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Discharge Correlations for Spillways with Radial Gates

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ABSTRACT

Equations used at the Tennessee Valley Authority (TVA) to compute free and gated (orifice) discharges through spillways with radial gates are presented along with correlations based on TVA model test data for discharge coefficients and submergence factors. The correlations and data may be applicable for estimating discharges through gated spillways that are similar to those at TVA and for which specific model test data are unavailable. Included in this paper, perhaps for the first time in the literature, are correlations and data indicating the headwater at which flow begins the transition from free discharge to gated discharge, the variation in the orifice discharge coefficient as headwater rises above the transition point, and the effect of tailwater submergence on gated discharge for given gate openings.

Keywords: *spillway, discharge, radial gate.*

1. INTRODUCTION

In recent years, the Tennessee Valley Authority (TVA) has developed or revised discharge rating curves, or "dam rating curves" (DRCs), for every dam in their river system for use in probable maximum flood (PMF) routing studies. Literature searches during this work revealed the lack of publicly available data for predicting discharges through spillways with radial gates. For a given gate opening, flow over a gated spillway may be free discharge or gated discharge, depending on headwater elevation, and may also be affected by tailwater submergence. Correlations for predicting free discharge and the effects of tailwater submergence on free discharge are available, at least for spillways with standard or ogee crests (e.g., USBR, 1987; USACE, 1988), but no data were found indicating the headwater at which flow begins the transition from free discharge to gated discharge or the discharge coefficients in the transition region. A curve showing a discharge coefficient as a function of radial gate opening for headwaters well above the transition region is available (USACE, 1988), but no data were found indicating submergence effects on radial gated flows.

For many of its spillways, the Tennessee Valley Authority (TVA) has model test data from which relationships between discharge, headwater, tailwater, and gate opening have been developed and used to generate spillway discharge tables specifying gate arrangements (gate openings and combinations of gates) for achieving desired discharges at various headwater and tailwater combinations. Normalized correlations developed using model test data from several of the tested spillways have been used to generate spillway discharge tables for TVA dams without specific model test data and without tailwater submergence effects. The normalized correlations, especially those for specifying orifice discharge coefficients for gated flows, may be useful for application to other spillways for which model test data are unavailable. Model test data from two spillways (Nickajack and Tellico) where tailwater submergence affects gated discharges under normal operating conditions have also been put into normalized form, making them at least helpful for estimating submergence effects on gated flows at dams for which model test data are unavailable.

Kirkpatrick (1957) presented model test data collected for eleven TVA spillways and plotted the free discharge coefficient data for nine of them against normalized head, using the "design head" for a standard crest as the reference head. As shown by the examples in Figure 1, in which several TVA spillway crests are compared with a standard crest as specified by the USACE (1988), most TVA crests are not standard, typically having a milder downstream slope than a standard crest to prevent negative pressures at moderately low discharges. Kirkpatrick estimated a standard crest design head, H_o, for each spillway after comparing its shape with that of a standard crest. This technique was later applied to estimate design heads for additional spillways for which model test data were available. The design heads were used to develop normalized correlations for the head at which the overflowing nappe first touches the lip of a partially opened gate and for the orifice flow discharge coefficients for heads above the gate lip (Harshbarger et. al., 1985).

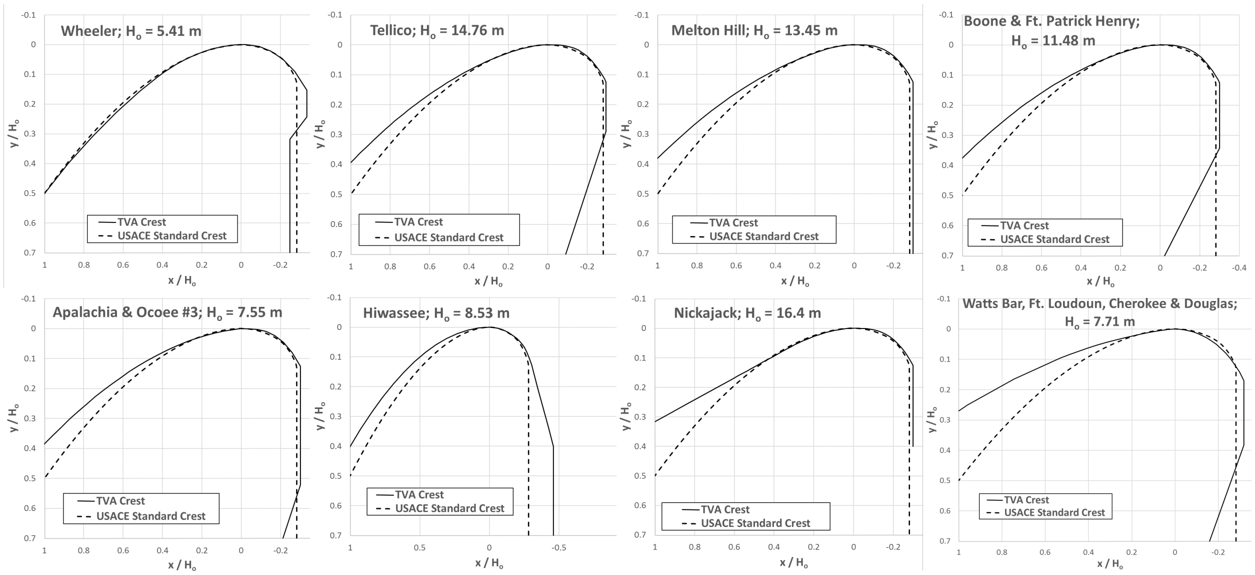

Figure 1. TVA Crests Compared to USACE Standard Crest

2. EQUATIONS FOR FLOW OVER A GATED SPILLWAY

Figure 2 illustrates radial gate geometry and defines variables indicating gate position. Gate opening, G, may be indicated by the vertical distance between the gate lip and the spillway surface, G_v; or by the minimum, or normal-to-the-spillway surface, distance between the gate lip and the spillway surface, G_n. Gate position may be indicated by the vertical opening above the crest centerline, V, by G, or by angle β or ϕ.

Figure 3 illustrates discharge under a partially opened radial gate on a spillway for conditions where the overflowing nappe just touches the lower lip of the gate. This condition occurs when $H_c = H_{L1}$ where $H_{L1} = H_{L1}(G)$ = value of H_c at which a rising, overflowing nappe first impinges on the lip of a gate opened to position G. The discharge under the gate is free discharge for $H_c <= H_{L1}$ and gated (or orifice) discharge for $H_c > H_{L1}$.

Free discharge is computed using a weir-type equation as follows (neglecting pier contraction and abutment effects):

$$Q_f = S_f C_f L_c H_c^{3/2} \tag{1}$$

in which Q_f = free discharge, $S_f = S_f(d/H_c)$ = tailwater submergence factor, $C_f = C_f(H_c)$ = discharge coefficient, $H_c = HW - z_c$ = total energy head on overflowing crest, z_c = crest elevation, HW = headwater elevation, TW = tailwater elevation, $d = TW - z_c$ = tailwater submergence, and L_c = length of overflowing crest (width of spillway bay). The TVA physical models typically included three to five spillway bays and the piers between them, with a half-pier at each bounding wall in the flume. Consequently, the effects of pier contractions are implicitly included in the discharge coefficients derived from the model test data.

Figure 4 depicts flow under a partially opened radial gate with headwater elevation well above the gate lip. For tailwater submergence, d, less than a transition value, d_1, gated discharge is computed using an orifice equation as follows:

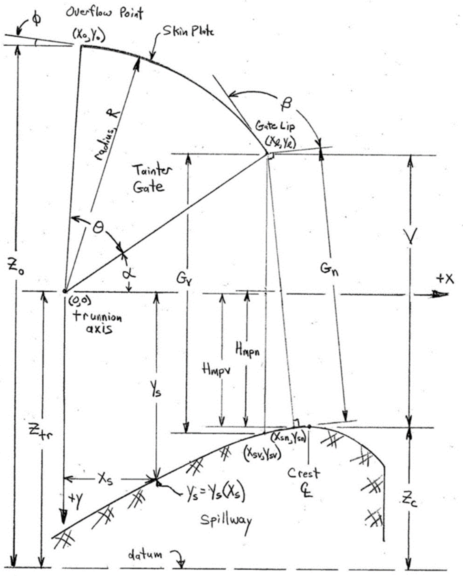

Figure 1. Definition Sketch for Radial Gate Geometry

$$Q_{g1} = C_{g1} S_{g1} G L_c \sqrt{2g\left(H_c - H_{mp}\right)} \tag{2}$$

in which Q_{g1} = gated discharge; $d_1 = d_1(G, H_c)$ = transition value of tailwater submergence, d; $G = G_v$ or G_n = gate opening for current gate setting as used in the determination of C_{g1} from model test data; $C_{g1} = C_{g1}(G, H_c\text{-}H_{L1})$ = discharge coefficient; $S_{g1} = S_{g1}(G, d/H_c, H_c)$ = tailwater submergence factor; g = acceleration of gravity; and H_{mp} = H_{mpv} or H_{mpn} = the elevation of the midpoint of the opening G_v or G_n minus the crest elevation z_c as used in the determination of C_{g1} from model test data.

For d greater than d_1, gated discharge is computed using the alternate equation:

$$Q_{g2} = C_{g2} G L_c \sqrt{2g(H_c - d)} \tag{3}$$

in which Q_{g2} = gated discharge; and $C_{g2} = C_{g2}(G)$ = discharge coefficient.

In the presentations below, H_{L1} and C_{g1} are based on G_v and H_{mpv} as the physical and normalization parameters to be consistent with the correlations provided by Harshbarger et. al (1985). However, d_1, C_{g2}, and S_{g1} are based on G_n and H_{mpn} as the physical and normalization parameters to be consistent with the definitions of these relationships in TVA software for computing spillway discharge.

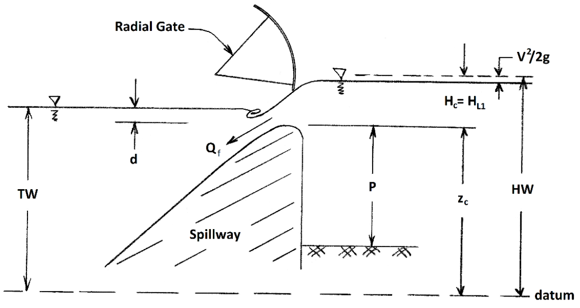

Figure 2. Transition HW between Free and Gated Discharge

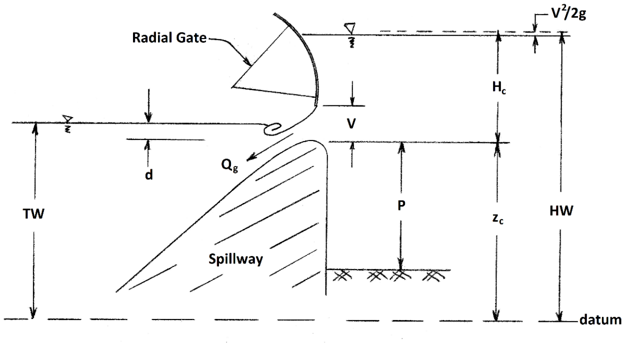

Figure 4. Gated Discharge under Spillway Gate

3. COEFFICIENTS FOR FREE DISCHARGE

The free discharge coefficient and submergence factor relationships, $C_f(H_c)$ and $S_f(d/H_c)$, are both significantly affected by variations in crest shape and upstream depth, P. In addition, the submergence factor relationship is also affected by downstream depth and apron details. The TVA model test data are not sufficient to define general correlations for these relationships, but a few examples are illustrated here.

Figure 5 compares $C_f(H_c/H_o)$ for several TVA dams at which $P/H_o > 2.5$ with $C_f(H_c/H_o)$ for "high overflow dams" (large P/H_o) of standard crest shape. The TVA curves are fits to the model test data for each dam. The legend lists the dams in order of increasing deviation of crest shape from the standard shape. As expected for crest shapes with higher downstream elevations, the discharge coefficients are lower than those for a standard crest. For the TVA crests, the reduction in C_f generally increases with increasing deviation of the crest shape from standard. All curves inFigure 5 represent conditions with adjacent bays open, without abutment effects. As mentioned above, the TVA model test data implicitly include the effects of pier contractions. It is unclear whether or not the same can be said for the USACE curve.

Figure 6 compares $S_f(d/H_c)$ curve fits to model test data for three TVA dams with a curve for an ogee crest with equal upstream and downstream bed elevations (USACE, 1988). Although it may not be obvious from the plot, effects of submergence occur for $d/H_c > 0.2$ for Tellico, $d/H_c > 0.4$ for Watts Bar, and $d/H_c > 0.6$ for Nickajack. Additional free discharge and submergence relationships for TVA Dams were reported by Kirkpatrick (1957).

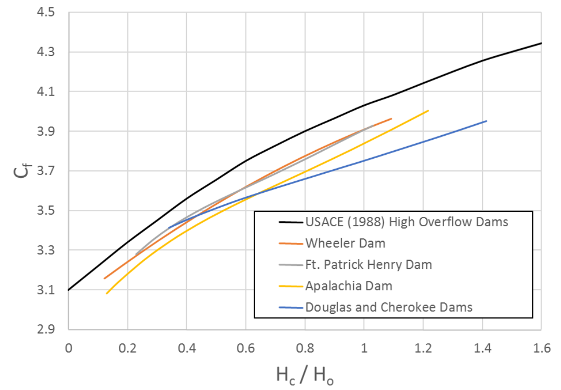

Figure 3. Free Discharge Coefficient Relationships

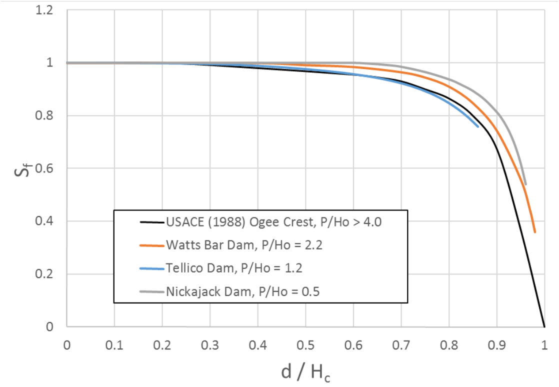

Figure 4. Submergence Factor Relationships

4. TRANSITION HEAD BETWEEN FREE AND ORIFICE DISCHARGE

Figure 7 shows a correlation provided in Harshbarger et. al (1985) for the relationship $H_{L1}/H_o(G_v/H_o)$ compared to the model test data for the five TVA dams from which it was derived. Figure 7 also shows data for Hiwassee Dam, which was not included in the correlation development. The correlation is defined as follows:

$$\frac{H_{L1}}{H_o} = \begin{cases} 1.648\frac{G_v}{H_o} & \cdots for\frac{G_v}{H_o} \leq 0.088 \\ 0.145 + 1.183\left(\frac{G_v}{H_o} - .088\right) & \cdots for\ \frac{G_v}{H_o} > 0.088 \end{cases} \tag{4}$$

The consistency of the data is impressive considering the differences among the spillways as quantified in Table 1, in which R = gate radius (see Figure 2) and x_{seat} = distance between the spillway crest centerline and the gate seat (the location of the gate lip on the spillway surface when the gate is closed). Comparison of the parameters suggests little difference between the Hiwassee Dam spillway and the other TVA spillways listed, but, as shown in Figure 7, the correlation for H_{L1} does not fit the model test data for Hiwassee as well as it fits the model test data for the other dams. Figure 1 illustrates that the upstream face of the Hiwassee spillway is sloped while the upstream faces of the other TVA spillways are vertical, which apparently affects the slope of the $H_{L1}/H_o(G_v/H_o)$ relationship. These results suggest that the correlation defined by Equation 6 is most useful for spillways with vertical upstream faces.

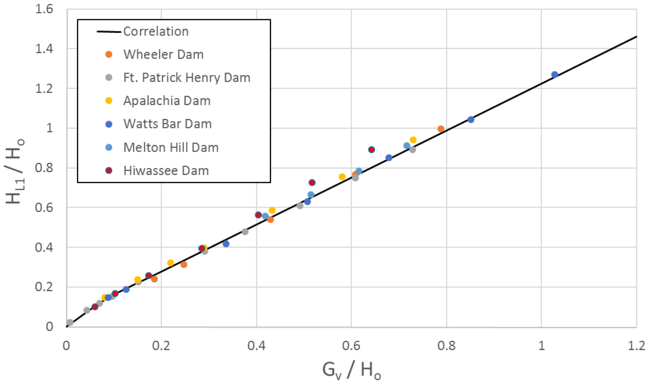

Figure 7. Transition Head, H_{L1}, between Free Discharge and Orifice Discharge

Table 1. Parameter Comparison for TVA Spillways

Dam	H_o (m)	P/H_o	R (m)	L_c (m)	x_{seat}/H_o
Wheeler	5.03	2.6	5.33	12.19	0
Ft. Patrick Henry	10.67	3.2	10.97	10.67	0.152
Apalachia	7.01	4.2	9.75	9.75	0.173
Watts Bar	7.16	2.2	12.19	12.19	0.146
Melton Hill	12.5	0.65	12.5	12.19	0.165
Hiwassee	7.93	4.0	6.86	9.75	0.212

5. DISCHARGE COEFFICIENTS FOR GATED FLOW

Figure 8 and Table 2 show correlations provided by Harshbarger et. al (1985) for the relationship $C_{g1v}(G_v/H_o, H_c\text{-}H_{L1}/H_o)$ as estimated from TVA model test data for Wheeler, Ft. Patrick Henry, Apalachia, Watts Bar, and Melton Hill Dams. Subscript v on C_{g1} indicates that its definition is based on use of G_v and H_{mpv} in Equation 2. The dashed line for $H_c\text{-}H_{L1}/H_o = 0$ is not unique but is determined for any given spillway by equating gated discharge from Equation 2 to free discharge from Equation 1 with $H_c = H_{L1}(G_v/H_o)$. Depending on its shape, it may be necessary to adjust the other curves to ensure that C_{g1v} for all values of $H_c\text{-}H_{L1}/H_o > 0$ are less than those indicated by the dashed line. Because the data for a given G_v indicate that C_{g1v} tends to a constant as $H_c\text{-}H_{L1}$ increases, the correlation for $H_c\text{-}H_{L1}/H_o = 0.1$ is used for $H_c\text{-}H_{L1}/H_o \geq 0.1$. For the range $0.1 \geq H_c\text{-}H_{L1}/H_o \geq 0$, Harshbarger et. al claim a maximum deviation in C_{g1v} of ±2 percent for the dams from which the correlations were developed.

For comparison, Figure 9 shows the relationship $C_{g1v}(G_v/H_o, H_c\text{-}H_{L1}/H_o)$ as developed from specific model test data for six TVA dams. These relationships [in the form $C_{g1n}(V, H_c\text{-}H_{L1})$ where subscript n on C_{g1} indicates that its definition is based on use of G_n and H_{mpn} in Equation 2], with linear interpolation between the specified curves, are used in TVA's spillway discharge calculation software to determine values of C_{g1} for use in computing gated discharges at each dam.

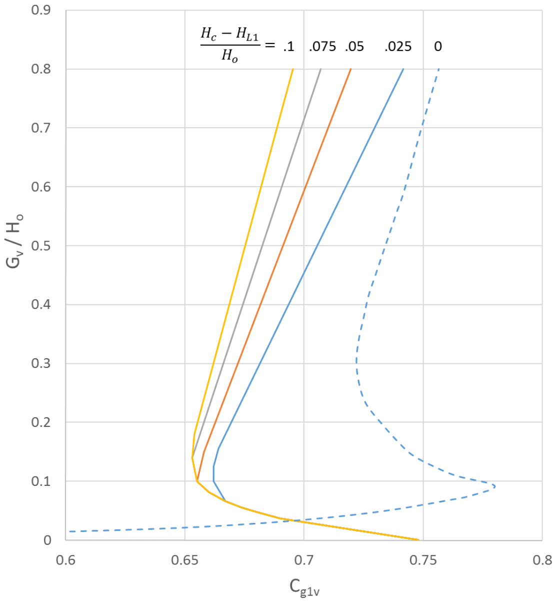

Figure 8. General Correlation for Discharge Coefficient, C_{g1v}

Table 2. Discharge coefficient

H_c-H_{L1}/H_o=0.1		H_c-H_{L1}/H_o=0.075		H_c-H_{L1}/H_o=0.05		H_c-H_{L1}/H_o=0.025	
G_v/H_o	C_{g1v}	G_v/H_o	C_{g1v}	G_v/H_o	C_{g1v}	G_v/H_o	C_{g1v}
0	0.748	0	0.748	0	0.748	0	0.748
0.03	0.7	0.03	0.7	0.03	0.7	0.03	0.7
0.037	0.69	0.037	0.69	0.037	0.69	0.037	0.69
0.0475	0.68	0.0475	0.68	0.0475	0.68	0.0475	0.68
0.055	0.674	0.055	0.674	0.055	0.674	0.055	0.674
0.066	0.667	0.066	0.667	0.066	0.667	0.066	0.667
0.081	0.66	0.081	0.66	0.081	0.66	0.1	0.662
0.1	0.655	0.1	0.655	0.1	0.655	0.125	0.662
0.14	0.653	0.14	0.653	0.15	0.658	0.155	0.664
0.18	0.654	0.8	0.707	0.8	0.720	0.8	0.742
0.8	0.695						

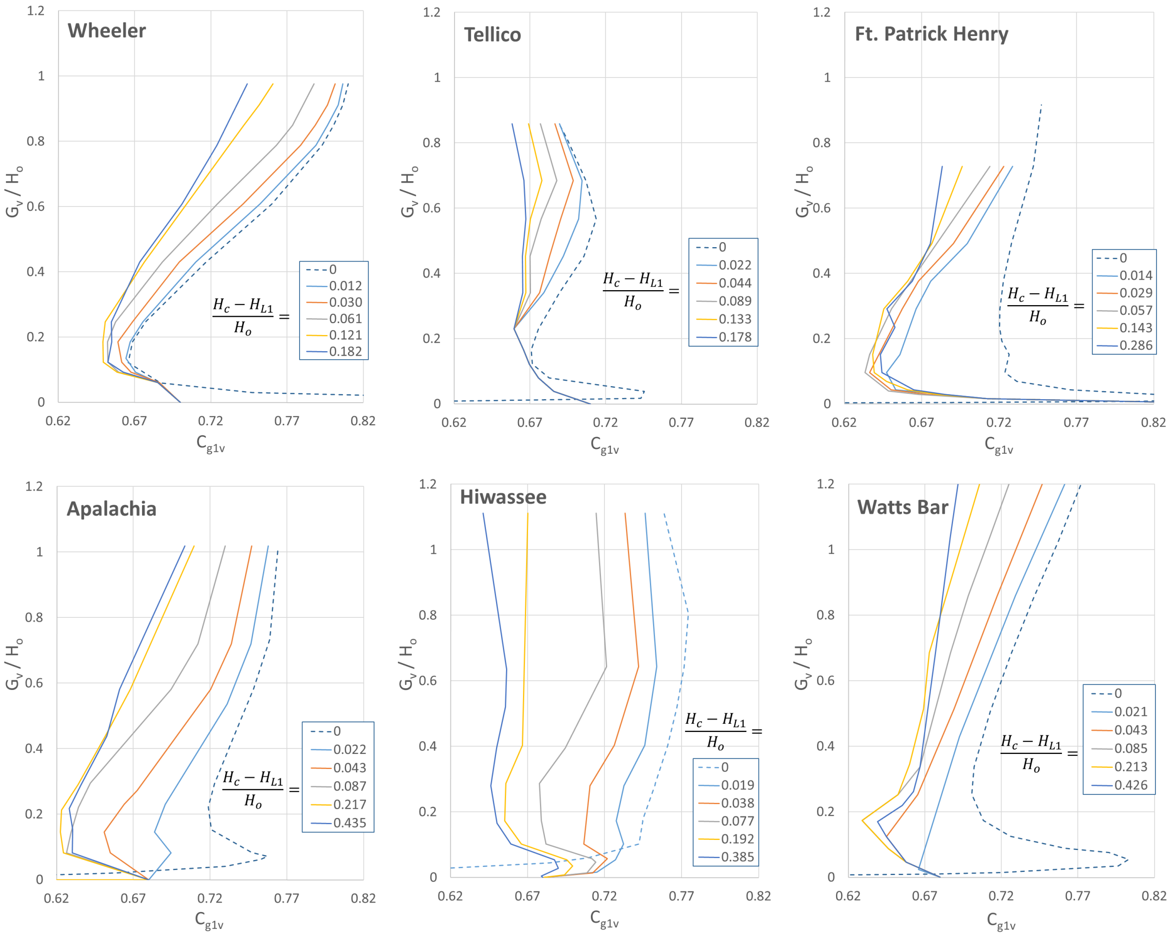

Figure 9. C_{g1v} Relationships for TVA Dams

Figure 10 compares curves developed from TVA model data for $C_{g1n}(\beta)$ (β is defined in Figure 2) at high values of H_c-H_{L1}/H_o with suggested design curves for the same conditions on a standard crest (USACE, 1988). The USACE curve for x_{seat}/H_o = 0 agrees reasonably well with the curve for Wheeler spillway, which is the only represented TVA spillway with x_{seat}/H_o = 0 and is the spillway illustrated in Figure 1 that most resembles a standard crest. However, the USACE curve for 0.3 ≥ x_{seat}/H_o ≥ 0.1 specifies values of C_{g1n} that are 5 to 10 percent higher at large openings (large β) than those for the TVA curves. For a standard crest, the suggested design curves indicate that moving the valve seat downstream from the crest increases the values of C_{g1n}. However, for crests that are not standard, the TVA data suggest the opposite. It is also noted that, as mentioned earlier, the TVA model data implicitly include spillway pier effects, whereas the published data are unclear on this point.

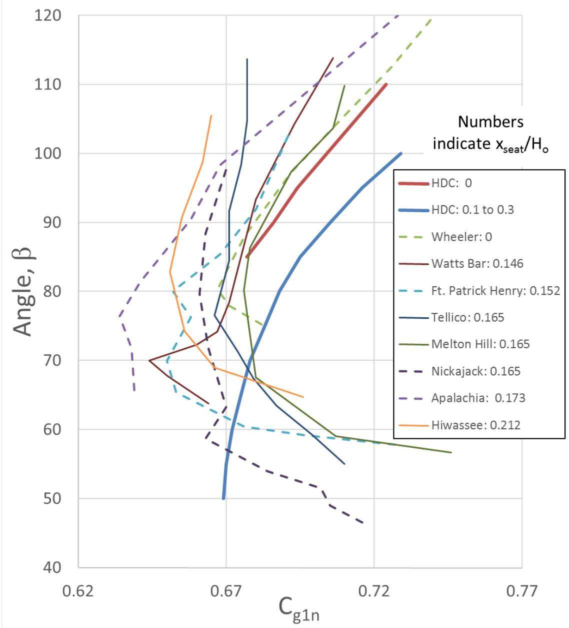

Figure 10. TVA C_{g1n} Compared with Curves from Hydraulic Design Criteria (USACE, 1988)

6. SUBMERGENCE EFFECTS ON GATED DISCHARGE

The model test data for Tellico and Nickajack spillways, which are the only TVA spillways for which data were collected with tailwater submergence affecting gated discharges, indicate that Equation 3, with a value of C_{g2} that is constant or slightly variable with head, is valid for tailwater submergence, d, greater than a transition value, d_1, which may vary with head, H_c. For tailwater submergence below the transition value ($d < d_1$), discharge is computed using Equation 2 with submergence factor $S_{g1} = S_{g1}(G, d/H_c, H_c)$ defined from the model test data.

For three example gate openings, two for Nickajack and one for Tellico, Figure 11 shows the variation of C_{g2n} with both d/G_n and d/H_c for all values of positive d included in the model test data. For the smaller openings (1.024 m and 2.13 m), C_{g2n} becomes approximately constant for values of d exceeding both a minimum d and a minimum value of d/H_c, these two criteria defining d_1. The plots for Nickajack with $V = 6.76$ m show that the model test data range, limited to the expected operating range, was not wide enough at the largest gate openings to determine either d_1 or C_{g2n}. The scatter in these plots also illustrate the reason that C_{g2n} is not simply specified as a function of d/G_n or d/H_c for all values of d greater than zero, but instead, for better precision in computing discharge, S_{g1} is defined and Equation 2 is used to compute discharge for $d < d_1$.

For various gate openings, V, Figure 12 shows the estimated minimum values of d/G_n and d/H_c for which Equation 3 with C_{g2n} is valid for computing gated discharge. For TVA's spillway discharge calculation software, the curves in Figure 12 are extrapolated in order to estimate values for gate openings above those for which values are shown even though they are not needed under normal operating conditions. The transition value of d, d_1, is determined from Equation 5. Figure 13 shows the variation of C_{g2n} with gate opening, V, as estimated from the model test data.

$$d_1(G_n, H_c) = \begin{cases} G_n\left(\frac{d}{G_n}\right)_{min} & \cdots for\ \frac{G_n}{H_c}\left(\frac{d}{H_c}\right) \geq \left(\frac{d}{H_c}\right)_{min} \\ H_c\left(\frac{d}{H_c}\right)_{min} & \cdots for\ \frac{G_n}{H_c}\left(\frac{d}{H_c}\right) < \left(\frac{d}{H_c}\right)_{min} \end{cases} \tag{5}$$

Analysis of the model test data indicates that for any given value of H_c/G_n, a $S_{g1}(d/H_c)$ relationship developed from data for one gate opening can be applied for $d < d_1$ to another gate opening as a reasonable approximation for extrapolation and interpolation purposes. Figure 14 illustrates $S_{g1}(d/H_c, H_c/G_n)$ as developed for gate opening V = 2.13 m at Tellico Dam. The "free discharge" curve is the $S_f(d/H_c)$ relationship, as shown in Figure 6, extended smoothly to $d/H_c = 1$. For this curve and V = 2.13 m, $H_c/G_n = H_{L1}/G_n = 1.44$. The $S_{g1}(d/H_c)$ relationships for $H_c/G_n = 3$ and $H_c/G_n = 6.5$ were determined from the model test data, which are all in the range $3 < H_c/G_n < 6.5$. The range of valid C_{g2n} is below the curved portion and to the right of the vertical portion of the dashed curve representing $d_1(H_c)$. The additional $S_{g1}(d/H_c)$ relationships from other gate openings are added for completeness and to cover the range of unusual operating conditions. The $S_{g1}(d/H_c)$ relationship for $H_c/G_n = 2$ is a composite curve developed from data for several other openings. The $S_{g1}(d/H_c)$ relationship for $H_c/G_n = 8.6$ was developed from the data for V = 1.52 m. For TVA's spillway discharge calculation software, linear interpolation between the curves in Figure 14 is used to determine in-between values for the V = 2.13 m gate opening at Tellico.

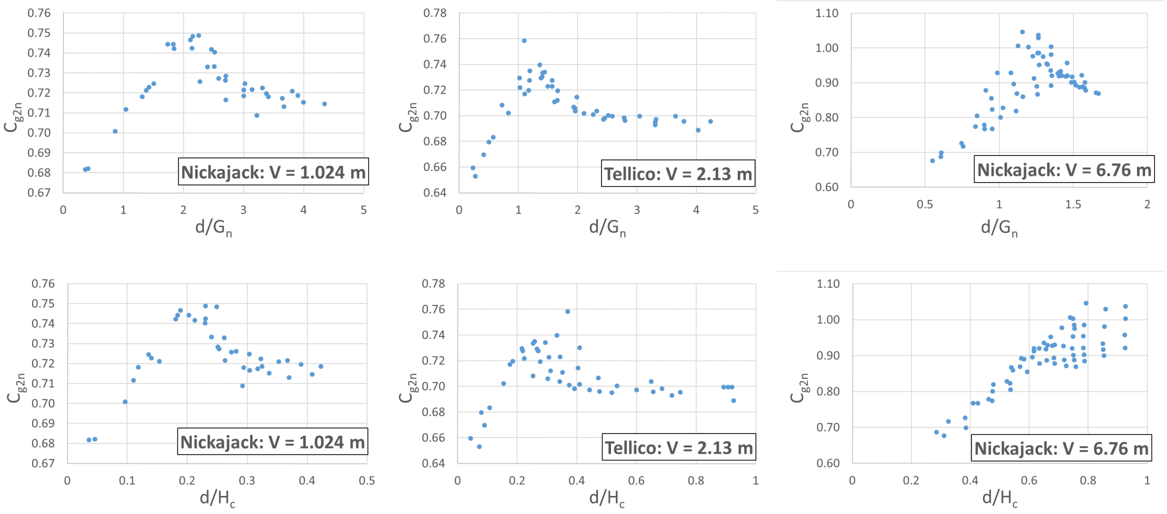

Figure 11. Variation of C_{g2n} with d/G_n and d/H_c

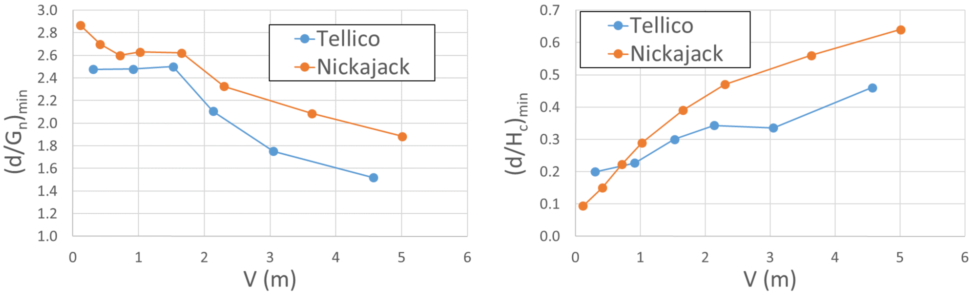

Figure 12. Minimum Values of d for use of C_{g2n}

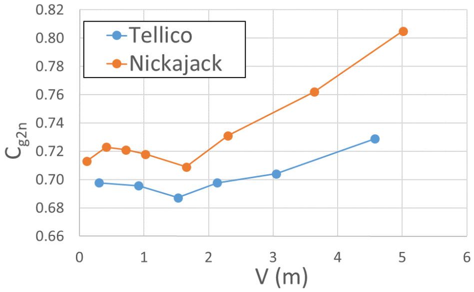

Figure 13. Variation of C_{g2n} with V

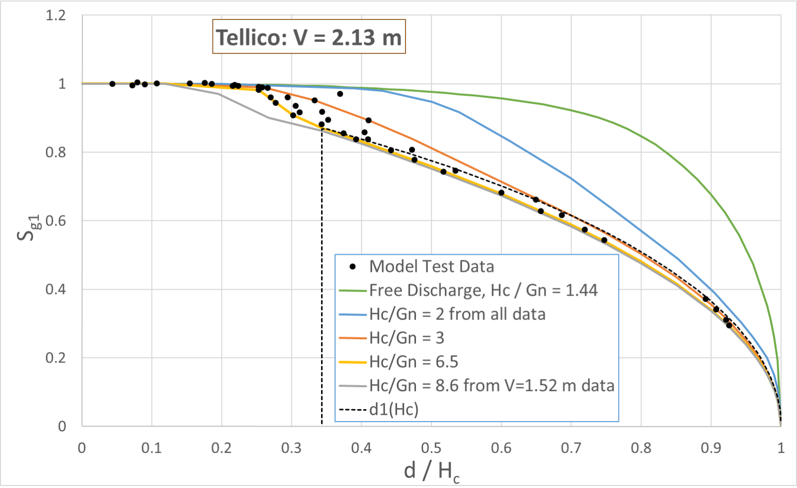

Figure 14. S_{g1} for V = 2.13 m at Tellico Spillway

Figure 15 shows a selection of $S_{g1}(d/H_c)$ relationships for Tellico and Nickajack Dams. The curves labeled “composite” were developed using data from two or more gate openings. The other curves are specific examples for particular gate openings. The lower portions of the curves for $H_c/G_n > 2.3$ were generated using constant values of C_{g2n} to compute S_{g1} from Equations 2 and 3. Figure 15 also illustrates a significant difference between two $S_{g1}(d/H_c)$ relationships for different gate openings at nearly the same value H_c/G_n (3.1 and 3.2). The difference is consistent with the observation that the minimum d/H_c value for submergence effects varies widely with gate opening at Nickajack, from about 0.1 for V = 0.411 m to about 0.6 for $V > \approx 6.7$ m.

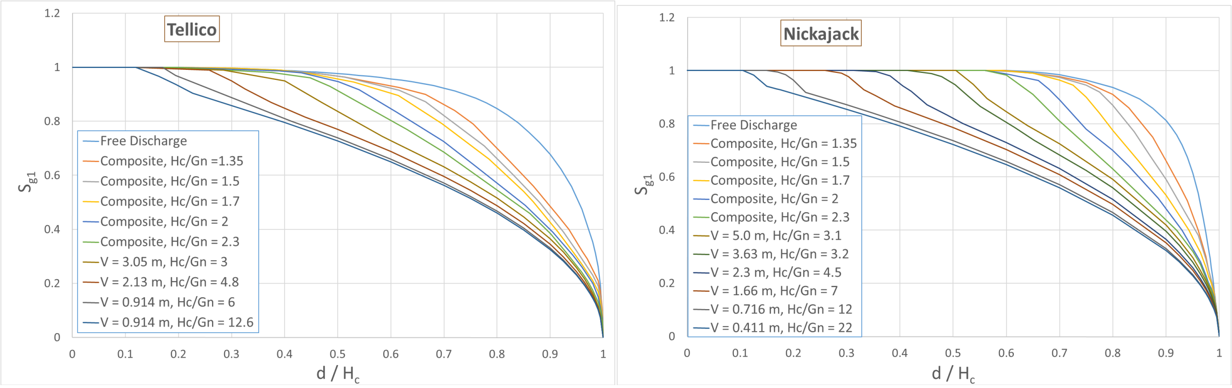

Figure 15. S_{g1} for Tellico and Nickajack Spillways

7. CONCLUSIONS

Data and correlations are presented for radially gated spillway discharge with possible submergence effects based on TVA model test data. The correlations for the transition head, H_{L1}, between free and gated discharge (Figure 7 and Equation 4) and for the gated discharge coefficient, C_{g1}, as a function of gate opening and head (Figure 8 and Figure 9) should provide reasonable estimates of discharge (within 5 percent) for gated spillways that are similar to TVA spillways but for which specific model test data are unavailable. Applicability of data for two TVA dams on submergence effects (Figure 12, Figure 13, Figure 14, and Figure 15) to other spillways is less certain, but it may still be useful when no other data are available. For large gate openings (low H_c/G_n) at other TVA dams, TVA has used the data shown in Figure 15 for the purpose of developing dam rating curves applicable to probable maximum flood conditions. In those cases, the submergence relationship for free discharge was known and was used as the bounding free discharge submergence relationship. For gated discharge submergence, the Tellico data were used for dams at which submergence affects free discharge for $d/H_c >\approx 0.2$, the Nickajack data were used for dams at which submergence affects free discharge for $d/H_c >\approx 0.6$, and an average between the two was used for dams at which submergence affects free discharge for $d/H_c >\approx 0.4$. The accuracy of this approach is uncertain, but for the unusual flood conditions under which gated discharge at large openings is affected by submergence at these dams, the approximation is considered acceptable. For smaller gate openings, a more reasonable approach for estimating submergence effects on gated discharge may be to specify C_{g2} using the data in Figure 13 as a guide and use Equation 3 to compute discharge for all $H_c > H_{L1}$. A drawback of this approach is that the discharge function $Q\ (H_c)$ will have a discontinuity at $H_c = H_{L1}$. Depending on the requirements of the application, this approximation and discontinuity may be acceptable.

8. ACKNOWLEDGMENTS

This work expands and builds on the foundation established by Ken Kirkpatrick, who was TVA's spillway expert for nearly forty years before retiring in the early 1980s.

9. REFERENCES

Creager, W. P. and J. D. Justin, 1950, Hydroelectric Handbook, 2nd Edition, John Wiley & Sons, New York.

Harshbarger, E. D., B. J. Clift, and J. W. Boyd, 1985, "Method for Estimating Discharge at Overflow Spillways with Curved Crests and Radial Gates," TVA (Tennessee Valley Authority) Report WR28-2-900-123, January.

Kirkpatrick, K. W., 1957, "Discharge Coefficients for Spillways at TVA Dams," Trans. American Society of Civil Engineers, Paper No. 2855, vol. 22, pp. 190-210.

USACE (U. S. Army Engineer Waterways Experiment Station), 1988, Hydraulic Design Criteria, Eighteenth issue, Vicksburg, MS.

USBR (U. S. Bureau of Reclamation), 1987, Design of Small Dams, United Stated Department of the Interior, 3rd Edition, Washington DC.