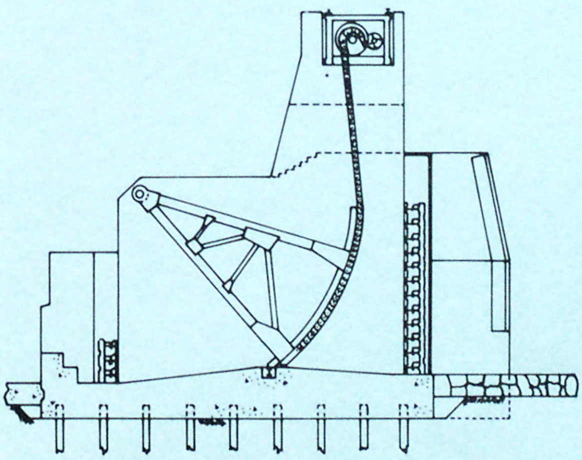
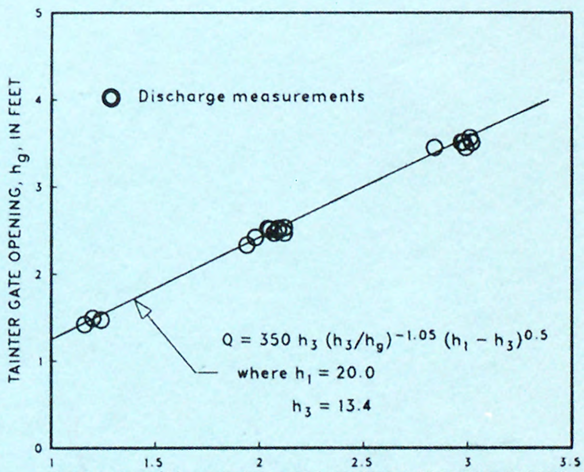
DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 16, MUSCATINE, IOWA

U.S. GEOLOGICAL SURVEY

Water Resources Investigations Report 86-4136



TAINTER GATE - SECTIONAL VIEW



Prepared in cooperation with the

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

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By Albert J. Heinitz

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Iowa City, Iowa
1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, SECRETARY

GEOLOGICAL SURVEY

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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	Radius from trunnion centerline to gate R.P.	ft
R.P.	Reference point to which elevations are run for the purpose of computing the gate opening	
$\Delta h = h_1 - h_3$	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 16, MUSCATINE, IOWA

By Albert J. Heinitz

ABSTRACT

The water level of the navigation pools on the Mississippi River are maintained by the operation of tainter and roller gates at the lock and dams. Discharge ratings for the gates on Lock and Dam 16, at Muscatine, 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 depth, headwater depth, and vertical height of gate opening, were determined for conditions of submerged-orifice 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 Mississipppi 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 16 was placed in operation July 10, 1937.

This is the third in a series of reports relating to discharge ratings and hydraulic characteristics of the control gates at locks and dams on the Mississippi River. The reports for Locks and Dams 11 (Heinitz, 1985a) and 14 (Heinitz, 1985b), preceded this report. Discharge ratings for Locks and Dams 11, 14 and 16 were done concurrently, therefore, corroborating rating development for each of the locks and dams.

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 16. 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 tainter and roller gates 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 and comparison of submerged-orifice-flow discharges to hydraulic-model-rating discharges. Furthermore, a comparison is made of discharges computed from methods described in this study to those computed using the gate openings listed in the U.S. Army Corps of Engineers' gate-operation schedule for Lock and Dam 16.

Acknowledgments

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 16, located at Muscatine, 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

Four types of flow-control structures are present at Lock and Dam 16 (fig. 2). These are tainter gates, roller gates, navigation lock and a fixed spillway. 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 structures 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.

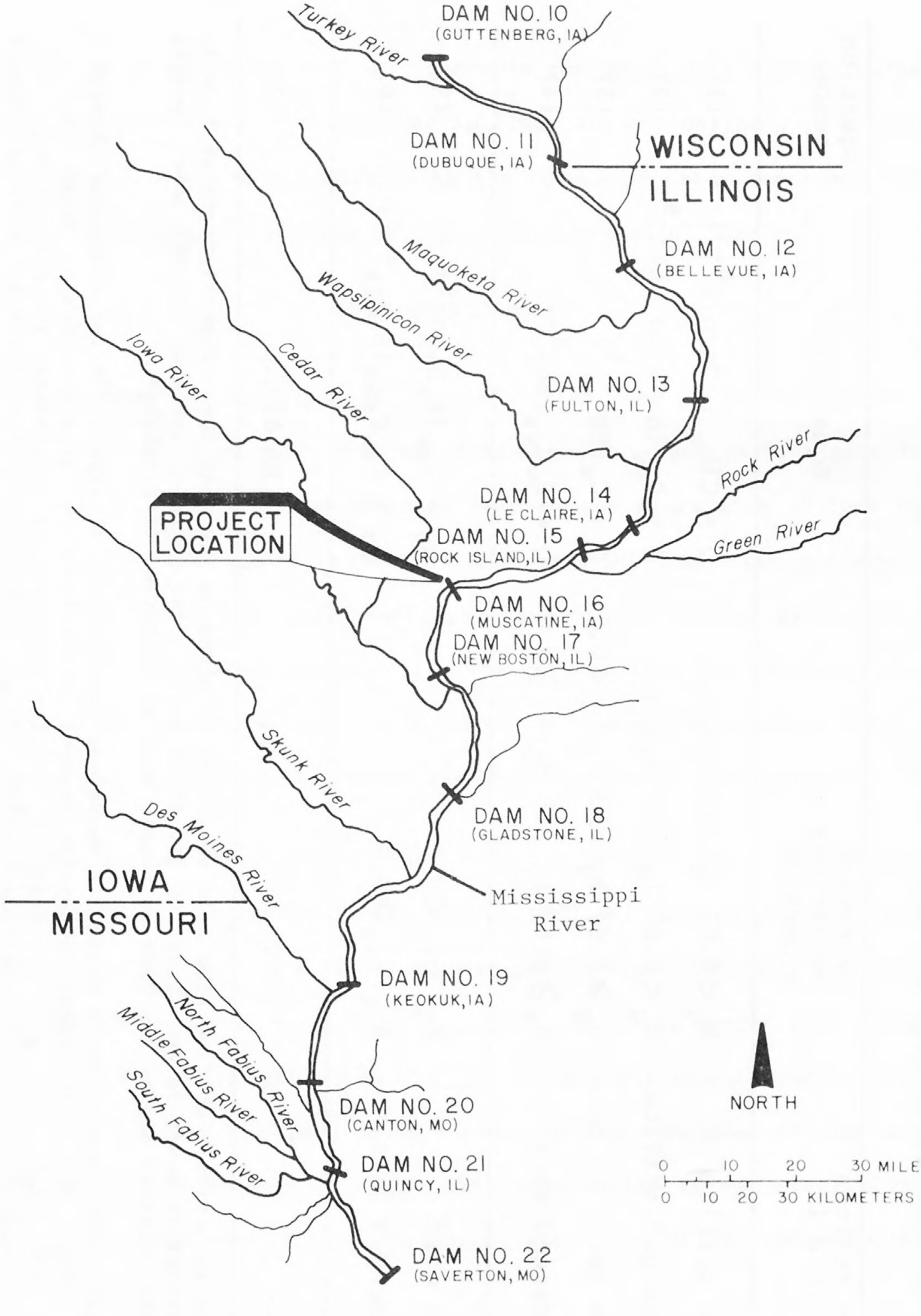


Figure 1.--Inland Waterway Navigation System of the upper Mississippi River basin (modified from U.S. Army Corps of Engineers, 1980, pl. 1).

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. Coefficients for the fixed spillway are not defined. 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.

DAM OPERATION

Lock and Dam 16 contains 15 tainter gates and 4 roller gates for controlling the pool elevation upstream from the dam. Each tainter gate is 40 feet wide and 20 feet high and operates between the piers with 40-foot clear openings. Each roller gate is 80 feet wide and 20 feet high and operates between piers with 80-foot clear openings. Five of the tainter gates, located adjacent to the lock, are separated from the remainder of the tainter gates by the four roller gates, which are situated at about mid-channel (fig. 2). Sectional views of the tainter and roller gates are shown in figure 3.

Submerged-orifice flow predominates when the control gates at Dam 16 are in operation (U.S. Army Corps of Engineers, 1980, pl. 28). Free orifice flow would very rarely occur at a low-head, navigation-type structure such as Dam 16 and would not occur at the dam under normal operating conditions. Three of the tainter gates (1, 10 and 19) are of the submergible type, capable of being lowered 3 feet below the normal crest elevation. The remainder of the tainter gates are of the non-submergible type and close on the curved steel channels embedded in the concrete sills. The roller gates are of the non-submergible type.

Free-weir flow would occur at gates 1, 10 and 19 in the submerged position with flow over the crest of the gates. These gates are used to release accumulated trash through the gates and generally are not operated in the

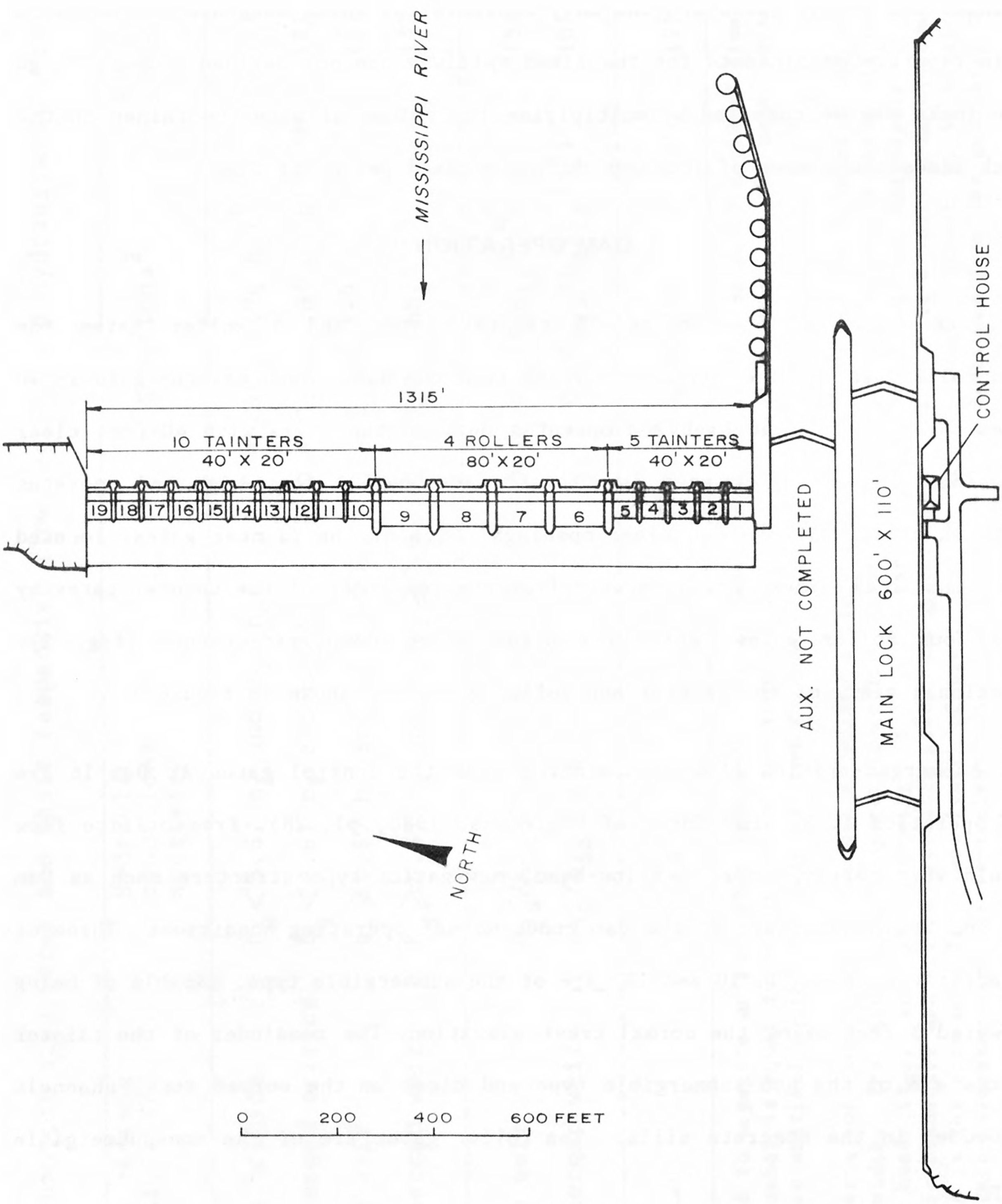
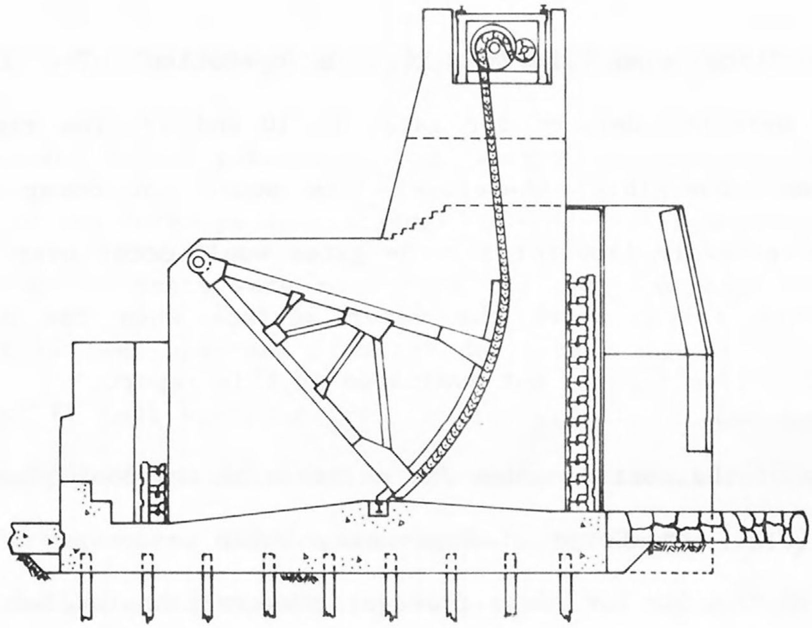
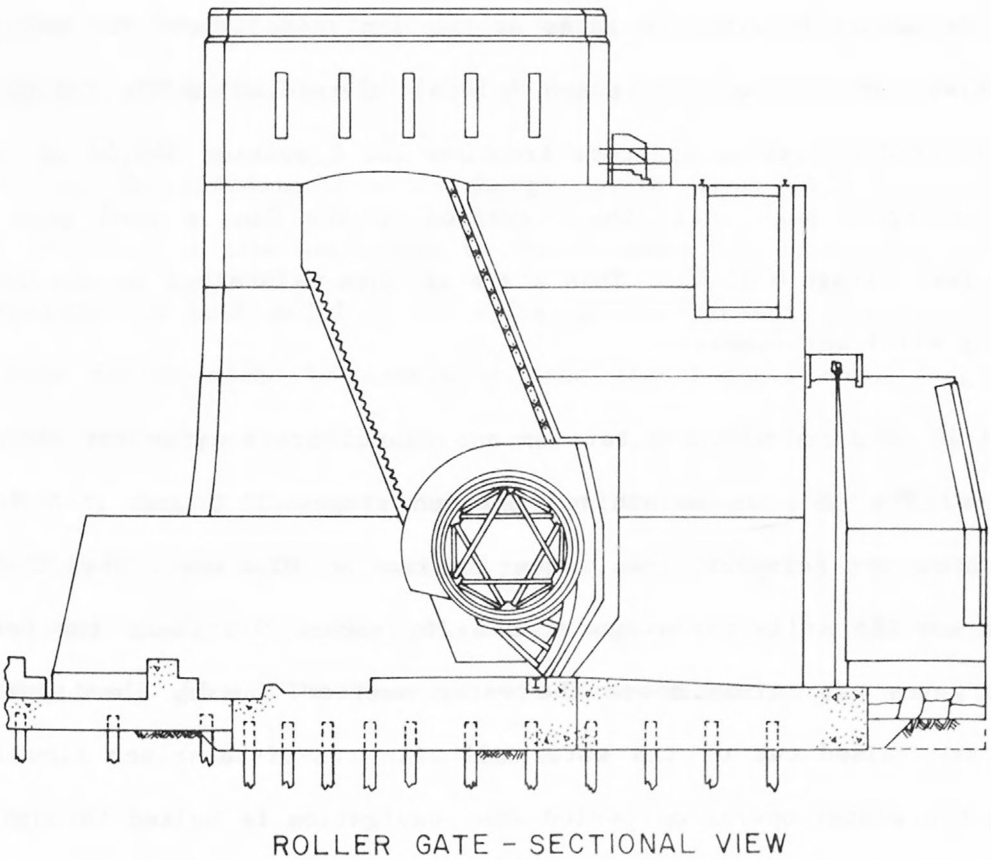


Figure 2.-- Location of flow-control structures (modified from U.S. Army Corps of Engineers, 1980, pl. 2).



TAINTER GATE - SECTIONAL VIEW



ROLLER GATE - SECTIONAL VIEW

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

submerged position when the dam is in operation. The free-weir flow coefficients were not defined for gates 1, 10 and 19. The remainder of the gates are non-submergible, therefore, flow would not occur over the gate crests. Submerged-weir flow for all the gates would 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.

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 CA" (U.S. Army Corps of Engineers, 1980, pl. 28) was put in operation with the 1938 navigation season. The plan allows high water to recede naturally with the gates at the dam raised above the water surface until elevation 545.56 feet (stage = 10.4) is reached on the Fairport, Iowa, gage, located 6.3 miles upstream from Dam 16. Elevation 545.56 is maintained at the Fairport gage until the elevation on the Dam 16 pool gage rises to 545.00 feet (stage = 11.4). This stage is then maintained on the Dam 16 pool gage for all lower flows.

Dam 16 is a run-of-the-river dam and cannot store water for flood control purposes. The pool is maintained between stages 11.0 and 11.5 feet while maintaining the Fairport, Iowa, water surface at 10.4 feet. When the river is rising and the tailwater stage at Dam 16 reaches 9.2 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. During the winter operation period when navigation is halted through Lock and Dam 16, the pool is maintained within the winter operating stage of 10.4 and 11.4 feet.

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 about 22 feet upstream from the downstream edge of the tainter-gate sills and about 27 feet upstream from 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 velocity measurements were made to define vertical velocity curves and 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 pounds) from a collapsible crane (Rantz and others, 1982).

A total of 45 measurements of discharge ranging from 1,100 to 11,300 cubic feet per second in a gate were made in the forebays of the tainter and roller gate structures of Lock and Dam 16. 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. The results of these measurements are listed in table 2.

Table 2.--Summary of current-meter discharge measurements and hydraulic-control data for control gates at Mississippi River Lock and Dam 16

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	11-08-83	20.00	13.35	3.50	4.03	2,980	0	3.32	0.270	SO
2	11-08-83	20.00	13.35	3.50	3.45	2,990	+ 2.7	3.88	0.271	SO
3	11-09-83	20.00	13.30	1.50	1.47	1,240	+ 4.2	9.05	0.112	SO
3	11-08-83	20.01	13.36	2.50	2.50	2,090	+ 0.5	5.36	0.189	SO
3	11-08-83	20.01	13.36	3.50	3.51	2,970	+ 0.3	3.82	0.269	SO
3	11-08-83	20.01	13.36	4.50	4.53	4,020	+ 3.9	2.96	0.364	SO
3	10-23-84	19.72	14.94	6.00	6.09	4,480	+ 0.4	2.45	0.428	SO
3	10-23-84	19.71	14.94	7.00	7.10	5,300	+ 1.3	2.10	0.506	SO
4	11-08-83	20.01	13.36	3.50	3.56	3,010	0	3.76	0.272	SO
5	11-08-83	20.01	13.36	3.50	3.51	2,980	+ 0.7	3.82	0.270	SO
6	11-08-83	20.01	13.36	3.51		4,410	+ 0.2	3.81	0.200	SO
7	11-08-83	20.03	13.38	2.50		3,120	- 0.3	5.35	0.141	SO
7	11-08-83	20.03	13.38	3.50		4,390	0	3.82	0.198	SO
7	11-08-83	20.03	13.38	4.50		5,590	- 0.9	2.97	0.253	SO
7	10-23-84	19.79	14.97	6.00		6,450	+ 0.8	2.50	0.306	SO
7	10-23-84	19.79	14.96	6.50		7,090	+ 2.2	2.30	0.336	SO
7	10-23-84	19.78	14.96	7.00		7,740	+ 3.6	2.14	0.367	SO
7	10-23-84	19.77	14.94	7.50		8,720	+ 4.1	1.99	0.414	SO
7	10-23-84	19.77	14.93	8.00		9,910	+ 1.5	1.87	0.470	SO
7	10-23-84	19.76	14.93	8.50		11,300	+ 0.9	1.76	0.537	SO
8	11-09-83	20.00	13.30	1.00		1,210	- 4.0	13.30	0.055	SO
8	11-08-83	20.03	13.38	3.50		4,290	- 2.3	3.82	0.194	SO
8	10-23-84	19.75	14.92	7.00		7,700	+ 2.9	2.13	0.366	SO
8	10-23-84	19.76	14.92	8.00		9,460	- 3.2	1.86	0.449	SO
9	11-08-83	20.03	13.38	3.50		4,210	- 4.1	3.82	0.190	SO
10	11-08-83	20.03	13.38	1.50	1.71	1,100	+ 1.9	7.84	0.100	SO
10	11-08-83	20.03	13.38	2.50	2.71	1,830	- 2.1	4.94	0.166	SO
10	11-08-83	20.03	13.38	3.50	3.81	2,800	+ 0.4	3.52	0.254	SO
10	10-23-84	19.74	14.92	5.00	5.28	3,440	+ 0.6	2.83	0.327	SO
10	10-23-84	19.73	14.93	6.00	6.27	4,200	+ 0.2	2.38	0.400	SO
11	11-09-83	20.00	13.30	2.50	2.47	2,120	+ 2.9	5.38	0.192	SO
12	11-09-83	20.00	13.30	1.50	1.49	1,200	- 0.8	8.93	0.109	SO
12	11-09-83	20.00	13.30	2.50	2.51	2,050	- 1.9	5.30	0.186	SO
12	11-09-83	20.00	13.30	3.50	3.51	3,020	+ 1.7	3.79	0.274	SO
13	11-09-83	20.00	13.30	2.50	2.53	2,120	+ 0.5	5.26	0.192	SO
14	11-09-83	20.00	13.30	2.50	2.47	2,070	+ 0.5	5.38	0.188	SO
14	10-23-84	19.73	14.93	5.00	4.98	3,520	- 2.5	3.00	0.335	SO
14	10-23-84	19.72	14.94	6.00	6.02	4,340	- 1.4	2.48	0.414	SO
15	11-09-83	20.00	13.30	2.50	2.33	1,940	+ 0.5	5.71	0.176	SO
16	11-09-83	20.00	13.30	1.50	1.42	1,160	+ 0.9	9.37	0.105	SO
16	11-09-83	20.00	13.30	2.50	2.42	1,980	- 1.5	5.50	0.179	SO
16	11-09-83	20.00	13.30	3.50	3.45	2,840	- 2.7	3.86	0.257	SO
17	11-09-83	20.00	13.30	2.50	2.52	2,090	- 0.5	5.28	0.189	SO
18	11-09-83	20.00	13.30	2.50	2.52	2,040	- 2.9	5.28	0.185	SO
19	11-09-83	20.00	13.30	2.50	2.72	1,830	- 2.7	4.89	0.166	SO

1/ h_1 = Pool stage + 8.60 feet.
2/ h_3 = Tailwater stage + 8.60 feet.
3/ SO = submerged-orifice flow.

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 the discharge equations.

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 gate sill are obtained by adding 8.60 feet to the gage readings. The stages can be referenced to sea level by adding the zero gage datum, 533.60 feet (1912 adjustment), to the stages. The gage-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.

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 vertical 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 16 is the top downstream corner of a brace plate riveted to connecting members of the gate structure (fig. 4). The top of the plate is 0.98 foot below the top edge of the gate arm and the R.P. is 15.78 feet from the trunnion centerline. The R.P. is the same for all the tainter gates. The elevation of each reference point was determined by levels from established benchmarks on the piers between the gates (U.S. Army Corps of Engineers, 1939a). The gate opening, h_g, is computed from the equation:

$$h_g = 24.00 - 30.04 \sin(33.290 + \phi_u) \qquad (8)$$

where $\phi_u = \sin^{-1}[(549.00 - \text{R.P. elev.})/15.78]$

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

The relation between the "true" gate opening (h_g) and the gage-indicator readings for non-submergible gates can be determined by closing the gate ($h_g = 0$) and computing the included angle of the gate structure using the R.P.

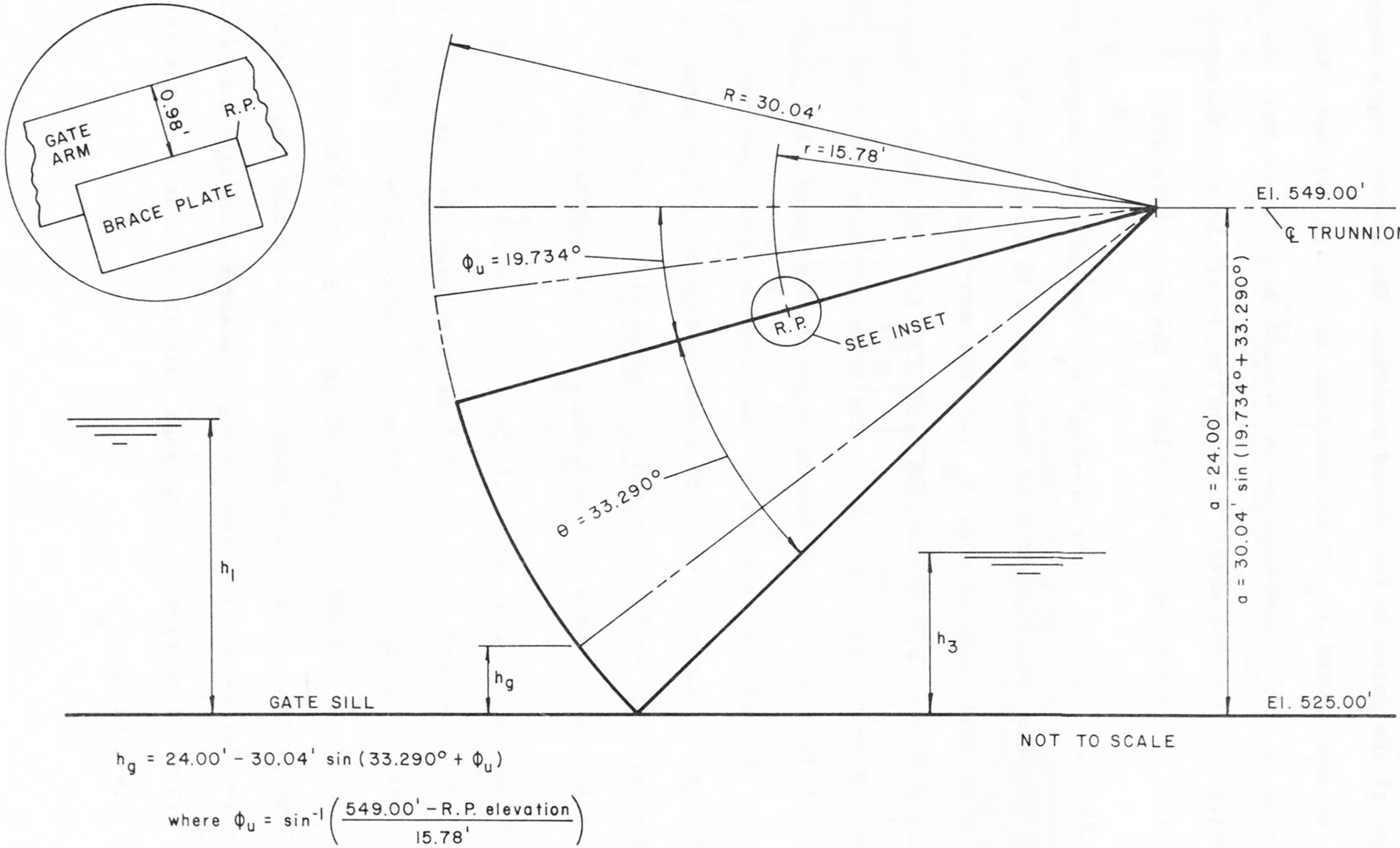


Figure 4.--Details of tainter gates at Mississippi River Lock and Dam 16.
See page vi for definition of symbols.

elevations of the gates in the closed position. The average angle computed for 4 gates in the closed (h_g = 0) position is 33.290 degrees (fig. 4). The deviation of h_g for these 4 gates is +/-0.01 foot. Note that the angle of 33.290 degrees is not the total "included" angle of the gate structure because the R.P. is 0.98 foot below the top edge of the upper gate arm.

The average, computed, gate opening (h_g) for all the tainter gates with the gage-indicator settings at 2.50 feet, was 2.55 feet with variations from 2.33 to 3.03 feet. The average h_g for the non-submergible gates (2-5 and 11-18) was 2.52 feet with variations from 2.33 to 2.56. These differences can be attributed primarily to error in the gage-indicator settings and to the variance of the seals on the bottom edge of the gates. The gage-indicator corrections (e) and the relation of the computed gate openings (h_g) to the 2.50 foot gage indicator setting are shown in figure 5. Also shown in figure 5 is the discharge for each of the tainter gates at the 2.50 foot gage setting, the discharges range from 1,830 to 2,140 cubic feet per second.

A gage-indicator error of 0.10 foot will result in about a 5-percent deviation in discharge from the rating discharge at the 2.50-foot gage setting. This deviation from the rating discharge increases with lower gage settings (about 10 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.

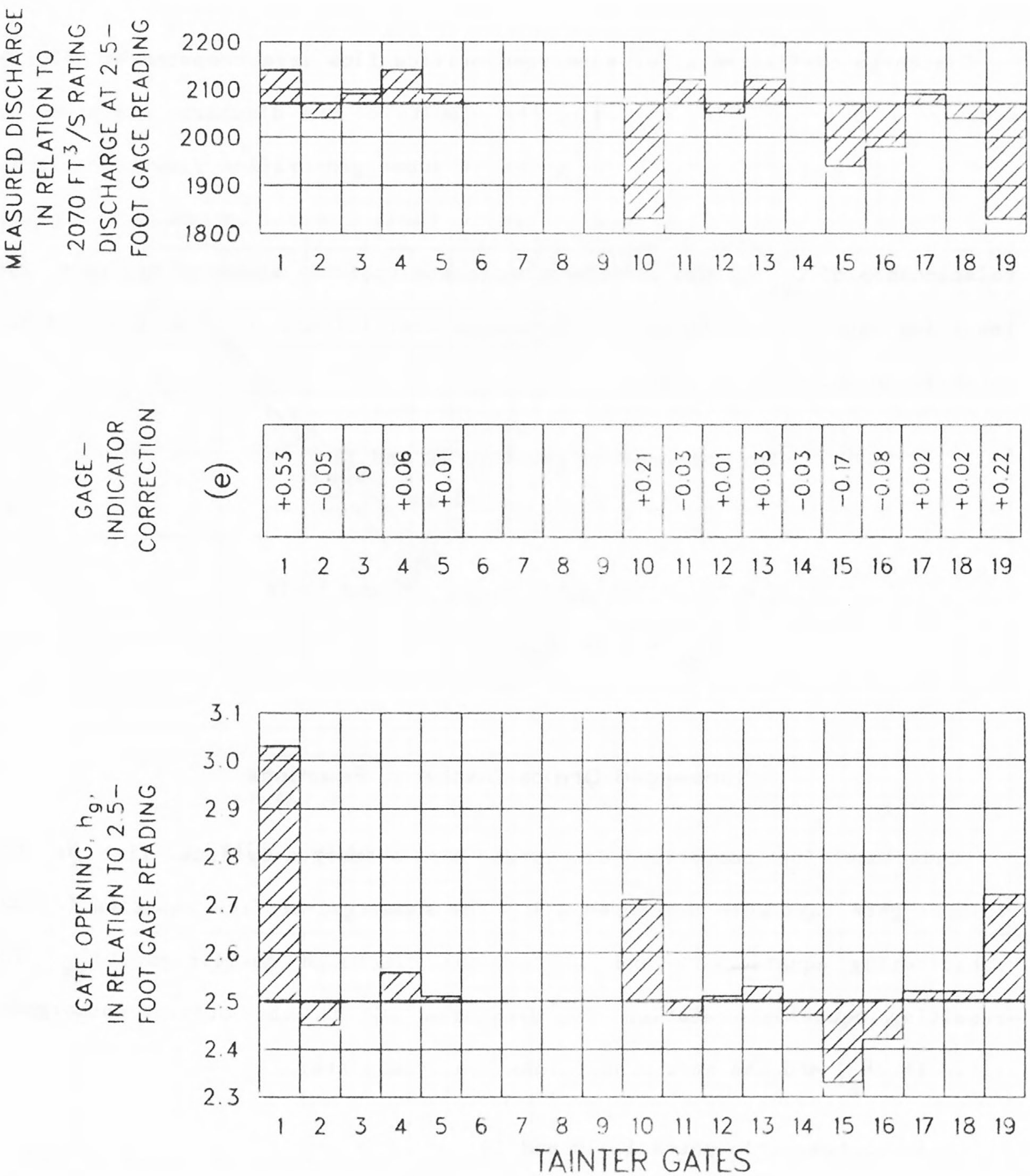


Figure 5.--Gage-indicator corrections and comparison of gate openings and discharges at 2.5-foot gage-indicator settings for tainter gates.

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 resulting equations, relating the discharge coefficients, C_{gs}, to the orifice-submergence ratio, h_3/h_g, are:

For submergible gates 1, 10 and 19

$$C_{gs} = 1.11 \, (h_3/h_g)^{-1.18} \quad (9)$$

For non-submergible gates 2-5 and 11-18

$$C_{gs} = 1.09 \, (h_3/h_g)^{-1.05} \quad (10)$$

Submerged-Orifice Discharge Equations

Equations for computing discharge for submerged-orifice flow in the tainter-gate bays were developed using the submerged-orifice equation (2) and substituting equations 9 and 10 for the discharge coefficient, C_{gs}. The resulting equations relating the discharge (Q) to the orifice-submergence ratio (h_3/h_g) and the static-head loss ($h_1 - h_3$) are:

For submergible gates 1, 10 and 19

$$Q = 356 \, h_3 \, (h_3/h_g)^{-1.18} \, (h_1 - h_3)^{0.5} \quad (11)$$

where h_g for gate 1 = gage reading + 0.53 foot and

h_g for gates 10 and 19 = gage reading + 0.22 foot.

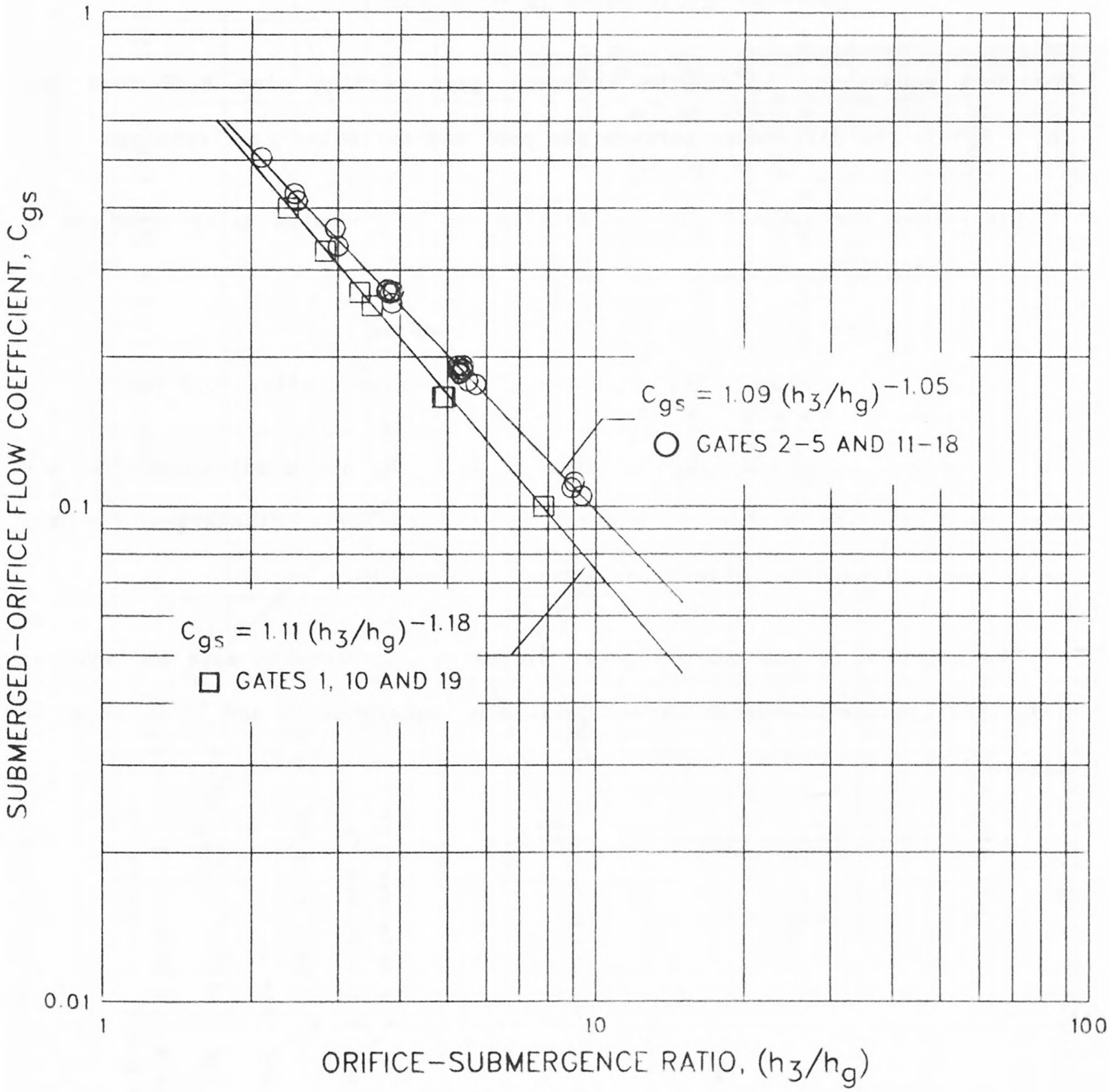


Figure 6.--Relation between submerged-orifice flow coefficient and orifice-submergence raatio for tainter gates.

For non-submergible gates 2-5 and 11-18:

$$Q = 350\ h_3\ (h_3/h_g)^{-1.05}\ (h_1 - h_3)^{0.5} \qquad (12)$$

where h_g = gage reading + the gage indicator correction (e), shown in figure 5. (The average correction, e, for the non-submergible gates is -0.02 foot).

For both equations, h_3 is the tailwater-gage reading plus 8.60 feet and $(h_1 - h_3)$ is the difference between the pool and tailwater-gage readings.

Discharges for gates 1, 10 and 19 also can be computed using equation 12 for the following conditions:

where (1) h_g for gate 1 = gage reading, and

(2) h_g for gates 10 and 19 = gage reading -0.2 foot.

The discharges computed using equation 12 with the above adjustments to the gage readings are within 5 percent of the measured discharges for the measurements listed in table 2 for gates 1, 10 and 19.

The relation of the current-meter discharge measurements made on November 8-9, 1983, to the discharge curves defined by equations 11 and 12 is shown in figure 7.

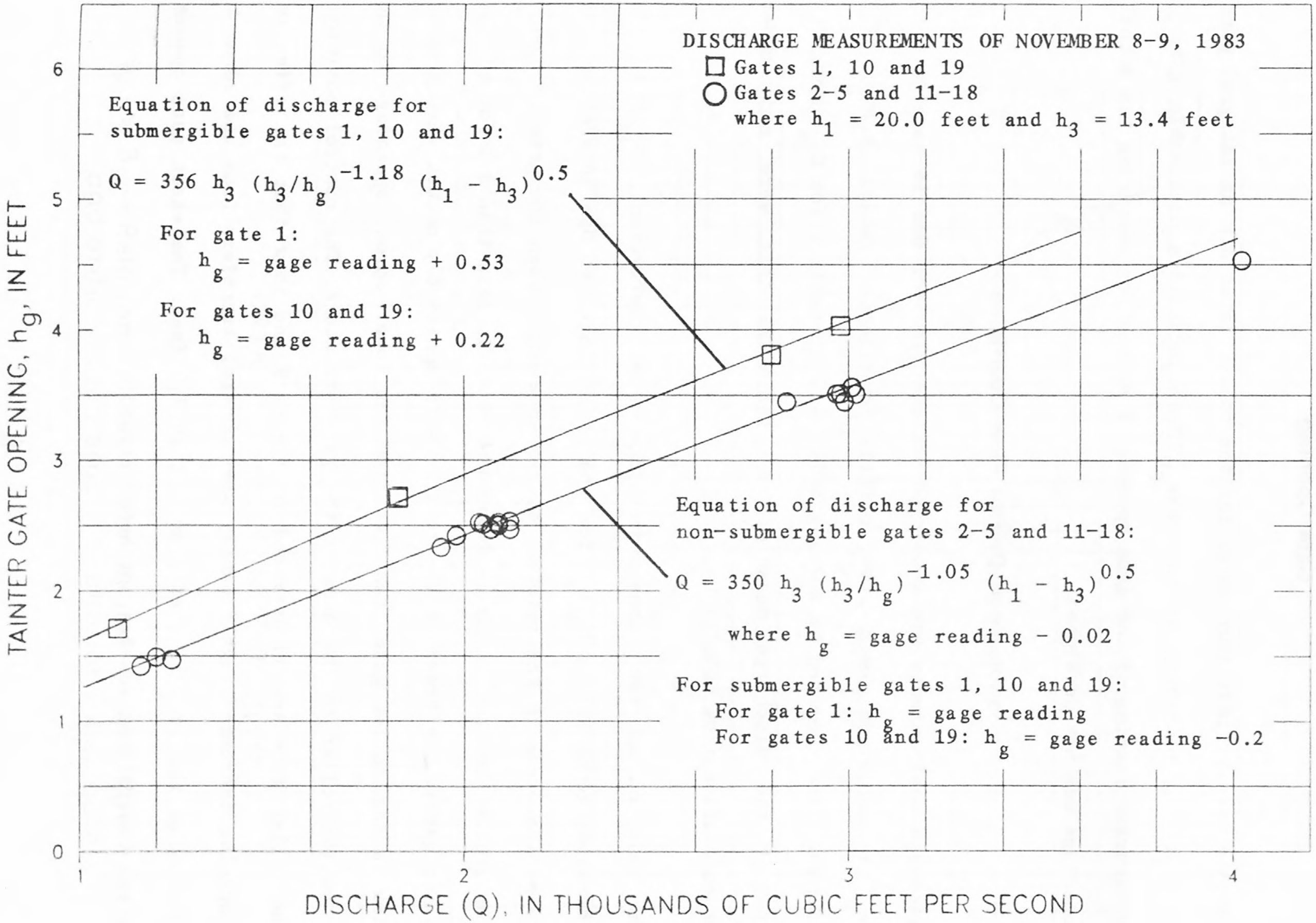


Figure 7.--Comparison of current-meter discharge measurements of November 8-9, 1983, to rating curve for tainter gates.

ROLLER-GATE FLOW

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 Coefficient

Discharge coefficients for submerged-orifice flow for Dam 16 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 Dam 16 are shown in figure 8. The break in the relation occurs at a point when the gate is open 7 feet or greater and the orifice-submergence ratio is less than 2.1 for the Dam 16 roller gates. The break in the relationship apparently occurs when control of flow in the roller gate 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 9 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.

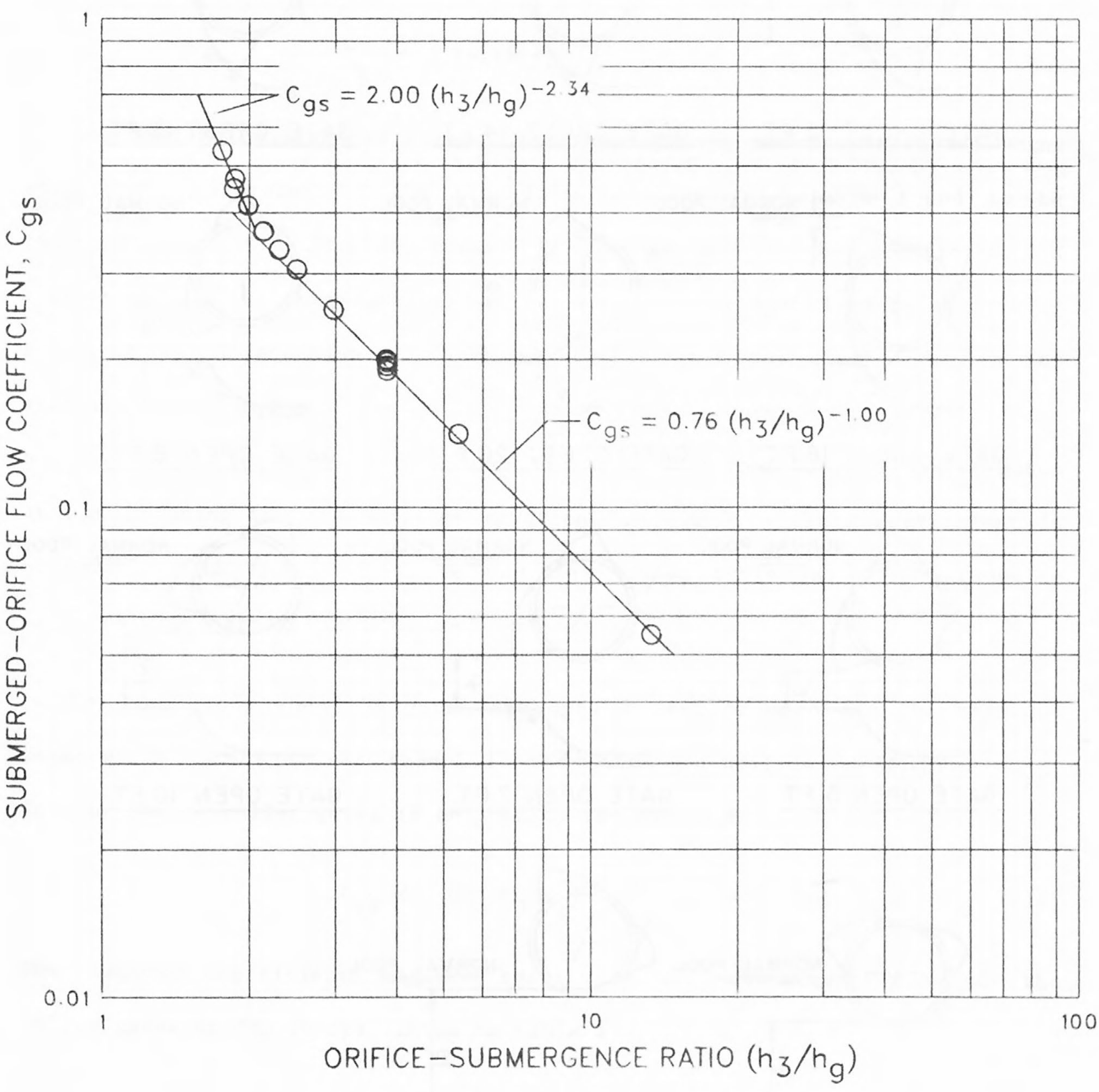


Figure 8.--Relation between submerged–orifice flow coefficient and orifice–submergence ratio for roller gates.

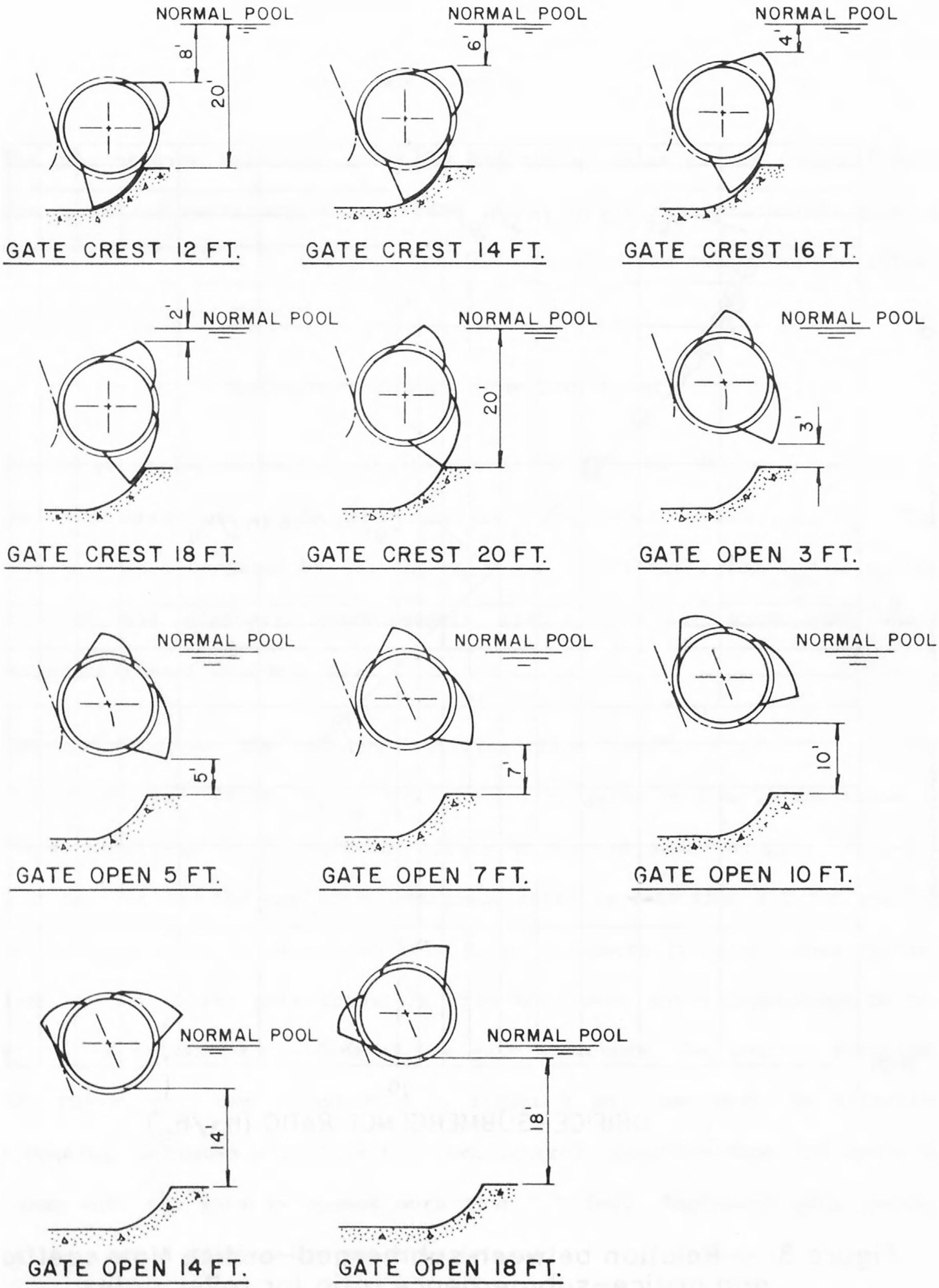


Figure 9.--Positions of roller gates for selected crests and openings (modified from U.S. Army Corps of Engineers, 1940, fig. 35).

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:

$$C_{gs} = 0.76 \ (h_3/h_g)^{-1.00} \tag{13}$$

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 13. 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 Dam 16 using the free-orifice equation (1) was 0.74. This coefficient is compatible 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 more and the orifice-submergence ratio is less than 2.1, the submerged-orifice coefficient, C_{gs}, for the Dam 16 roller gates is defined by the equation:

$$C_{gs} = 2.00 \ (h_3/h_g)^{-2.34} \tag{14}$$

The computed coefficients and the results of the measurements made for the roller gates at Dam 16 are listed in table 2.

Submerged-Orifice Discharge Equation

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 13 for the discharge 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:

$$Q = 486\ h_g\ (h_1 - h_3)^{0.5} \tag{15}$$

where $h_1 - h_3$ = the difference between the pool and tailwater-gage readings.

An equation for computing discharge for submerged-orifice flow when the roller gates are open 7.0 feet or more and h_3/h_g is less than 2.1 feet was developed using the submerged-orifice flow equation (2) and substituting equation 14 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:

$$Q = 1{,}280\ h_3\ (h_3/h_g)^{-2.34}\ (h_1 - h_3)^{0.5} \tag{16}$$

where h_3 = the tailwater-gage reading plus 8.60 feet,

h_g = the gate opening, and

$h_1 - h_3$ = the difference between the pool and tailwater-gage readings.

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DISCHARGE EQUATIONS AND RATINGS

The discharge equations applicable to the control gates when Dam 16 is in operation have been compiled and are 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 Dam 16 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 11.40 feet (h_1 = 20.00 feet). Discharges for any other headwater, tailwater, and gate-opening relations 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 using hydraulic models of the gates, are shown in figures 10 and 11. Corresponding discharge rating curves defined by the methods outlined in this report are shown for comparison. Discharges defined by the 2 methods for each of the gate openings for the tainter gates generally are within about 20 percent. Discharges defined by the 2 methods for each of the gate openings for the roller gates generally are within about 10 percent for gate openings of 6 feet or less. Large deviations occur between the ratings as the gates are opened greater than 7.0 feet.

Table 3. Summary of discharge equations for control gates at Mississippi River Lock and Dam 16

Gate	Flow regime	Equation of discharge 1/, 2/	Equation number
Tainter gates 1, 10 and 19	Submerged orifice	$Q = 356\ h_3\ (h_3/h_g)^{-1.18}\ (h_1 - h_3)^{0.5}$	(11)
Tainter gates 2-5 and 11-18	Submerged orifice	$Q = 350\ h_3\ (h_3/h_g)^{-1.05}\ (h_1 - h_3)^{0.5}$	(12)
Roller gates	Submerged orifice $h_g < 7.0$ or > 7.0 when $h_3/h_g > 2.1$	$Q = 486\ h_g\ (h_1 - h_3)^{0.5}$	(15)
Roller gates	Submerged orifice $h_g \geq 7.0$ and $h_3/h_g < 2.1$	$Q = 1{,}280\ h_3\ (h_3/h_g)^{-2.34}\ (h_1 - h_3)^{0.5}$	(16)

1/ Q = Discharge, in cubic feet per second
h_1 = Pool stage + 8.60 feet
h_3 = Tailwater stage + 8.60 feet
h_g for tainter gages = gage reading + gage-indicator correction, e (fig. 5).
(the average gage-indicator correction for gates 2-5, 11-18 is -0.02 foot)
h_g for roller gates = gage reading

2/ 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 16 with upstream pool stage of 11.40 feet

Gage reading (feet)	Tainter-gate discharge (cubic feet per second)1/, 2/ for indicated tailwater stage (feet)								
	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
0.5	441	415	388	360	329	296	259	217	166
1.0	934	879	821	761	696	627	549	460	350
1.5	1440	1350	1270	1170	1070	966	846	709	540
2.0	1950	1840	1720	1590	1460	1310	1150	962	733
2.5	2470	2330	2180	2020	1850	1660	1460	1220	929
3.0	3000	2820	2640	2450	2240	2010	1760	1480	1130
3.5	3530	3320	3110	2880	2630	2370	2080	1740	1330
4.0	3/<u>4070</u>	3830	3580	3310	3030	2730	2390	2000	1530
4.5	4600	<u>4330</u>	4050	3750	3430	3090	2710	2270	1730
5.0	5150	4840	<u>4530</u>	4190	3840	3450	3030	2540	1930
5.5	5690	5350	5000	<u>4640</u>	4240	3820	3350	2800	2130
6.0	6240	5870	5490	5080	4650	4180	3670	3070	2340
6.5	6780	6380	5970	5530	<u>5060</u>	4550	3990	3340	2550
7.0	7340	6900	6450	5980	5470	4920	4310	3610	2750
7.5	7890	7420	6940	6430	5880	<u>5290</u>	4640	3890	2960
8.0	8440	7940	7430	6880	6300	5670	4960	4160	3170
8.5	9000	8470	7920	7330	6710	6040	5290	4430	3380
9.0	9560	8990	8410	7790	7130	6410	<u>5620</u>	4710	3590
9.5	10100	9520	8900	8240	7550	6790	5950	4980	3800
10.0	10700	10000	9390	8700	7960	7170	6280	5260	4010

1/Discharges for tainter gates 2-5 and 11-18 were computed using equation:

$$(12) \quad Q = 350\, h_3 (h_3/h_g)^{-1.05} (h_1 - h_3)^{0.5}$$

where h_g = gage reading + (average e = -0.02),
h_1 = 20.00 feet (11.40 + 8.60), and
h_3 = tailwater stage + 8.60 feet.

2/Discharges for tainter gates 1, 10 and 19 also can be approximated using equation 12 (table 4) for the conditions:

(1) h_g for gate 1 = gage reading, and
(2) h_g for gates 10 and 19 = gage reading -0.2 foot.

3/Discharges greater than those underlined may exceed those allowable for safe gate operation (U.S. Army Corps of Engineers, 1980).

Table 5.--Discharge rating table for submerged-orifice flow for a single roller gate at Mississippi River Lock and Dam 16 with upstream pool stage of 11.40 feet

Gage reading (feet)	Roller-gate discharge (cubic feet per second)1/ for indicated tailwater stage (feet)								
	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
0.5	745	704	661	615	565	510	448	376	288
1.0	1490	1410	1320	1230	1130	1020	896	753	575
1.5	2240	2110	1980	1840	1690	1530	1340	1130	863
2.0	2980	2820	2640	2460	2260	2040	1790	1510	1150
2.5	3730	3520	3310	3070	2820	2550	2240	1880	1440
3.0	4470	4230	3970	3690	3390	3060	2690	2260	1730
3.5	5220	4930	4630	4300	3950	3570	3140	2640	2010
4.0		5630	5290	4920	4520	4080	3580	3010	2300
4.5		6340	5950	5530	5080	4590	4030	3390	2590
5.0			6610	6150	5650	5100	4480	3760	2880
5.5			7270	6760	6210	5610	4930	4140	3160
6.0				7380	6780	6120	5380	4520	3450
6.5				7990	2/7340	6630	5820	4890	3740
7.0					7780	7140	6270	5270	4020
7.5					9140	7550	6720	5650	4310
8.0						8780	7100	6020	4600
8.5	Discharges in this area may					10100	8180	6360	4890
9.0	be greater than those allowable					11600	9350	7270	5150
9.5	for safe gate operation (U.S. Army						10600	8250	5850
10.0	Corps of Engineers, 1980).						12000	9300	6590

1/Discharges were computed using equations:

$$(15) \quad Q = 486\, h_g (h_1 - h_3)^{0.5} \quad \text{and}$$

$$(16) \quad Q = 1{,}280\, h_3\, (h_3/h_g)^{-2.34} (h_1 - h_3)^{0.5}$$

where h_g = gage reading,
h_1 = 20.00 feet (11.40 + 8.60), and
h_3 = tailwater stage + 8.60 feet.

2/Underline denotes change in rating from equation 15 to equation 16.

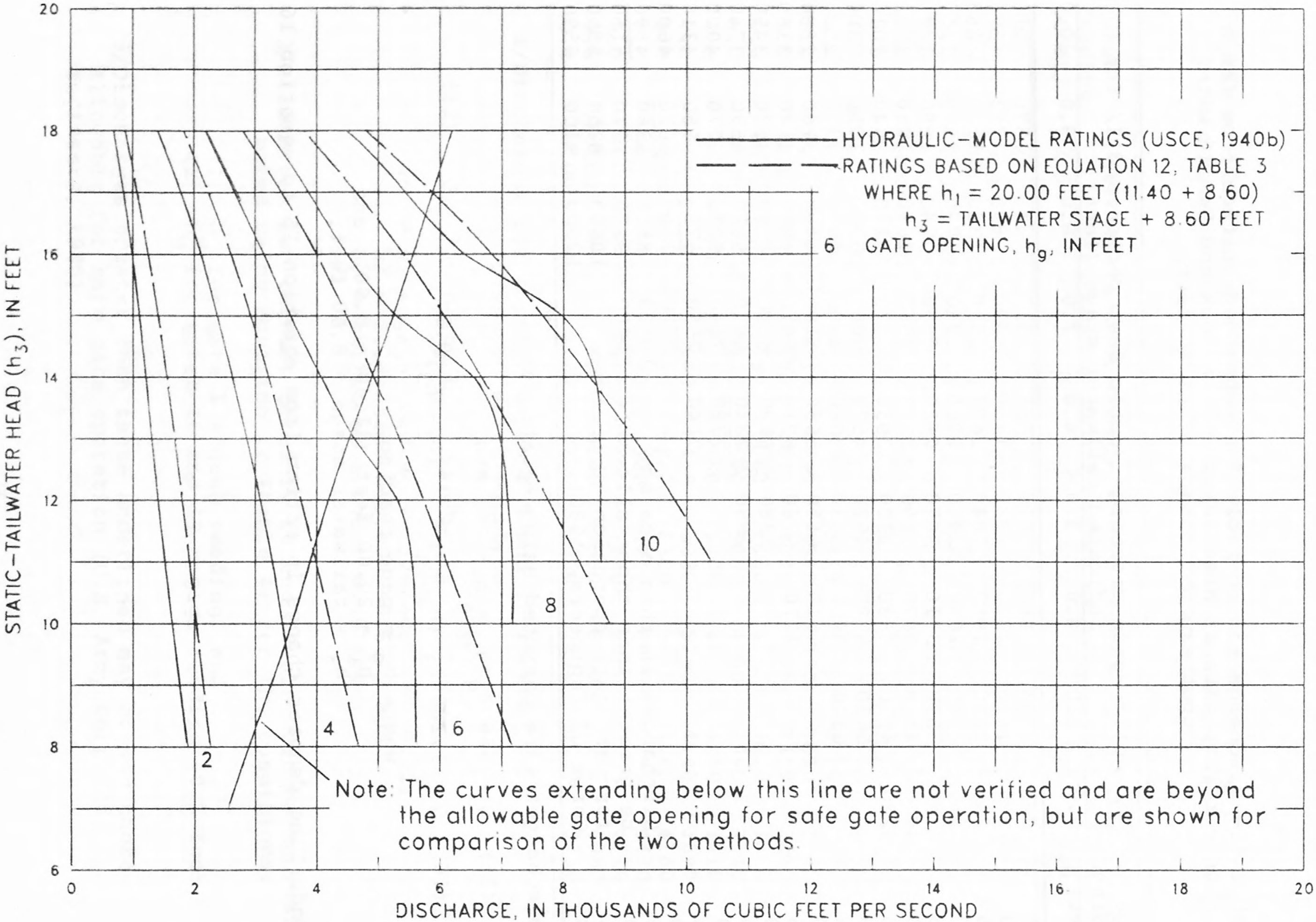

Figure 10.--Discharge ratings for submerged-orifice flow for a single tainter gate compared to hydraulic-model ratings.

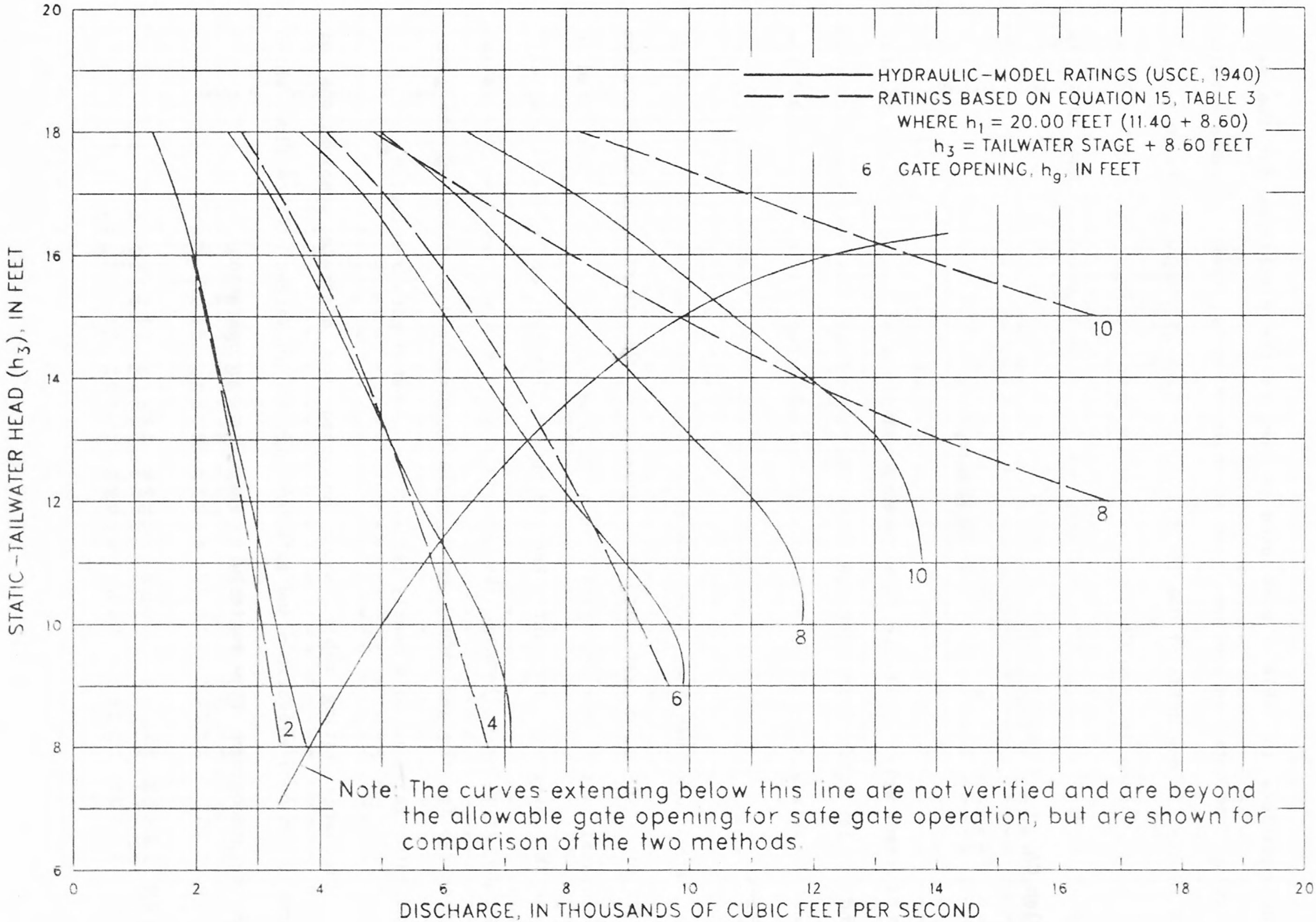

Figure 11.—Discharge ratings for submerged orifice flow for a single roller gate compared to hydraulic–model ratings.

The equations in table 3 were used to compute the discharges for the gate settings indicated in the operation schedule, Plan CA, shown in table 6 which is in use for operation of Dam 16. Discharges generally were within 10 percent of those listed in Plan CA until the roller gate openings exceeded 7 feet at which time the discharges increased to 40 percent greater than those in Plan CA.

SUMMARY

Current-meter discharge measurements made in the forebays of the tainter and roller gates of Lock and Dam 16 were used to develop discharge coefficients and equations of discharge for submerged-orifice flow for all the gates.

Methodology has been described to compute the true gate openings of the tainter gates. The gate-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 accidently 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 gate-indicator gages 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.

Table 6.--Comparison of rating discharges (column 1) to discharges specified in Gate Operation Schedule Plan CA
[Modified from U.S. Army Corps of Engineers, 1980, pl. 28]

	Gate Operation Schedule Plan CA for controlled tailwater stages with headwater stage of 11.40 feet																					
				Gate opening, (feet), for gate indicated																		
				Tainter					Roller				Tainter									
Rating 1/ discharge ft³/s	Discharge ft³/s	Tailwater stage (feet)	Head (feet)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
13,400	11,800	2.4	9.0	-3.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5
16,100	15,000	2.6	8.8	-3.0	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	0.5	0.5	0.5	0.5
19,700	18,000	2.8	8.6	-3.0	1.5	1.5	1.5	1.5	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
24,000	22,300	3.0	8.4	-3.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	0.5	0.5
28,200	25,700	3.2	8.2	-3.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0
29,700	28,500	3.4	8.0	1.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0
32,600	31,100	3.6	7.8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	1.0	1.0
35,600	33,800	3.8	7.6	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.0	1.0	1.0
38,000	36,200	4.0	7.4	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	2.0	1.5	1.5	1.0	1.0	1.0
40,700	38,800	4.2	7.2	2.5	2.5	2.5	2.5	2.5	3.0	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5
43,500	41,100	4.4	7.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5
45,800	43,500	4.6	6.8	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.5
48,800	46,000	4.8	6.6	3.5	3.5	3.0	3.0	3.0	3.5	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
51,400	48,500	5.0	6.4	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	2.0	2.0	2.0
54,200	50,800	5.2	6.2	3.5	3.5	3.5	3.5	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	2.0	2.0
56,800	53,000	5.4	6.0	4.0	4.0	4.0	4.0	3.5	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0
59,000	55,200	5.6	5.8	4.0	4.0	4.0	4.0	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	2.0
61,600	57,600	5.8	5.6	4.5	4.5	4.0	4.0	4.0	4.5	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.0	3.0	3.0	2.5
63,100	59,800	6.0	5.4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0
66,300	62,000	6.2	5.2	4.5	4.5	4.5	4.5	4.5	5.0	5.0	4.5	4.5	4.5	4.5	4.5	4.0	4.0	3.5	3.5	3.5	3.0	3.0
68,800	64,100	6.4	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.5	4.0	4.0	3.5	3.5	3.5	3.5	3.5
71,100	66,300	6.6	4.8	5.0	5.0	5.0	5.0	5.0	5.5	5.5	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.0	4.0	3.5	3.5	3.5
74,900	68,600	6.8	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.5	5.5	5.5	5.0	5.0	4.0	4.0	4.0	4.0	4.0
76,900	70,900	7.0	4.3	6.0	6.0	6.0	5.5	5.5	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	4.5	4.5	4.5	4.0	4.0
80,800	73,100	7.2	4.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.5	5.5	5.0	5.0	5.0	5.0	4.5
83,200	75,200	7.4	3.8	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.0	6.0	6.0	5.5	5.5	5.5	5.0	5.0	5.0	5.0
87,100	77,600	7.6	3.5	7.0	7.0	7.0	6.5	6.5	7.0	7.0	7.0	7.0	6.5	6.5	6.0	6.0	6.0	6.0	5.5	5.5	5.5	5.5
90,800	79,800	7.8	3.2	7.0	7.0	7.0	7.0	7.0	8.0	8.0	8.0	7.0	7.0	7.0	6.5	6.5	6.5	6.5	6.0	6.0	5.5	5.5
96,600	81,900	8.0	2.9	7.0	8.0	8.0	8.0	8.0	9.0	8.0	8.0	8.0	7.0	7.0	7.0	7.0	7.0	7.0	6.5	6.5	6.5	6.0
106,000	84,000	8.2	2.6	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0	9.0	9.0	8.0	8.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
108,000	86,000	8.4	2.3	8.0	8.0	8.0	9.0	9.0	10.0	10.0	9.0	9.0	9.0	8.0	8.0	8.0	8.0	8.0	7.0	7.0	7.0	7.0
123,000	88,000	8.6	2.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.0	9.0	9.0	9.0	9.0	9.0

1/ Computed using equations in table 3 with headwater stage of 11.40 feet.

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