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Hydraulic Evaluation of Discharge Over Rock Closing Dams on the Upper Mississippi River

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Introduction

Prototype data was used for calibrating a weir equation to improve predictions of discharge over closing dams on the Upper Mississippi River (UMR). Closing dams are weir-like rock structures constructed across secondary channels to reduce flow break-outs from the main channel to backwater areas. Most of the closing dams in the St. Paul District reach of the UMR were constructed over 100 years ago as part of inland navigation system improvements. Originally constructed as emerged structures, they were permanently submerged when the locks and dams were constructed in the mid 1930's. In the last decade, some of the original closing dams have been modified, and new ones have been constructed, both for navigation channel improvement and for habitat rehabilitation. Being able to accurately predict the discharge over closing dams, will result in better management decisions and project designs.

Variable List

- **H** = Depth of headwater over structure crest
- **h** = Depth of tailwater over structure crest
- **hl** = Head loss across structure (ie. hl = H - h)
- **h/H**= submergence ratio
- **A** = Wetted area of structure (based on Tailwater)
- **L** = Crest length of structure (ie. lateral dimension)
- **W** = Crest width (ie. upstream to downstream measurement)
- **Q** = Discharge
- **Cf** = Weir coefficient for free flow
- **Cs** = Weir coefficient for submerged flow
- **g** = acceleration of gravity
- **R** = Hydraulic Radius of rock structure

Available Prototype Data

Hydrodynamic and geometric data for several closing dams (or rock weirs) are listed in Table 1. This information was obtained through the St. Paul Districts', River Monitoring Program.

Table 1. Hydrodynamic and geometric data at closing dams.

Benover Slough Rock Weir, Pool 8, UMR River Mile 686.7								
L/D 8 Flow (CFS)	Site Flow (CFS)	hl (ft)	A (ft2)	L (ft)	W (ft)	H (ft)	h (ft)	Date of Measurements
115650	2565	0.28	640	150	20	4.53	4.25	04/21/93
81850	1804	0.23	575	148	20	4.11	3.88	05/04/93
77625	1517	0.20	480	148	20	3.45	3.25	06/02/93
Wisconsin Channel Closing Dam, Pool 4, UMR River Mile 793.1								
L/D 3 Flow (CFS)	Site Flow (CFS)	hl (ft)	A (ft2)	L (ft)	W (ft)	H (ft)	h (ft)	Date of Measurement
16000	3580	.021	2870	640	50	4.5	4.48	10/21/92
Belvidere Slough, Closing Dam 2, Pool 5, UMR River Mile 747.5								
L/D 5 Flow (CFS)	Site Flow (CFS)	hl (ft)	A (ft2)	L (ft)	W (ft)	H (ft)	h (ft)	Date of Measurement
30350	3282	0.06	1775	584	50	3.1	3.04	10/22/92
Peterson Lake Rock Weir, Site 8, Pool 4, UMR River Mile 754.4								
L/D 4 Flow (CFS)	Site Flow (CFS)	hl (ft)	A (ft2)	L (ft)	W (ft)	H (ft)	h (ft)	Date of Measurement
97600	3473	0.36	881	190	5	5	4.64	04/17/96
Sommers Chute Rock Weir, Pool 7, UMR River Mile 706.4								
L/D 7 Flow (CFS)	Site Flow (CFS)	hl (ft)	A (ft2)	L (ft)	W (ft)	H (ft)	h (ft)	Date of Measurements
68300	15800	0.44	2770	410	15	7.2	6.76	03/21/95
77500	20200	0.57	2890	410	15	7.6	7.03	03/27/95
53700	11800	0.27	2675	410	15	6.8	6.53	06/06/95
33650	5890	0.09	2580	410	15	6.4	6.31	07/08/95
27200	5000	0.04	2560	410	15	6.3	6.26	09/18/95

Review of Weir Equations and Coefficients

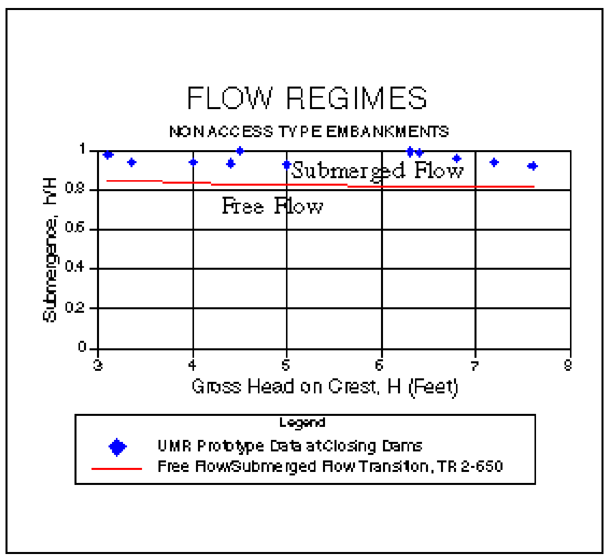
Closing dams are essentially broad crested weirs, and if a weir coefficient can be determined, and other physical characteristics calculated or measured, discharge over the structure can be predicted. The discharge characteristics at weirs are satisfied by the following two equations:

Free Flow: $Q = Cf * L * H^{3/2}$

Submerged Flow: $Q = Cs * L * h * (2g*hl)^{1/2}$

The criteria for free versus submerged flow is based on the relationship between tailwater and headwater depth (Reference 3, Arkansas River Study). A plot of this is shown on Figure 1, along with the prototype data measured at closing dams in the St. Paul District. In all cases, flow was submerged. Because of this, the focus of this study will be on determining representative values of Cs for use in the submerged flow equation.

Figure 1 - Prototype data from St Paul District Closing Dams Plotted on Plate 40 of Waterways Experiment Sation Technical Report 2-650 (reference 3)



Relationships between the discharge coefficient and flow characteristics at the structure are available from references 1 through 4. In the Arkansas River Study (Reference 3), Cs varied from 1.2 to 2, depending on the submergence ratio h/H. In a similar Waterways Experiment Station study on channel control structures for the Souris River, Minot, North Dakota (Reference 2) a weir coefficient of 1.25 was used to predict flow over rock weirs. Yarnell (Reference 4), used the free flow equation for all flow conditions and found a wide range of weir coefficients.

In the Arkansas River study, it was concluded that the roughness of the four stone gradations didn't have an appreciable effect on discharge characteristics. Gradations investigated were both coarser and finer than those typically used by the St. Paul District in closing dam construction. However, in the 1964 USGS report "Discharge Characteristics of Embankment Shaped Weirs" it was concluded that boundary roughness affected the coefficient of discharge and that because of this the embankment width was important also.

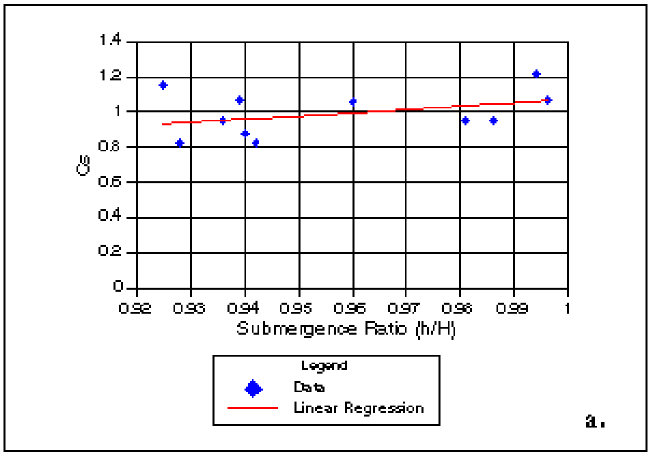
Calculated Weir Coefficient Based on Field Data

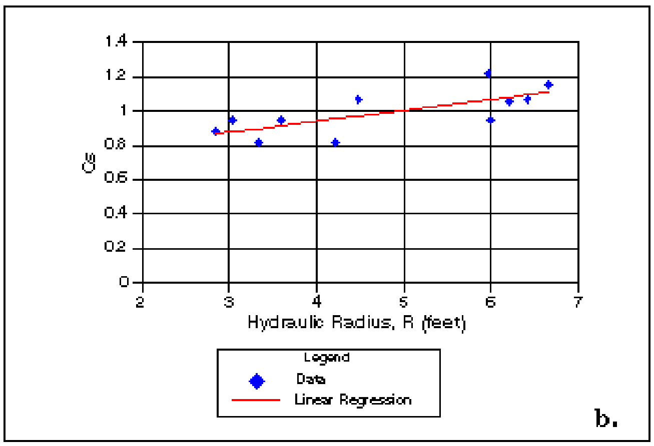
Using the available prototype data, the equation for submerged flow was solved for Cs (Table 2). The average value of Cs of 0.99 (range of 1.22 to 0.82) is less than those found in the literature. For example, Plate 44 of the Arkansas River Report gives values of Cs of 1.3 to 2.0 for the same range of submergence ratios. Plots of Cs versus hydrodynamic and structure characteristics are shown on Figure 2. There appears to be weak trends of increasing weir coefficient value with increasing submergence ratio and hydraulic radius (R^2 = 0.14 and 0.53 respectively). Best-fit lines were drawn showing this trend. No trend was apparent between weir coefficient and weir width.

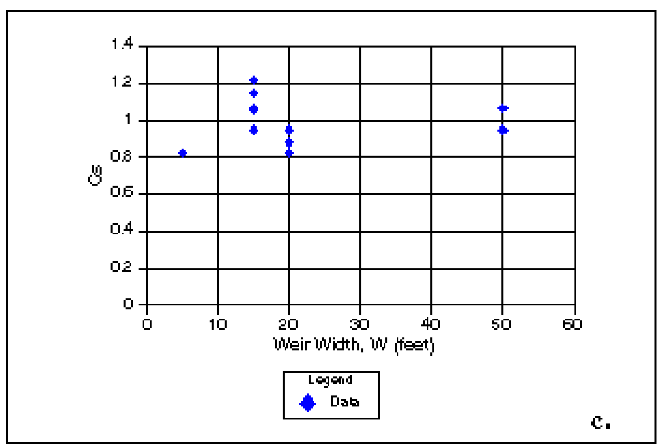
Table 2. Hydrodynamic data, geometric data, and calculated values of Cs at closing dams.

Site	Date	Cs	R (ft)	h (ft)	h/H	W (ft)
Benover Slough	04/21/93	0.95	3.60	4.12	.936	20
Benover Slough	05/04/93	0.82	3.33	3.77	.942	20
Benover Slough	06/02/93	0.88	2.85	3.15	.940	20
Wisconsin Channel	10/21/92	1.07	4.48	4.48	.996	50
Belvidere Slough	10/22/92	0.95	3.04	3.04	.981	50
Sommers Chute	03/21/95	1.07	6.41	6.76	.939	15
Sommers Chute	03/27/95	1.15	6.65	7.03	.925	15
Sommers Chute	06/06/95	1.06	6.20	6.53	.960	15
Sommers Chute	07/08/95	0.95	6.00	6.31	.986	15
Sommers Chute	09/18/95	1.22	5.96	6.26	.994	15
Peterson Lake, Site 8	04/17/96	0.82	4.21	4.64	.928	5
Averages		0.99				

Figures 2a,2b, and 2c: Submerged Flow Weir Coefficent, Cs, versus Closing Dam Prototype Data







Conclusions

a. Flow over closing dams on the Upper Mississippi River is usually submerged and the equation for submerged flow should be used with a weir coefficient of 0.99.

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$Q = Cs * L * h * (2 g * hl)^{1/2}$ Cs = 0.99

b. The submerged flow weir coefficient increases slightly with increasing submergence ratio and hydraulic radius (Figure 2). No trend was apparent between the weir coefficient and weir width.

References:

1. U.S Geological Survey Water Supply Paper 1617-A "*Discharge Characteristics of Embankment Shaped Weirs*" 1964

2. Waterways Experiment Station Report HL-81-3 "*Channel Control Structures for Souris River, Minot,ND*" 1981

3. Waterways Experiment Station Technical Report 2-650, "*Stability of Riprap and Discharge Characteristics, Overflow Embankments, Arkansas River, Arkansas*". 1964

4. Yarnell, D.L. and F.A. Nagler (1930) *Flow of Flood Water Over Railway and Highway Embankments*. Public Roads, Vol 11, Number 2.