DISCHARGE RATINGS FOR CONTROL GATES AT MISSISSIPPI RIVER LOCK AND DAM 14, LE CLAIRE, IOWA

By Albert J. Heinitz

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Donald Paul Hodel, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

U.S. Geological Survey
Water Resources Division
P.O. Box 1230
Iowa City, Iowa 52244

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SYMBOLS AND UNITS

Symbol	Definition	Unit
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	Vertical gate opening	ft
N	Number of lockages occurring between recordings	
Q	Computed discharge per gate	ft^3/s
Q_s	Computed fixed-spillway discharge	ft^3/s

Symbol	Definition	Unit
R	Radius from trunnion centerline to upstream face of a Tainter gate	ft
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	
$\geq$	Greater than or equal to	

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-	
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
	-Area-	
acres	4,047	square meters (m^2)
square miles (mi^2)	2.590	Square kilometers (km^2)
	-Volume-	
cubic feet (ft^3)	0.02832	cubic meters (m^3)
cubic feet per second-day (ft^3/s-day)	2,447	cubic meters (m^3)
acre-feet (acre-ft)	1,233	cubic meters (m^3)
	-Flow-	
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)

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ABSTRACT

The water level of the navigation pools on the Mississippi River are maintained by the operation of tainter and roller gates at the locks and dams. Discharge ratings for the gates on Lock and Dam 14, at Le Claire, Iowa, were developed from current-meter discharge measurements made in the forebays of the gate structures.

Methodology is given to accurately compute the vertical gate openings of the tainter gates.

Discharge coefficients, in equations that express discharge as a function of tailwater head, headwater head, and vertical 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 14 was placed in operation June 14, 1939.

This is the second 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 report for Lock and Dam 11 at Dubuque, Iowa, (Heinitz, 1985) preceded this report. The discharge ratings for Locks and Dams 11, 14 and 16 were done concurrently. During the course of the studies, it was observed that the hydraulic characteristics of the roller gates at Dams 11 and 14 had some similarity. For this reason, the submerged orifice flow coefficients for the Dam 11 roller gates were used to corroborate the Dam 14 rating development in this study.

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 develope discharge ratings for the control gates at Lock and Dam 14. 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 14.

Acknowledgements

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

LOCATION OF STUDY AREA

Lock and Dam 14, located at Le Claire, Iowa, is a unit of the Inland Waterway Navigation System of the Upper Mississippi River Basin. Figure 1 shows a general map of the system within the Rock Island District (U.S. Army Corps of Engineers, 1980, plate 1).

FLOW CONTROLS

Three types of flow controls are present on the structures of Lock and Dam 14. These are tainter gates, roller gates and the navigation lock. Detailed theoretical as well as physical descriptions of these flow control structures are beyond the scope of this report, and therefore are not included. Readers interested in this subject are referred to Davis and Sorensen (1952), Rouse (1949), Creager and Justin (1950), and King and Brater (1954). Table 1 summarizes the hydraulic conditions that define each regime of flow and the corresponding generalized steady-state discharge equations. An important parameter common to all types of flow control is the discharge coefficient, which is discussed in the following paragraph.

The discharge coefficients (C) 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 (Q) 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.

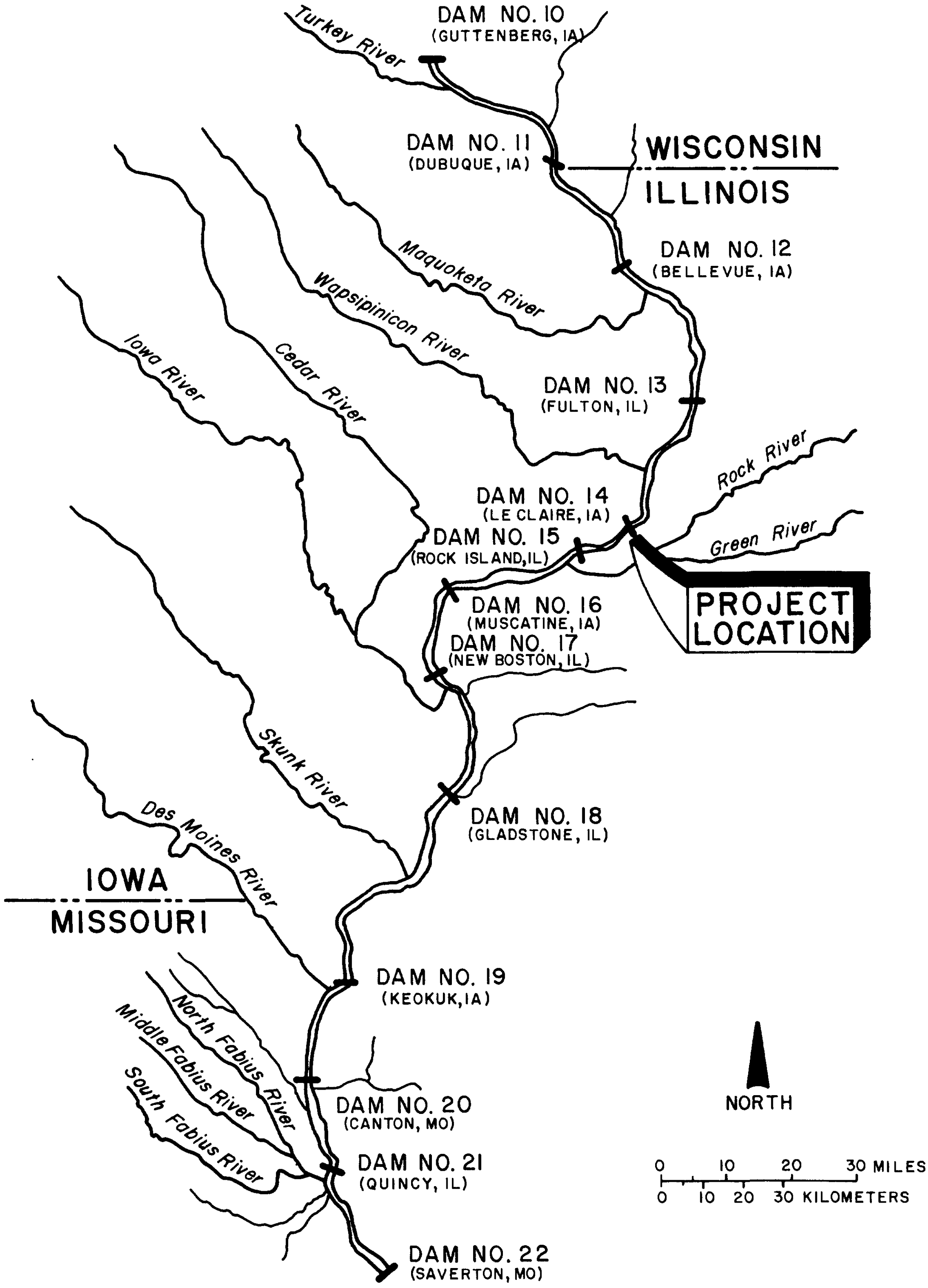

Figure 1.--Inland Waterway Navigation System of the Upper Mississippi River Basin (modified from USCE, 1980, plate 1).

Table 1.--Flow controls and their respective hydraulic equations

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

* Same for flow over gate crest with gate in submerged position

The bracketed portions 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 headwater and 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. Headwater and tailwater heads are the vertical distances from the gate sill or spillway crest to upstream and downstream pool elevations, respectively.

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.

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

Types of Flow at Dam 14 Control Gates

Submerged orifice flow predominates when the control gates at Dam 14 are in operation (U.S. Army Corps of Engineers, 1980, plate 29). Free orifice flow would very rarely occur at a low-head navigation-type structure as found on Dam 14 and would not occur at the dam under normal operating conditions. Calibration requires the development of a relation between the discharge coefficient, C_{gs}, in equation 2 and the gate submergence ratio, h_3/h_g.

Free weir flow at the Dam 14 roller gates would occur primarily with the gates in a submerged condition with flow over the crests of the gates. Calibration of these gates requires the definition of the relation between the discharge coefficient, C_{sw}, in equation 5 and the headwater, h_{1s}, over the gate crest. The gates are operated in the submerged position in the winter when there is no commercial navigation and the dam is out of operation. 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, therefore, flow would not occur over the gate crests. Submerged weir flow would also occur over the tainter and roller gate sills with the gates raised above the water surface when the dam is out of operation. This type flow is not evaluated in this report.

DAM OPERATION

Lock and Dam 14 contains 13 tainter gates and 4 roller gates for controlling the pool elevation upstream from the dam. Four of the tainter gates, located adjacent to the lock, are separated from the remainder of the tainter gates by the 4 roller gates, which are situated at about mid-channel (fig. 2). Sectional views of the tainter and roller gates are shown in figure 3.

The tainter gates are of the non-submergible type and close on the curved steel channels embedded in the concrete sills. Each gate is 60 feet wide and operates between piers with 60 feet clear openings.

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

Operation of the control gates for maintaining the pool elevation is based on a study (U.S. Army Corps of Engineers, 1980) conducted to determine the optimum use of the dam for river flowage, conservation interests and towboat service. Operation "Plan A" (U.S. Army Corps of Engineers, 1980, plate 29) was adopted and put into use on April 17, 1940 and remains in effect. "Plan A" allows the high water levels to recede naturally until the authorized pool elevation for lower flows is reached.

Dam 14 is a run-of-the-river dam and cannot store water for flood control purposes. The pool is maintained between stages 14.5 and 15.0 feet. When the river is rising and the tailwater stage reaches 12.6 feet, the tainter and roller gates are raised above the water surface. During flood periods, the gates are raised out of the water allowing run-of-the-river flow to occur.

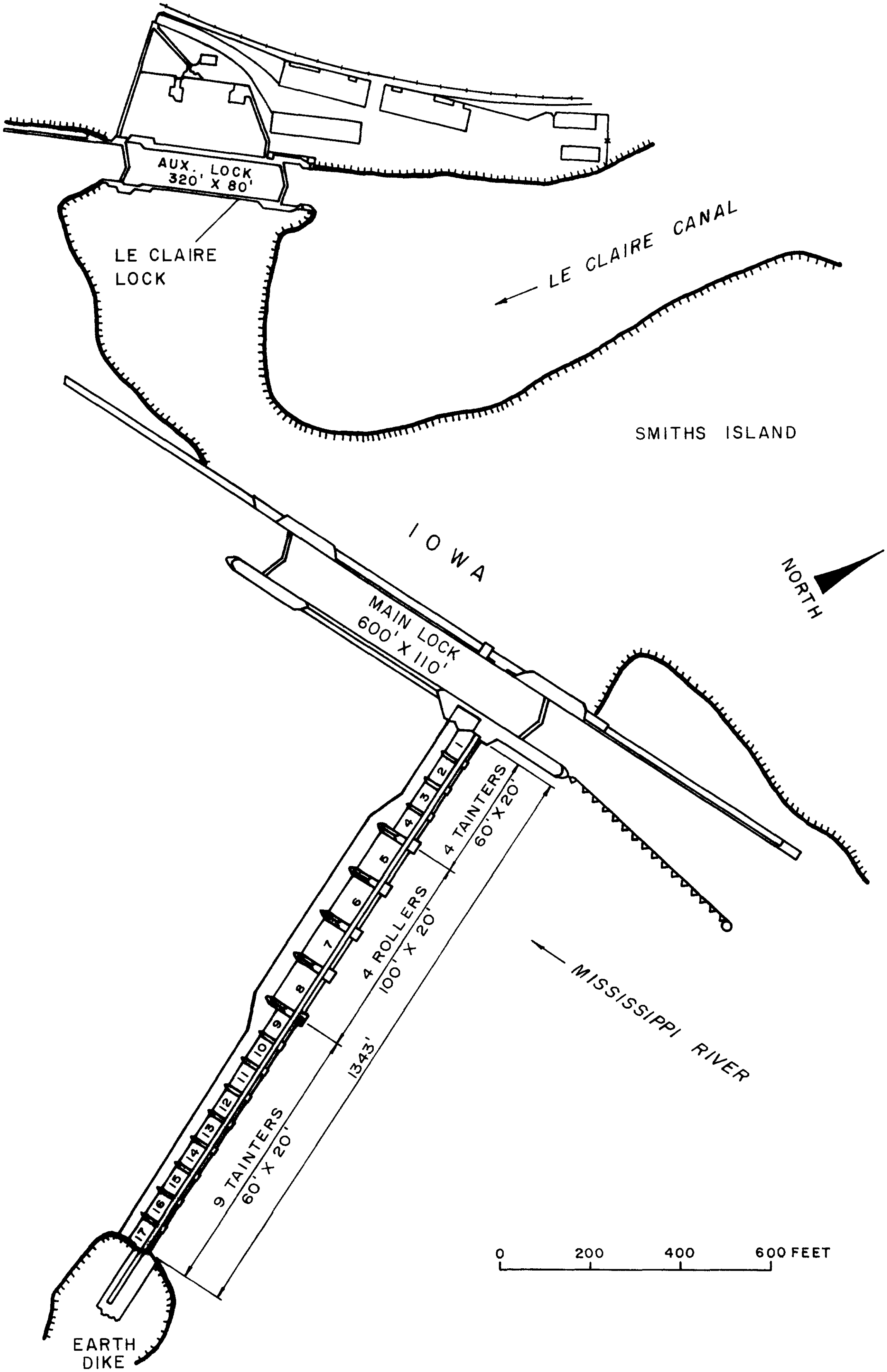

Figure 2.--Location of tainter and roller gates at Lock and Dam 14 on the Mississippi River (from USCE, 1980, plate 2).

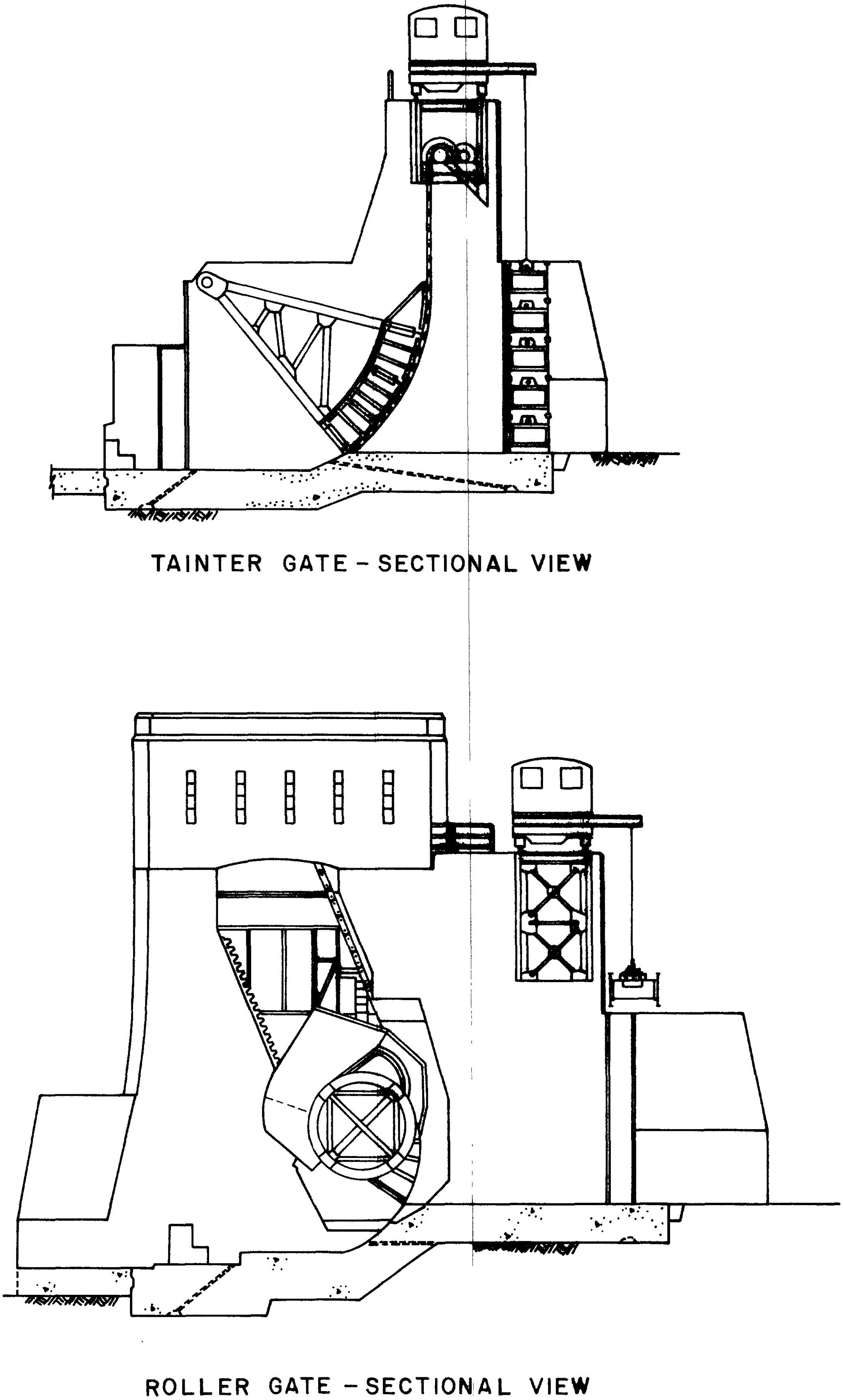

Figure 3.--Sectional views of tainter and roller gates on Mississippi River Lock and Dam 14 (modified from USCE, 1980, plates 5 and 6).

During winter, when there is no commercial navigation and the pools become ice covered, the roller gates at Dam 14 are placed in the submerged position. The tainter gates are operated the same as in summer with submerged orifice flow. The pool is maintained within the winter operating limits of 13.9 to 14.9 feet stage.

DISCHARGE AND STAGE MEASUREMENTS

The tainter and roller gates are built with a roadway over the structures giving access to the forebays with standard current-meter measuring equipment. The discharge measurements were made from the upstream edge of the roadway which is approximately 22 feet upstream from the downstream edge of the tainter gate sills and approximately 27 feet upstream from the roller gates. The distance of the measuring equipment from the orifice and control structure appeared to be adequate to allow measurements of good quality to be made. Some vertical velocity curves were taken to verify the standard 0.2 and 0.8 method of velocity observation. The measurements were made with equipment normally used for measuring large streams; velocity was measured using a type AA current meter suspended with Columbus-type sounding weights (50-150 pound) from a collapsible crane (Rantz and others, 1982).

The concurrent pool and tailwater stages for the measurements were obtained from the gages in the operations building. The headwater (h_1) and tailwater (h_3) referenced to the sill are obtained by adding 5.08 feet to the gage readings. The stages can be referenced to mean sea level elevation by adding the zero gage datum, 557.08 feet (1912 adjustment), to the stages. The gate-opening settings for the tainter gates were read from the staff-indicator gages on the tainter gates and those for the roller gates were read from the shaft indicator marks on the operating machinery.

A total of 43 measurements of discharge ranging from 738 to 20,800 cubic feet per second in a gate were made in the forebays of the roller and tainter gate structures of Lock and Dam 14. Discharge coefficients for all the gates of the same design could be developed from measurements on a single gate. However, to insure greater accuracy because of the fluctuations of the pool and tailwater during the measurements and to account for variations in entrance and exit conditions, several gates were selected for calibration. Discharge through each of the gate bays was measured at least once for submerged orifice flow. Only roller gate no. 7 was measured with the gates in a free weir flow position. The results of these measurements are listed in table 2.

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

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

Table 2 - Summary of current-meter discharge measurements and hydraulic control data for control gates at Mississippi River Lock and Dam 14.

Gate number	Date	Pool 1/ stage in feet	T/W 2/ stage in feet	Gage reading G in feet	Gate opening h_g in feet	Dis-charge in ft³/s	Deviation from rating in percent	h_3/h_g	C_{gs}	Flow 3/ regime
1	09-13-83	14.96	4.94	1.50	1.35	2,060	+ 4.6	7.42	0.135	SO
2	09-13-83	14.96	4.94	2.00	1.83	2,630	+ 0.8	5.48	0.172	SO
3	09-13-83	14.96	4.94	1.50	1.26	1,720	- 6.5	7.95	0.112	SO
3	09-28-83	14.96	6.50	3.00	2.84	3,520	- 3.6	4.08	0.217	SO
3	09-28-83	14.96	6.49	4.00	3.80	4,820	+ 0.8	3.04	0.298	SO
3	05-14-84	14.02	9.55	6.00	5.78	4,740	- 9.2	2.53	0.319	SO
3	05-14-84	14.02	9.55	8.00	7.77	7,500	+ 9.2	1.88	0.504	SO
3	05-14-84	14.02	9.55	9.00	8.79	9,580	+24.4	1.66	0.644	SO
4	09-13-83	14.96	4.94	1.50	1.46	2,000	- 5.7	6.86	0.131	SO
5	09-13-83	14.98	4.90	2.10		3,930	+ 9.8	4.75	0.155	SO
6	09-13-83	15.00	4.88	2.60		4,670	+ 5.2	3.83	0.184	SO
6	09-28-83	14.96	6.52	4.50		7,040	+ 0.3	2.58	0.260	SO
6	05-14-84	14.02	9.55	7.00		7,520	- 5.4	2.09	0.303	SO
6	05-14-84	14.02	9.55	8.50		13,300	0	1.72	0.536	SO
6	05-14-84	14.02	9.55	9.50		20,800	+ 2.5	1.54	0.839	SO
7	09-13-83	15.02	4.72	2.00		3,460	0	4.90	0.137	SO
7	11-08-83	14.95	5.05	1.00s	1.20b	1,610	+40.0		12.24w	FW
7	11-08-83	14.95	5.05	2.00s	2.20b	2,100	0		6.43w	FW
7	11-08-83	14.95	5.05	4.00s	4.20b	4,110	+ 2.0		4.78w	FW
7	11-08-83	14.95	5.05	6.00s	6.20b	5,990	+ 0.7		3.88w	FW
7	11-08-83	14.95	5.05	7.00s	7.20b	6,930	+ 0.3		3.59w	FW
8	09-13-83	15.02	4.70	2.00		3,400	- 1.5	4.89	0.135	SO
9	09-13-83	14.98	4.94	1.00	1.01	1,510	+ 0.7	9.92	0.099	SO
10	09-13-83	14.98	4.94	1.00	0.94	1,460	+ 3.5	10.66	0.096	SO
11	09-13-83	15.02	4.78	1.00	0.95	1,430	0	10.38	0.094	SO
11	09-28-83	14.95	6.50	3.00	2.98	3,610	- 5.2	3.89	0.223	SO
11	09-28-83	14.96	6.51	4.00	3.92	4,970	+ 1.0	2.96	0.307	SO
11	05-14-84	14.02	9.55	6.00	5.97	4,760	-11.5	2.45	0.320	SO
11	05-14-84	14.02	9.55	8.00	7.97	7,110	+ 1.1	1.84	0.478	SO
11	05-14-84	14.02	9.55	9.00	9.09	9,210	+15.8	1.61	0.619	SO
12	09-13-83	15.02	4.78	1.00	0.95	1,440	+ 0.7	10.38	0.095	SO
13	09-13-83	15.02	4.72	1.00	1.13	1,650	- 2.4	8.67	0.109	SO
14	09-12-83	14.60	4.57	1.00	0.96	1,410	- 1.4	10.05	0.096	SO
14	05-14-84	14.02	9.55	6.00	5.95	5,470	+ 2.1	2.46	0.367	SO
14	05-14-84	14.02	9.55	8.00	7.93	8,140	+16.3	1.84	0.547	SO
14	05-14-84	14.02	9.55	9.00	8.93	9,840	+25.8	1.64	0.661	SO
15	09-12-83	14.60	4.57	1.00	0.99	1,500	+ 2.0	9.75	0.102	SO
15	09-14-83	14.94	4.92	2.00	1.94	2,670	- 3.3	5.15	0.175	SO
15	09-28-83	14.95	6.49	3.02	2.99	4,000	+ 4.7	3.87	0.247	SO
15	09-28-83	14.96	6.52	4.00	3.91	5,140	+ 4.7	2.97	0.317	SO
16	09-12-83	14.60	4.57	1.00	0.83	1,290	+ 3.2	11.63	0.088	SO
17	09-12-83	14.60	4.57	0.50	0.39	738	+19.4	24.74	0.050	SO
17	09-13-83	14.95	4.94	1.50	1.36	1,910	- 3.5	7.37	0.125	SO

1/ h_1 = Pool stage + 5.08 feet.
2/ h_3 = Tailwater (T/W) stage + 5.08 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.

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 14 is the top of a slotted bolt head holding a guide plate on the gate arm (fig. 4). The bolt selected, of four bolts, is the one closest to the pier and to the trunnion and is 18.00 feet from the trunnion centerline. The R.P. is the same for all the gates except for gate 1 where a chiseled arrow was set on the left (as viewed facing downstream) gate arm and gate 17 where a chiseled arrow was set on the right gate arm. These R.P.'s were set 18.00 feet from the trunnion centerline. The guide plates on gates 1 and 17 were not accessible for determining elevations. Elevations of the R.P.'s were determined by levels from established benchmarks on the piers between the gates (U.S. Army Corps of Engineers, 1939). The vertical gate opening, h_g, is computed from the equation:

$$h_g = 22.00 - 27.531 \sin(40.622 + \phi_u) \qquad (8)$$

where

$$\phi_u = \sin^{-1} [(574.00 - \text{R.P. elev.})/18.00]$$

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

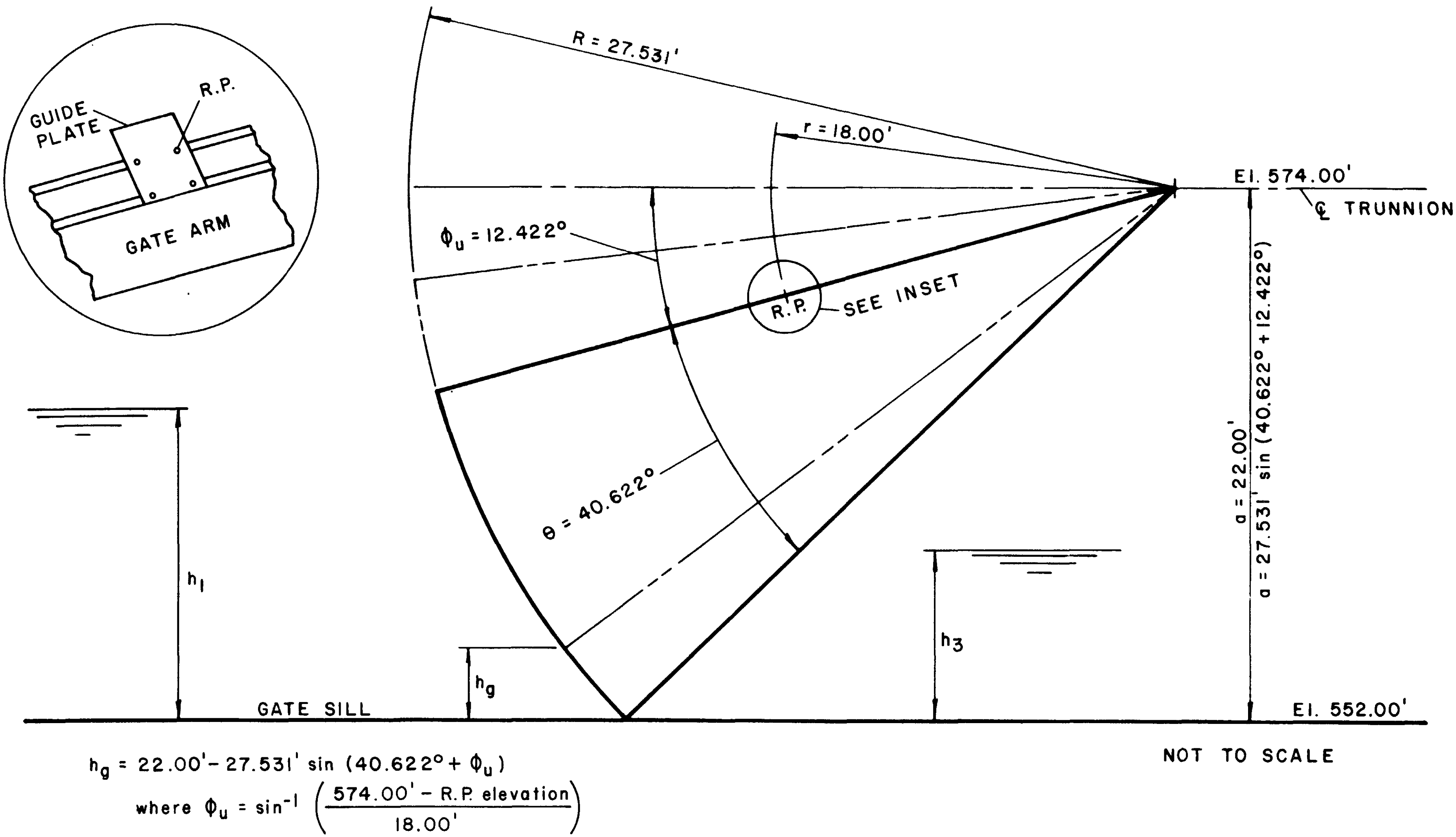

Figure 4. Details of tainter gates at Mississippi River Lock and Dam 14.

The average gate opening (h_g) computed for 5 gates in the closed ($h_g = 0$) position prior to calibration of the included angle was 0.19 foot with variations from 0.17 to 0.21 foot. 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 the 5 gates was 40.622 degrees (fig. 4). The deviation of h_g for these 5 gates is +/- 0.02 foot.

The average adjusted gate opening (h_g), with the gage indicator settings at 1.00 foot for all the tainter gates, was 0.93 foot with variations from 0.76 to 1.13 feet. 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 1.00 foot gage indicator settings are shown in figure 5. Also shown is the discharge for each of the tainter gates, these range from 1,140 to 1,650 cubic feet per second.

A gage indicator error of 0.10 foot will give about a 10 percent deviation in discharge from the rating discharge at the 1.00 foot gage setting. This deviation from the rating decreases at higher gage settings (about 4 percent at the 2.00 feet gage setting and 2.5 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.

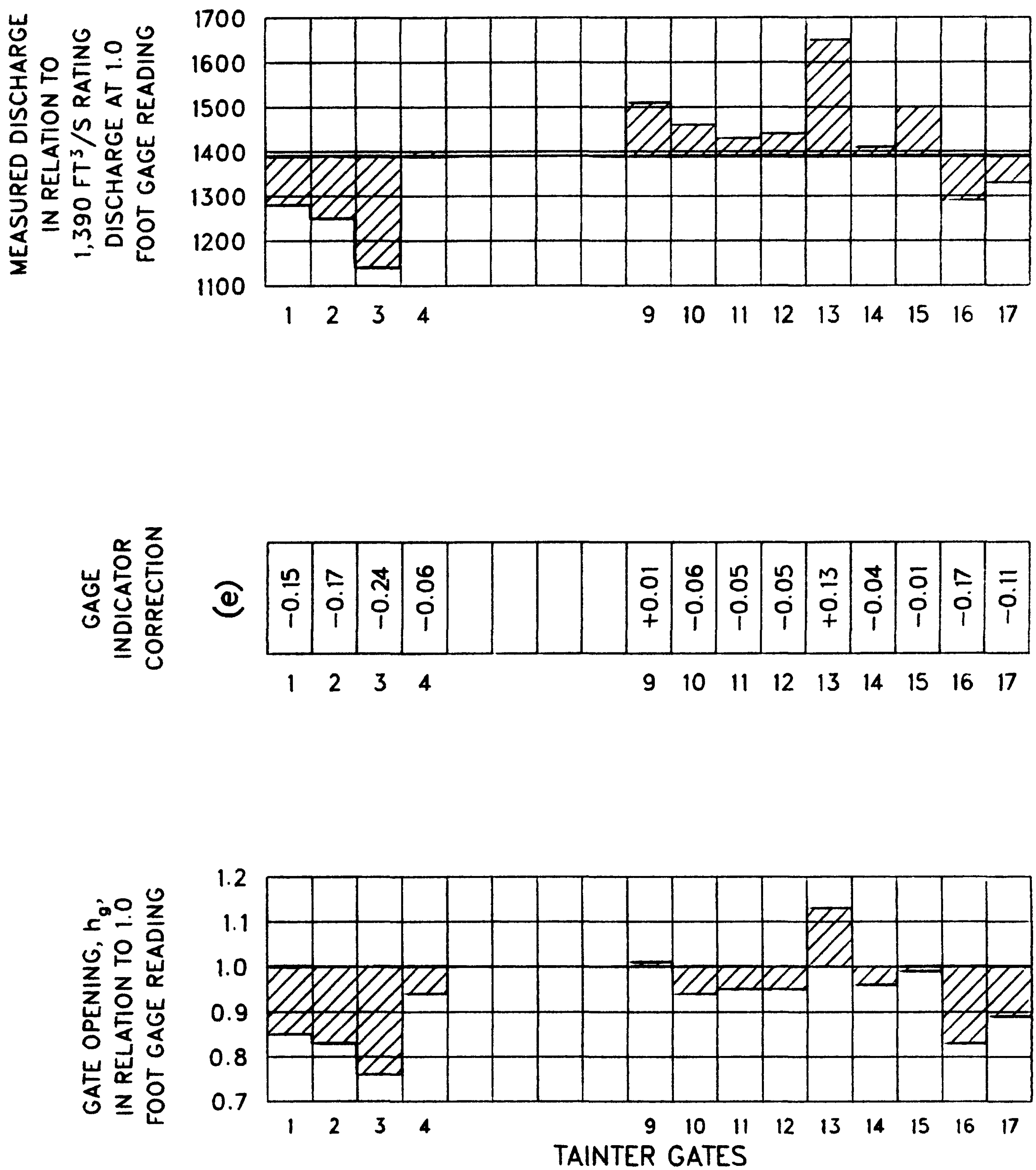

Figure 5. — Gage indicator corrections and comparison of gate openings and discharges at 1.0 feet gage indicator settings for tainter gates on Mississippi river Lock and Dam 14.

Submerged Orifice Flow Coefficients

Discharge coefficients for submerged orifice flow were computed by solving equation (2) in table 1 for C_{gs} using the results of the discharge measurements (table 2) that were made with the gates in submerged orifice flow conditions. The flow coefficients, C_{gs}, are listed in table 2 and a graph defining the relationship of C_{gs} to the orifice submergence ratio is shown in figure 6. The resulting equation, relating the discharge coefficient, C_{gs}, to the gate submergence ratio, h_3/h_g, is:

$$C_{gs} = 0.83\ (h_3/h_g)^{-0.93} \qquad (9)$$

The flow 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). Discharges must be relatively high with the gates open 8 feet or greater before submergence ratios of less than 1.9 will occur (USCE, 1980, plate 29). This condition will occur about 3 percent of the time (USCE, 1980, plate 19), such as on the rise of a flood peak before the gates are raised above the water surface and on the recession of a flood peak after the gates have been lowered back into the water.

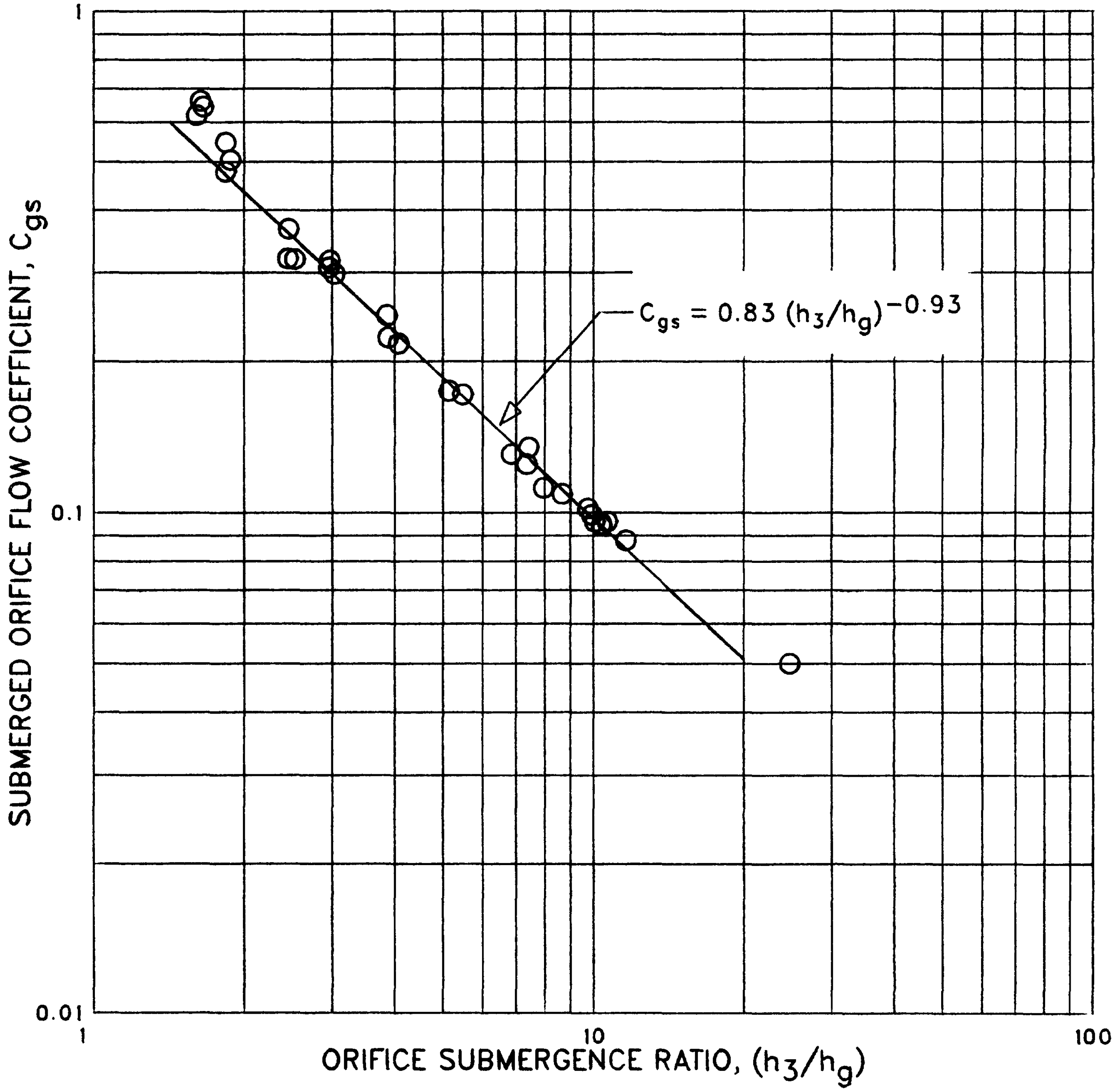

Figure 6. – Submerged orifice flow coefficient–submergence ratio relation for Mississippi River Lock and Dam 14 tainter gates

Submerged Orifice Discharge Equation

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

$$Q = 400\ h_3\ (h_3/h_g)^{-0.93}\ (h_1 - h_3)^{0.5} \qquad (10)$$

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 -0.07 foot), h_3 is the tailwater gage reading plus 5.08 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 12-13, 28, 1983, to the discharge curve defined by equation (10).

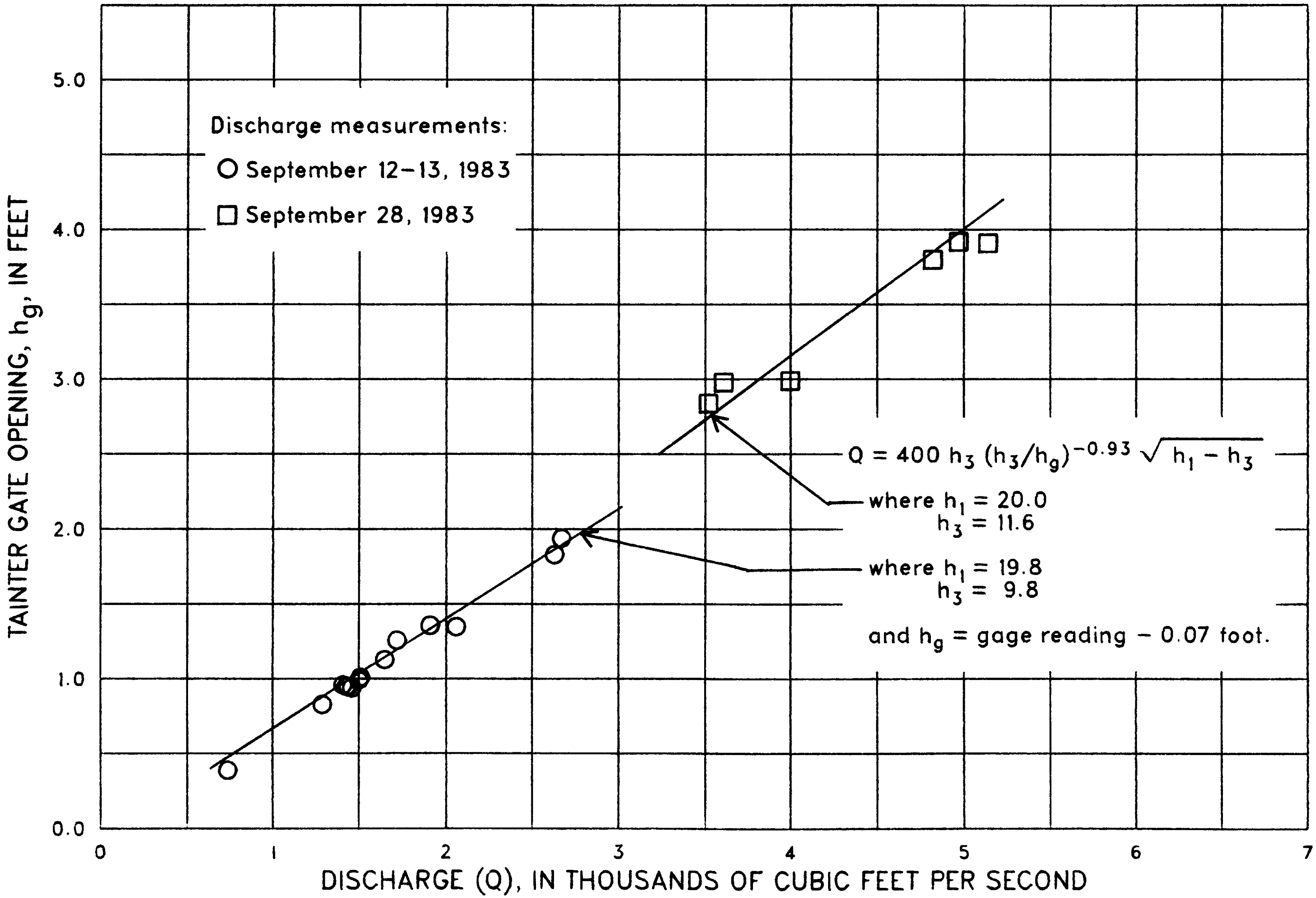

Figure 7. – Comparison of current–meter discharge measurements of September 12–13, 28, 1983, to rating curves for tainter gates at Mississippi River Lock and Dam 14.

ROLLER GATE FLOW

The roller gates at Dams 11 and 14 are the same type of structure and have the same hydraulic-model rating relationship. The development of discharge ratings at both dams are being done concurrently, therefore, enabling use of data from both dams in developing discharge ratings for the gates at each of the dams.

Gate Opening

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

The relation of the submerged orifice flow coefficient, C_{gs}, to the orifice submergence ratio, h_3/h_g, for the roller gates on Dams 11 and 14 are shown in figure 8. (Discharge coefficients for measurements subsequently made at Lock and Dam 13 are also shown in figure 8). The break in the relationship occurs at a point when the gate is open 7 feet or greater and the submergence ratio is less than 2.4 for the Dam 11 roller gates and less than 1.9 for the Dam 14 roller gates. The break in the relationship apparently occurs when

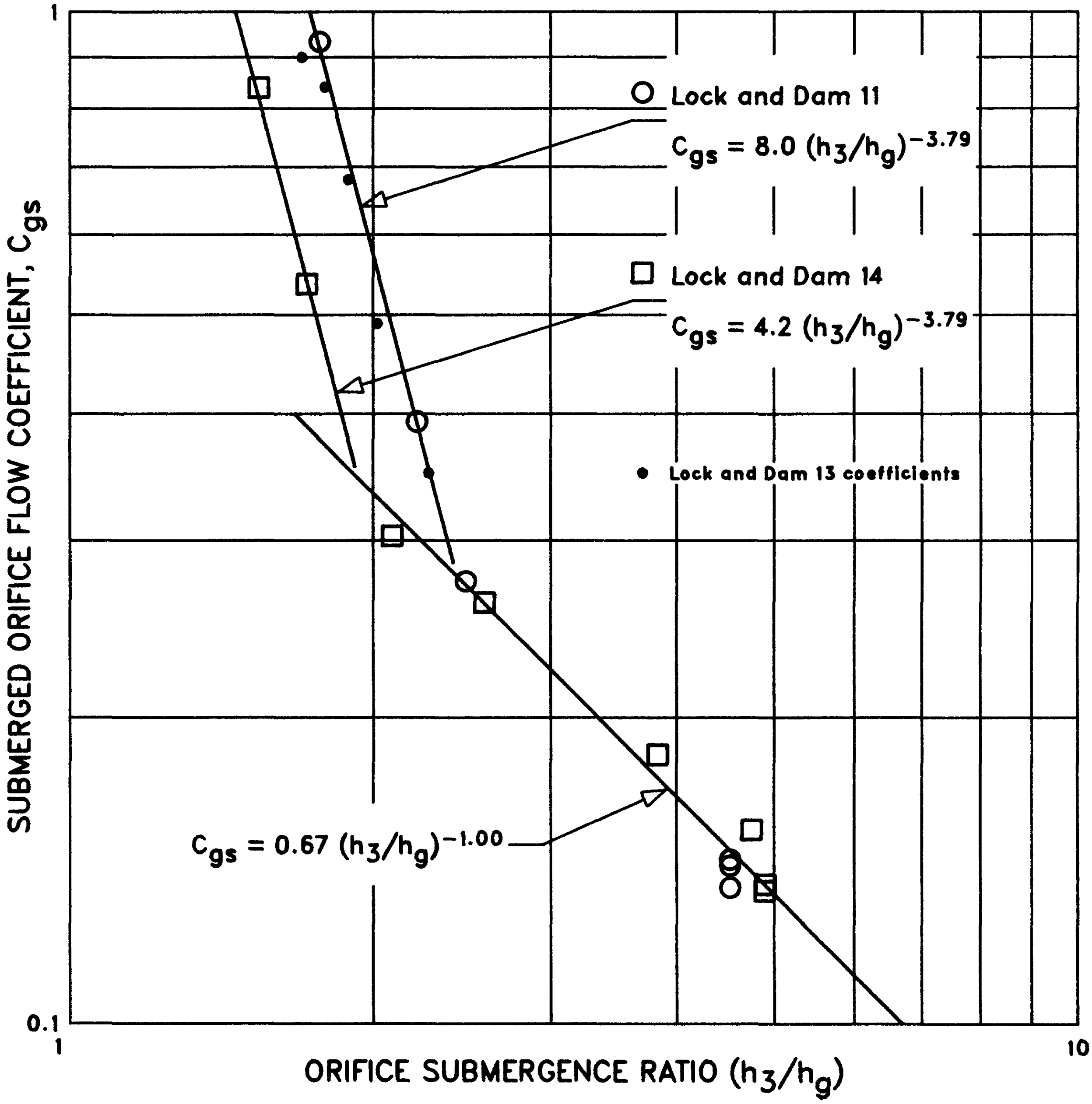

Figure 8. – Submerged orifice flow coefficient–submergence ratio relation for roller gates at Mississippi River Locks and Dams 11 and 14.

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 9 and show that the gate opening increases significantly when control transfers from the apron to the drum when the gate is opened more than 7.0 feet. The exact gate opening where the control changes has not been defined.

The resulting equation, relating the discharge coefficient, C_{gs}, to the gate submergence ratio, h_3/h_g, for the roller gates when the gates are open less than 7 feet is defined by the equation:

$$C_{gs} = 0.67 \ (h_3/h_g)^{-1.00} \tag{11}$$

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 found in equation 11. When substituted for the coefficient in the submerged orifice flow equation (2), the equation reduces to the free-orifice equation (1). The average of the coefficients computed for the roller gates at dams 11 and 14 using the free orifice equation (1) was 0.67. This coefficient is in total agreement with those in King and Brater (1954, table 26) for rectangular orifices with partially suppressed contraction.

For conditions when the gates are open 7 feet or greater and the submergence ratio is less than 1.9, the discharge coefficient, C_{gs}, for the Dam 14 roller gates is defined by the equation:

$$C_{gs} = 4.20 \ (h_3/h_g)^{-3.79} \tag{12}$$

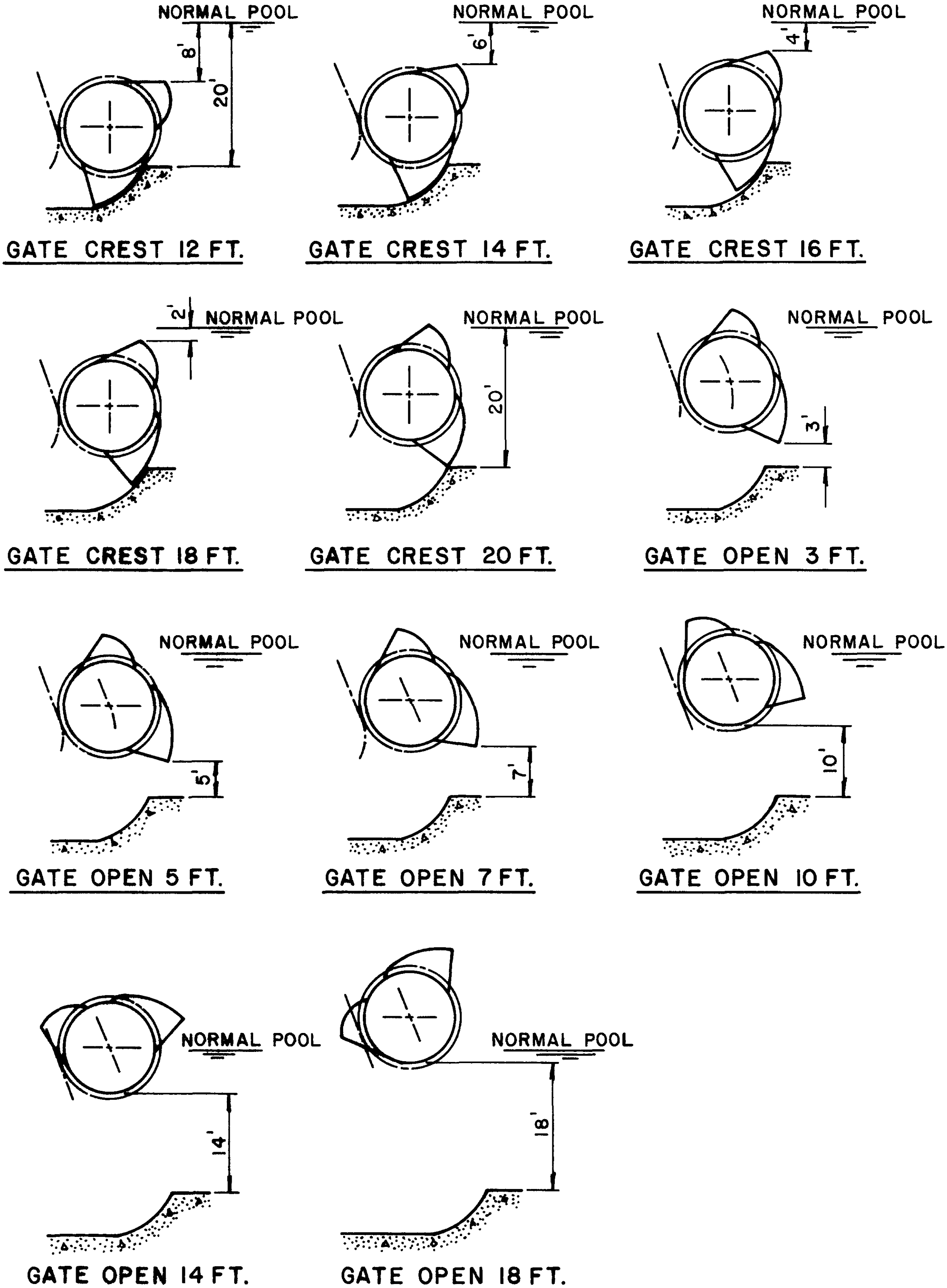

Figure 9 -- Positions of roller gates for selected openings (Modified from USCE, 1940, Figure 35).

The computed coefficients and the results of the measurements made in the roller gates at Dam 14 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 orifice flow equation (2) and substituting equation 11 for the discharge coefficient, C_{gs}. The resulting equation relating the discharge (Q) to the gate opening (h_g) and the static headwater ($h_1 - h_3$) is:

$$Q = 537\ h_g\ (h_1 - h_3)^{0.5} \qquad (13)$$

where $h_1 - h_3$ is the difference between the pool and tailwater gage readings. This equation is also applicable to submerged orifice flow in the roller gates at Lock and Dam 11 with the gates open less than 7.0 feet.

An equation for computing discharge for orifice flow when the roller gates are open 7.0 feet or greater and h_3/h_g is less than 1.9 feet was developed using the orifice flow equation (2) and substituting equation (12) for the discharge coefficient, C_{gs}. The resulting equation, relating the discharge (Q) to the tailwater (h_3), submergence ratio (h_3/h_g) and the static headwater ($h_1 - h_3$) is:

$$Q = 3{,}370\ h_3\ (h_3/h_g)^{-3.79}\ (h_1 - h_3)^{0.5} \qquad (14)$$

where h_3 is the tailwater gage reading plus 5.08 feet, h_g is the gage reading and $h_1 - h_3$ is the difference between the pool and tailwater gage readings. If the Dam 14 roller gates are operated within the range of allowable safe gate openings (USCE,1980, plate 31), the discharges defined by equation 14 would not become effective (table 5). The allowable safe gate openings for the Dam 14 roller gates are established at a much lower discharge than those for Dam 11.

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. Discharge coefficient-headwater relations were originally developed in corroboration with the Lock and Dam 11 coefficients. However, the coefficient-headwater relation for Lock and Dam 14 is published separately in this report and is modified slightly from that shown in the Lock and Dam 11 report. The discharges computed by either development are the same, however, the relation shown in figure 10 of this report defines the coefficients more accurately for the Lock and Dam 14 roller gates.

The resulting equation, relating the discharge coefficient to the headwater (h_{1s}) is:

$$C_{sw} = 9.6\ (h_{1s})^{-0.50} \tag{15}$$

where h_{1s} = Gage reading + 0.17 + (pool stage - 14.92)

The correction to the gage readings was derived from the observed gage reading at the point of zero flow.

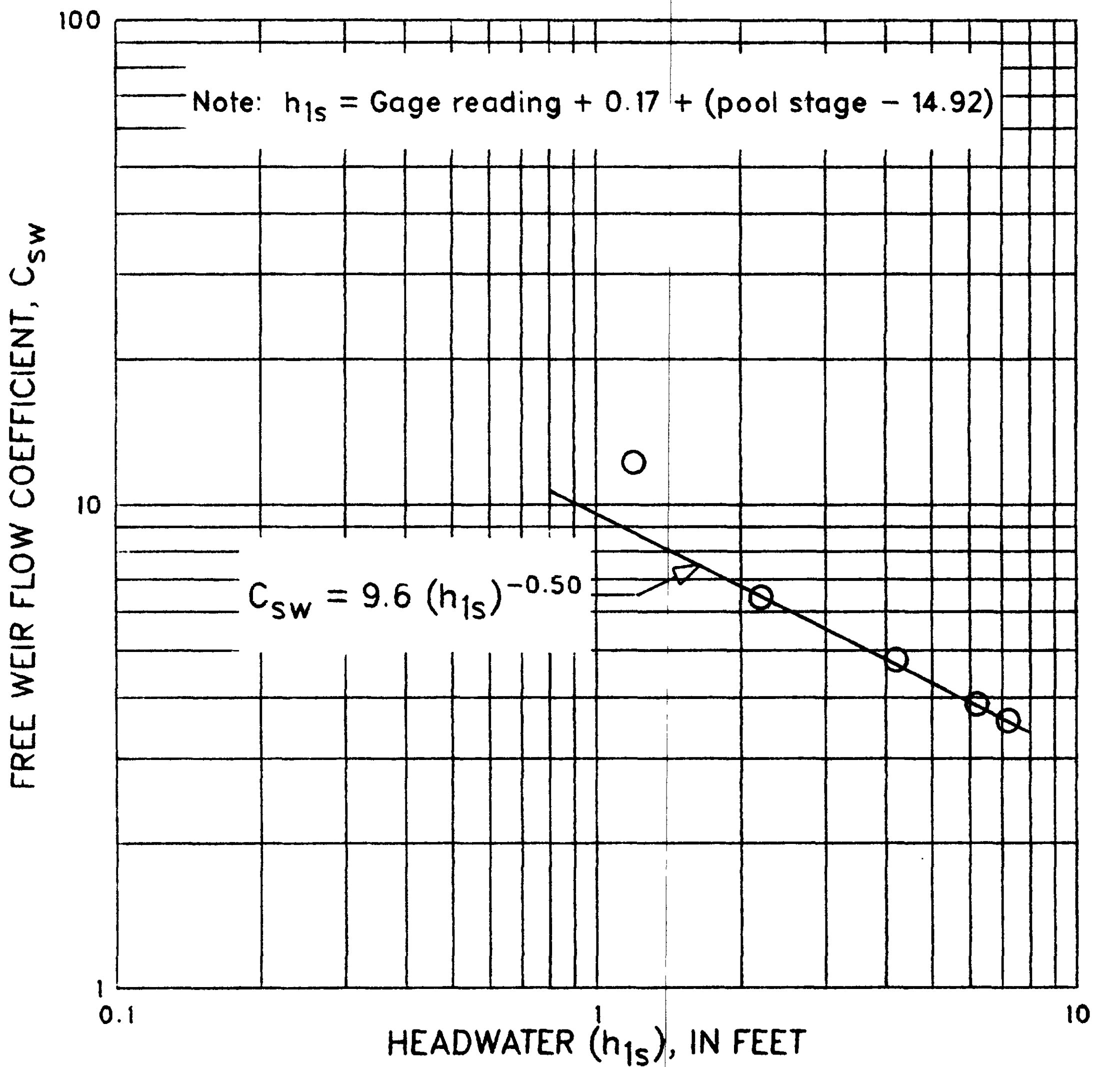

Figure 10. – Free weir flow coefficient–headwater relation for roller gates in submerged position for Mississippi River Lock and Dam 14.

Free Weir Discharge Equation

An equation for computing discharge for free weir flow for the roller gates in a submerged position was developed using the free weir flow equation (5) and substituting the above equation (15) for the discharge 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:

$$Q_s = 960\ h_{1s} \qquad (16)$$

where h_{1s} is as defined for equation 15 above. The discharge measurements made at Locks and Dams 11, 12 and 13 are also shown in figure 11.

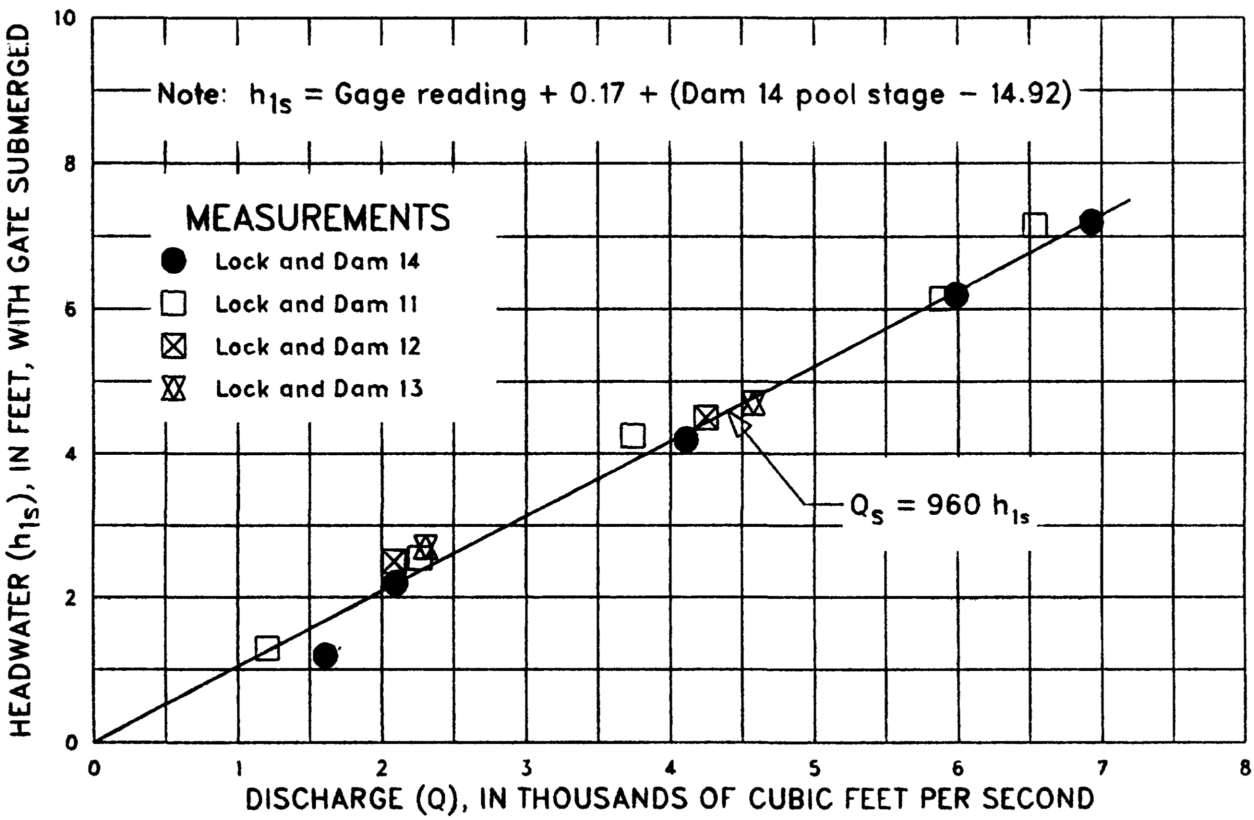

Figure 11. – Discharge–headwater relation for free weir flow for roller gates in submerged position, Mississippi River Lock and Dam 14.

DISCHARGE EQUATIONS AND RATINGS

The discharge equations applicable to the control gates when Dam 14 is in operation have been compiled and listed in table 3.

Rating tables for both the tainter and roller gates were developed for the predominant flow regime of submerged-orifice flow when the Dam is in operation. These ratings, tables 4 and 5, list discharges for tailwater stages at 1 foot increments and gate openings at 0.5 foot increments and are applicable only with the upstream pool stage at 14.92 feet (h_1 = 20.00 feet). Discharges for any other headwater, tailwater, and gate opening relationships encountered can easily be computed using the applicable equations in table 3 with a small programable computer.

Discharge rating curves for submerged orifice flow at selected gate openings (h_g) for the tainter and roller gates, prepared from laboratory tests on hydraulic models of gates are shown in figures 12 and 13. Corresponding discharge rating curves defined by the methods outlined in this report are shown for comparison. Discharges defined by the 2 methods for the tainter gates are within about 20 percent. Discharges defined by the 2 methods for the roller gates are generally within about 10 percent for gate openings of 6 feet or less. Large deviations occur between the ratings as the gates are opened greater than 7.0 feet.

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 14. Discharges generally were close to those in Plan A until the roller gate openings exceeded 7 feet at which time the discharges increased to 16 percent greater than those in Plan A.

Table 3. Summary of discharge equations for control gates at Mississippi River Lock and Dam 14.

Equation number	Flow regime	Equation of discharge
For tainter gate flow:		
(10)	Submerged orifice	$Q = 400\ h_3\ (h_3/h_g)^{-0.93}\ (h_1 - h_3)^{0.5}$
For roller gate flow:		
(13)	Submerged orifice $h_g < 7.0$ or ≥ 7.0 when $h_3/h_g > 2.4$	$Q = 537\ h_g\ (h_1 - h_3)^{0.5}$
(14)	Submerged orifice $h_g \geq 7.0$ and $h_3/h_g < 2.4$	$Q = 3{,}370\ h_3\ (h_3/h_g)^{-3.79}\ (h_1 - h_3)^{0.5}$
(16)	Free weir*	$Q_s = 960\ h_{1s}$

Note: The approach velocity head is included in $(h_1 - h_3)$.

Q = Discharge, in cubic feet per second
h_1 = Pool stage + 5.08 feet
h_3 = Tailwater stage + 5.08 feet
h_g for tainter gages = gage reading + gage indicator correction, e (fig. 5).
(average e for all the tainter gates = -0.07 foot)
h_g for roller gates = gage reading
* For free weir flow over roller gate crest: h_{1s} = gage reading + 0.17 + (pool stage - 14.92)

Table 4. Discharge rating table for submerged-orifice flow for a single tainter gate at Mississippi River Lock and Dam 14 with upstream pool stage of 14.92 feet.

GAGE READING (feet)	Tainter gate discharge, in ft³/s, for tailwater stage, in feet, indicated. 4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
.5	704	676	645	611	575	534	489	439	380
1.0	1440	1380	1320	1250	1180	1090	1000	899	779
1.5	2150	2070	1970	1870	1760	1630	1500	1340	1160
2.0	2840	2730	2610	2470	2320	2160	1980	1770	1540
2.5	3520	3380	3230	3060	2880	2670	2450	2200	1900
3.0	4190	4020	3840	3640	3420	3180	2920	2610	2270
3.5	4850	4660	4450	4220	3960	3690	3380	3030	2620
4.0	5510	5290	5050	4790	4500	4180	3830	3440	2980
4.5	6160	5910	5640	5350	5030	4670	4280	3840	3330
5.0	6800	6530	6230	5910	5550	5160	4730	4240	3680
5.5	7440	7140	6820	6460	6080	5650	5170	4640	4020
6.0	8080	7750	7400	7020	6600	6130	5620	5040	4360
6.5	8710	8360	7980	7560	7110	6610	6060	5430	4710
7.0	9340	8960	8560	8110	7620	7090	6490	5820	5050
7.5	9960	9560	9130	8650	8130	7560	6930	6210	5380
8.0	10600	10200	9700	9190	8640	8030	7360	6600	5720
8.5	11200	10800	10300	9730	9150	8500	7790	6980	6050
9.0	*	11300	10800	10300	9650	8970	8220	7370	6390
9.5	*	11900	11400	10800	10200	9440	8650	7750	6720

* Free-orifice flow conditions exist at indicated tailwater stage and gage readings.

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

Discharges for table 4 were computed using equation:

$$(10) \quad Q = 400\, h_3 (h_3/h_g)^{-0.93} (h_1 - h_3)^{0.5}$$

where h_g = gage reading + (average e = -0.07)
h_1 = 20.00 feet (14.92 + 5.08)
h_3 = tailwater stage + 5.08 feet

Table 5. Discharge rating table for submerged-orifice flow for a single roller gate at Mississippi River Lock and Dam 14 with upstream pool stage of 14.92 feet.

GAGE READING (feet)	Roller gate discharge, in ft³/s, for tailwater stage, in feet, indicated.								
	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
.5	887	846	802	756	706	653	596	532	459
1.0	1770	1690	1600	1510	1410	1310	1190	1060	918
1.5	2660	2540	2410	2270	2120	1960	1790	1590	1380
2.0	3550	3380	3210	3020	2830	2610	2380	2130	1840
2.5	4440	4230	4010	3780	3530	3270	2980	2660	2290
3.0	5320	5070	4810	4530	4240	3920	3570	3190	2750
3.5	6210	5920	5610	5290	4940	4570	4170	3720	3210
4.0	7100	6770	6420	6050	5650	5230	4760	4250	3670
4.5	7990	7610	7220	6800	6360	5880	5360	4780	4130
5.0	8870	8460	8020	7560	7060	6530	5960	5320	4590
5.5	9760	9300	8820	8310	7770	7190	6550	5850	5050
6.0	10600	10100	9620	9070	8480	7840	7150	6380	5510
6.5	11500	11000	10400	9820	9180	8490	7740	6910	5960
7.0				*14500	*10800	9150	8340	7440	6420
7.5					*14100	*10600	8930	7970	6880
8.0						*13500	*10200	8500	7340
8.5							*12800	*9580	7800
9.0								*11900	*8670
9.5									*10600

Note: Discharges greater than those underlined may exceed those allowable for safe gate operation (USCE, 1980, plate 32).

* Discharges computed using equation 14.

Discharges for table 5 were computed using equations:

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

(14) $$Q = 3{,}370\ h_3 (h_3/h_g)^{-3.79} (h_1 - h_3)^{0.5}$$

where h_g = gage reading
h_1 = 20.00 feet (14.92 + 5.08)
h_3 = tailwater stage + 5.08 feet

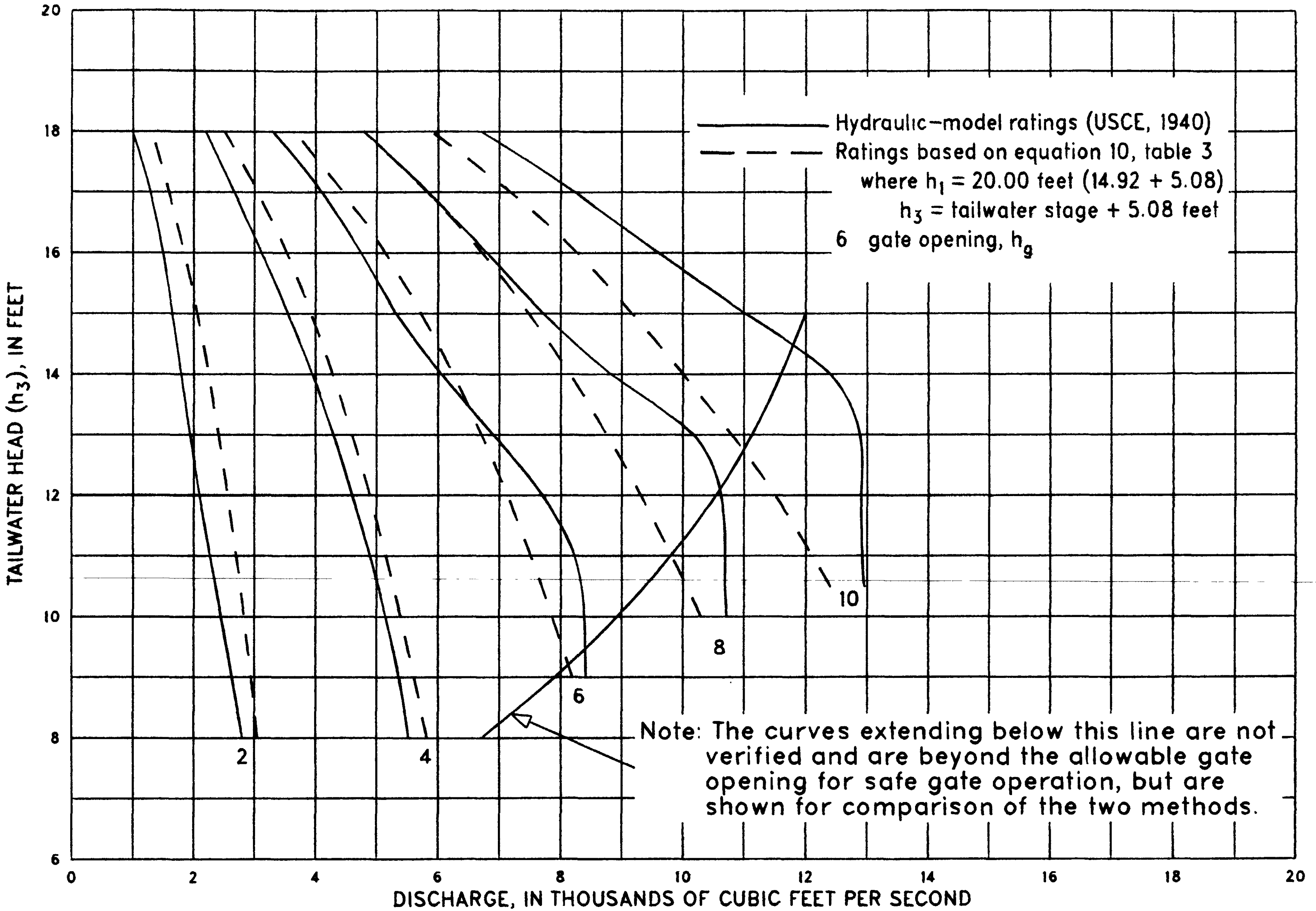

Figure 12. – Discharge ratings for submerged orifice flow for a single tainter gate at Mississippi River Lock and Dam 14 compared to hydraulic–model ratings.

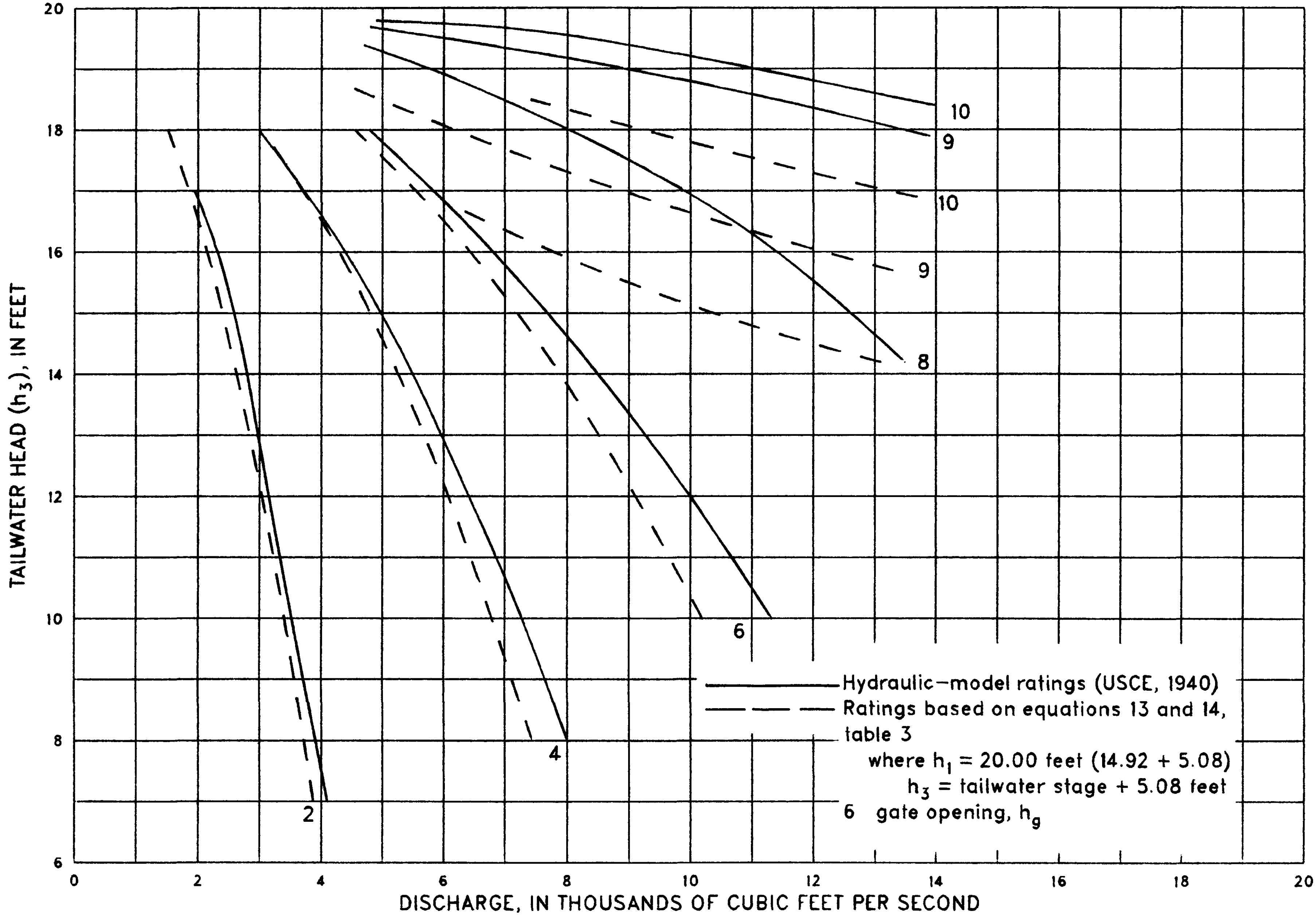

Figure 13 – Discharge ratings for submerged orifice flow for a single roller gate at Mississippi River Lock and Dam 14 compared to hydraulic–model ratings.

MISSISSIPPI RIVER LOCK AND DAM 14
GATE OPERATION SCHEDULE PLAN A FOR CONTROLLED TAILWATER STAGES

(A)	Discharge in ft³/s	Tail-water stage (feet)	Head in feet	Gate opening, in feet, for gate indicated																
				Tainter				Roller				Tainter								
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
14,100	12,500	4.0	10.9	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
23,300	22,000	4.2	10.7	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5
28,000	27,500	4.4	10.5	0.5	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5
32,500	32,000	4.6	10.3	0.5	1.0	1.0	1.0	1.5	2.0	2.0	2.0	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	0.5
37,200	37,000	4.8	10.1	0.5	1.0	1.5	1.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.0	1.0	0.5
40,700	41,000	5.0	9.9	0.5	1.0	1.5	1.5	2.0	2.5	2.5	2.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0.5
45,000	45,500	5.2	9.7	0.5	1.0	1.5	2.0	2.5	3.0	3.0	3.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0.5
49,300	50,000	5.4	9.5	0.5	1.5	2.0	2.0	3.0	3.0	3.0	3.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	0.5
54,300	54,400	5.6	9.3	1.0	2.0	2.0	2.5	3.0	3.0	3.5	3.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0
57,200	57,800	5.8	9.1	1.0	2.0	2.5	2.5	3.0	3.5	3.5	3.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	1.0
61,800	62,300	6.0	8.9	1.5	2.5	2.5	2.5	3.5	3.5	3.5	3.5	2.5	2.5	2.5	2.5	2.5	2.5	2.0	2.0	1.5
65,300	66,300	6.2	8.7	1.5	2.5	2.5	3.0	3.5	4.0	4.0	4.0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.5
69,100	70,000	6.4	8.5	1.5	3.0	3.0	3.0	4.0	4.0	4.0	4.0	3.0	3.0	3.0	3.0	2.5	2.5	2.5	2.5	1.5
72,400	73,800	6.6	8.3	1.5	3.0	3.0	3.0	4.0	4.5	4.5	4.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.5	1.5
76,500	78,000	6.8	8.1	1.5	3.5	3.5	3.5	4.5	4.5	4.5	4.5	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0	1.5
80,100	81,800	7.0	7.9	1.5	3.5	3.5	3.5	4.5	5.0	5.0	5.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.0	1.5
83,800	85,500	7.2	7.7	2.0	4.0	4.0	4.0	5.0	5.0	5.0	5.0	4.0	4.0	3.5	3.5	3.5	3.5	3.5	3.5	1.5
87,800	90,000	7.4	7.5	2.0	4.0	4.0	4.0	5.0	5.5	5.5	5.5	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5	2.0
91,800	94,000	7.6	7.3	2.0	4.5	4.5	4.5	5.5	5.5	5.5	5.5	4.5	4.5	4.5	4.0	4.0	4.0	4.0	4.0	2.0
97,800	100,500	7.8	7.1	2.5	4.5	4.5	5.0	6.0	6.0	6.0	6.0	5.0	4.5	4.5	4.5	4.5	4.5	4.5	4.5	2.0
101,000	103,800	8.0	6.9	2.5	5.0	5.0	5.0	6.0	6.0	6.0	6.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	2.0
104,000	107,500	8.2	6.7	2.5	5.0	5.0	5.5	6.5	6.5	6.5	6.5	5.5	5.0	5.0	5.0	5.0	5.0	5.0	5.0	2.5
108,000	111,000	8.4	6.5	2.5	5.5	5.5	5.5	6.5	6.5	6.5	6.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	3.0
111,000	115,000	8.6	6.3	2.5	5.5	6.0	6.0	7.0	7.0	7.0	7.0	6.0	6.0	6.0	5.5	5.5	5.5	5.5	5.5	3.0
119,000	119,000	8.8	6.1	3.0	6.0	6.0	6.0	7.0	8.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	3.0
130,000	122,500	9.0	5.9	3.0	6.0	6.0	6.5	8.0	8.0	8.0	8.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	3.0
132,000	126,000	9.2	5.7	3.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	7.0	7.0	7.0	7.0	6.5	6.0	6.0	6.0	3.0
151,000	130,000	9.4	5.5	3.0	7.0	7.0	7.0	9.0	9.0	9.0	8.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	6.5	3.0
161,000	139,000	9.6	5.3	3.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0	8.0	8.0	8.0	8.0	8.0	8.0	7.5	7.0	3.0
161,000	142,000	9.8	5.1	4.0	8.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	4.0

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

Table 6. Comparison of rating discharges to flow of Lock and Dam 14 Gate Operation Schedule Plan A. [Modified from USCE, 1980, plate 29]

CONCLUSIONS

Current-meter discharge measurements made in the forebays of the tainter and roller gates of Lock and Dam 14 were used to develop discharge coefficients and equations of discharge for submerged-orifice flow for all the gates and free-weir flow for the roller gates in a submerged position.

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

Discharge rating tables were developed for discrete combinations of downstream pool elevations and gate openings for submerged-orifice flow which is the predominant flow regime when the dam is in operation.

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