DISCHARGE RATINGS FOR CONTROL GATES
AT MISSISSIPPI RIVER LOCK AND DAM 20,
CANTON, MISSOURI

By Albert J. Heinitz

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information, write to:

District Chief
Water Resources Division
P.O. Box 1230
Iowa City, Iowa 52244

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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	
$>$	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 20, CANTON, MISSOURI

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 20, at Canton, Missouri, were developed from current-meter discharge measurements made in the forebays of the gate structures. Methodology is given to accurately compute the gate openings of the tainter gates. Discharge coefficients, in equations that express discharge as a function of tailwater head, forebay head, and height of gate opening, were determined for conditions of submerged-orifice flow. A comparison 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.

INTRODUCTION

The present navigation system on the upper Mississippi River between St. Paul, Minnesota, and St. Louis, Missouri, was initiated in 1930 when Congress passed the River and Harbor Act authorizing funds for its development. This legislation provided for a navigation channel at least 9 feet deep and 400 feet wide, to be established by constructing a series of locks and dams, and maintained by channel dredging. The dams create a series of "steps" which allow towboats or other river vessels to travel upstream or downstream. Each dam controls the level of its pool and the locks lift or lower vessels from one pool to the next. Lock and Dam 20 was placed in operation July 9, 1936.

This is the eighth in a series of reports that relate to discharge ratings and hydraulic characteristics of the control gates at locks and dams on the Mississippi river. The other seven reports present similar information for Locks and Dams 11, 12, 13, 14, 16, 18 and 22 (Heinitz, 1985-86).

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 20. 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 originally developed from laboratory tests on a hydraulic model of tainter and roller gates (U.S. Army Corps of Engineers, 1940) had never been verified with field data.

The scope of the work covered in this report includes results of current-meter discharge measurements, methodology for computing tainter-gate openings, development of discharge coefficients and equations of discharge, definition of rating tables of discharge for submerged-orifice flow and a comparison of submerged-orifice flow discharges to hydraulic-model rating discharges.

Acknowledgments

This project was completed in cooperation with the U.S. Army Corps of Engineers, Rock Island District. Special acknowledgment 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 20, located at Canton, Missouri, is a unit of the Inland Waterway Navigation System of the upper Mississippi River Basin. The part of the navigation system within the Rock Island District (U.S. Army Corps of Engineers, 1980, pl. 1) is shown in figure 1.

FLOW-CONTROL STRUCTURES

Three types of flow-control structures are present at Lock and Dam 20. These are tainter gates, roller gates and the navigation lock. Detailed theoretical as well as physical descriptions of these flow-control structures are beyond the scope of this report, and, therefore, are not included. Readers interested in this subject are referred to Davis and Sorensen (1952), Rouse (1949), Creager and Justin (1950) and King and Brater (1954). The hydraulic conditions that define each flow regime and the corresponding generalized steady-state discharge equations for the flow-control structures are summarized in table 1. An important parameter common to all types of flow-control 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.

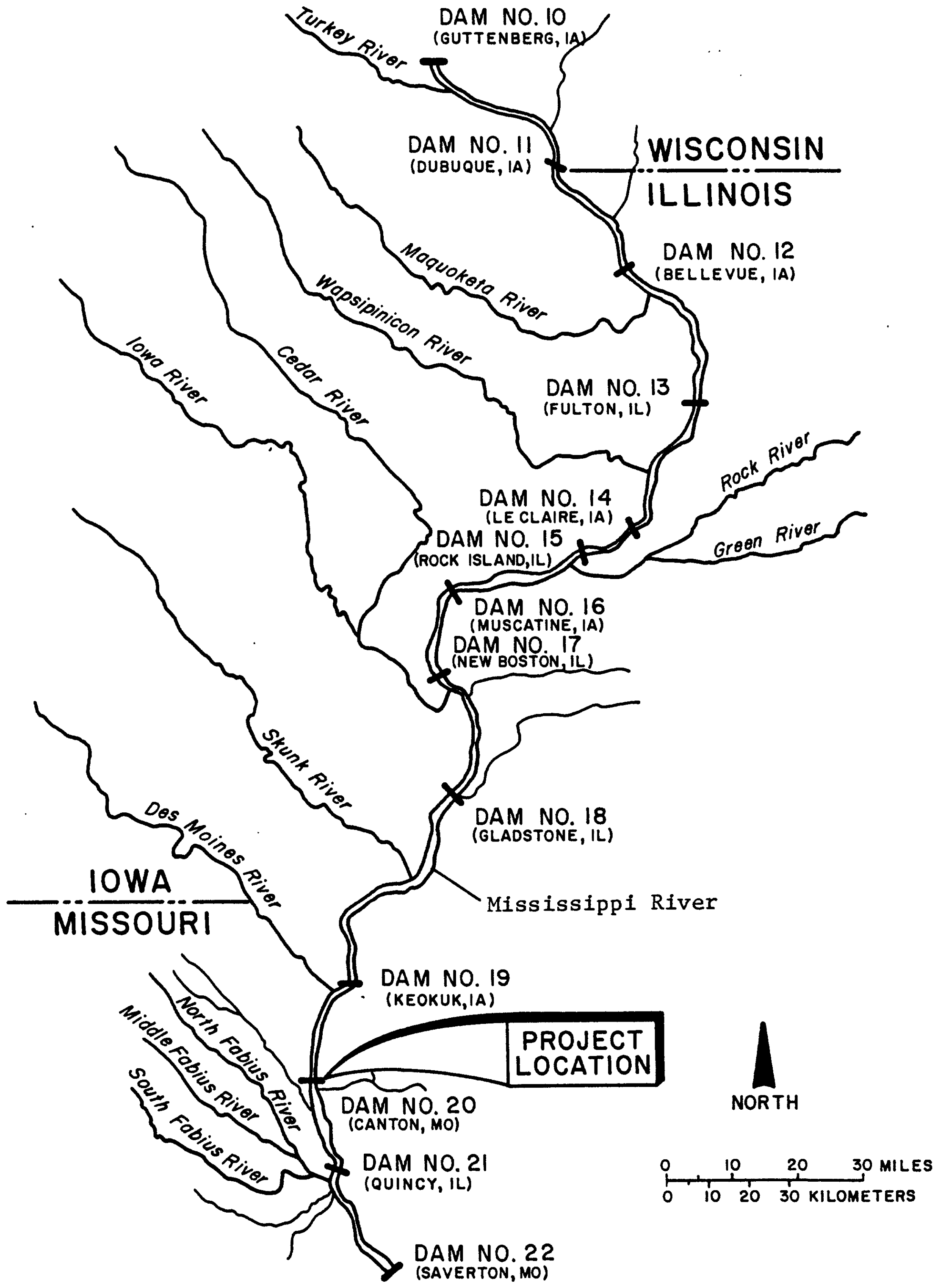


Figure 1.--Inland Waterway Navigation System of the upper Mississippi River basin (modified from U.S. Army Corps of Engineers, 1980, pl. 1).

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. 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 20 contains 40 tainter gates and 3 roller gates for controlling the pool elevation upstream from the dam. Each tainter gate is 40 feet wide and 20 feet high and operates between piers with 40-foot clear openings. Each roller gate is 60 feet wide and 20 feet high and operates between piers with 60-foot clear openings. Twelve 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 20 are in operation (U.S. Army Corps of Engineers, 1980, pl. 28). Free-orifice flow would very rarely occur at a low-head, navigation-type structure such as Dam 20 and would not occur at the dam under normal operating conditions. Six of the tainter gates (1, 2, 17, 18, 42 and 43) are of the submergible type, capable of being lowered 3 feet below the normal crest elevation. The remainder of the tainter gates are of the non-submergible type and close on the curved steel channels embedded in the concrete sills. The roller gates are of the non-submergible type.

Free-weir flow would occur at the submergible tainter gates when they are in the submerged position as the flow would occur over the crest of the gates.

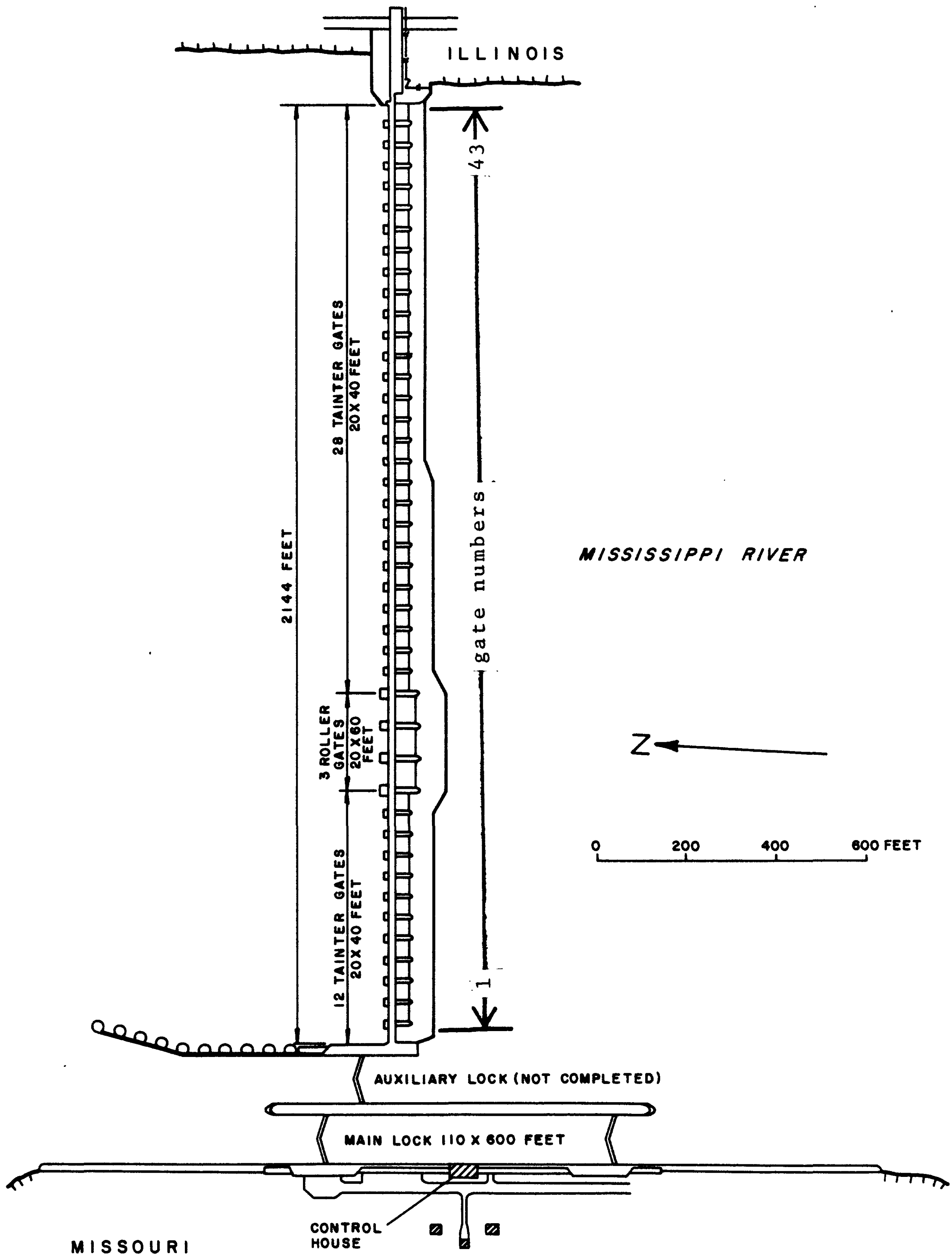
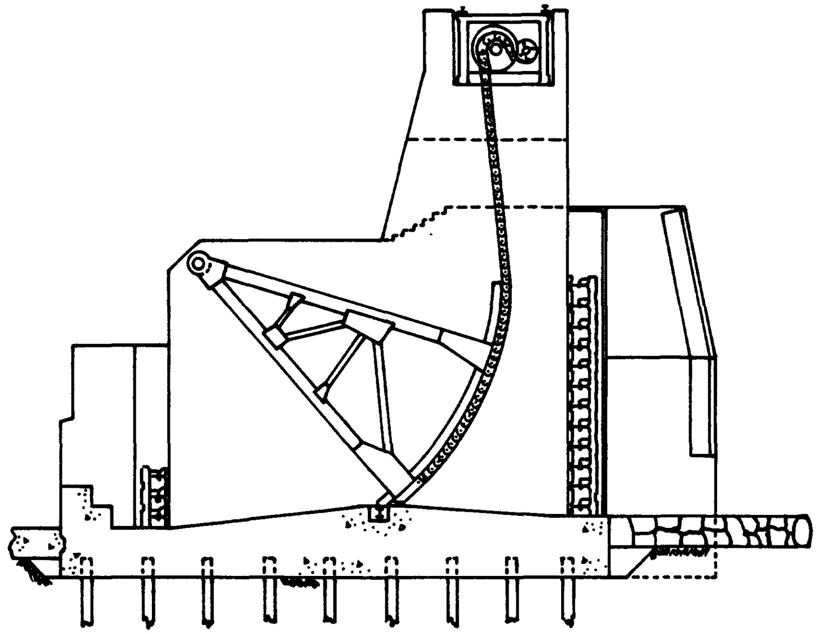
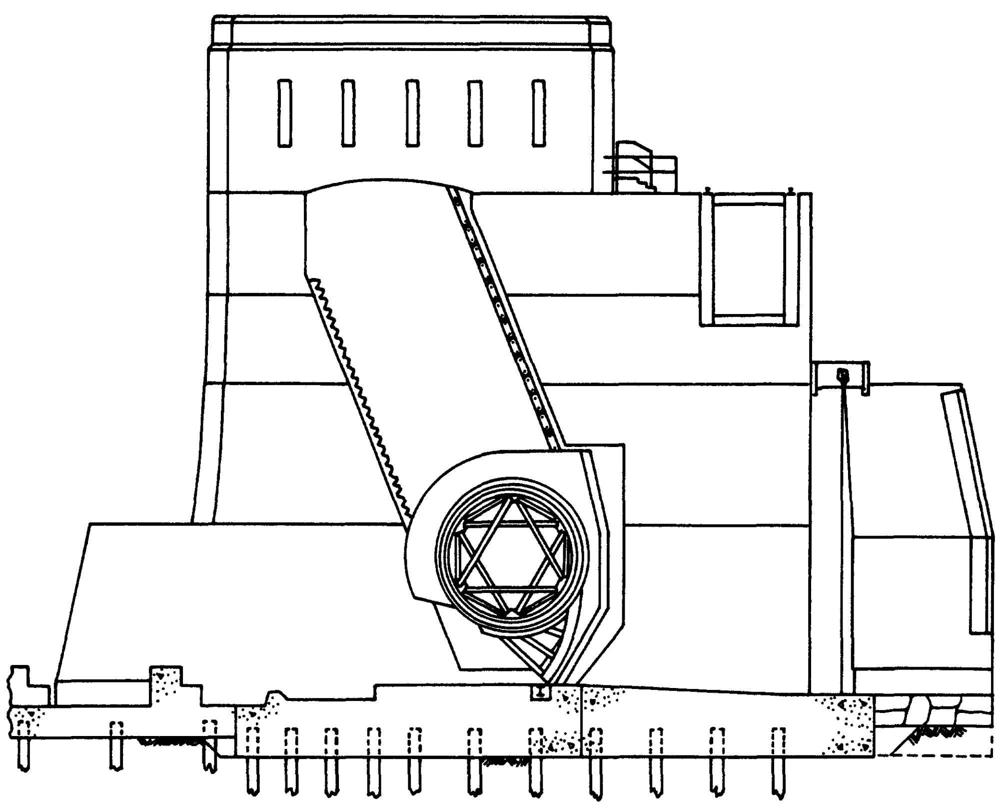


Figure 2.--Location of flow-control structures (modified from U.S. Army Corps of Engineers, 1980, pl. 2).



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).

These gates are used to release accumulated trash through the gates and generally are not operated in the submerged position when the dam is in operation. The free-weir flow coefficients were not defined for the submergible gates. The remainder of the gates are non-submergible, therefore, flow would not occur over the gate crests. Submerged-weir flow for all the gates would occur over the gate sills with the gates raised above the water surface when the dam is out of operation. This type flow is not evaluated in this report.

Operation of the control gates for maintaining the pool elevation is based on a study (U.S. Army Corps of Engineers, 1980) conducted to determine the optimum use of the dam for river flowage, conservation interests, and towboat service. Operation "Plan CD" (U.S. Army Corps of Engineers, 1980, pl. 28) was put in operation with the 1941 navigation season. The plan allows high water to recede naturally with the gates at the dam raised above the water surface until elevation 475.5 feet (stage = 7.0) is reached on the pool gage. The dam is then operated in order to maintain established stages at the Gregory Landing gage and at the lower Keokuk Lock and Dam 19 gage.

Dam 20 is a run-of-the-river dam and is not operated to store water for flood control purposes. The pool is maintained between stages 8.5 and 13.0 feet during normal operation. During flood periods, the gates are raised out of the water allowing run-of-the-river flow to occur. During the winter operation period when navigation is halted through Lock and Dam 20, the pool is maintained within the winter operating stage of 10.5 to 11.5 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. Discharge measurements were made from the upstream edge of the roadway which is about 22 feet upstream from the downstream edge of the tainter-gate sills and about 27 feet upstream from the roller gates. The distance of the measuring equipment from the orifice and control structure appeared to be adequate to allow accurate measurements to be made. Some velocity measurements were made to define vertical velocity curves and to verify the standard 0.2 and 0.8 method of velocity observation. The measurements were made with equipment normally used for measuring large streams. Velocity was measured using a type AA current meter suspended with Columbus-type sounding weights (50-150 pounds) from a collapsible crane (Rantz and others, 1982). A 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 53 measurements of discharge ranging from 616 to 9,910 cubic feet per second in a gate were made in the forebays of the tainter and roller gate structures of Lock and Dam 20. 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 measurements were made in 21 of the tainter gate bays and all 3 of the roller gate bays. 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 20

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	9-10-85	18.04	12.94	2.00	2.14	1,090	- 3.5	6.05	0.116	SO
3	6-03-85	18.48	14.94	3.21	3.30	1,820	- 1.1	4.53	0.202	SO
4	6-03-85	18.41	14.94	4.04	4.20	2,470	+ 5.6	3.56	0.276	SO
4	6-05-85	18.80	14.90	6.04	6.32	4,090	+ 8.2	2.36	0.433	SO
7	9-09-85	18.10	12.99	2.05	2.10	1,450	+ 3.6	6.19	0.154	SO
8	9-09-85	18.10	12.98	1.87	1.96	1,320	+ 1.5	6.62	0.140	SO
10	9-09-85	18.13	13.01	2.05	2.09	1,310	- 5.8	6.22	0.139	SO
10	6-04-85	18.31	14.61	3.00	3.05	1,790	+ 2.9	4.79	0.198	SO
11	6-03-85	18.40	14.94	3.86	3.91	2,300	+ 6.0	3.82	0.258	SO
11	6-04-85	18.31	14.61	4.85	4.94	2,930	+ 2.4	2.96	0.325	SO
13	9-09-85	18.10	12.98	2.00		1,800	+ 3.4	6.49	0.127	SO
13	6-24-86	18.40	16.65	11.00		6,880	- 8.0	1.51	0.649	SO
13	6-25-86	18.90	17.00	11.50		8,620	- 0.9	1.48	0.765	SO
13	6-25-86	18.84	16.98	12.00		9,910	- 2.8	1.42	0.890	SO
14	9-09-86	18.10	12.98	2.00		1,680	- 3.4	6.49	0.119	SO
14	9-09-86	18.10	12.98	3.00		2,670	+ 2.3	4.33	0.197	SO
14	6-03-85	18.44	14.94	4.00		2,890	+ 0.3	3.74	0.215	SO
14	6-03-85	18.56	14.94	5.00		3,560	- 2.7	2.99	0.260	SO
14	6-24-86	18.41	16.67	10.00		5,410	+ 4.6	1.67	0.511	SO
15	9-09-85	18.13	13.01	2.00		1,710	- 1.7	6.50	0.121	SO
15	6-03-85	18.56	14.94	3.00		2,110	- 4.1	4.98	0.154	SO
15	6-03-85	18.55	14.94	4.00		2,780	- 5.1	3.74	0.204	SO
15	6-25-86	18.83	16.97	8.00		4,130	- 1.7	2.12	0.371	SO
15	6-24-86	18.42	16.68	9.00		4,730	+ 3.5	1.85	0.447	SO
17	9-09-85	18.15	13.00	2.05	2.19	1,160	- 0.9	5.94	0.122	SO
17	6-04-85	18.32	14.62	2.07	2.20	973	- 0.3	6.64	0.108	SO
17	6-04-85	18.32	14.60	3.00	3.15	1,480	- 0.7	4.64	0.164	SO
17	6-03-85	18.52	14.94	5.04	5.22	2,550	- 3.0	2.86	0.281	SO
17	6-25-86	18.72	16.90	7.00	7.20	2,730	+ 2.2	2.35	0.373	SO
17	6-25-86	18.94	17.04	7.88	8.10	3,080	- 1.6	2.10	0.408	SO
18	6-04-85	18.32	14.62	2.07	2.36	1,040	- 1.9	6.20	0.115	SO
18	6-04-85	18.32	14.60	3.00	3.33	1,560	- 1.9	4.38	0.173	SO
18	6-03-85	18.52	14.94	4.82	5.21	2,760	+ 5.3	2.87	0.302	SO
19	6-25-86	18.77	16.92	7.00	7.05	2,780	- 4.1	2.40	0.376	SO
19	6-25-86	18.99	17.06	7.96	7.96	3,360	0	2.14	0.442	SO
20	6-04-85	18.32	14.60	1.94	1.97	1,110	0	7.41	0.123	SO
20	6-05-85	18.80	14.92	4.04	4.11	2,440	+ 0.8	3.63	0.259	SO
20	6-25-86	18.78	16.93	7.04	7.22	2,880	- 3.4	2.34	0.390	SO
23	6-04-85	18.33	14.59	1.97	2.01	1,130	- 0.9	7.26	0.125	SO
23	6-05-85	18.80	14.93	3.93	3.96	2,270	- 2.6	3.77	0.241	SO
26	6-05-85	18.81	14.93	1.97	1.92	1,070	- 3.2	7.78	0.113	SO
29	6-05-85	18.81	14.93	2.00	2.08	1,250	+ 4.2	7.18	0.132	SO
30	6-25-86	19.10	17.12	8.83	9.12	3,690	- 5.6	1.88	0.477	SO
31	6-25-86	19.09	17.11	8.88	9.20	3,620	- 8.3	1.86	0.468	SO
33	9-09-85	18.15	13.00	1.87	1.90	1,300	+ 2.4	6.84	0.137	SO
33	6-04-85	18.30	14.60	3.88	4.03	2,400	+ 3.4	3.62	0.266	SO
33	6-04-85	18.32	14.60	6.00	6.14	3,670	+ 2.2	2.38	0.406	SO
34	9-10-85	18.02	12.92	1.90	2.13	1,530	+ 7.7	6.07	0.163	SO
37	6-04-85	18.31	14.61	3.93	4.10	2,320	- 1.7	3.65	0.257	SO
37	6-04-85	18.32	14.60	6.00	6.22	3,520	- 3.0	2.35	0.389	SO
38	9-09-85	18.15	13.00	2.86	2.99	2,000	- 1.0	4.35	0.211	SO
42	9-09-85	18.15	13.01	0.90	1.23	616	+ 3.7	10.58	0.065	SO
42	9-10-85	18.03	12.93	2.00	2.32	1,210	- 2.4	5.57	0.129	SO

1/ h_1 = Pool stage + 8.50 feet.
2/ h_3 = Tailwater (T/W) stage + 8.50 feet.
3/ SO designates submerged-orifice flow.

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

The concurrent pool and tailwater stages for the measurements were obtained from the gages in the operations control building. The static-headwater head (h_1) and static-tailwater head (h_3) referenced to the gate sill are obtained by adding 8.50 feet to the stages. The stages can be referenced to sea level by adding the zero gage datum, 468.50 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 11.50 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).

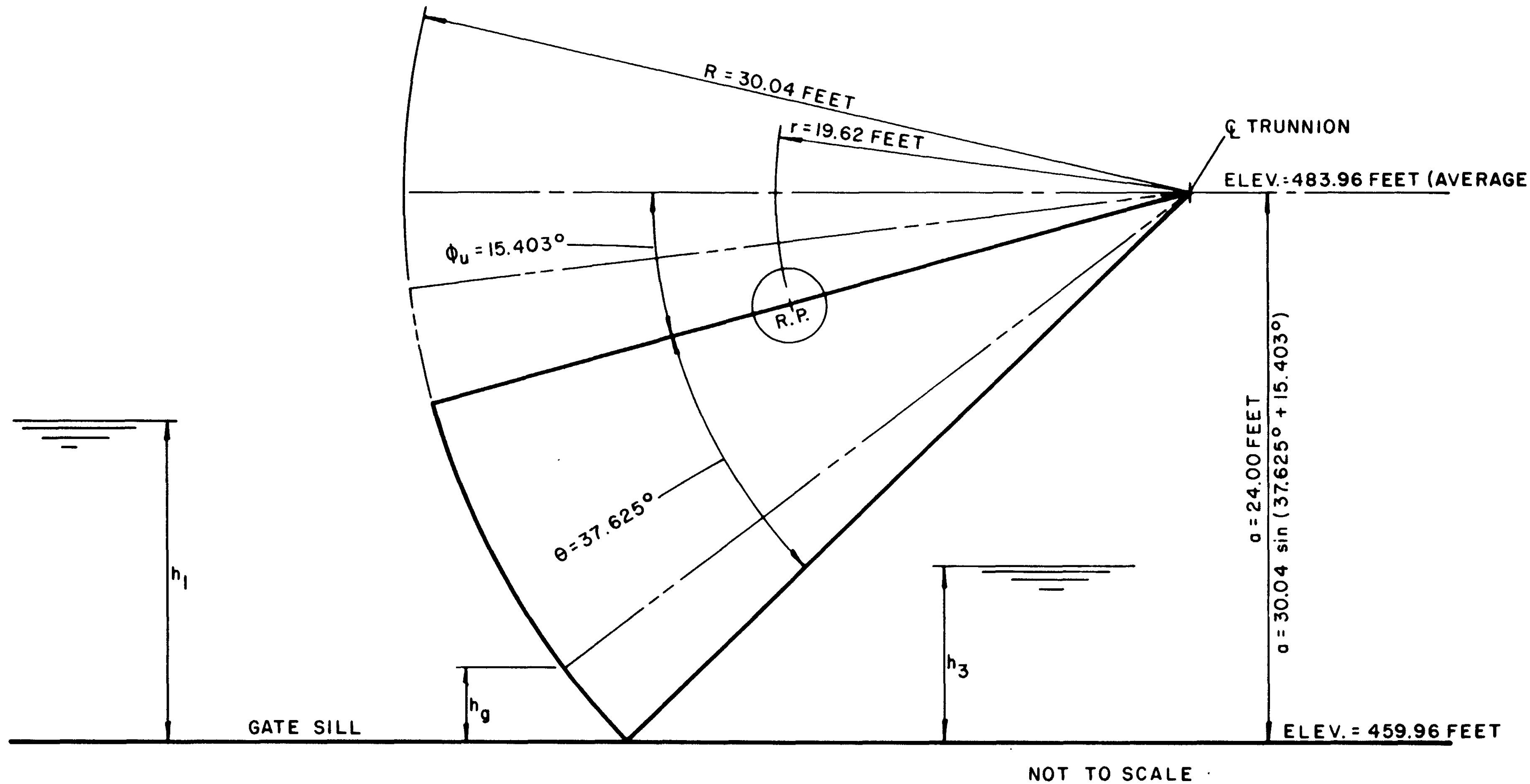
The reference point (R.P.) established for computing the gate opening, h_g, for the tainter gates on Dam 20 is a chisel mark on top of the gate arm. The R.P. is 19.62 feet from the trunnion centerline and is the same for all the tainter gates. Elevations of the R.P.'s were determined by levels from established benchmarks on the piers between the gates (U.S. Army Corps of Engineers, 1973). The gate opening, h_g, is computed from the equation:

$$h_g = 24.00 - 30.04 \sin(37.625 + \phi_u) \qquad (8)$$

where $\phi_u = \sin^{-1}$ [(Trunnion elev. - R.P. elev.)/19.62]

The terms in the equation are graphically displayed in figure 4. The average elevation of the trunnion centerline was found at 483.958 feet with variations from 483.907 to 484.014 feet.

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



$$h_g = 24.00 - 30.04 \sin(37.625° + \phi_u)$$

$$\text{where } \phi_u = \sin^{-1}\left(\frac{\text{TRUNNION ELEV.} - \text{R.P. ELEV.}}{19.62}\right)$$

Figure 4.--Details of tainter gates at Mississippi River Lock and Dam 20. See page vi for definition of symbols.

R.P. elevations of the gates in the closed position. The average angle computed for 9 gates in the closed (h_g = 0) position is 37.625 degrees (fig. 4). The maximum deviation of h_g using the average included angle of 37.625 degrees for these 9 gates is +0.021/-0.027 foot. The included angle for the submergible gates was not separately determined and may be different than that shown for the non-submergible gates.

The computed gage-indicator corrections for all the non-submergible tainter gates vary, generally in the range from +0.15 to +0.03 foot, with maximum individual corrections from +0.23 to -0.10 foot. A +0.08 foot correction was used in the computations using all the non-submergible tainter gates. The average computed gage-indicator correction for the submergible gates is +0.25 foot. These differences can be attributed primarily to error in the gage-indicator settings and to the variance of the seals on the bottom edge of the gates. The gage-indicator corrections (e) and the relation of the computed gate openings (h_g) to the 0 gage-indicator setting are shown in figure 5.

A gage indicator error of 0.10 foot will give about a 5-percent deviation in discharge from the rating discharge at the 2.50-foot gage setting. This deviation from the rating discharge increases with lower gage settings (about 10 percent at the 1.00-foot gage setting) and decreases at higher gage settings (about 3 percent at the 4.00-foot gage setting). The deviation of discharge from the rating discharge for the individual gates could be minimized by adjusting the gage indicators to more nearly reflect the computed gate opening, h_g.

GAGE–INDICATOR CORRECTION (e), IN FEET

TAINTER GATES	Gage-indicator correction (e), in feet
1	+0.04
2	+0.31
3	+0.09
4	+0.07
5	+0.04
6	+0.10
7	+0.05
8	+0.09
9	+0.05
10	+0.05
11	+0.05
12	+0.12
16	+0.07
17	+0.13
18	+0.30
19	−0.10
20	+0.03
21	+0.07
22	+0.12
23	+0.04
24	+0.05
25	+0.05
26	−0.02
27	+0.11
28	+0.03
29	+0.09
30	+0.06
31	+0.05
32	+0.03
33	+0.04
34	+0.23
35	+0.02
36	+0.10
37	+0.14
38	+0.12
39	+0.15
40	+0.11
41	0
42	+0.34
43	+0.35

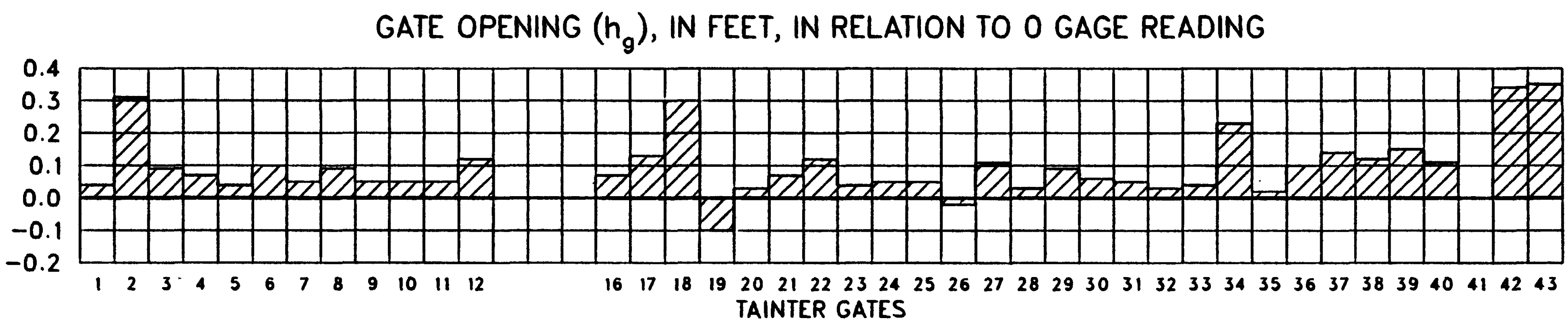


Figure 5.--Gage-indicator corrections and comparison of gate openings at 0 gage-indicator settings for tainter gates on Mississippi River Lock and Dam 20

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

For submergible gates 1, 2, 17, 18, 42 and 43

$$C_{gs} = 0.99 \ (h_3/h_g)^{-1.17} \tag{9}$$

For non-submergible gates 3-12, 16 and 19-41

$$C_{gs} = 0.97 \ (h_3/h_g)^{-1.03} \tag{10}$$

Submerged-Orifice Discharge Equations

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

For submergible gates 1, 2, 17, 18, 42 and 43:

$$Q = 318 \ h_3 \ (h_3/h_g)^{-1.17} \ (h_1 - h_3)^{0.5} \tag{11}$$

where h_g = gage reading + 0.20 foot, based on average correction for gates 1, 2, 17 and 18. The indicated correction for gates 42 and 43 is +0.34 foot, however, these two gates are seldom in operation.

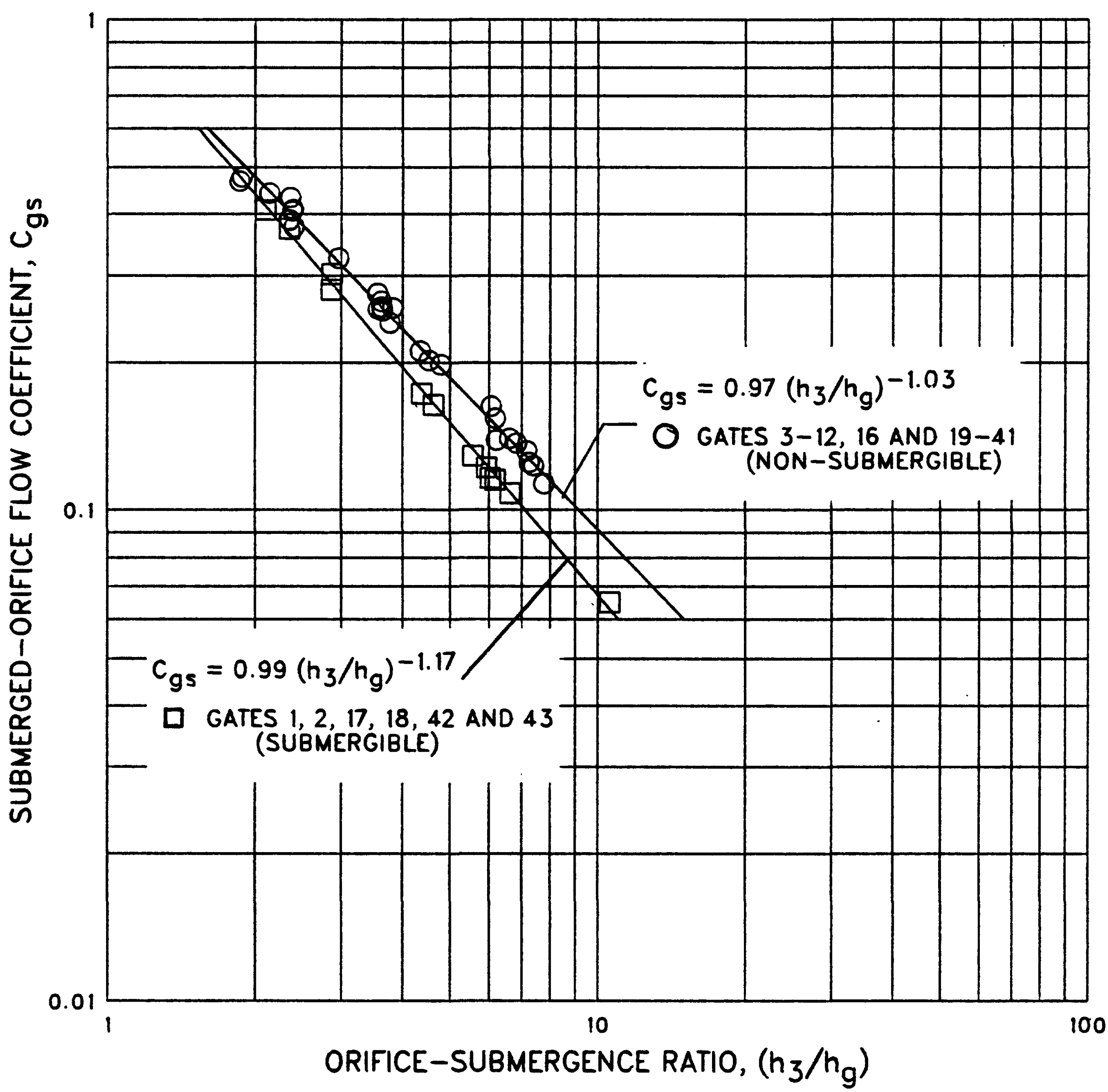


Figure 6.—Relation between submerged–orifice flow coefficient and orifice–submergence ratio for Lock and Dam 20 tainter gates

For non-submergible gates 3-12, 16 and 19-41:

$$Q = 311\ h_3\ (h_3/h_g)^{-1.03}\ (h_1 - h_3)^{0.5} \tag{12}$$

where h_g = gage reading + the gage-indicator correction (e), shown in figure 5. (The average correction, e, for the non-submergible gates is +0.08 foot).

For both equations 11 and 12, h_3 = the tailwater stage plus 8.50 feet and $(h_1 - h_3)$ = the difference between the pool and tailwater stages.

The relation of the current-meter discharge measurements made on June 3-4, 1985, to the discharge curves defined by equations 11 and 12 is shown in figure 7.

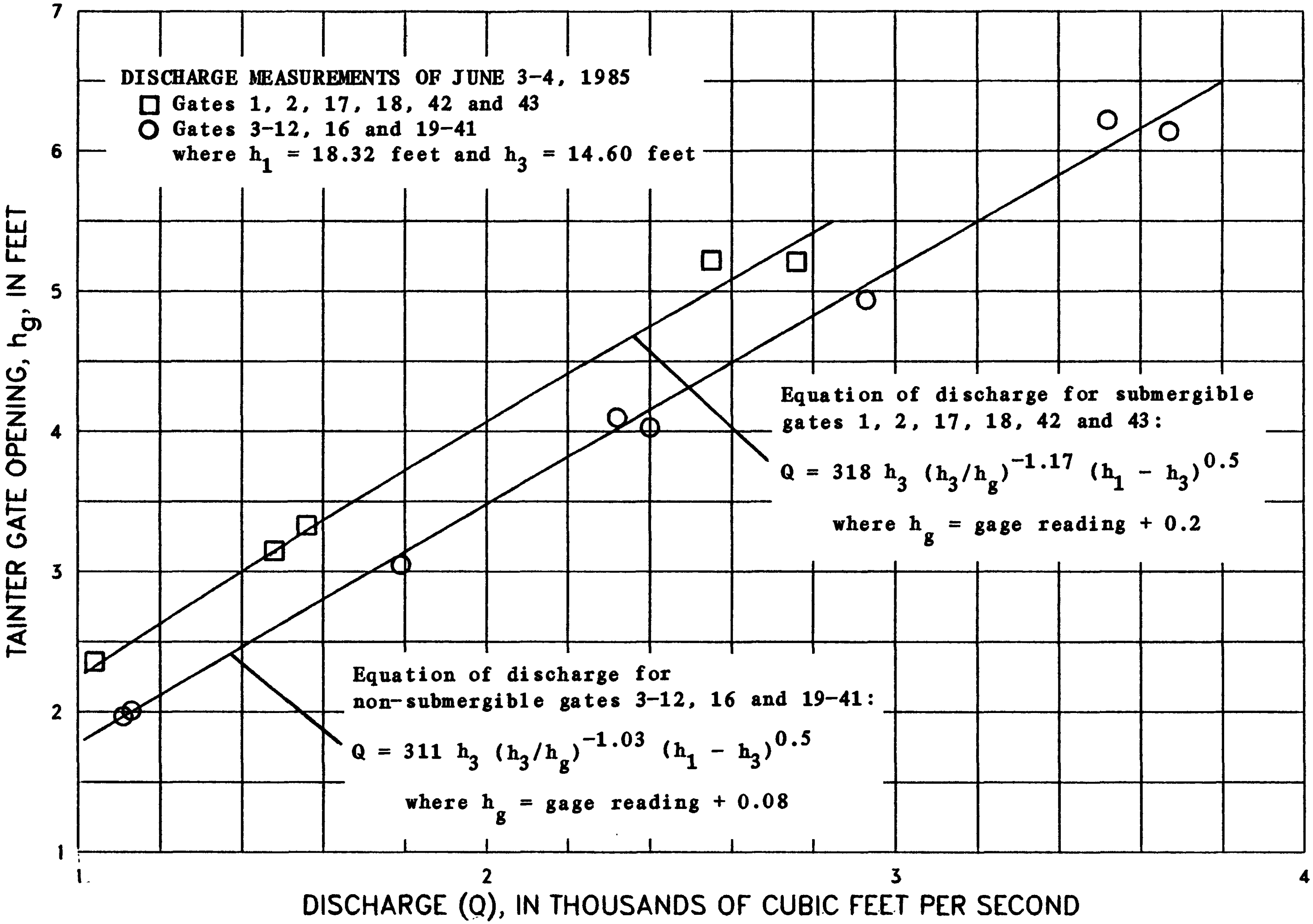


Figure 7.--Comparison of current-meter discharge measurements of June 3-4, 1985, to rating curves for tainter gates at Mississippi River Lock and Dam 20

ROLLER-GATE FLOW

Gate Opening

The gate-opening indicator marks for the roller gates (numbers 13-15) are an integral part of the operating machinery of the gate. These indicators presumably give a fairly accurate reading of the gate opening. A method for measuring the actual gate openings was not developed.

Submerged-Orifice Flow Coefficients

Discharge coefficients for submerged-orifice flow for Dam 20 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 20 is shown in figure 8. The break in the relation occurs at a point when the gate is open greater than 9 feet and the orifice-submergence ratio is less than 1.7 for the Dam 20 roller gates. The break in the relationship apparently occurs when control of flow in the roller gate transfers from the lower apron (appendage to the drum) on the roller to the drum of the gate structure. The control positions of a typical roller gate are illustrated in figure 9 and show that the effective gate opening increases significantly when control transfers from the apron to the drum when the gate is opened more than 7.0 feet. This transfer of control from the apron to the drum for the Lock and Dam 20 roller gates occurs when the gate is opened greater than 9.0 feet. The exact gate opening where the control changes has not been defined.

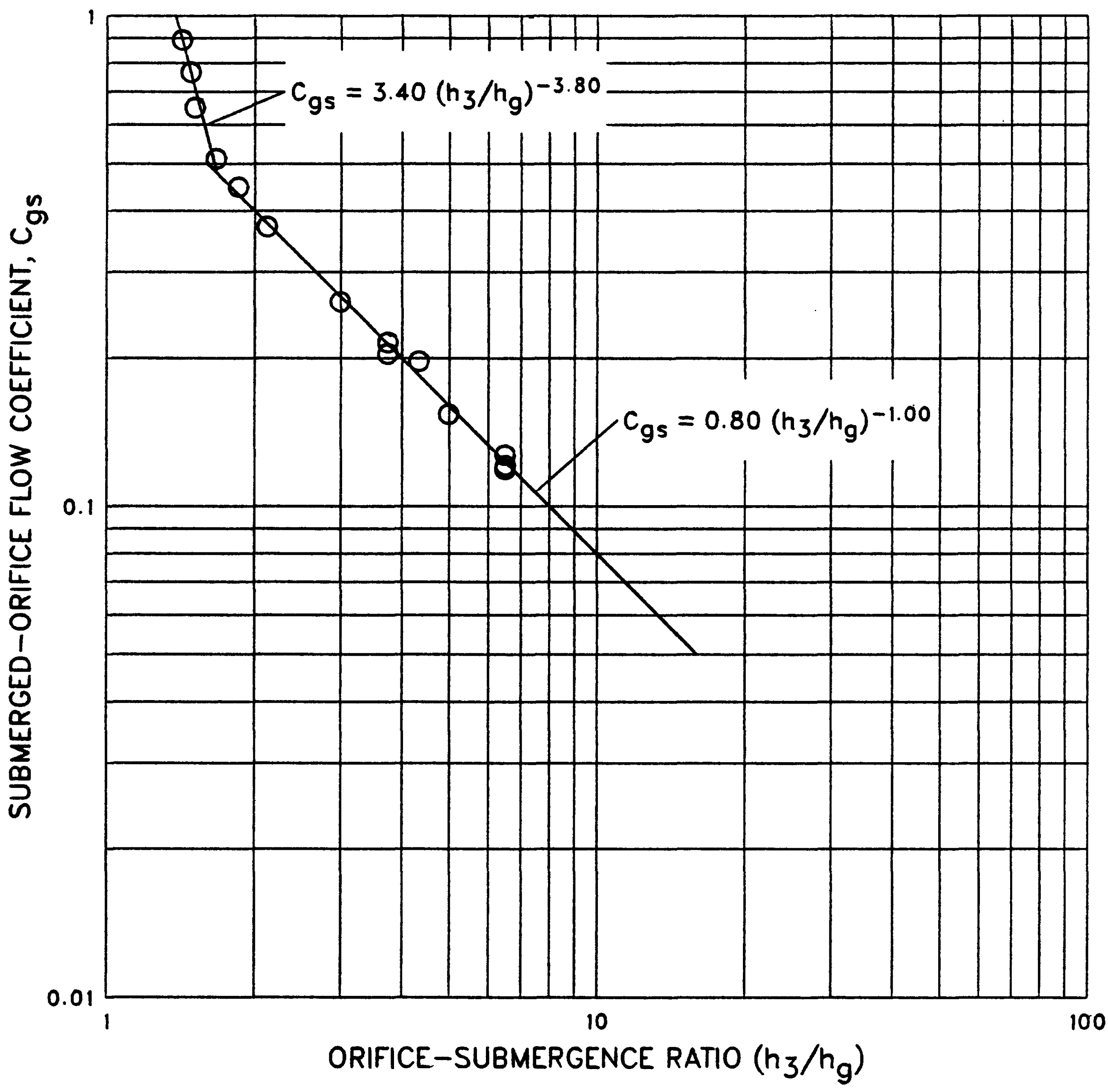


Figure 8.––Relation between submerged–orifice flow coefficient and orifice–submergence ratio for Lock and Dam 20 roller gates.

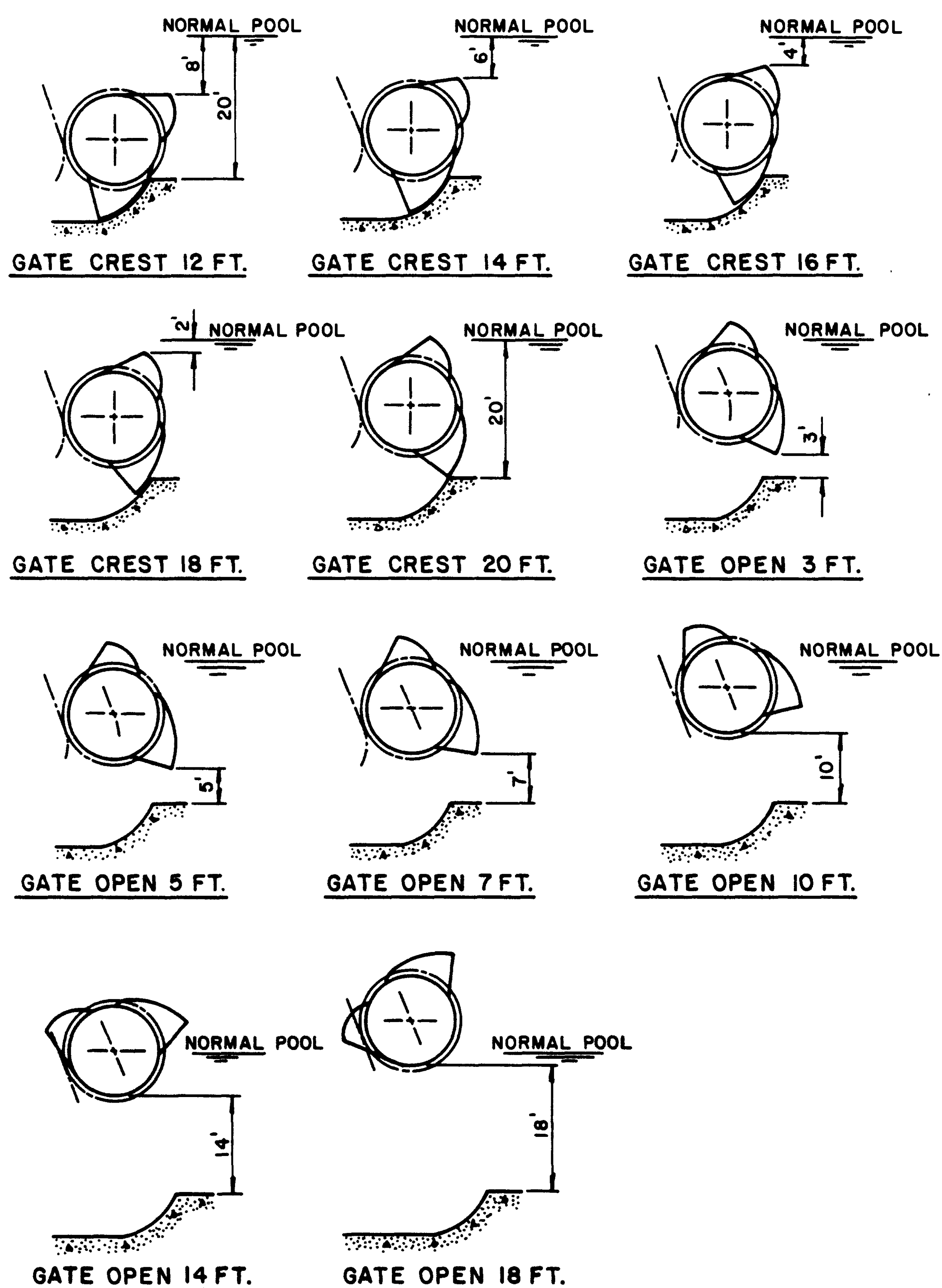


Figure 9.--Positions of roller gates for selected crests and openings (modified from U.S. Army Corps of Engineers, 1940, fig. 35).

The resulting equation, relating the submerged-orifice coefficient, C_{gs}, to the orifice-submergence ratio, h_3/h_g, for the roller gates when the gates are open 9 feet or less is defined by the equation:

$$C_{gs} = 0.80 \ (h_3/h_g)^{-1.00} \tag{13}$$

As noted by Collins (1977) and described by King and Brater (1954), many structures calibrated by the procedures outlined above are found to be independent or nearly independent of submergence. If the coefficient is independent of the submergence, the slope of the straight line relation will be -1.00 as in equation 13. When substituted for the coefficient in the submerged orifice flow equation (2), the equation reduces to the free-orifice equation (1). The average of the coefficients computed for the roller gates at Dam 20 using the free-orifice equation (1) was 0.80. This coefficient is compatible with those in King and Brater (1954, table 26) for rectangular orifices with partially suppressed contraction.

For conditions when the gates are open greater than 9 feet and the orifice-submergence ratio is less than 1.7, the submerged-orifice coefficient, C_{gs}, for the Dam 20 roller gates is defined by the equation:

$$C_{gs} = 3.40 \ (h_3/h_g)^{-3.80} \tag{14}$$

The computed coefficients and the results of the measurements made for the roller gates at Dam 20 are listed in table 2.

Submerged-Orifice Discharge Equations

An equation for computing discharge for submerged-orifice flow when the roller gates are open 9 feet or less was developed using the submerged-orifice flow equation (2) and substituting equation 13 for the discharge coefficient, C_{gs}. The resulting equation relating the discharge (Q) to the gate opening (h_g) and the static-head loss (h_1 - h_3) is:

$$Q = 385\ h_g\ (h_1 - h_3)^{0.5} \tag{15}$$

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 greater than 9.0 feet and h_3/h_g is less than 1.7 feet was developed using the submerged-orifice flow equation (2) and substituting equation 14 for the discharge coefficient, C_{gs}. The resulting equation, relating the discharge (Q) to the static-tailwater head, (h_3), orifice-submergence ratio (h_3/h_g) and the static-head loss (h_1 - h_3) is:

$$Q = 1{,}640\ h_3\ (h_3/h_g)^{-3.80}\ (h_1 - h_3)^{0.5} \tag{16}$$

where h_3 = the tailwater stage plus 8.50 feet,

h_g = the gate opening, and

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

DISCHARGE EQUATIONS AND RATINGS

The discharge equations applicable to the control gates when Dam 20 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 20 is in operation. These ratings, tables 4a, 4b and 5, list discharges for static-head loss and gate openings at 0.5-foot increments. The discharges in tables 4a and 4b were computed with a static-headwater, h_1, of 18.00 feet. Discharges for other headwaters encountered during operation of the Dam will generally be within 1 percent of those shown in the tables. Discharges for any headwater, tailwater, and gate-opening relations encountered can easily be computed using the applicable equations in table 3 with a small programable computer.

Discharge rating curves for submerged-orifice discharge at selected gate openings (h_g) for the tainter and roller gates, prepared from laboratory tests using hydraulic models of the gates, are shown in figures 10 and 11. Corresponding discharge rating curves defined by the methods outlined in this report are shown for comparison. Discharges defined by the 2 methods for each of the gate openings for the tainter gates generally are within about 20 percent. Discharges defined by the 2 methods for each of the gate openings for the roller gates generally are within about 10 percent for gate openings of 9 feet or less. Large deviations occur between the ratings as the roller gates are opened greater than 9.0 feet.

Table 3.--Summary of discharge equations for control gates at Mississippi River Lock and Dam 20

Gate	Flow regime	Equation of discharge 1/, 2/	Equation number
Tainter gates 1, 2, 17, 18, 42 and 43	Submerged orifice	$Q = 318\ h_3\ (h_3/h_g)^{-1.17}\ (h_1 - h_3)^{0.5}$	(11)
Tainter gates 3-12, 16, 19-41	Submerged orifice	$Q = 311\ h_3\ (h_3/h_g)^{-1.03}\ (h_1 - h_3)^{0.5}$	(12)
Roller gates	Submerged orifice $h_g \leqslant 9.0$ or > 9.0 when $h_3/h_g > 1.7$	$Q = 385\ h_g\ (h_1 - h_3)^{0.5}$	(15)
Roller gates	Submerged orifice $h_g > 9.0$ and $h_3/h_g < 1.7$	$Q = 1{,}640\ h_3\ (h_3/h_g)^{-3.80}\ (h_1 - h_3)^{0.5}$	(16)

1/ Q = Discharge, in cubic feet per second
h_1 = Pool stage + 8.50 feet
h_3 = Tailwater stage + 8.50 feet
h_g for tainter gages = gage reading + gage-indicator correction, e (fig. 5).
(the average gage-indicator correction for gates 1, 2, 17 and 18 = +0.2 foot, and that for gates 42 and 43 = +0.34 foot)
(the average gage-indicator correction for gates 3-12, 16, 19-41 = +0.08 foot)
h_g for roller gates = gage reading

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

Table 4a.--Discharge rating table for submerged-orifice flow for a single non-submergible tainter gate at Mississippi River Lock and Dam 20

Gage reading (feet)	Tainter gate discharge (in ft^3/s) for indicated static-head loss (pool - tailwater stage, in feet)																		
	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
.5	115	163	200	231	258	283	306	328	348	367	386	403	420	437	453	468	484	498	513	527
1.0	218	309	379	438	490	538	581	622	661	697	732	765	798	829	859	889	917	946	973	1000
1.5	323	458	561	648	725	796	860	920	977	1030	1080	1130	1180	1230	1270	1310	1360	1400	1440	1480
2.0	429	607	745	861	963	1060	1140	1220	1300	1370	1440	1500	1570	1630	1690	1750	1800	1860	1910	1960
2.5	536	758	930	1070	1200	1320	1430	1530	1620	1710	1790	1880	1960	2030	2110	2180	2250	2320	2390	2450
3.0	643	910	1120	1290	1440	1580	1710	1830	1940	2050	2150	2250	2350	2440	2530	2620	2700	2780	2860	2940
3.5	751	1060	1300	1510	1680	1850	2000	2140	2270	2400	2510	2630	2740	2850	2950	3050	3150	3250	3340	3440
4.0	859	1220	1490	1720	1930	2110	2290	2450	2600	2740	2880	3010	3140	3260	3380	3490	3610	3720	3830	3930
4.5	967	1370	1680	1940	2170	2380	2570	2750	2930	3090	3240	3390	3530	3670	3800	3940	4060	4190	4310	4430
5.0	1080	1520	1870	2160	2420	2650	2860	3070	3250	3430	3610	3770	3930	4080	4230	4380	4520	4660	4790	4930
5.5	1190	1680	2060	2380	2660	2920	3150	3380	3590	3780	3970	4150	4330	4500	4660	4820	4980	5130	5280	5430
6.0	1300	1830	2250	2600	2910	3190	3450	3690	3920	4130	4340	4540	4730	4910	5090	5270	5440	5610	5770	5930
6.5	1410	1990	2440	2820	3150	3460	3740	4000	4250	4480	4710	4920	5130	5330	5530	5720	5900	6080	6260	6430
7.0	1520	2140	2630	3040	3400	3730	4030	4310	4580	4830	5080	5310	5530	5750	5960	6160	6360	6560	6750	6940
7.5	1630	2300	2820	3260	3650	4000	4330	4630	4910	5190	5450	5700	5940	6170	6390	6610	6830	7040	7240	7440
8.0	1740	2460	3010	3480	3900	4270	4620	4940	5250	5540	5820	6080	6340	6590	6830	7060	7290	7510	7730	7950
8.5	1850	2610	3200	3700	4140	4540	4910	5260	5580	5890	6190	6470	6740	7010	7260	7510	7760	7990	8230	8460
9.0	1960	2770	3400	3930	4390	4820	5210	5570	5920	6250	6560	6860	7150	7430	7700	7960	8220	8470	8720	8960
9.5	2070	2930	3590	4150	4640	5090	5510	5890	6260	6600	6930	7250	7550	7850	8140	8420	8690	8950	9220	9470
10.0	2180	3090	3780	4370	4890	5370	5800	6210	6590	6960	7300	7640	7960	8270	8570	8870	9160	9440	9710	9980
10.5	2290	3240	3980	4600	5140	5640	6100	6530	6930	7310	7680	8030	8370	8700	9010	9320	9620	9920	10200	10500
11.0	2400	3400	4170	4820	5390	5910	6390	6840	7270	7670	8050	8420	8780	9120	9450	9780	10100	10400	10700	11000
11.5	2520	3560	4360	5040	5640	6190	6690	7160	7600	8030	8430	8810	9180	9540	9890	10200	10600	10900	11200	11500
12.0	2630	3720	4560	5270	5900	6460	6990	7480	7940	8380	8800	9200	9590	9970	10300	10700	11000	11400	11700	12000

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

Discharges for non-submergible tainter gates 3-12, 16 and 19-41 were computed using equation:

$$Q = 311\, h_3 (h_3/h_g)^{-1.03} (h_1 - h_3)^{0.5} \qquad (12)$$

where h_g = gage reading + (average e = +0.08)
h_1 = 18.00 feet (9.50 + 8.50)
h_3 = tailwater stage + 8.50 feet

Table 4b.--Discharge rating table for submerged-orifice flow for a single submergible tainter gate at Mississippi River Lock and Dam 20

Gage reading (feet)	Tainter gate discharge (in ft^3/s) for indicated static-head loss (pool - tailwater stage, in feet)																			
	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
.5	91	129	159	185	208	229	249	268	286	303	320	336	353	369	385	401	417	433	449	465
1.0	171	243	299	347	391	430	467	503	536	569	601	632	663	693	723	753	783	813	843	874
1.5	257	365	450	522	587	647	703	756	806	855	903	950	996	1040	1090	1130	1180	1220	1270	1310
2.0	348	494	608	706	794	874	950	1020	1090	1160	1220	1280	1350	1410	1470	1530	1590	1650	1710	1780
2.5	442	628	773	897	1010	1110	1210	1300	1390	1470	1550	1630	1710	1790	1870	1940	2020	2100	2180	2260
3.0	539	766	943	1090	1230	1360	1470	1580	1690	1790	1890	1990	2090	2180	2280	2370	2470	2560	2660	2750
3.5	639	908	1120	1300	1460	1610	1750	1880	2000	2120	2240	2360	2470	2590	2700	2810	2920	3030	3150	3260
4.0	741	1050	1300	1500	1690	1860	2020	2180	2320	2460	2600	2740	2870	3000	3130	3260	3390	3520	3650	3790
4.5	845	1200	1480	1720	1930	2130	2310	2480	2650	2810	2970	3120	3270	3420	3570	3720	3870	4010	4170	4320
5.0	951	1350	1660	1930	2170	2390	2600	2790	2980	3160	3340	3510	3680	3850	4020	4190	4350	4520	4690	4860
5.5	1060	1510	1850	2150	2420	2660	2890	3110	3320	3520	3720	3910	4100	4290	4470	4660	4850	5030	5220	5410
6.0	1170	1660	2040	2370	2670	2940	3190	3430	3660	3890	4100	4320	4530	4730	4940	5140	5350	5550	5760	5970
6.5	1280	1820	2240	2600	2920	3220	3500	3760	4010	4260	4490	4730	4960	5180	5410	5630	5850	6080	6310	6540
7.0	1390	1980	2440	2830	3180	3500	3800	4090	4360	4630	4890	5140	5390	5640	5880	6120	6370	6610	6860	7110
7.5	1510	2140	2630	3060	3440	3790	4110	4420	4720	5010	5290	5560	5830	6100	6360	6620	6890	7150	7420	7690
8.0	1620	2300	2840	3290	3700	4080	4430	4760	5080	5390	5690	5990	6280	6560	6850	7130	7410	7700	7990	8280
8.5	1740	2470	3040	3530	3970	4370	4750	5100	5450	5780	6100	6420	6730	7030	7340	7640	7950	8250	8560	8870
9.0	1850	2640	3240	3770	4230	4660	5070	5450	5810	6170	6510	6850	7180	7510	7830	8160	8480	8810	9140	9470
9.5	1970	2800	3450	4010	4500	4960	5390	5800	6190	6560	6930	7290	7640	7990	8330	8680	9020	9370	9720	10100
10.0	2090	2970	3660	4250	4780	5260	5720	6150	6560	6960	7350	7730	8100	8470	8840	9210	9570	9940	10300	10700
10.5	2210	3150	3870	4490	5050	5560	6050	6500	6940	7360	7770	8170	8570	8960	9350	9740	10100	10500	10900	11300
11.0	2330	3320	4080	4740	5330	5870	6380	6860	7320	7760	8200	8620	9040	9450	9860	10300	10700	11100	11500	11900
11.5	2460	3490	4300	4990	5610	6180	6710	7220	7700	8170	8630	9070	9510	9950	10400	10800	11200	11700	12100	12600
12.0	2580	3670	4510	5240	5890	6490	7050	7580	8090	8580	9060	9530	9990	10400	10900	11400	11800	12300	12700	13200

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

Discharges for submergible tainter gates 1, 2, 17, 18, 42 and 43 were computed using equation:

(11) $Q = 318\, h_3 (h_3/h_g)^{-1.17} (h_1 - h_3)^{0.5}$

where h_g = gage reading + (average e = +0.2)
h_1 = 18.00 feet (9.50 + 8.50)
h_3 = tailwater stage + 8.50 feet

Table 5.--Discharge rating table for submerged-orifice flow for a single roller gate at Mississippi River Lock and Dam 20

Gage reading (feet)	Roller gate discharge (in ft^3/s) for indicated static-head loss (pool - tailwater stage, in feet)																			
	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
.5	136	193	236	272	304	333	360	385	408	430	451	472	491	509	527	544	561	578	593	609
1.0	272	385	472	544	609	667	720	770	817	861	903	943	982	1020	1050	1090	1120	1160	1190	1220
1.5	408	578	707	817	913	1000	1080	1160	1230	1290	1350	1410	1470	1530	1580	1630	1680	1730	1780	1830
2.0	544	770	943	1090	1220	1330	1440	1540	1630	1720	1810	1890	1960	2040	2110	2180	2240	2310	2370	2430
2.5	681	963	1180	1360	1520	1670	1800	1930	2040	2150	2260	2360	2450	2550	2640	2720	2810	2890	2970	3040
3.0	817	1160	1410	1630	1830	2000	2160	2310	2450	2580	2710	2830	2940	3060	3160	3270	3370	3470	3560	3650
3.5	953	1350	1650	1910	2130	2330	2520	2700	2860	3010	3160	3300	3440	3570	3690	3810	3930	4040	4150	4260
4.0	1090	1540	1890	2180	2430	2670	2880	3080	3270	3440	3610	3770	3930	4070	4220	4360	4490	4620	4750	4870
4.5	1230	1730	2120	2450	2740	3000	3240	3470	3680	3870	4060	4240	4420	4580	4740	4900	5050	5200	5340	5480
5.0	1360	1930	2360	2720	3040	3330	3600	3850	4080	4300	4510	4720	4910	5090	5270	5440	5610	5780	5930	6090
5.5	1500	2120	2590	2990	3350	3670	3960	4240	4490	4730	4970	5190	5400	5600	5800	5990	6170	6350	6530	6700
6.0	1630	2310	2830	3270	3650	4000	4320	4620	4900	5170	5420	5660	5890	6110	6330	6530	6730	6930	7120	7300
6.5	1770	2500	3060	3540	3960	4330	4680	5010	5310	5600	5870	6130	6380	6620	6850	7080	7300	7510	7710	7910
7.0	1910	2700	3300	3810	4260	4670	5040	5390	5720	6030	6320	6600	6870	7130	7380	7620	7860	8090	8310	8520
7.5	2040	2890	3540	4080	4570	5000	5400	5780	6130	6460	6770	7070	7360	7640	7910	8170	8420	8660	8900	9130
8.0	2180	3080	3770	4360	4870	5330	5760	6160	6530	6890	7220	7540	7850	8150	8430	8710	8980	9240	9490	9740
8.5	2310	3270	4010	4630	5170	5670	6120	6550	6940	7320	7670	8020	8340	8660	8960	9260	9540	9820	10100	10300
9.0	2450	3470	4240	4900	5480	6000	6480	6930	7350	7750	8130	8490	8830	9170	9490	9800	10100	10400	10700	11000

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

Discharges for roller gates 13-15 were computed using equation:

$$Q = 385\, h_g (h_1 - h_3)^{0.5} \quad (15)$$

where h_g = gage reading
h_1 = 20.00 feet (11.50 + 8.50)
h_3 = tailwater stage + 8.50 feet

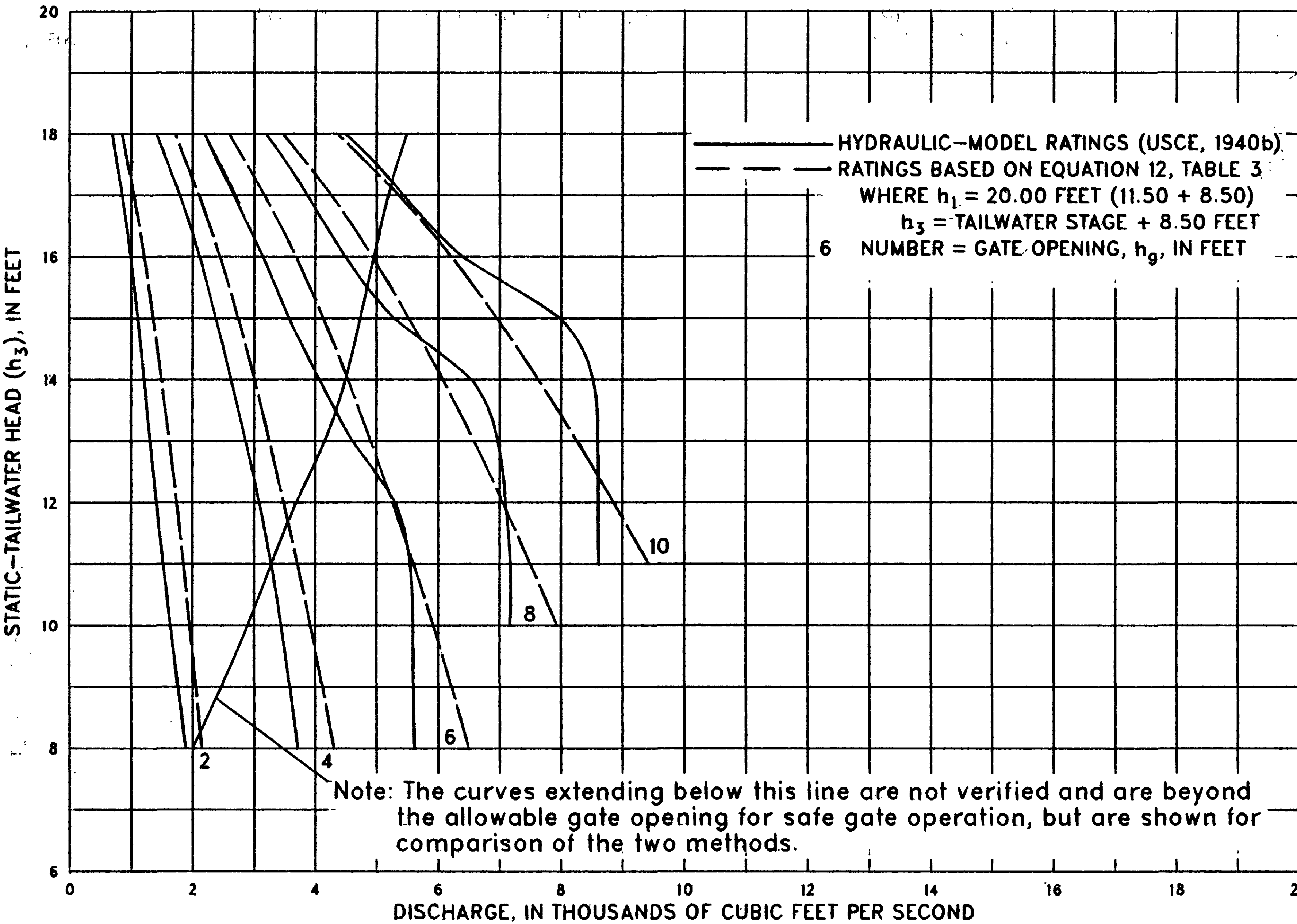


Figure 10.--Discharge ratings for submerged-orifice flow for a single non-submergible tainter gate compared to hydraulic-model rating at Mississippi River Lock and Dam 20

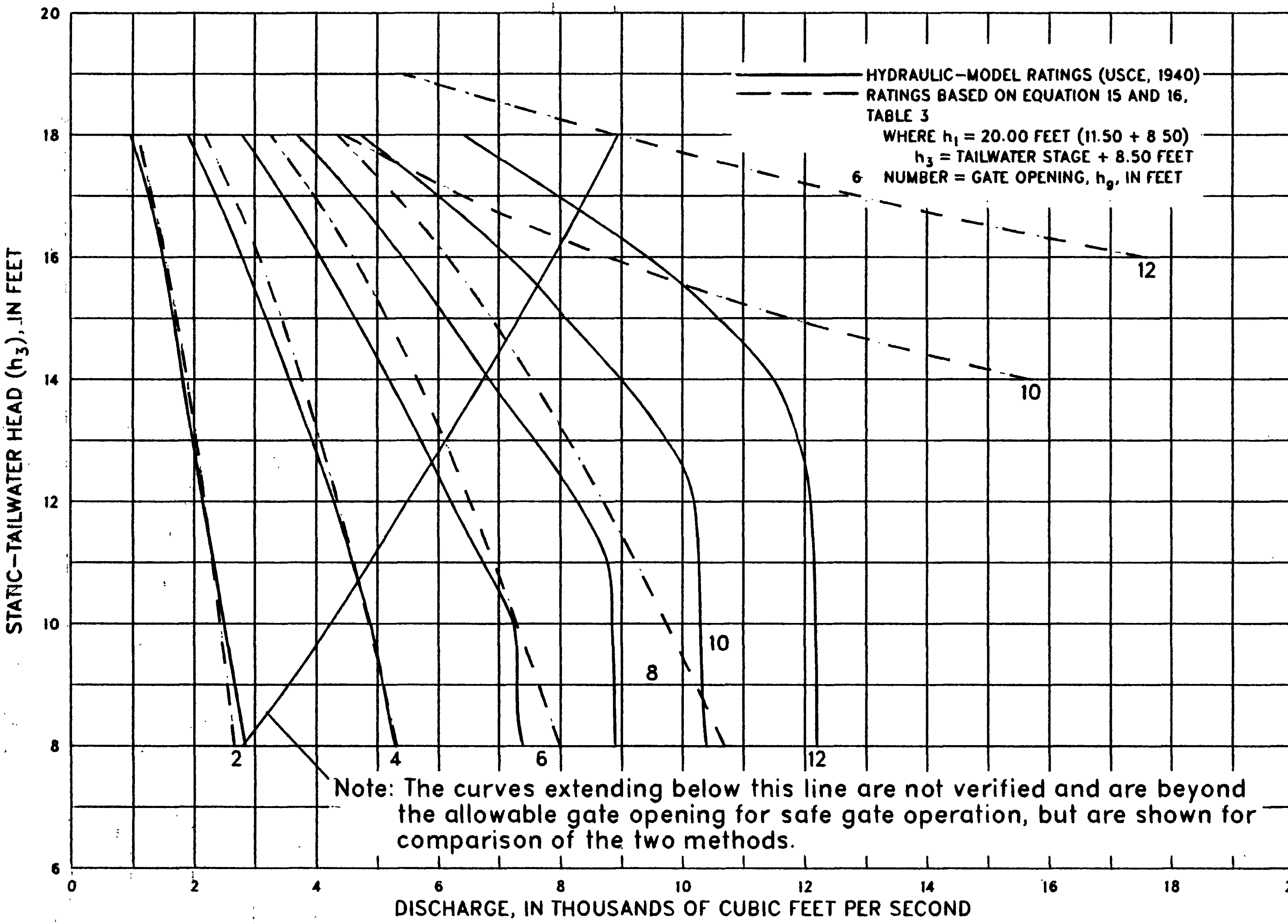


Figure 11.––Discharge ratings for submerged orifice flow for a single roller gate compared to hydraulic–model ratings at Mississippi River Lock and Dam 20

SUMMARY

Current-meter discharge measurements made in the forebays of the tainter and roller gates of Lock and Dam 20 were used to develop discharge coefficients and equations of discharge for submerged-orifice flow for all the gates.

Methodology has been described to compute the true gate openings of the tainter gates. The gate-position indicator gages for the tainter gates could be accurately set to the true gate opening (h_g) by 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-position indicator gages to more nearly reflect the computed gate opening, h_g.

Discharge rating tables were developed for discrete combinations of static-head loss and gate openings for submerged-orifice flow, which is the predominant flow regime when the dam is in operation. Comparison 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.

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