DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 11, DUBUQUE, IOWA

By Albert J. Heinitz

U.S. GEOLOGICAL SURVEY

Water Resources Investigations Report 85-4105

Prepared in cooperation with the

U.S. ARMY CORPS OF ENGINEERS,
ROCK ISLAND DISTRICT

Iowa City, Iowa
1985

Reprinted with revisions, 1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, SECRETARY

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SYMBOLS AND UNITS

Symbol	Definition	Unit
A	Area of lock chamber	ft^2
a	Elevation difference, trunnion centerline to sill	ft
B	Lateral width of a tainter or roller gate	ft
B_s	Length of fixed spillway	ft
C	Free-orifice flow coefficient of discharge	
C_{gs}	Submerged-orifice flow coefficient of discharge	
C_{sw}	Free-weir flow coefficient of discharge, fixed spillway	
C_{sws}	Submerged-weir flow coefficient of discharge, fixed spillway	
C_w	Free-weir flow coefficient of discharge, gate crest	
C_{ws}	Submerged-weir flow coefficient of discharge, gate crest	
g	Acceleration due to gravity	ft/s^2
G	Gage indicator reading	ft
H_1	Total headwater head including velocity head referenced to gate sill	ft
h_1	Static-headwater head referenced to gate sill	ft
h_3	Static-tailwater head referenced to gate sill	ft
H_{1s}	Total headwater head including velocity head referenced to the gate crest	ft
h_{1s}	Static-headwater head referenced to gate crest	ft
h_{3s}	Static-tailwater head referenced to gate crest	ft
h_g	Gate opening	ft
N	Number of lockages occurring between recordings	

Symbol	Definition	Unit
Q	Computed discharge per gate	ft^3/s
Q_s	Computed fixed-spillway discharge	ft^3/s
Q_L	Computed lock-chamber discharge	ft^3/s
R	Radius from trunnion centerline to upstream face of a tainter gate	ft
R.P.	Reference point to which elevations are run for the purpose of computing the gate opening	
r	Radius from trunnion centerline to gate R.P.	ft
$\Delta h=h_1 - h_3$	Static-head loss through structure	ft
Δt	Time between recordings	sec
θ	Included angle between radial lines from the trunnion centerline through the R.P. and through the lower lip of the gate	deg
ϕ_u	The angle measured from the horizontal to the radial line from the trunnion centerline through the gate R.P. with the gate in a closed position	deg
$<$	Less than	
$>$	Greater than	
$\geq$	Equal to or greater than	

FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM UNITS (SI)

The following factors may be used to convert the inch-pound units published herein to the International System of Units (SI)

Multiply inch-pound units	By	To obtain SI units
	-Length-	
foot (ft)	0.3048	meters
mile	1.609	kilometers
	-Area-	
square foot (ft^2)	0.0929	square meter
	-Flow-	
cubic feet per second (ft^3/s)	0.02832	cubic meters per second
	-Acceleration-	
foot per second squared (ft/s^2)	0.3048	meter per second squared
	-Weight-	
pound	0.4536	kilogram

DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 11, DUBUQUE, IOWA

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ABSTRACT

The water level of the navigation pools on the Mississippi River are maintained by the operation of tainter and roller gates at the locks and dams. Discharge ratings for the gates on Lock and Dam 11, at Dubuque, Iowa, were developed from current-meter discharge measurements made in the forebays of the gate structures. Methodology is given to accurately compute the gate openings of the tainter gates. Discharge coefficients, in equations that express discharge as a function of tailwater head, forebay head, and height of gate opening, were determined for conditions of submerged-orifice and free-weir flow. A comparison of the rating discharges to the hydraulic-model rating discharges is given for submerged-orifice flow for the tainter and roller gates.

INTRODUCTION

The present navigation system on the Upper Mississippi River between St. Paul, Minnesota, and St. Louis, Missouri, was initiated in 1930 when Congress passed the River and Harbor Act authorizing funds for its development. This legislation provided for a navigation channel at least 9 feet deep and 400 feet wide, to be established by constructing a series of locks and dams, and maintained by channel dredging. The dams create a series of "steps" which allow towboats or other river vessels to travel upstream or downstream. Each dam controls the level of its pool and the locks lift or lower vessels from one pool to the next. Lock and Dam 11 was placed in operation September 14, 1937.

This is the first in a series of reports relating to discharge ratings and hydraulic characteristics of the control gates at locks and dams on the Mississippi River. Discharge ratings are concurrently being developed for Locks and Dams 14 and 16. During the course of these studies it was observed that the hydraulic characteristics of the roller gates at Dams 11 and 14 were nearly identical. For this reason, the flow coefficients for the Dam 14 roller gates were used to corroborate the Dam 11 rating development in this study.

Revisions

The equations for computing the flow coefficients and the discharges for the condition of "free-weir" flow (gates submerged) for both the tainter and roller gates have been revised. Lock and Dam 11 is operated in the free-weir flow position during the winter season to maintain the winter pool elevation.

The following is a list of revisions that were made:

1) Equations 11 and 12 for free-weir flow for the tainter gates.
2) Figures 8 and 9 which illustrate equations 11 and 12.
3) Equations 18 and 19 for free-weir flow for the roller gates.
4) Figures 12 and 13 which illustrate equations 18 and 19.
5) Table 2 which lists the corrected gate openings and flow coefficients for conditions of free-weir flow.
6) Table 3 which contains equations 12 and 19 and the corrections for obtaining the static-headwater head for free-weir flow.

Purpose and Scope

Central to the efficient operation of the navigation system is the availability of reliable discharge ratings for the flow control structures. The purpose of this report is to describe the results of a study to develop discharge ratings for the control gates at Lock and Dam 11. The ratings were developed by using the results of current-meter discharge measurements, made in the forebays of the control gate structures, to verify and evaluate the discharge coefficients for the theoretical discharge equations. Discharge ratings (U.S. Army Corps of Engineers, 1940) originally developed from laboratory tests on a hydraulic-model of the gates on Lock and Dam 11 had never been verified with field data.

The scope of the work covered in this report includes results of current-meter discharge measurements, methodology for computing tainter gate openings, development of discharge coefficients and equations of discharge, definition of rating tables of discharge for submerged-orifice flow, comparison of submerged orifice flow discharges to hydraulic-model rating discharges, and a comparison of discharges computed from methods described in this study to those listed in the U.S. Army Corps of Engineers' gate operation schedule for Lock and Dam 11.

Acknowledgements

This project was completed in cooperation with the U.S. Army Corps of Engineers, Rock Island District. Personnel from the Corps assisted in making current-meter discharge measurements at the dam. Special acknowledgement is given to the Corps' Lockmaster for arranging to have the gates adjusted as needed for the measurements.

LOCATION OF STUDY AREA

Lock and Dam 11, located at Dubuque, Iowa, is a unit of the Inland Waterway Navigation System of the Upper Mississippi River Basin. The part of the navigation system within the Rock Island District (U.S. Army Corps of Engineers, 1980, pl. 1) is shown in figure 1.

FLOW-CONTROL STRUCTURES

Three types of flow control structures are present at Lock and Dam 11. These are tainter gates, roller gates and the navigation lock. Detailed theoretical as well as physical descriptions of these flow-control structures are beyond the scope of this report, and therefore are not included. Readers interested in this subject are referred to Davis and Sorensen (1952), Rouse (1949), Creager and Justin (1950), and King and Brater (1954). The hydraulic conditions that define each flow regime and the corresponding generalized steady-state discharge equations for the flow-control structures are summarized in table 1. An important parameter common to all types of flow control is the discharge coefficient.

The discharge coefficients are functions of various independent hydraulic control variables, of which the most significant are: the static-headwater head (h_1), the static-tailwater head (h_3), and the gate opening (h_g). A discharge coefficient is defined as the ratio of measured discharge to theoretical discharge (ASCE, 1962). Discharge coefficients are determined by measuring discharge during conditions when the hydraulic control variables are known and fixed. This procedure, referred to as calibration, may be performed on a hydraulic-model under controlled laboratory conditions or in the field at the dam.

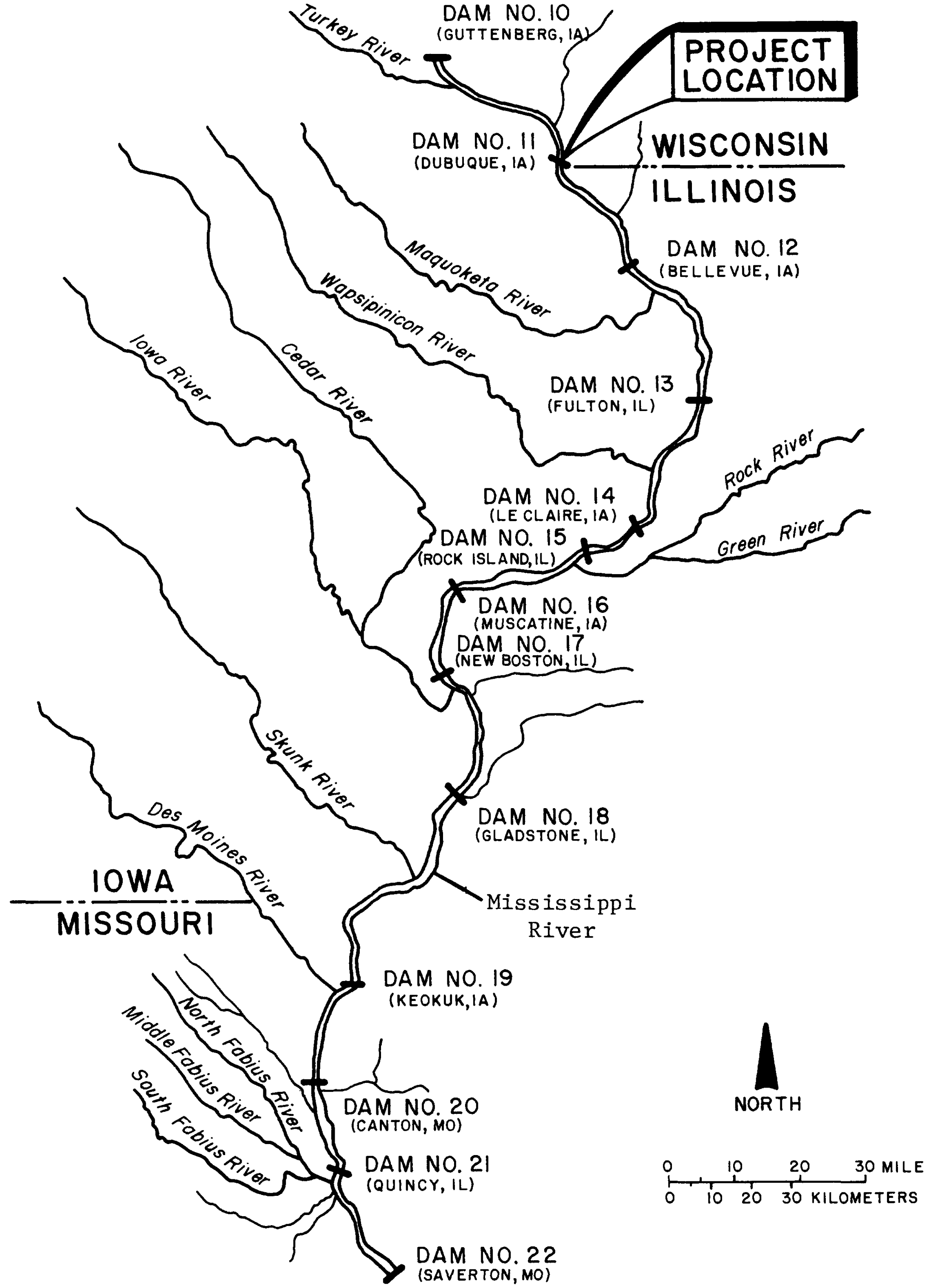


Figure 1.--Inland Waterway Navigation System of the upper Mississippi River basin (modified from U.S. Army Corps of Engineers, 1980, pl. 1).

Table 1.--Flow-control structures and their respective flow regimes and hydraulic equations

Flow-control structure	Flow regimes possible 1/	Hydraulic conditions necessary	Equations 2/	Equation number
Tainter and roller gates	Free orifice	$h_g < 0.67\ h_1$ and $h_3 < h_g$	$Q = C[h_g\ B(2g\ h_1)^{0.5}]$	(1)
	Submerged orifice	$h_g < 0.67\ h_1$ and $h_3 \geqslant h_g$	$Q = C_{gs}[h_3\ B(2g\ \ h)^{0.5}]$	(2)
	Free weir	$h_g \geqslant 0.67\ h_1$ and $h_3/h_1 < 0.6$	$Q = C_w[Bh_1^{1.5}]$	(3)
	Submerged weir	$h_g \geqslant 0.67\ h_1$ and $h_3/h_1 \geqslant 0.6$	$Q = C_w C_{ws}[Bh_1^{1.5}]$	(4)
Fixed spillway 3/	Free weir	$h_{3s}/h_{1s} < 0.6$	$Q_s = C_{sw}[B_s h_{1s}^{1.5}]$	(5)
	Submerged weir	$h_{3s}/h_{1s} \geqslant 0.6$	$Q_s = C_{sw} C_{sws}[B_s h_{1s}^{1.5}]$	(6)
Locks	--	$h > 0$	$Q_L = NA\ \Delta h/\Delta t$	(7)

1/The criteria used to separate orifice flow from weir flow is based on the fact that critical depth of flow in a rectangular channel is equal to two-thirds of the total head in the approach section. As the gate opening is increased above critical depth, the gate no longer acts as a control of discharge.

2/The bracketed parts of equations 1 through 6 represent the theoretical expression for discharge through a gate B units in width. The independent hydraulic-control variables are static-headwater head (h_1) static-tailwater head (h_3), and gate opening (h_g). The variable, Δh, represents the difference between the static-headwater and static-tailwater heads, and Δt, represents a time interval. N is the number of lockages and A is the area or width times length of the lock. The gravitational constant, g, is equal to 32.2 ft/s². Static-headwater and static-tailwater heads are the vertical distances from the gate sill or spillway crest to upstream and downstream pool elevations, respectively.

3/Same for flow over gate crest with gate in submerged position.

Tainter and roller gates are the only controls for which data are evaluated in this report. Flow through the locks can be computed by multiplying the volume of water contained in the lock times the number of lockages during a fixed period of time.

Types of Flow at Dam 11 Control Structures

Submerged-orifice flow predominates when the control gates at Dam 11 are in operation (U.S. Army Corps of Engineers, 1980, pl. 30). Free-orifice flow would very rarely occur at a low-head navigation-type structure as found on Dam 11 and would not occur at the dam under normal operating conditions. Calibration requires the development of a relation between the discharge coefficient, C_{gs}, in equation 2 and the orifice-submergence ratio, h_3/h_g.

Free-weir flow at Dam 11 would occur primarily with the gates in a submerged condition with flow over the crests of the gates. Calibration of these gates requires the definition of the relation between the discharge coefficient, C_{sw}, in equation 5 and the static-headwater head, h_{1s}, over the gate crest. The gates are operated in the submerged position in the winter when there is no commercial navigation. Submerged-weir flow could occur with the gates in a submerged condition at a time of high flow in the river. However, the gates would normally be raised above the water surface before submerged-weir flow would occur over the gate crests. Submerged-weir flow would also occur over the gate sills with the gates raised above the water surface when the dam is out of operation. This type flow is not evaluated in this report.

DAM OPERATION

Lock and Dam 11 contains 13 tainter gates and 3 roller gates for controlling the pool elevation upstream from the dam. Five of the tainter gates, located adjacent to the lock, are separated from the remainder of the tainter gates by the 3 roller gates, which are situated at about mid-channel (fig. 2). Sectional views of the tainter and roller gates are shown in figure 3.

The tainter gates are of the submergible type, capable of being lowered 8 feet below the sill elevation. Each gate is 60 feet wide and operates between piers with 60 feet clear openings.

The roller gates are of the submergible type, capable of 8 feet of submergence. Each gate is 20 feet high and 100 feet wide and operates between piers with 100 feet clear openings.

Operation of the control gates for maintaining the pool elevation is based on a study (U.S. Army Corps of Engineers, 1980) conducted to determine the optimum use of the dam for river flowage, conservation interests and towboat service. Operation "Plan A" (U.S. Army Corps of Engineers, 1980, pl. 30) was adopted and put into use on April 17, 1940 and remains in effect. "Plan A" allows the high water levels to recede naturally until the authorized pool elevation for lower flows is reached.

Dam 11 is a run-of-the-river dam and cannot store water for flood control purposes. The pool is maintained between stages 14.4 and 14.9 feet. When the river is rising and the tailwater stage reaches 14.1 feet, the tainter and roller gates are raised above the water surface. During flood periods, the gates are raised out of the water allowing run-of-the-river flow to occur.

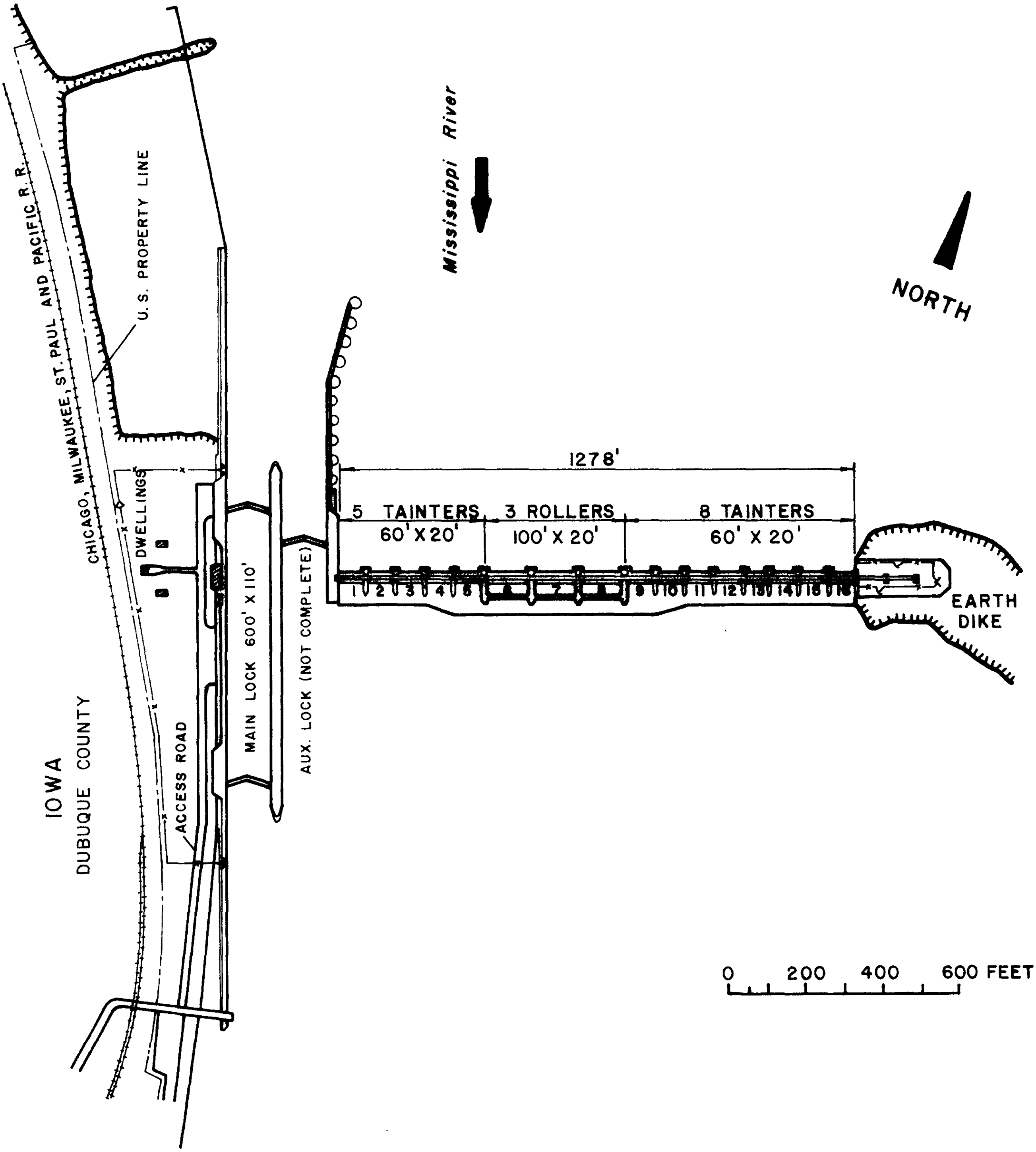
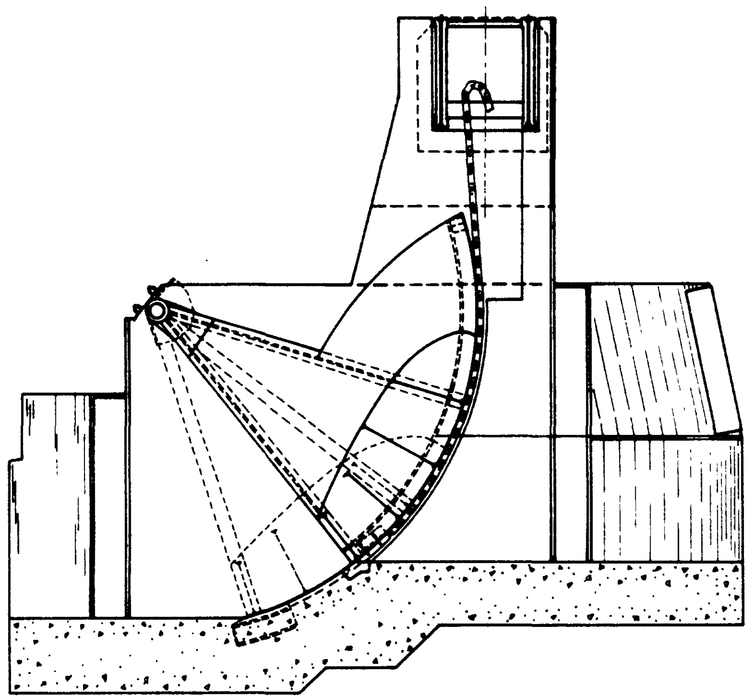


Figure 2.--Location of flow-control structures (modified from U.S. Army Corps of Engineers, 1980, pl. 2).



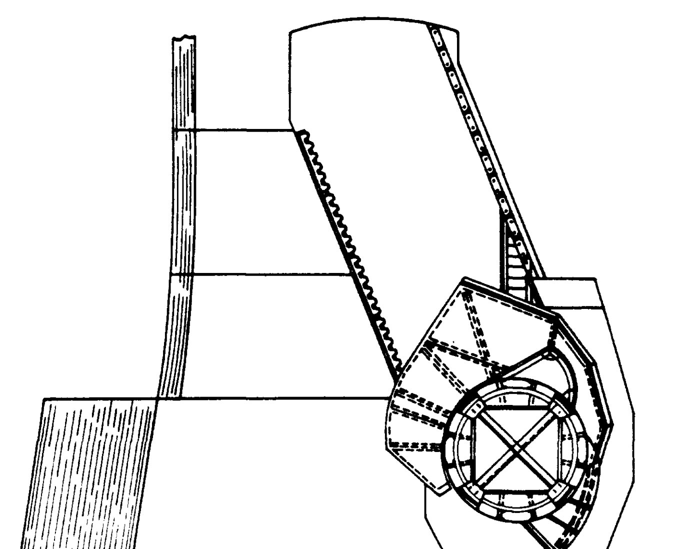


Figure 3.--Sectional views of tainter and roller gates (modified from U.S. Army Corps of Engineers, 1980, pls. 5 and 6).

During winter, when there is no commercial navigation and the pools become ice covered, the tainter and roller gates at Dam 11 are placed in the submerged position. The pool is maintained within the winter operating limits of 13.8 to 14.8 feet stage.

DISCHARGE AND STAGE MEASUREMENTS

The tainter and roller gates are built with a roadway over the structures giving access to the forebays with standard current-meter measuring equipment. The discharge measurements were made from the upstream edge of the roadway which is approximately 20 feet upstream from the downstream edge of the tainter gate sills and approximately 25 feet for the roller gates. The distance of the measuring equipment from the orifice and control structure appeared to be adequate to allow accurate measurements to be made. Some vertical velocity curves were taken to verify the standard 0.2 and 0.8 method of velocity observation. The measurements were made with equipment normally used for measuring large streams, velocity was measured using a type AA current meter suspended with Columbus-type sounding weights (50-150 pound) from a collapsible crane (Rantz and others, 1982).

The concurrent pool and tailwater stages for the measurements were obtained from the gages in the operations control building. The static-headwater head (h_1) and static-tailwater head (h_3) referenced to the sill are obtained by adding 5.20 feet to the gage readings. The stages can be referenced to mean sea level elevation by adding the zero gage datum, 588.20 feet (1912 adjustment), to the stages. The gate-opening settings for the tainter gates were read from the staff-indicator gages on the tainter gates and those for the roller gates were read from the shaft indicator marks on the operating machinery.

A total of 49 measurements of discharge ranging from 350 to 19,300 cubic feet per second in a gate were made in the forebays of the roller and tainter gates of Lock and Dam 11. Discharge coefficients for all the gates of the same design could be developed from measurements on a single gate. However, to insure greater accuracy because of the fluctuations of the pool and tailwater during the measurements and to account for variations in entrance and exit conditions, several gates were selected for calibration. Discharge through each of the gate bays was measured at least once for submerged-orifice flow. Only tainter gate no. 12 and roller gate no. 7 were measured with the gates in a free-weir flow position. The results of these measurements are listed in table 2.

Leakage, which is common to submergible gates because of the clearance provided between the gate and sill for lowering the gates, was not separately determined. The flow attributable to leakage is included in the discharge measurements and in the discharge equations.

Discharge measurements made at the Lock and Dam 14 roller gates were used to corroborate the data for the Lock and Dam 11 roller gates in defining the discharge rating because the gates are the same type of structure and share the same hydraulic-model discharge rating.

Table 2.--Summary of current-meter discharge measurements and hydraulic-control data for control gates at Mississippi River Lock and Dam 11

Gate number	Date	Head-water head h_1 1/ (feet)	Tail-water head h_3 2/ (feet)	Gage reading G (feet)	Gate opening h_g (feet)	Dis-charge (ft³/s)	Deviation from rating (percent)	Sub-mer-gence ratio (h_3/h_g)	Flow coef-ficent (C_{gs})	Flow 3/ regime
1	10-04-83	19.87	11.31	2.00	2.10	2,550	+ 7.5	5.39	0.160	SO
2	09-29-82	20.00	13.77	4.50	4.17	4,190	+ 0.5	3.30	0.253	SO
2	10-03-83	19.97	11.39	2.00	1.74	1,920	+ 0.5	6.55	0.119	SO
2	10-04-83	19.87	11.20	1.00	0.94	1,030	+ 5.4	11.91	0.065	SO
2	10-04-83	19.87	11.10	0.50	0.37	510	+44.9	30.00	0.032	SO
2	04-24-84	19.73	17.49	8.00	7.81	4,840	- 0.6	2.24	0.384	SO
2	04-24-84	19.73	17.49	10.00	9.88	6,540	+ 3.6	1.77	0.519	SO
2	04-24-84	19.73	17.49	12.00	11.88	8,790	+13.6	1.47	0.698	SO
3	10-03-83	19.97	11.39	2.00	2.01	2,350	+ 4.9	5.67	0.147	SO
4	09-29-83	20.00	13.72	4.50	4.49	4,640	+ 2.2	3.06	0.280	SO
4	10-03-83	19.97	11.39	2.00	2.02	2,320	+ 2.7	5.64	0.145	SO
4	10-04-83	19.87	11.31	1.00	1.05	1,140	+ 4.6	10.77	0.072	SO
4	10-04-83	19.87	11.31	0.50	0.47	568	+25.7	24.06	0.036	SO
4	04-24-84	19.75	17.49	10.00	10.03	7,040	+ 9.0	1.74	0.557	SO
5	10-03-83	19.97	11.39	2.00	2.00	2,290	+ 3.2	5.70	0.142	SO
6	10-04-83	19.87	11.31	2.50		3,790	- 3.6	4.52	0.143	SO
6	04-23-84	19.80	17.67	10.00		19,300	+ 2.2	1.77	0.933	SO
7	10-04-83	19.87	11.31	2.50		3,850	- 2.0	4.52	0.145	SO
7	11-07-83	20.00	11.10	4.50		7,250	+ 0.6	2.47	0.273	SO
7	11-07-83	20.05	11.05	1.00s	1.30b	1,210	+ 6.1		8.16w	FW
7	11-07-83	20.00	11.10	2.30s	2.55b	2,270	- 1.3		5.57w	FW
7	11-07-83	19.95	11.15	4.00s	4.20b	3,740	- 3.1		4.35w	FW
7	11-07-83	19.90	11.25	6.00s	6.15b	5,890	+ 2.8		3.86w	FW
7	11-07-83	19.88	11.33	7.00s	7.13b	6,540	- 2.2		3.44w	FW
7	04-23-84	19.80	17.67	8.00		8,130	0	2.21	0.393	SO
8	10-04-83	19.87	11.31	2.50		3,610	- 8.1	4.52	0.136	SO
9	10-03-83	19.97	11.39	2.00	2.02	2,290	+ 1.3	5.64	0.143	SO
10	10-03-83	19.97	11.39	2.00	2.15	2,380	- 1.7	5.30	0.148	SO
11	09-29-83	20.02	13.60	4.00	3.92	4,070	+ 2.8	3.47	0.246	SO
11	10-03-83	19.97	11.39	2.00	1.94	2,150	- 0.5	5.87	0.134	SO
11	10-04-83	19.87	11.25	1.00	1.00	1,050	+ 1.0	11.25	0.066	SO
11	10-04-83	19.87	11.20	0.50	0.42	400	- 0.5	26.67	0.025	SO
11	04-23-84	19.80	17.78	8.00	8.01	4,640	+ 2.3	2.22	0.382	SO
11	04-23-84	19.80	17.78	10.00	10.02	6,160	+ 1.0	1.77	0.507	SO
11	04-23-84	19.79	17.78	12.00	12.02	8,330	+12.6	1.48	0.687	SO
12	10-03-83	19.97	11.39	2.00	1.92	2,100	- 1.4	5.93	0.131	SO
12	11-07-83	19.88	11.30	1.00s	1.08b	535	+19.2		7.94w	FW
12	11-07-83	19.92	11.20	1.95s	2.07b	883	- 5.4		4.94w	FW
12	11-07-83	19.95	11.15	4.00s	4.15b	2,120	- 4.1		4.18w	FW
12	11-07-83	20.00	11.10	6.00s	6.20b	3,690	- 1.6		3.98w	FW
12	11-07-83	20.05	11.10	7.00s	7.25b	4,640	+ 0.2		3.96w	FW
13	10-03-83	19.97	11.39	2.00	2.00	2,240	+ 0.9	5.70	0.139	SO
14	09-29-83	20.02	13.60	4.00	3.89	3,760	- 4.3	3.50	0.227	SO
14	10-03-83	19.97	11.39	2.00	1.93	2,060	- 3.7	5.90	0.129	SO
14	10-04-83	19.87	11.10	1.00	0.95	967	- 2.8	11.68	0.061	SO
14	10-04-83	19.87	11.10	0.50	0.39	350	- 6.2	28.46	0.022	SO
14	04-24-84	19.77	17.30	8.00	8.01	5,010	- 4.9	2.16	0.383	SO
15	10-03-83	19.97	11.39	2.00	1.90	2,120	0	6.00	0.132	SO
16	10-03-83	19.97	11.39	2.00	2.00	2,240	+ 0.9	5.70	0.140	SO

1/ h_1 = Pool stage + 5.20 feet.
2/ h_3 = Tailwater stage + 5.20 feet.
3/ SO = submerged-orifice flow.
FW = free-weir flow.
b Computed headwater, h_{1s}, over gate crest.
s Gate in submerged position.
w Coefficient, C_{sw}, for free-weir flow.

TAINTER GATE FLOW

Computation of Gate Opening

The gate opening, h_g, is the most important variable in calibrating the flow through tainter gates. In most cases the gate opening cannot be measured directly in the field during operation of the structure. Therefore, the gate opening is computed indirectly using pertinent geometric properties of the gates and direct measurements of the elevation of a selected reference point on each gate. Dimensions of gate structure members that can not be measured on the gate are obtained from the construction plans. These include the gate radius, R, and the included angle, θ, of the gate structure (fig. 4).

The reference point (R.P.) established for computing the gate opening, h_g, for the tainter gates on Dam 11 is on the top of the upper gate arm, 0.15 foot (1 level rod, Chicago type, width) from where the gate arm intersects with the arched crest of the gate structure (fig. 4). The R.P. is 15.60 feet from the trunnion centerline and is the same for all the gates. Elevations of the R.P.'s were determined by levels from established benchmarks on the piers between the gates (U.S. Army Corps of Engineers, 1937). The vertical gate opening, h_g, is computed from the equation:

$$h_g = 24.00 - 30.04 \sin(38.167 + \phi_u) \qquad (8)$$

where

$$\phi_u = \sin^{-1} [(607.00 - \text{R.P. elev.})/15.60]$$

The terms in the equation are graphically displayed in figure 4.

The average computed tainter gate opening (h_g), with the gage-indicator settings at 2.00 feet, was 2.12 feet with variations from 2.02 to 2.28 feet. This difference can be attributed primarily to error in the gage-indicator

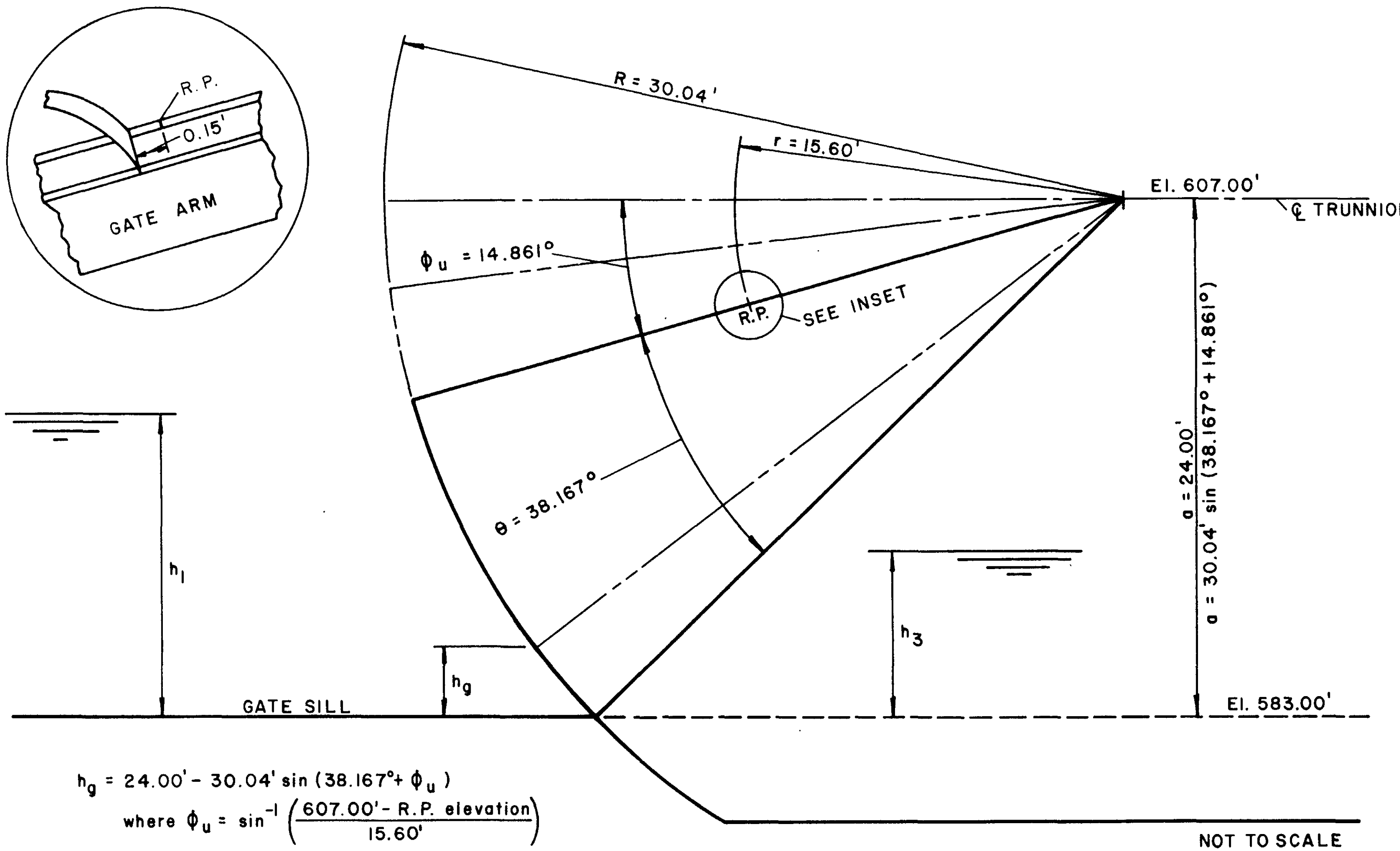


Figure 4.--Details of tainter gates at Mississippi River Lock and Dam 11.
See page vi for definition of symbols.

settings and to the variance of the seals on the bottom edge of the gates. Because the gates are submergible, there is no way to determine at what position the gates are in a "closed" position. Defining the relation between the "true" gate opening (h_g) and the gage-indicator is relatively straight forward for non-submergible gates, such as those for Lock and Dam 14, where $h_g = 0$ can be determined by closing the gate. (With the gates at Dam 14 in a closed position ($h_g = 0$), computations of the gate openings (h_g) erroneously indicate that the gates are open an average of 0.19 foot. This 0.19 foot error was eliminated by adjusting the included angle of the gate). The decision was arbitrarily made to adjust the Dam 11 average gate opening (h_g) of 2.12 feet to the gage-indicator reading of 2.00 feet. This was done by adjusting the included angle (37.839 degrees) of the gate structure to 38.167 degrees (fig. 4). The advantage of using this approach is that the discharge for the average gate openings can be computed using the gage indicator readings directly. The adjusted h_g values range from 1.90 to 2.15 feet. Corrections (e) for the individual gates and the relation of the gate openings (h_g) to the 2.00-foot gage-indicator setting are shown in figure 5. Also shown is the discharge measured at each of the tainter gates, these range from 2,060 to 2,550 cubic feet per second.

A gage-indicator error of 0.10 foot will give about a 5 percent deviation in discharge from the rating discharge at the 2.00-foot gage setting. This deviation from the rating discharge increases with lower gage settings (about 11 percent at the 1.00-foot gage setting) and decreases at higher gage settings (about 3 percent at the 4.00-foot gage setting). The deviation of discharge from the rating discharge for the individual gates could be minimized by adjusting the gage indicators to more nearly reflect the computed gate opening, h_g.

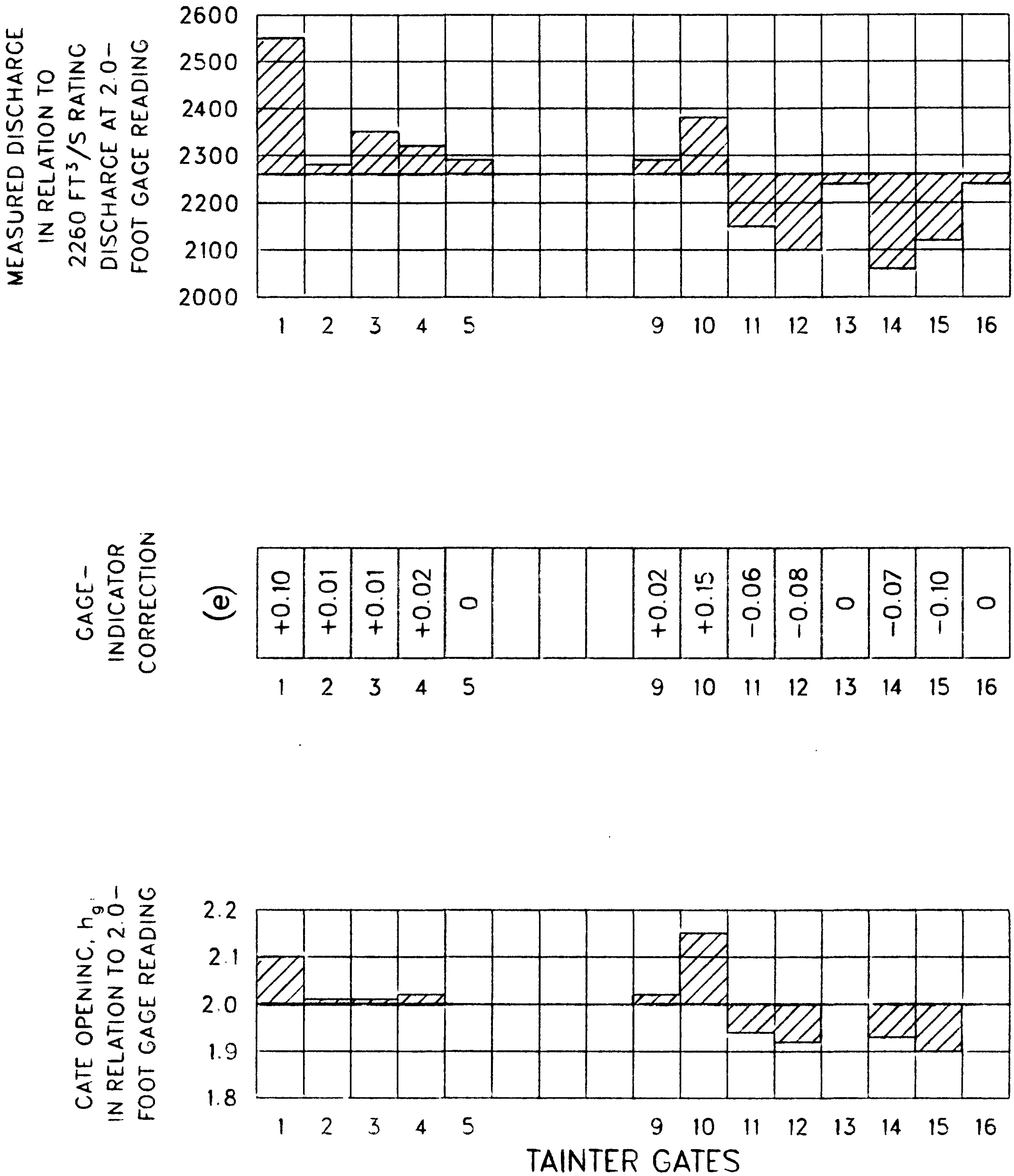


Figure 5 --Cage-indicator corrections and comparison of gate openings and discharges at 2 0-foot gage-indicator settings for tainter gates on Mississippi river Lock and Dam 11.

The initial gate opening, h_g, and discharge for gate 2 using the 2.00-foot gage setting was 1.74 feet and 1,920 cubic feet per second. The gage indicator for gate 2 was found out of alignment and was reset to coincide with the gage setting of gate 3 by U.S. Army Corps of Engineer personnel after the measurements were made.

Submerged-Orifice Flow Coefficients

Discharge coefficients for submerged-orifice flow were computed by solving equation 2 in table 1 for C_{gs} using the results of the discharge measurements (table 2) that were made with the gates in submerged-orifice flow conditions. The flow coefficients, C_{gs}, are listed in table 2 and a graph defining the relationship of C_{gs} to the orifice-submergence ratio is shown in figure 6. The scatter of the C_{gs} values at the low end of the relation is the result of very low velocities encountered with the gates open only 0.5 foot. These points were discounted when computing the regression coefficients for the equation. The resulting equation, relating the submerged-orifice coefficient, C_{gs}, to the orifice-submergence ratio, h_3/h_g, is:

$$C_{gs} = 0.94\ (h_3/h_g)^{-1.10} \qquad (9)$$

The submerged-orifice coefficient, C_{gs}, at submergence ratios less than about 1.7 are greater than those extrapolated from the curve relation (fig. 6) and indicates that a new coefficient relation may exist in this range. This trend was also noted by Collins (1977). Discharges must be relatively high with the gates open 10 feet or greater before submergence ratios of less than 1.7 will occur (U.S. Army Corps of Engineers, 1980, pl. 30). This condition

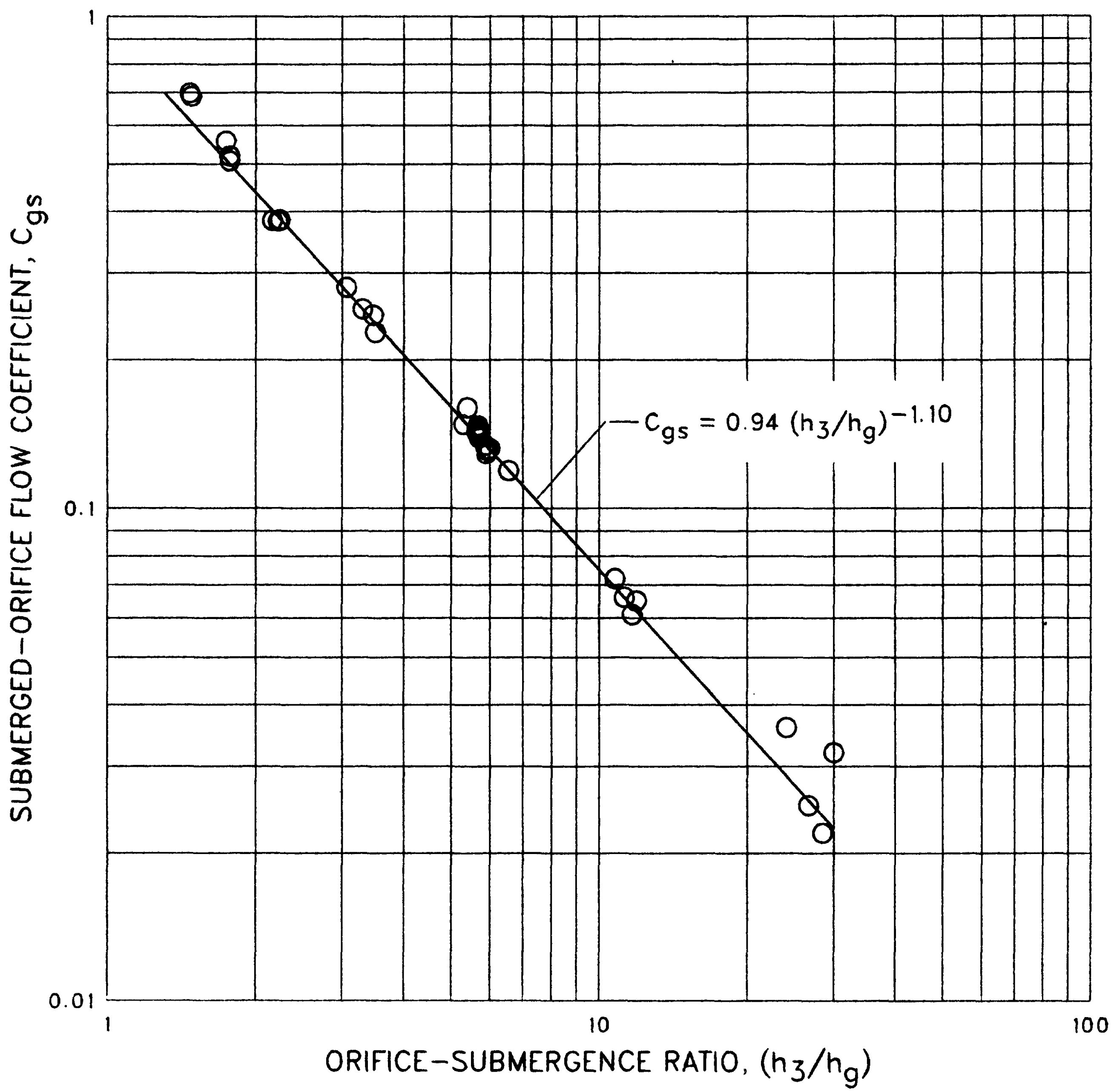


Figure 6.--Relation between submerged-orifice flow coefficient and orifice-submergence ratio for Lock and Dam 11 tainter gates.

will occur about 5 percent of the time (U.S. Army Corps of Engineers, 1980, pl. 20), such as on the rise of a flood peak before the gates are raised above the water surface and on the recession of a flood peak after the gates have been lowered back into the water.

Submerged-Orifice Discharge Equation

An equation for computing discharge for submerged-orifice flow in the tainter gate bays was developed using the submerged-orifice equation (2) and substituting equation 9 for the submerged-orifice coefficient, C_{gs}. The resulting equation relating the discharge (Q) to the orifice-submergence ratio (h_3/h_g) and the static-head loss ($h_1 - h_3$) is:

$$Q = 452\ h_3\ (h_3/h_g)^{-1.10}\ (h_1 - h_3)^{0.5} \tag{10}$$

where h_g = gage-indicator reading + the individual gage-indicator correction (e) shown in figure 5 (the average correction, e, for all the tainter gage indicators is 0), h_3 is the tailwater gage reading plus 5.20 feet and $h_1 - h_3$ is the difference between the pool and tailwater gage readings.

The relation of the current-meter discharge measurements made at the tainter gates on October 3-4, 1983, to the discharge curve defined by equation 10 is shown in figure 7.

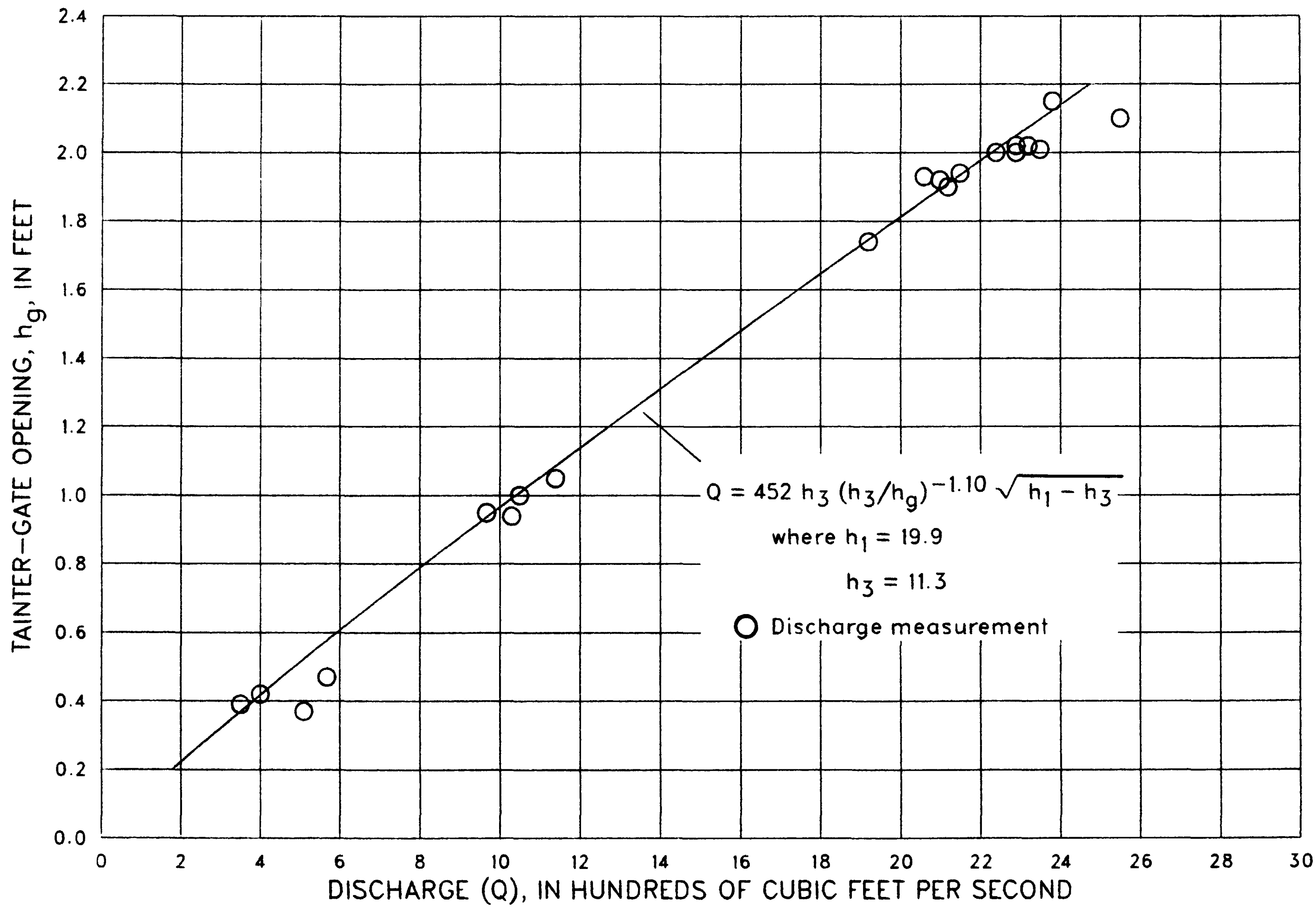


Figure 7.--Comparison of current-meter discharge measurements of October 3-4, 1983, to rating curve for tainter gates at Mississippi River Lock and Dam 11.

Free-Weir Flow Coefficients

Discharge coefficients for free-weir flow for tainter gate no. 12 were computed by solving equation 5 in table 1 for C_{sw} using the results of the discharge measurements (table 2) that were made with the gate in a submerged position. The free-weir coefficients, C_{sw}, are listed in table 2 and a graph defining the relationship of C_{sw} to the static-headwater head (h_{1s}) over the gate crest is shown in figure 8. The resulting equation, relating the free-weir coefficient, C_{sw}, to the static-headwater head, h_{1s}, is:

$$C_{sw} = 3.6\ (h_{1s})^{-0.86} + 3.3 \qquad (11)$$

where h_{1s} = Gage reading + 0.20 + (pool stage - 14.80). This coefficient-headwater relation is further corroborated by data from Locks and Dams 12 and 13 which are also shown in figure 8. The correction to the gage readings for Lock and Dam 11 was derived from the observed gage reading at the point of zero flow and elevations of the R.P. taken at each of the gate settings when a measurement of discharge was made.

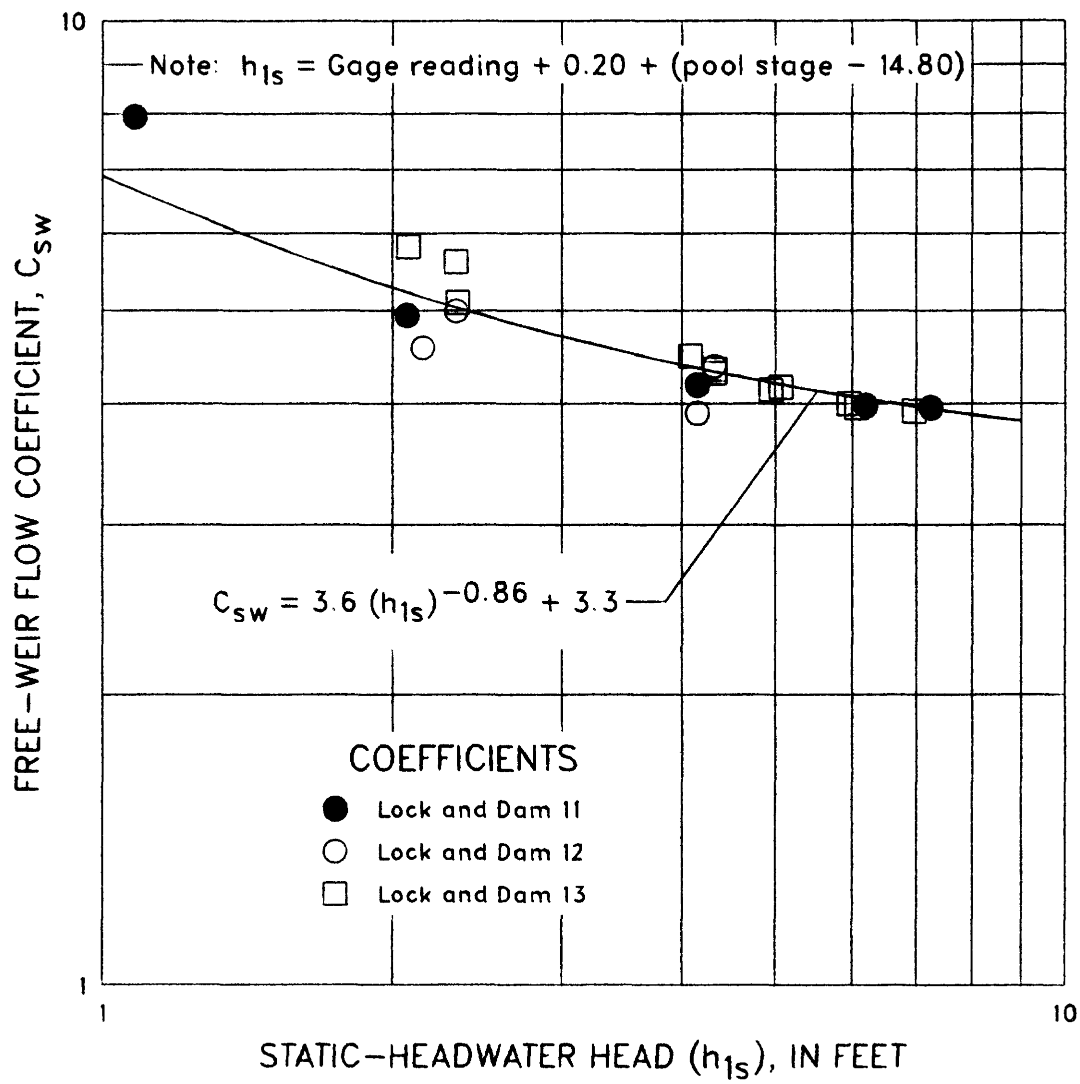


Figure 8.--Relation between free-weir flow coefficient and static-headwater head for tainter gates in submerged position for Lock and Dam 11.

Free-Weir Discharge Equation

An equation for computing free-weir flow in tainter gate no. 12 was developed using the free-weir flow equation 5 and substituting equation 11 for the free-weir coefficient, C_{sw}. The resulting equation, graphically illustrated in figure 9, relating the discharge (Q_s) to the static-headwater head (h_{1s}) over the gate crest is:

$$Q_s = 198\ (1.09\ h_{1s}^{\ 0.64} + h_{1s}^{\ 1.50}) \qquad (12)$$

where h_{1s} is as defined for equation 11 above. Also shown in figure 9 are the discharge measurements made at Locks and Dams 12 and 13. For comparison, however, the discharges for the measurements at Locks and Dams 12 and 13 were adjusted from the 64.2 feet tainter gate widths to the 60.0 feet tainter gate width of the Lock and Dam 11 gates.

The pool stage at Lock and Dam 11 is frequently maintained at about 14.80 feet stage. At that stage, h_{1s} can be expressed as a direct function of G, the gage indicator reading, and discharge can be expressed in terms of G only. When the pool stage is near or at 14.80 feet, the following equation (13) can be used to compute the discharge directly from the gage indicator reading, G:

$$Q = 218 + 289G + 48G^2 \qquad (13)$$

The accuracy of computing free-weir discharge for tainter gates other than no. 12 can not be predicted until the gage indicators are checked for each gate in the submerged position.

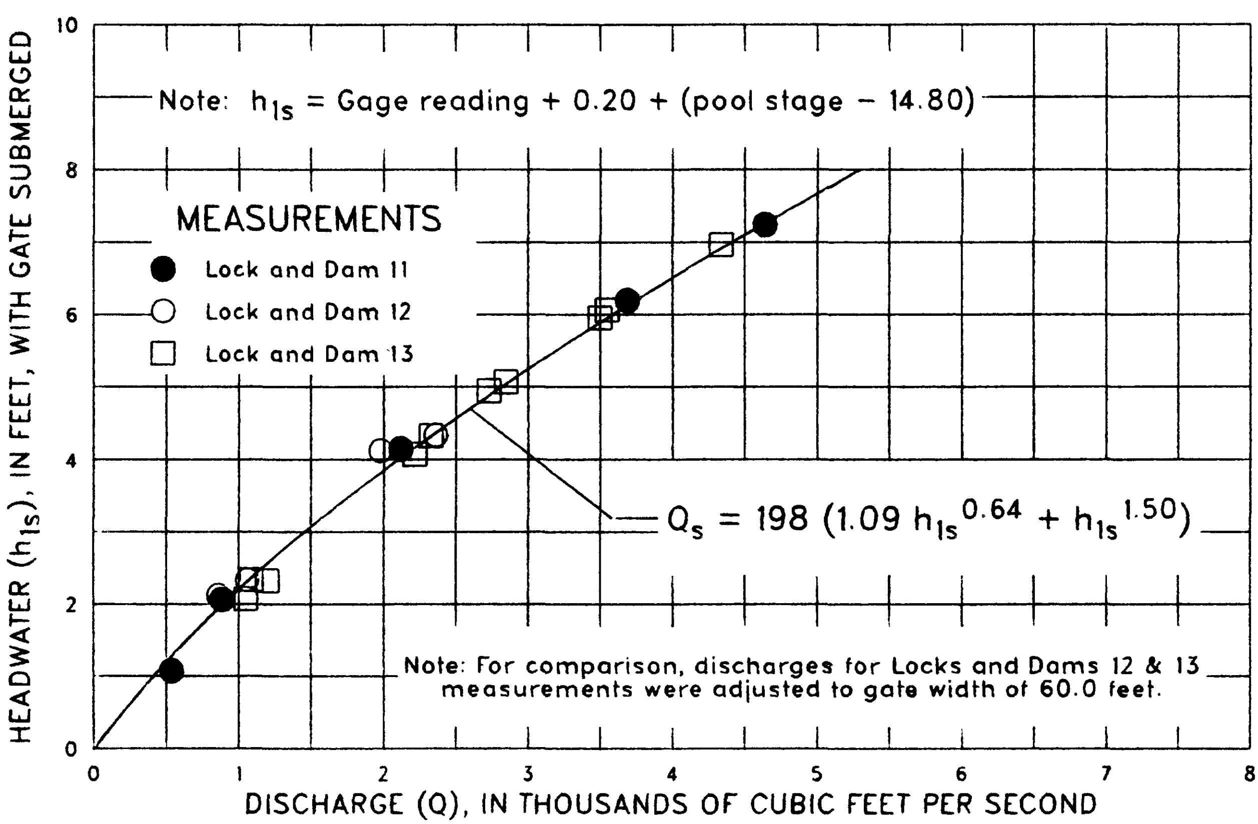


Figure 9.--Relation between discharge and headwater for free-weir flow for tainter gates in submerged position for Lock and Dam 11.

ROLLER GATE FLOW

The roller gates at Dams 11 and 14 are the same type of structure and have the same hydraulic-model rating. The development of discharge ratings at both dams are being done concurrently, therefore, enabling use of data from both dams for developing discharge ratings for the gates at each of the dams. (Some discharge measurements were subsequently made at Lock and Dam 13 and the discharge coefficients for these measurements are also shown in figure 10.)

Gate Opening

The gate opening indicator marks for the roller gates are an integral part of the operating machinery of the gate. These indicators presumably give a fairly accurate reading of the gate opening. A method for measuring the actual gate openings was not developed.

Submerged-Orifice Flow Coefficients

Discharge coefficients for submerged-orifice flow for Dams 11 and 14 were used to define the relation with the orifice-submergence ratio, h_3/h_g. The coefficients were computed by solving equation 2 in table 1 for C_{gs} using the results of the discharge measurements (table 2) that were made under submerged-orifice flow conditions.

The relation of the submerged-orifice flow coefficient, C_{gs}, to the orifice-submergence ratio, h_3/h_g, for the roller gates on Dams 11 and 14 are shown in figure 10. The break in the relation occurs at a point when the gate is open 7 feet or greater and the submergence ratio is less than 2.4 for the Dam 11 roller gates and less than 1.9 for the Dam 14 roller gates. The break in the relationship apparently occurs when control of flow of the roller gate

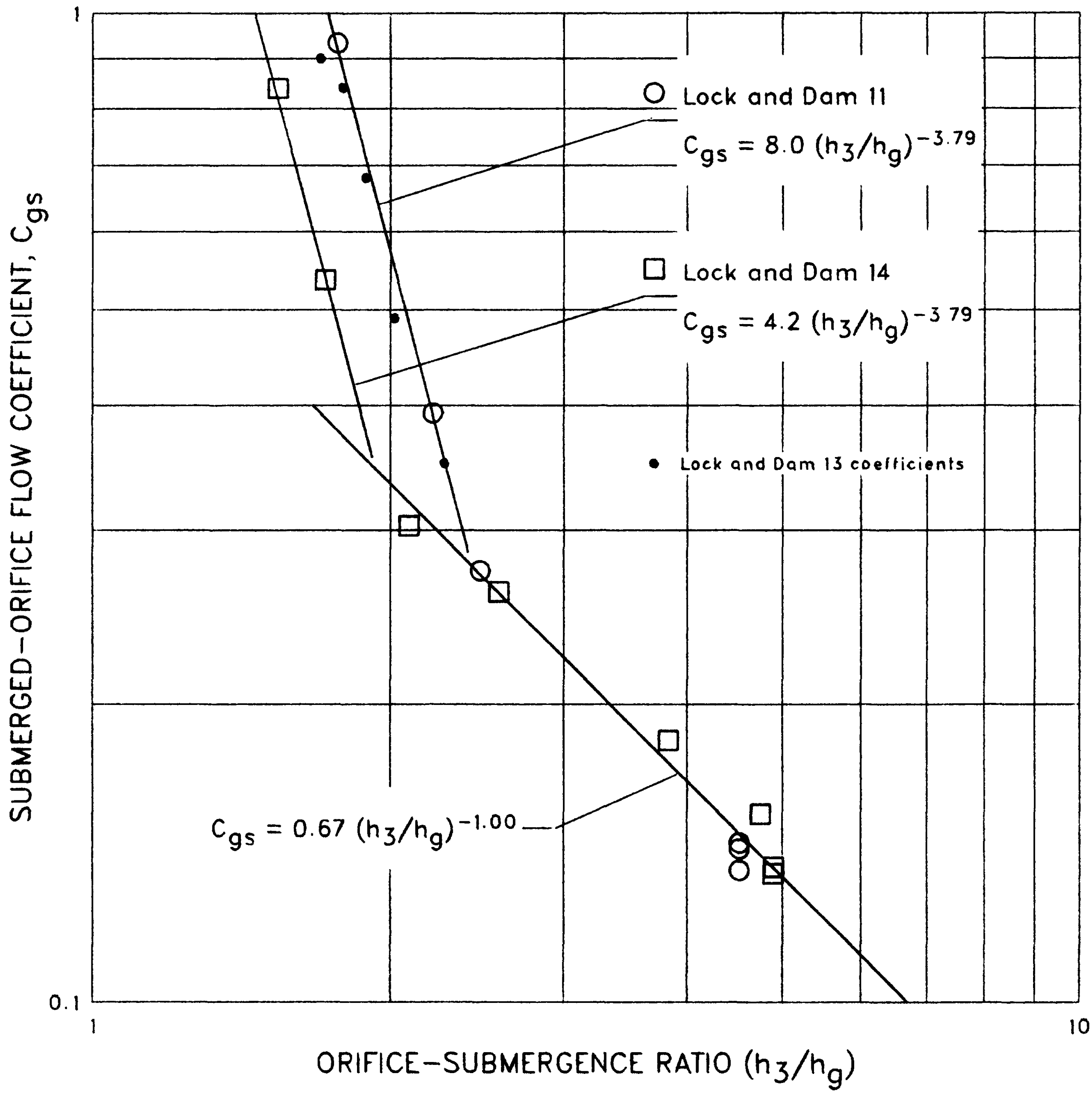


Figure 10.--Relation between submerged-orifice flow coefficient and orifice-submergence ratio for Lock and Dam 11 roller gates.

transfers from the lower apron (appendage to the drum) on the roller to the drum of the gate structure. The control positions of the roller gate are illustrated in figure 11 and show that the effective gate opening increases significantly when control transfers from the apron to the drum when the gate is opened more than 7.0 feet. The exact gate opening where the control changes has not been defined. The resulting equation, relating the submerged-orifice coefficient, C_{gs}, to the orifice-submergence ratio, h_3/h_g, for the roller gates when the gates are open less than 7 feet is defined by the equation:

$$C_{gs} = 0.67 \, (h_3/h_g)^{-1.00} \tag{14}$$

As noted by Collins (1977) and described by King and Brater (1954), many structures calibrated by the procedures outlined above are found to be independent or nearly independent of submergence. If the coefficient is independent of the submergence, the slope of the straight line relation will be -1.00 as in equation 14. When substituted for the coefficient in the submerged orifice flow equation (2), the equation reduces to the free-orifice equation (1). The average of the coefficients computed for the roller gates at dams 11 and 14 using the free orifice equation (1) was 0.67. This coefficient is in total agreement with those in King and Brater (1954, table 26) for rectangular orifices with partially suppressed contraction.

For conditions when the gates are open 7 feet or greater and the submergence ratio is less than 2.4, the submerged-orifice coefficient, C_{gs}, for the Dam 11 roller gates is defined by the equation:

$$C_{gs} = 8.00 \, (h_3/h_g)^{-3.79} \tag{15}$$

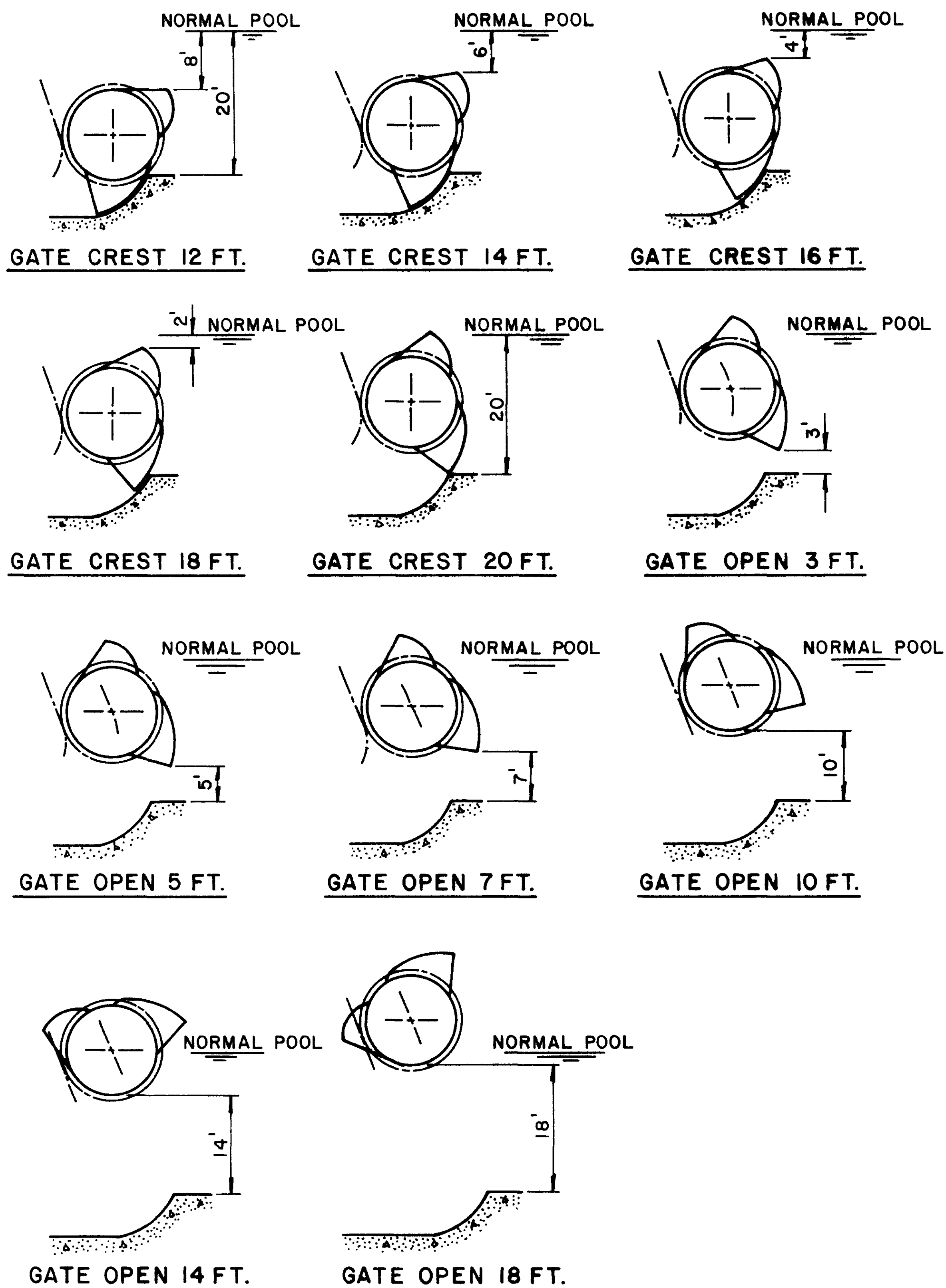


Figure 11--Positions of roller gates for selected crests and openings (modified from U.S. Army Corps of Engineers, 1940, fig. 35).

The computed coefficients and the results of the measurements made in the roller gates at Dam 11 are listed in table 2.

Submerged-Orifice Discharge Equations

An equation for computing discharge for submerged-orifice flow when the roller gates are open less than 7.0 feet was developed using the submerged-orifice flow equation (2) and substituting equation 14 for the submerged-orifice coefficient, C_{gs}. The resulting equation relating the discharge (Q) to the gate opening (h_g) and the static-head loss (h_1 - h_3) is:

$$Q = 537\ h_g\ (h_1 - h_3)^{0.5} \tag{16}$$

where h_1 - h_3 is the difference between the pool and tailwater gage readings. This equation is also applicable to submerged-orifice flow in the roller gates at Lock and Dam 14 with the gates open less than 7.0 feet.

An equation for computing discharge for submerged-orifice flow when the roller gates are open 7.0 feet or greater and h_3/h_g is less than 2.4 feet was developed using the submerged-orifice flow equation (2) and substituting equation 15 for the discharge coefficient, C_{gs}. The resulting equation, relating the discharge (Q) to the static-tailwater head (h_3), orifice-submergence ratio (h_3/h_g) and the static-head loss (h_1 - h_3) is:

$$Q = 6{,}420\ h_3\ (h_3/h_g)^{-3.79}\ (h_1 - h_3)^{0.5} \tag{17}$$

where h_3 is the tailwater gage reading plus 5.20 feet, h_g is the gate opening and h_1 - h_3 is the difference between the pool and tailwater gage readings.

Free-Weir Flow Coefficient

Discharge coefficients for free-weir flow for the roller gates in a submerged position at Dam 11 were computed by solving equation 5 in table 1 for C_{sw} using the results of the discharge measurements (table 2) that were made with the gates in a submerged position. A graph showing the relationship of C_{sw} to the static-headwater head (h_{1s}) over the gate crest is shown in figure 12. The resulting equation, relating the discharge coefficient to the static-headwater head (h_{1s}) is:

$$C_{sw} = 8.67 \, (h_{1s})^{-0.46} \qquad (18)$$

where h_{1s} = Gage reading + 0.25 + (pool stage - 14.80). This coefficient-headwater relation is further corroborated by data from Locks and Dams 12, 13 and 14 which are also shown in figure 12. The correction to the gage readings was derived from the observed gage reading at the point of zero flow.

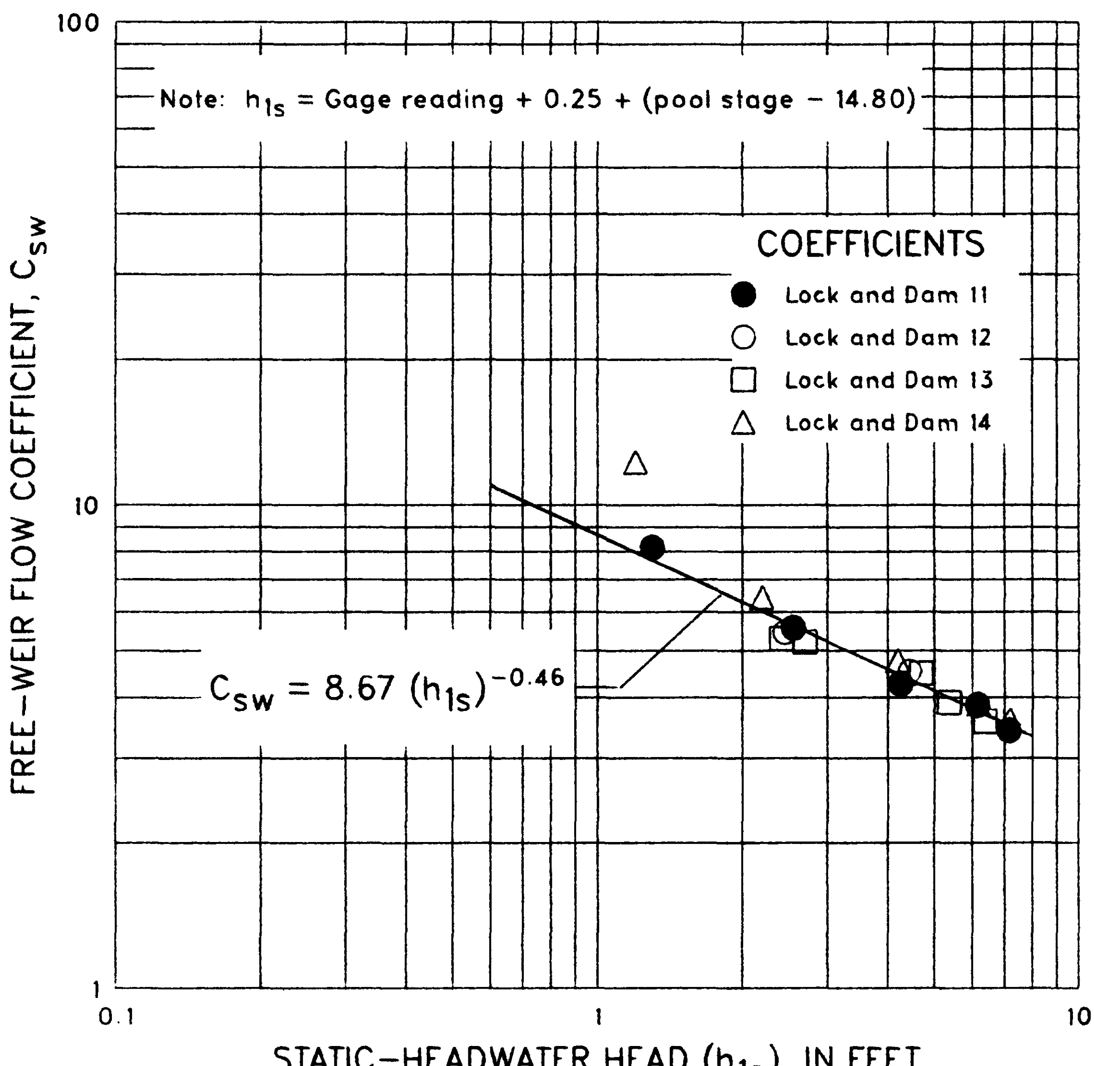


Figure 12.−−Relation between free−weir flow coefficient and static−headwater head for roller gates in submerged position for Lock and Dam 11.

Free-Weir Discharge Equation

An equation for computing discharge for free-weir flow for the roller gates in a submerged position at Dam 11 was developed using the free-weir flow equation (5) and substituting equation 18 for the discharge coefficient, C_{sw}. The resulting equation, graphically illustrated in figure 13, relating the discharge (Q_s) to the static-headwater head (h_{1s}) over the gate crest is:

$$Q_s = 867 \ (h_{1s})^{1.04} \qquad (19)$$

where h_{1s} is as defined for equation 18 above. Also shown in figure 13 are the discharge measurements made at Locks and Dams 12, 13 and 14. These measurements were used to corroborate the rating development for Lock and Dam 11.

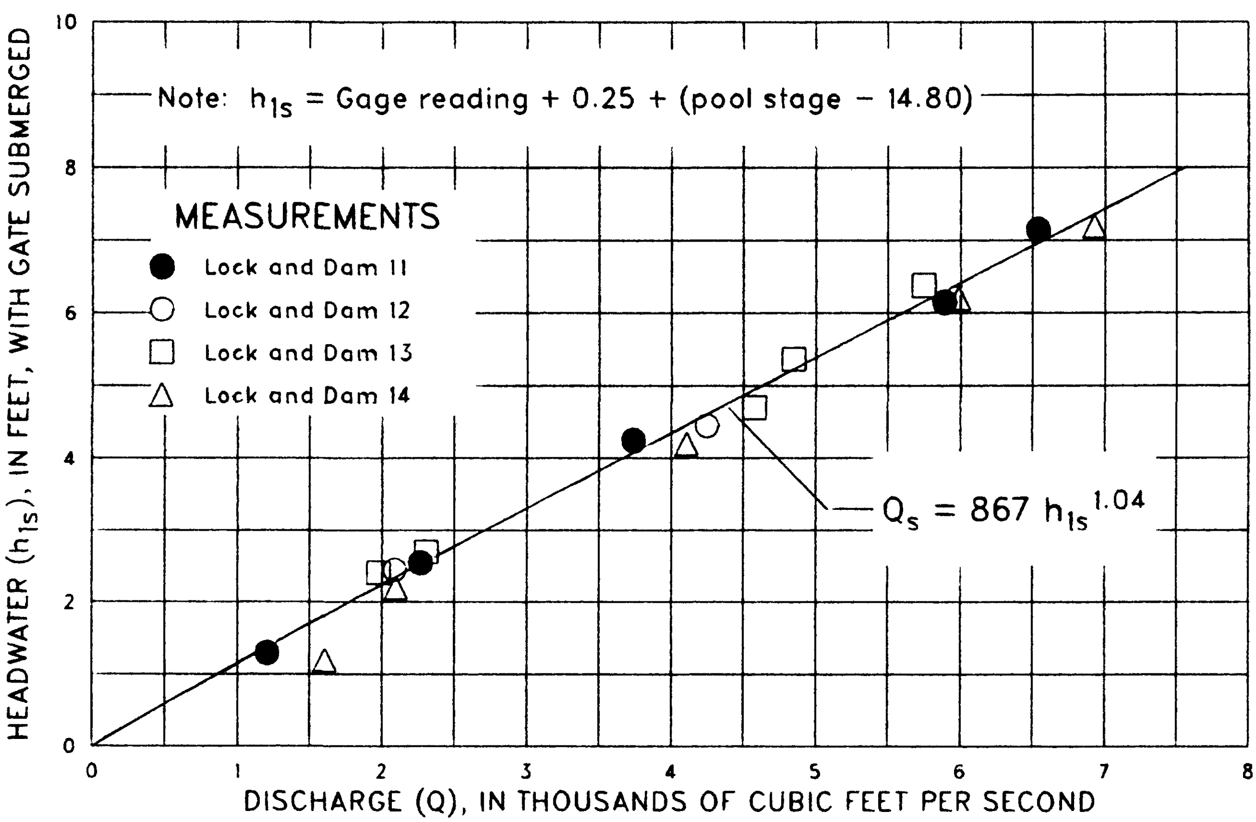


Figure 13.--Relation between discharge and headwater for free-weir flow for roller gates in submerged position for Lock and Dam 11.

DISCHARGE EQUATIONS AND RATINGS

The discharge equations applicable to the control gates when Dam 11 is in operation have been compiled and listed in table 3.

Rating tables for both the tainter and roller gates were developed for the predominant flow regime of submerged-orifice flow when the Dam is in operation. These ratings, tables 4 and 5, list discharges for tailwater stages at 1 foot increments and gate openings at 0.5 foot increments and are applicable only with the upstream pool stage at 14.80 feet (h_1 = 20.00 feet). Discharges for any other headwater, tailwater and gate opening relationships encountered can easily be computed using the applicable equations in table 3 with a small programable computer.

Discharge rating curves for submerged-orifice discharge at selected gate openings (h_g) for the tainter and roller gates, prepared from laboratory tests on the hydraulic model of Lock and Dam 11, are shown in figures 14 and 15. Corresponding discharge rating curves defined by methods outlined in this report are shown for comparison. Discharges defined by the 2 curves for the tainter gates are comparable (within about 10 percent) until the gates are open more than 8 feet with the tailwater depth less than 12.0 feet. At this point, the discharge computed using equation 10 increases at a much greater rate than those defined by the hydraulic-model rating curves. Discharges defined by the 2 curves for the roller gates are also comparable except those in the range of 7 to 8 feet of gate opening. In this range, the discharges computed by equation 17 increases at a much greater rate than those shown by the hydraulic-model rating curves.

Table 3.--Summary of discharge equations for control gates at Mississippi River Lock and Dam 11.

Gate	Flow regime	Equation of discharge 1/, 3/	Equation number
Tainter gates	Submerged orifice	$Q = 452\ h_3(h_3/h_g)^{-1.10}(h_1 - h_3)^{0.5}$	(10)
Tainter gates	Free Weir 2/	$Q_s = 198\ (1.09\ h_{1s}^{0.64} + h_{1s}^{1.50})$	(12)
Roller gates	Submerged orifice $h_g < 7.0$ or $\geqslant 7.0$ when $h_3/h_g > 2.4$	$Q = 537\ h_g(h_1 - h_3)^{0.5}$	(16)
Roller gates	Submerged orifice $h_g \geqslant 7.0$ and $h_3/h_g < 2.4$	$Q = 6{,}420\ h_3(h_3/h_g)^{-3.79}(h_1 - h_3)^{0.5}$	(17)
Roller gates	Free weir 2/	$Q_s = 867\ h_{1s}^{1.04}$	(19)

1/ Q = Discharge, in cubic feet per second
h_1 = Pool stage + 5.20 feet
h_3 = Tailwater stage + 5.20 feet
h_g for tainter gages = gage reading + gage indicator correction, e (fig. 5).
(average e for all the tainter gates = 0.0 foot)
h_g for roller gates = gage reading

2/ For free weir flow over gate crest:
Tainter gate: h_{1s} = gage reading + 0.20 + (pool stage - 14.80)
Roller gate: h_{1s} = gage reading + 0.25 + (pool stage - 14.80)

3/ The approach velocity head is included in $(h_1 - h_3)$.

Table 4. Discharge rating table for submerged-orifice flow for a single tainter gate at Mississippi River Lock and Dam 11 with upstream pool stage of 14.80 feet.

GAGE READING (feet)	Tainter gate discharge, in ft^3/s, for tailwater stage, in feet, indicated.								
	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
.5	555	523	491	459	425	389	352	311	265
1.0	1190	1120	1050	983	911	835	754	667	569
1.5	1860	1750	1640	1540	1420	1300	1180	1040	889
2.0	2550	2400	2260	2110	1950	1790	1620	1430	1220
2.5	3260	3070	2890	2690	2490	2290	2070	1830	1560
3.0	3980	3760	3530	3290	3050	2800	2530	2230	1910
3.5	4720	4450	4180	3900	3610	3310	2990	2650	2260
4.0	5470	5150	4840	4520	4180	3840	3470	3060	2610
4.5	6220	5870	5510	5140	4760	4370	3950	3490	2980
5.0	6990	6590	6180	5770	5350	4900	4430	3920	3340
5.5	7760	7320	6870	6410	5940	5450	4920	4350	3710
6.0	8540	8050	7560	7060	6540	5990	5410	4790	4080
6.5	9330	8790	8250	7700	7140	6540	5910	5230	4460
7.0	10100	9540	8960	8360	7740	7100	6410	5670	4840
7.5	10900	10300	9660	9020	8350	7660	6920	6120	5220
8.0	11700	11000	10400	9680	8970	8220	7430	6570	5600
8.5	12500	11800	11100	10300	9590	8790	7940	7020	5990
9.0	13300	12600	11800	11000	10200	9360	8460	7480	6380
9.5	*	13300	12500	11700	10800	9930	8980	7940	6770
10.0	*	14100	13300	12400	11500	10500	9500	8400	7160

* Free-orifice flow conditions exist at indicated tailwater stage and gate openings.

Note: Discharges greater than those underlined may exceed those allowable for safe gate operation (USCE, 1980).

Discharges for table 4 were computed using equation:

$$(10) \quad Q = 452\, h_3 (h_3/h_g)^{-1.10} (h_1 - h_3)^{0.5}$$

where h_g = gage reading + (average e = 0)
h_1 = 20.00 feet (14.80 + 5.20)
h_3 = tailwater stage + 5.20 feet

Table 5. Discharge rating table for submerged-orifice flow for a single roller gate at Mississippi River Lock and Dam 11 with upstream pool stage of 14.80 feet.

GAGE READING (feet)	Roller gate discharge, in ft^3/s, for tailwater stage, in feet, indicated. 4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
.5	882	841	796	750	700	647	588	523	449
1.0	1760	1680	1590	1500	1400	1290	1180	1050	899
1.5	2650	2520	2390	2250	2100	1940	1760	1570	1350
2.0	3530	3360	3190	3000	2800	2590	2350	2090	1800
2.5	4410	4200	3980	3750	3500	3230	2940	2620	2250
3.0	5290	5040	4780	4500	4200	3880	3530	3140	2700
3.5	6180	5880	5580	5250	4900	4530	4120	3660	3150
4.0	7060	6720	6370	6000	5600	5170	4710	4190	3590
4.5	7940	7560	7170	6750	6300	5820	5290	4710	4040
5.0	8820	8410	7960	7500	7000	6470	5880	5230	4490
5.5		9250	8760	8250	7700	7110	6470	5760	4940
6.0		10100	9560	9000	8400	7760	7060	6280	5390
6.5			10400	9750	9100	<u>8410</u>	<u>7650</u>	<u>6800</u>	5840
7.0						15000	11300	8420	<u>6290</u>
7.5						19500	14700	10900	7950
8.0	Discharges in this area may be greater						18800	14000	10100
8.5	than those allowable for safe gate							17600	12800
9.0	operation (USCE,1980).							21800	15900
9.5									19500

Note: Underline denotes change in rating from equation 16 to equation 17.

Discharges for table 5 were computed using equations:

$$(16) \quad Q = 537\ h_g(h_1 - h_3)^{0.5}$$

$$(17) \quad Q = 6{,}420\ h_3(h_3/h_g)^{-3.79}(h_1 - h_3)^{0.5}$$

where h_g = gage reading
h_1 = 20.00 feet (14.80 + 5.20)
h_3 = tailwater stage + 5.20 feet

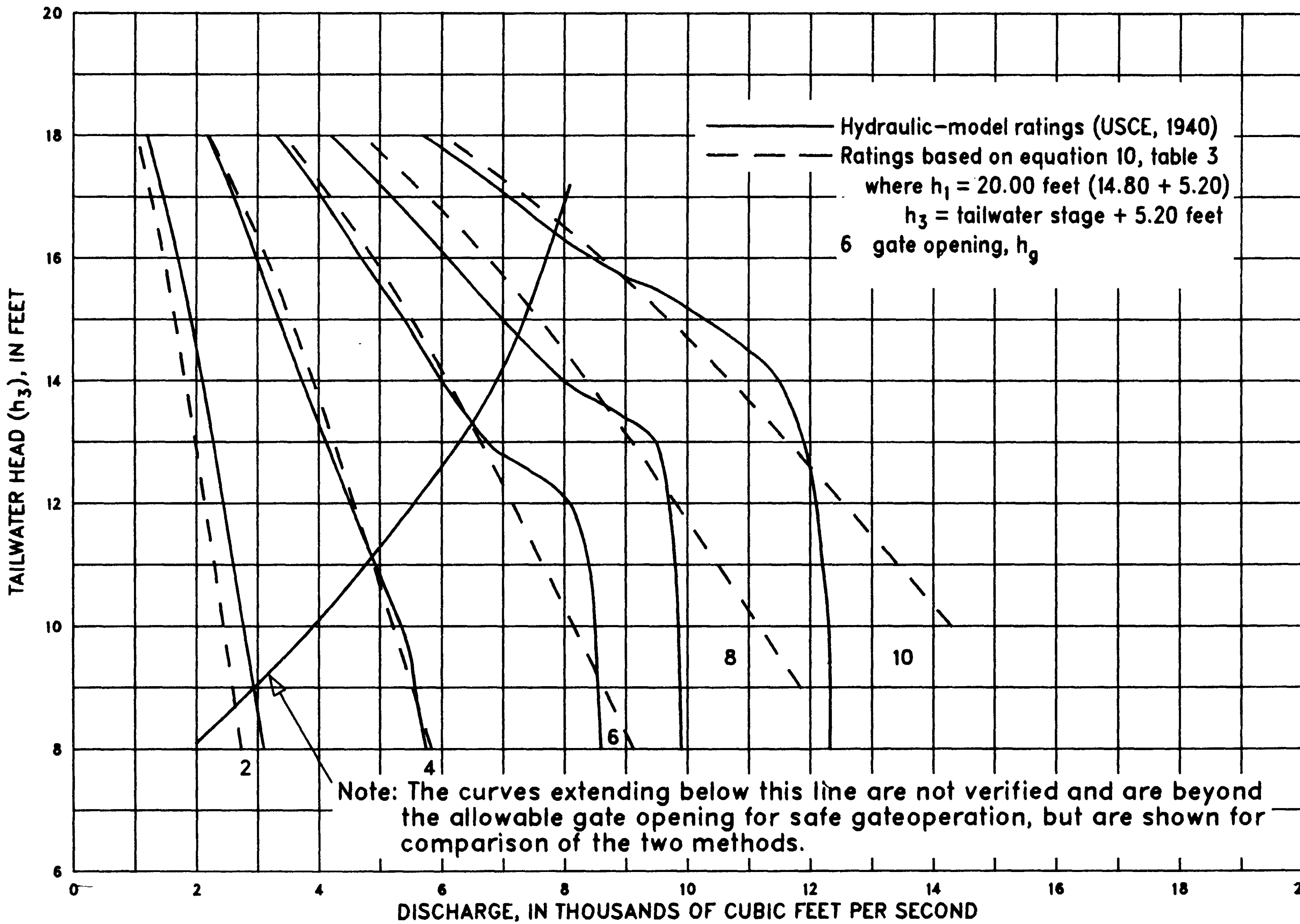


Figure 14. – Discharge ratings for submerged orifice flow for a single tainter gate at Mississippi River Lock and Dam 11 compared to hydraulic–model ratings.

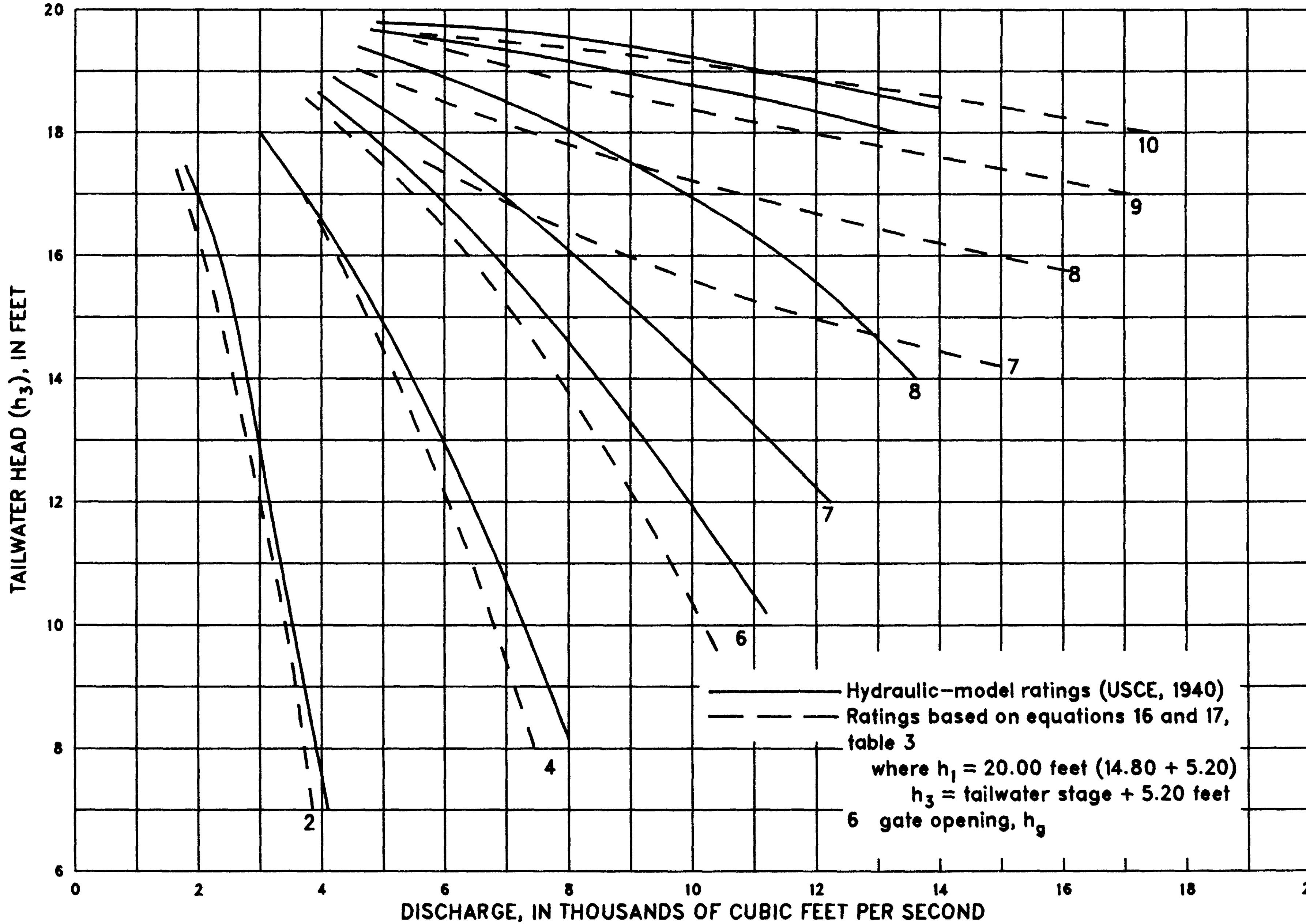


Figure 15. — Discharge ratings for submerged orifice flow for a single roller gate at Mississippi River Lock and Dam 11 compared to hydraulic–model ratings.

The equations in table 3 were used to compute the discharges for the gate settings indicated in the operation schedule, Plan A, shown in table 6 which is in use for operation of Dam 11. Discharges for the two methods were generally within 5 percent until the roller gate openings exceeded 7 feet at which time the discharges defined by the equations in table 3 increased to nearly 40 percent greater than those shown in Plan A.

MISSISSIPPI RIVER LOCK AND DAM 11
GATE OPERATION SCHEDULE PLAN A FOR CONTROLLED TAILWATER STAGES

(A)	Discharge in ft³/s	Tail-water stage (feet)	Head in feet	Gate opening, in feet, for gate indicated															
				Tainter					Roller			Tainter							
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
18,700	17,700	4.2	10.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5
22,600	21,500	4.4	10.4	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5
26,900	25,500	4.6	10.2	2.0	2.0	2.0	1.5	1.5	2.0	1.5	1.5	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5
30,000	28,200	4.8	10.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5
33,700	32,000	5.0	9.8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.0	0.5	0.5	0.5
36,500	34,000	5.2	9.6	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.0	1.0	1.0
38,800	36,600	5.4	9.4	2.5	2.5	2.5	2.5	2.0	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.0	1.0	1.0
41,700	39,000	5.6	9.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.5	2.5	2.0	1.5	1.5	1.5	1.0	1.0
44,400	41,200	5.8	9.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.0
45,700	43,800	6.0	8.8	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
47,900	46,000	6.2	8.6	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5
49,400	48,000	6.4	8.4	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.0	2.0	2.0	2.0	1.5	1.5
51,800	50,200	6.6	8.2	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	1.5	1.5
54,100	52,400	6.8	8.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0
56,100	54,800	7.0	7.8	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0
58,300	57,000	7.2	7.6	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.0
60,500	59,000	7.4	7.4	4.0	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5
62,200	61,000	7.6	7.2	4.0	4.0	4.0	4.0	3.5	4.0	4.0	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5
64,200	63,200	7.8	7.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0	3.0	3.0	3.0
67,200	65,400	8.0	6.8	4.5	4.5	4.5	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0	3.0
69,600	67,500	8.2	6.6	4.5	4.5	4.5	4.5	4.5	4.0	4.0	4.0	4.5	4.5	4.0	3.5	3.5	3.0	3.0	3.0
70,500	69,300	8.4	6.4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.0	3.5	3.5	3.0	3.0	3.0
73,100	71,300	8.6	6.2	5.0	5.0	5.0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.0	4.0	4.0	3.5	3.5	3.0
75,300	73,300	8.8	6.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	5.0	4.5	4.0	4.0	4.0	3.5	3.5	3.5
77,800	75,300	9.0	5.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.5	4.5	4.0	4.0	4.0
79,800	77,500	9.2	5.6	5.5	5.5	5.0	5.0	5.0	5.5	5.5	5.5	5.0	5.0	4.5	4.5	4.5	4.0	4.0	4.0
82,000	79,100	9.4	5.4	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.0	5.0	4.5	4.0	4.0
83,400	81,000	9.6	5.2	6.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	4.5	4.5	4.5
87,000	83,200	9.8	5.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.0	5.0	4.5	4.5	4.5
89,400	85,400	10.0	4.8	6.0	6.0	6.0	6.5	6.5	6.5	6.5	6.5	6.5	6.0	6.0	5.5	5.5	4.5	4.5	4.5
92,800	87,600	10.2	4.6	6.0	6.5	6.5	7.0	7.0	6.5	6.5	6.5	7.0	6.5	6.0	6.0	6.0	5.0	5.0	5.0
101,400	89,800	10.4	4.4	6.5	6.5	6.5	7.0	7.0	7.0	7.0	7.0	7.0	6.5	6.5	6.5	6.5	5.5	5.0	5.0
118,500	92,000	10.6	4.2	6.5	6.5	7.0	7.0	7.5	8.0	8.0	8.0	7.5	7.0	6.5	6.5	6.5	5.5	5.0	5.0
129,100	94,000	10.8	4.0	7.0	7.0	7.5	7.5	8.0	8.5	8.5	8.5	7.5	7.0	7.0	6.5	6.5	6.0	5.5	5.0
125,700	98,600	11.2	3.6	7.5	7.5	8.0	8.0	8.0	8.5	8.5	8.5	8.0	8.0	8.0	7.5	7.5	6.5	6.0	5.5
134,200	103,000	11.6	3.2	8.0	8.0	9.0	9.0	10.0	9.0	9.0	9.0	10.0	9.0	8.0	8.0	8.0	7.0	6.0	6.0
132,100	107,200	12.0	2.8	9.0	9.0	10.0	10.0	10.0	9.0	9.0	9.0	10.0	10.0	10.0	10.0	9.0	8.0	7.0	7.0

(A) Discharge, in cubic feet per second, computed using equations in table 3.

Table 6. Comparison of rating discharges to flow of Lock and Dam 11 Gate Operation Schedule Plan A. (Modified from USCE, 1980, plate 30)

SUMMARY

Current-meter discharge measurements made in the forebays of the tainter and roller gates of Lock and Dam 11 were used to develop discharge coefficients and equations of discharge for submerged-orifice flow for all the gates and free-weir flow for the roller gates in a submerged postion and for tainter gate no. 12 in a submerged position.

Methodology has been described to compute the actual gate openings of the tainter gates. The indicator gages for the tainter gates could be accurately set to the true gate opening (h_g) using the techniques described in case the gages were accidentally knocked out of alignment or if the bottom seals on the gates were changed. The deviation of the discharge from the rating discharge for the individual gates could be minimized by adjusting the gage indicators to more nearly reflect the computed gate opening, h_g.

Discharge rating tables were developed for discrete combinations of downstream pool elevations and gate openings for submerged-orifice flow, which is the predominant flow regime when the dam is in operation. Comparisons of the discharges defined by the hydraulic-model ratings and those computed by the equations developed in this study are given for selected gate openings. Discharges defined by methods outlined in this study are also given for comparison to those used in the operation schedule, Plan A, which is in use for the operation of Lock and Dam 11.

Additional data are needed to calibrate the staff-gage indicators on the tainter gates for free-weir flow with the gates in a submerged position.

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