1.616	0.321	3.758	2.84		0.232	0.893	1.407	
1.616	0.320	3.762	2.58		0.257	0.966	1.436	
2.379	0.713	3.786	6.48		0.262	0.787	1.358	
2.306	0.713	3.834	5.60		0.270	0.857	1.375	
2.347	0.713	3.899	3.80		0.308	0.898	1.427	
2.368	0.714	3.940	2.63		0.339	0.958	1.475	
2.396	0.718	3.985	1.86		0.370	1.006	1.519	
1.968	0.720	3.257	19.48		0.058	0.492	1.088	
2.026	0.722	3.355	17.06		0.100	0.573	1.140	
2.134	0.724	3.483	12.91		0.142	0.630	1.200	
2.226	0.734	3.490	9.01		0.198	0.707	1.269	
0.488	0.378	3.008	26.40	0.281	0.024	0.882	1.086	
0.536	0.382	3.300	3.59		0.158	0.878	1.381	
0.565	0.383	3.373	1.65		0.175	0.907	1.457	
0.566	0.386	3.375	1.65		0.211	1.106	1.581	
0.580	0.386	3.409	0.55		0.234	1.219	1.661	
1.220	0.542	3.059	18.42		0.024	0.515	1.044	
1.336	0.549	3.290	12.40		0.058	0.664	1.118	
1.441	0.562	3.427	9.02		0.102	0.644	1.181	
1.488	0.564	3.690	7.36		0.130	0.728	1.245	
1.557	0.569	3.405	4.61		0.175	0.794	1.308	
1.587	0.571	3.432	3.97		0.211	0.877	1.370	
1.587	0.576	3.450	3.44		0.254	0.968	1.443	
1.598	0.570	3.704	2.13		0.290	1.057	1.509	
1.609	0.579	3.730	1.10		0.322	1.109	1.348	
2.170	0.776	3.045	20.48		0.024	0.476	1.050	
2.309	0.807	3.189	16.97		0.065	0.509	1.078	
2.465	0.821	3.326	13.31		0.102	0.533	1.134	
2.510	0.801	3.506	11.40		0.159	0.617	1.168	
2.600	0.782	3.511	8.86		0.175	0.676	1.227	
2.438	0.776	3.565	7.57		0.211	0.768	1.278	
2.480	0.780	3.609	6.00		0.254	0.809	1.350	
2.489	0.771	3.698	3.86		0.290	0.867	1.376	
2.526	0.769	3.712	2.87		0.368	0.931	1.419	
1.441	0.630	3.95	0.50	3.44	3.44	0.753	6.76	3
1.619	0.698	3.95	0.28			0.753	6.77	
1.732	0.694	3.92	1.08			0.680	6.79	
1.760	0.698	3.90	2.00			0.882	6.77	
1.734	0.698	3.75	4.75			0.379	3.77	
1.684	0.697	3.66	7.25			0.285	6.75	
2.028	0.801	3.49	12.40			0.198	6.72	
1.205	0.591	3.44	30.28			0.115	5.68	
0.857	0.598	0.78	81.80			0.012	5.61	4
3.462	0.912	3.38	3.44			0.468	5.59	3
3.465	0.915	3.40	4.86			0.560	5.32	
3.402	0.913	3.20	5.34			0.483	5.24	
3.708	0.908	3.46	6.38			0.372	5.29	
3.836	0.925	3.42	12.69			0.409	5.36	
3.580	0.907	3.30	14.38			0.401	5.28	
3.359	0.909	3.28	20.48			0.359	5.25	
3.320	0.911	3.08	23.08			0.315	5.40	
3.180	0.912	2.90	29.40			0.308	5.36	
2.853	0.916	2.80	32.20			0.275	5.22	
1.980	0.911	2.65	38.70			0.257	5.24	
1.619	0.909	2.22	46.22			0.158	5.36	
1.090	0.808	1.42	64.90			0.064	5.28	

DAM B

(1) q Per foot of width	(2) H Feet	(3) C	(4) Percent decrease in C	(5) P1 + B Feet	(6) P2 + B Feet	(7) hd/H	(8) (hd + d)/H	(9) Type of flow
3.826	0.618	3.791	0.052	3.16	3.16	0.789	5.322	3 and 4
2.789	0.620	3.758	1.67			0.686	5.317	
2.748	0.620	3.700	3.33			0.489	5.317	
2.702	0.620	3.638	5.04			0.394	5.327	
2.640	0.619	3.542	6.84			0.334	5.332	
2.498	0.617	3.390	11.33			0.238	5.353	
2.078	0.616	2.815	26.00			0.168	5.338	
1.878	0.616	2.578	32.36			0.157	5.346	
1.718	0.612	2.347	38.30			0.109	5.360	
1.171	0.603	1.609	57.70			0.083	5.376	
4.109	1.062	3.881	2.03			0.640	4.360	
4.032	1.061	3.729	2.48			0.496	4.400	
3.934	1.061	3.706	8.00			0.386	4.400	
3.845	1.061	3.602	9.31			0.221	4.370	
3.703	1.038	3.500	11.21			0.290	4.410	
2.820	1.050	2.620	33.70			0.133	4.370	
2.173	1.034	2.072	47.46			0.069	4.425	
1.790	1.048	1.680	57.40			0.065	4.395	
1.486	1.051	1.414	64.08			0.050	4.425	
1.114	1.037	1.066	73.20			0.049	4.410	
3.336	1.058	3.036	21.42		0.024	0.632	1.032	4
3.254	1.064	3.050	22.48		0.024	0.398	1.023	
3.225	1.067	3.012	23.68		0.024	0.287	1.023	
3.087	1.057	2.848	28.94		0.022	0.165	1.021	
2.282	1.041	2.150	46.02		0.022	0.079	1.021	
1.607	1.086	2.423	43.93		0.022	0.060	1.021	
1.465	0.600	3.069	16.40		0.024	0.556	1.043	1
1.460	0.610	3.085	19.09		0.022	0.366	1.056	4
1.456	0.610	3.053	15.29		0.022	0.126	1.036	
1.187	0.609	2.723	26.82		0.022	0.122	1.036	
1.144	0.609	2.421	32.69		0.022	0.106	1.036	
0.882	0.610	1.747	51.60		0.022	0.066	1.036	
3.798	1.049	3.518	10.81		0.190	0.480	1.154	
3.772	1.049	3.517	10.94		0.191	0.644	1.154	
3.768	1.066	3.513	10.82		0.190	0.614	1.160	1
3.770	1.068	3.514	10.79		0.186	0.459	1.178	
3.724	1.068	3.470	12.10		0.186	0.279	1.176	4
3.467	1.068	3.340	15.29		0.188	0.183	1.176	
3.066	1.057	2.818	25.72		0.187	0.106	1.180	
1.189	0.620	2.658	29.18		0.188	0.072	1.503	
3.937	1.044	3.690	6.47		0.302	0.772	1.298	1
3.962	1.048	3.674	6.96		0.301	0.768	1.287	
3.950	1.048	3.676	6.81		0.296	0.700	1.282	
3.830	1.048	3.580	7.22		0.293	0.382	1.282	2
3.665	1.043	3.436	9.83		0.305	0.290	1.282	
3.408	1.061	3.477	11.86		0.305	0.225	1.285	
3.233	1.058	3.038	23.09		0.298	0.176	1.286	4
2.968	1.060	2.775	29.85		0.296	0.115	1.286	
1.746	0.617	3.402	0.44		0.362	1.083	1.490	1
1.735	0.617	3.375	1.16		0.303	0.942	1.474	
1.723	0.616	3.363	1.48		0.300	0.508	1.487	2
1.718	0.616	3.361	1.75		0.296	0.372	1.486	
1.700	0.617	3.305	3.09		0.296	0.316	1.478	
1.664	0.616	3.267	4.05		0.294	0.205	1.477	3
1.543	0.616	3.190	11.75		0.296	0.156	1.477	4
1.389	0.621	2.857	27.17		0.298	0.081	1.477	
1.172	0.616	2.489	32.17		0.298	0.035	1.485	
0.991	0.615	2.084	42.67		0.296	0.069	1.480	
1.715	0.617	3.540	1.80		0.300	1.088	1.486	1
1.465	0.615	3.319	2.85		0.294	0.311	1.478	2
1.101	0.616	2.442	32.46		0.296	0.068	1.477	4
0.791	0.616	2.059	45.07		0.296	0.048	1.477	
1.919	0.617	3.583	2.36		0.298	0.280	1.478	3
[illegible]	0.617	3.548	1.30		0.298	0.588	1.480	1
4.008	1.056	3.673	6.32		0.365	0.841	1.356	
4.081	1.054	3.680	4.43		0.368	0.807	1.357	
3.990	1.056	3.605	4.88		0.365	0.776	1.357	
3.960	1.055	3.671	4.89		0.360	0.780	1.351	
3.839	1.050	3.622	4.06		0.366	0.696	1.356	2
3.851	1.084	4.581	3.40		0.361	0.389	1.356	
3.696	1.083	3.406	11.66		0.365	0.232	1.350	
3.472	1.057	3.165	17.84		0.364	0.185	1.384	3
3.377	1.057	3.015	21.81		0.360	0.180	1.351	
2.896	1.080	2.655	31.19		0.366	0.109	1.358	4
2.380	1.080	2.128	44.84		0.364	0.075	1.350	
1.725	0.627	3.361	1.68		0.365	1.154	1.472	1
1.758	0.638	3.373	3.32		0.367	1.026	1.469	

DAM B (Continued)

(1) q Per foot of width	(2) H Feet	(3) C	(4) Percent decrease in C	(5) P1 + B Feet	(6) P2 + B Feet	(7) hd/H	(8) (hd + d)/H	(9) Type of Flow
1.731	0.616	3.377	1.00	3.84	0.353	0.542	1.571	2
1.718	0.616	3.345	1.96		0.348	0.435	1.564	
1.720	0.616	3.445	2.24		0.346	0.354	1.561	
1.677	0.615	3.466	4.15		0.344	0.267	1.552	
1.592	0.616	3.306	8.58		0.343	0.171	1.558	3
1.320	0.616	2.728	24.46		0.346	0.096	1.561	4
4.027	1.047	3.760	2.59		0.440	0.930	1.420	1
4.063	1.056	3.745	2.98		0.436	0.906	1.412	
4.042	1.056	3.728	3.47		0.429	0.848	1.408	2
3.991	1.055	3.681	4.63		0.429	0.822	1.407	
3.477	1.056	3.207	16.91		0.434	0.194	1.411	3
1.739	0.616	3.593	0.55		0.440	1.331	1.714	1
1.736	0.617	3.581	0.42		0.435	1.849	1.708	
1.734	0.617	3.581	0.42		0.435	0.811	1.708	2
1.718	0.617	3.533	1.75		0.436	0.365	1.705	3
1.053	0.616	2.188	39.12		0.436	0.095	1.708	4
4.062	1.050	3.776	2.15		0.432	0.996	1.469	1
4.068	1.058	3.769	2.39		0.488	0.868	1.462	
4.032	1.066	3.717	3.70		0.488	0.800	1.457	2
3.975	1.055	3.667	5.00		0.482	0.390	1.457	
3.611	1.054	3.322	3.75		0.432	0.236	1.457	3
2.342	1.044	2.198	43.05		0.482	0.086	1.462	4
1.739	0.616	3.598	0.05		0.488	1.429	1.784	1
1.739	0.616	3.598	0.05		0.483	1.242	1.784	
1.739	0.617	3.580	0.28		0.483	0.846	1.786	2
1.736	0.617	3.581	0.25		0.483	0.436	1.784	
1.703	0.617	3.512	2.36		0.483	0.311	1.786	3
1.583	0.615	3.376	6.09		0.483	0.198	1.786	
1.469	0.616	3.038	15.37		0.482	0.122	1.765	4
2.072	0.615	2.223	38.16		0.482	0.049	1.784	
4.093	1.064	3.783	2.30		0.346	1.021	1.819	1
4.093	1.061	3.766	2.34		0.342	0.971	1.816	
4.090	1.064	3.785	2.44		0.340	0.418	1.812	2
3.918	1.055	3.614	6.90		0.341	0.258	1.812	3
3.893	1.058	3.406	12.22		0.340	0.168	1.513	
3.410	1.052	3.160	18.63		0.340	0.159	1.518	
3.087	1.050	2.889	26.01		0.340	0.125	1.514	4
2.188	1.048	2.089	47.56		0.640	0.058	1.515	
1.731	0.617	3.612	0.28		0.348	1.530	1.896	1
1.748	0.617	3.602	0.49		0.341	1.368	1.878	
1.760	0.617	3.602	0.49		0.341	0.666	1.878	2
1.759	0.617	3.665	[illegible]		0.341	0.497	1.878	
1.713	0.615	3.535	3.40		0.341	0.367	1.878	3
1.697	0.617	3.501	3.25		0.341	0.262	1.878	
1.572	0.617	2.839	21.57		0.341	0.108	1.878	4
1.063	0.615	2.207	39.03		0.341	0.049	1.878	
4.181	1.056	3.854	0.22		0.364	1.400	1.809	1
4.191	1.057	3.859	0.34		0.364	1.302	1.798	
4.189	1.058	3.846	0.59		0.365	0.614	1.799	2
4.037	1.060	3.702	2.32		0.363	0.301	1.806	3
3.011	1.061	2.998	22.84		0.364	0.180	1.802	
3.231	1.064	3.614	6.57		0.364	0.258	1.802	
2.455	1.068	2.284	40.79		0.364	0.006	1.805	4
1.744	0.617	3.594	0.03		0.351	2.088	2.379	1
1.751	0.617	3.594	0.06		0.347	2.012	2.377	
1.751	0.618	3.594	0.06		0.328	1.006	2.377	2
1.728	0.617	3.585	0.30		0.365	0.648	2.377	3
1.708	0.619	3.507	2.48		[illegible]	0.160	2.378	
1.610	0.640	2.759	26.36		0.365	0.131	2.380	4
0.958	0.620	1.539	46.46		0.365	0.048	2.383	
4.194	1.092	3.887	0.07		1.022	1.581	1.987	1
4.194	1.056	3.867	0.07		1.010	1.507	1.986	
4.162	1.057	3.837	1.39		1.011	0.829	1.988	2
4.114	1.058	3.792	2.27		1.007	0.484	1.968	3
3.898	1.056	3.602	4.61		1.006	0.237	1.986	
3.553	1.061	3.415	13.18		1.008	0.207	1.987	
3.161	1.055	2.924	24.34		1.002	0.147	1.868	3 & 4
2.527	1.050	2.332	39.46		1.008	0.044	1.985	4
4.290	1.086	3.964	0.78		3.442	1.782	3.612	2
4.278	1.084	3.948	0.120		3.449	1.880	3.394	
4.278	1.084	3.948	0.10		2.433	1.088	3.300	3
4.278	1.057	3.932	0.61		3.432	0.723	3.301	4
4.256	1.057	3.904	1.42		3.432	0.643	3.361	3
4.187	1.057	3.885	5.36		3.422	0.457	3.301	
4.096	1.056	3.770	4.48		3.432	0.377	3.308	
3.385	1.062	3.110	21.06		2.440	0.209	3.319	

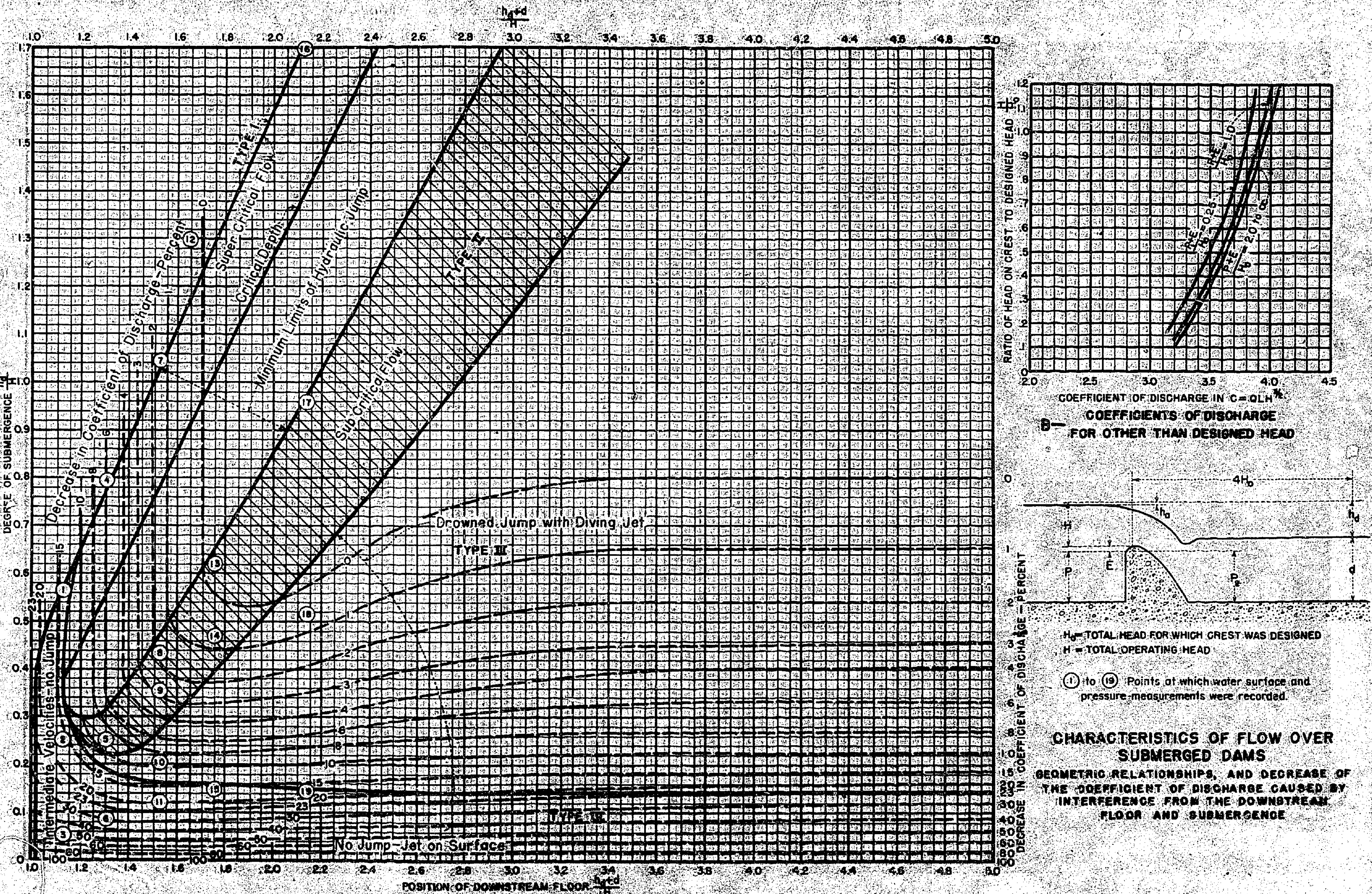
Test Results on Coefficients of Discharge

The data contained in Table 1 were used to plot the dimensionless curves on Figure 3A. For the sake of clarity the points are not shown on the graph. The main coordinates involve the degree of submergence and the position of the downstream floor. The heavy solid lines divide the graph into zones comprising the various types of flow encountered, such as supercritical flow, the hydraulic jump, drowned jump, and flow approaching complete submergence. The dashed lines indicate the decrease in the coefficient of discharge in percent, based on the coefficient of discharge for free flow at the same head. Beginning at the top of the sheet and reading downward, the flow designated as Type I, was at supercritical velocities illustrated by Plots 4, 7, 12, and 16 of Figures 4 and 5. The decrease in the coefficient of discharge in this region is not caused by submergence in the usual sense, but is entirely an effect produced by the downstream apron.

As the tailwater was raised, or the value of $\frac{h_d}{H}$ decreased, a hydraulic jump occurred in which both supercritical and tranquil flow were present. The former is the Type I flow and the latter is represented by the zone designated as Type II flow. The curves comprising Types I and II should not be confused with the depth versus specific energy curve, commonly associated with hydraulic jump computations, as the latter represents values of depths and energy for one discharge. Many discharges are represented in the curves on Figure 3A. The hydraulic jump is shown in Plots 5, 8, 9, 13, 14, and 17 on Figures 4 and 5.

As the value of $\frac{h_d}{H}$ continued to decrease, a third type of flow became prevalent, designated as the drowned jump or Type III flow. The jet of water flowing over the dam continued to follow the dam face, but the tailwater depth was too great to allow a good hydraulic jump to form. This type of flow is illustrated in Plots 10 and 18 on Figures 4 and 5.

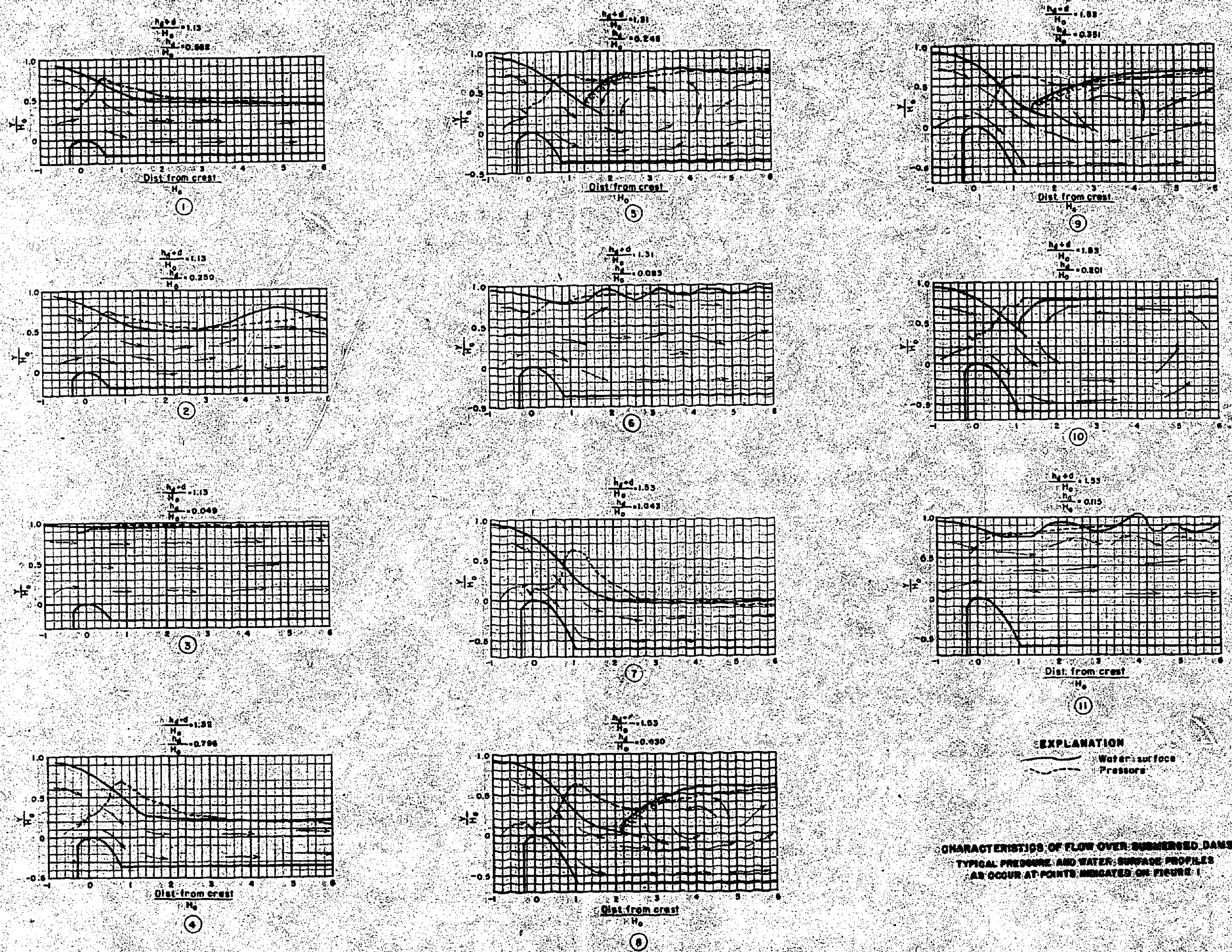
With still further decrease in the value of $\frac{h_d}{H}$, a fourth type of flow occurred which was truly submerged. In this case, the jet of water flowing over the dam no longer followed down the face, but separated assuming a course ahead as indicated in Plots 11, 15, and 19 on Figures 4 and 5. This type of flow is confined to the zone designated as Type IV. Except for small values of $\frac{h_d+d}{H}$, flow throughout Zone IV was very unstable.



CHARACTERISTICS OF FLOW OVER SUBMERGED DAMS

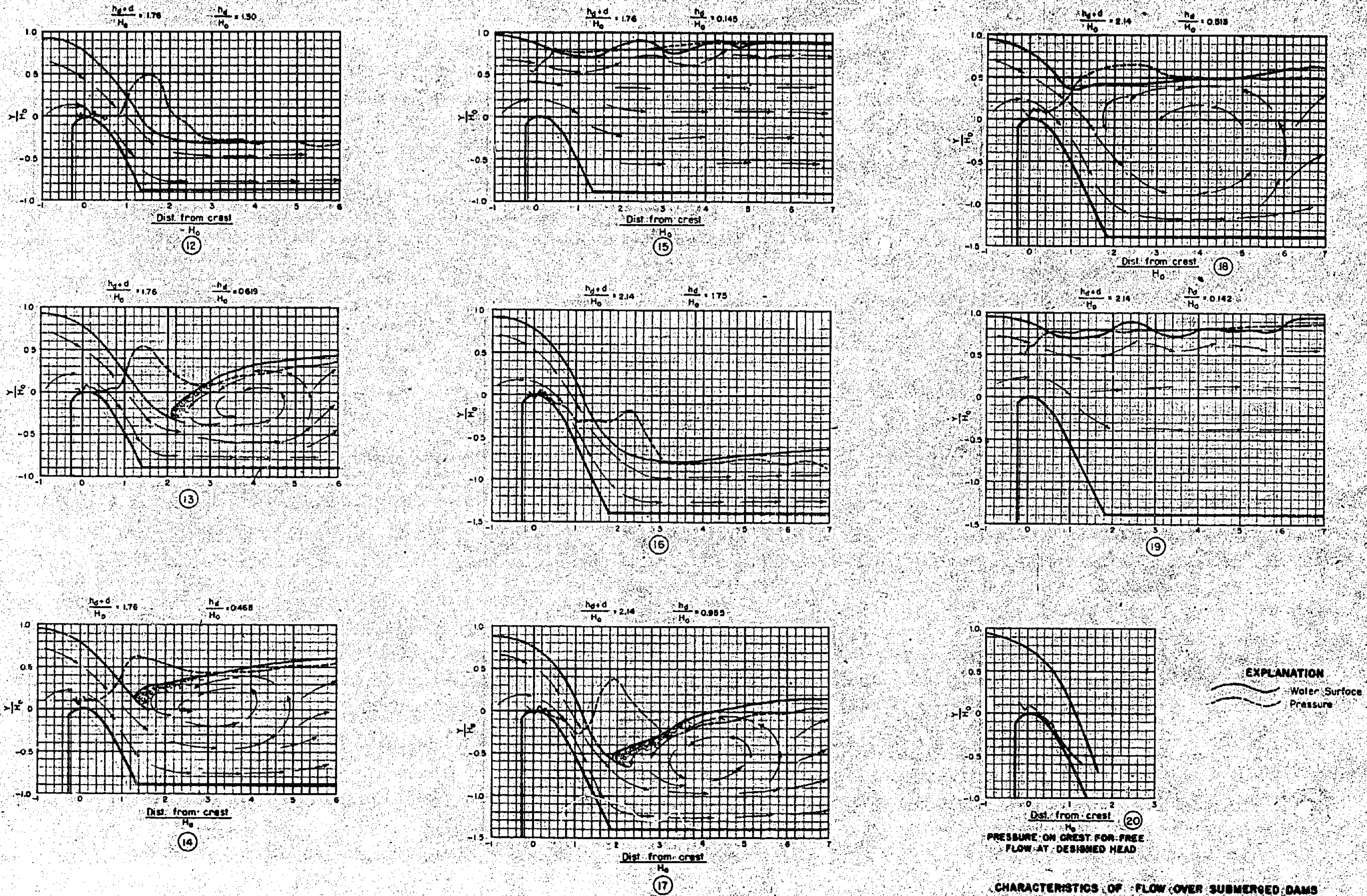
GEOMETRIC RELATIONSHIPS, AND DECREASE OF THE COEFFICIENT OF DISCHARGE CAUSED BY INTERFERENCE FROM THE DOWNSTREAM FLOOR AND SUBMERGENCE

FIGURE 4



CHARACTERISTICS OF FLOW OVER SUBMERGED DAMS

TYPICAL PRESSURE AND WATER SURFACE PROFILES AS OCCUR AT POINTS INDICATED ON FIGURE 1



CHARACTERISTICS OF FLOW OVER SUBMERGED DAMS

TYPICAL PRESSURE AND WATER SURFACE PROFILES AS OCCUR AT POINTS INDICATED ON FIGURE 1

An inspection of the dashed lines on Figure 3A, of constant decrease in the discharge coefficient, indicates that where these lines are vertical, the decrease in the coefficient of discharge was principally due to the effect of the downstream floor and independent of submergence. As the downstream floor neared the crest of the dam, or $\frac{h_d + d}{H}$ approched 1.0, the coefficient of discharge decreased to 23 percent. With the downstream floor level with the crest, the dam was virtually a broad crested weir for which the theoretical decrease should approximate 23 percent.

Where the lines designated as decrease in coefficient, are horizontal for values of $\frac{h_d + d}{H}$ greater than 1.70, the downstream floor no longer affected the coefficient of discharge and the decrease in discharge coefficient was caused entirely by submergence. For values of $\frac{h_d + d}{H}$ less than 1.70 the decrease in the coefficient was produced by floor effect or a combination of submergence and floor effect.

It appears odd that the dash lines for Type III flow should rise as the value of $\frac{h_d + d}{H}$ increases. This was caused by a change in flow and can be clarified by reference to Plots 14 and 18 on Figure 5. Plot 14 is Type II flow and Plot 18 is Type III flow while the value of $\frac{h_d}{H}$ is practically the same for the two. In the first case, a true hydraulic jump existed and little submergence effect was present. In the second case, the tailwater depth was approximately the same, but the backwater effect was more pronounced. In other words, the point of contact between the jet falling over the dam and the tailwater occurs at $\frac{Y}{H_o} = 0.15$ in Plot 14 and 0.35 in Plot 18. In all cases, the depth of flow on the downstream floor was measured at a point $4H_o$, or four times the designed head, downstream from the crest of the dam.

Free flow coefficients of discharge have been plotted with respect to the ratio of the operating head to the designed head on a dam, for different depths of the approach channel on Figure 3B. The data for plotting the curves was obtained principally from models tested, over a period of time, in the Bureau Hydraulic Laboratory. A check on this data from other sources 1/ showed excellent agreement. The purpose of

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1/ Davis Handbook of Applied Hydraulics, Page 341 (data of E. W. Lane). Davis Handbook of Applied Hydraulics, Page 23 (data of W. L. Voorduin). "The Submerged Weir as a Measuring Device," by Glen Nelson Cox, University of Wisconsin Engineering Experiment Station Bulletin No. 67.

the curves on Figure 3B is to aid the designer in determining the reduction or increase in the free flow coefficient for a given dam operating at other than the designed head.

Test Results on Pressures

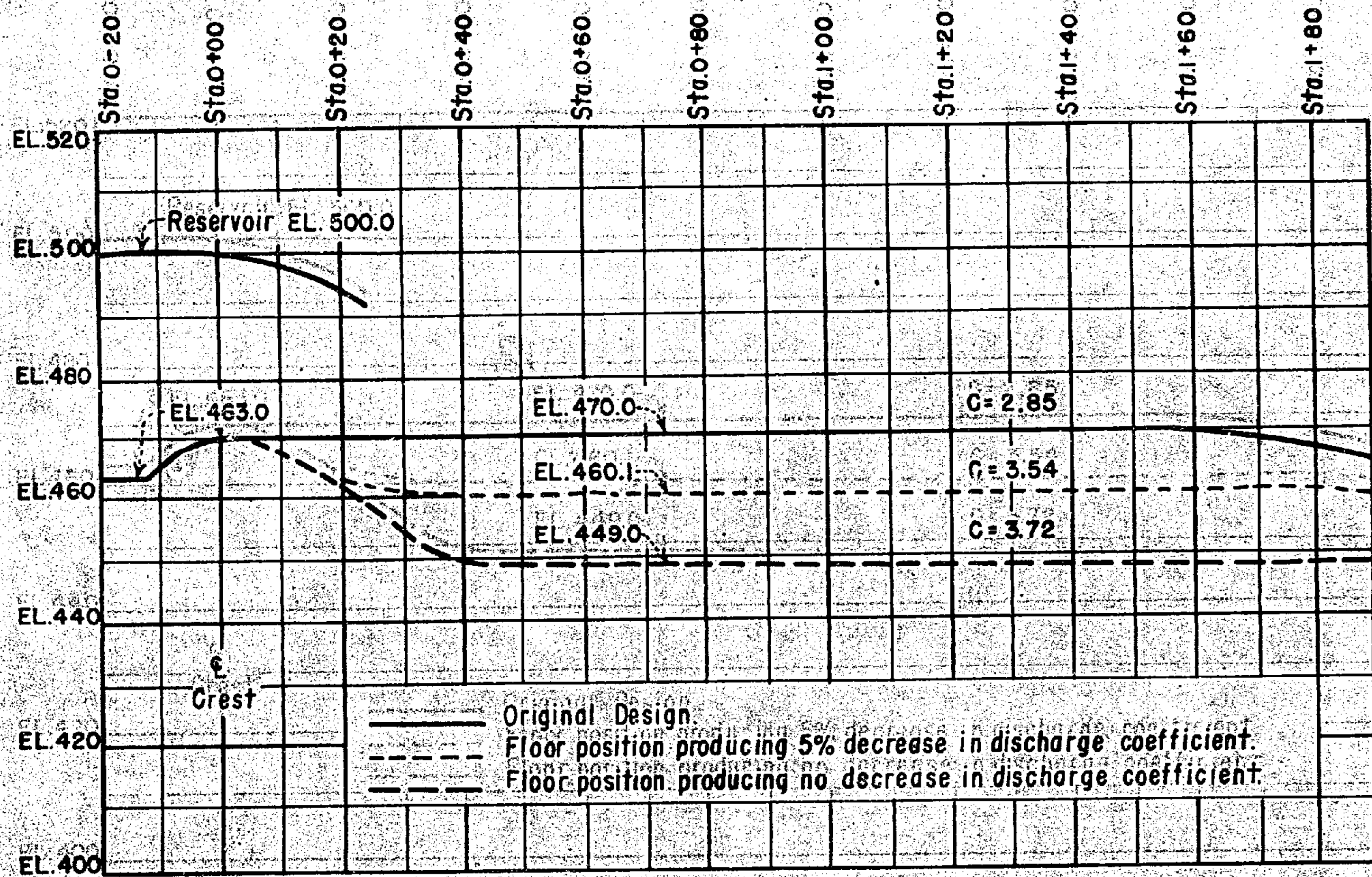
In addition to typing the flow and plotting the decrease in the coefficient of discharge for each case, pressures and water surface profiles were measured along the flume for a few representative types of flow on Dam B. The runs were all made with the dam operating at the designed head, H_o, and the results, Figures 4 and 5, have been plotted in dimensionless terms with respect to this head. The axes of coordinates originate at the crest of the dam. The conditions under which these runs were made are indicated by the numbers within the circles on Figure 3A. These runs were made in an effort to provide data on stability determinations for small dams.

Application of Results

The following examples serve to illustrate the use of the preceding information on submerged dams. Earth dam spillways are usually flat in longitudinal cross-section as they closely follow the profile of the dam. The gate section and upstream portion of one of these is shown by the full line on Figure 6. The coefficient of discharge for this spillway is 2.85. In contrast, the coefficient of discharge for the shape indicated by the dashed line on the same Figure is 3.725. The latter shape was designed such that the overflow section would fit the shape of the undernappe of the sheet of water flowing over it for the maximum discharge condition. This phase of design was covered in Hydraulic Laboratory Report HYD-118. The economy involved in providing a small ogee at the gate section is evident from the above coefficient and it is now common practice to design earth dam gate sections in this manner. The following example illustrates the method of determining the position of the floor downstream from the ogee.

Example 1

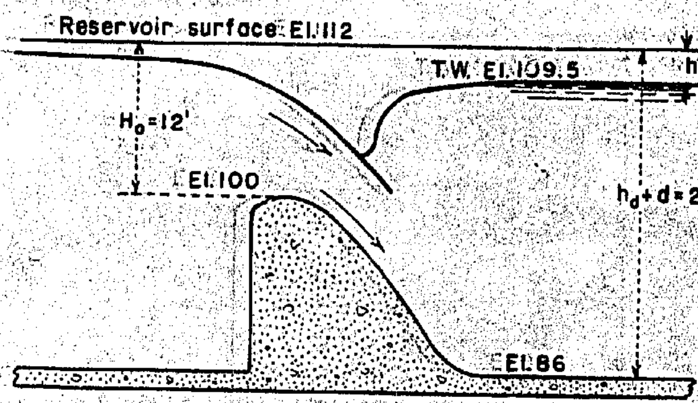
Design the downstream portion of the overflow section of the earth dam spillway in Figure 6 for a minimum amount of excavation, allowing a decrease in the free flow coefficient of discharge not to exceed 5 percent for the maximum discharge condition. The crest of the overflow section is at elevation 470.0 and the total head on the crest H_o = 30.0 feet. The flow immediately downstream from the overflow section will occur at less than critical depth and will therefore resemble that of Type I on Figure 3A. Tailwater is not a consideration in this case.



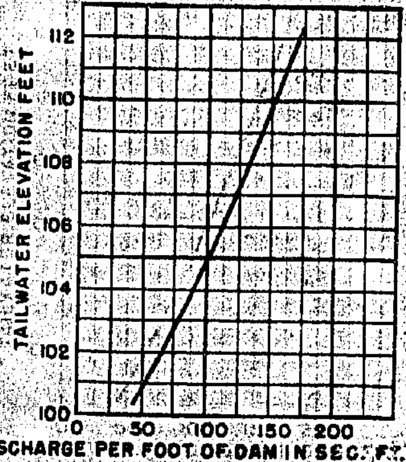
SUBMERGED DAM STUDIES
RESULTS OF EXAMPLE I

FIGURE 6

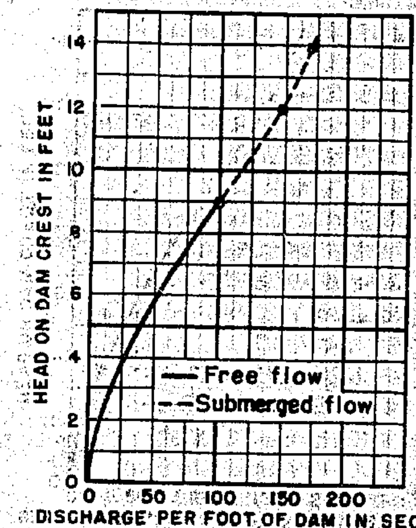
FIGURE 7



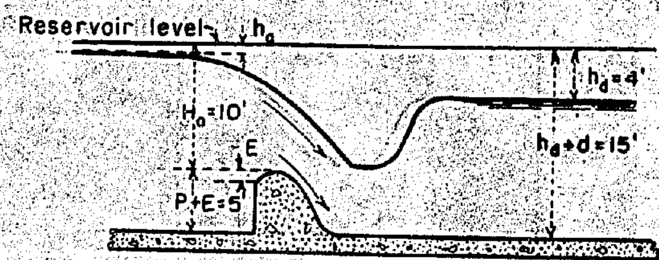
A — SUBMERGED DAM FOR EXAMPLE 2



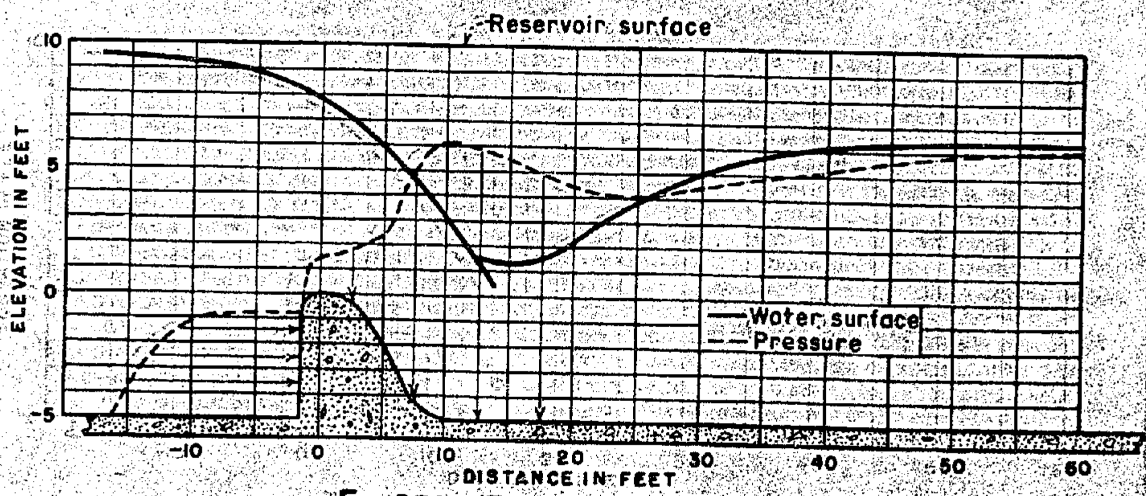
B — TAILWATER — DISCHARGE FOR EXAMPLE 3



C — RESULTS OF EXAMPLE 3



D — DAM FOR EXAMPLE 4



E — RESULTS OF PROBLEM 4

SUBMERGED DAM STUDIES

DETAILS AND RESULTS OF
EXAMPLES 2, 3 AND 4

By following down the line for Type I flow (Figure 3A), to a decrease in the coefficient of discharge of 5 percent, the values of the main coordinates at this point are $\frac{h_d}{H_o} = 0.81$ and $\frac{h_d + d}{H_o} = 1.33$.

$$h_d = 0.81 \times 30.0 = 24.30 \text{ feet and}$$
$$h_d + d = 1.33 \times 30.0 = 39.90 \text{ feet.}$$

The position of the floor should therefore be 39.90 feet below the reservoir level for the maximum flow condition or 500.00 - 39.90 = 460.1 feet in elevation. This floor is indicated by the dotted line on Figure 6.

The depth of flow on a horizontal floor at a point $4H_o$, or 120 feet downstream from the crest, d = 39.90 - 24.30 = 15.60 feet, and Graph 4 on Figure 4 indicates the type of flow to be expected. The coefficient of discharge for the downstream floor at elevation 5460.1 (Figure 6) will be 3.54.

Example 2

Given the dam shown in Figure 7A for which the shape and free flow coefficient of discharge were determined by the method previously described in Hydraulic Laboratory Report HYD-118. Compute the discharge per foot of crest length and determine the type of flow which will be encountered for the conditions shown. The free flow coefficient of discharge is 3.90.

$$\frac{h_d}{H_o} = \frac{2.5}{12} = 0.208$$

$$\frac{h_d + d}{H_o} = \frac{26}{12} = 2.168$$

Entering Figure 3A with these values, it is found that the point falls within Region III. A drowned jump will occur and the coefficient of discharge will be 9 percent less than the free flow coefficient.

The actual coefficient of discharge for the flow conditions shown therefore will be $C_s = 3.90 \times 0.91 = 3.55$.

The discharge per foot of length of dam will be

$$Q = CH^{3/2} = 3.55 \times 12^{3/2} = 14.75 \text{ second-feet.}$$

These examples serve as an introduction to the use of curves on Figure 3A. The solution of the following example requires successive approximations.

Example 3

Given the tailwater curve shown on Figure 7B for the dam in Example 2. Compute a headwater curve for the same range of discharges.

One point on the head-discharge curve was determined in Example 2. A second point will be chosen for a discharge of 170 second-feet per foot of crest, which will involve greater than the designed head on the crest. This corresponds to a tailwater elevation of 112.0, Figure 7B.

Assuming H = 13.5 feet.

$$\frac{h_d}{H} = \frac{1.5}{13.5} = 0.111 \text{ and}$$

$$\frac{h_d + d}{H} = \frac{27.5}{13.5} = 2.04$$

From Figure 3A the decrease in the coefficient of discharge, compared to that for a free crest, is 25 percent, and the flow is indicative of Region IV.

The ratio of the estimated head to the designed head is $\frac{13.5}{12} = 1.125$.

From Graph B on Figure 3, the free flow discharge coefficient for a head of 13.5 feet on the crest and $\frac{P_1 + E}{H_o} = \frac{14}{12} = 1.165$, is 3.99.

The actual coefficient of discharge is therefore 3.99 x 0.75 = 2.99.

$$H^{3/2} = \frac{Q}{C} = \frac{170}{2.99} = 56.9$$

and H = 14.8 feet, which is larger than the assumed value.

Choosing a new value of H = 13.9, the process is repeated. Other new values are

$$\frac{h_d}{H} = \frac{1.9}{13.9} = 0.137$$

$$\frac{h_d + d}{H} = \frac{27.9}{13.9} = 2.007$$

$$\text{and } \frac{H}{H_o} = \frac{13.9}{12} = 1.16$$

From Figure 3A, C = 18 percent decrease.

From Figure 3B, C for free crest = 4.00.

The actual coefficient of discharge for the case at hand

$$C_s = 4.00 \times 0.82 = 3.28$$

$$H^{3/2} = \frac{170}{3.28} = 52.0$$

and H = 13.93 feet, which agrees reasonably well with the assumed value. This locates a second point on the head-discharge curve Figure 7C.

An attempt now will be made to determine the head at which submergence begins. Choosing a discharge of 100 second-feet, the tailwater, Figure 7B, is at elevation 105.

Assuming H = 9 feet,

$$\frac{h_d}{H} = \frac{4}{9} = 0.445$$

$$\frac{h_d + d}{H} = \frac{23}{9} = 2.556 \quad \text{and} \quad \frac{H}{H_o} = \frac{9}{12} = 0.75.$$

From Figure 3A, C = 1.7 percent decrease.

From Figure 3B, the free flow coefficient C = 3.77.

Then $C_s = 3.77 \times 0.983 = 3.706$.

$$H^{3/2} = \frac{100}{3.706} = 27.0$$

and H = 9.00 feet.

This agrees with the assumed head and thus locates a third value very close to the point at which submerged flow begins. The remainder of the curve is completed by substituting free flow coefficients in the equation $Q = CH^{3/2}$. The completed head-discharge curve is shown on Figure 7C.

Example 4

From the dimensions shown on Figure 7D, determine the approximate water surface and the hydraulic pressures opposing uplift on the dam and apron, for the head and tailwater elevation given. The free flow coefficient C = 3.80.

From Figure 3A,

$$\frac{h_d}{H_o} = \frac{4}{10} = 0.40$$

and $$\frac{h_d + d}{H_o} = \frac{15}{10} = 1.50.$$

The curves also show that a hydraulic jump can be expected downstream from the dam for these conditions accompanied by a 2.5 percent decrease in the coefficient of discharge. The decrease is produced principally by floor effect and not submergence. Figure 3 A also indicates that flow over the dam will be similar to that shown in Graphs 8 and 9 on Figure 4. It should again be mentioned that the diagrams on Figures 4 and 5 are for flow at the designed head only, at which pressures on the dam for the free flow condition appraoch zero.

The water surface and pressure curves for Example 4 can be obtained by averaging the coordinates from Graphs 8 and 9, Figure 4, and multiplying the values of H_o as outlined in Table 2.

Table 2

		Water surface		Pressure profile	
$\frac{X}{H_o}$	X Feet	$\frac{Y}{H_o}$	Y Feet	$\frac{Y}{H_o}$	Y Feet
-1	-10	0.92	+9.2		
-0.5	-5	0.89	8.9		
0	0	0.79	7.9	0.15	+1.5
+0.5	+5	0.59	5.9	0.24	2.4
1.0	10	0.31	3.1	0.62	6.2
1.5	15	0.13	1.3	0.55	5.5
2.0	20	0.22	2.2	0.44	4.4
2.5	25	0.38	3.8	0.41	4.1
3.0	30	0.49	4.9	0.45	4.5
3.5	35	0.57	5.7	0.49	4.9
4.0	40	0.62	6.2	0.52	5.2
5.0	50	0.64	6.4	0.58	5.8
+6.0	+60	0.64	+6.4	0.62	+6.2

The water surface and hydraulic gradient from Table 2 have been plotted on Figure 7E. The pressures have been plotted vertically above the points at which they were measured.

The pressures on the upstream face of the dam can be obtained from Figure 8. The information on Figures 8, 9, 10, and 11, which applies to dams with vertical and sloping upstream faces, was obtained from experimental data described in HYD-122.

To illustrate the method of procedure, the pressures on the upstream face of the dam in Example 4 will be determined.

$$C_s = 3.80 \times 0.975 = 3.706,$$

$$Q = CH^{3/2} = 3.706 \times 10^{3/2} = 117.2 \text{ second-feet per foot of crest,}$$

$$V_a = \frac{Q}{A} = \frac{117.2}{15} = 7.81 \text{ feet per second,}$$

and $$h_a = \frac{V^2}{2g} = \frac{(7.81)}{2g} = 0.948 \text{ feet (velocity head of approach).}$$

FIGURE 8

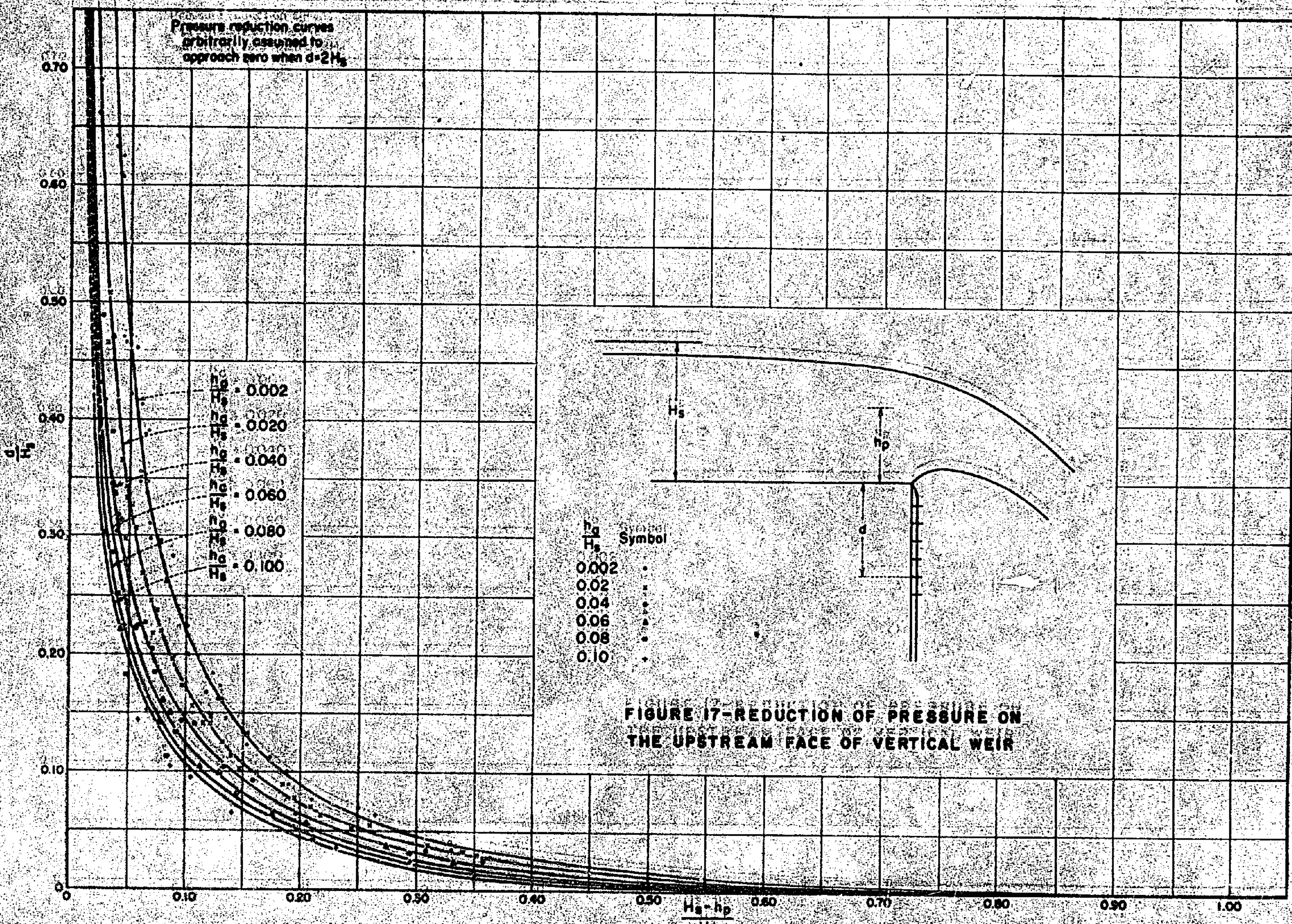


FIGURE 17-REDUCTION OF PRESSURE ON THE UPSTREAM FACE OF VERTICAL WEIR

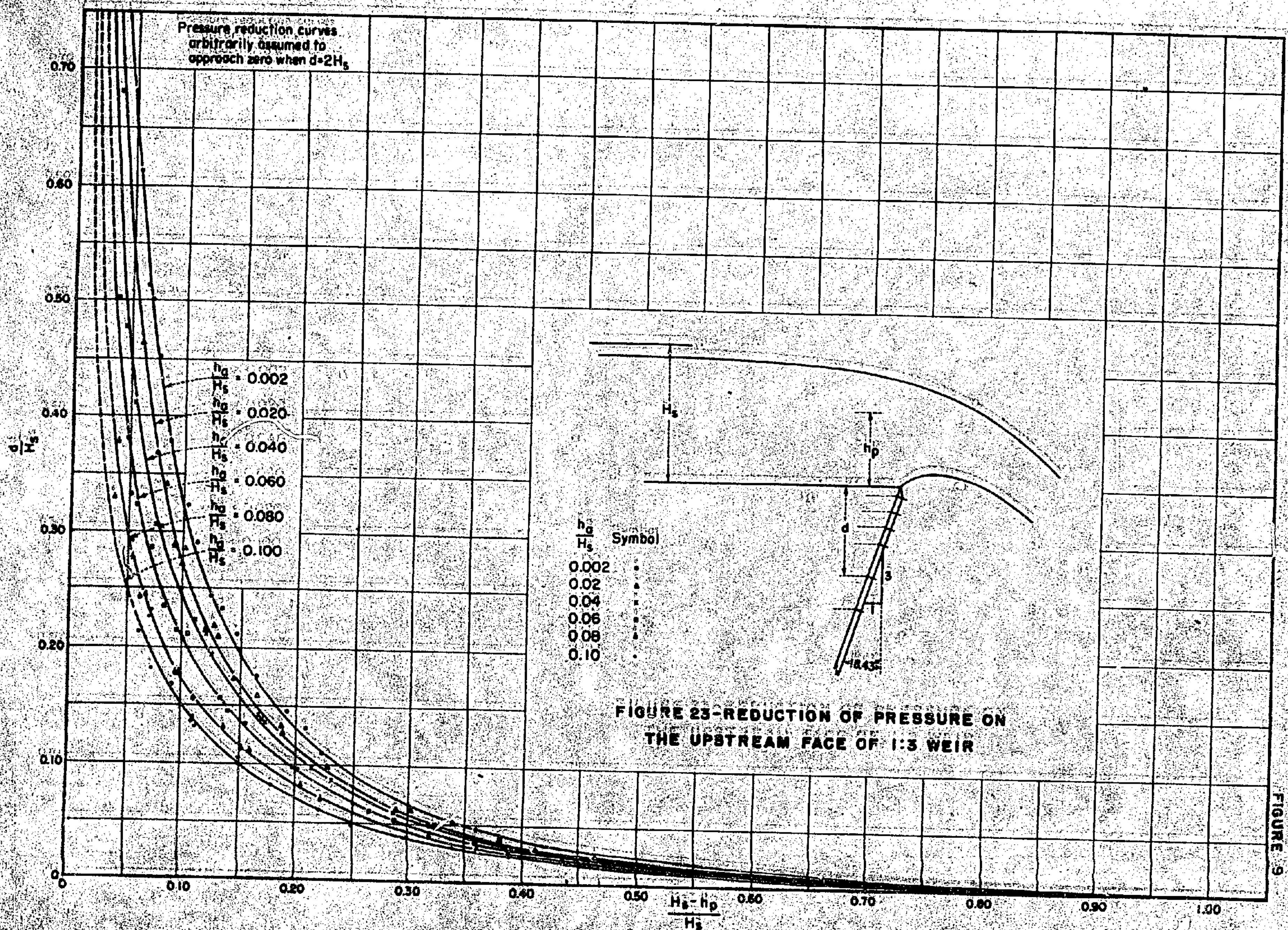


FIGURE 23-REDUCTION OF PRESSURE ON THE UPSTREAM FACE OF 1:3 WEIR

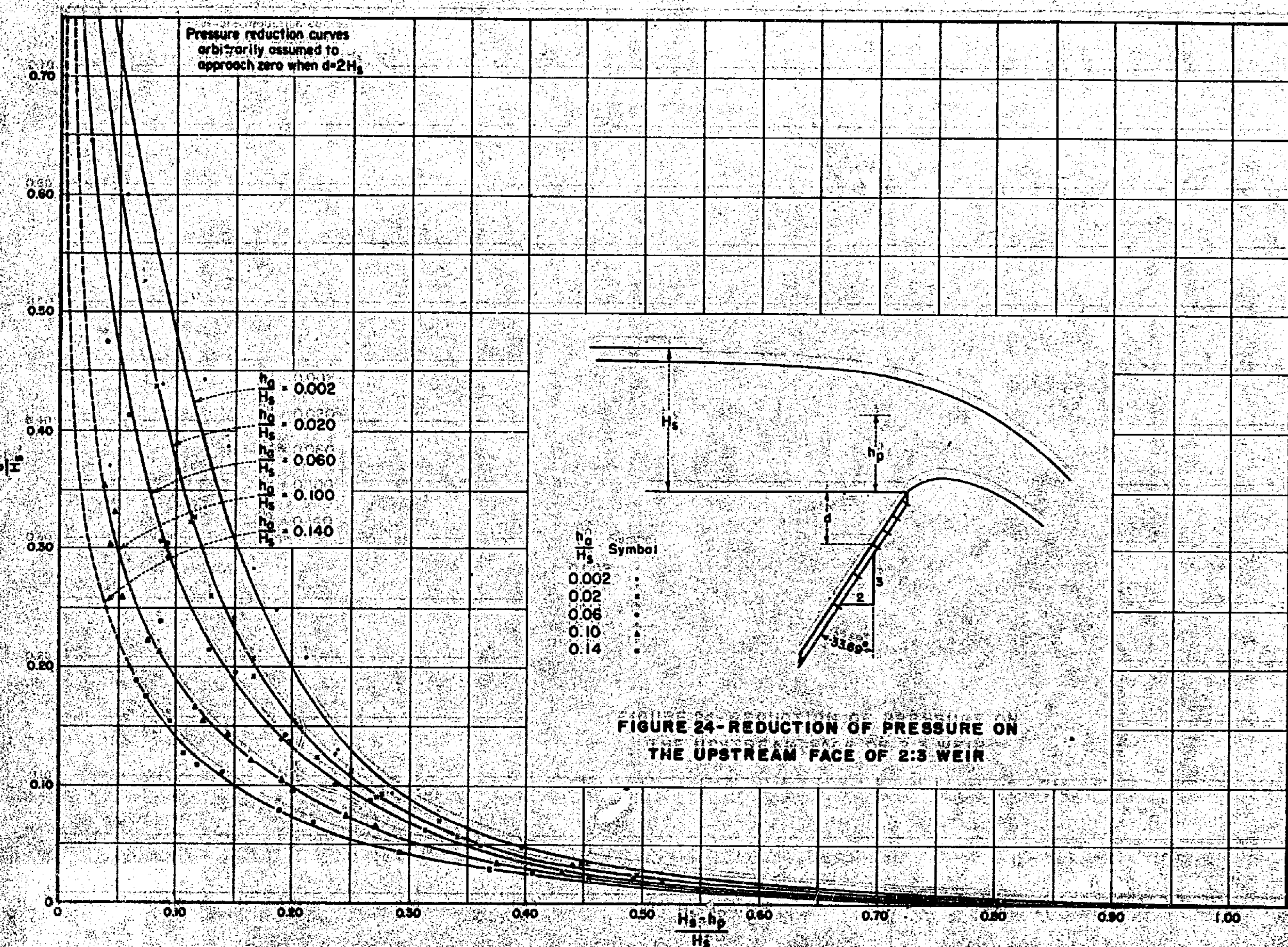


FIGURE 24 - REDUCTION OF PRESSURE ON THE UPSTREAM FACE OF 2:3 WEIR

FIGURE 10

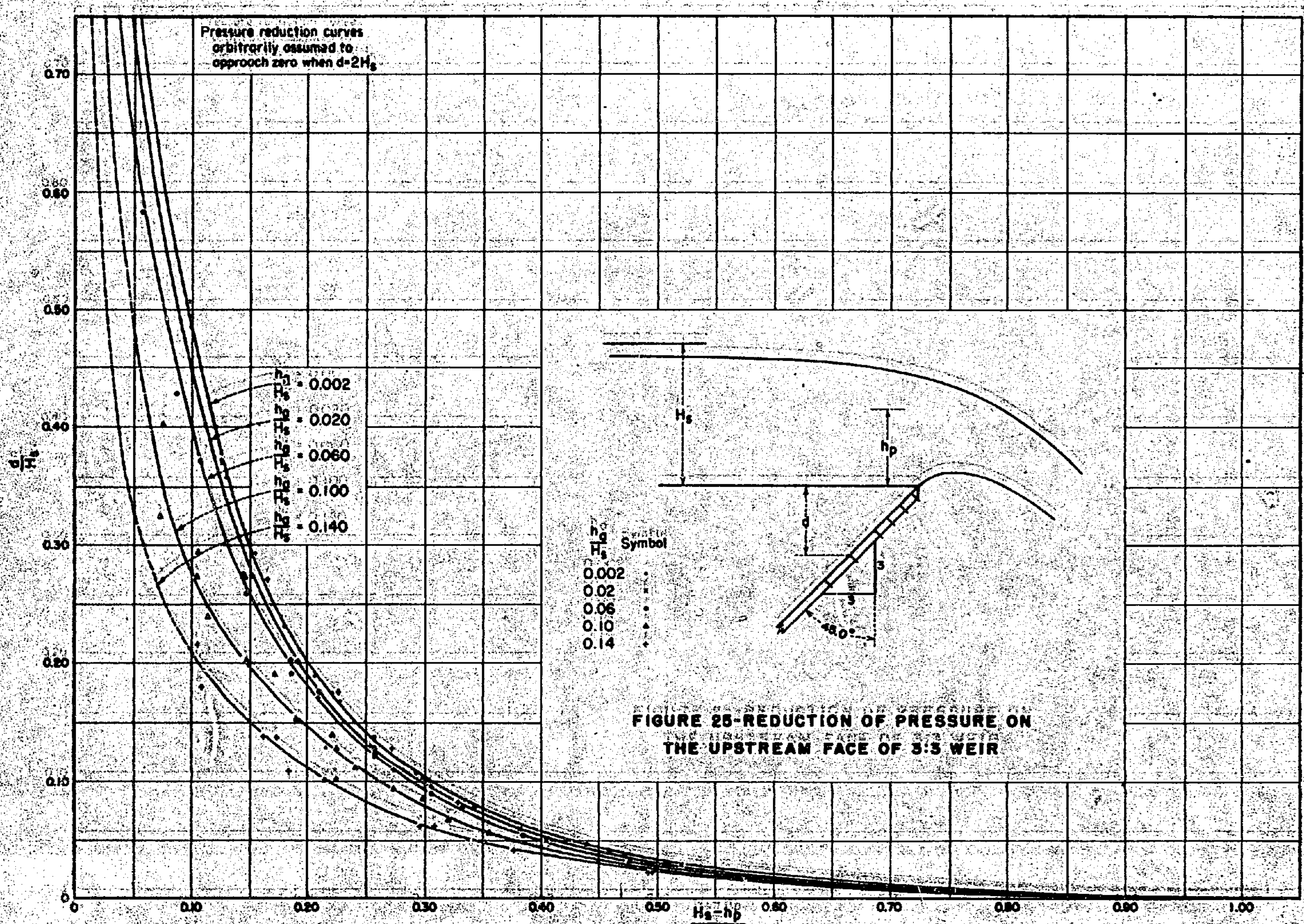


FIGURE 25-REDUCTION OF PRESSURE ON THE UPSTREAM FACE OF 3:3 WEIR

Assuming $H_s = H_o$,

$$\frac{h_a}{H_s} = \frac{0.948}{10} = 0.0948.$$

Entering Figure 12A, with this value,

$$\frac{E}{H_s} = 0.075,$$

$$H_s = H_o + E,$$

$$H_s = 10 + 0.075 H_s,$$

then $H_s = \frac{10}{0.925} = 10.79$ feet (approximately).

The procedure is repeated to obtain additional accuracy by using the new value of H_s.

$$\frac{H_a}{H_s} = \frac{0.948}{10.79} = 0.0879.$$

From Figure 12A, $\frac{E}{H_s} = 0.077.$

The expression for H_s becomes

$$H_s = 10 + 0.077 H_s$$

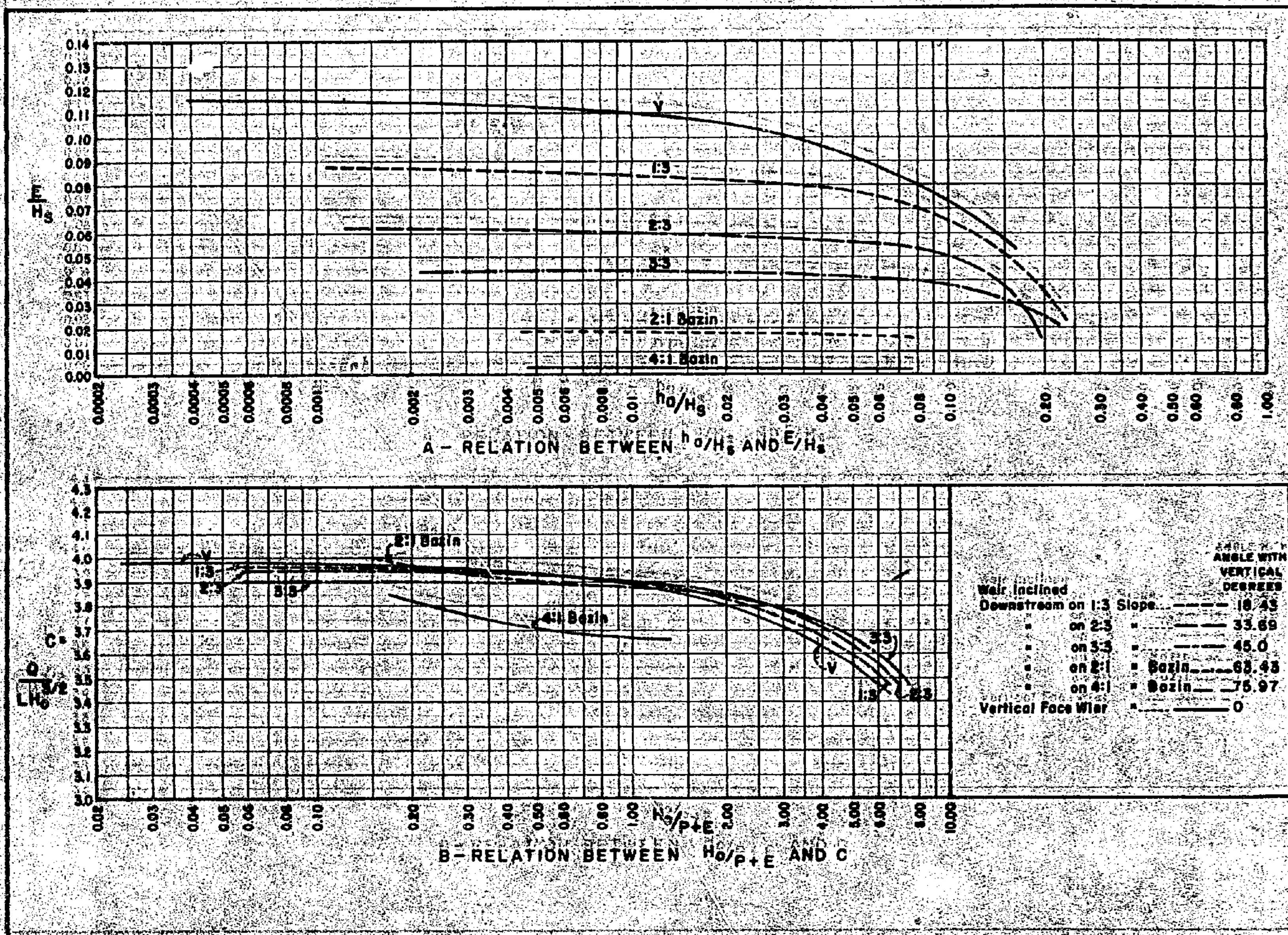
and $H_s = \frac{10}{0.923} = 10.84$ feet.

A new value of $\frac{H_a}{H_s} = \frac{0.948}{10.84} = 0.0875$ and $E = 0.077 \times 10.84 = 0.83$ feet.

The accuracy here is probably greater than necessary, but serves to illustrate the method for obtaining H_s. By choosing values of $\frac{d}{H_s}$ and making use of Figure 8, the pressures on the upstream face of the dam are obtained. The method is illustrated in Table 3.

Figure 12 is the same as Figure 6 in HYD-118.

FIGURE 12



A – RELATION BETWEEN h_o/H_s AND E/H_s

B – RELATION BETWEEN $H_o/P+E$ AND C

Table 3

$\frac{H_a}{H_s} = 0.0875$ $H_s = 10.84$ feet

d Feet	$\frac{d}{H_s}$	$\frac{H_s - h_p}{H_s}$	h_p Feet	$h_p + d$ Feet
0	0	1.0	0	0
0.1	0.01	0.400	6.50	6.60
0.2	0.02	0.300	7.59	7.79
0.5	0.05	0.195	8.73	9.23
1.0	0.10	0.110	9.65	10.65
2.0	0.20	0.050	10.30	12.30
3.0	0.30	0.030	10.52	13.52
4.0	0.40	0.020	10.62	14.62

The above coordinates are referred to the spring point of the overflow section and these are shown plotted on Figure 7E. The next step constitutes determining the forces produced by uplift pressures, the weight of the concrete in the dam and apron, etc., with all other forces known, then dam and apron can be analyzed in sections or as a whole for stability. This report purposely supplies only the downward and horizontal acting hydraulic pressures on the dam and apron.

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1/ The experimental information in this book deserves detailed study.
