DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 21, QUINCY, ILLINOIS

By Albert J. Heinitz

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SYMBOLS AND UNITS

Symbol	Definition	Unit
A	Length times width of lock chamber	ft^2
a	Elevation difference, trunnion centerline to sill	ft
B	Lateral width of a gate opening or 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, gate crest or fixed spillway	
C_{sws}	Submerged-weir flow coefficient of discharge, gate crest or fixed spillway	
C_w	Free-weir flow coefficient of discharge, gate sill	
C_{ws}	Submerged-weir flow coefficient of discharge, gate sill	
g	Acceleration due to gravity	ft/s^2
G	Gate-position 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 or fixed spillway crest	ft
h_{1s}	Static-headwater head referenced to gate crest or fixed spillway crest	ft
h_{3s}	Static-tailwater head referenced to gate crest or fixed spillway crest	ft

SYMBOLS AND UNITS--continued

Symbol	Definition	Unit
h_g	Gate opening	ft
N	Number of lockages occurring between recordings	
Q	Computed 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 metric (International System) units:

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

Note: The numerical values of the flow coefficients of discharge given in this report can only be used in the English (inch-pound) units.

DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 21, QUINCY, ILLINOIS

By Albert J. Heinitz

ABSTRACT

The water levels 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 21, at Quincy, Illinois, 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 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 21 was placed in operation July 23, 1938.

This is the tenth in a series of reports that relate to discharge ratings and hydraulic characteristics of the control gates at locks and dams on the Mississipi River. The other nine reports present similar information for Locks and Dams 11, 12, 13, 14, 16, 17, 18, 20 and 22 (Heinitz, 1985, 1986 and 1987). Discharge ratings for these Locks and Dams corroborated rating development for Lock and Dam 21.

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 21. 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, 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 21.

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 21, located at Quincy, Illinois, 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 21. 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.

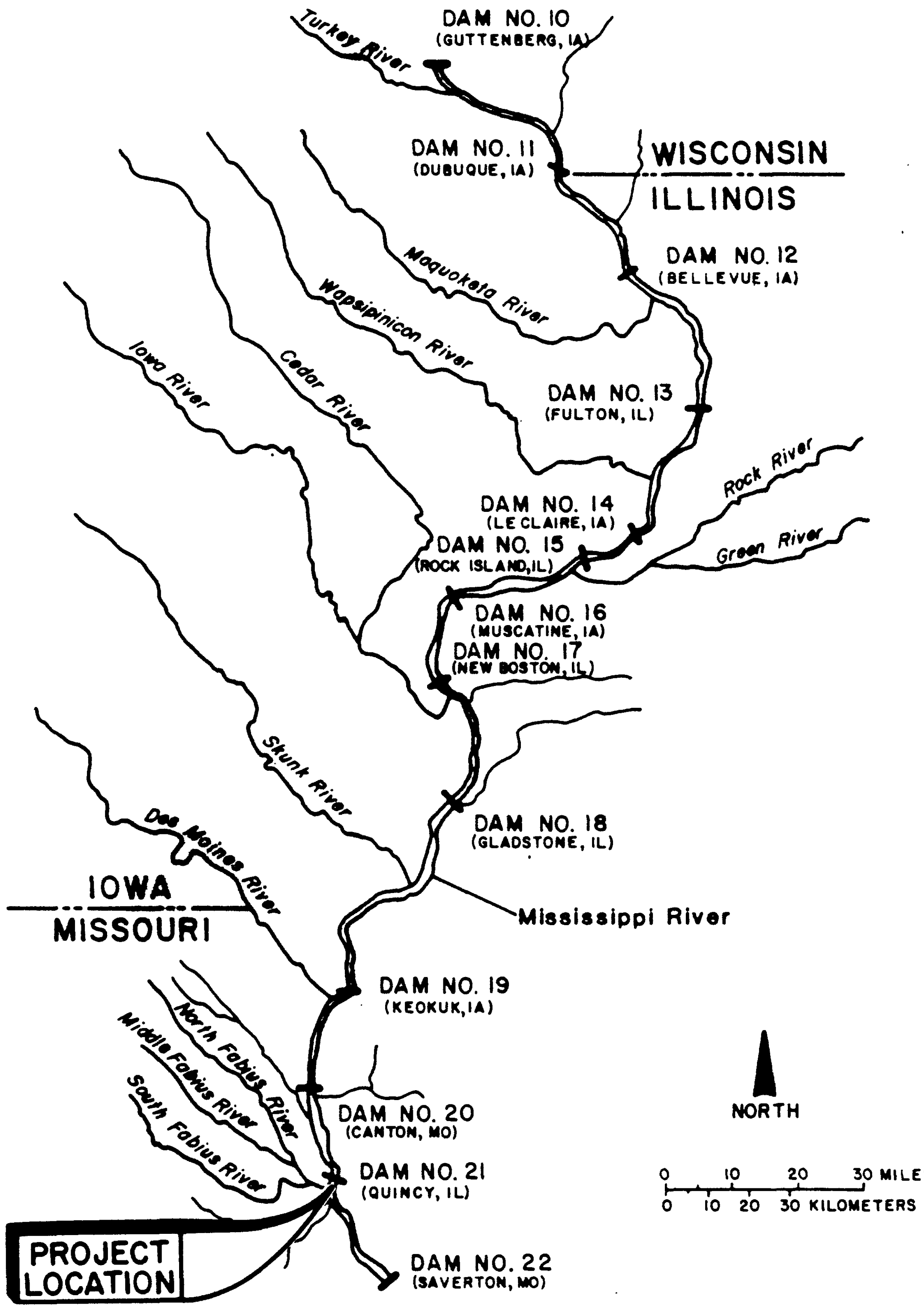


Figure 1.--Inland Waterway Navigation System of the upper Mississippi River basin (modified from U.S. Army Corps of Engineers, 1980, pl. 1).

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 $h_3 \geqslant h_g$	$Q = C_{gs}[h_3\ B(2g \Delta h)^{0.5}]$	(2)
	Free weir (sill)	$h_g \geqslant 0.67\ h_1$ and $h_3/h_1 < 0.6$	$Q = C_w[Bh_1^{1.5}]$	(3)
	Submerged weir (sill)	$h_g \geqslant 0.67\ h_1$ and $h_3/h_1 \geqslant 0.6$	$Q = C_w C_{ws}[Bh_1^{1.5}]$	(4)
	3/ Free weir (crest)	$h_{3s}/h_{1s} < 0.6$	$Q = C_{sw}[Bh_{1s}^{1.5}]$	(5)
	3/ Submerged weir (crest)	$h_{3s}/h_{1s} \geqslant 0.6$	$Q = C_{sw} C_{sws}[Bh_{1s}^{1.5}]$	(6)
Locks	--	$h > 0$	$Q_L = NA \Delta h/\Delta t$	(7)

1/The criterion used to separate orifice flow from weir flow is that the critical depth of flow in a rectangular channel is equal to two-thirds of the total head in the approach section. When 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 or h_{1s}) static-tailwater head (h_3), and gate opening (h_g). Static-headwater and static-tailwater heads are the vertical distances from the gate sill, gate crest or spillway crest to upstream and downstream pool elevations, respectively. 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.

3/Same for flow over fixed spillway crest.

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 21 contains 10 tainter gates and 3 roller gates for controlling the pool elevation upstream from the dam. Each tainter gate is 64.2 feet wide and 20 feet high and operates between piers with 64.2-foot clear openings. The tainter gates are of the submergible type, capable of being lowered 8 feet below the sill elevation. Each roller gate is 100 feet wide and 20 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. Five 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 21 are in operation (U.S. Army Corps of Engineers, 1980, pl. 25). Free-orifice flow rarely occurs at a low-head, navigation-type structure such as Dam 21 and would not occur at this dam under normal operating conditions.

Free-weir flow at Dam 21 would occur primarily with the gates in a submerged condition with flow over the crests of the gates. 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

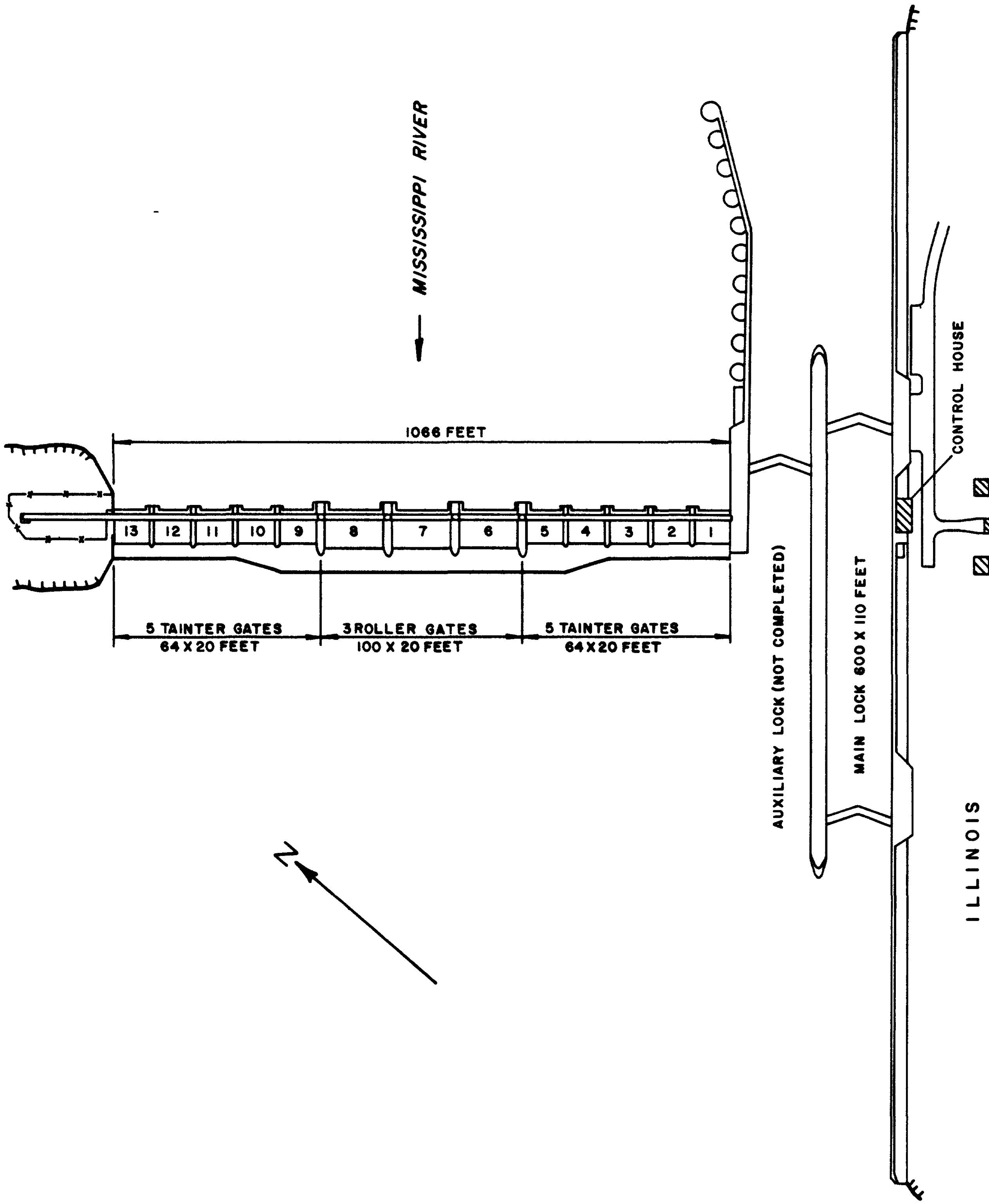
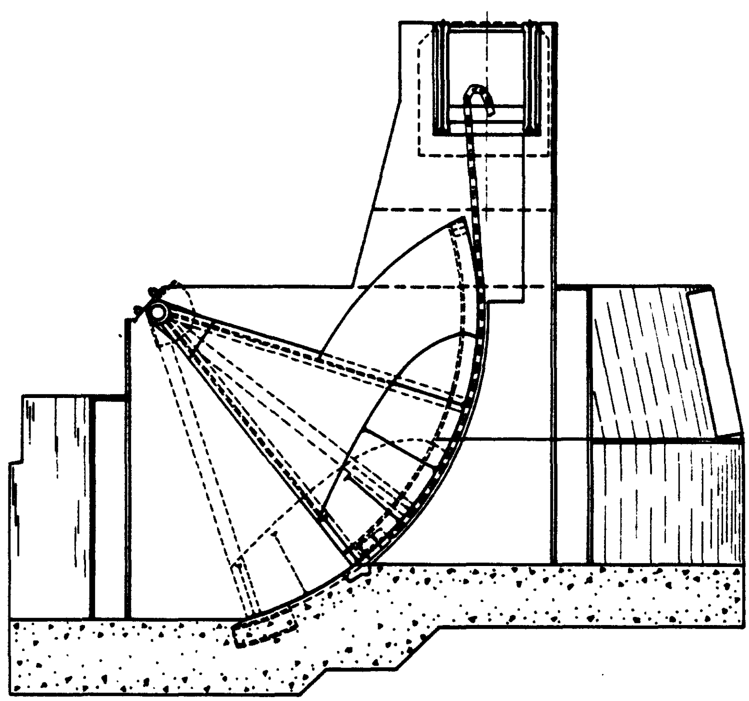
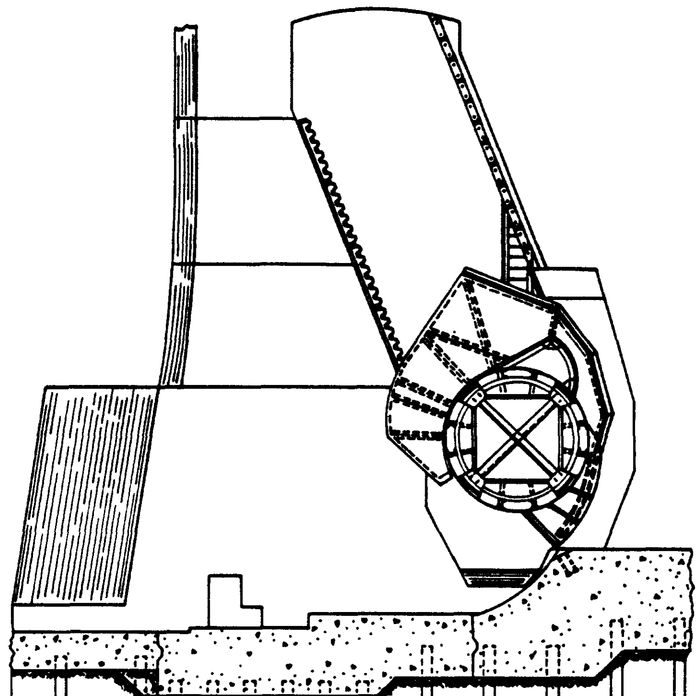


Figure 2.--Location of flow-control structures (modified from U.S. Army Corps of Engineers, 1980, pl. 2).



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).

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.

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. 25) was adopted and put into use beginning with the 1940 navigation season 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 21 is a run-of-the-river dam and is not operated to store water for flood control purposes. The pool is maintained between stages 11.80 and 12.30 feet when the dam is in operation. When the river is rising and the tailwater stage reaches 11.2 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 winter, when there is no commercial navigation and the pools become ice covered, the tainter and roller gates at Dam 21 are placed in the submerged position. The pool is maintained within the winter operating stage of 11.2 to 12.2 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 58 measurements of discharge ranging from 1,290 to 23,400 cubic feet per second in a gate were made in the forebays of the tainter and roller gate structures of Lock and Dam 21. 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 was measured at least once through all but two (1 and 13) of the gate bays for submerged orifice flow. Only tainter gate numbers 4, 9 and 11 and roller gate number 7 were measured with the gates in a free weir flow position. 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 21

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	6-23-86	19.79	17.03	7.00	7.02	5,030	- 2.1	2.43	0.345	SO
2	6-23-86	19.78	17.03	8.00	7.98	5,860	0	2.13	0.403	SO
2	6-23-86	19.80	17.03	9.00	8.99	6,670	+ 0.3	1.89	0.457	SO
3	3-04-87	19.76	14.18	3.00	3.00	3,060	0	4.73	0.177	SO
4	3-04-87	19.74	14.23	2.00	1.99	1,920	- 3.5	7.15	0.112	SO
4	3-04-87	19.68	14.30	3.00	2.99	3,040	+ 1.3	4.78	0.178	SO
4	9-16-86	19.95	14.61	4.00	3.99	4,140	+ 3.0	3.66	0.238	SO
4	9-16-86	19.95	14.61	5.00	4.98	5,280	+ 4.6	2.93	0.304	SO
4	9-17-86	20.58	15.32	4.00s	4.58b	2,600	- 3.4		4.13w	FW
5	9-16-86	19.95	14.67	5.00	5.02	5,280	+ 4.4	2.92	0.304	SO
5	6-23-86	19.88	17.06	6.00	6.02	4,370	- 1.6	2.83	0.296	SO
5	6-23-86	19.87	17.05	7.00	7.01	4,840	- 6.7	2.43	0.328	SO
5	6-23-86	19.82	17.03	8.00	8.01	5,460	- 7.8	2.13	0.373	SO
6	3-03-87	20.40	13.70	3.00		3,680	-11.8	4.57	0.129	SO
6	9-16-86	19.90	14.62	4.50		5,130	- 7.6	3.25	0.190	SO
7	3-03-87	20.35	14.05	3.00		3,950	- 2.2	4.68	0.140	SO
7	3-03-87	20.38	14.13	4.00		5,350	- 0.4	3.53	0.189	SO
7	3-04-87	19.76	14.18	4.00		4,940	- 2.6	3.55	0.184	SO
7	9-16-86	19.90	14.56	4.50		5,580	0	3.24	0.207	SO
7	3-03-87	20.38	14.13	5.00		6,750	+ 0.6	2.83	0.238	SO
7	9-16-86	19.90	14.56	5.50		7,000	+ 2.5	2.65	0.259	SO
7	6-24-86	20.00	16.58	6.00		6,180	+ 3.7	2.76	0.251	SO
7	6-24-86	19.90	16.63	7.00		7,210	+ 6.0	2.38	0.299	SO
7	6-23-86	19.86	17.01	8.00		9,360	+ 2.1	2.13	0.406	SO
7	6-24-86	20.02	16.57	8.50		12,700	- 7.3	1.95	0.515	SO
7	6-23-86	19.85	16.97	9.00		14,300	- 1.4	1.89	0.619	SO
7	6-24-86	20.00	16.58	10.00		23,400	- 7.1	1.66	0.952	SO
7	3-03-87	20.40	13.70	2.00s	2.95b	2,650	- 0.7		5.23w	FW
7	3-03-87	20.15	13.80	3.00s	3.70b	3,340	- 1.2		4.69w	FW
7	9-17-86	20.55	15.29	4.00s	5.10b	4,740	+ 0.4		4.12w	FW
7	3-03-87	20.20	14.02	5.00s	5.75b	5,350	0		3.88w	FW
8	3-03-87	20.40	14.13	3.00		4,350	+ 7.9	4.71	0.153	SO
8	3-04-87	20.68	14.30	3.00		3,940	- 3.2	4.77	0.136	SO
8	9-16-86	19.83	14.58	4.50		5,540	0	3.24	0.207	SO
9	9-16-86	19.95	14.51	3.00	2.98	2,890	- 3.7	4.87	0.166	SO
9	9-16-86	19.90	14.65	5.00	5.00	5,160	+ 2.8	2.93	0.299	SO
9	9-16-86	19.96	14.52	3.00s	2.96b	1,620	+ 5.2		4.95w	FW
9	9-16-86	19.99	14.53	5.00s	4.99b	2,820	- 6.3		3.94w	FW
10	3-03-87	20.40	14.13	2.00	2.03	2,210	+ 1.8	6.96	0.121	SO
10	3-04-87	19.68	14.30	2.00	2.03	2,040	+ 1.5	7.04	0.119	SO
10	6-24-86	20.12	16.63	6.00	6.06	4,640	- 6.8	2.74	0.290	SO
10	6-24-86	20.10	16.63	7.00	7.08	5,740	- 1.4	2.35	0.360	SO
10	6-24-86	20.09	16.62	8.00	7.98	6,590	0	2.08	0.413	SO
10	6-24-86	20.12	16.63	9.00	8.96	7,930	+ 6.6	1.86	0.496	SO
11	3-03-87	20.40	13.80	2.00	1.92	2,010	- 4.7	7.19	0.110	SO
11	9-16-86	19.88	14.64	3.00	3.00	3,010	+ 1.4	4.88	0.174	SO
11	3-03-87	20.37	14.13	3.00	2.92	3,090	- 1.9	4.84	0.170	SO
11	3-03-87	20.38	14.13	4.00	3.92	4,180	- 2.1	3.60	0.230	SO
11	9-16-86	19.88	14.64	5.00	4.98	5,240	+ 4.8	2.94	0.304	SO
11	3-03-87	20.40	13.80	2.00s	2.55b	1,310	+ 2.3		5.01w	FW
11	9-16-86	19.96	14.51	2.50s	2.46b	1,290	+ 4.9		5.21w	FW
11	3-03-87	20.10	14.02	4.00s	4.10b	2,310	- 0.9		4.33w	FW
11	9-16-86	19.98	14.52	5.00s	4.98b	3,050	+ 1.7		4.27w	FW
12	3-04-87	19.74	14.22	2.00	1.94	2,060	+ 6.2	7.33	0.120	SO
12	9-16-86	19.99	14.53	5.00	4.94	5,250	+ 3.8	2.94	0.300	SO
12	6-24-86	20.18	16.66	6.00	5.90	4,880	+ 0.4	2.82	0.303	SO
12	6-24-86	20.10	16.62	7.00	6.94	5,710	0	2.39	0.358	SO
12	6-24-86	20.16	16.63	8.00	7.90	6,550	- 0.3	2.10	0.407	SO

1/ h_1 = Pool stage + 7.80 feet.
2/ h_3 = Tailwater (T/W) stage + 7.80 feet.
3/ SO designates submerged-orifice flow.
FW designates free-weir flow.
b Computed headwater, h_{1s}, over gate crest.
s Gate in submerged position
w Coefficient, C_{sw}, for free-weir 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 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 7.80 feet to the stage readings. The stages can be referenced to sea level by adding the zero gage datum, 457.80 feet (1912 adjustment), to the stages.

The gate-opening settings for the tainter gates were read from the gate-position indicator gages on the tainter gates and those for the roller gates were read from the gate-position indicator marks on the operating machinery. For submerged orifice flow, the gate-position gages indicate the gate opening between the gate sill and the bottom of the gate. For free-weir flow, the gate-position gages indicate the static-headwater head over the crest of the gate at the normal operating pool stage of 12.20 feet. Subsequently, the gate-position indicator gage readings will be referred to as "gage readings" and the pool and tailwater gage readings will be referred to as "stages".

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 cannot 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 21 is the top of a rivet on an angle iron connecting the top gate arm to the arched crest of the gate structure. The rivet is the second, of four rivets, from the pier and is 0.5 foot below the top edge of the gate arm (fig. 4). The R.P. is 17.72 feet from the trunnion centerline and is the same for all the gates. The elevation of each R.P. and the trunnion centerlines was determined by levels from established benchmarks on the piers between the gates (U.S. Army Corps of Engineers, 1974). The vertical gate opening, h_g, is computed from the equation:

$$h_g = 26.00 - 32.53 \sin(33.770 + \phi_u) \qquad (8)$$

where $\phi_u = \sin^{-1}$[(Trunnion elev. - R.P. elev.)/17.72]

The terms in the equation are graphically displayed in figure 4. The average elevation of the trunnion centerlines was found at 476.023 feet with variations from 475.977 to 476.064 feet.

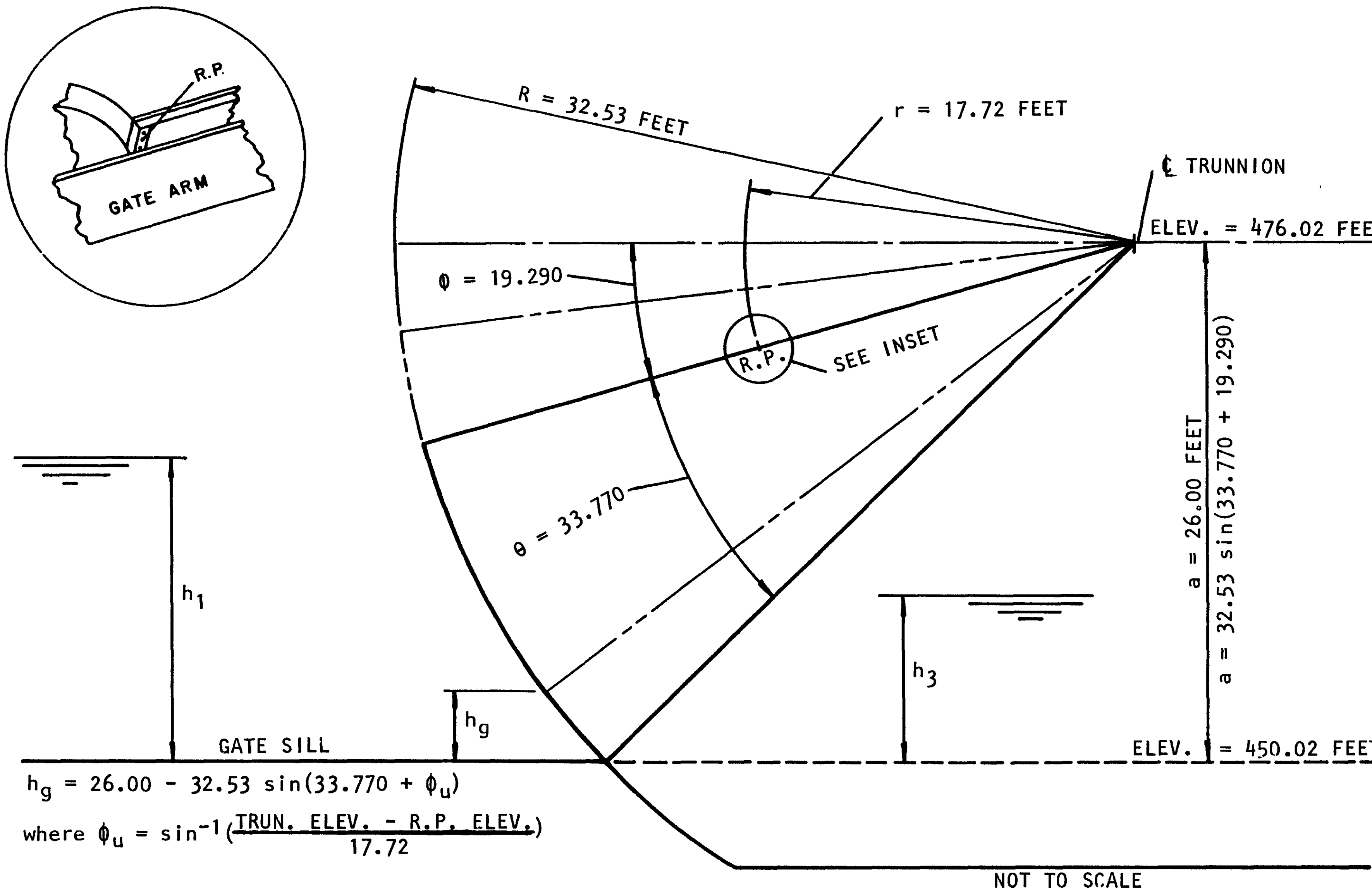


Figure 4.--Details of tainter gates at Mississippi River Lock and Dam 21. See page vi for definition of symbols

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 included angle of the Dam 21 tainter gate structure so that the average computed gate openings (h_g) would be the same as the gage-indicator readings. The resulting angle of the gate structure is 33.770 degrees (fig. 4). Note that the angle of 33.770 degrees is not the full included angle of the gate structure because the R.P. is 0.5 foot below the top edge of the upper gate arm. The advantage of using this approach is that the discharge for the average gate openings can be computed using the gage-indicator readings directly. 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. Corrections to the gage indicators for gates 1 and 13 were not obtained and will have to be assumed to be zero.

A gage-indicator error of 0.10 foot will result in about a 5-percent deviation in discharge from the rating discharge at the 2.00 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-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.

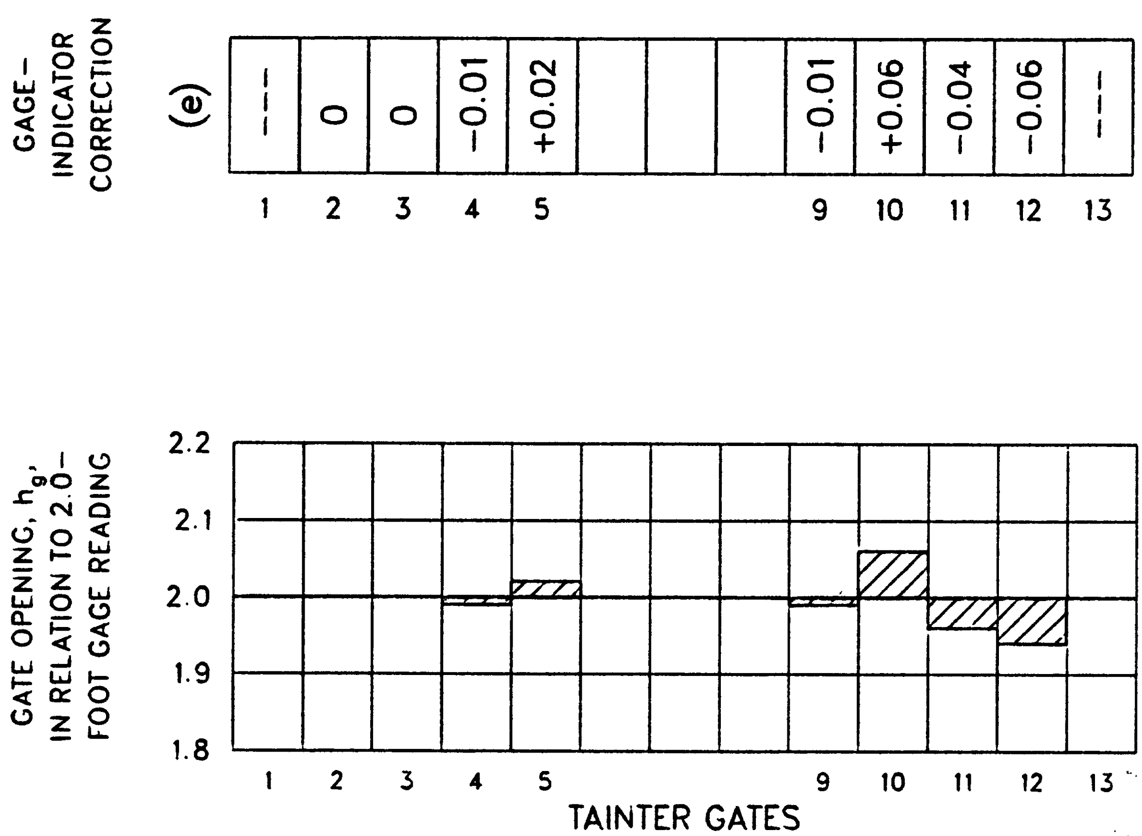


Figure 5.—–Gage–indicator corrections and comparison of gate openings at 2.0–foot gage–indicator settings for tainter gates on Mississippi river Lock and Dam 21.

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

$$C_{gs} = 0.88\ (h_3/h_g)^{-1.03} \qquad (9)$$

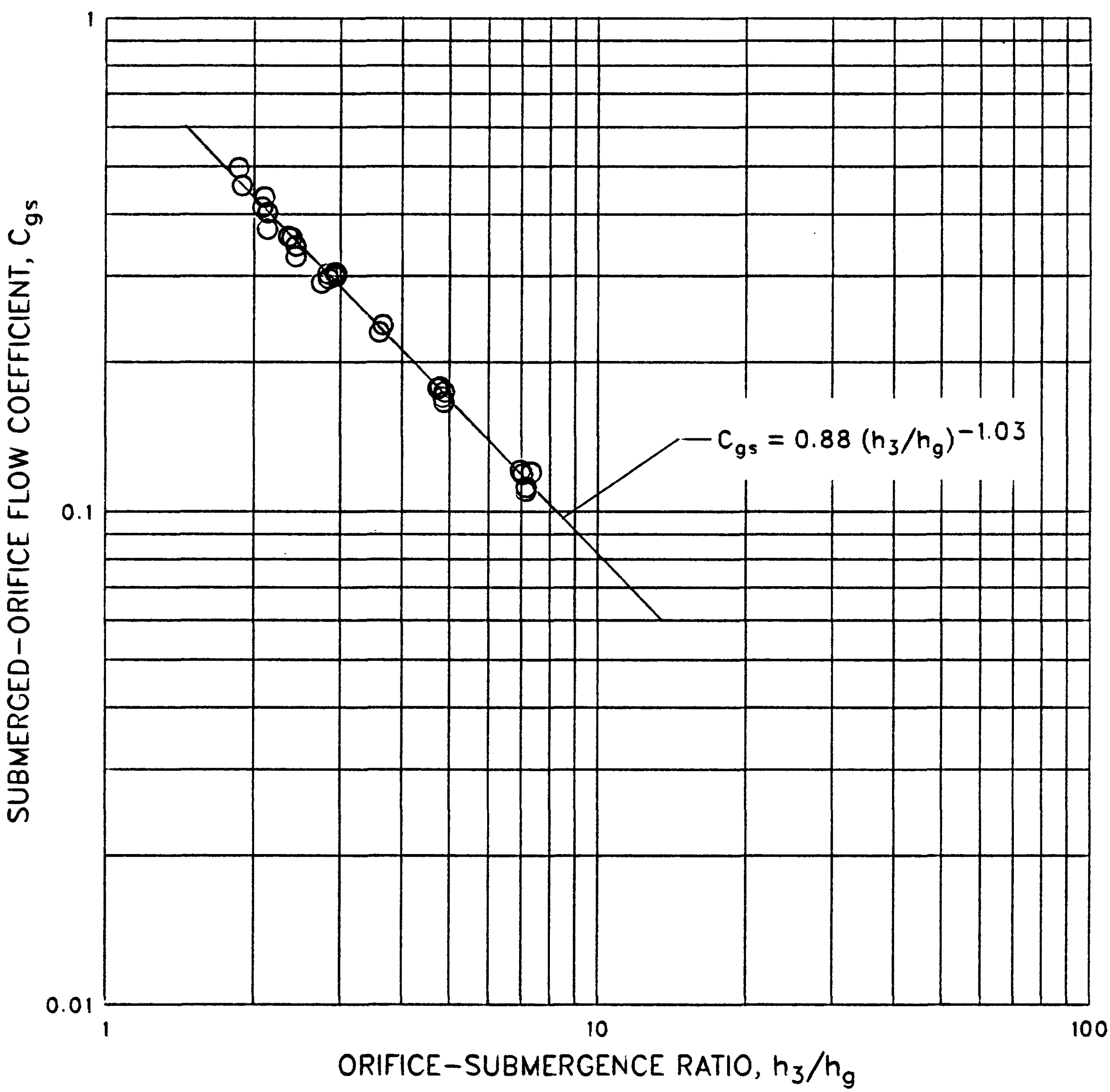


Figure 6.--Relation between submerged-orifice flow coefficient and orifice-submergence ratio for Lock and Dam 21 tainter gates.

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:

$$Q = 453\ h_3\ (h_3/h_g)^{-1.03}\ (h_1 - h_3)^{0.5} \qquad (10)$$

where h_g = gage 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 = the tailwater stage plus 7.80 feet and $h_1 - h_3$ = the difference between the pool and tailwater stages.

The relation of the current-meter discharge measurements made at the tainter gates on March 3-4, 1987, to the discharge curve defined by equation 10 is shown in figure 7.

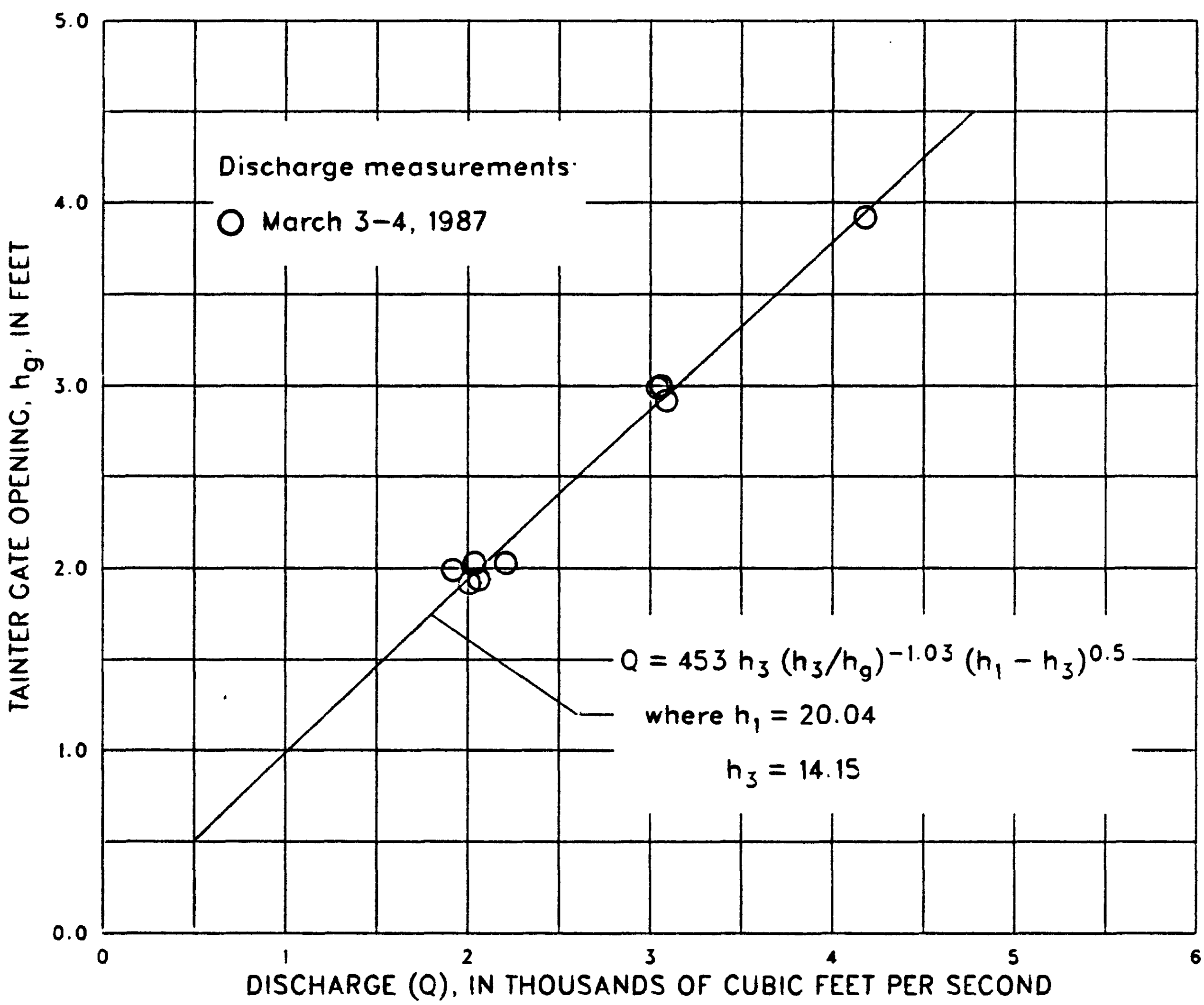


Figure 7.--Comparison of current-meter discharge measurements of March 3-4, 1987, to rating curves for tainter gates at Mississippi River Lock and Dam 21.

Free-Weir Flow Coefficients

Discharge coefficients for free-weir flow for tainter gates 4, 9 and 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 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 + (pool stage - 12.20). Also shown in figure 8 are the coefficients for Locks and Dams 11, 13 and 18. These coefficients were used to corroborate the coefficient-headwater relation for Lock and Dam 21.

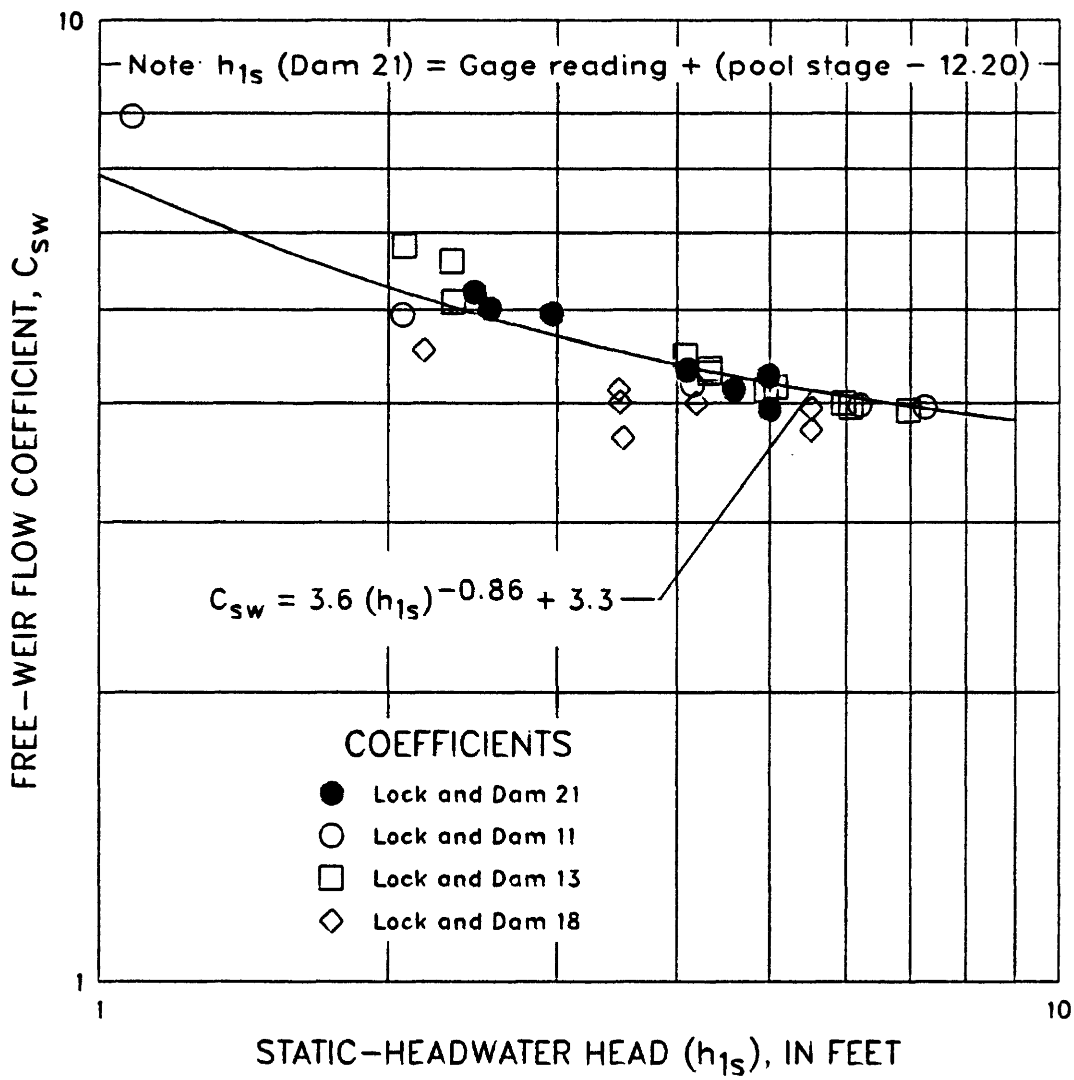


Figure 8.--Relation between free-weir flow coefficient and static-headwater head for tainter gates in submerged position for Lock and Dam 21.

Free-Weir Discharge Equation

An equation for computing free-weir flow in the tainter gates 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) to the static-headwater (h_{1s}) over the gate crest is:

$$Q = 212\ (1.09\ h_{1s}^{0.64} + h_{1s}^{1.50}) \qquad (12)$$

where h_{1s} is as defined for equation 11 above. Also shown in figure 9 are the discharge measurements made at Locks and Dams 11, 13 and 18. For comparison, however, the discharges for the measurements at Lock and Dam 11 were adjusted from the 60.0 feet tainter gate width to the 64.2 feet tainter gate width of the Lock and Dam 21 gates. These measurements were used to corroborate the rating development for Lock and Dam 21.

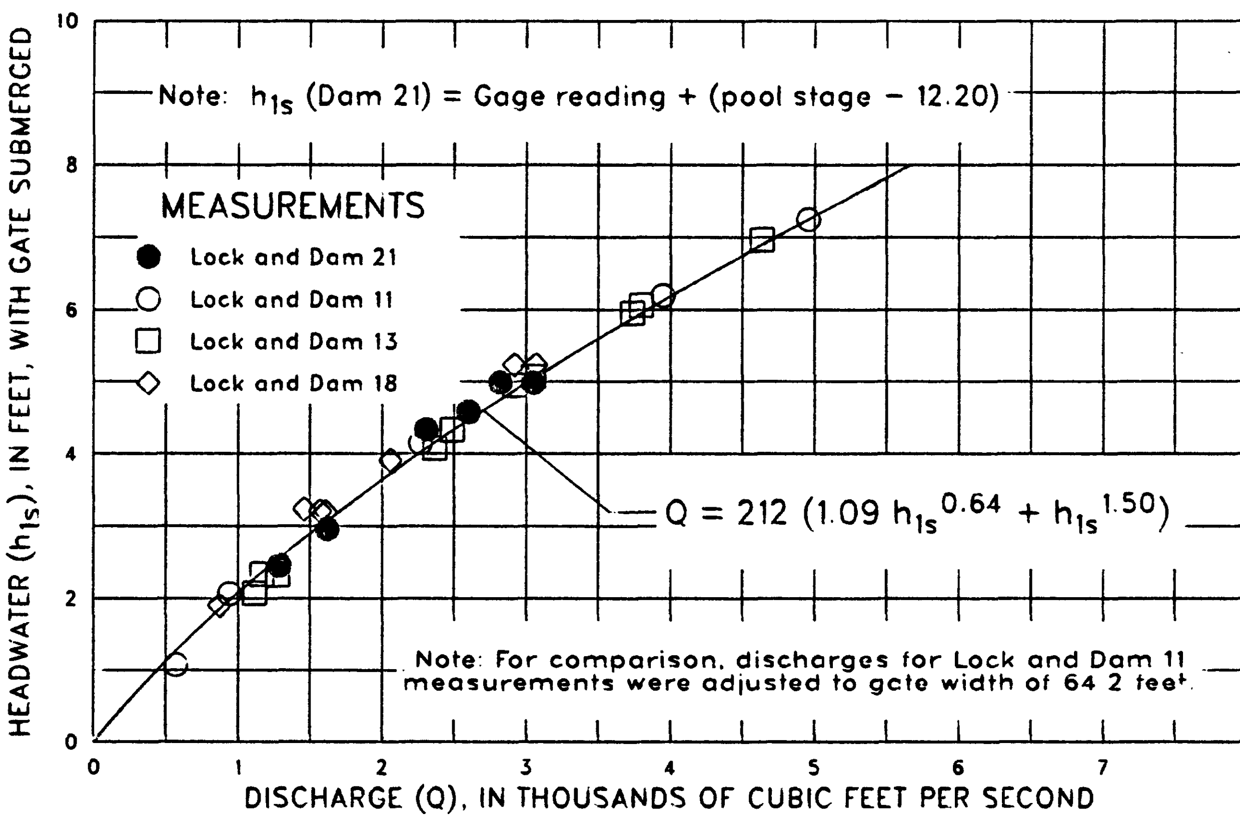


Figure 9.—Relation between discharge and headwater for free-weir flow for tainter gates in submerged position for Lock and Dam 21.

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 21 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 21 is shown in figure 10. The break in the relation occurs at a point when the gate is open 7 feet or more and the submergence ratio is less than 2.3 for the Dam 21 roller gates. The break in the relationship apparently occurs when control of flow of 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 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.

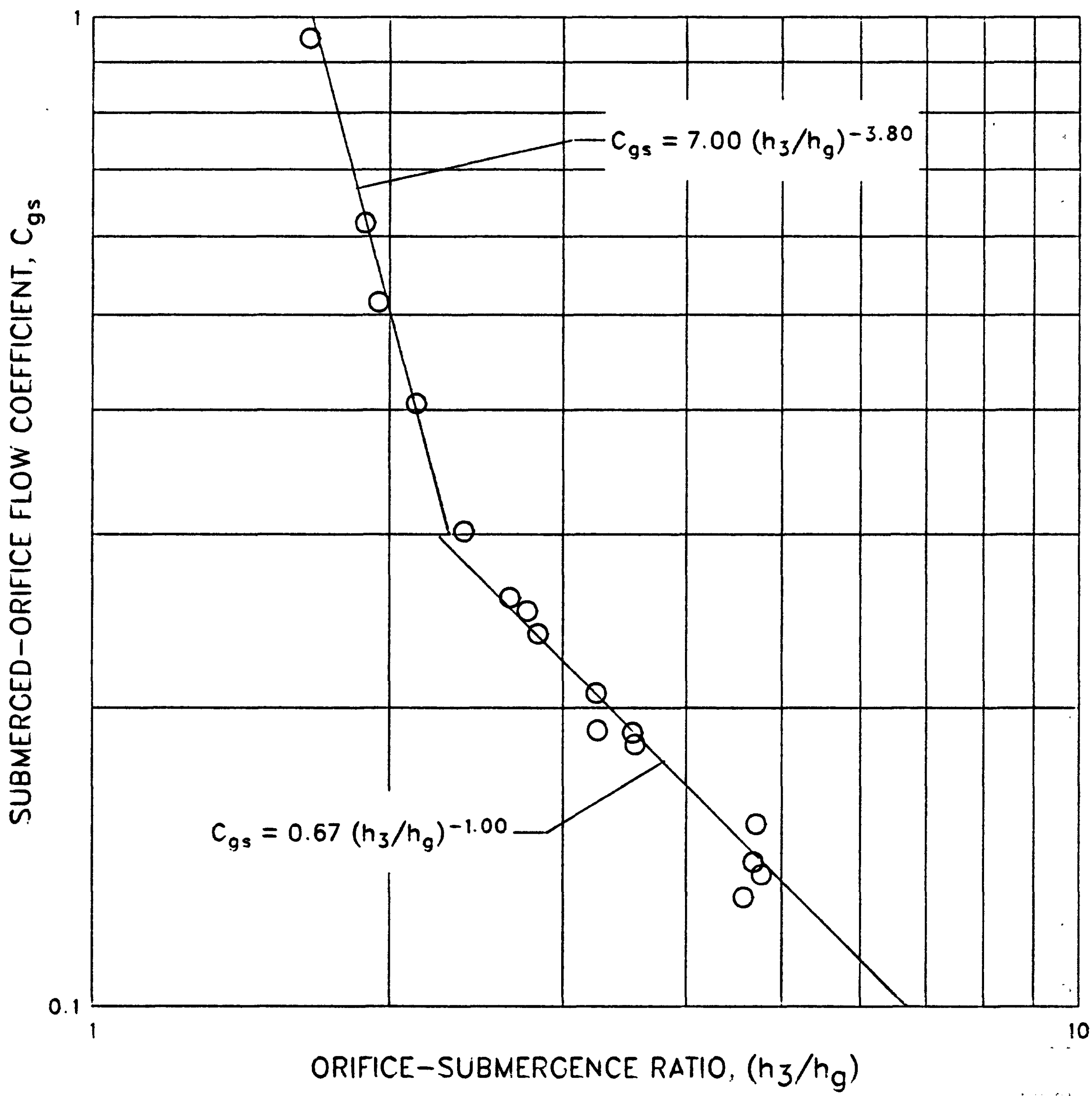


Figure 10.--Relation between submerged-orifice flow coefficient and orifice-submergence ratio for Lock and Dam 21 roller gates

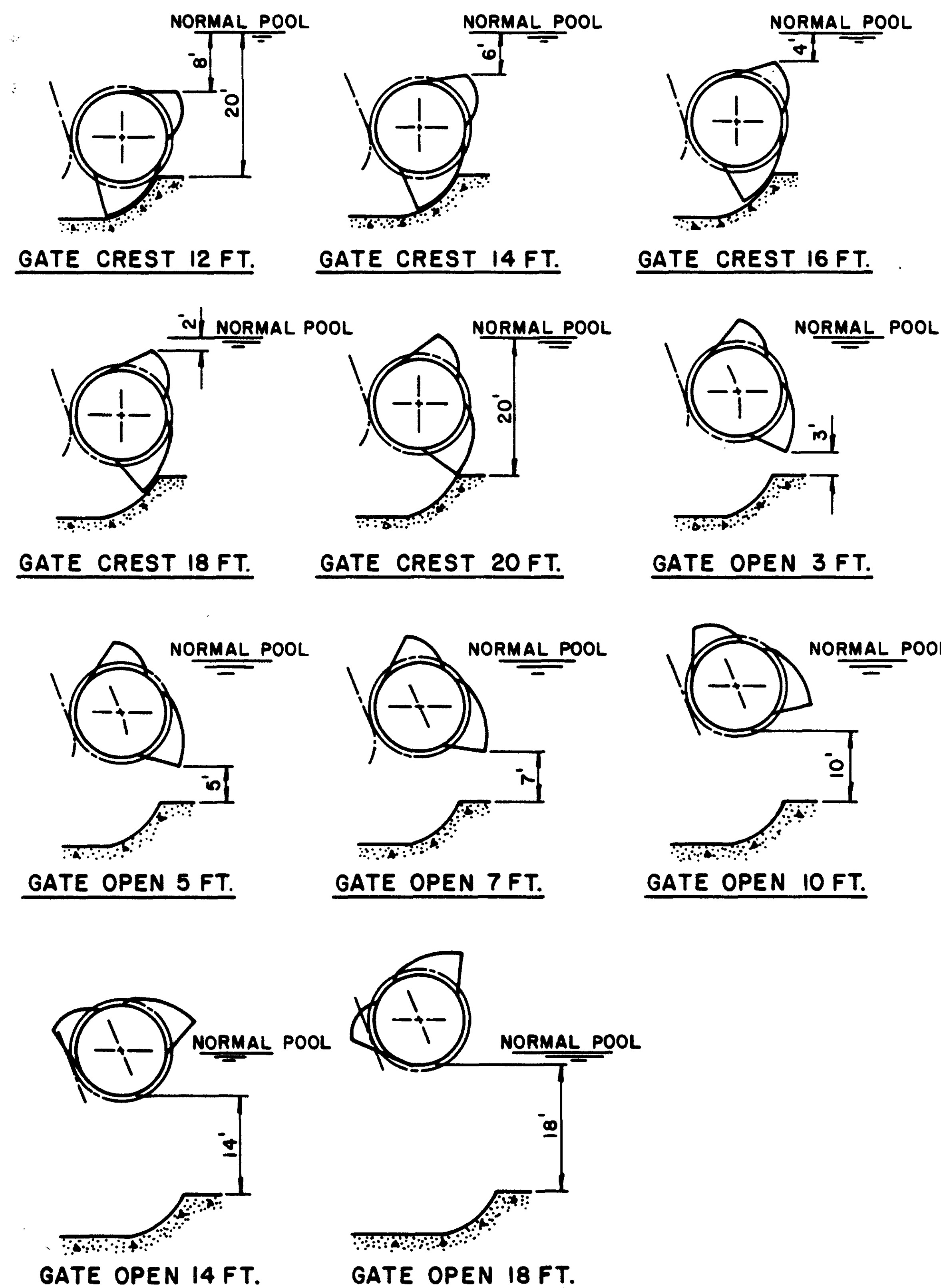


Figure 11.--Positions of roller gates for selected crests and openings (modified from U.S. Army Corps of Engineers, 1940, fig. 35).

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:

$$C_{gs} = 0.67\ (h_3/h_g)^{-1.00} \qquad (13)$$

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 21 using the free-orifice equation (1) was 0.67. This same coefficient was also computed for the roller gates at Locks and Dams 11, 12, 13 and 14. The 0.67 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 more and the orifice-submergence ratio is less than 2.3, the submerged-orifice coefficient, C_{gs}, for the Dam 21 roller gates is defined by the equation:

$$C_{gs} = 7.00\ (h_3/h_g)^{-3.80} \qquad (14)$$

The computed coefficients and the results of the measurements made for the roller gates at Dam 21 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 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:

$$Q = 537\ h_g\ (h_1 - h_3)^{0.5} \tag{15}$$

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

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 2.3 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-headloss (h_1 - h_3) is:

$$Q = 5{,}610\ h_3\ (h_3/h_g)^{-3.80}\ (h_1 - h_3)^{0.5} \tag{16}$$

where h_3 = tailwater stage plus 7.80 feet, h_g = gate opening and $h_1 - h_3$ = difference between the pool and tailwater stages.

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 static-headwater head (h_{1s}) over the gate crest is shown in figure 12. The equation relating the discharge coefficient to the headwater (h_{1s}) is:

$$C_{sw} = 8.67\ (h_{1s})^{-0.46} \tag{17}$$

where h_{1s} = Gage reading + 0.55 + (pool stage - 12.20) for Dam 21. The coefficient-headwater relation is further corroborated by data from Locks and Dams 11, 13 and 18 which are also shown in figure 12. The correction of 0.55 to the gage-indicator readings was derived from the observed pool stage at the point of zero flow over the gate crest.

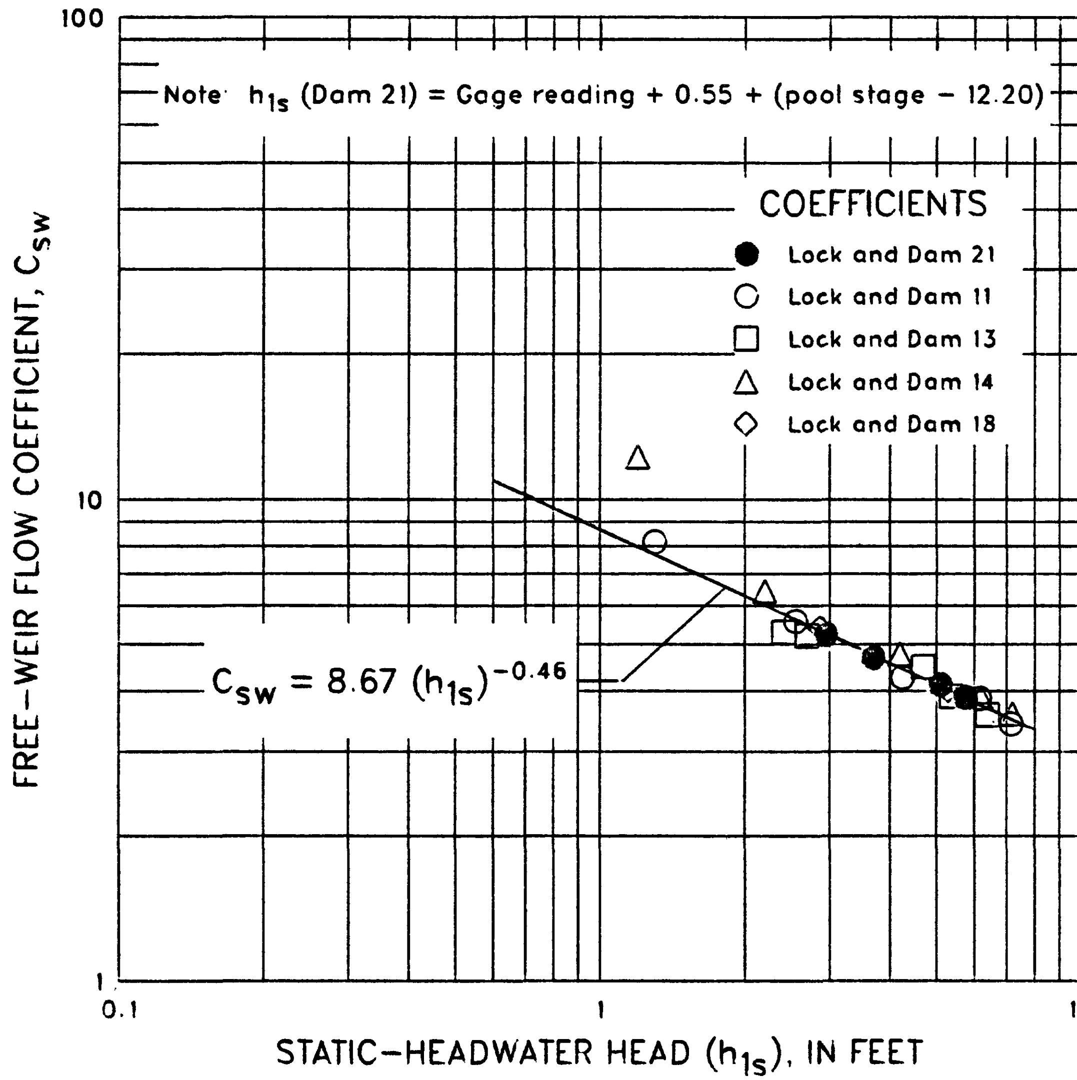


Figure 12.--Relation between free-weir flow coefficient and static-headwater head for roller gates in submerged position for Lock and Dam 21.

Free-Weir Discharge Equation

An equation for computing discharge for free-weir flow for the roller gates in a submerged position at Dam 21 was developed using the free-weir flow equation (5) and substituting equation 17 for the free-weir coefficient, C_{sw}.

The resulting equation, graphically illustrated in figure 13, relating the discharge (Q) to the static-headwater head (h_{1s}) over the gate crest is:

$$Q = 867\ (h_{1s})^{1.04} \tag{18}$$

where h_{1s} is as defined for equation 17 above. Also shown in figure 13 are the discharge measurements made at Locks and Dams 11, 13 and 18. These measurements were used to corroborate the rating development for Lock and Dam 21.

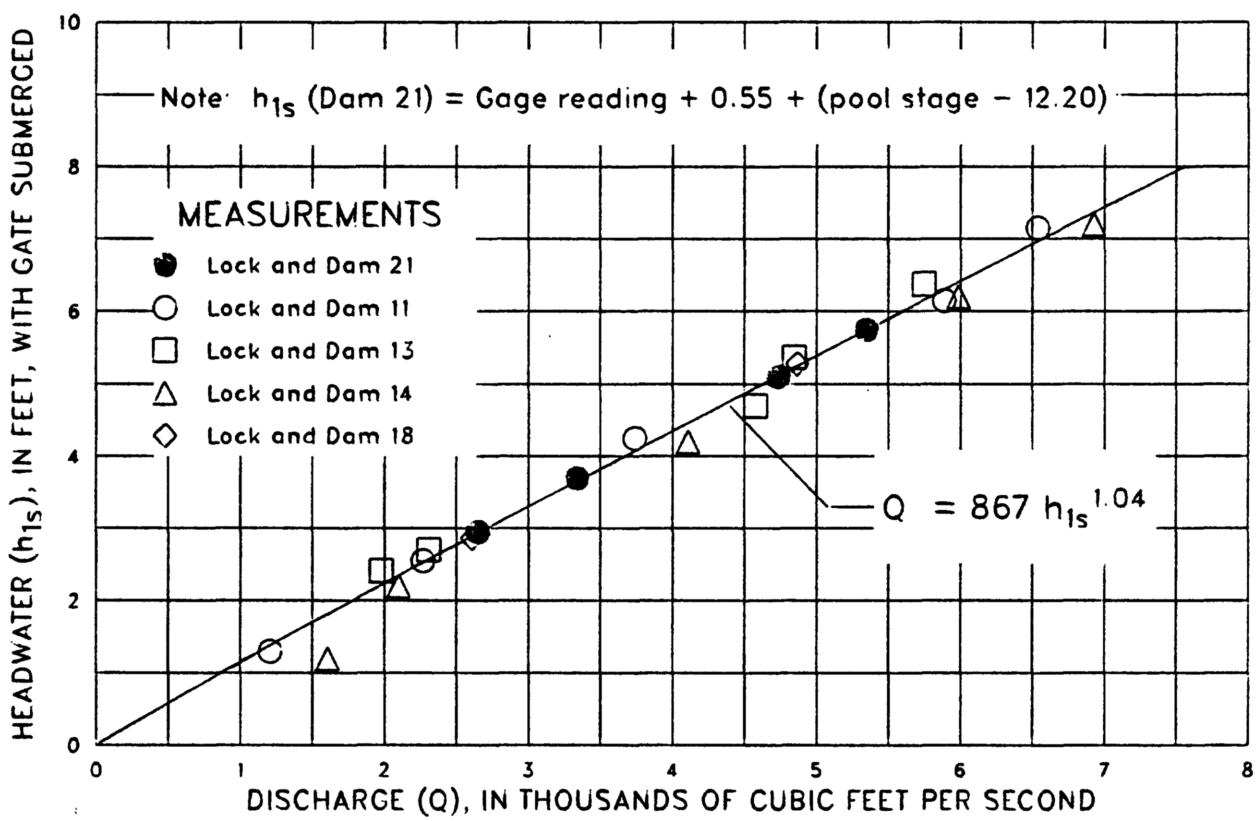


Figure 13.--Relation between discharge and headwater for free-weir flow for roller gates in submerged position for Lock and Dam 21.

DISCHARGE EQUATIONS AND RATINGS

The discharge equations applicable to the control gates when Dam 21 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 21 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 12.20 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 flow at selected gate openings (h_g) for the tainter and roller gates, prepared from laboratory tests using hydraulic models of gates, 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 methods for the tainter gates are comparable (within about 10 percent) until the gates are opened beyond the allowable gate opening for safe gate operation. At this point, the discharges defined by the two methods begin to deviate considerably. Discharges defined by the 2 methods 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 16 increase 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 21.

Gate	Flow regime	Equation of discharge 1/, 3/	Equation number
Tainter gates	Submerged orifice	$Q = 453\ h_3(h_3/h_g)^{-1.03}(h_1 - h_3)^{0.5}$	(10)
Tainter gates	Free Weir 2/	$Q = 212\ (1.09\ h_{1s}^{0.64} + h_{1s}^{1.50})$	(12)
Roller gates	Submerged orifice $h_g < 7.0$ or $\geqslant 7.0$ when $h_3/h_g > 2.3$	$Q = 537\ h_g(h_1 - h_3)^{0.5}$	(15)
Roller gates	Submerged orifice $h_g \geqslant 7.0$ and $h_3/h_g < 2.3$	$Q = 5{,}610\ h_3(h_3/h_g)^{-3.80}(h_1 - h_3)^{0.5}$	(16)
Roller gates	Free weir 2/	$Q = 867\ h_{1s}^{1.04}$	(18)

1/ Q = Discharge, in cubic feet per second
h_1 = Pool stage + 7.80 feet
h_3 = Tailwater stage + 7.80 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 + (pool stage - 12.20)
Roller gate: h_{1s} = gage reading + 0.55 + (pool stage - 12.20)

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 21 with upstream pool stage of 12.20 feet

Gage reading (feet)	Tainter gate discharge, in ft3/s, for indicated tailwater stage (feet) 2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
.5	662	627	590	551	511	467	419	365	302
1.0	1350	1280	1200	1130	1040	953	855	745	616
1.5	2050	1940	1830	1710	1580	1450	1300	1130	936
2.0	2760	2610	2460	2300	2130	1950	1750	1520	1260
2.5	3470	3290	3100	2890	2680	2450	2200	1910	1580
3.0	4190	3970	3730	3490	3230	2950	2650	2310	1910
3.5	4910	4650	4380	4090	3790	3460	3110	2710	2240
4.0	5630	5330	5020	4700	4350	3970	3560	3100	2570
4.5	6360	6020	5670	5300	4910	4490	4020	3510	2900
5.0	7090	6710	6320	5910	5470	5000	4480	3910	3230
5.5	7820	7410	6970	6520	6030	5520	4950	4310	3570
6.0	8550	8100	7630	7130	6600	6030	5410	4710	3900
6.5	9290	8800	8280	7740	7170	6550	5880	5120	4240
7.0	10000	9490	8940	8360	7740	7070	6340	5530	4570
7.5		10200	9600	8970	8310	7590	6810	5930	4910
8.0			10300	9590	8880	8110	7280	6340	5250
8.5				10200	9450	8640	7750	6750	5590
9.0					10000	9160	8220	7160	5920
9.5						9680	8690	7570	6260
10.0						10200	9160	7980	6600
10.5							9630	8390	6940
11.0							10100	8800	7290

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

Discharges for table 4 were computed using equation:

$$(10) \quad Q = 453\, h_3 (h_3/h_g)^{-1.03} (h_1 - h_3)^{0.5}$$

where h_g = gage reading + (average e = 0)
h_1 = 20.00 feet (12.20 + 7.80)
h_3 = tailwater stage + 7.80 feet

Table 5.--Discharge rating table for submerged-orifice flow for a roller gate at Mississippi River Lock and Dam 21 with upstream pool stage of 12.20 feet

Gage reading (feet)	Roller gate discharge, in ft3/s, for indicated tailwater stage (feet) 2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
.5	858	814	769	720	669	612	550	480	398
1.0	1720	1630	1540	1440	1340	1220	1100	961	796
1.5	2570	2440	2310	2160	2010	1840	1650	1440	1190
2.0	3430	3260	3080	2880	2670	2450	2200	1920	1590
2.5	4290	4070	3840	3600	3340	3060	2750	2400	1990
3.0	5150	4890	4610	4320	4010	3670	3300	2880	2390
3.5	6000	5700	5380	5040	4680	4290	3850	3360	2790
4.0	6860	6520	6150	5760	5350	4900	4400	3840	3190
4.5	7720	7330	6920	6480	6020	5510	4950	4320	3580
5.0		8140	7690	7200	6690	6120	5500	4800	3980
5.5			8460	7930	7350	6740	6050	5280	4380
6.0			9230	8650	8020	7350	6600	5760	4780
6.5				9370	8690	7960	7150	6240	5180
7.0						11000	8240	6720	5580
7.5						14300	10700	7870	5970
8.0	Discharges in this area may						13700	10100	7090
8.5	be greater than those allowable							12700	8930
9.0	for safe gate operation (USCE, 1980).								11100
9.5									13600

Note: Underline denotes change in rating from equation 15 to equation 16.

Discharges for table 5 were computed using equations:

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

(16) $Q = 5{,}610\ h_3(h_3/h_g)^{-3.80}(h_1 - h_3)^{0.5}$

where h_g = gage reading
h_1 = 20.00 feet (12.20 + 7.80)
h_3 = tailwater stage + 7.80 feet

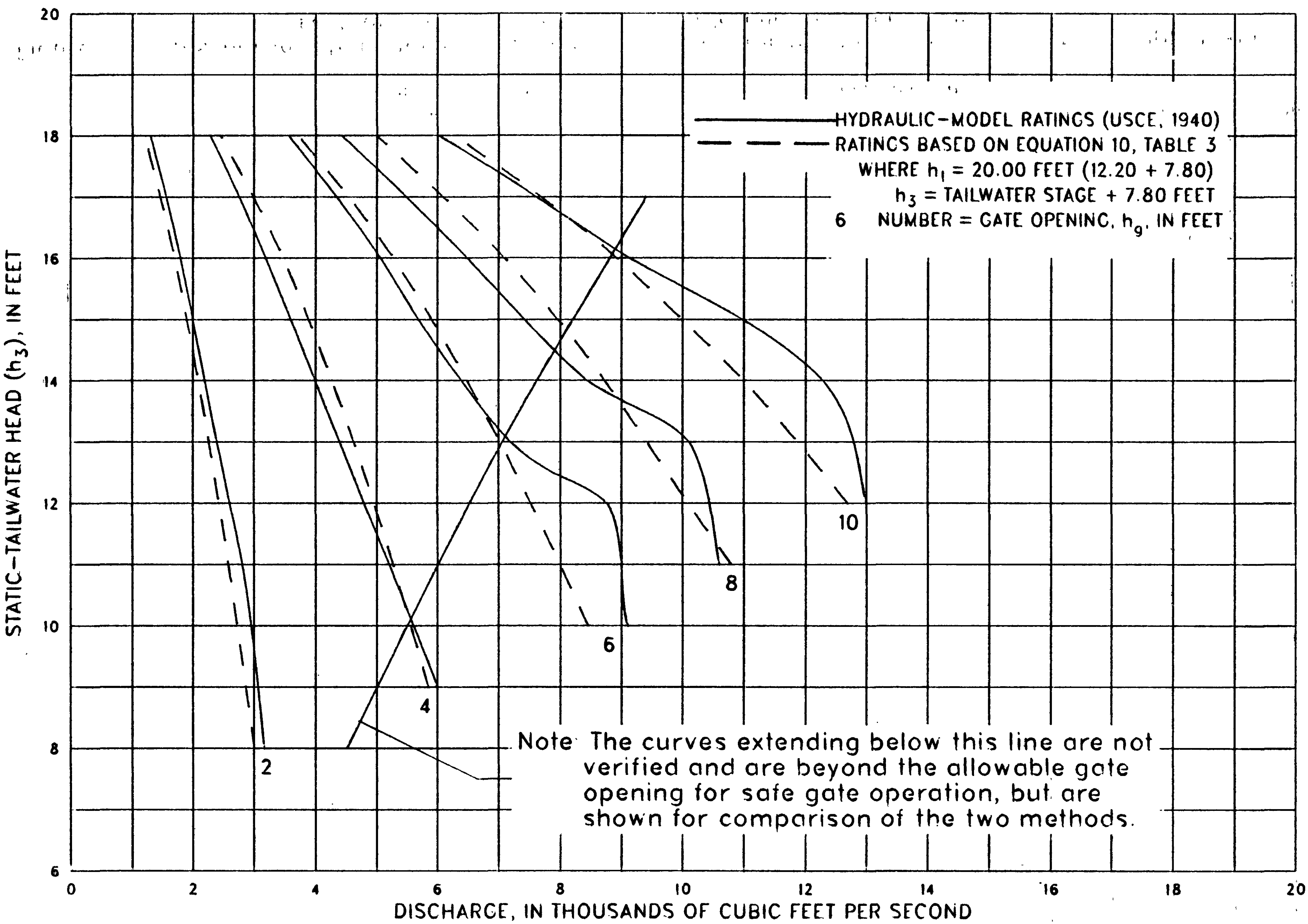


Figure 14.--Discharge ratings for submerged-orifice flow for a single tainter gate at Mississippi River Lock and Dam 21 compared to hydraulic-model ratings.

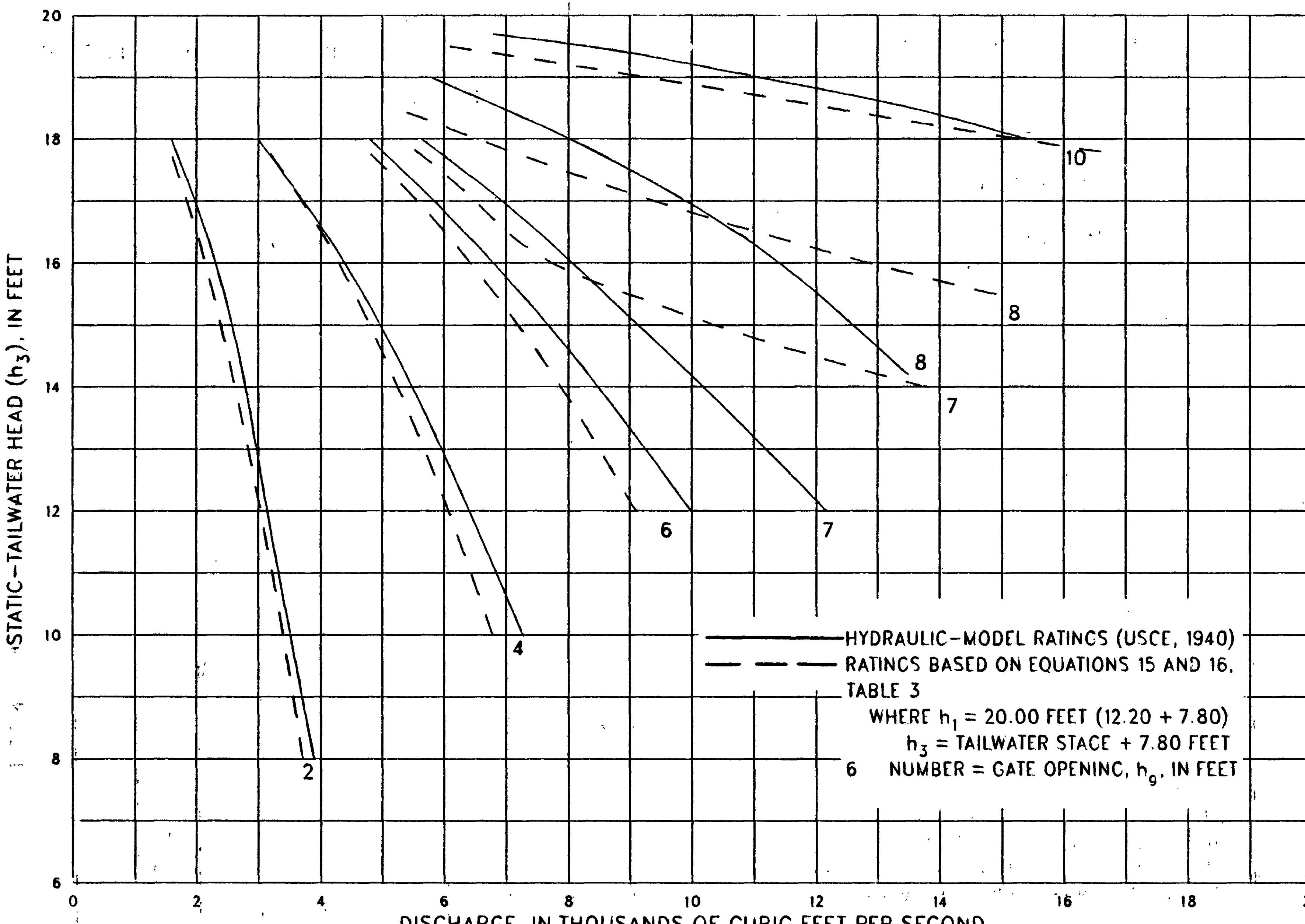


Figure 15.—Discharge ratings for submerged-orifice flow for a single roller gate at Mississippi River Lock and Dam 21 compared to hydraulic-model ratings.

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 21. Discharges for the two methods were generally within 8 percent until the roller gate openings exceeded 7 feet at which time the discharges defined by the equations in table 3 increased to 40 percent greater than those shown in Plan A.

Table 6.--Comparison of rating discharges (column 1) to discharges specified in Gate Operation Schedule Plan A for Mississippi River Lock and Dam 21
[Modified from U.S. Army Corps of Engineers, 1980, pl. 25]

Rating 1/ discharge (ft³/s)	Gate Operation Schedule Plan A for controlled tailwater stages with headwater stage of 12.20 feet															
	Discharge (ft³/s)	Tailwater stage (feet)	Head (feet)	Gate opening, (feet), for gate indicated												
				Tainter					Roller			Tainter				
				1	2	3	4	5	6	7	8	9	10	11	12	13
18,700	17,200	2.0	10.2	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
22,000	20,000	2.2	10.0	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
24,200	22,800	2.4	9.8	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0
26,800	25,200	2.6	9.6	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
29,700	27,500	2.8	9.4	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.0
31,800	29,800	3.0	9.2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.0
34,200	32,000	3.2	9.0	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
37,100	34,200	3.4	8.8	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
39,400	36,500	3.6	8.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
41,700	38,700	3.8	8.4	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	2.0	2.0	1.5	1.5
43,400	40,900	4.0	8.2	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
45,500	43,000	4.2	8.0	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
48,600	45,100	4.4	7.8	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
50,100	47,100	4.6	7.6	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0
51,900	49,100	4.8	7.4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	2.5	2.5	2.5
54,200	51,000	5.0	7.2	4.0	4.0	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.0	2.5	2.5
56,100	52,900	5.2	7.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
58,300	54,900	5.4	6.8	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.5	3.0	3.0
60,300	56,800	5.6	6.6	4.5	4.5	4.5	4.5	4.0	4.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0
62,000	58,700	5.8	6.4	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
63,800	60,600	6.0	6.2	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.0	4.0	3.5	3.5
66,100	62,500	6.2	6.0	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.5	4.5	4.5	4.0	3.5	3.5
67,400	64,500	6.4	5.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	4.5	4.0	3.5	3.5
69,900	66,600	6.6	5.6	5.5	5.5	5.5	5.5	5.0	5.0	5.0	5.0	5.0	4.5	4.5	4.0	4.0
71,600	68,600	6.8	5.4	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	4.5	4.0	4.0
73,300	70,600	7.0	5.2	6.0	6.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	4.5	4.5
75,100	72,700	7.2	5.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.5	5.5	5.5	5.0	4.5	4.5
77,100	74,800	7.4	4.8	6.5	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.5	5.5	5.0	5.0
78,600	76,900	7.6	4.6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.0	6.0	6.0	5.5	5.0	5.0
80,700	79,000	7.8	4.4	7.0	7.0	7.0	6.5	6.5	6.5	6.5	6.5	6.5	6.0	6.0	5.5	5.5
82,800	81,200	8.0	4.2	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	6.5	6.5	6.0	5.5	5.5
88,000	83,400	8.2	4.0	7.0	7.0	7.0	7.0	8.0	8.0	7.0	7.0	7.0	6.5	6.5	6.0	6.0
95,300	85,500	8.4	3.8	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	7.0	7.0	6.5	6.0	6.0
95,900	87,600	8.6	3.6	7.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	7.0	7.0	6.5	6.0
102,000	89,800	8.8	3.4	8.0	8.0	8.0	8.0	9.0	9.0	8.0	8.0	8.0	8.0	7.0	7.0	7.0
111,000	92,000	9.0	3.2	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
127,000	96,500	9.4	2.8	9.0	9.0	9.0	9.0	10.0	10.0	10.0	10.0	9.0	9.0	8.0	8.0	8.0
143,000	101,000	9.8	2.4	9.0	10.0	10.0	10.0	11.0	11.0	11.0	11.0	10.0	10.0	9.0	9.0	8.0
149,000	105,000	10.2	2.0	10.0	11.0	11.0	11.0	11.0	12.0	12.0	11.0	11.0	11.0	10.0	10.0	9.0

1/ Computed using equations in table 3 with headwater stage of 12.20 feet.

SUMMARY

Current-meter discharge measurements made in the forebays of the tainter and roller gates of Lock and Dam 21 were used to develop discharge coefficients and equations of discharge for submerged-orifice and free-weir flow for all the gates.

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

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 21.

SELECTED REFERENCES

American Society of Civil Engineers, 1962, Nomenclature for hydraulics: ASCE Manuals and Reports No. 43, 501 p.

Collins, D.L., 1977, Computation of records of streamflow at control structure: U.S. Geological Survey Water-Resources Investigations 77-8, 57 p.

Creager, W.P., and Justin, J.D., 1950, Hydro-electric Handbook: New York, John Wiley, 1151 p.

Davis, C.V., and Sorensen, K.E., 1952, Handbook of Applied Hydraulics: McGraw-Hill , 800 p.

Heinitz, A.J., 1985, Discharge Ratings For Control Gates at Mississippi River Lock and Dam 11, Dubuque, Iowa: U.S. Geological Survey Water-Resources Investigations Report 85-4105, 43 p.

________, 1985, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 14, Le Claire, Iowa: U.S. Geological Survey Water-Resources Investigations Report 85-4261, 38 p.

________, 1986, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 12, Bellevue, Iowa: U.S. Geological Survey Water-Resources Investigations Report 86-4135, 43 p.

________, 1986, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 13, Fulton, Illinois: U.S. Geological Survey Water-Resources Investigations Report 86-4134, 43 p.

________, 1986, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 16, Muscatine, Iowa: U.S. Geological Survey Water-Resources Investigations Report 86-4136, 36 p.

________, 1986, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 22, Saverton, Missouri: U.S. Geological Survey Water-Resources Investigations Report 86-4137, 37 p.

REFERENCES....continued

________, 1987, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 18, Gladstone, Illinois: U.S. Geological Survey Water-Resources Investigations Report 87-4110, 44 p.

________, 1987, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 20, Canton, Missouri: U.S. Geological Survey Water-Resources Investigations Report 87-4149, 36 p.

________, 1987, Discharge Ratings for Control Gates at Mississippi River Lock and Dam 17, New Boston, Illinois: U.S. Geological Survey Water-Resources Investigations Report 87-_____, 40 p.

King, H.W., and Brater, E.F., 1954, Handbook of hydraulics (4th ed.): New York, McGraw-Hill, 640 p.

Rantz, S.E. and others, 1982, Measurement and computation of streamflow, Volume 1. Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Rouse, Hunter, 1949, Engineering hydraulics, Iowa Institute of Hydraulic Research, State University of Iowa: New York, John Wiley, 1039 p.

U.S. Army Corps of Engineers, 1937, Mississippi River Lock and Dam 21, Dam pier position data: Rock Island, Illinois, 1 p.

________, 1939, Laboratory tests on hydraulic models of roller gate stilling basins: Rock Island, Illinois, 279 p.

________, 1940a, Laboratory tests on hydraulic model to determine roller gate coefficients for upper Mississippi River navigation dams: Rock Island, Illinois, 72 p.

________, 1940b, Laboratory tests on hydraulic model of Lock and Dam No. 11, Mississippi River, Dubuque, Iowa: Rock Island, Illinois, 111 p.

________, 1980, Upper Mississippi River basin, Mississippi River-nine foot channel, Appendix 21, Master reservoir regulation manual, Lock and Dam No. 21: Rock Island, Illinois, 93 p.