DISCHARGE RATINGS FOR TAINTER GATES AND ROLLER GATES AT LOCK AND DAM NO. 7 ON THE MISSISSIPPI RIVER, LA CRESCENT, MINNESOTA

By S.R. Corsi and J.G. Schuler

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
mile (mi)	1.609	kilometer
pound (lb)	453.6	gram .
foot (ft)	0.3048	meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1912 (NGVD of 1912)–a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1912. To obtain elevation in reference to the National Geodetic Vertical Datum of 1929 at Lock and Dam No. 7, sub'ract 0.49 feet from those elevations referenced to NGVD of 1912. NGVD of 1912 is still used throughout the Mississippi River navigation system.

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ABSTRACT

The water-surface elevations on the Inland Waterway Navigation System of the upper Mississippi River are controlled during normal operating conditions by various flow controls at 29 locks and dams. The headwater (navigation pool) and tailwater elevations at Lock and Dam No. 7 are controlled by the regulation of 11 tainter gates and 5 roller gates. Discharge ratings for these tainter and roller gates were developed for use in computing discharge through Dam No. 7 and to aid in regulating the navigation pool within its normal operating limits of 639.00 ± 0.20 feet (NGVD 1912). Hydraulic-control variables and discharges were measured at the tainter and roller gates and analyzed for this report.

Fifty-two current-meter measurements of discharges that ranged from discharges too low to measure to 12,600 cubic feet per second were made in the forebays of the tainter and roller gates. The measured discharges were used to define flow regimes as a function of static-headwater depth (h_1), static-tailwater depth (h_3), and vertical height of tainter or roller gate opening (h_g). Submerged-orifice flow is the predominant flow regime at Lock and Dam No. 7.

Twenty-four discharge measurements were used to develop submerged-orifice discharge coefficient relations for the 11 tainter gates. Twenty discharge measurements were used to develop a submerged-orifice discharge coefficient relation for the five roller gates. Coefficients of discharge (C_{gs}) ranged from 0.126 (h_g = 1 foot) to 1.089 (h_g = 10 feet) for tainter gates and from 0.050 (h_g = 1 foot) to 0.302 (h_g = 14 feet) for roller gates. Discharge was measured at three different tainter gates with the gates closed (h_g = 0) to evaluate the tainter-gate leakage-discharge relations. No measurable leakage was observed. The resulting equations can be used to compute discharge at Lock and Dam No. 7 for the tainter and roller gates under normal flow conditions. Discharge rating tables for the tainter and roller gates are given with a headwater elevation of 639.00 feet normal pool elevation for selected tailwater elevations and gate openings.

INTRODUCTION

The Inland Waterway Navigation System presently in use for the upper Mississippi River Basin was incorporated in 1930 when U.S. Congress passed the River and Harbor Act. The funding of the River and Harbor Act allowed for the construction of flow-regulating lock and dam structures and periodic channel dredging to maintain a 9-ft-deep by 400-ft-wide channel between Minneapolis, Minn., and St. Louis, Mo., for navigation. The St. Paul, Minn., office of the U.S. Army Corps of Engineers regulates the control structures on the Mississippi River from the St. Anthony Falls locks and dam in Minneapolis to Lock and Dam No. 10. These lock and dam structures are used for navigation and do not have any flood-control benefits.

Lock and Dam No. 7, the subject of this report, is 702.5 river mi. upstream from the mouth of the Ohio River and 4.6 river mi. upstream from the city of La Crosse, Wis. With reference to other flow-regulating structures, Lock and Dam No. 7 is 23.3 river mi. upstream from Lock and Dam No. 8 and 11.8 river mi. downstream from Lock and Dam No. 6 (fig. 1). The Mississippi River upstream from Lock and Dam No. 7 has a total drainage area of 62,340 mi^2 (U.S. Army Corps of Engineers, 1971, p. 1-3).

The flow control system at Lock and Dam No. 7 consists of 5 roller gates, 11 tainter gates, a navigation lock, an auxiliary lock, a storage area, an earth dike, and a submersible dam. The total structure is 10,766 ft long (fig. 2). The total bridge length (which includes the tainter and roller gates, the locks, and the storage yard) is 1,093 ft; the earth dike is 9,003 ft long and the submersible dam is 670 ft. long. Various combinations of tainter- and roller-gate openings at Lock and Dam No. 7 are currently (1994) used to maintain the headwater (navigation pool) elevation within the normal operating limits of 639.0 ± 0.2 ft (U.S. Army Corps of Engineers, 1971, p. 6; all elevations in this report are referenced to the NGVD 1912).

Because the water-surface slope between flow-regulating structures can approach zero during periods of low flow, the traditional methods that require slope to calculate discharge are not satisfactory at Lock and Dam No. 7. Previous to this study, discharges determined by using theoretical equations for discharge through the gates had not been verified by field measurements. Therefore, a cooperative effort between the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers, St. Paul District, was initiated to develop field-verified coefficients for the equations of discharge for the 11 tainter and 5 roller gates at Lock and Dam No. 7.

Purpose and Scope

The purpose of this report is to present discharge ratings for the tainter- and roller-gate flow controls under normal operating conditions at Lock and Dam No. 7. Coefficients for the theoretical equations of discharge were developed from discharge measurements made in the forebays of the tainter and roller gates. These discharge measurements were used to develop discharge-coefficient relations for hydraulic-control conditions that occur during normal operating periods. The equations of discharge were used to compute discharge rating tables for most combinations of headwater and tailwater elevations and vertical height of tainter- or roller-gate openings under normal operating conditions.

This study was limited to the analysis of submerged-orifice flow under the tainter and roller gates. No attempts were made to define or develop discharge ratings for flow through the navigation lock, possible flow over the earth dike, or open-river flow when all gates are out of the water.

Acknowledgments

A special thanks is extended to Lockmaster Terry Jessessky and the crew at Lock and Dam No. 7, who were helpful in providing desired gate openings and gage-height information. A special thanks is also extended to Terry Alexander, whose information and report on Lock and Dam No. 25 (Alexander, 1992) were instrumental in the design of this project and the format of this report.

THEORETICAL EQUATIONS FOR DISCHARGE

Under normal flow conditions, the tainter gates and the roller gates pass most of the flow through Lock and Dam No. 7, and the Lock passes a small but measurable amount of water; no flow passes over the earth dike or the submersible dam. For this reason, equations of discharge have been developed only for the tainter and roller gates in this study. The theory behind the equations was described by Alexander (1992, pp. 4-5) as follows:

> Collins (1977, p. 2-3) and Stuthmann and Sanders (1982, p. A-36 through A-40) summarize the hydraulic-control conditions that define flow regimes possible at some flow- regulating structures and present their corresponding theoretical equations of discharge. The hydraulic theory used to develop these equations assumes steady, uniform flow. This theory requires that energy and mass are conserved between an approach section and a section just downstream from the control structure. Possible flow regimes, necessary hydraulic-control conditions, and the

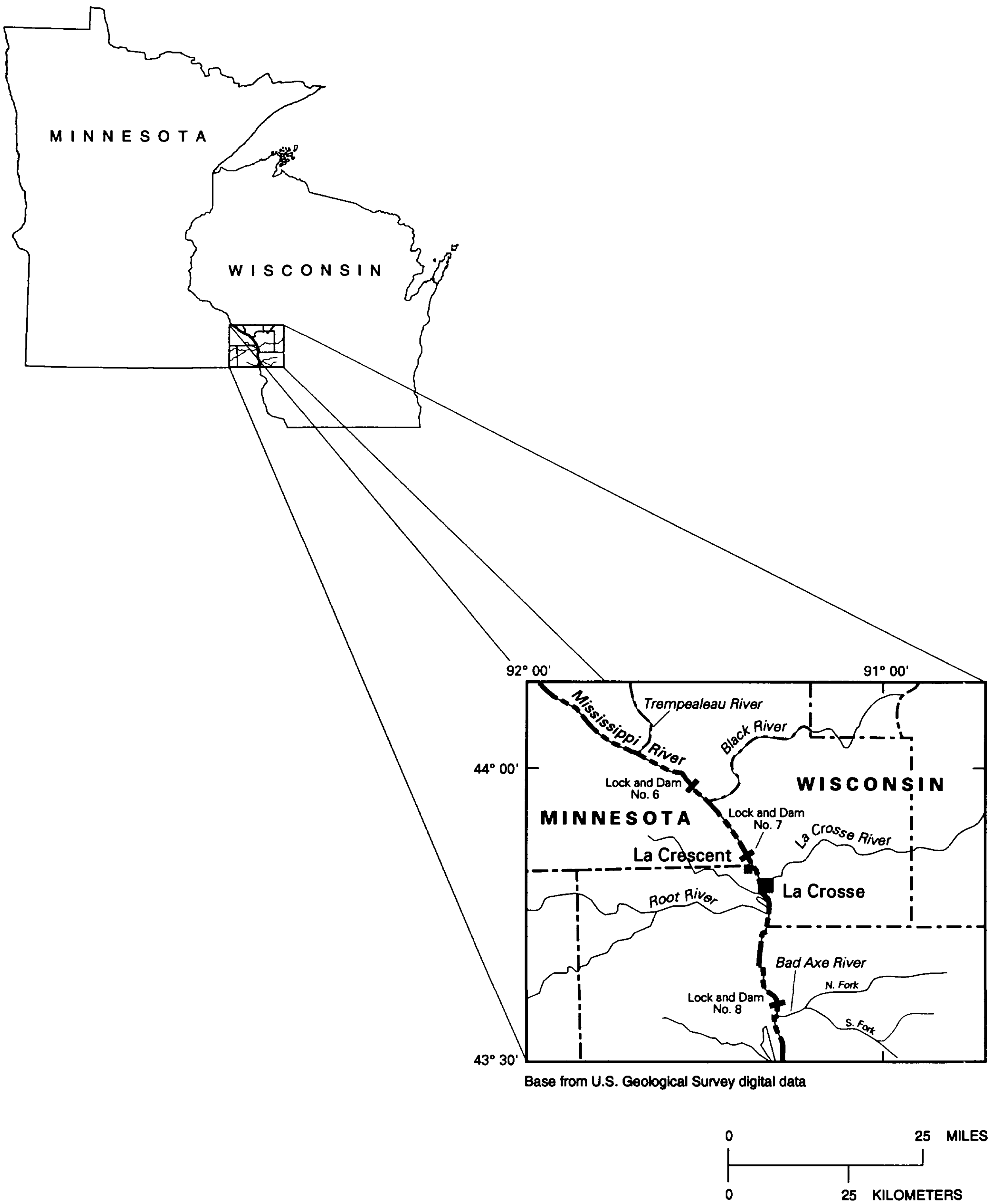

Figure 1. Location of Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

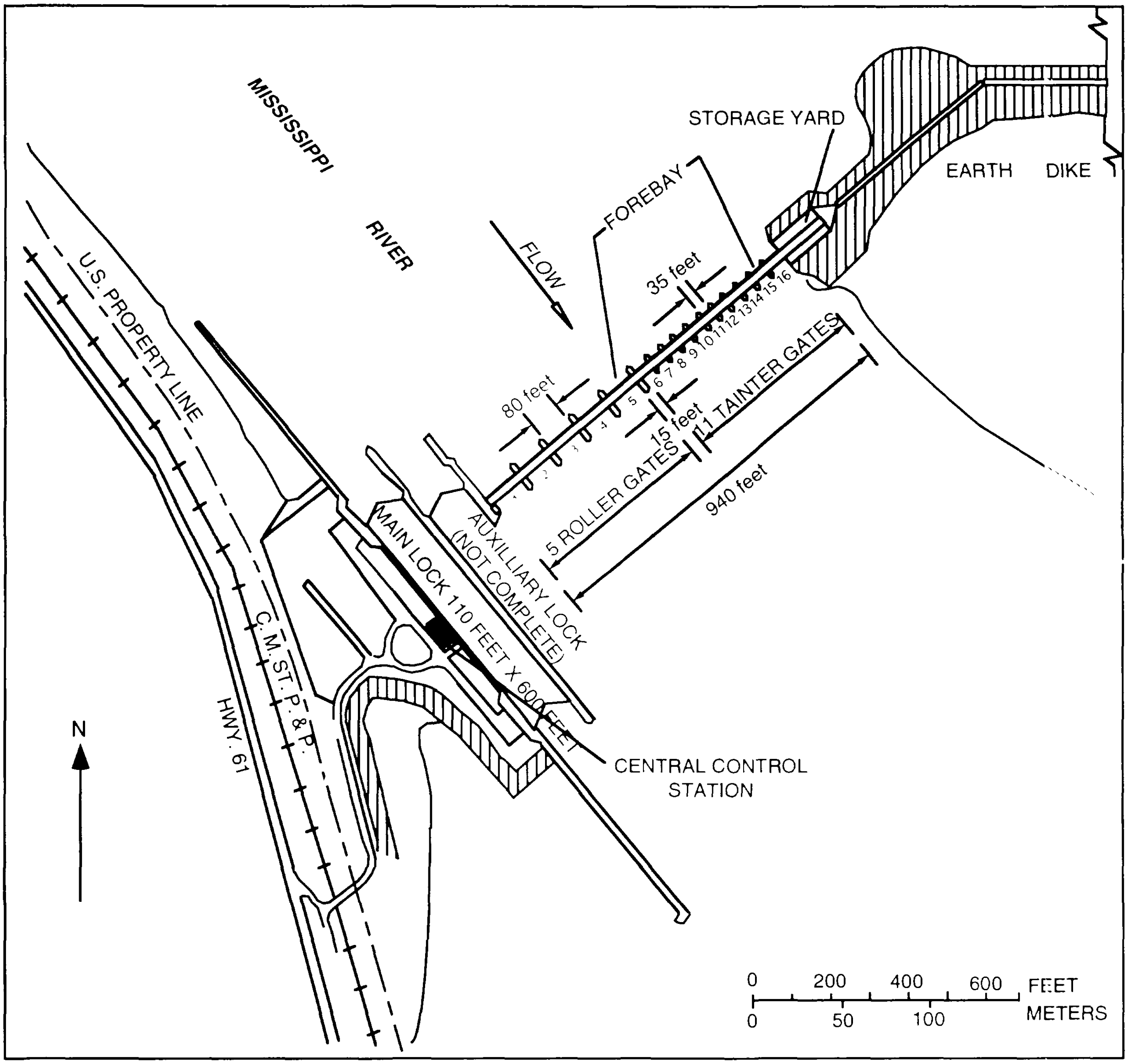

Figure 2. Location of tainter and roller gates at Lock and Dam No. 7

theoretical equations of discharge for flow controlled by a tainter or roller gate are summarized in [table 1, in this report].

The bracketed parts of these four equations represent theoretical expressions of discharge for a tainter or roller gate B units in width. The independent hydraulic-control variables are static-headwater depth (h_1), static-tailwater depth (h_3), and vertical height of tainter or roller gate opening (h_g). The static depths (h_1 and h_3) are the vertical distances between the headwater and tailwater elevations and the sill [fig. 3 and 4, in this report]. The coefficients of discharge (C, C_{gs}, C_w, and C_{ws}) are unknown, but can be determined through a calibration process. These coefficients are defined by the ratio of measured discharge to theoretical discharge; therefore, a coefficient of discharge can be calculated from each current-meter measurement of discharge if all other hydraulic-control variables are known or fixed.

Tainter and Roller Gates

The independent hydraulic-control variables h_g, h_1, and h_3 are used to determine the tainter- and roller-gate flow regimes. The hydraulic-control conditions that separate orifice and weir flow regimes is based on a critical-depth analysis of flow in a rectangular section. In this analysis, one assumes that flow over the downstream edge of the sill is critical unless the gate or the tailwater prevent critical flow. If h_g is less than the critical depth ($0.67h_1$), then orifice flow occurs under the gate. If the gate opening equals or exceeds the critical depth and the tailwater depth is less than the gate opening, the gate opening has no effect on the discharge. In this case, weir flow results, and the concrete gate sill functions as a broad-crested weir (Collins, 1977, p. 4; Stuthmann and Sanders, 1982, p. A-37). The hydraulic-control conditions used to determine the pertinent equations of discharge for this study are listed in table 1.

Under normal flow conditions, the tainter and roller gates at Lock and Dam No. 7 operate within the submerged-orifice flow regime. During high-flow, the gates are periodically raised completely out of the water. In this case, free-weir or submerged-weir conditions would apply. Only one discharge measurement at each type of gate was made while the gates were raised completely out of the water solely for informational purposes. The free-weir and submerged-weir flow regimes were not studied for this report. During winter and spring, the roller gates are submerged periodically so that ice or other debris can be flushed over the top of the gates (Terry Jessessky, U.S. Army Corps of Engineers, oral commun., 1993). Three measurements were made for reference purposes when the gates were submerged; the measurements are not sufficient for complete analysis of this flow condition. The predominant tainter and roller gate flow regime is submerged-orifice flow; therefore, it is the only type of flow described in this report.

MEASUREMENTS OF HYDRAULIC-CONTROL VARIABLES AND DISCHARGES

The five roller gates operate between pier walls with 80-ft openings and are 20 ft high. The 11 tainter gates operate between pier walls with 35-ft openings and are 15 ft high. The roller and tainter gates are built under a service deck that allows access to the individual forebays; thus, discharge could be measured using standard USGS current-meter measuring equipment.

Stage-discharge relations for all flow regimes can be developed from measurements of hydraulic-control variables and discharges at a single roller or tainter gate if all gates are of the same design (Collins, 1977, p. 4); however, in an attempt to average variations in roller- and tainter-gate entrance and exit losses, 44 current-meter discharge measurements were made in the forebays of 5 roller gates and 11 tainter gates during submerged-orifice flow conditions. Also, three current-meter discharge measurements were made with the gates completely closed, two current-meter measurements were made with the gates completely out of the water, and three measurements were made at roller gates with the gate completely submerged. These measurements of hydraulic-control variables and discharges were used to develop stage-discharge relations for submerged-orifice flow (table 1).

Table 1. Theoretical equations of discharge for flow controlled by a tainter or roller gate

Abbreviations:

h_g, vertical height of tainter or roller gate opening
h_1, static-headwater depth
h_3, static-tailwater depth
Q, discharge
C, free-orifice flow coefficient of discharge
B, tainter or roller gate width
g, acceleration due to gravity
C_{gs}, submerged-orifice flow coefficient of discharge
Δh, static head differential (h_1-h_3)
C_w, free weir flow coefficient of discharge
C_{ws}, submerged-weir flow coefficient of discharge
<, less than; >, greater than; ≥, greater than or equal to

Table modified from Collins (1977)

Flow regime	Hydraulic-control conditions	Equation of discharge	Equation no.
Free-orifice	$h_g<0.67h_1$ and $h_3 < h_g$	$Q = C[h_gB(2gh_1)^{0.5}]$	1
Submerged-orifice	$h_g < 0.67h_1$ and h_3 h_g, or [a]$h_g > 0.67h_1$ and $h_3 > h_g$	$Q = C_{gs}[h_3B(2g\Delta h)^{0.5}]$	2
Free-weir	h_g $0.67h_1$ and $h_3/h_1 < 0.6$	$Q = C_w[Bh_1{}^{1.5}]$	3
Submerged-weir	h_g $0.67h_1$, h_3/h_1 0.6, and [a]$h_3<h_g$	$Q = C_wC_{ws}[Bh_1{}^{1.5}]$	4

[a]Stuthmann and Sanders (1982, p. A-37).

Discharge measurements for the roller- and tainter-gate openings were made between the pier walls along the upstream handrail of the service deck approximately 32 ft upstream from the roller gates and 12 ft upstream from the tainter gates. During these discharge measurements, velocity observations were made by use of a Price type AA current meter suspended with a Columbus sounding weight (100 or 150 lb) from a collapsible bridge boom. The four-point method for discharge measurement was used instead of the traditional two-point method because of the influence of tainter and roller gates on the vertical velocity profile. In the traditional two-point method, 2 velocity observations are made at depths of 0.2 and 0.8 of the static-headwater depth at approximately 20 locations across the width of the section being measured (Rantz and others, 1982, p. 134). The four-point method used for this study consists of velocity observations at depths of 0.2, 0.4, 0.6, and 0.9 of the static-headwater depth at approximately 15 locations across the width of the section being measured. The four-point method was used because comparison of the two-point method with the vertical-velocity curve method (0.1-depth increments between 0.1 and 0.9 of the static-headwater depth; Rantz and others, 1982, p.132) showed differences of as much as 12 percent. Several three-point and four-point methods where the velocities were measured at different combinations of depths were tested. The four-point method described above was the only method that resulted in differences from the vertical-velocity curve method of 5 percent or less over a selected range of gate settings.

To minimize the effects of differential gate openings on the flow field in the measurement sections (the effects of differential gate openings on the flow field were not analyzed in this study), field personnel ensured that the gates on both sides were set at the same opening. All gate openings were set by U.S. Army Corps of Engineers personnel. The roller gates were set by use of a position-indicator gage inside the roller-gate pier house, and the

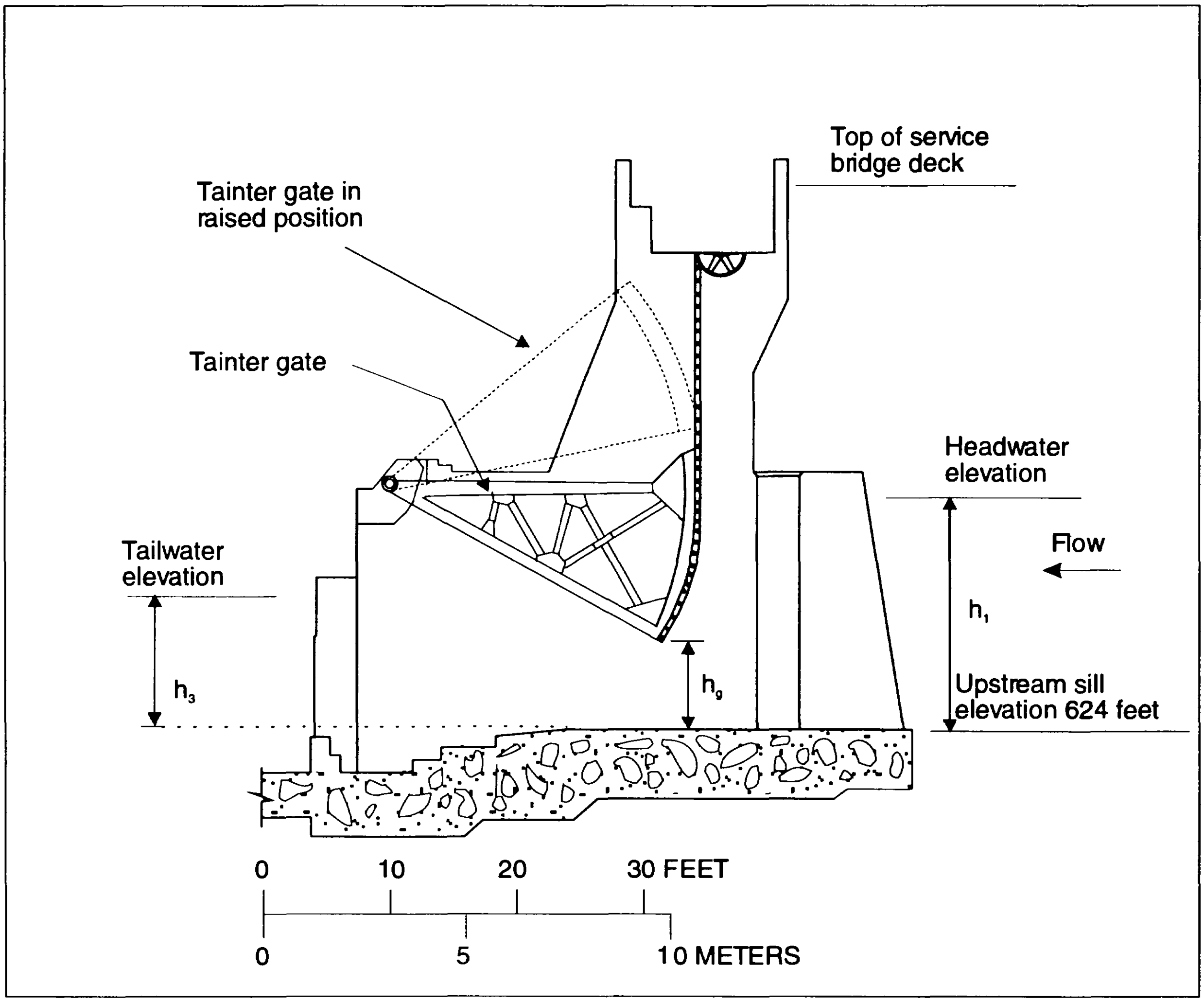

Figure 3. Sectional view of tainter gate

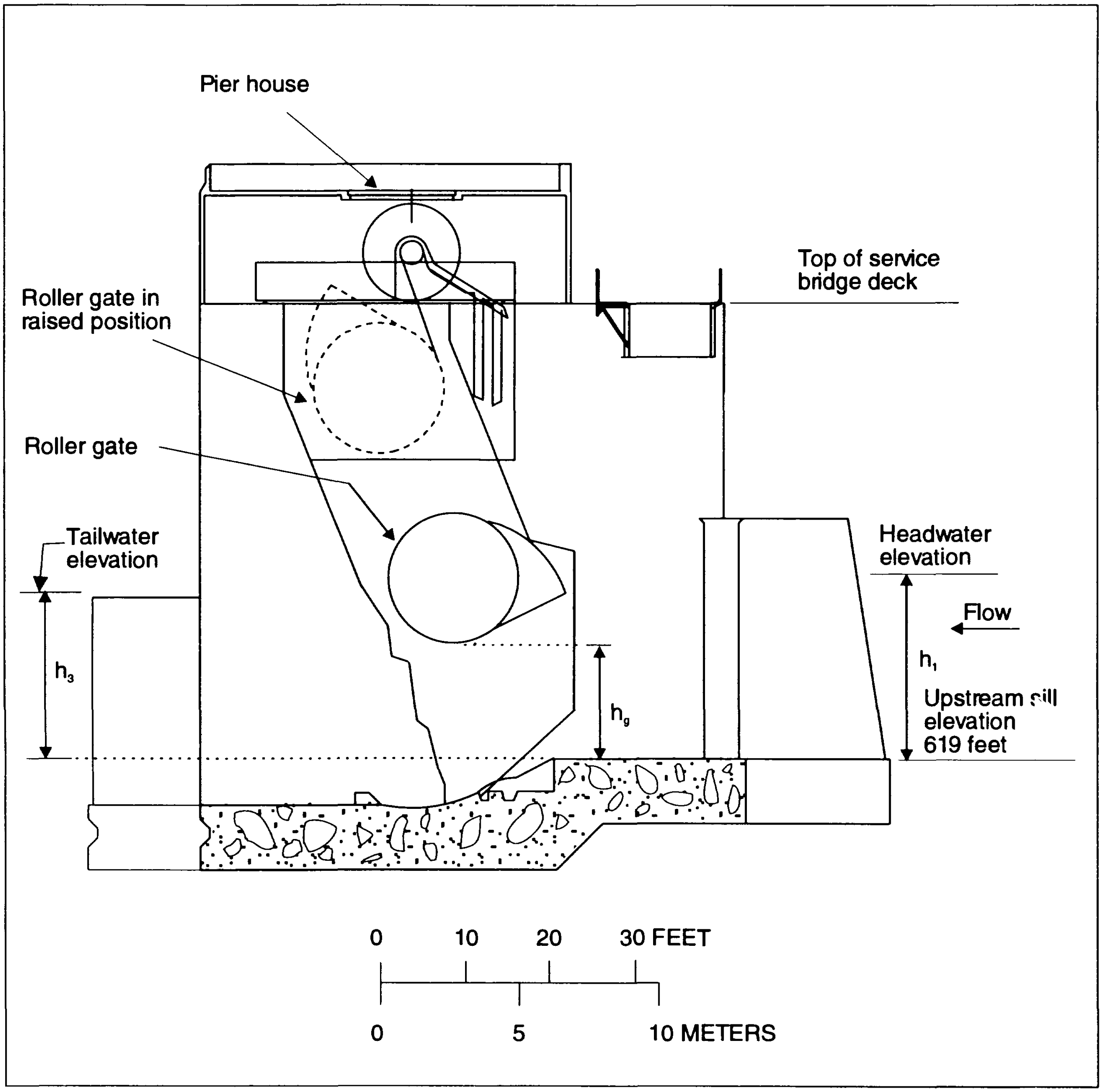

Figure 4. Sectional view of roller gate

tainter gate openings were set from the service deck by referencing the gate-indicator gages on the downstream pier walls. The 16 gates at Lock and Dam No.7 are of the submersible type, and accurate calculation of a true roller- or tainter-gate opening is impossible. Therefore, the gate and position-indicator gages were assumed to be correct within ±0.1 ft. Gate leakage is common to submersible roller or tainter gates because of clearance between the gate and the sill or piers and from normal wear and tear on the gates. In this study, the magnitude of the leakage discharge per gate was not measurable; therefore, leakage was not separated from the current-meter discharge measurements. The headwater and tailwater elevations were monitored from U.S. Army Corps of Engineers continuous-recording gages in the control house. The static headwater and static tailwater depths, h_1 and h_3, are referenced to the tainter-gate sill elevation of 624.00 ft and the roller-gate sill elevation of 619.00 ft.

EQUATIONS OF DISCHARGE

The gates at Lock and Dam No. 7 operate within the submerged-orifice flow regime during normal flow conditions. Submerged-orifice flow equations of discharge (eq. 2, table 1) were developed for the tainter and roller gates at Lock and Dam No. 7. Field measurements were used as input to equation 2 to develop the coefficients of discharge, C_{gs}. Relations between C_{gs} and the orifice-submergence ratio (h_3/h_g) were developed by use of ordinary-least-squares regression.

Tainter Gates

Twenty-four coefficients of discharge, C_{gs}, were computed (eq. 2, table 1) by use of the results of the current-meter discharge measurements made at hydraulic-control conditions that satisfy submerged-orifice flow criteria. The computed coefficients ranged from 0.126 (h_g = 1 ft) to 1.089 (h_g = 10 ft) and are listed in table 2. The relation between the coefficient of discharge (C_{gs}) and orifice-submergence ratio (h_3/h_g) was determined by ordinary-least-squares regression of the natural logarithms of each variable. As can be seen in figure 5, the relation can be represented by two straight lines in log-log space. The breakpoint between the two lines is at an orifice-submergence ratio of about 1.5.

The discharge-coefficient equation for orifice-submergence ratios from 1.5 to 8.5 is

$$C_{gs} = 0.975\left(\frac{h_3}{h_g}\right)^{-0.975} . \qquad (5)$$

For orifice-submergence ratios of 1.4 to 1.5 the equation is

$$C_{gs} = 5.05\left(\frac{h_3}{h_g}\right)^{-5.03} . \qquad (6)$$

Three current-meter discharge measurements made at $h_g = 0$ (gates 9-11) indicate that leakage through the tainter gates is negligible. Very low magnitude, multidirectional water velocities made it impossible to determine the amount of leakage. For this reason, the measurements made at $h_g = 0$ are not included in the data tables in this report.

The relations for C_{gs} in equations 5 and 6 can be substituted into the theoretical submerged-orifice equation of discharge (eq. 2, table 1) to determine the final equations of discharge for the tainter gates on Lock and Dam No. 7. For orifice-submergence ratios of 1.5 to 8.5, the equation of discharge is

$$Q = 0.975 h_3 B\left(\frac{h_3}{h_g}\right)^{-0.975} (2g(h_1 - h_3))^{0.5} . \qquad (7)$$

For orifice-submergence ratios of 1.4 to 1.5, the equation of discharge is

$$Q = 5.05 h_3 B\left(\frac{h_3}{h_g}\right)^{-5.03} (2g(h_1 - h_3))^{0.5} \qquad (8)$$

where Q is the discharge,
h_3 is the static-tailwater depth,
h_3/h_g is the orifice-submergence ratio,
B is the width of the gate,
g is acceleration due to gravity, and
(h_1-h_3) is the static-head differential.

Table 2. Summary of hydraulic-control variables and current-meter discharge measurements at Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

[Measurements are listed in order of increasing vertical height of gate opening; static depth, headwater and tailwater elevations minus sill elevation; h_1, static-headwater depth; h_3, static-tailwater depth; h_g, vertical height of tainter or roller gate opening; h_3/h_g, orifice-submergence ratio; Q, discharge; C_{gs}, submerged-orifice flow coefficient of discharge; ft, feet; ft^3/s, cubic feet per second;--, not definable]

Tainter or roller gate number	Date of measurement	Static depth					
		h_1 (ft)	h_3 (ft)	h_g (ft)	h_3/h_g	Q (ft^3/s)	C_{gs}
		Roller gates					
1	10/5/92	19.99	12.40	2	6.2	2,890	0.132
	9/16/93	20.16	15.05	5	3	5,790	.265
	4/2/93	20.40	18.01	12	1.5	8,670	.485
2	10/6/92	19.97	12.38	1	12.4	1,250	.057
	8/18/92	19.87	12.32	2	6.2	2,580	.119
	9/16/92	20.36	13.56	3	4.5	3,820	.168
	9/16/93	20.16	15.09	5	3	5,500	.252
	3/30/93	20.10	15.86	7	2.3	6,730	.321
	3/31/93	20.27	16.87	9	1.9	8,180	.410
	4/1/93	20.34	17.70	10	1.8	7,730	.419
	4/2/93	20.40	18.25	12	1.5	8,380	.488
	4/8/93	20.16	18.69	14	1.3	9,980	.686
	4/8/93	20.15	18.69	14	1.3	9,460	.652
3	9/15/92	20.10	13.00	2	6.5	2,630	.118
	4/14/93	21.21	20.64	OPEN	--	12,600	--
4	10/6/92	19.95	12.33	-1	--	650	--
	10/6/92	19.96	12.47	-2	--	1,260	--
	10/6/92	19.88	12.52	-3	--	1,770	--
	10/6/92	19.94	12.33	1	12.3	1,080	.049
	8/18/92	19.83	12.28	2	6.1	2,740	.126
	9/16/92	20.26	13.32	3	4.4	3,910	.173
	3/31/93	20.29	16.79	9	1.9	8,590	.426
	4/1/93	20.35	17.62	10	1.8	8,010	.429
5	8/18/92	19.85	12.28	2	6.1	2,960	0.136

Table 2. Summary of hydraulic-control variables and current-meter discharge measurements at Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota--Continued

Tainter or roller gate number	Date of measurement	Static depth		h_g (ft)	h_3/h_g	Q (ft³/s)	C_{gs}
		h_1 (ft)	h_3 (ft)				
		Tainter gates					
6	10/19/93	15.12	8.50	1	8.5	889	.145
	4/8/93	15.13	13.68	10	1.4	5,040	1.089
7	4/1/93	15.39	12.39	5	2.5	2,300	.382
	4/8/93	15.13	13.67	10	1.4	4,680	1.009
8	10/19/93	15.12	8.52	1	8.5	825	.134
9	10/9/92	15.18	7.86	1	7.9	784	.131
	4/2/93	15.42	13.36	9	1.5	3,660	.680
10	10/8/92	15.01	7.55	1	7.5	729	.126
	9/17/93	15.22	10.18	4.5	2.3	2,920	.455
	5/27/93	14.9	12.09	5	2.4	2,150	.378
	5/26/93	14.98	12.34	7	1.8	3,390	.602
	4/2/93	15.42	13.34	9	1.5	3,690	.683
11	10/8/92	15.03	7.40	1	7.4	771	.134
	3/31/93	15.24	11.48	4	2.9	2,000	.320
	4/1/93	15.38	12.50	7	1.8	3,650	.613
	4/14/93	16.21	15.64	OPEN	--	4,510	--
12	10/7/92	14.87	7.39	1	7.4	752	.132
13	10/7/92	14.91	7.37	1	7.4	751	.132
14	10/7/92	14.91	7.34	1	7.3	778	.137
	3/31/93	15.28	11.64	4	2.9	1,970	.316
15	10/8/92	15.04	7.41	1	7.4	783	.136
	4/7/93	15.03	13.62	9	1.5	2,900	.638
16	10/8/92	15.04	7.41	1	7.4	817	.142
	5/27/93	14.88	12.13	7	1.7	3,330	.589
	4/7/93	15.03	13.60	9	1.5	2,930	.641

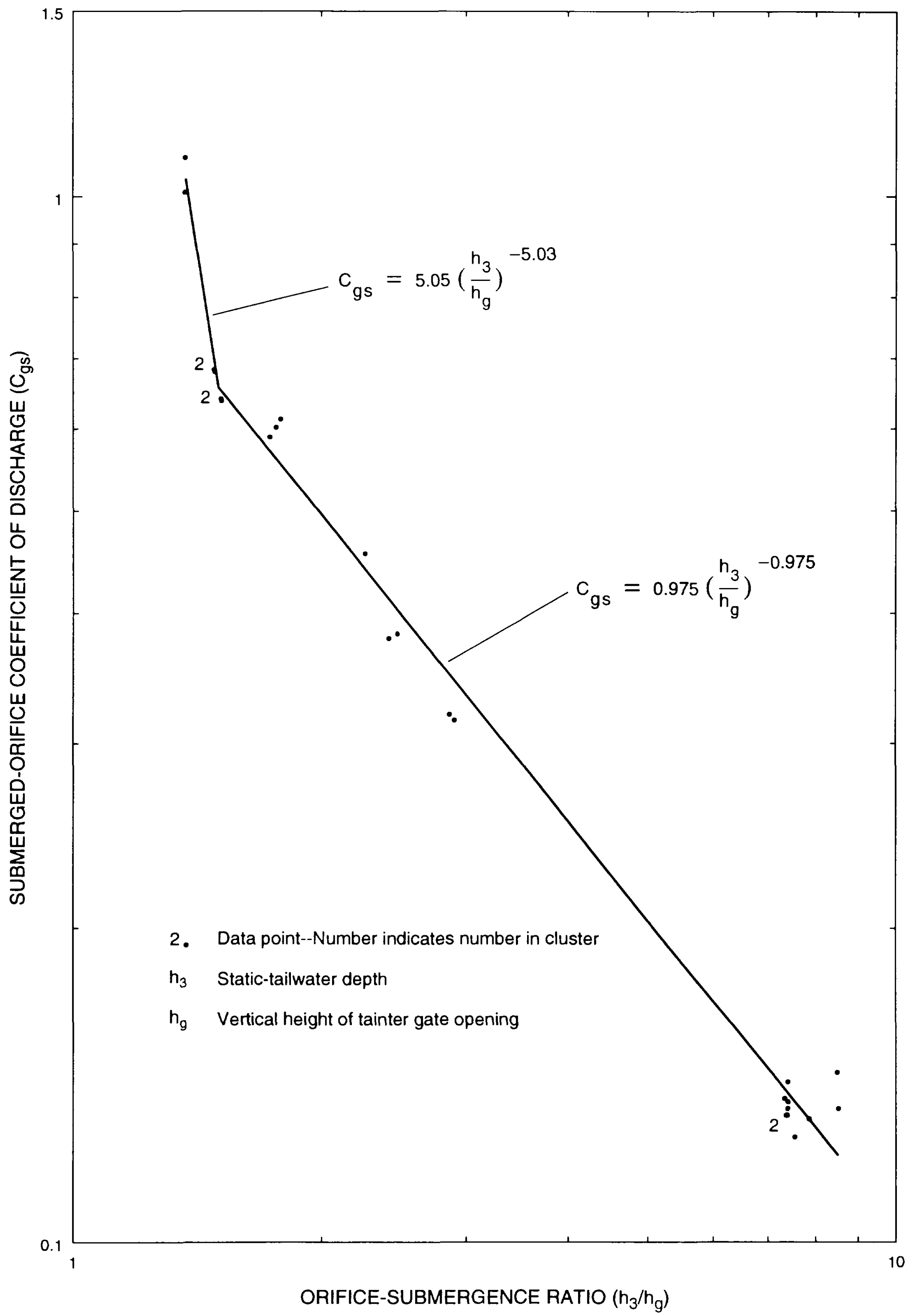

Figure 5. Relation between submerged-orifice discharge coefficients and orifice-submerged ratios for tainter gates, Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

Roller Gates

Twenty coefficients of discharge, C_{gs}, were computed (eq. 2, table 1) by use of the results of the current-meter discharge measurements made at hydraulic-control conditions that satisfy submerged-orifice flow criteria. The computed coefficients ranged from 0.050 (h_g = 1 ft) to 0.302 (h_g = 14 ft) and are listed in table 2. The coefficient of discharge (C_{gs}) and orifice-submergence ratio (h_3/h_g) relation was determined by ordinary-least-squares regression of the natural logarithms of each variable. As can be seen in figure 6, the relation can be represented by two straight lines in log-log space. The breakpoint between the two lines is at an orifice-submergence ratio of about 1.5. The discharge coefficient equation for orifice-submergence ratios from 1.5 to 12.4 is

$$C_{gs} = 0.78\left(\frac{h_3}{h_g}\right)^{-1.03} \qquad (9)$$

For orifice-submergence ratios of 1.3 to 1.5, the equation is

$$C_{gs} = 1.4\left(\frac{h_3}{h_g}\right)^{-2.55} \qquad (10)$$

The relations for C_{gs} in equations 9 and 10 can be substituted into the theoretical submerged-orifice equation of discharge (eq. 2, table 1) to determine the final equations of discharge for the roller gates on Lock and Dam No. 7. For orifice-submergence ratios of 1.5 to 12.4, the equation of discharge is

$$Q = 0.78h_3B\left(\frac{h_3}{h_g}\right)^{-1.03}(2g(h_1 - h_3))^{0.5} \qquad (11)$$

For orifice-submergence ratios of 1.3 to 1.5, the equation of discharge is

$$Q = 1.4h_3B\left(\frac{h_3}{h_g}\right)^{-2.55}(2g(h_1 - h_3))^{0.5}, \qquad (12)$$

where Q is the discharge,
h_3 is the static-tailwater depth,
h_3/h_g is the orifice-submergence ratio,
B is the width of the gate,
g is acceleration due to gravity, and
(h_1-h_3) is the static-head differential.

DISCHARGE RATINGS FOR TAINTER AND ROLLER GATES

The discharge equations applicable to submerged-orifice flow at each tainter and roller gate at Lock and Dam No. 7 are summarized in table 3. The constant terms (gate width, gravitational constant, and regression constant) are combined into a single term in each equation in the table.

Discharge rating tables for a headwater elevation of 639.00 ft and normal tailwater elevations and gate openings were developed from the equations for submerged-orifice flow under a single tainter gate (table 4) and a single roller gate (table 5). The discharge through Dam No. 7 for any combination of headwater-tailwater elevations and gate openings, during normal submerged-orifice operating conditions, can be computed by use of the equations of discharge given in table 3.

SUMMARY

Lock and Dam No. 7 includes 11 tainter gates and 5 roller gates that are regulated to control the water-surface elevation of the navigation pool and discharge of the Mississippi River, La Crescent, Minn. Discharge relations for these tainter and roller gates during normal operating conditions have been developed and are presented in this report. These relations can be used by the U.S. Army Corps of Engineers (St. Paul District) in their water-control management of the upper Mississippi River Basin. During high flow, all gates are raised out of the water to allow open-river flow. This unregulated condition was not evaluated in this study.

Fifty-two current-meter measurements of discharges that ranged from discharge too low to measure to 12,600 ft^3/s were made in the forebays

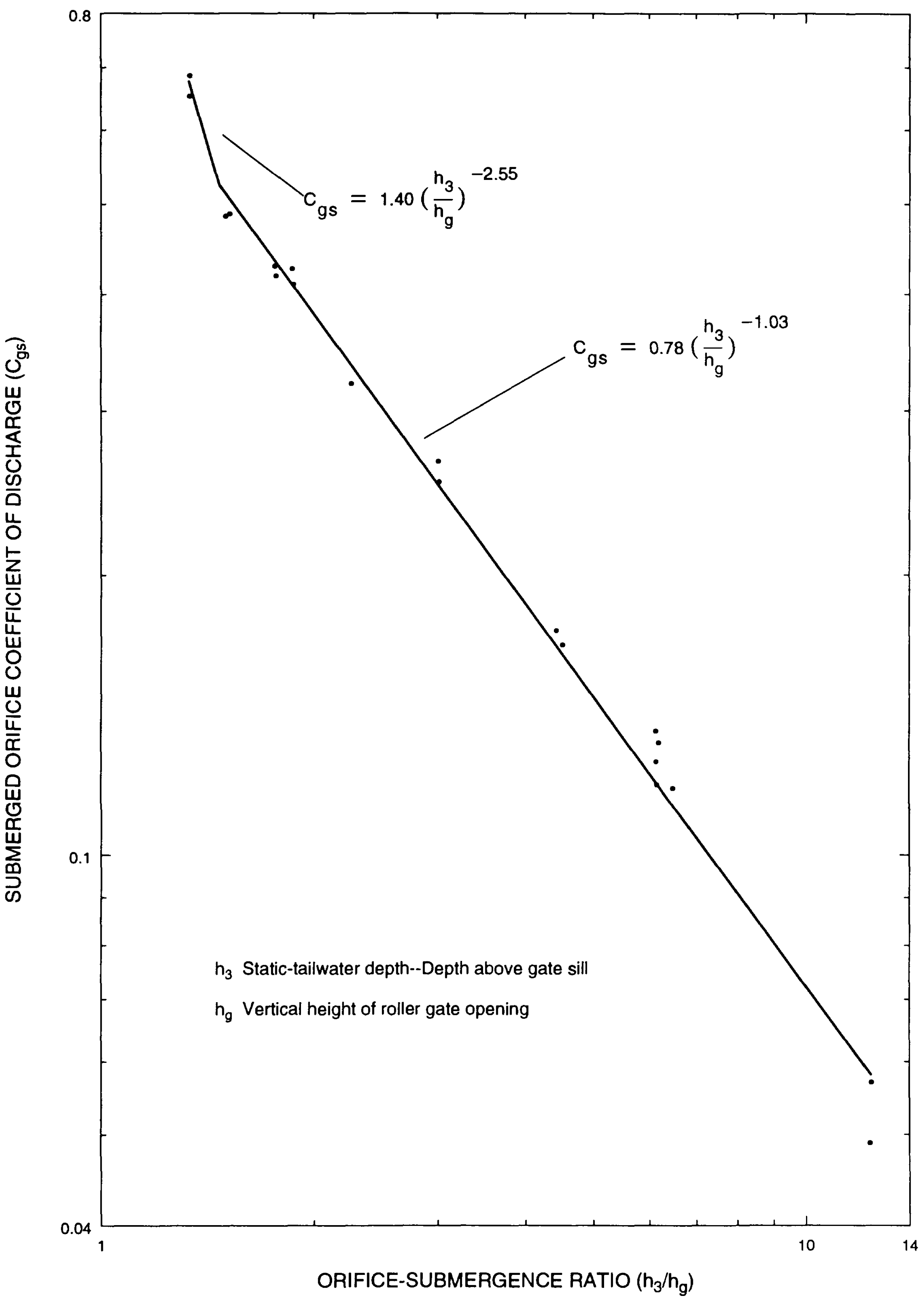

Figure 6. Relation between submerged-orifice discharge coefficients and orifice-submerged ratios for tainter gates, Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

Table 3. Summary of theoretical discharge equations for submerged-orifice flow under a single tainter or roller gate at Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

[≤, less than or equal to; h_3, static-tailwater depth, in feet; h_g, vertical height of tainter or roller gate opening, in feet; Q, discharge, in cubic feet per second; h_1, static-headwater depth, in feet; g, acceleration due to gravity, in feet per second squared]

Flow control	Hydraulic-control conditions	Equation of discharge	Equation number
Tainter gate	$1.5 \leq \frac{h_3}{h_g} \leq 8.5$	$Q = 274h_3 \left(\frac{h_3}{h_g}\right)^{-0.975} (h_1 - h_3)^{0.5}$	7
Tainter gate	$1.4 \leq \frac{h_3}{h_g} \leq 1.5$	$Q = 1420h_3 \left(\frac{h_3}{h_g}\right)^{-5.03} (h_1 - h_3)^{0.5}$	8
Roller gate	$1.5 \leq \frac{h_3}{h_g} \leq 12.4$	$Q = 500h_3 \left(\frac{h_3}{h_g}\right)^{-1.03} (h_1 - h_3)^{0.5}$	11
Roller gate	$1.3 \leq \frac{h_3}{h_g} < 1.5$	$Q = 899h_3 \left(\frac{h_3}{h_g}\right)^{-2.55} (h_1 - h_3)^{0.5}$	12

of selected tainter and roller gates. A total of 24 coefficients of discharge (C_{gs}) ranging from 0.126 to 1.089 were used to define the submerged-orifice discharge-coefficient relation for the 11 tainter gates. Twenty coefficients of discharge (C_{gs}) ranging from 0.050 to 0.302 were used to define the submerged-orifice discharge-coefficient relation for the five roller gates. Submerged-orifice flow was the predominant flow regime at Lock and Dam No. 7. Discharge was measured at three different tainter gates with the gates closed ($h_g = 0$) to evaluate the tainter-gate leakage-discharge relations. No measurable leakage was observed.

From these relations, the equations of discharge (two for tainter gates and two for roller gates) were developed that express discharge per gate (Q) as a function of the discrete hydraulic-control variables of static-headwater depth (h_1), static-tailwater depth (h_3), and vertical height of gate opening (h_g). The four equations of discharge are presented so that a tainter or roller gate elevation-discharge rating can be computed for any discrete combination of headwater-tailwater elevations and gate opening. Discharge rating tables for submerged-orifice flow under a single tainter gate and a single roller gate are given for normal navigation pool (headwater) elevations of 639.00 ft and selected tailwater elevations.

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Table 4. Discharge rating table for a tainter gate with submerged-orifice flow for normal headwater and tailwater elevations at Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

[ft, feet; ft^3/s, cubic feet per second; --, outside normal control conditions for Lock and Dam No. 7]

Gate opening (ft)	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	630.50	631.00	631.50	632.00	632.50	633.00
0.5	426	414	401	388	--	--
1.0	837	813	789	763	737	709
2.0	1,640	1,600	1,550	1,500	1,450	1,390
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	632.50	633.00	633.50	634.00	634.50	635.00
3.0	2,150	2,070	1,980	1,890	1,800	1,700
4.0	2,850	2,740	2,630	2,510	2,380	2,250
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	634.50	635.00	635.50	636.00	636.50	637.00
5.0	2,960	2,790	2,620	2,420	2,220	1,980
6.0	3,530	3,340	3,120	2,900	2,650	2,370
7.0	4,110	3,880	3,630	3,370	3,080	2,750
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	635.5	636.00	636.50	637.00	637.50	638.00
8.0	4,920	3,840	3,500	3,140	2,720	2,220
9.0	--	6,940	5,370	4,100	3,050	2,490
10	--	--	--	6,970	5,180	3,660

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U.S. Army Corps of Engineers, 1971, Mississippi River nine foot channel navigation project: La Crescent, Minn., Reservoir regulations manual, Lock and Dam No. 7, appendix 7.

Table 5. Discharge rating table for a roller gate with submerged-orifice flow for normal headwater and tailwater elevations at Lock and Dam No. 7 on the Mississippi River, La Crescent, Minnesota

[ft^3/s, cubic feet per second; ft, feet; --, outside normal control conditions for Lock and Dam No. 7]

Gate opening (ft)	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	630.50	631.00	631.50	632.00	632.50	633.00
1.0	1,360	1,310	1,270	1,230	1,180	1,130
2.0	2,770	2,680	2,600	2,510	2,410	2,310
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	631.50	632.00	632.50	633.00	633.50	634.00
3.0	3,940	3,800	3,660	3,510	3,360	3,200
4.0	5,300	5,120	4,920	4,730	4,520	4,300
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	633.00	633.50	634.00	634.50	635.00	635.50
5.0	5,950	5,690	5,420	5,130	4,840	4,520
6.0	7,170	6,860	6,540	6,190	5,830	5,450
7.0	8,410	8,040	7,660	7,260	6,840	6,390
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	634.50	635.00	635.50	636.00	636.50	637.00
8.0	8,330	7,850	7,330	6,780	6,190	5,530
9.0	9,410	8,860	8,280	7,660	6,990	6,240
10	10,500	9,870	9,230	8,540	7,790	6,960
	Discharge, in ft^3/s, for a headwater elevation of 639.00 ft and indicated tailwater elevations, in ft					
	635.50	636.00	636.50	637.00	637.50	638.00
11	10,200	9,420	8,590	7,680	6,640	5,420
12	12,300	10,900	9,500	8,400	7,260	5,930
13	15,100	13,400	11,700	9,980	8,280	6,490
14	18,200	16,100	14,100	12,100	10,000	7,840