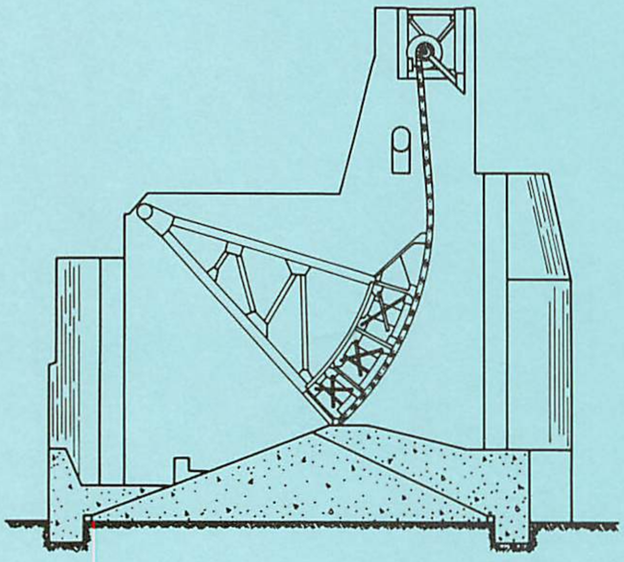
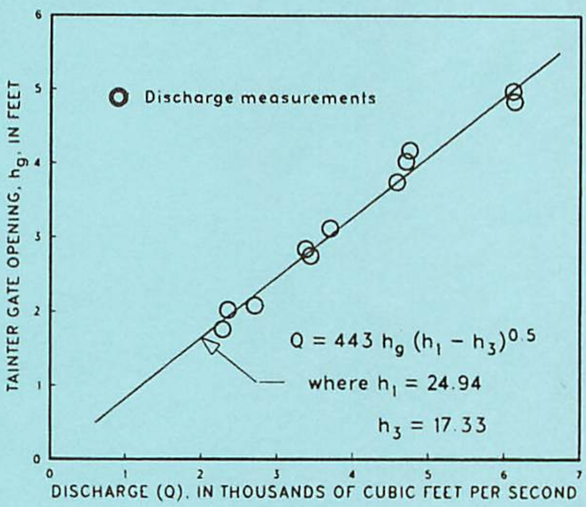
DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 22, SAVERTON, MISSOURI

U.S. GEOLOGICAL SURVEY

Water Resources Investigations Report 86-4137



TAINTER GATE - SECTIONAL VIEW



Prepared in cooperation with the

U.S. ARMY CORPS OF ENGINEERS,
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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.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 22, SAVERTON, MISSOURI

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 locks and dams. Discharge ratings for the gates on Lock and Dam 22, at Saverton, Missouri, 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. Rating discharges are given for comparison to those used in the operation schedule, Plan A, which is in use for the operation of Lock and Dam 22.

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 22 was placed in operation July 22, 1938.

This is the sixth 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, 12, 13, 14 and 16 (Heinitz, 1985a, 1986b, 1986a, 1985b and 1986c) preceded this report. Discharge ratings for these Locks and Dams corroborated rating development for Lock and Dam 22.

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 22. 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 hydraulic models of the 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 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 22.

Acknowledgments

This project was completed in cooperation with the U.S. Army Corps of Engineers, Rock Island District. 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 22, located at Saverton, Missouri, 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 22. 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.

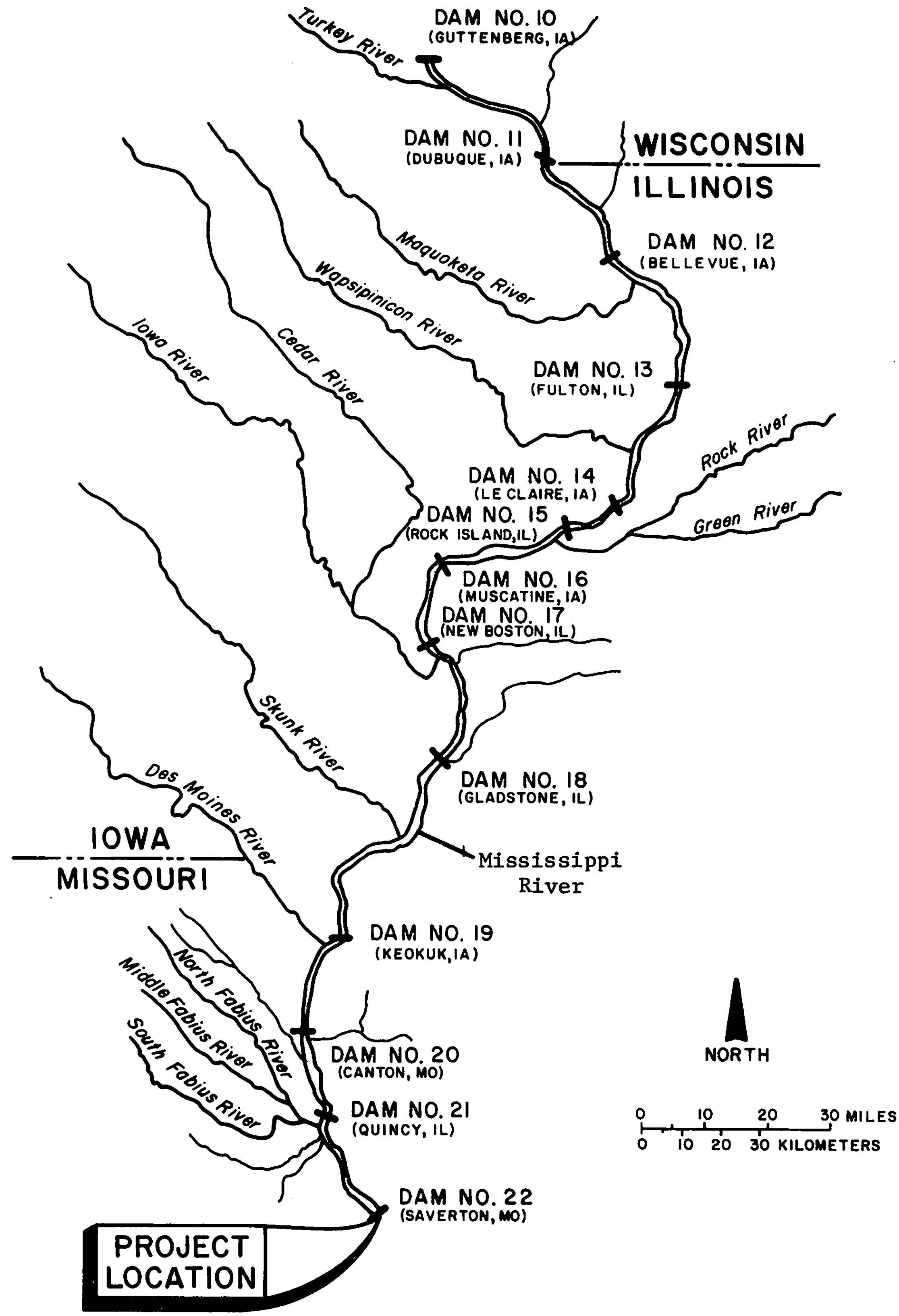


Figure 1.--Inland Waterway Navigation System of the upper Mississippi River basin (modified from U.S. Army Corps of Engineers, 1980, pl. 1).

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 22 contains 10 tainter gates and 3 roller gates for controlling the pool elevation upstream from the dam. Each tainter gate is 60 feet wide and 25 feet high and operates between the piers with 60-foot clear openings. The tainter gates are of the non-submergible type except for gate 13 which is submergible and is capable of being lowered 8 feet below the sill elevation. Each roller gate is 100 feet wide and 25 feet high and operates between piers with 100-foot clear openings. The roller gates are of the submergible type, capable of 8 feet of submergence. Three of the tainter gates, located adjacent to the lock, are separated from the remainder of the tainter gates by the three 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 22 are in operation (U.S. Army Corps of Engineers, 1980, pl. 27). Free-orifice flow rarely occurs at a low-head, navigation-type structure such as Dam 22 and would not occur at this dam under normal operating conditions.

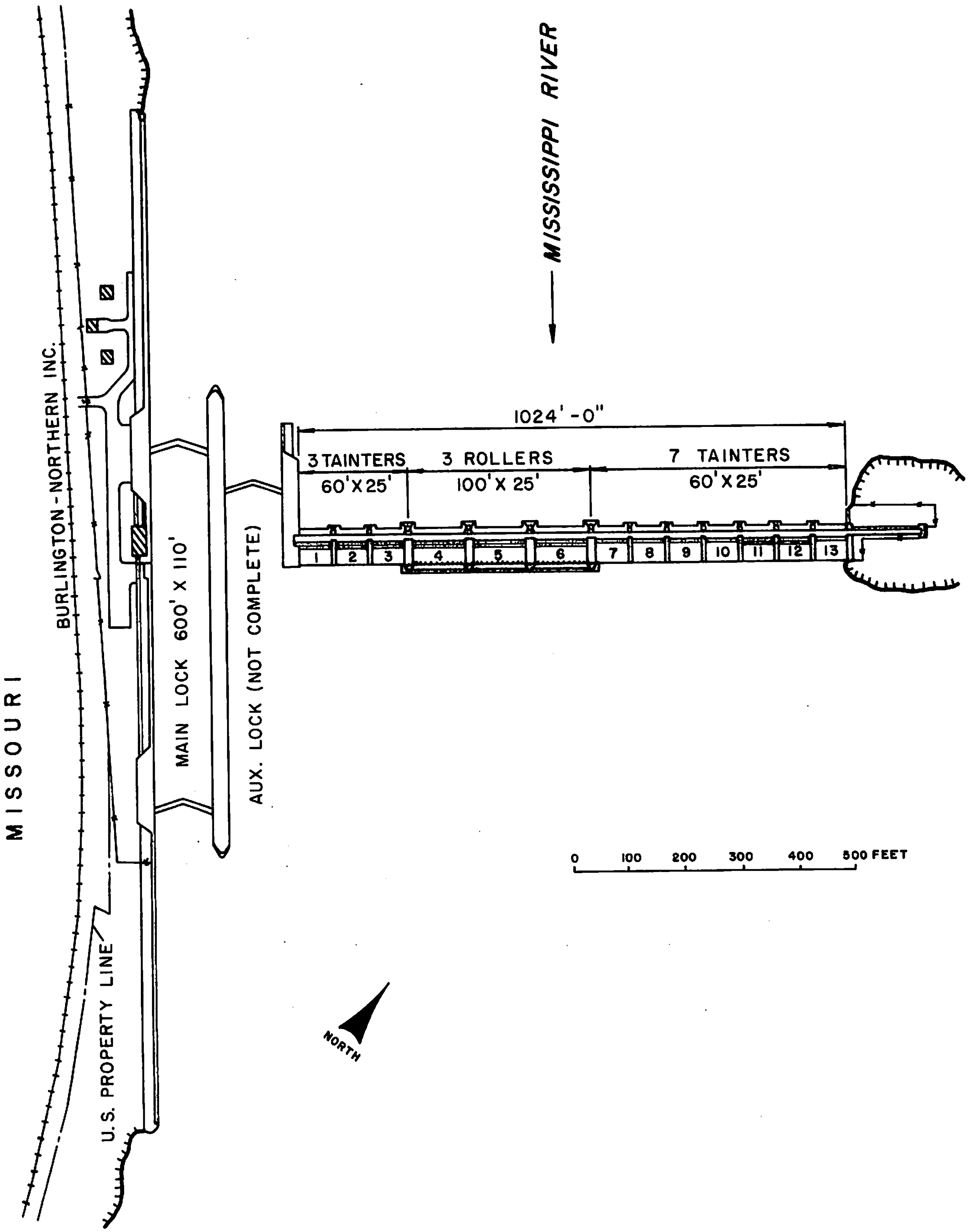
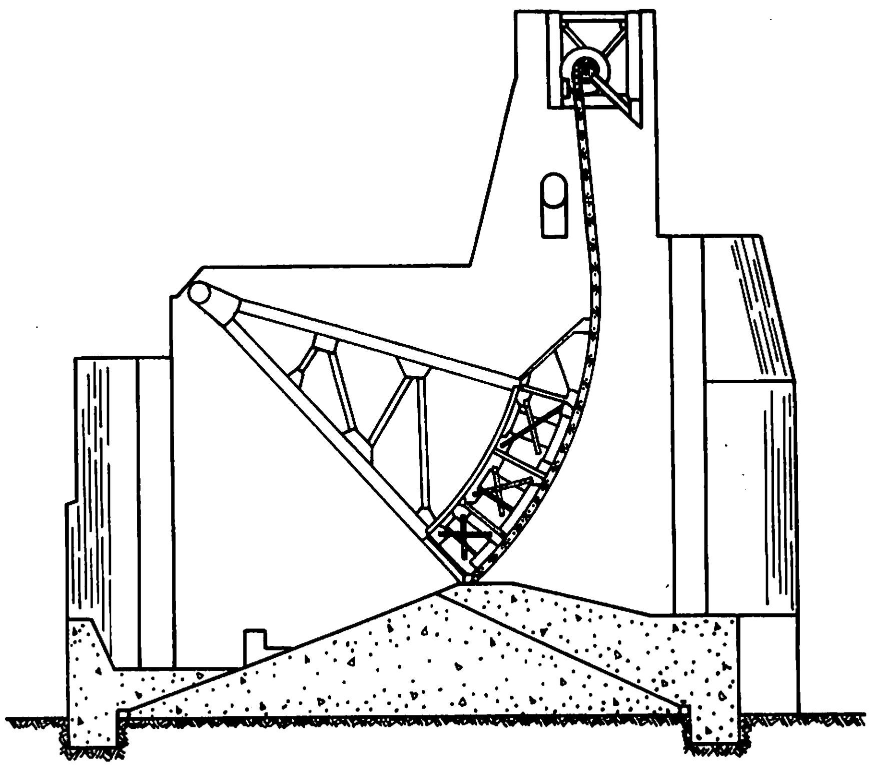
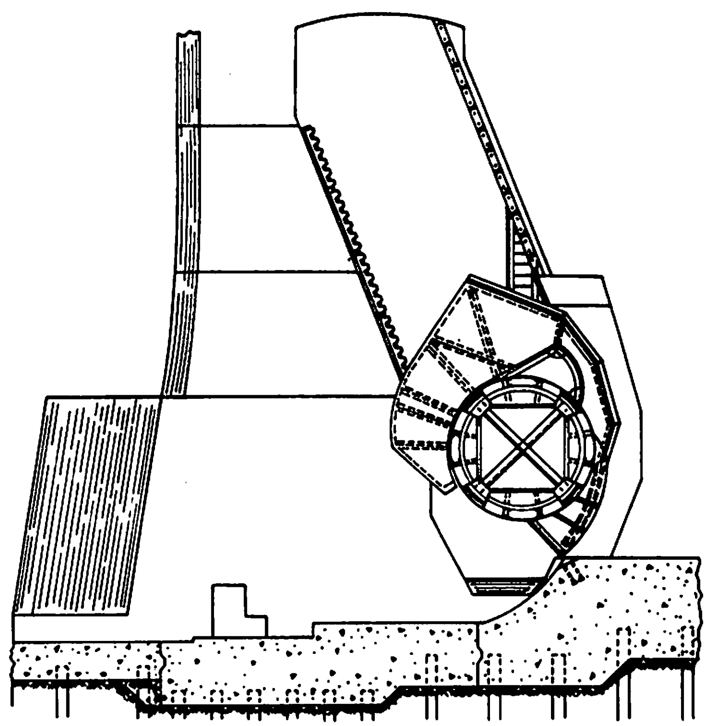


Figure 2.--Location of flow-control structures at Lock and Dam 22 (modified from U.S. Army Corps of Engineers, 1980, pl. 2).



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).

Free-weir flow at the Dam 22 roller gates would occur primarily with the gates in a submerged condition with flow over the crests of the gates. The roller gates are operated in the submerged position in the winter when there is no commercial navigation. Submerged-weir flow could occur with the roller 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. The tainter gates are non-submergible (with the exception of gate 13), therefore, flow would not occur over the gate crests.

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. 27) was adopted and put into use with the 1940 navigation season and remains in effect. Plan "A" allows high water levels to recede naturally until the authorized pool elevation for lower flows is reached.

Dam 22 is a run-of-the-river dam and cannot store water for flood control purposes. The pool is maintained between stages 13.0 and 13.5 feet. When the river is rising and the tailwater stage reaches 12.4 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 Pool 22, the pool is maintained within the winter operating stage of 12.9 to 13.4 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 20 feet upstream from the downstream edge of the tainter-gate sills and about 25 feet upstream 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 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 cable stay was used on top of the upstream piers to prevent the meter from running downstream into the gate orifice when the gates were opened 5 feet or more.

A total of 44 measurements of discharge ranging from 2,280 to 27,200 cubic feet per second in a gate were made in the forebays of the roller and tainter gates of Lock and Dam 22. 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. No measurements were made in gate 1 because the forebay was filled with logs and debris and no measurements were made in gates 12 and 13 because these 2 gates were out of operation for construction during the period when discharge measurements were made. Only roller gate number 4 was measured with the gate 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.

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 11.60 feet to the gage readings. The stages can be referenced to sea level by adding the zero gage datum, 446.10 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.

Table 2.--Summary of current-meter discharge measurements and hydraulic-control data for control gates at Mississippi River Lock and Dam 22

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
2	09-10-85	24.86	17.21	3.00	2.75	3,440	+ 2.1	6.26	0.150	SO
2	09-10-85	24.86	17.22	4.00	3.75	4,580	- 0.2	4.59	0.200	SO
2	09-10-85	24.85	17.25	5.00	4.84	6,130	+ 3.7	3.56	0.268	SO
2	05-28-85	24.85	20.26	7.00	6.90	6,110	- 6.7	2.94	0.293	SO
2	05-28-85	24.84	20.26	8.00	7.97	7,120	- 5.8	2.54	0.341	SO
2	05-28-85	24.84	20.26	9.00	9.02	8,270	- 3.3	2.25	0.396	SO
2	11-04-85	24.74	22.43	10.00	10.07	7,380	+ 8.8	2.23	0.450	SO
2	11-04-85	24.74	22.44	12.00	12.18	9,230	+12.8	1.84	0.564	SO
2	11-04-85	24.73	22.47	14.00	14.23	11,400	+20.2	1.58	0.702	SO
3	09-12-85	25.11	17.74	2.00	2.02	2,360	- 2.9	8.78	0.102	SO
3	09-10-85	24.86	17.22	4.00	4.03	4,700	- 4.7	4.27	0.205	SO
3	09-12-85	25.13	17.74	5.00	4.98	6,110	+ 1.8	3.56	0.263	SO
4	09-10-85	24.84	17.26	4.00		6,430	- 2.7	4.32	0.169	SO
4	05-29-85	24.82	19.96	6.00		7,730	- 2.6	3.33	0.219	SO
4	05-29-85	24.80	19.97	7.00		9,310	+ 0.9	2.85	0.264	SO
4	05-29-85	24.79	19.97	7.50		10,100	+ 2.2	2.66	0.287	SO
4	05-29-85	24.75	19.99	8.00		10,600	+ 1.0	2.50	0.303	SO
4	11-05-85	25.02	21.96	8.00		8,360	- 0.5	2.74	0.271	SO
4	05-28-85	24.84	20.26	9.00		11,900	+ 2.6	2.25	0.342	SO
4	11-05-85	24.99	21.99	9.00		9,520	+ 1.8	2.44	0.312	SO
4	05-28-85	24.84	20.26	10.00		13,600	+20.5	2.03	0.391	SO
4	11-05-85	24.86	21.99	10.00		11,200	+ 3.7	2.20	0.375	SO
4	11-05-85	24.84	21.99	11.00		14,400	- 6.5	2.00	0.484	SO
4	11-04-85	24.74	22.39	12.00		19,200	+ 3.8	1.87	0.697	SO
4	11-05-85	24.82	21.98	12.00		22,400	+ 4.7	1.83	0.754	SO
4	11-05-85	24.82	21.98	13.00		27,200	- 6.2	1.69	0.916	SO
4	09-11-85	24.91	17.14	2.00s	2.21b	2,280	+15.1		6.94w	FW
4	09-11-85	24.91	17.14	4.00s	4.21b	3,720	- 3.9		4.31w	FW
6	09-10-85	24.86	17.22	4.00		6,660	+ 0.5	4.30	0.174	SO
7	09-11-85	24.92	17.26	4.00	4.18	4,750	- 7.2	4.13	0.207	SO
8	09-11-85	24.94	17.24	2.00	1.76	2,290	+ 6.0	9.80	0.100	SO
8	09-11-85	24.93	17.28	3.00	2.84	3,380	- 2.9	6.08	0.147	SO
8	05-29-85	24.74	19.94	6.00	5.94	5,440	- 5.6	3.36	0.259	SO
8	05-29-85	24.74	19.94	7.00	6.97	6,580	- 2.7	2.86	0.313	SO
8	05-29-85	24.72	19.94	8.00	7.97	7,500	- 2.8	2.50	0.358	SO
8	11-05-85	24.74	21.92	8.00	8.05	6,490	+ 8.3	2.72	0.367	SO
8	11-05-85	24.73	21.88	10.00	10.12	7,260	- 4.1	2.16	0.409	SO
8	11-05-85	24.70	21.88	12.00	12.20	9,590	+ 5.6	1.79	0.543	SO
8	11-05-85	24.66	21.90	13.00	13.25	9,910	+ 1.6	1.65	0.566	SO
10	09-11-85	24.96	17.22	1.96	2.08	2,710	+ 5.9	8.28	0.118	SO
10	09-11-85	24.94	17.24	3.00	3.12	3,700	- 3.6	5.53	0.161	SO
11	05-30-85	25.06	19.88	6.00	5.96	5,840	- 2.8	3.34	0.268	SO
11	05-30-85	25.08	19.88	7.00	6.94	6,800	- 3.0	2.86	0.312	SO
11	05-29-85	24.76	19.94	8.00	8.03	7,720	- 1.2	2.48	0.367	SO

1/ h_1 = Pool stage + 11.60 feet.
2/ h_3 = Tailwater stage + 11.60 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 22 is a chisel mark on top of the upper gate arm. The R.P. is 26.58 feet from the trunnion centerline and is the same for all the gates. The elevation of each R.P. and the trunnion centerline was determined by levels from established benchmarks on the piers between the gates (U.S. Army Corps of Engineers, 1975). The vertical gate opening, h_g, is computed from the equation:

$$h_g = 30.00 - 40.05 \sin(32.940 + \phi_u) \qquad (8)$$

where $\phi_u = \sin^{-1}$ [(Trunnion elev. - R.P. elev.)/26.58]

The terms in the equation are graphically displayed in figure 4. The average elevation of the trunnion centerlines was found at 464.50 feet with variations from 464.49 to 464.51 feet.

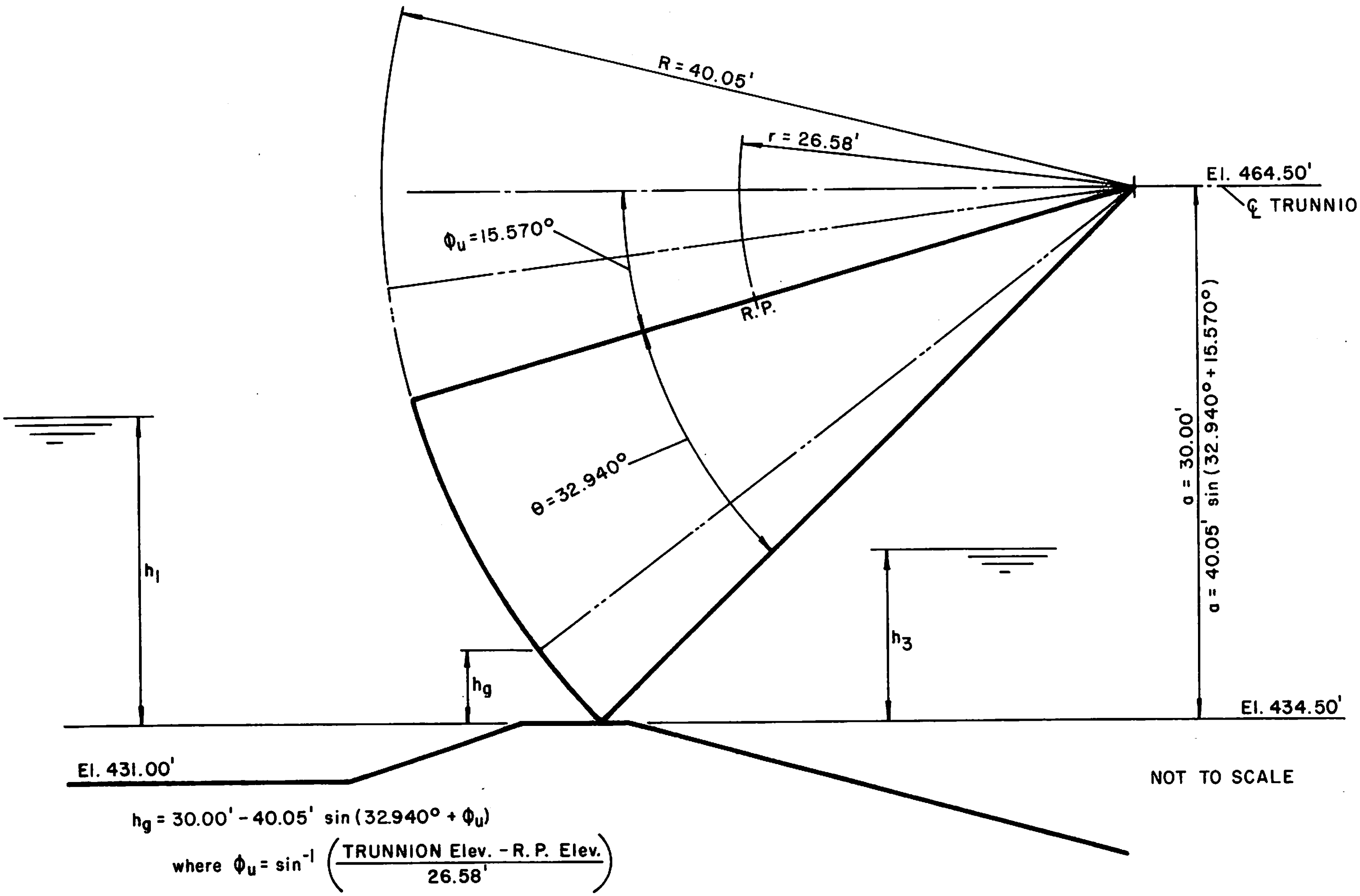


Figure 4.--Details of tainter gates at Mississippi River Lock and Dam 22.
See page vi for definition of symbols.

The relation between the "true" gate opening (h_g) and the gage-indicator readings for non-submergible gates can be calibrated by closing the gate (h_g = 0) and computing the included angle of the gate structure using the R.P. elevation of the gates in the closed position. The average included angle, θ, computed for gates 2, 3, 8 and 10 in the closed position was 32.940 degrees. Gage-indicator corrections based on the average included angle of 32.940 degrees for gates 1-3, 7-11 range from -0.25 to +0.16 foot with an average correction of zero. 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. Corrections for the individual gage indicators (e) and the relation of the gate openings (h_g) at the 2.00-foot gage-indicator settings are shown in figure 5. Also shown is the discharge for each of the tainter gates, these range from 2,140 to 2,640 cubic feet per second. Corrections to the gage indicators for gates 12 and 13 were not defined because elevations could not be obtained for the R.P.s with the gates under construction.

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 10 percent at the 1.00-foot gage setting) and decreases at higher gage settings (about 3 percent at the 4.00 feet 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.

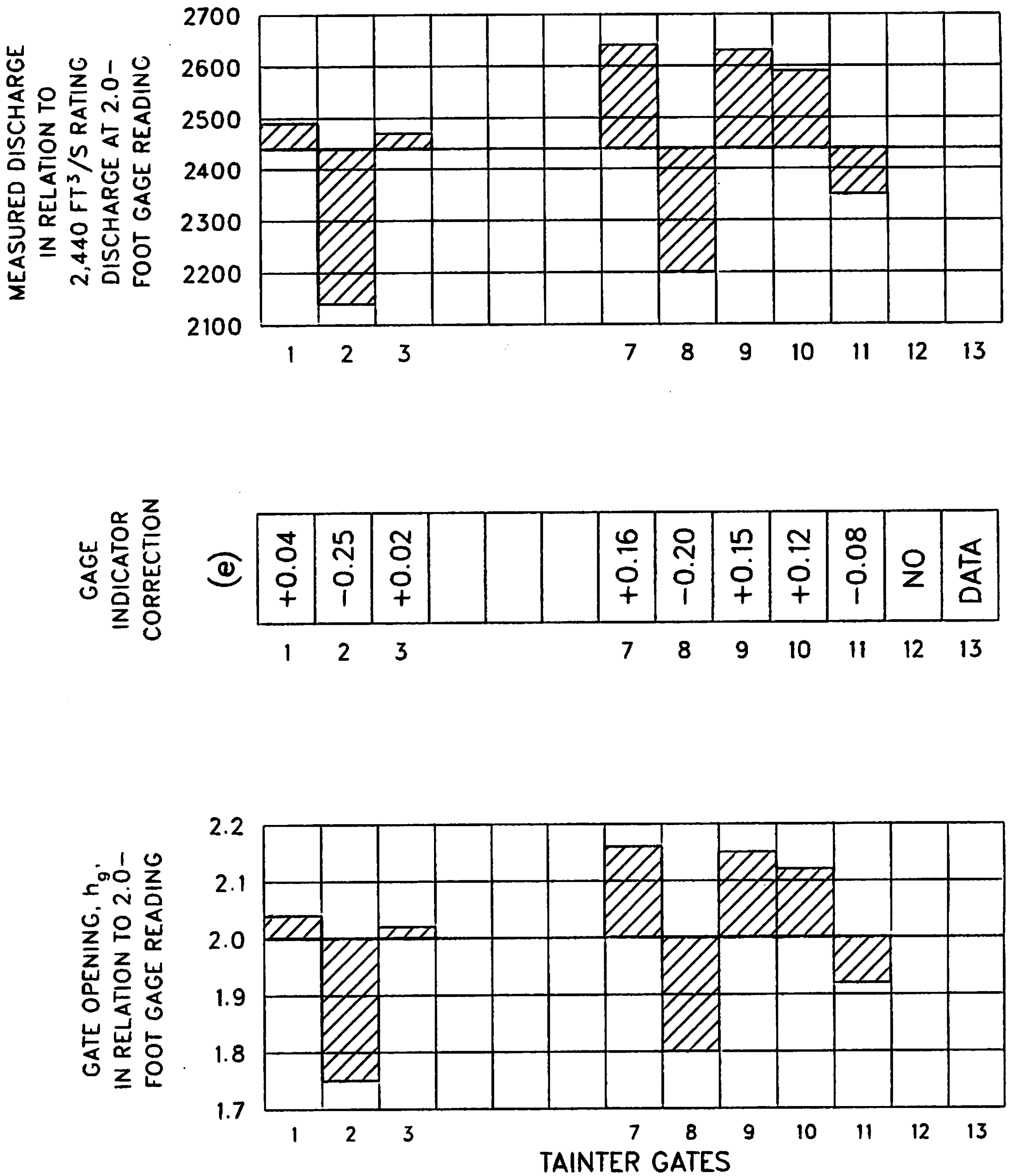


Figure 5.--Gage-indicator corrections and comparison of gate openings and discharges at 2.0-foot gage-indicator settings for tainter gates on Mississippi river Lock and Dam 22.

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 submerged-orifice 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 equation, relating the submerged-orifice coefficient, C_{gs}, to the orifice-submergence ratio, h_3/h_g, is:

$$C_{gs} = 0.92\ (h_3/h_g)^{-1.00} \tag{9}$$

As noted by Collins (1977) and described by King and Brater (1954), many structures calibrated by the procedures outlined above are determined 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 9. When substituted for the coefficient in the submerged orifice flow equation (2), the equation reduces to the free-orifice equation (1).

The submerged-orifice coefficient, C_{gs}, at submergence ratios less than about 1.9 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).

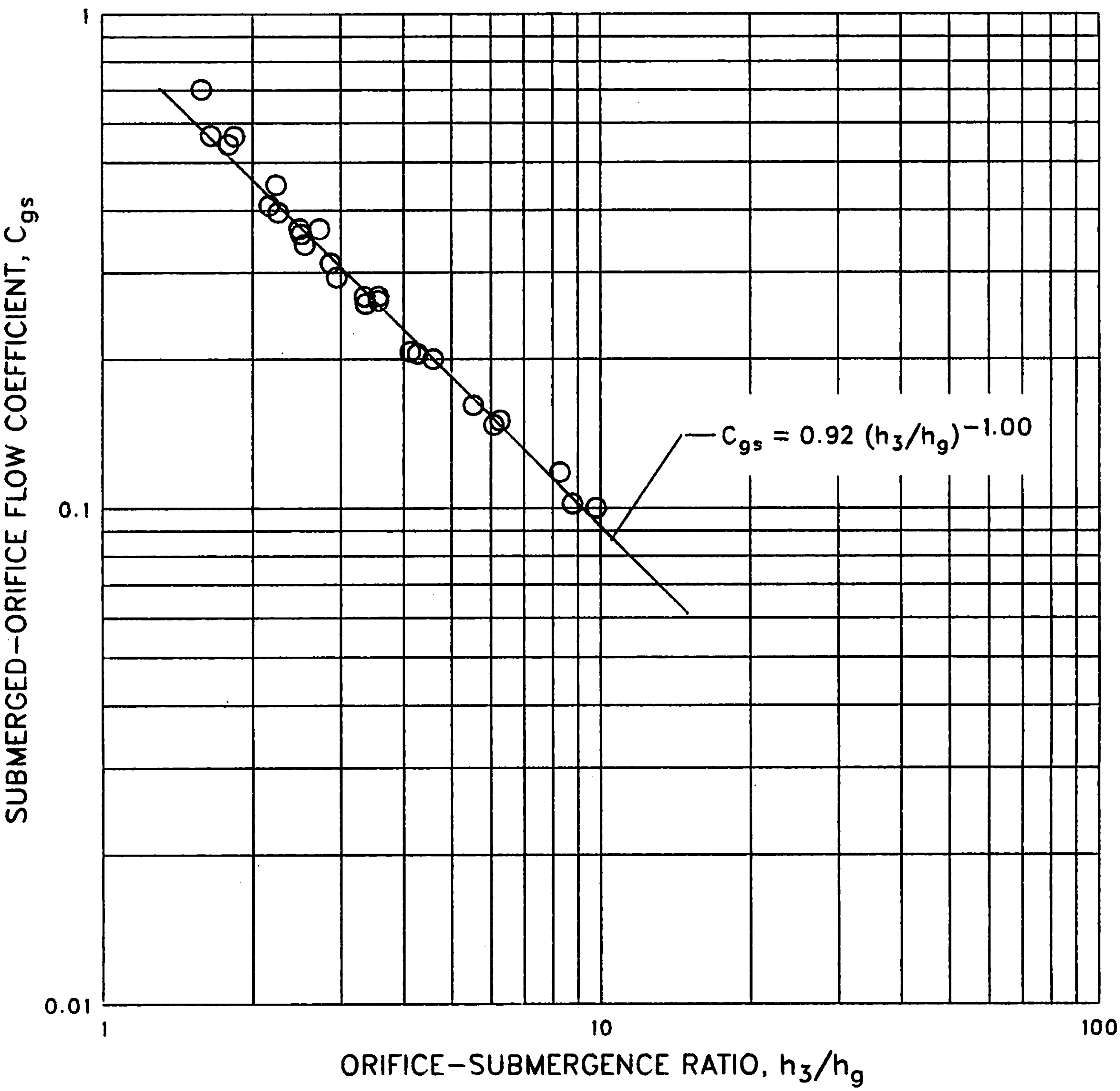


Figure 6.--Relation between submerged-orifice flow coefficient and orifice-submergence ratio for Lock and Dam 22 tainter gates.

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-headloss $(h_1 - h_3)$ is:

$$Q = 443\, h_g\, (h_1 - h_3)^{0.5} \qquad (10)$$

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 11.60 feet and $h_1 - h_3$ is the difference between the pool and tailwater gage readings.

Figure 7 shows the relation of the current-meter discharge measurements made at the tainter gates on September 10-12, 1985, to the discharge curve defined by equation (10).

Note that the gage-indicator correction for gate 13 was not defined. Gate 13 is submergible and experience with ratings for submergible gates at other Locks and Dams suggests that the submerged-orifice flow rating for gate 13 would be different than that for the non-submergible gates. A separate rating for gate 13 was not defined. Discharge computed for gate 13 using equation 10 should be within 5-15 percent accuracy and should have no significant affect on the flow determination for Lock and Dam 22.

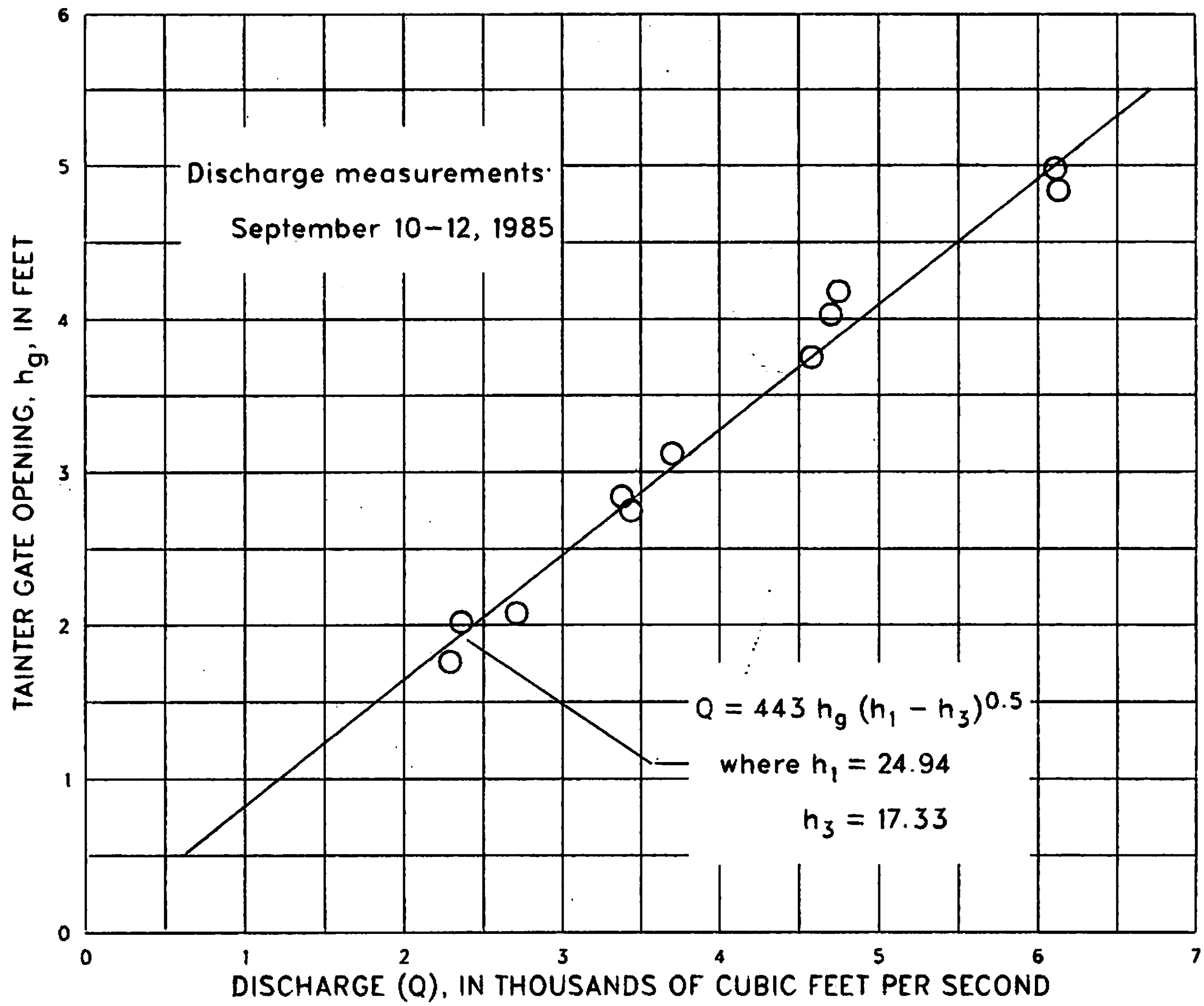


Figure 7.--Comparison of current-meter discharge measurements of September 10-12, 1985, to rating curves for tainter gates at Mississippi River Lock and Dam 22.

Free Weir Flow

Tainter gate 13 on Lock and Dam 22 is submergible and could be in a free weir flow condition when submerged with flow over the gate crest. Flow for this condition was not defined because the gate is not operated in a submerged position when the dam is in operation.

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 22 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 22 is shown in figure 8. The break in the relationship occurs at a point when the gate is open greater than 9 feet and the orifice-submergence ratio is less than 2.2 for the Dam 22 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 a typical 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. This transfer of control from the apron to the drum for the Lock and Dam 22 roller gates occurs when the gate is opened greater than 9.0 feet. The exact gate opening where the control changes has not been defined.

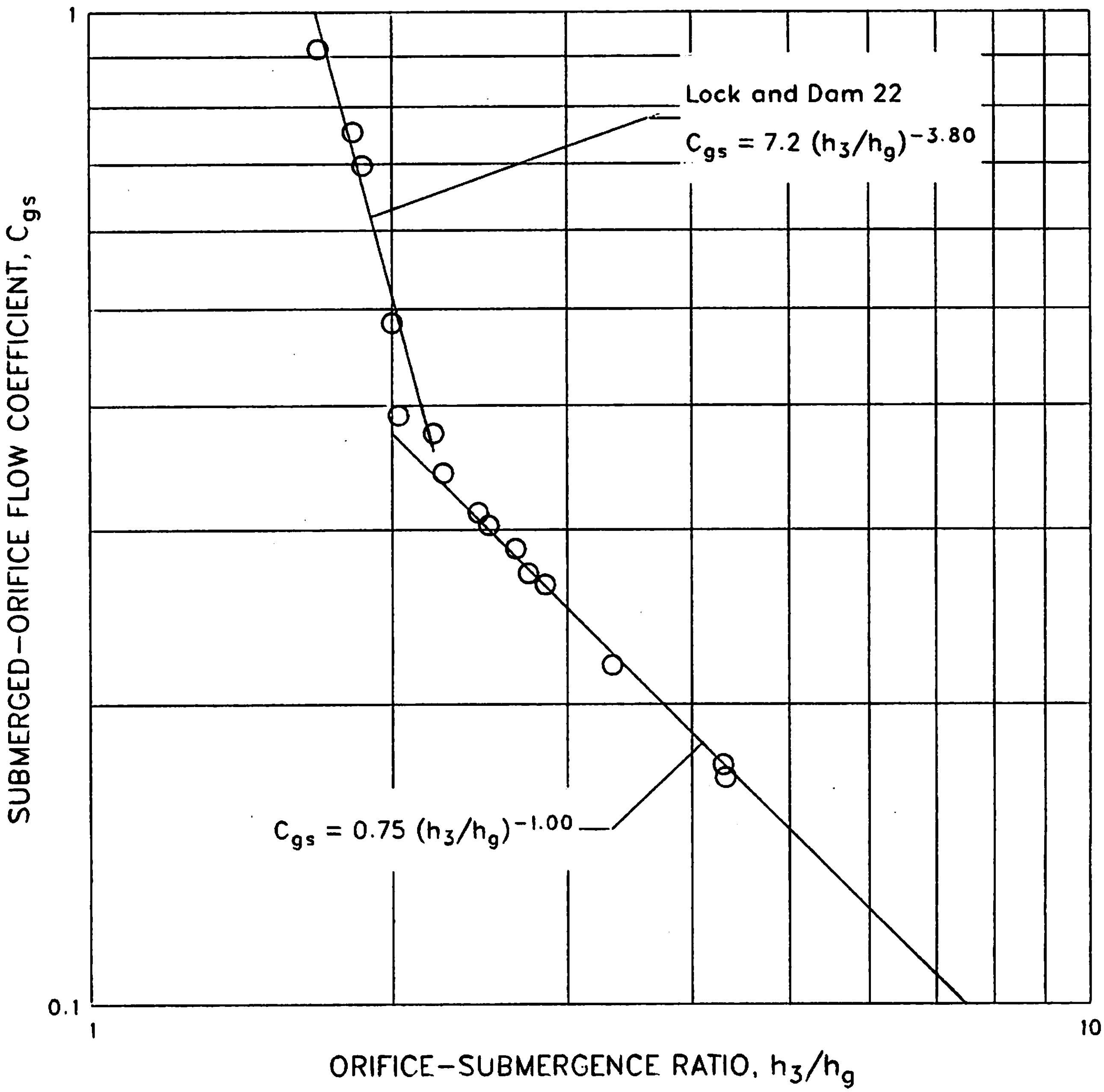


Figure 8.--Relation between submerged-orifice flow coefficient and orifice-submergence ratio for Lock and Dam 22 roller gates.

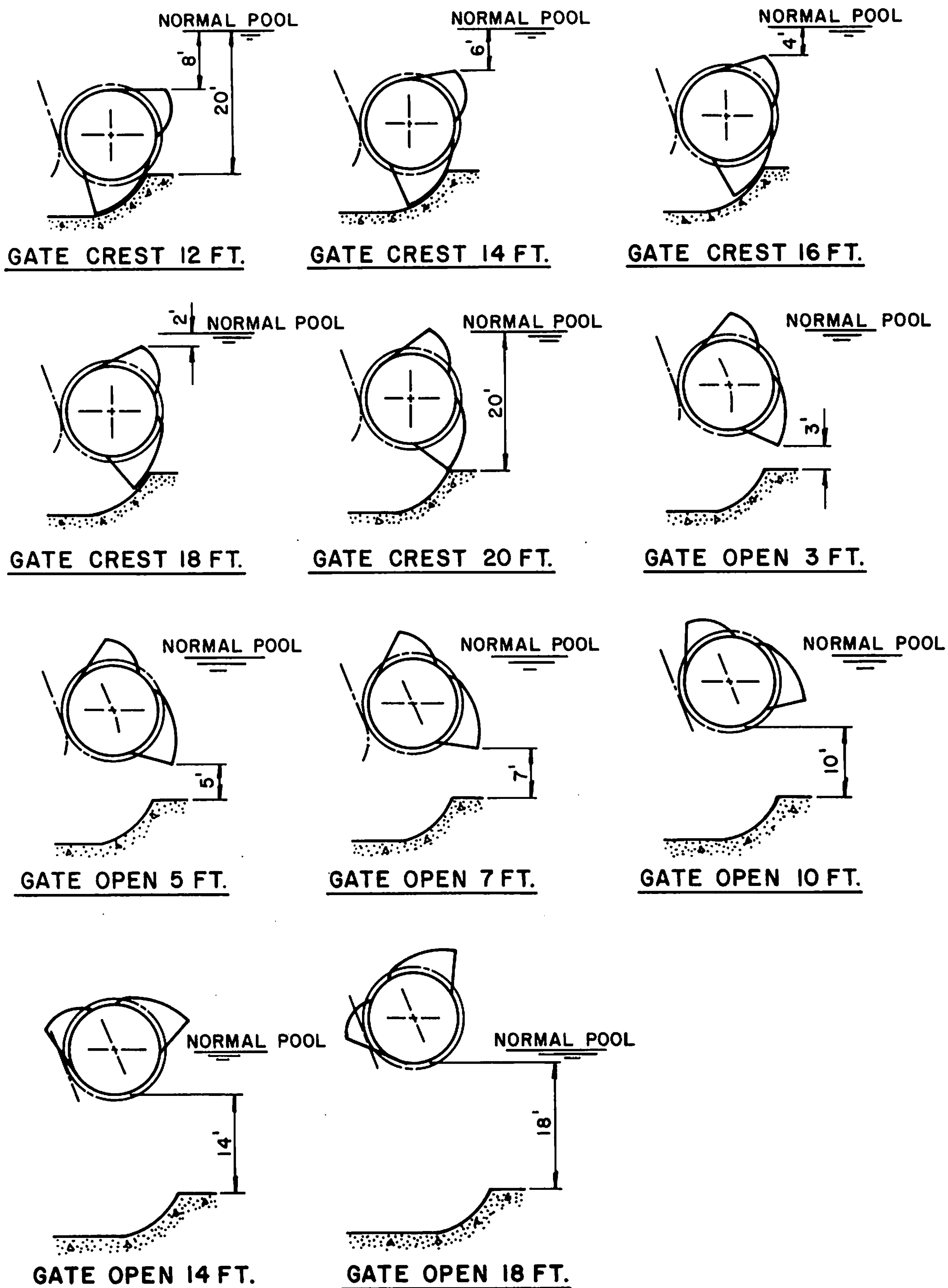


Figure 9.--Positions of roller gates for selected crests and openings (modified from U.S. Army Corps of Engineers, 1940, fig. 35).

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 9 feet or less is defined by the equation:

$$C_{gs} = 0.75 \ (h_3/h_g)^{-1.00} \qquad (11)$$

For conditions when the gates are open greater than 9 feet and the submergence ratio is less than 2.2, the submerged-orifice coefficient, C_{gs}, for the Dam 22 roller gates is defined by the equation:

$$C_{gs} = 7.20 \ (h_3/h_g)^{-3.80} \qquad (12)$$

The computed coefficients and the results of the measurements made in the roller gates at Dam 22 are listed in table 2.

Submerged-Orifice Discharge Equation

An equation for computing discharge for submerged-orifice flow when the roller gates are open 9.0 feet or less was developed using the submerged-orifice flow equation (2) and substituting equation 11 for the submerged-orifice coefficient, C_{gs}. The resulting equation relating the discharge (Q) to the gate opening (h_g) and the static-headloss (h_1 - h_3) is:

$$Q = 600\ h_g\ (h_1 - h_3)^{0.5} \tag{13}$$

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 greater than 9.0 feet and h_3/h_g is less than 2.2 feet was developed using the submerged-orifice flow equation (2) and substituting equation 12 for the submerged-orifice 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-headloss (h_1 - h_3) is:

$$Q = 5{,}770\ h_3\ (h_3/h_g)^{-3.80}\ (h_1 - h_3)^{0.5} \tag{14}$$

where h_3 = the tailwater gage reading plus 11.60 feet, h_g is the gate opening, and h_1 - h_3 = 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 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 headwater (h_{1s}) over the gate crest is shown in figure 10. The resulting equation, relating the free-weir coefficient to the headwater (h_{1s}) is:

$$C_{sw} = 8.67 \ (h_{1s})^{-0.46} \qquad (15)$$

where h_{1s} = Gage reading + 0.30 + (pool stage - 13.40) for Dam 22. The coefficient-headwater relation was further corroborated by data from Locks and Dams 11, 13 and 14 which are also shown in figure 10. The correction to the gage readings was derived from the observed gage reading at the point of zero flow over the gate crest.

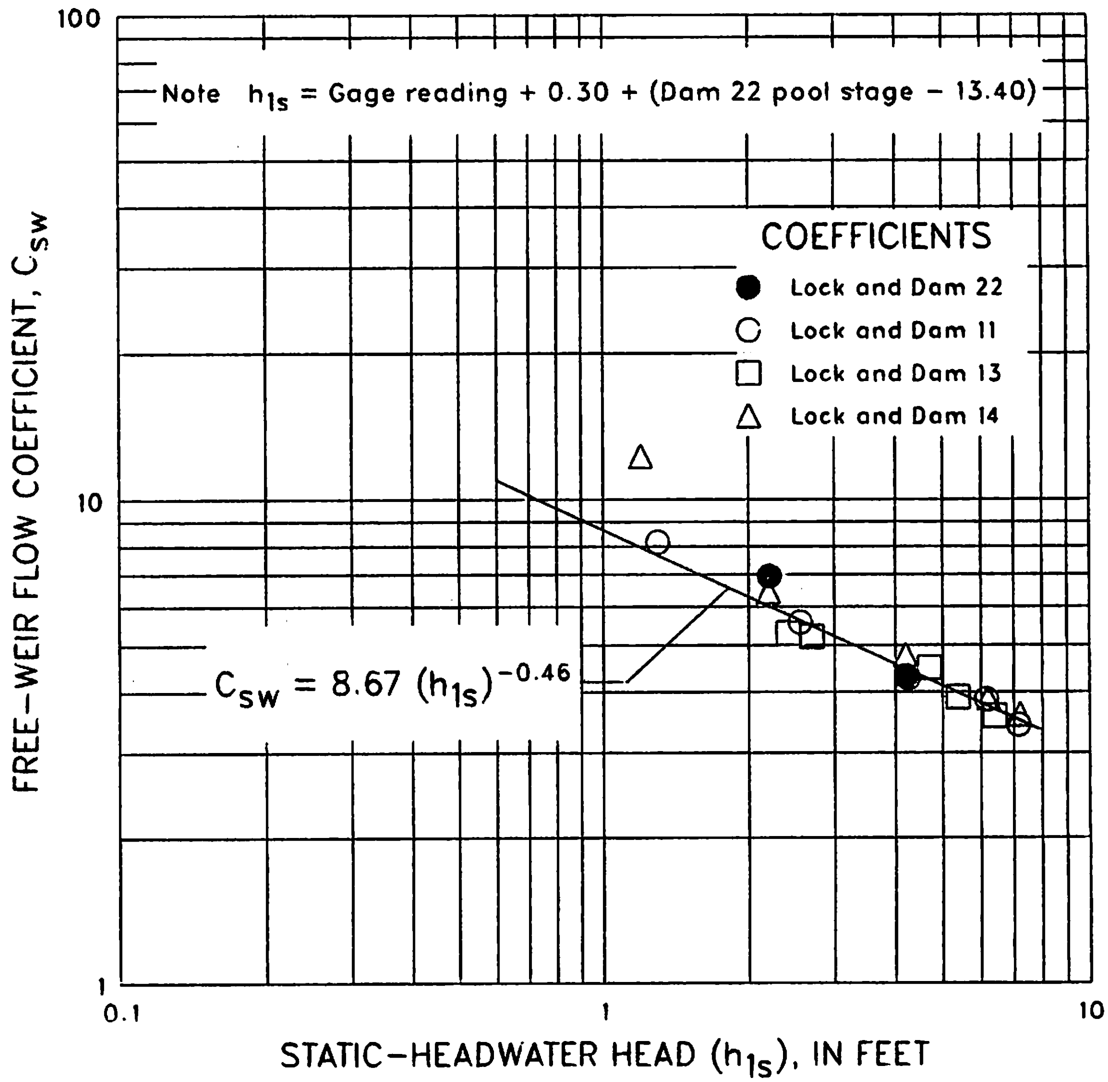


Figure 10.−−Relation between free−weir flow coefficient and static−headwater head for roller gates in submerged position for Lock and Dam 22.

Free-Weir Discharge Equation

An equation for computing discharge for free-weir flow for the roller gates in a submerged position at Dam 22 was developed using the free-weir flow equation (5) and substituting equation 15 for the free-weir coefficient, C_{sw}. The resulting equation, graphically illustrated in figure 11, relating the discharge (Q_s) to the headwater (h_{1s}) over the gate crest is:

$$Q_s = 867 (h_{1s})^{1.04} \qquad (16)$$

where h_{1s} is as defined for equation 15 above. The discharge-headwater relation was further corroborated by discharge measurements made at Locks and Dams 11, 13 and 14 which are also shown in figure 11.

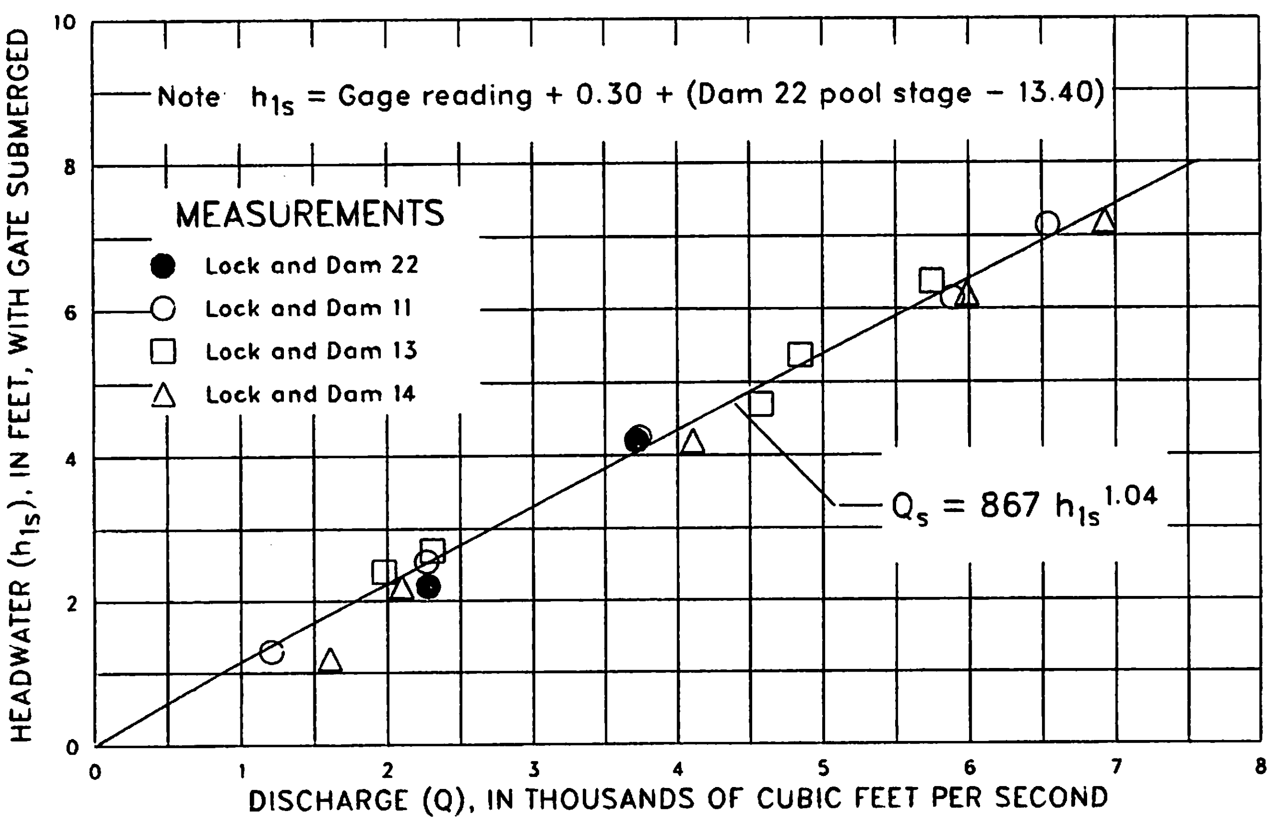


Figure 11.--Relation between discharge and headwater for free-weir flow for roller gates in submerged position for Lock and Dam 22.

DISCHARGE EQUATIONS AND RATINGS

The discharge equations applicable to the control gates when Dam 22 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 22 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 13.40 feet (h_1 = 25.00 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.

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 is use for operation of Dam 22. Discharges for the two methods generally were within 5-14 percent until the roller gate openings exceeded 10 feet at which time the discharges defined by the equations in table 3 increased to 39 percent greater than those shown in Plan A.

Table 3.--Summary of discharge equations for control gates at Mississippi River Lock and Dam 22.

Gate	Flow regime	Equation of discharge 1/, 3/	Equation number
Tainter gates	Submerged orifice	$Q = 443 = h_g(h_1 - h_3)^{0.5}$	(10)
Roller gates	Submerged orifice $h_g \leqslant 9.0$ or > 9.0 when $h_3/h_g \geqslant 2.2$	$Q = 600\ h_g(h_1 - h_3)^{0.5}$	(13)
Roller gates	Submerged orifice $h_g > 9.0$ and $h_3/h_g < 2.2$	$Q = 5{,}770\ h_3(h_3/h_g)^{-3.80}(h_1 - h_3)^{0.5}$	(14)
Roller gates	Free weir 2/	$Q_s = 867\ h_{1s}^{1.04}$	(16)

1/ Q = Discharge, in cubic feet per second
h_1 = Pool stage + 11.60 feet
h_3 = Tailwater stage + 11.60 feet
h_g for tainter gages = gage reading + gage indicator correction, e (fig. 5).
(average e for all the tainter gates = 0.0)
h_g for roller gates = gage reading

2/ For free weir flow over gate crest:
Roller gate: h_{1s} = gage reading + 0.30 + (pool stage - 13.40)

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 22 with upstream pool stage of 13.40 feet.

Gage reading (feet)	Tainter gate discharge, in ft^3/s, for indicated tailwater stage (feet)								
	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0
.5	714	679	642	603	560	515	465	408	343
1.0	1430	1360	1280	1210	1120	1030	929	817	686
1.5	2140	2040	1930	1810	1680	1540	1390	1230	1030
2.0	2860	2720	2570	2410	2240	2060	1860	1630	1370
2.5	3570	3400	3210	3010	2800	2570	2320	2040	1720
3.0	4290	4070	3850	3620	3360	3090	2790	2450	2060
3.5	5000	4750	4490	4220	3920	3600	3250	2860	2400
4.0	5710	5430	5140	4820	4480	4120	3720	3270	2750
4.5	<u>6430</u>	6110	5780	5420	5040	4630	4180	3680	3090
5.0	7140	<u>6790</u>	6420	6030	5600	5150	4650	4080	3430
5.5	7860	7470	<u>7060</u>	6630	6160	5660	5110	4490	3770
6.0	8570	8150	7700	7230	6720	6180	5580	4900	4120
6.5		8830	8350	<u>7830</u>	7280	6690	6040	5310	4460
7.0			8990	8440	<u>7840</u>	7210	6500	5720	4800
7.5				9040	8410	7720	6970	6130	5150
8.0				9640	8970	<u>8240</u>	7430	6530	5490
8.5					9530	8750	7900	6940	5830
9.0						9260	<u>8360</u>	7350	6180
9.5						9780	8830	7760	6520
10.0							9290	8170	6860
10.5							9760	<u>8580</u>	7210
11.0								8980	7550
11.5								9390	7890
12.0								9800	8240
12.5									8580
13.0									8920
13.5									9260
14.0									9610

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) $$Q = 443\ h_g(h_1 - h_3)^{0.5}$$

where h_g = gage reading + (average e = 0)
h_1 = 25.00 feet (13.40 + 11.60)
h_3 = tailwater stage + 11.60 feet

Table 5.--Discharge rating table for submerged-orifice flow for a single roller gate at Mississippi River Lock and Dam 22 with upstream stage of 13.40 feet.

Gage reading (feet)	Roller gate discharge, in ft^3/s, for indicated tailwater stage (feet) 3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0
.5	967	920	869	816	759	697	629	553	465
1.0	1930	1840	1740	1630	1520	1390	1260	1110	930
1.5	2900	2760	2610	2450	2280	2090	1890	1660	1390
2.0	3870	3680	3480	3260	3040	2790	2520	2210	1860
2.5	4840	4600	4350	4080	3790	3490	3150	2770	2320
3.0	5800	5520	5220	4900	4550	4180	3780	3320	2790
3.5	6770	6440	6090	5710	5310	4880	4400	3870	3250
4.0	7740	7360	6960	6530	6070	5580	5030	4430	3720
4.5	8710	8280	7830	7340	6830	6270	5660	4980	4180
5.0	9670	9200	8690	8160	7590	6970	6290	5530	4650
5.5	10600	10100	9560	8980	8350	7670	6920	6080	5110
6.0		11000	10400	9790	9110	8370	7550	6640	5580
6.5			11300	10600	9870	9060	8180	7190	6040
7.0				11400	10600	9760	8810	7740	6510
7.5					11400	10500	9440	8300	6970
8.0					12100	11200	10100	8850	7440
8.5						11900	10700	9400	7900
9.0						12500	11300	9960	8370
9.5							13200	10500	8830
10.0							16000	12300	9300
10.5								14800	11000
11.0								17700	13100
11.5								20900	15500
12.0								24600	18200
12.5								28800	21300
13.0									24700
13.5									28500
14.0									32700

Discharges in this area may be greater than those allowable for safe gate operation (USCE, 1980).

Note: Underline denotes change in rating from equation 13 to equation 14.

Discharges for table 5 were computed using equations:

(13) $$Q = 600\, h_g (h_1 - h_3)^{0.5}$$

(14) $$Q = 5{,}770\, h_3 (h_3/h_g)^{-3.80} (h_1 - h_3)^{0.5}$$

where h_g = gage reading
h_1 = 25.00 feet (13.40 + 11.60)
h_3 = tailwater stage + 11.60 feet

Table 6.--Comparison of rating discharges (column 1) to discharges specified in Gate Operation Schedule Plan A for Mississippi River Lock and Dam 22
[Modified from U.S. Army Corps of Engineers, 1980, pl. 27]

Rating 1/ discharge (ft³/s)	Gate Operation Schedule Plan A for controlled tailwater stages with headwater stage of 13.40 feet: Discharge (ft³/s)	Tailwater stage (feet)	Head (feet)	Gate opening, (feet), for gate indicated: Tainter 1	Tainter 2	Tainter 3	Roller 4	Roller 5	Roller 6	Tainter 7	Tainter 8	Tainter 9	Tainter 10	Tainter 11	Tainter 12	Tainter 13
14,800	13,000	3.4	10.0	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
21,800	19,000	3.6	9.8	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
25,300	22,000	3.8	9.6	1.5	1.5	1.5	1.5	1.5	1.0	1.5	1.5	1.5	1.0	1.0	1.0	1.0
32,100	28,200	4.0	9.4	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.0	1.0	1.0	1.0
36,000	32,000	4.2	9.2	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	1.5	1.0	1.0	1.0
40,100	35,800	4.4	9.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	1.5	1.0	1.0
44,200	39,000	4.6	8.8	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	1.5	1.5
47,000	42,300	4.8	8.6	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.5
51,800	46,200	5.0	8.4	3.0	3.0	3.0	3.5	3.0	3.0	3.0	3.0	3.0	3.0	2.5	2.0	2.0
56,100	50,000	5.2	8.2	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	2.5	2.0	2.0
59,200	53,000	5.4	8.0	4.0	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	2.5	2.5
62,200	56,300	5.6	7.8	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.5	3.0	2.5	2.5
66,500	59,900	5.8	7.6	4.5	4.0	4.0	4.5	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0
69,600	63,000	6.0	7.4	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
72,800	66,200	6.2	7.2	5.0	5.0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.0	4.0	3.5	3.5
76,000	69,500	6.4	7.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.0	4.0	3.5	3.5
77,800	72,200	6.6	6.8	5.0	5.0	5.0	5.5	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.0	4.0
81,800	75,200	6.8	6.6	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	5.0	4.5	4.5	4.5	4.5
84,600	78,200	7.0	6.4	6.0	5.5	5.5	6.0	5.5	5.5	5.5	5.5	5.5	5.0	5.0	4.5	4.5
87,400	81,000	7.2	6.2	6.0	6.0	6.0	6.0	6.0	5.5	6.0	5.5	5.5	5.5	5.0	5.0	5.0
89,800	83,800	7.4	6.0	6.5	6.5	6.0	6.5	6.5	6.0	6.0	6.0	5.5	5.5	5.0	5.0	5.0
92,200	86,400	7.6	5.8	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.0	6.0	5.5	5.0	5.0
94,600	89,500	7.8	5.6	7.0	7.0	6.5	7.0	7.0	6.5	6.5	6.5	6.5	6.0	5.5	5.5	5.5
97,100	92,200	8.0	5.4	7.0	7.0	7.0	8.0	7.0	7.0	7.0	6.5	6.5	6.0	6.0	6.0	5.5
99,700	95,000	8.2	5.2	7.0	7.0	8.0	8.0	8.0	7.0	7.0	7.0	6.5	6.5	6.5	6.0	6.0
102,000	97,800	8.4	5.0	7.0	8.0	8.0	8.0	8.0	8.0	8.0	7.0	7.0	6.5	6.5	6.5	6.5
105,000	100,300	8.6	4.8	8.0	8.0	8.0	9.0	8.0	8.0	8.0	8.0	7.0	7.0	7.0	6.5	6.5
107,000	103,200	8.8	4.6	8.0	8.0	8.0	9.0	9.0	9.0	8.0	8.0	8.0	7.0	7.0	7.0	6.5
109,000	106,000	9.0	4.4	9.0	9.0	9.0	9.0	9.0	9.0	8.0	8.0	8.0	8.0	8.0	7.0	7.0
114,000	108,500	9.2	4.2	9.0	9.0	9.0	10.0	9.0	9.0	9.0	9.0	8.0	8.0	8.0	8.0	7.5
120,000	111,200	9.4	4.0	9.0	9.0	9.0	10.0	10.0	10.0	9.0	9.0	9.0	9.0	8.0	8.0	8.0
130,000	113,700	9.6	3.8	9.0	9.0	10.0	11.0	11.0	10.0	9.0	9.0	9.0	9.0	9.0	8.0	8.0
135,000	116,300	9.8	3.6	9.0	10.0	10.0	11.0	11.0	11.0	10.0	10.0	9.0	9.0	9.0	9.0	9.0
143,000	119,000	10.0	3.4	10.0	10.0	10.0	11.5	11.5	11.5	10.0	10.0	10.0	10.0	10.0	9.0	9.0
152,000	122,200	10.2	3.2	10.0	11.0	11.5	12.0	12.0	12.0	11.0	10.0	10.0	10.0	10.0	10.0	10.0
163,000	128,000	10.6	2.8	11.0	12.0	12.0	13.0	13.0	12.0	12.0	12.0	12.0	12.0	11.0	11.0	11.0
186,000	133,800	11.0	2.4	13.0	13.0	13.5	14.0	14.0	14.0	13.5	13.0	13.0	13.0	12.5	12.0	12.0

1/ Computed using equations in table 3 with headwater stage of 13.40 feet.

SUMMARY

Current-meter discharge measurements made in the forebays of the tainter and roller gates of Lock and Dam 22 were used to develop discharge coefficients and equations of discharge for submerged-orifice flow for all the gates, except for gate 13, and free-weir flow for the roller gates in a submerged position.

Methodology has been described to compute the 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 tailwater stages and gate openings for submerged-orifice flow, which is the predominant flow regime when the dam is in operation.

Discharges defined by methods outlined in this study are given for comparison to those used in the operation schedule, Plan A, which is in use for the operation of Lock and Dam 22.

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