NEW CALIBRATION METHOD FOR SUBMERGED RADIAL GATES

A.J. Clemmens[1]

ABSTRACT

Calibration equations for free-flowing radial gates typically provide sufficient accuracy for irrigation district operations. However, many districts have difficulty in determining accurate discharges when the downstream water level begins to submerge the gate. Based on laboratory studies, we have developed a new calibration method for free-flowing and submerged radial gates that allows for multiple gates and widely varying upstream and downstream channel conditions. The method uses the energy equation on the upstream side of the structure and the momentum equation on the downstream side. An iterative solution is required to solve these two equations, but this allows calibration from free flow to submerged flow right through the transition. Adjustments to the energy equation for free flow are described, along with an additional energy adjustment for the transition to submerged flow. An application is used to describe the new procedure and how it overcomes the limitations of current energy-based methods.

INTRODUCTION

Radial gates are a common water control structure in much of the western United States. Their advantage over vertical sluice gates is that the lifting force is minimal. The U.S. Bureau of Reclamation has used these as a standard structure for nearly a century. They are also used in private irrigation projects, and projects of the U.S. Army Corps of Engineers. These structures are pervasive in canals and regulated streams in the central and western United States.

Calibration methods for free-flowing radial gates are available in standard references and have been used with reasonable success to measure flow. Calibration of submerged flows, however, has had mixed success, with errors up to 50% reported in some cases. These calibration methods are based exclusively on the energy equation. Some use the momentum equation to define the limit between submerged and free flow. However, a major flaw with all these methods is that they are all based on upstream and downstream channels that are the same width and have the same floor elevation as the gate. This rarely occurs in practice. Where multiple gates occur, submerged calibration has proven successful only when all gates are open the same amount and their total width is similar to the width of the downstream channel (e.g., the head of the All American Canal).

[1] Laboratory Director, U.S. Water Conservation Laboratory, 4331 E. Broadway, Phoenix, AZ 85040 bclemmens@uswcl.ars.ag.gov

In 1999, we conducted a study on the calibration of radial gates in the Hydraulics Lab of the U.S. Water Conservation Laboratory. Details of the experimental setup are provided in Tel (2000). In this paper, we present a solution method for submerged radial gates that uses the energy equation on the upstream side of the gate (the same as for free flow) and the momentum equation on the downstream side. A new transition between submerged and free flow is defined as an adjustment to the energy equation.

FREE FLOW

The calibration of flow under a vertical sluice gate is a classic problem in hydraulic engineering and has been studied for more than a century. Montes (1997) provides an excellent summary of the theoretical and experimental studies that have been conducted under free-flow conditions. However, our theoretical understanding of even free-flowing sluice gates is incomplete. For practical application, the errors associated with the theoretical disagreements are relatively small, being at most ± 5%, and within field calibration needs. Field calibrations are often needed anyway because of J-seals, etc. The foundation for the research on submerged flow is a reliance on the free-flow theory, thus it is worth discussion.

The complexity of the problem stems from our inability to theoretically determine the free surface configuration downstream from the gate, even in free flow. The jet emanating from under the gate reaches a minimum depth at the vena contracta (Section 2 in Figure 1). The theoretical difficulties are associated with defining the contraction coefficient δ (ratio of minimum depth y_j to gate opening w) for the variety of flow configurations encountered. In general, the contraction coefficient varies with the angle of the gate θ and the ratio of gate opening to upstream energy head, w/H_1.

If we apply the energy equation between Sections 1 and 2, we get

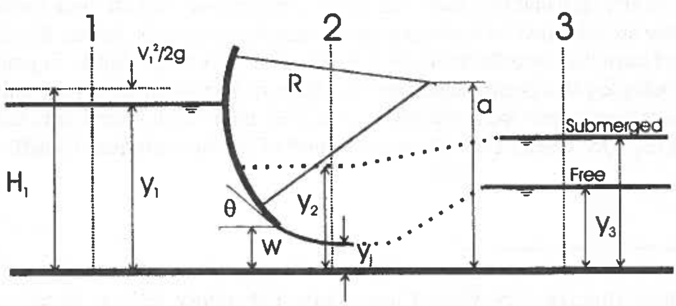

Figure 1. Definition sketch for radial gate.

$$H_1 = H_j + \Delta H = y_j + \alpha_j \frac{v_j^2}{2g} + \xi \frac{v_j^2}{2g} \quad (1)$$

where H_1 is the total head at section 1, H_j is the energy head at the vena contracta, • H is the head loss between Section 1 and the vena contracta, y_j is the depth at the vena contracta or jet, v_j is the average velocity in the jet, α_j is the velocity distribution coefficient for the jet (i.e., correction to the velocity head due to nonuniform velocity), g is the acceleration of gravity, and ξ is the energy loss coefficient. For simplicity, we will assume $\alpha_j = 1$. Any deviation from unity by α_j will end up in ξ, giving a combined coefficient.

Since the discharge is equal to velocity times area, in the jet we have $Q = \delta w b_c v_j$; where $y_j = \delta w$, and b_c is the gate width. Substituting for v_j and y_j in Equation 1 and solving for discharge gives:

$$Q = \delta w b_c \sqrt{\frac{2g(H_1 - \delta w)}{1+\xi}} \quad (2)$$

For a given geometry, this provides a relationship between discharge and upstream energy head, with only the contraction coefficient, •,•and the loss coefficient, ξ, to be evaluated.

This differs substantially from prior solutions of the radial-gate energy equation in several ways. First, it is expressed in terms of upstream energy head rather than depth. This allows one to have an upstream velocity head that is not related to the flow in any one gate, for example when multiple gates and weirs are used. Second, it includes as energy loss term rather than relying on empirical discharge coefficients. And finally, the contraction coefficient is not buried in the discharge coefficient. These differences allow us to determine the head-discharge relationships for a wider range of conditions than other methods.

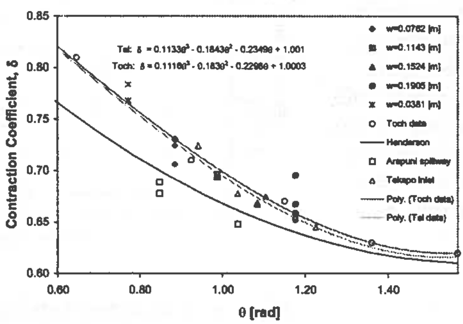

Figure 2. Radial gate contraction coefficient, •,• as a function of gate angle, θ.

In our study, the contraction coefficients were found by measuring the gate opening and measuring the pressure in the jet at the vena contracta with a Prandtl tube. For several runs, we measured the pressure distribution within the jet, and it was essentially hydrostatic, verifying that our single pressure readings were sufficient to define the contraction coefficient. Our resulting contraction coefficients (Fig. 2) were in excellent agreement with those found by Toch (1955) in laboratory studies. The contraction coefficient is strongly influenced by gate angle. We found almost no influence of w/H_1 on the contraction coefficient, in keeping with the results for planar sluice gates (Montes 1997).

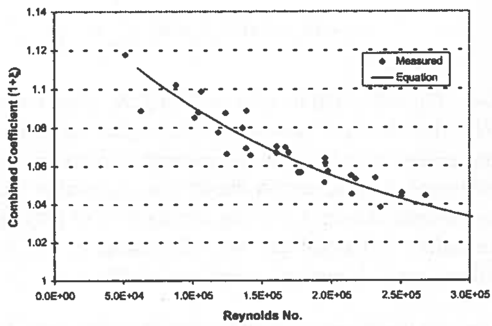

Figure 3. Combined velocity distribution and energy coefficient as a function of entrance Reynolds number for free flowing radial gate.

We chose to relate the measured energy loss to the velocity head in the jet, since the jet velocity head seems to be the most representative of the overall energy head that is causing/influencing the loss (Fig. 3). We found a strong relationship between the energy loss coefficient and the Reynolds number at the upstream face of the gate. Of significance to this research is that these energy losses are relatively high for laboratory models where Reynolds numbers are low. For prototype gates, Reynolds numbers may be an order of magnitude higher, suggesting energy losses on the order of 1% or 2%.

Solution of Equation 2 with the coefficients from Figures 2 and 3 agreed with laboratory data to within about 1% in all but a few cases (Fig. 4).

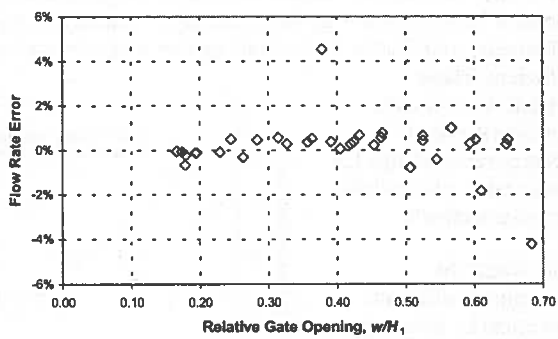

Figure 4. Accuracy of radial gate free-flow discharge computed with energy equation and curve fits for contraction coefficient and energy loss coefficient.

SUBMERGED CONDITIONS

Only a few studies on submerged radial gates are available in the literature. The most common approach has been to use an empirical discharge coefficient according to the amount of submergence. This approach was suggested by Henry (1950) and Rajaratnam and Subramanya (1967) for vertical sluice gates and used by Buyalski (1983) for radial gates. One difficulty with this approach is that the curves are very steep, resulting in a large change in discharge coefficient for a small change in upstream depth or gate opening. Another approach (Bos 1989) is to use the same discharge coefficient as for free flow, but with the water level difference across the gate replacing the upstream depth. A challenge with this approach is to determine when to use the upstream head and when to use the head differential. The standard textbook approach is to use the conjugate depth equation for a rectangular channel to determine whether or not the gate is submerged (e.g., as suggested by Bos (1989)).

These approaches have a major flaw when applied to practical situations. All of the studies and the conjugate depth relationship assume that the downstream channel is of the same cross section as the gate. The calibration results are highly dependent upon this condition, even though it is rarely found in practice. The current approaches cannot easily deal with these real-world conditions.

Where a hydraulic jump occurs, energy losses are difficult, if not impossible, to predict with an energy-based equation. This usually requires solution of the momentum equation. However, it is also not practical to solve the momentum equation from the upstream section to the downstream section since the forces on the gate are unknown. Instead, we propose to use the energy equation from the upstream side to the vena contracta, where we think we can capture the essential flow conditions, and the momentum equation from the vena contracta to the downstream section. Under normal operation, the depth and velocity at the vena contracta will not be measured. Instead, those conditions must be inferred from the equations.

Starting with the energy equation on the upstream side of the gate, we postulate

$$H_1 = y_1 + \frac{v_1^{\,2}}{2g} = y_2 + \frac{v_j^{\,2}}{2g} + \xi\frac{v_j^{\,2}}{2g} \tag{3}$$

In Equation 3, the subscript j refers to the "live stream" conditions in the jet at the vena contracta and the subscript 2 refers to the vena contracta location, whether free or submerged. Equation 3 implies a nearly linear relationship between y_1 and y_2 for any constant discharge and gate opening. However, laboratory results differ substantially from this result, as shown in Figure 5. At high submergence, the relationship looks reasonable, suggesting that the jet is the same size as under free flow, even though submerged.

Such results were also found by Rajaratnam and Subramanya (1967a), among others. At the beginning of submergence, the flow just downstream from the gate, as y_2 is increased holding all else constant, comprises an incomplete jump gradually approaching the classical wall jet (Rouse et al. 1959), and finally becoming the standard wall jet with the jet similar in configuration to the jet under free flow. While the partial jump is present, increases in tailwater elevation have almost no effect on upstream water level. But as the "wall-jet" condition is approached, further increases in tailwater depth are reflected in upstream depth changes.

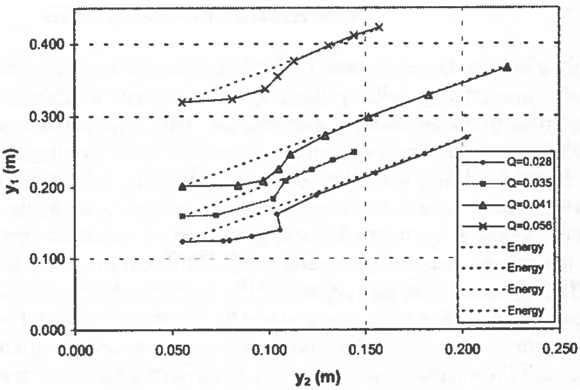

Figure 5. Preliminary application of energy equation from upstream side of radial gate structure to vena contracta.

Numerical modeling of this behavior between Sections 1 and 2 with the energy equation requires a reduction in jet velocity, and for a constant discharge, an expansion in the jet thickness (as suggested by Tel (2000)). In a simpler, and ultimately equivalent procedure, we postulate a kinetic energy correction term, E_{Corr}, for the transition zone, such that

$$H_1 = y_2 + \frac{v_j^2}{2g} + \xi \frac{v_j^2}{2g} - E_{Corr} \tag{4}$$

with v_j held fast at the free-flow value. E_{Corr} is evidently zero under free flow, as well as under fully submerged flow. In our preliminary analysis, we determined values for E_{Corr} as a function of relative submergence (shown below). Solving Equation 4 for discharge yields

$$Q = \delta w b_c \sqrt{\frac{2g\left(H_1 - y_2 + E_{Corr}\right)}{1+\xi}} \tag{5}$$

Solution of Equation 5 for submerged discharge requires, in addition to what is needed for free flow in Equation 2, an estimate of the energy correction, E_{Corr}, and an estimate for the depth, y_2, at the vena contracta. This depth is extremely difficult to measure in the field. The flow there is highly turbulent, rolling and "*frothy*" such that a surface measurement is insufficient to determine the true depth (i.e., as reflected in the pressure below the surface). This depth is not currently measured in the field and likely will never be. Instead, the water depth in the downstream channel, y_3, is measured. To utilize the measured depth, y_3, instead of y_2, a momentum relationship between Sections 2 and 3 is introduced.

Conservation of momentum, applied from the section with the vena contracta to Section 3, can be written as:

$$Qv_e + b_c g \frac{y_2^2}{2} + \frac{F_w}{\rho} = Qv_3 + \frac{F_3}{\rho} \tag{6}$$

where v_e is the effective velocity in the jet (discussed below), v_3 is the downstream velocity, ρ is the density of water (mass per unit volume), F_3 is the hydrostatic-pressure force exerted by the downstream water depth, and F_w is the component of the force of water on all surfaces between Sections 2 and 3 in the direction of flow, including hydrostatic forces on all walls. This surface can be determined by taking the downstream area and projecting it back to Section 2 (assuming the section only expands from Section 2 to Section 3). Projected surfaces include the edges of the piers that separate the individual gates, closed gates, weir overfall sections, and the canal walls where the cross section expands. For rectangular cross sections, the force terms reduce to $bgy^2/2$, with subscripts 3 or w on b and y. For the short distances involved here, we can ignore the channel friction and bed slope effects.

Equations 5 and 6 represent solutions for flow on the upstream and downstream sides of the vena contracta, with Q and y_2 unknown, and the rest derivable from the measured water depths, gate opening, cross-section shapes, and empirical •,• ξ, and E_{Corr}. Application of these two equations is complicated by 1) quantification of the energy loss coefficient, 2) application of the energy equation under slightly submerged conditions, and 3) estimation of the wall forces for application of the momentum equation. The force on the walls is assumed to be based on a water depth there -- hypothesized to be between the depths at Sections 2 and 3. The effective water depth at the walls is found as the weighted average of these two depths, with weighting coefficient p:

$$y_w = py_3 + (1-p)y_2 \tag{7}$$

Laboratory experiments were performed to test the applicability of these equations. We solved Equation 6 for E_{Corr} with the measured values of Q, y_1, and y_2, and with ξ from the free-flow tests. The resulting energy correction relative to the change in depth at the vena contracta $[E_{Corr}/(y_2-y_j)]$ is shown in Figure 6 as a function of this change in depth relative to the free-flow jet thickness $[(y_2-y_j)/y_j]$.

The consistency of the relationship shown in Figure 6 for different discharges (and w/H_1 values) is encouraging! It essentially says that for small submergence depths, the contribution of that depth increase to the apparent increase in energy is small (i.e., almost 100% of the depth increase is canceled with E_{Corr}).

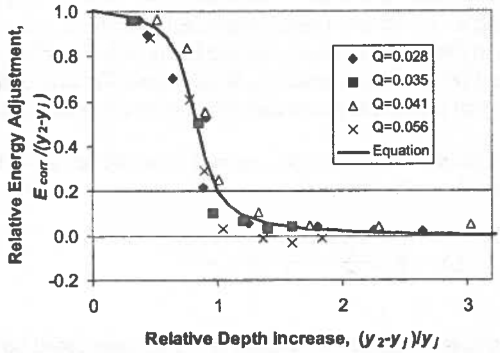

Figure 6. Relative energy adjustment required to apply free-flow energy equation to submerged flow for a radial gate up to the vena contracta.

A curve was fit to the relationship in Figure 6 to compute E_{Corr} for use in Equation 5. An equivalent jet velocity was determined by replacing the second and fourth terms on the right hand side of Equation 4:

$$\frac{v_e^2}{2g} = \frac{v_j^2}{2g} - E_{Corr} \tag{8}$$

The equivalent velocity then replaces the jet velocity in the momentum equation. This formulation leaves the computed upstream energy loss unchanged, except with Reynolds number (which changes with discharge and upstream depth as the gate becomes submerged).

The measured data were used to determine the coefficient p for the effective wall pressure. While there was some scatter in the data, a strong trend was not apparent. For the remaining analysis, an average value of 0.643 was used.

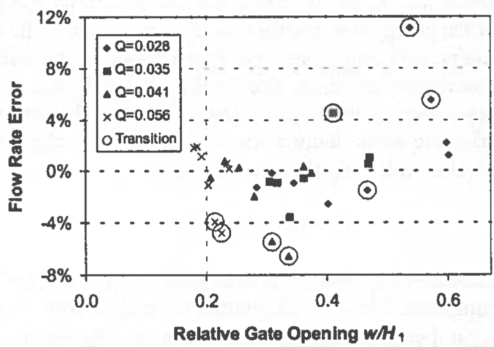

Figure 7. Error in discharge resulting from use of the Energy-Momentum method as a function of relative gate opening.

At this point, some verification of the relationships was attempted. The energy and momentum equations

(5 and 6) were solved with only knowledge of the upstream and downstream water levels. The relationships in Figures 2, 3 and 6 were used, along with p =0.643. The resulting errors in discharge are shown in Figure 7. The circled values are those that fall within the sharp transition range in Figure 6 (energy adjustment values between 0.2 and 0.8). Those within the transition zone have errors that ranged from –8% to 12%, while all the other values are estimated to within –4% to 3%. We also speculate that the relative depth at which the transition shown in Figure 6 occurs is a function of the ratio w/H_1, although there are not enough data points to define such a relationship (i.e., Figure 6 would have to have a family of curves). Further studies are needed to define this relationship as a function of w/H_1. Also, additional studies of submergence are needed at values of w/H_1 above 2/3, a theoretical limit at low submergence, but which can be greatly exceeded at high submergence.

APPLICATION

As an example, we show an application at the Salt River Project (SRP) in Arizona. At some check structures, operators report errors in computed flows as high as 50%. SRP has been using the submerged radial-gate calibration method suggested by Bos (1989). Under this method, the gate is assumed to be submerged when the downstream water level reaches the conjugate depth. In Figure 8, the calibration relationships for a fixed gate and given upstream water level are shown as a function of downstream (afterbay) depth. The horizontal line at the top represents free flow (i.e., not influenced by downstream depth). The far right point of this horizontal line represents the depth conjugate to the free-flowing jet thickness at its vena contracta for a downstream channel of the same width as the gate. The lower heavy line is the energy-based submerged-flow

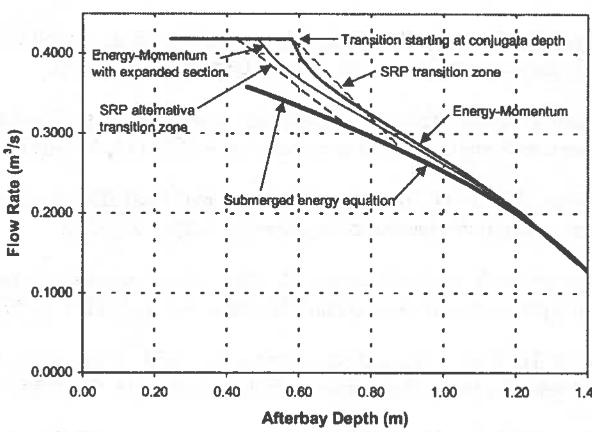

Figure 8. Radial-gate flow rates computed with energy equation (as used by SRP) and the Energy-Momentum method. (Fixed gate opening and upstream depth).

solution recommended by Bos (1989), where discharge is proportional to the square root of the head difference. No recommendation is given on transitioning from the conjugate depth point to the submerged-flow line. A straight drop is implied, but is clearly unreasonable. SRP chose to use a 1 foot (0.3 m) transition zone, described essentially by a straight line. When compared to the Energy-Momentum solution proposed here (heavy line to upper right), this is not an unreasonable approximation. Note that both solutions start the transition at the same downstream depth, as they should. However, SRP found that their transition equation did not fit their field data very well. As an alternative, they chose to place the transition zone in the middle of their 0.3 m interval (0.15 m on either side of conjugate depth). For some cases this provided a better fit. (An additional transition zone in between these two has also been used). Also shown in Figure 8 is the Energy-Momentum solution when the downstream channel is twice as wide as the gate. Submergence occurs at a lower downstream depth – i.e., the conjugate depth has changed. Their need to provide different transition zones for these gates can be entirely explained by application of the E-M method, as shown by the range of downstream depth at which submergence starts. The energy-equation solutions for submerged flow are not able to predict such performance.

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