The Energy Correction for Calibration of Submerged Radial Gates

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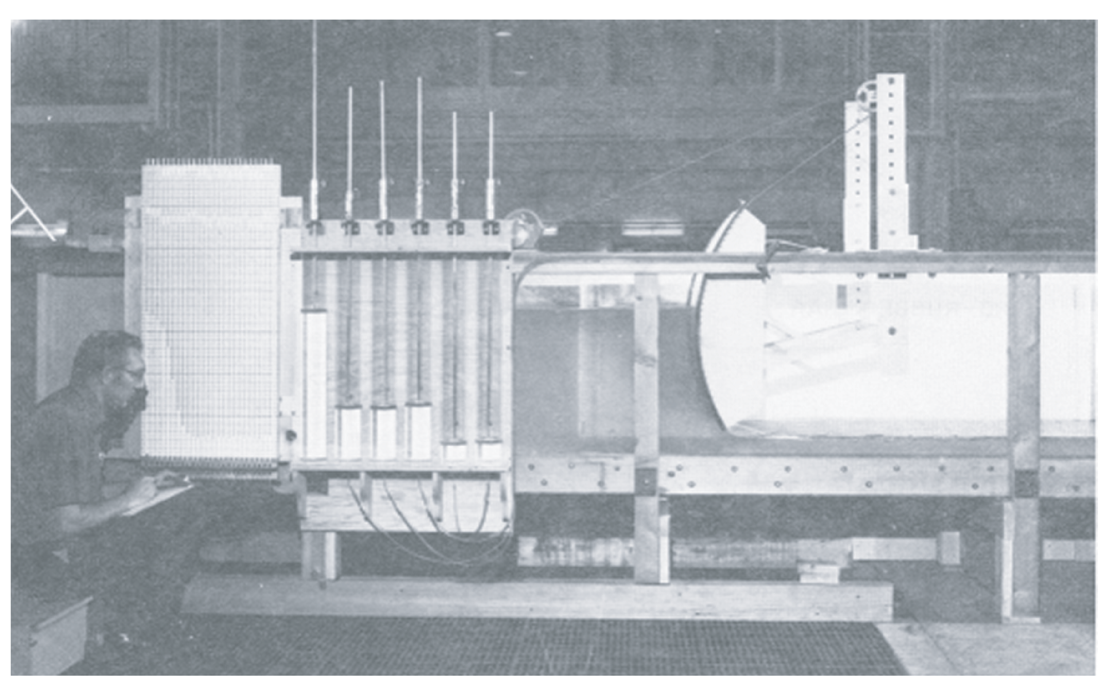
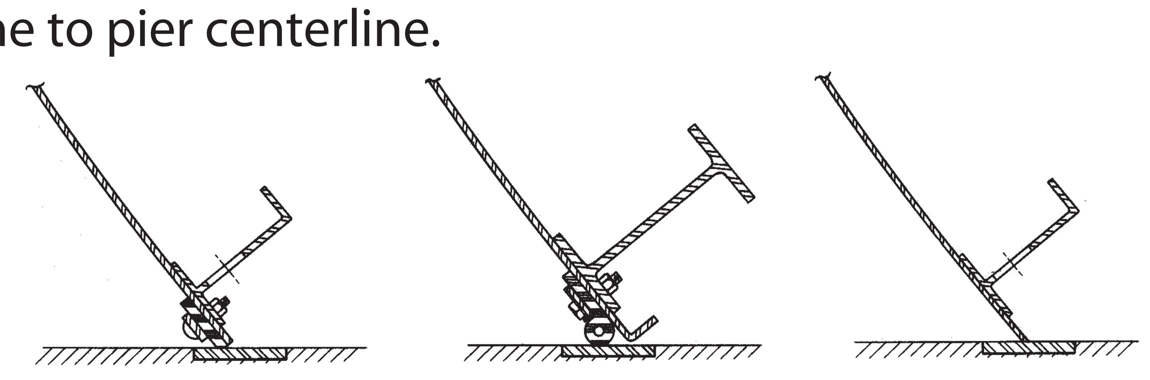
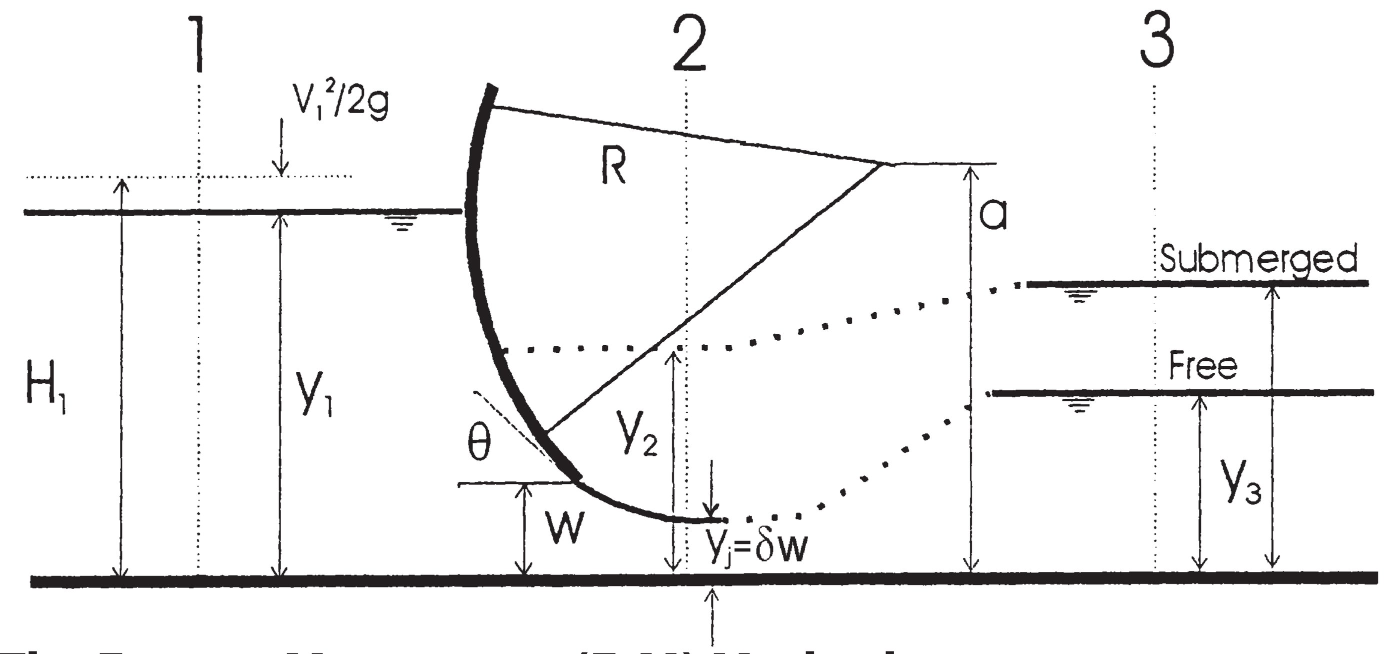
Background: The Energy-Momentum method (Clemmens et al. 2001) is a new algorithm for calibrating free-flowing and submerged radial gates for accurate discharge measurement. The method can be applied to existing canal radial gate structures and has the potential for better accuracy than simple energy-based methods, especially when structures have expanding exit channels, non-symmetric settings of multiple gates, or gates operating in the transition zone between free and fully submerged flow..

Objective: Use a previous set of laboratory data collected by Buyalski (1983) to develop improvements to the empirical components of the Energy-Momentum calibration method for submerged radial gates, especially the energy correction factor, which is important for calibration through the transition zone.



Tests conducted at the Bureau of Reclamation's Water Resources Research Laboratory (Buyalski 1983): This dataset offers an opportunity to test and refine the energy correction model using data collected over a wide range of conditions. Buyalski tested 9 gate configurations consisting of 3 seal types (sharp-edged, hard rubber bar, and music note or "J" seal), and 3 different ratios of gate radius to trunnion pin height. Seven different gate openings were tested for each configuration, with gate opening to trunnion pin height ratios varying from 0.1 to 1.2. Nearly 2650 test runs were made, with more than 80 percent of the tests in submerged conditions. The tested gates were 0.711 m (2.333 ft) wide, with a gate radius of 0.702 m (2.302 ft). The gates were installed in a channel that was 0.762 m (2.5 ft) wide, with a single half-pier filling the gate bay, so that the model simulated a section from gate centerline to pier centerline.





The Energy-Momentum (E-M) Method

The ENERGY EQUATION is applied from the upstream pool (1) to the vena contracta (2).

In FREE FLOW, the depth y_2 is determined by knowing the gate opening and the contraction coefficient of the gate, which varies with the gate opening and the gate seal configuration. With y_2 known, the measured upstream depth and gate opening can be used to compute the flow rate.

Empirical factors affecting the free flow calibration are the gate contraction coefficient and a combined velocity distribution and upstream energy loss factor, 1+ξ.

In SUBMERGED FLOW, the downstream pool depth, y_3, is measured. The depth at the vena contracta, y_2, is determined by applying the momentum equation from the vena contracta (2) to the downstream pool (3). The energy equation is also modified by an **energy correction factor**, E_{Corr}, that accounts for changes in the thickness and velocity of the jet at the vena contracta as the flow condition passes through the transition zone. The energy correction applies only in the transition zone; it goes to zero in free flow and infinitely submerged flow. The energy equation and resulting discharge equation for submerged flow are:

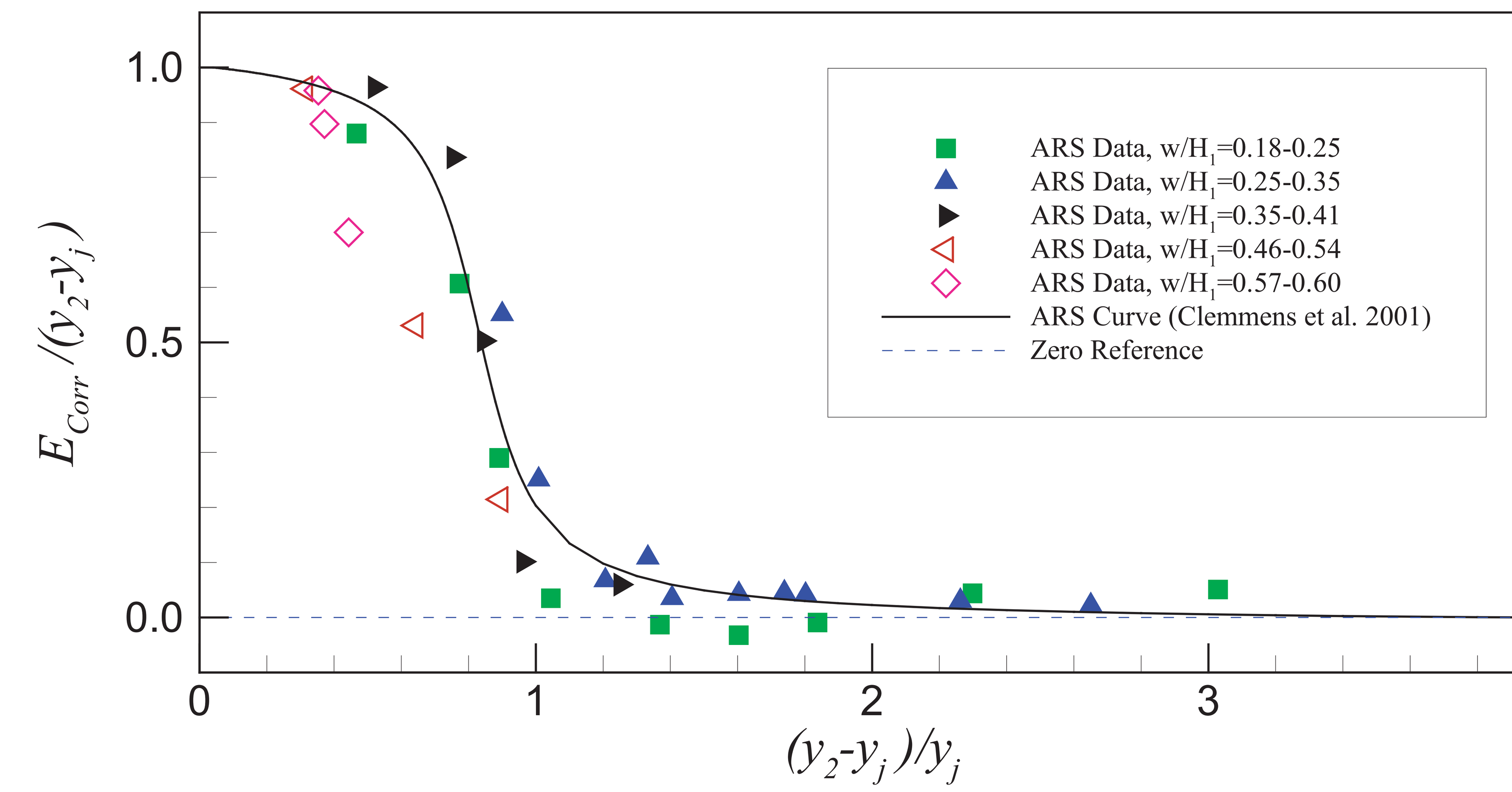
$$H_1 = y_2 + \frac{v_j^2}{2g} + \frac{v_j^2}{2g} - E_{Corr}$$

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

The empirical factors affecting the submerged flow calibration are those given above for free flow, plus the energy correction factor and a weighting factor used to estimate flow forces on the downstream channel boundaries for the momentum equation.

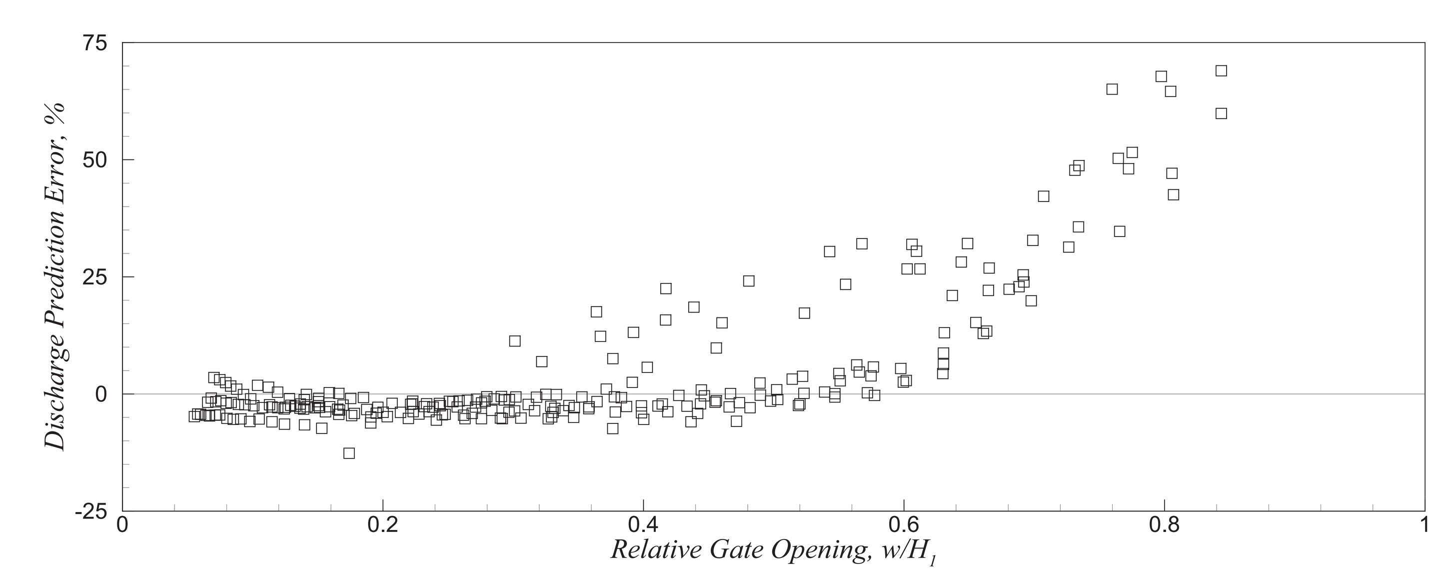
Tests by the Agricultural Research Service (ARS) established initial empirical relations for the energy correction factor, the upstream velocity distribution and energy loss coefficient, and the momentum equation weighting factor. These tests also verified existing relationships for the contraction coefficient of sharp-edged gates.

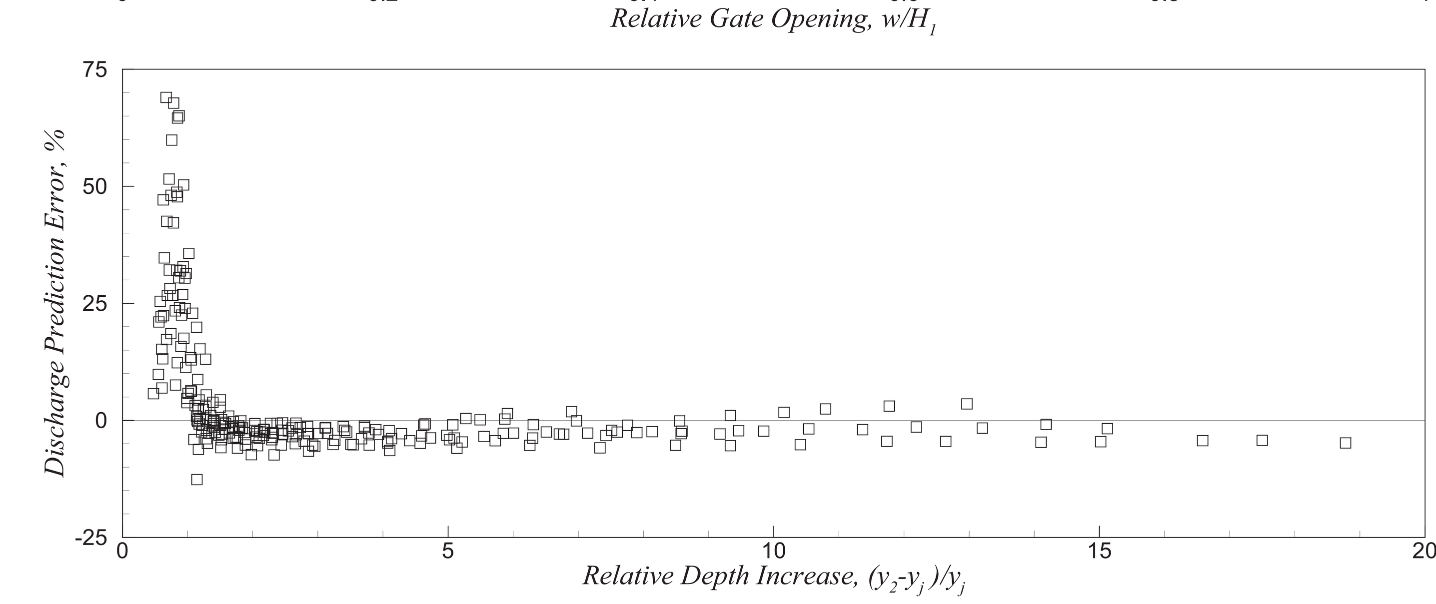
The Energy Correction Factor: The energy correction factor relationship obtained from the ARS tests is shown below. The correction factor is expressed relative to the total depth increase at the vena contracta, and as a function of the relative submergence of the jet.



ARS submerged flow tests were conducted at only one gate opening. Clemmens et al. (2001) suggested that tests over a wide range of relative gate openings (w/H_1, where w is the gate opening and H_1 is the upstream head) might show that the energy correction factor was influenced by the w/H_1 ratio.

Initial Testing of the E-M Method: To test the performance of the E-M Method, including the energy correction described by Clemmens et al. (2001), the method was used to compute the flows for a subset of the Buyalski data, and the computed flows are compared to actual flow rates in the figure below.





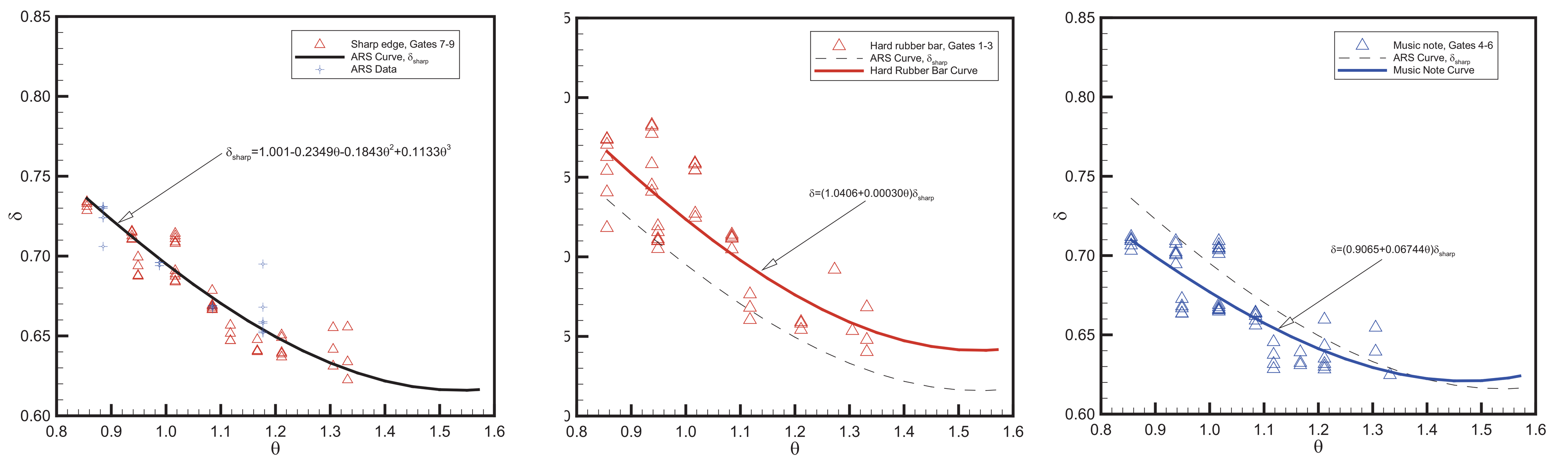
Calibration errors in the transition zone were very large, indicating that the energy correction was not yet accurate enough. The greatest errors occurred at large relative gate openings, with relatively low submergence (i.e., tailwater levels only a little above the thickness of the free-flow vena contracta depth).

The large database of submerged flow tests by Buyalski (about 2000 test runs) offers an opportunity to test Clemmens' hypothesis about the effect of the relative gate opening, and possibly to develop an improved model for the energy correction factor.

The Energy Correction for Calibration of Submerged Radial Gates

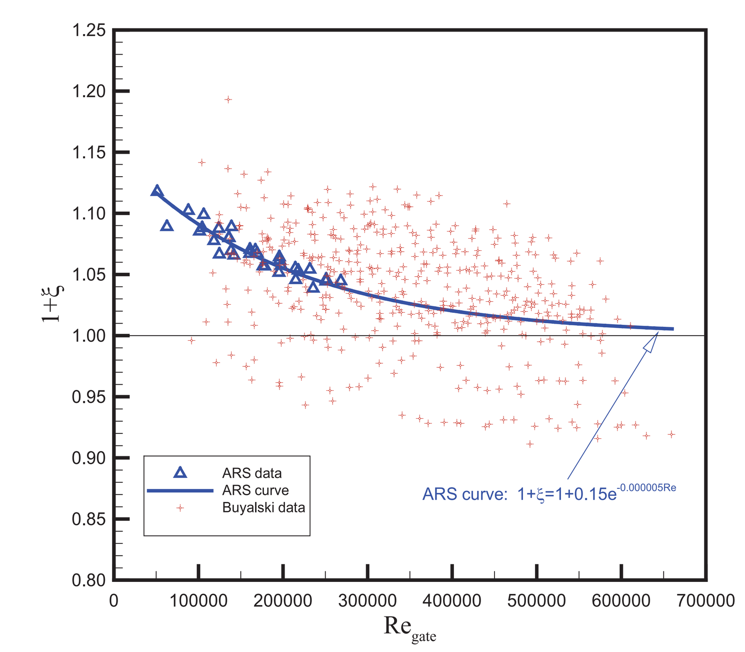
Analyzing the Buyalski Data Set

Step 1 - Contraction Coefficients: Use free-flow data to solve for contraction coefficients for the three gate seal types tested by Buyalski. This relies upon the relationship for the velocity distribution and upstream energy loss factor, 1+ξ, which was developed by Clemmens et al. (2001) for gate Reynolds numbers of 270,000 or less.



Buyalski's data confirms previously determined contraction coefficients for sharp-edged gates, and relationships are developed for the hard rubber bar and music note seal. These relationships may be suspect for very large gate openings. Buyalski tested gate openings greater than 90 degrees (1.57 radians) in submerged flow conditions, but these tests were excluded from this analysis because of uncertainty in the contraction coefficients at large gate openings, and because this is an unusual operating condition in real-world practice.

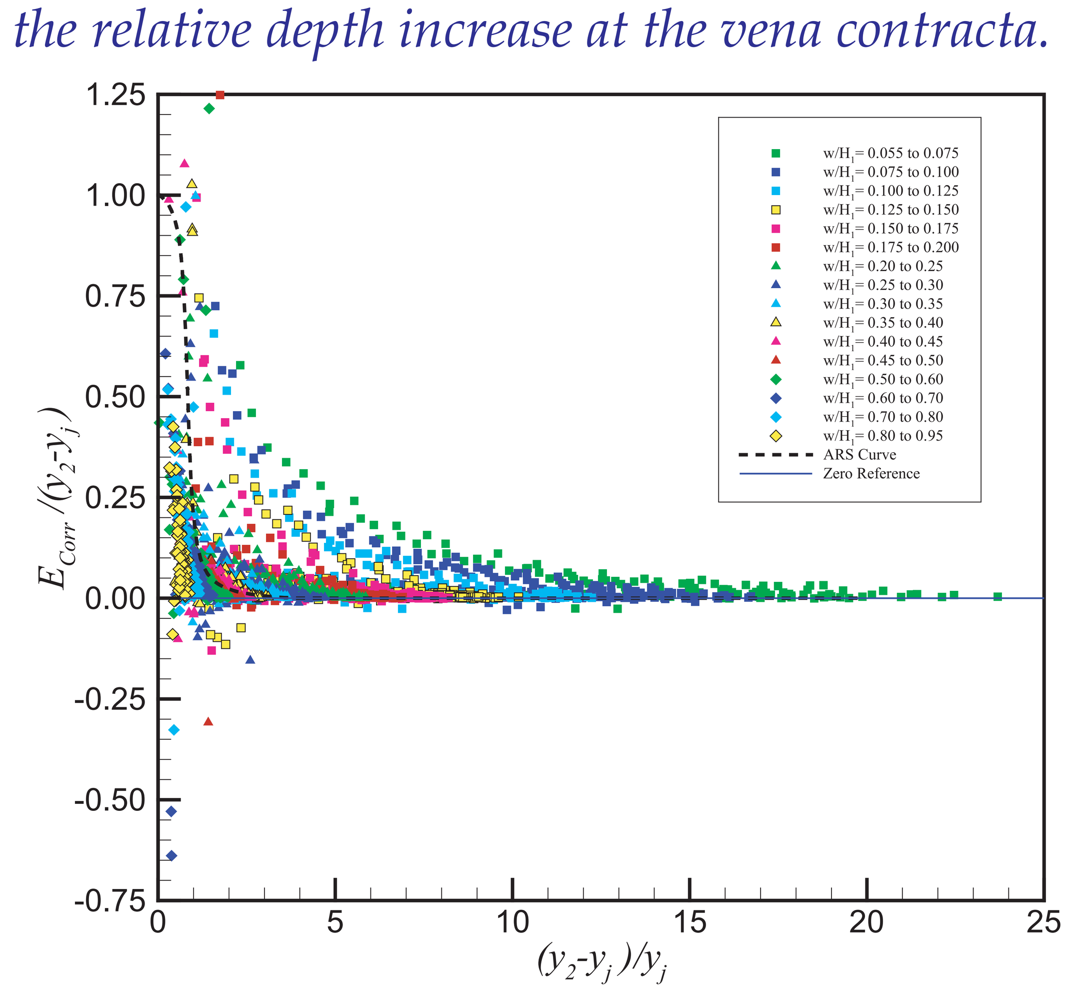
Step 2 - Verify Free-Flow Loss Coefficient: Use free-flow data at high Reynolds numbers (up to 650,000) and the contraction coefficients just determined to verify the velocity distribution and upstream energy loss factor relation for higher Reynolds numbers.

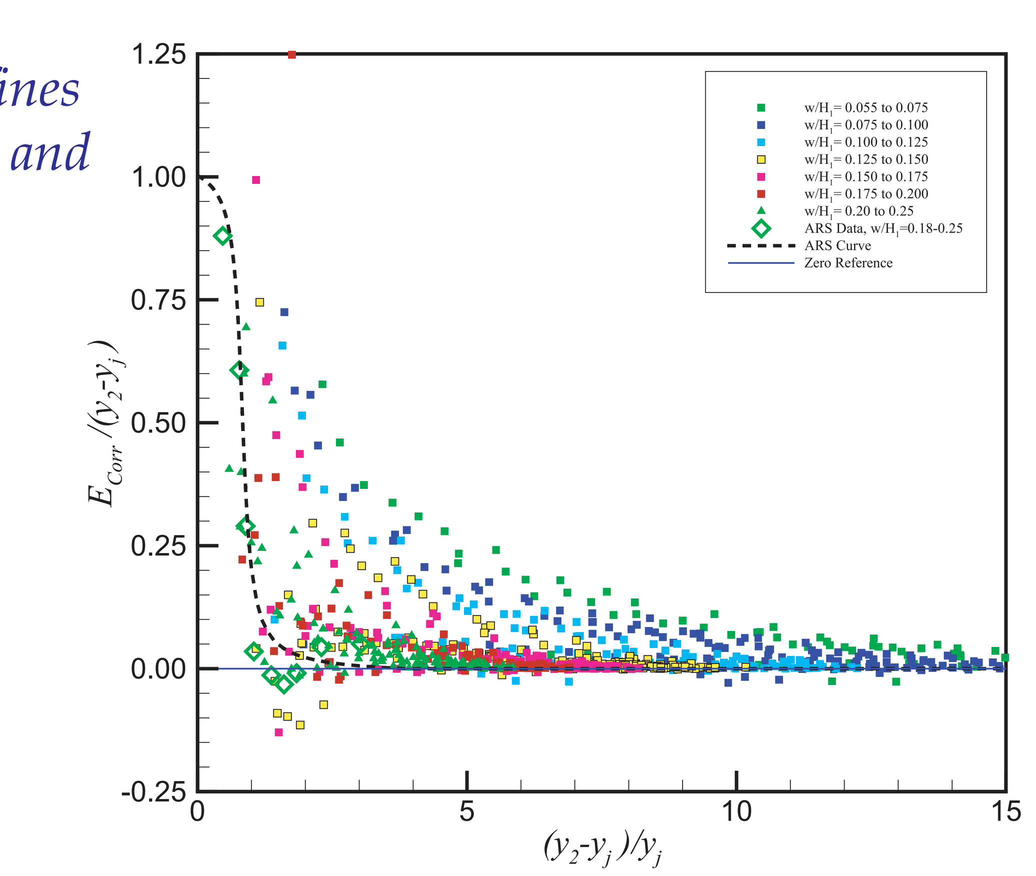


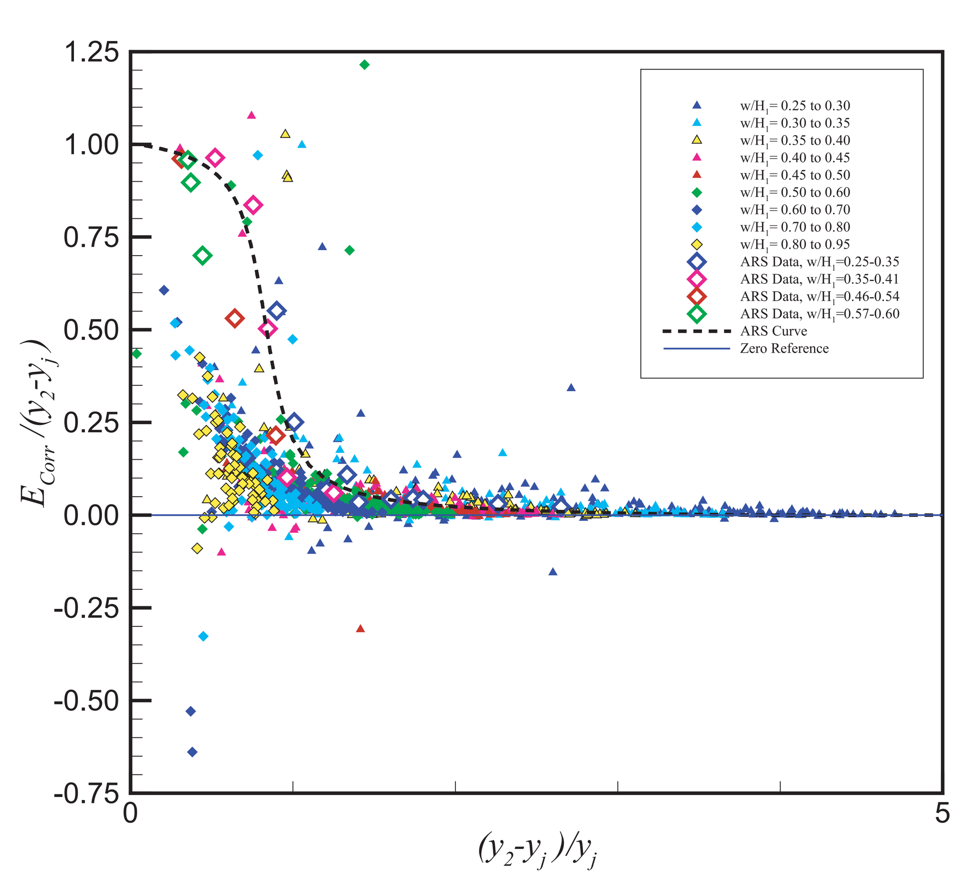
Scatter in the Buyalski data is much greater than that in the ARS data, but the Buyalski data confirms the ARS relationship and shows that it probably can be safely extended to higher Reynolds numbers. The greater scatter is due to differences in flow measurement uncertainty for the two test programs. Buyalski's tests used venturi meters with an uncertainty of about ±0.5%; the ARS tests used a weigh-tank with an uncertainty of about ±0.1%.

Step 3 - Energy Correction Factors: Use the submerged-flow data from the sharp-edged and hard rubber bar seal gates to determine energy correction factors for transition zone conditions, and explore new mathematical models that might better explain the observed behavior of the energy correction factors.

The figure below shows that a family of curves defines the relation between the relative energy correction and the relative depth increase at the vena contracta.



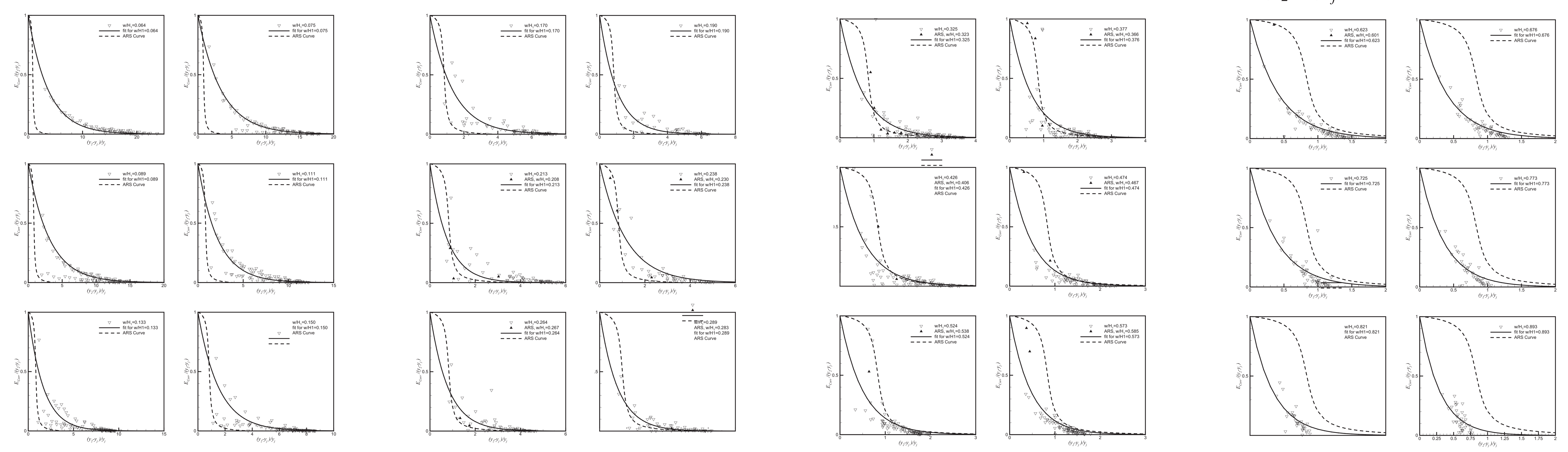




At small relative gate openings, w/H₁, the transition curve extends to large relative depth increases, while for large relative gate openings, the transition occurs very rapidly. This is most evident in the figures above, which show the data for small and large relative gate openings in more detail.

Step 4 - Develop Mathematical Model: Develop a mathematical model to describe the energy correction vs. relative depth increase relation, accounting for the effects of the relative gate opening. The equation form selected is:

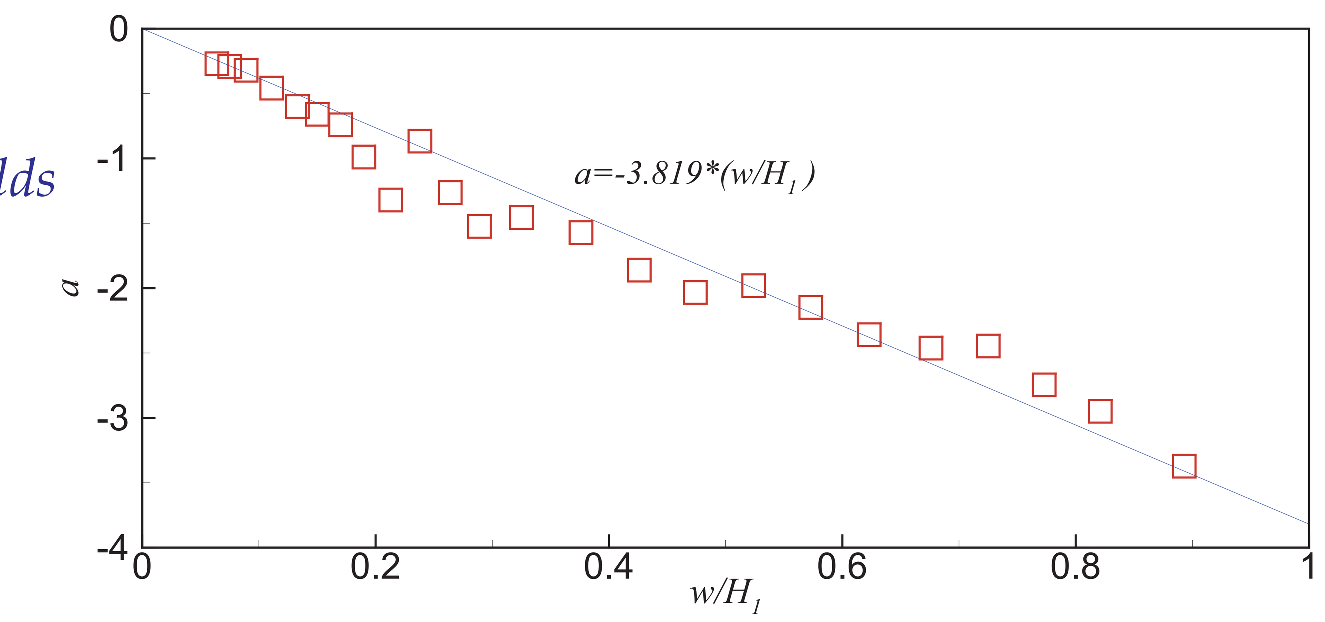
$$\frac{E_{Corr}}{y_2 - y_j} = e^{a\left(\frac{y_2-y_j}{y_j}\right)}$$



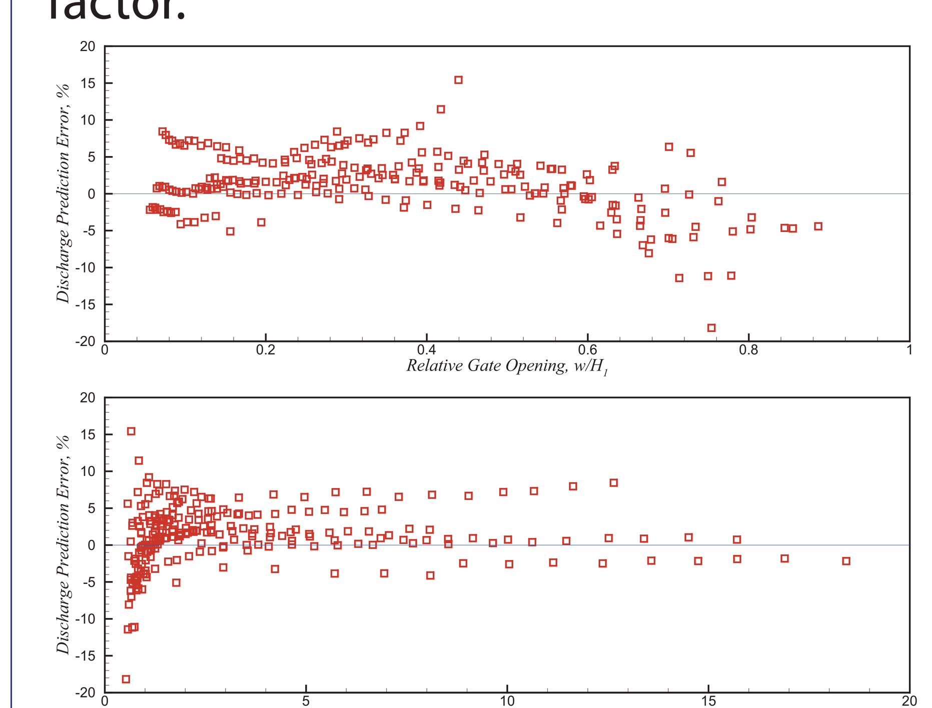
The data were subdivided into 24 narrow ranges of w/H_1 values, and suitable equation forms were investigated. The equation form originally used to fit the ARS data was not flexible enough to produce good fits for all ranges of w/H_1 values. A simple power curve equation worked best over the full range of the data. For w/H_1 values ranging from about 0.075 to 0.15 there seemed to be evidence of a possible dual relationship between the relative energy correction and relative depth increase. This may need to be further investigated in future laboratory or field tests.

The coefficients for each of the fitted power curve equations are plotted against the relative gate opening in the figure to the right. A linear regression accurately describes the variation of the coefficients. This yields the improved mathematical model for computing the energy correction.

$$\frac{E_{Corr}}{y_2 - y_j} = e^{-3.819\left(\frac{w}{H_1}\right)\left(\frac{y_2-y_j}{y_j}\right)}$$



Step 5 - Verify Improved Model: Use the data from Buyalski's tests of gates with music note seals to verify the performance of an improved E-M method that incorporates the effects of the relative gate opening on the energy correction factor.



The new model produces a significant improvement in the submerged flow calibration performance.

Error Description	Free flow: E-M model applied to sharp-edged gates	Free flow: E-M model applied to gates with music note seals	Submerged flow: Original E-M model applied to sharp-edged gates	Submerged flow: Modified E-M model applied to gates with music note seals
±2%	78%	64%	25%	42%
±5%	100%	99.4%	66%	78%
±10%	--	0.6%*	80%	98%
±20%	--	--	86%	100%
+20 to +70%	--	--	14%	0%
Statistics				
Mean	0.22%	0.40%	+4.80%	+0.84%
Median	0.29%	0.69%	-1.48%	+1.04%
Standard deviation	1.48%	1.97%	15.3%	4.18%

*One run originally classified as submerged by Buyalski; due to possible data transcription error on this run, it was ignored when computing statistics.