Issues and Problems with Calibration of Canal Gates

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ABSTRACT

Accurate flow measurement at irrigation canal check gates, bifurcations, and turnouts makes it possible for water managers to better match supply and demand, thereby reducing administrative spills and enabling delivery of the optimum amount of water to crops. Recent developments have improved our ability to accurately measure discharge at canal gates, and further improvements are possible. An ASCE Task Committee active since late 2002 has been working to focus research efforts in this area. This paper reviews recent developments, highlights areas in which research is now being performed, and discusses issues and difficulties yet to be overcome.

INTRODUCTION

Accurate flow measurement is a basic requirement for improving the efficiency of water deliveries. Many modern methods for operating canals in a more efficient manner rely upon real-time knowledge of flow rates throughout a canal system and require the ability to quickly and easily adjust flow rates at various locations throughout a system.

The most accurate flow measurements have usually been obtained from dedicated structures and equipment (e.g., flumes and weirs, acoustic flow meters, etc.). While dramatic improvements have been and continue to be made in these technologies, there is also a potential for making use of gates to provide accurate flow measurements. The advantages of using gates are several:

- Alleviates the need for dedicated flow measurement structures or flow meters, thus potentially reducing cost and saving the time spent on design, construction, or procurement,
- Provides flow measurement without incurring additional head loss, and

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- Facilitates automatic control by allowing accurate setting of gates to achieve target flow rates in real time.

Gates are used to control flows at a variety of locations within most canal systems. Outlet gates at dams, check gates in main canals, gates at major bifurcations, and turnout gates at the heads of laterals and at farm delivery points all offer the potential for flow measurement. Flow measurement capabilities have been incorporated into many standard gate types used at turnout locations. Examples include constant-head-orifice turnouts and meter gates, which have been used on some Bureau of Reclamation projects.

An ASCE Task Committee on Canal-Gate Flow Measurement was formed in late 2002. The committee has been attempting to focus efforts on the development of flow measurement capabilities at canal gates. The committee members include researchers, gate manufacturers, irrigation districts, and consultants. The committee's efforts have been concentrated in two areas:

1. Small gates of a modular, drop-in nature that are being widely used for both new construction and the rehabilitation and improvement of older canal systems, and

2. Large gates typically used at canal check structures and major bifurcations, such as radial gates and slide gates.

CALIBRATION OF SMALL CANAL GATES

The recognized need for more and better flow measurement capabilities in irrigation delivery systems has driven gate manufacturers to develop integrated packages that combine control and measurement capabilities. Most of the development in recent years has been on overflow-type gates, which can readily be used to control upstream canal water level, a popular manual and automatic operating technique. Wahlin and Replogle (1994) performed calibration tests on an idealized laboratory model and a prototype gate manufactured by Armtec Water Control Products. Their tests established free flow discharge coefficients and their variation with the angle of the gate leaf. They also developed correction factors for partially submerged flow.

Since the tests by Wahlin and Replogle, two other manufacturers have developed automated gates of this basic type that are calibrated for discharge measurement. The Langemann gate is a vertical lift bi-fold gate, and the Rubicon FlumeGate is a tilting weir gate with integral gate leaf and side plates. Both gates are modular in nature and designed to easily install into existing infrastructure. Both gates have been calibrated in controlled tests. The Langemann gate is also available with a long-throated flume extension added to the top edge of the gate leaf. This makes its calibration computable with the WinFlume software (Wahl et al. 2000) used to calibrate long-throated flumes and broad-crested weirs.

CALIBRATION OF LARGE CANAL CHECK GATES

Large canal check gates are typically sluice gates, either vertical slide gates or radial gates. Radial gates are especially common in canal check structures due to the low lifting force required during operation. Flow under a sluice gate and the calibration of sluice gates are classical problems in hydraulics, but despite many decades of research, universal calibration accuracy has remained elusive. The primary causes are the complexity and variability of the flow situation. Both free and submerged flow are possible, gate seals have an important influence, and variations in the geometry of check structures can play a large role (Fig. 1).

The traditional approach to calibration of sluice gates has been to apply the energy equation across the gate, treating it as a submerged orifice. Discharge coefficients have been determined empirically by laboratory and field testing. Accuracy in free flow has been reasonably good in most cases, but in submerged flow, accuracy has ranged from mediocre to poor. The most difficult conditions are flows in the transition zone from free to highly submerged flow, and sites where the downstream channel is much wider than the gate chamber.

Energy-Momentum Method for Radial Gates

A new approach to the calibration of radial gates is the technique described as the Energy-Momentum (E-M) method (Clemmens et al. 2003). This method also applies the energy equation, but only from the upstream pool to the vena contracta of the jet

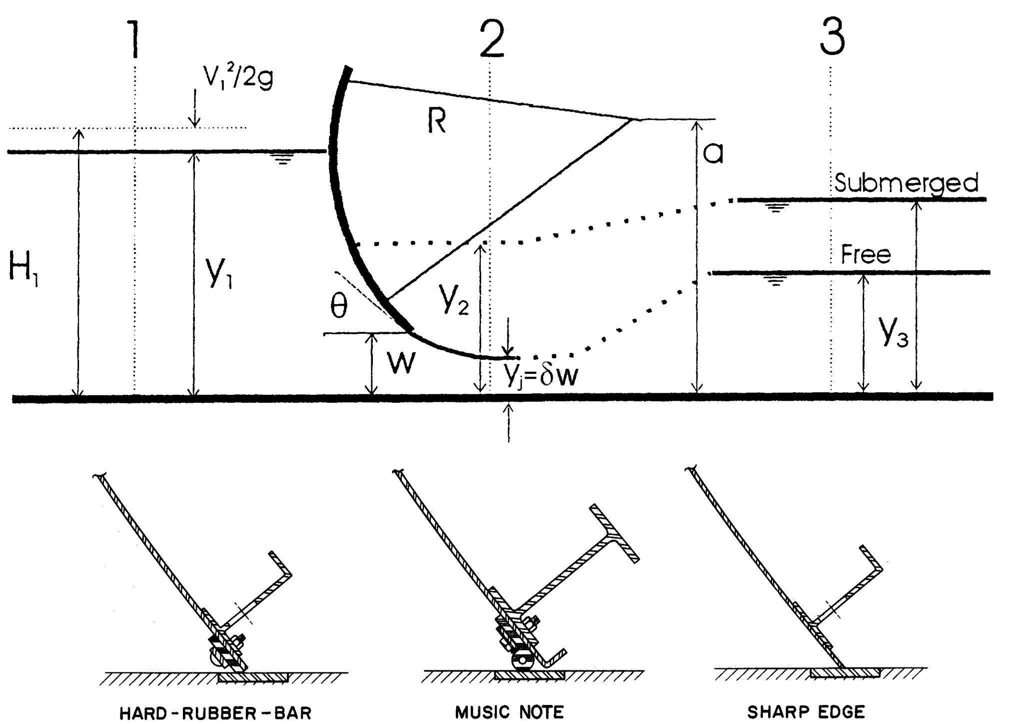

Figure 1. — Variables affecting radial gate calibration.

issuing from beneath the gate (section 2 in Fig. 1). In free flow, only the energy equation is needed. Energy losses on the upstream side of the gate are accounted for empirically, and the contraction coefficient for the opening must also be estimated. The free flow discharge equation is:

$$Q = dwb_c \sqrt{\frac{2g(H_1 - dw)}{1 + x}}$$

in which Q is the discharge, δ is the contraction coefficient, w is the vertical gate opening, b_c is the gate width, g is the acceleration of gravity, H_1 is the total head at section 1, and the quantity 1+ξ accounts for energy losses on the upstream side of the gate and the effects of nonuniform velocity distribution at the vena contracta. In free flow, the method provides flow measurement accuracy approaching that of flumes and weirs. The greatest source of uncertainty in most cases is the contraction coefficient, which is affected by the presence and condition of gate seals. For sharp-edged gates, the contraction coefficient is well known from many previous studies. Replogle et al. (2003) reported on operational evaluations of a new radial gate design that incorporates a 160-mm diameter half-pipe gate bottom intended to stabilize the contraction coefficient, but results have thus far been inconclusive.

In submerged flow, the energy equation is still applied from section 1 to the vena contracta. In theory, one could simply measure the flow depth, y_2, above the vena contracta point, but in practice it is usually difficult to accurately measure y_2, so the momentum equation is applied from section 2 to section 3 to allow one to determine y_2 from a depth measurement taken in a zone of quiescent flow. Clemmens et al. (2003) described the Energy-Momentum method in detail and provided empirical relationships needed to apply the model. These relationships were developed using data collected by the Agricultural Research Service (ARS) in their laboratory at Phoenix, Arizona (Tel 2000). The discharge equation in submerged flow is:

$$Q = dwb_c \sqrt{\frac{2g(H_1 - y_2 + E_{Corr})}{1 + x}}$$

with y_2 being the depth above the vena contracta location, and E_{Corr} being an energy correction term. The energy correction accounts for the fact that in slightly submerged flow, the jet at the vena contracta is thickened and slowed by the adverse pressure gradient created in the partially submerged hydraulic jump that takes place on the downstream side of the gate (as suggested by Tel 2000). This change in the hydrodynamics of the jet reduces the total energy head at the vena contracta, increasing the net energy available to drive flow through the gate. As a result, in the transition zone there is not a one-to-one correspondence between increases in the y_2 depth and the y_1 depth at a given constant flow rate (Clemmens et al. 2001) as one would otherwise expect for an orifice-controlled flow; the tailwater conditions only slightly affect the performance of the gate in this region, with the tailwater influence increasing as the submergence increases. Clemmens et al. (2003) presented a model for predicting this energy correction.

Submerged Flow Energy Correction

The energy correction model developed by Clemmens et al. (2003) was based on data collected from a relatively small range of flow conditions comprising four flow rates at a single gate position, with varying upstream and downstream depths. Clemmens et al. (2003) speculated that the energy correction relationship might vary as a function of the relative gate opening, w/H_1, but this could not be verified from their limited data.

Wahl (2003) used a data set originally collected in the late 1970's and early 1980's by the Bureau of Reclamation (Buyalski 1983) to examine the energy correction in more detail. This analysis showed that the relative gate opening was an important parameter affecting the relationship between the relative energy correction and the relative submergence. Wahl developed a new model for the energy correction and showed that it dramatically improved the accuracy of calibrations in the transition zone. However, several questions related to the energy correction still remain:

- There may be a dual relationship between the relative energy correction and the relative submergence at low relative gate openings (Wahl 2003). This may be due to unknown experimental errors in the Buyalski data set.

- More experimental data are needed at very slight submergence levels to help resolve differences between the forms of the equations for E_{Corr} developed by Clemmens et al. (2003) and Wahl (2003).

- The analysis of the Buyalski (1983) data relied upon the upstream energy loss and velocity distribution factor, $1+\xi$, and an empirical factor in the momentum equation. Errors in either of these terms could have influenced the results obtained by Wahl (2003).

Momentum Equation Issues

The momentum equation provides a way to determine y_2 from a measured downstream depth, y_3. Four issues potentially affect the momentum equation analysis.

1. We must account for hydrostatic forces on channel walls between sections 2 and 3.

2. We must account for the thickening and slowing of the jet at the vena contracta and the changes this causes in the momentum balance.

3. We must determine a suitable location for measuring y_3.

4. We may need to account for drag forces on the channel floor caused by boundary friction.

First, the downstream-directed forces exerted by channel boundaries between sections 2 and 3 must be estimated. This is accomplished by assuming that pressure distributions are hydrostatic and that a weighted flow depth, $y_w = py_3+(1-p)y_2$, is representative of the flow depth on these boundaries. The value of the weighting factor, *p*, has been estimated to be 0.64 in the tests conducted by ARS (Clemmens et al. 2003), but in other configurations (e.g., downstream channel much wider than the gate chamber) the value may be quite different.

The changes in jet thickness and velocity are dealt with by computing an effective velocity that is related to the energy correction,

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

This approach seems to work well and is not believed to require further study.

The best location for measuring y_3 has not been studied in detail at this time. It is desirable that y_3 be measured at a point where velocities are relatively uniform, the channel is still in alignment with the gate structure, and water levels are sufficiently steady to allow for accurate measurement. At many sites, downstream water level sensors are already used by canal operators, but most are located within a few meters of the gate; limited field testing suggests that locating the y_3 measurement station much further downstream (perhaps 30 to 50 m in typical situations) may significantly improve calibration accuracy.

When analyzing single gates, it is not necessary to estimate friction drag forces, since if the gate is operating in free flow, the momentum analysis is unnecessary, and if the gate is submerged, flow velocities downstream from the vena contracta are relatively low and friction forces are small. However, if a structure with multiple gates is analyzed and some gates operate in free flow while others are submerged, it does become necessary to estimate friction drag forces exerted on the high velocity jet issuing from the free flow gates. These forces are important to the overall momentum balance of the entire structure and will affect the flow depth y_2 at any submerged gates. Clemmens (2004) discusses these issues in more detail in a companion paper to be presented at this conference.

Other Issues with Multiple-Gate Check Structures

Gated check structures with multiple gates offer both challenges and opportunities. If all gates are synchronized, calibration is simplified, but in practice operators often prefer to put most gates into a fixed position and use just one or two gates to fine-tune the flow at a given check structure. On the upstream side of the structure, it becomes possible for the total energy head, H_1, to be different at each gate, although the magnitude of the differences will probably be small in most cases, since the velocity head approaching each of the gates is still relatively small compared to the total head. On the downstream side of the structure, there is the possibility that some gates may flow free while others are submerged. Application of the momentum equation becomes much more challenging because we must consider the momentum balance for the entire structure, while also examining the momentum balance for individual gates to determine free versus submerged flow. It also becomes necessary to compute friction forces on channel boundaries, as described earlier, and the determination of the force exerted by downstream channel walls may become more challenging due to complex flow conditions.

Check structures with multiple gates also present the opportunity to strategically position gates so that all gates can be kept out of the transition zone, where calibration uncertainty is the greatest. Some gates can be kept in free flow conditions while others are set to highly submerged operating points. Clemmens (2004) illustrates these possibilities.

Direct Measurement of y_2

The difficulties presented by structures with multiple gates are significant, and most are related to the determination of y_2 using the momentum equation. These problems could be avoided by directly measuring y_2. Turbulence downstream from the gate makes it impossible to physically measure the water surface elevation at this section with any accuracy, but a static pressure tube in the vena contracta could measure the pressure head in the vena contracta, which would be used to compute the equivalent y_2 depth.

Unfortunately, getting a pressure measurement from the vena contracta is difficult due to the high velocities and large flow forces on instrumentation inserted into the jet. Also, the location of the vena contracta will vary somewhat as the gate opening changes. It may be possible to identify one fixed location that could give a pressure measurement that is representative of the vena contracta pressure or could be indexed to it for all flow conditions, but this research has not yet been performed.

Applying the Energy-Momentum Method to Slide Gates

In theory, the Energy-Momentum method should be applicable to slide gates as well as radial gates. The energy correction developed for submerged radial gates should have direct application to slide gates, since it is accounting for changes in the hydrodynamics of the vena contracta jet caused by the partially submerged hydraulic jump. However, energy losses in the flow upstream from slide gates may differ substantially from those for radial gates. Previous investigators (e.g., Montes 1997 and 1999, Speerli and Hager 1999) have noted that flow patterns on the upstream sides of vertical slide gates are different from those upstream from radial gates, being characterized by strong vortex structures and recirculating eddies. These features are weak or absent when the gate is tilted slightly back from vertical (top of gate tilted toward upstream direction), as is the case with most radial gates. Other factors that could affect slide gates differently from radial gates are gate slots, guides, and associated width contractions. Issues surrounding the application of the momentum equation to slide gates are similar to those already discussed for radial gates.

Final Product

The final product of an effort to improve calibration procedures for canal check gates is likely to be a computer program of some type that can compute flow rates from measured water levels and gate positions, or gate positions required to deliver desired flow rates. A prototypical application that might serve as a model for such a computer program is the WinFlume program used to design and calibrate flow measuring flumes and weirs (Wahl et al. 2000). Although the hydraulic theory used to develop flume and weir calibrations is relatively complex and requires numerical solution, WinFlume is able to significantly simplify flume and weir calibrations for operational use by developing simple power-curve equations that closely fit theoretical head-discharge ratings of a particular structure. The curve-fit equations can be easily used in remote terminal units (RTU's) with limited memory and computational power. This would be desirable for canal check gates as well, but for the undershot gates discussed here, it is likely to be a very difficult objective to reach. In contrast to flumes and weirs for which there is a one-to-one relationship between measured head and computed discharge, for orifice-type check gates there are three independent variables, upstream head, downstream head, and gate opening, and the relationships between discharge and net head are extremely non-linear in the transition zone. Thus, it may not be possible to develop simple relationships that could be programmed into a computationally weak RTU.

Another related issue is the fact that with three independent variables it becomes difficult to produce rating tables in a compact form. Printed rating tables that provide sufficient detail become voluminous (Buyalski 1983), and are difficult to integrate into the supervisory control and data acquisition (SCADA) systems that are used to operate many modern canal systems. A different approach to the problem of canal check gate calibration is to develop a computer program that can be integrated with today's SCADA software. This product might take several possible forms:

- A stand-alone computer program,
- A Windows dynamic-link library (DLL) that can be called by other SCADA software,
- An Excel module that can be called by other Windows programs or Excel spreadsheets, or
- A web service that could be called over the Internet by a SCADA software package, or possibly by newer RTU's that have Internet connectivity.

It may even be possible to develop more than one of these products to meet a variety of operational needs, perhaps making use of a common source code library. These issues will have to be explored as this technology moves closer to real-world implementation.

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