DISCHARGE RATING CURVES FOR VERTICAL LIFT GATES ON SPILLWAY CRESTS

MISCELLANEOUS PAPER NO. 2-606

October 1963

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

PREFACE

This miscellaneous paper summarizes a study on discharge coefficients for vertical lift spillway crest gates. The study was made in connection with revision of the Engineer Manual, "Hydraulic Design of Spillways," EM 1110-2-1603, for the Office, Chief of Engineers by the Hydraulic Analysis Branch of the U. S. Army Engineer Waterways Experiment Station.

The study was accomplished and this paper prepared by the Hydraulics Division of the U. S. Army Waterways Experiment Station, under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division and Mr. F. B. Campbell, Chief of the Hydraulic Analysis Branch. The procedure described in this paper was conceived and developed by Mr. R. H. Multer, Hydraulic Engineer, Analysis Section. The necessary computations and preparation of this paper were also accomplished by Mr. Multer under the supervision of Mr. R. G. Cox, Chief of the Analysis Section.

Director of the Waterways Experiment Station during the study and preparation and publication of this paper was Col. Alex G. Sutton, Jr., CE. Technical Director was Mr. J. B. Tiffany.

DISCHARGE RATING CURVES FOR VERTICAL LIFT GATES ON SPILLWAY CRESTS

GENERAL

1. The development of discharge rating curves for gates installed on a spillway crest is important for reservoir regulation. Adequate rating curves can be readily developed if the spillway is model tested. In cases where model studies are not made, rating curves are usually based on discharge equations using empirical coefficients derived from laboratory and field investigations. The orifice-type discharge equation is commonly used for this purpose.

2. Examination of figure 1 shows that vertical lift crest gates have been used with a variety of crest shapes and approach geometries. Examination of figures 2 and 3 shows that direct analysis of the discharge data using the discharge relationship given by orifice type equations is unsatisfactory for the four cases considered. The lack of correlation of the discharge coefficients is attributed to insufficient knowledge of the hydraulic effects of the many geometrical variables involved. It is therefore essential that a procedure be found to correlate discharge data without attempting to evaluate the effects of the geometric variables. The purpose of this study is to devise such a procedure utilizing readily available data. Model studies of Falcon(1), Bluestone(2), Gorge High(3) and Mahoning(4) Dams spillways were selected for this purpose. As shown on figure 1, these spillways represent a wide variety of crest shapes, gate seat locations, approach conditions, and operating heads.

ANALYSIS

3. Study of model and prototype pressure profiles on gated crests disclosed the fact that for partly opened gates the pressure along the spillway is nearly atmospheric, i.e. the ratio of the pressure head to total head on the crest was small. The gate opening might, therefore, be considered to be an orifice with relatively small upstream head to orifice opening ratios, and with unusual approach geometry. A satisfactory equation for the discharge from such an orifice, written with gate notation, is:(5) (6)

$$Q_G = C_d \sqrt{2g}\, L(H^{3/2} - H_1{}^{3/2}) \qquad (1)$$

where

L = effective crest length including pier effects

H = total head at the bottom of the gate opening

H_1 = total head at the top of the gate opening

Q_G = discharge from a gate bay or series of gate bays depending on the L considered

C_d = discharge coefficient

In this study, the principal variables are defined as follows:

G_o = gate lip elevation - gate seat elevation

H = pool elevation - crest elevation

$H_1 = H - G_o$

These definitions are used because equation 1 is not an exact equation in this case and because the problem associated with using more sophisticated variables seems unwarranted.

4. In general, the discharge for a given crest with the gates removed from the flow (uncontrolled flow) is a quantity which may be computed with

with reasonable accuracy. It seems reasonable, therefore, to attempt to relate the gate discharge to the uncontrolled discharge. The equation for uncontrolled flow is:

$$Q = C_{df} \sqrt{2g}\, L\, H^{3/2} \qquad (2)$$

Dividing equation 1 by equation 2 and substituting $(H - G_o)$ for H_1

$$\frac{Q_G}{Q} = \mu \left[1 - (1 - \frac{G_o}{H})^{3/2} \right] \qquad (3)$$

μ is a coefficient which must be evaluated.

5. Figure 4 is a plot of discharge data sampled from model study reports of Gorge High(3), Mahoning(4), Bluestone(2), and Falcon(1) Dams. From this graph it appears that a satisfactory correlation between the data and equation 3 is obtained. It would seem also from figure 4 that μ could be assigned the average values there shown.

6. An evaluation of μ may be made for the particular case where the gate opening is equal to the depth of uncontrolled flow, d_f, at the gate seat location. When $G_o = d_f$, $Q_G = Q$, and from equation (3)

$$\mu = \frac{1}{1 - (1 - \frac{d_f}{H})^{3/2}} \qquad (4)$$

The relationship between d_f and H may be readily obtained from model rating curves because $G_o = d_f$ when $Q_G = Q$ and for each given value of Q there is a corresponding single value of H. This is to say that H is the head at the intersections of the controlled and uncontrolled rating curves. In this study d_f/H values were computed from smoothed plots of d_f versus H (figure 5).

7. If sufficient information is available equation 4 should provide a slightly better description of μ than would the average values given on figure 4. For the standard WES high vertical crest sufficient values of d_f versus H are available for evaluation of equation 4(7). Plots of d_f versus H (fig. 5) tend to be straight lines; thus if the corresponding weir has been studied a reasonable value of μ could also be deduced from the weir study data. An examination of the various data sets yields the additional information that:

a. Some slight varience of μ occurs for a given head as the gate opening changes. (See table 1 below.)

TABLE 1

Variation of μ With Gate Opening

Bluestone Dam Model Study

H	d_f	μ from Eq. 4	Gate Opening	μ from Eq. 3
			2	1.21
15	10.2	1.22	4	1.21
			6	1.17
			8	1.16
			Average	1.19
			2.5	1.11
			5	1.12
30	22	1.16	10	1.04
			15	1.04
			20	1.06
			Average	1.07

b. The average value of μ from equation 3 is approximately 0.96 of the μ from equation 4. (See table 2 below.)

TABLE 2

Relative μ Values

Project	H	μ from Eq. 3 (Average)	μ from Eq. 4	Ratios
Bluestone	15	1.19	1.22	0.98
	30	1.07	1.16	0.92
Gorge High	45	1.00	1.06	0.94
	25	1.07	1.10	0.97
Falcon	53.3	1.05	1.08	0.97
	63.3	1.07	1.09	0.99
			Average	0.96

d. If the range of H is restricted to

$$0.2\ H_d \leq H \leq H_d$$

$$0.70\ H \leq d_f \leq 0.85\ H$$

then from equation 4

$$1.19 \geq \mu \geq 1.06$$

From this information it would seem that an accurate equation for the discharge under a vertical lift gate would be

$$\frac{Q_G}{Q} = 0.96 \left[\frac{1}{1 - (1 - \frac{d_f}{H})^{3/2}}\right]\left[1 - \left(1 - \frac{G_o}{H}\right)^{3/2}\right] \qquad (5)$$

Unfortunately sufficient information is not generally available for evaluating d_f as a function of H. Thus, equation 4 is of little present value except as an explanation for the divergence of the data sets on figure 4. Since for any particular project $d_f/H = f\ (H/H_d)$, (H_d = the design head) and since $\mu \approx f_1\ (d_f/H)$, it is evident that $\mu \approx F\ (H/H_d)$.

TABLE 3

Comparison of Measured and Computed Discharges

MEASURED					COMPUTED - FIG. 6			
H	Q	G_o	Q_G	Rel H/H_d	G_o/H	Q_G/Q	Q_G	σ
				GORGE HIGH DAM				
50'	119,500	6	21,000	Near 1	.12	.175	20,900	0.5
		20	62,800		.40	.55	65,700	4.5
		30	89,000		.60	.76	90,800	2.0
30'	51,900	4	11,000	Near ½	.133	.21	10,900	1.0
		10	24,600		.333	.89	25,400	4.8
		16	36,300		.533	.74	38,800	5.8
15'	17,300	2	4,000		.133	.22	3,800	5.0
		4	7,400	Near 0.3	.266	.43	7,430	0
								$3.0 = \bar{\sigma}$
				BLUESTONE DAM				
30'	388,000	5	94,000	Near 1	.166	.25	96,500	2.6
		10	181,000		.333	.475	183,000	1.1
		20	338,000		.667	.85	328,000	3.0
20'	192,000	2.5	38,000	Near 2/3	.125	.20	38,400	1.0
		5	75,000		.25	.305	73,900	1.5
		10	138,000		.50	.70	13,500	2.2
10'	62,000	1.0	10,000	Near 1/3	.10	.165	10,200	2.0
		2.5	25,600		.25	.405	25,100	0
		5.0	50,000		.50	.74	45,900	8
								$1.8 = \bar{\sigma}$
				FALCON DAM				
63.3	500,000	10	123,000	1.0	.16	.245	123,000	0
		20	230,000		.32	.46	231,000	0
		30	321,000		.47	.63	316,000	1.6
43.3	283,000	10	97,000	2/3	.23	.36	102,000	5.1
		20	179,000		.46	.64	181,000	1.0
		30	247,000		.69	.89	252,000	2.0
23.3	102,000	5	35,000	1/3	.22	.36	36,700	2.2
		10	69,000		.43	.67	68,300	1.0
								$1.6 = \bar{\sigma}$
				MAHONING DAM*				
30'	92,000	4	17,600	1	.133	.210	19,300	1.6
		10	42,000		.33	.475	43,700	4.0
		20	80,000		.67	.85	78,200	2.3
15'	30,000	2	6,200	1/2	.133	.215	6,300	1.7
		4	12,600		.27	.415	12,600	0
		6	18,000		.40	.57	18,500	2.0
								$2.0 = \bar{\sigma}$

*V bottom gate, upstream position

Hence, useful average values of μ may be derived for various H/H_d ratios.

8. Figure 6 is a design chart based on the above considerations where μ was assumed to be 1.03 for relatively high heads and 1.14 for heads of 0.3 or less of the design head. Table 3 is a comparison of discharges computed using figure 6 and of discharges measured in the model. The relative accuracy of figure 6 may be seen in the following tabulation abstracted from table 3.

TABLE 4

Deviation of Computed and Measured Discharges

Model Study	Average Deviation of Computed from Measured Discharge
Gorge High Dam	3.0
Bluestone	1.8
Falcon	1.6
Mahoning	2.0

DISCUSSION

9. The particular form of the equation used to describe the discharge from a certain type of gate is probably not too important if the equation is dimensionally correct and the effects of all geometric variables on the discharge coefficient are considered. The important thing is that the effect of varying the geometry be understood. In some cases insufficient information is available for the multiple correlation of the effect of the several important variables. It is then a possibility that the effect of these variables may be accounted for by a lumping parameter. In this study the uncontrolled flow discharge Q was used as the lumping parameter. It is also felt that ratio correlation (here Q_G/Q) may provide better agreement between data sets than does analysis using absolute quantities

because linear errors in the calibration of measuring equipment are eliminated and the effect of scale is much reduced. For Bluestone Dam a definite discrepancy for discharges at various gate openings appeared in figures 21 and 22 of reference 2. At the common head value of 30 ft this discrepancy caused a 3% shift in μ. Figure 21(2) was used except in tables 3 and plate 4.

10. A probable error of less than 3% (table 3) was indicated in the use of figure 6 to rate vertical lift gates. This amount of error is well within the range of error of most hydraulic design information. Since errors in estimating Q produce only linear errors in the derived values of Q_G and since a review of recent model studies indicates that Q may be estimated quite accurately, errors in Q should present no problem in determining Q_G accurately.

11. A diverse group of structures was considered in this study. Therefore, figure 6 should be applicable to most design possibilities. It is believed that the theory developed here does not necessarily apply to low sills or gates located relatively far downstream from the crest because the pressure head at the spillway surface becomes a much larger proportional part of the total head. A parellel analysis should, however, prove satisfactory.

12. The effect of the gate lip geometry on discharge was not considered in this study. The model study of Mahoning Dam showed that for two different types of gate lips, one with a "V" bottom and the other with an elliptical bottom, a sizeable change in discharge occurred. The gate with the elliptical bottom had the greater discharge. It is suggested that if a gate with an elliptical bottom is contemplated, the gate opening in equation 3 be taken as the nominal gate opening plus the height of the gate

lip (measured to the top of the upstream fairing) (fig. 7). The Mahoning model data used in the basic study was for the "V" bottomed gate.

CONCLUSIONS

13. It is concluded that the uncontrolled flow discharge is a satisfactory parameter to account for changes in geometry when rating vertical lift gates. Using this parameter the equation

$$\frac{Q_G}{Q} = 0.96 \left[\frac{1}{1 - (1 - \frac{d_f}{H})^{3/2}} \right] \left[1 - (1 - \frac{G_o}{H})^{3/2} \right] \qquad (5)$$

was developed. Since sufficient information is not generally available for evaluating d_f as a function of H, it is necessary to resort to the equation

$$\frac{Q_G}{Q} = \mu \left[1 - (1 - \frac{G_o}{H})^{3/2} \right] \qquad (3)$$

and to use μ values which are averaged with respect to H/H_d. A design chart developed on this basis is shown on figure 6. It is estimated that the use of this chart or of figure 4 in computing gate discharges would produce errors of less than 3 percent. For gates with streamlined bottoms, it is recommended the gate opening be taken as G_o plus the gate lip height.

List of References

1. "Hydraulic Model Studies at Falcon Dam," USBR, Hydraulic Laboratory Report No. Hyd - 276, July 1950.

2. "Laboratory Tests on Hydraulic Models of Bluestone Dam," prepared by Carnegie Institute of Technology for Huntington District, CE, Feb. 1937.

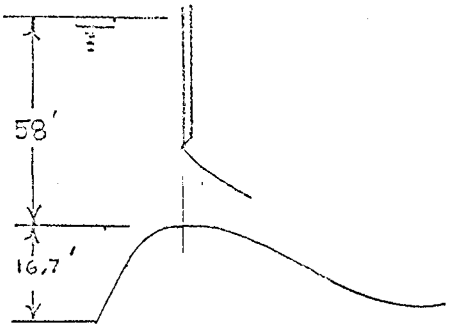
3. "Hydraulic Model Studies of Gorge High Dam Spillway and Outlet Works," USBR Hydraulic Laboratory Report No. Hyd-403, Sept. 1955.

4. "A Report on Hydraulic Model Studies for the Spillway and Outlet Works of Mahoning Dam," prepared for Pittsburgh District, CE, by USCE, unnumbered hydraulic report. Case School of Applied Science, May 1938.

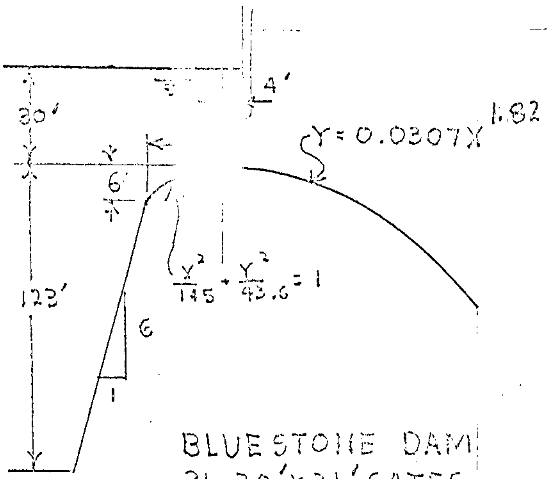
5. "Elementary Mechanics of Fluids," by H. Rouse, pp.90-91.

6. "Handbook of Hydraulics" by H. King, 3rd Ed., p.46.

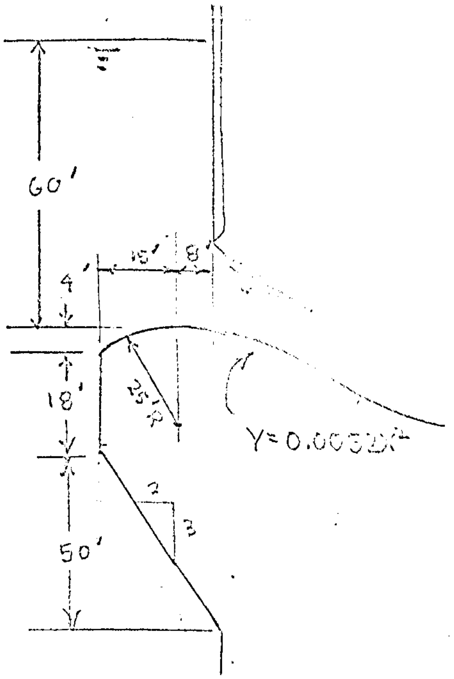
7. Hydraulic Design Criteria Chart 111-15, USAEWES.



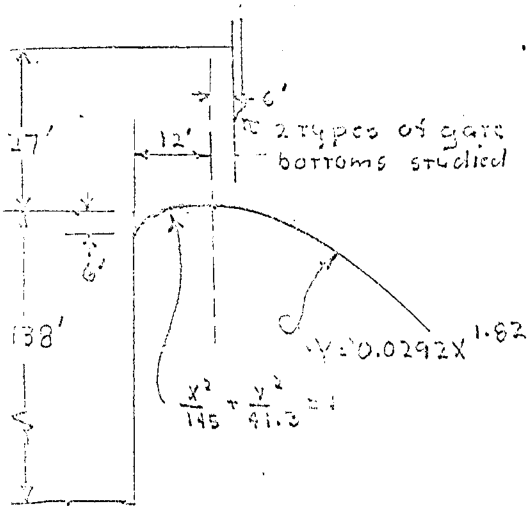
FALCON DAM
SCALE 1:130
6 - 50' × 50' GATES



BLUESTONE DAM
21 - 30' X 31' GATES
SCALE 1:36



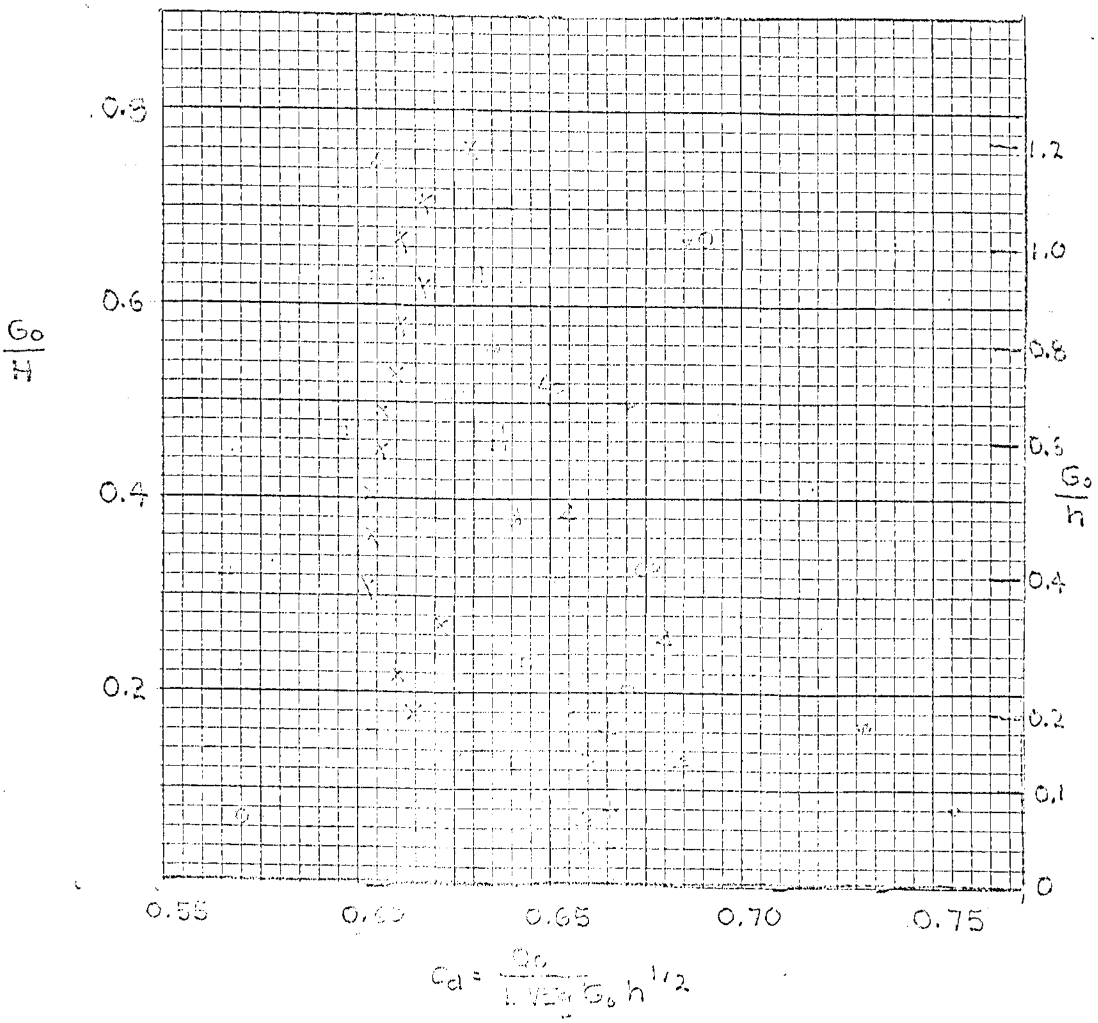
[illegible] HIGH DAM
SCALE 1:48
2 - 47' X 50' GATES

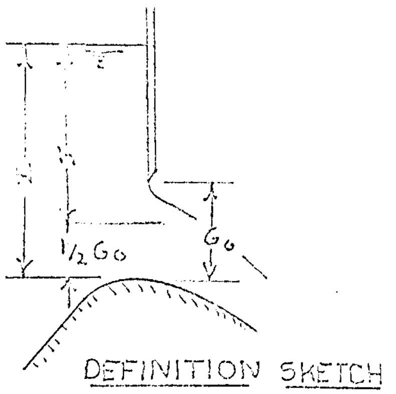


MAHONING DAM
SCALE 1:72
5 - 30' X 27' GATES

VERTICAL LIFT GATES
PROJECT DESCRIPTION

FIG. 1

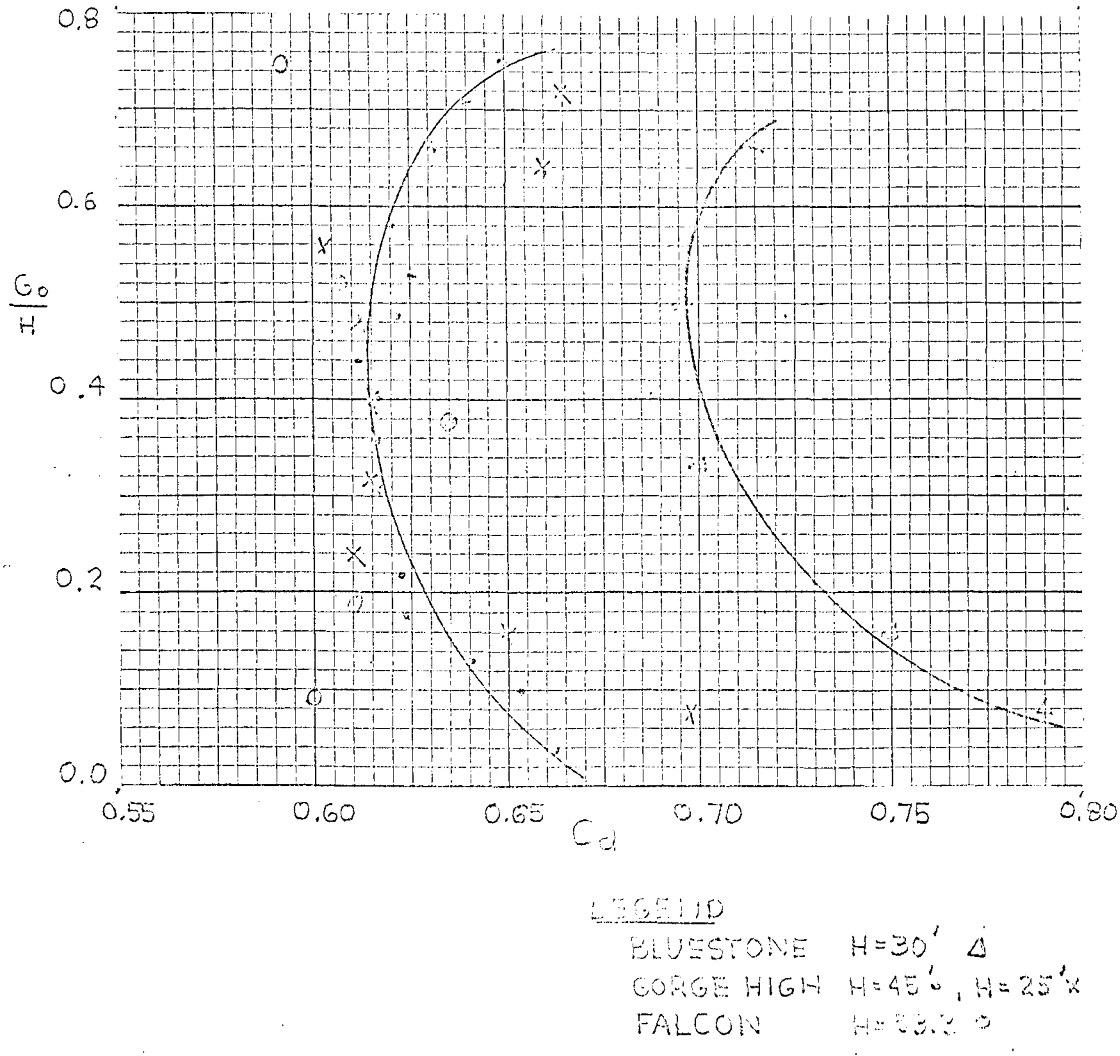


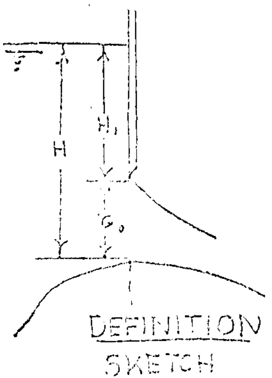


DEFINITION SKETCH

VERTICAL LIFT GATE
DISCHARGE COEFFICIENT
SIMPLE ORIFICE

FIG. 2



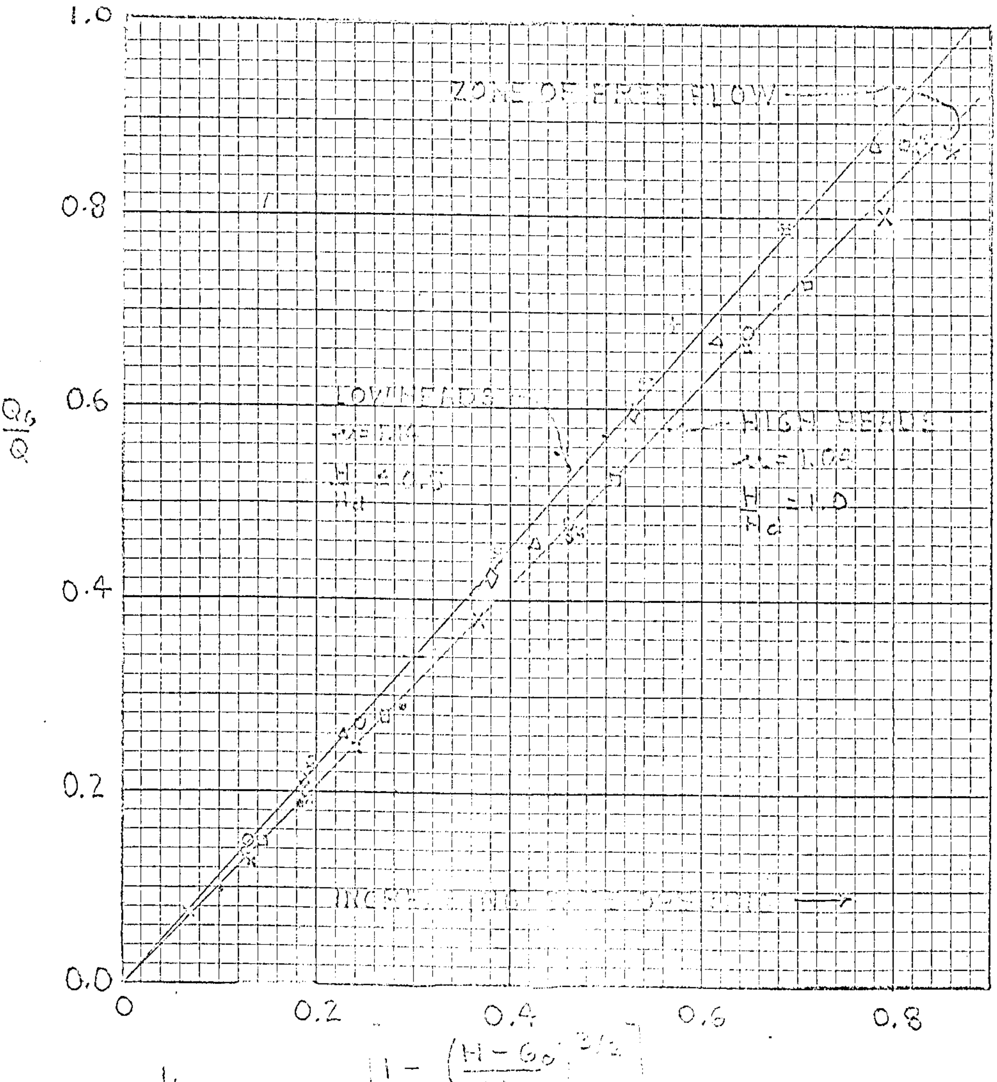


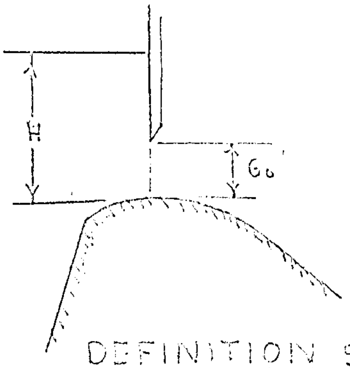
DEFINITION SKETCH

$$Q_G = C_d \sqrt{2g}\, L \left(H^{3/2} - H_1^{3/2}\right)$$
WHERE $H_1 = H - G_o$

VERTICAL LIFT GATES
DISCHARGE COEFFICIENTS

FIG. 3





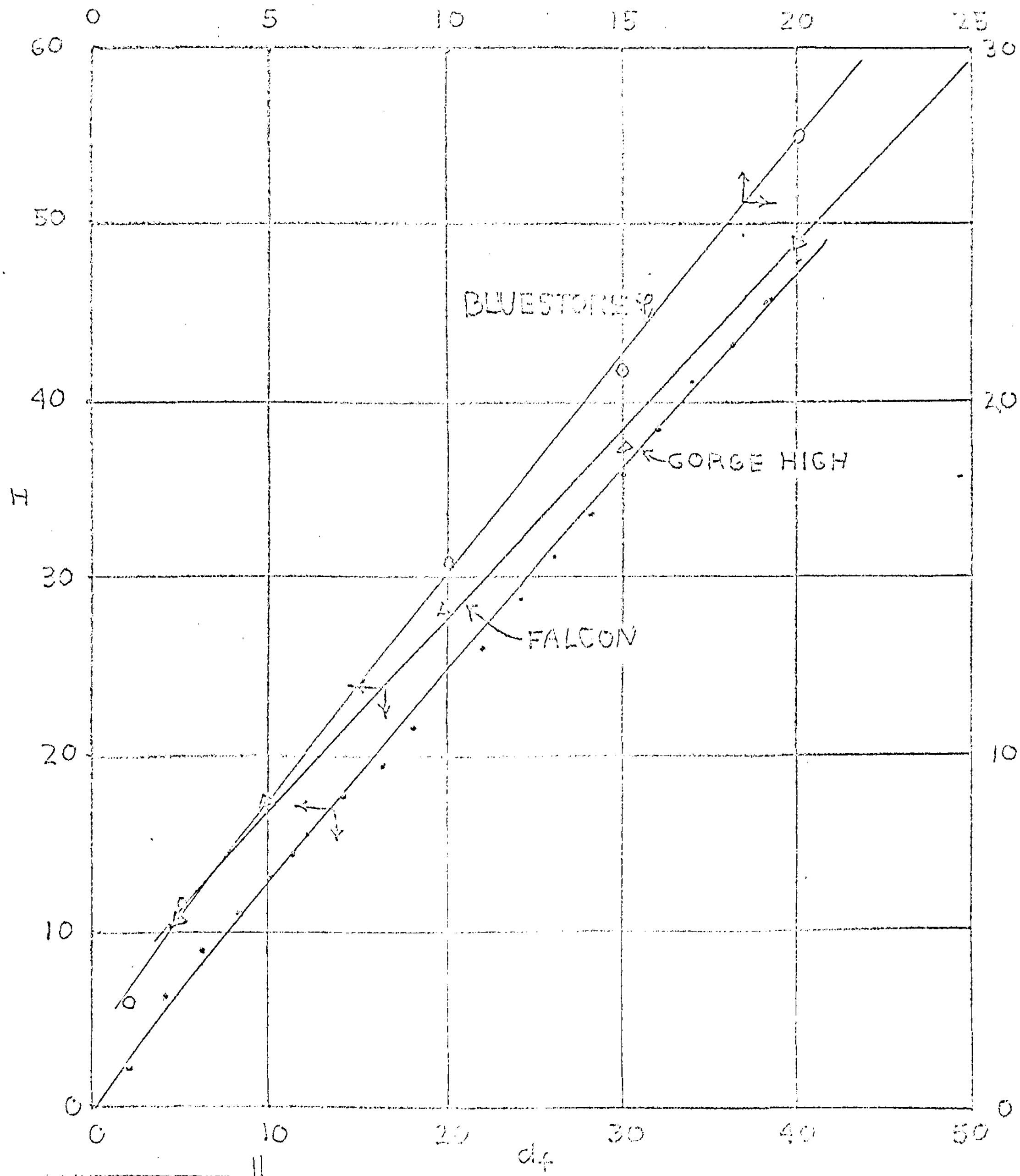
DEFINITION SKETCH

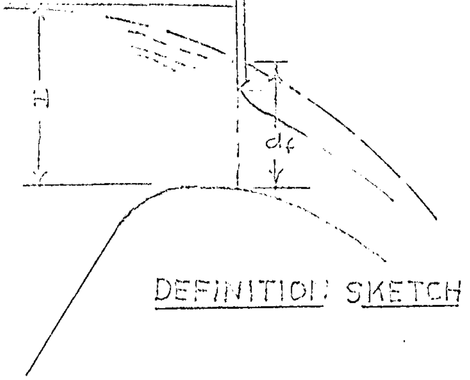
H = POOL ELEVATION - CREST ELEVATION
G_o = GATE LIP ELEV. - GATE SEAL ELEV.
Q = FREE FLOW DISCHARGE AT HEAD H
Q_o = DISCHARGE AT HEAD H AND GATE OPENING G_o

LEGEND
GORGE HIGH H = 45' ×, H = 25' △
BLUESTONE H = 30' ⊠, H = 15' ⊡
FALCON H = 53.3' ⊡, H = 23.3' ◇
MAHONING H = 30' ▽ H = 15' ◇
BLUESTONE (SEC. MODEL) H = 30' ○

VERTICAL LIFT GATES
RELATIVE DISCHARGE

FIG. 4

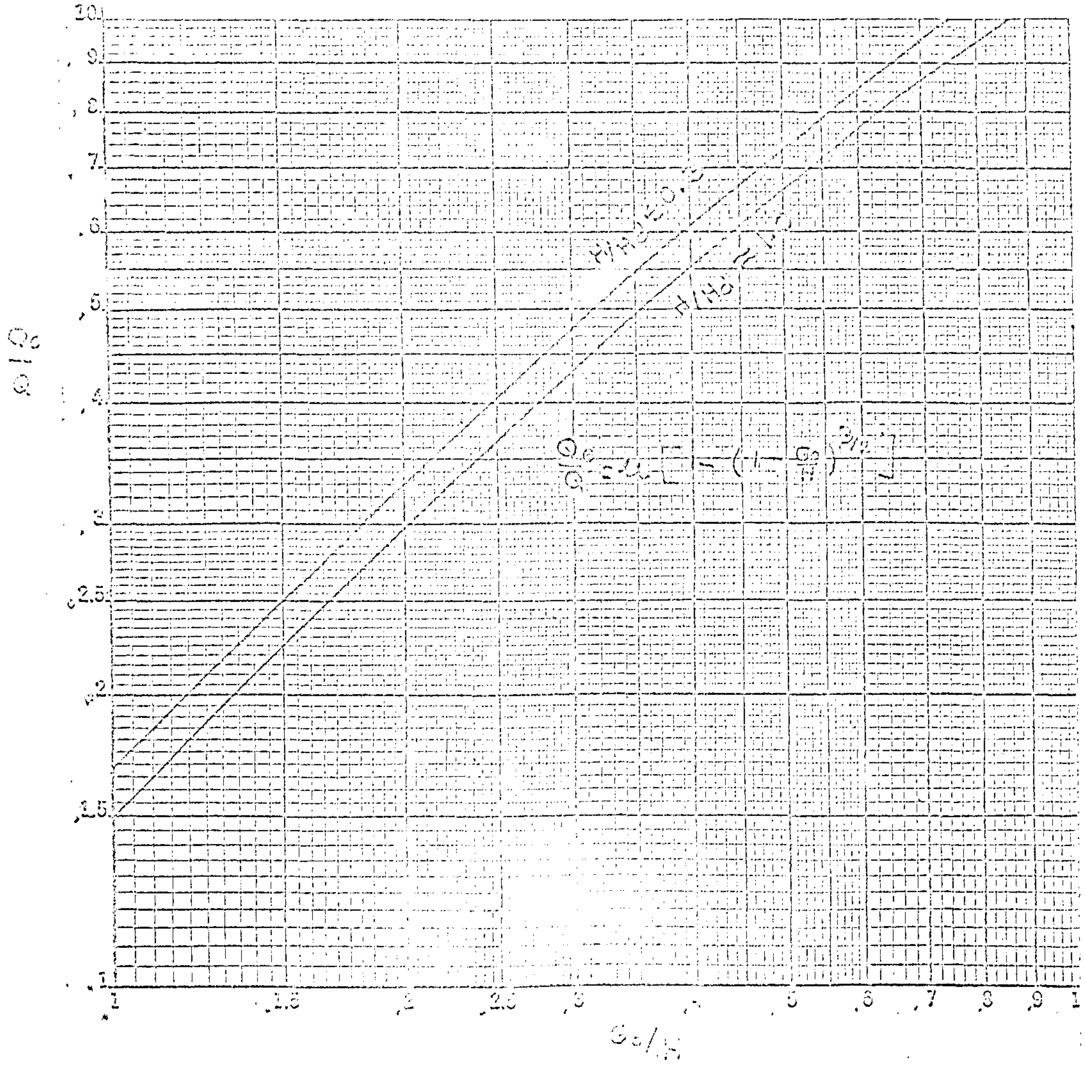




DEFINITION SKETCH

VERTICAL LIFT GATES
FREE FLOW DEPTH

FIG. 5



H = POOL ELEV. - CREST ELEV

Go = GATE LIP ELEV. - GATE SEAL ELEV.

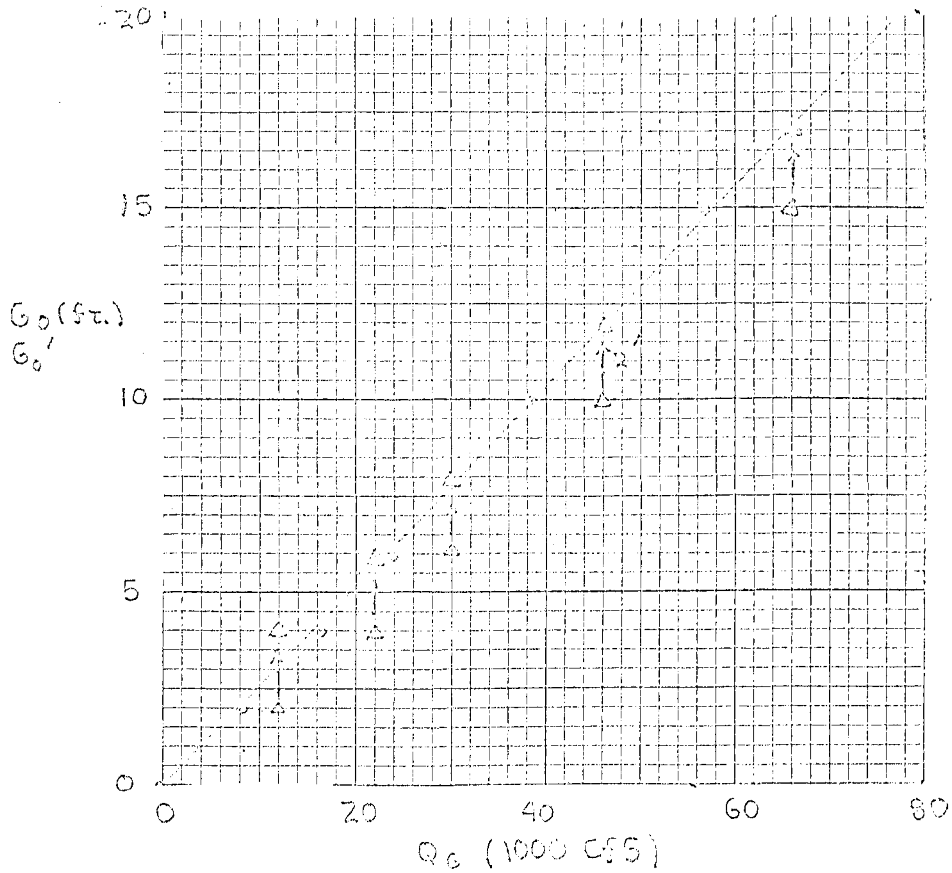
Q = FREE FLOW DISCHARGE AT HEAD H

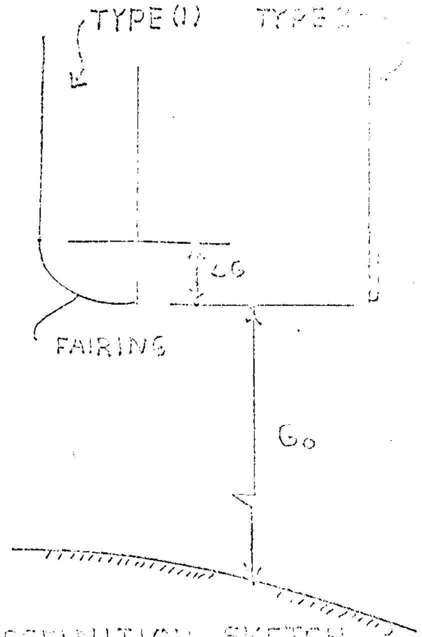
Qo = FLOW UNDER GATE AT SAME HEAD

NOTE: $\mu = 0.96\left[\frac{1}{1-(1-dH/H)^{3/2}}\right]$

VERTICAL LIFT GATE
DISCHARGE RATING

FIG. 6





DEFINITION SKETCH

NOTES: H = POOL ELEV ~ CREST
[illegible] = 25'
ΔG WAS SCALED AS
2' (CRUDE)
$G_o' = G_o + \Delta G$
DATA FROM MAHONING
DAM MODEL STUDY

LEGEND

G_o, TYPE (2) [illegible] ○
G_o, TYPE (1) GATE Δ
G_o', " " " [illegible]

VERTICAL LIFT GATES
INVESTIGATION OF
ELIPTICAL GATE LIP

FIG. 7

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