HYDRAULIC EFFECTS OF PERPENDICULAR WATER APPROACH VELOCITY ON METER GATE FLOW MEASUREMENT

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ABSTRACT

Hydraulic Effects of Perpendicular Water Approach Velocity on Meter Gate Flow Measurement

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Accurate flow measurement is required to effectively manage water resources. California Senate Bill X7-7 (SB X7-7), legislates this need by requiring agricultural water providers serving areas greater than 25,000 acres to develop an Agricultural Water Management Plan (AWMP) and adopt pricing based at least partly on volumetric water deliveries (DWR, 2009). This study focused on two of the most common flow measurement/flow control devices used in California open channel water conveyance systems: the circular meter gate and the rectangular meter gate. Testing was conducted on three Armco-type (round gates over round discharge pipe) gates measuring 12”, 18”, and 24” and two rectangular gates (rectangular gates over round discharge pipe) measuring 18” and 24”. The three round gates used in the study were the Model 101C produced and provided by Fresno Valve and Castings Incorporated. The two rectangular meter gates were manufactured by Mechanical Associates located in Visalia, California and provided by the San Luis Canal Company located in Dos Palos, California. Testing was conducted in an outdoor laboratory setting at the Irrigation Training and Research Center’s (ITRC) Water Resources Facility at the California Polytechnic State University in San Luis Obispo, California under a variety of flow conditions as experienced in the field in order to: 1) evaluate the effectiveness of these gates as flow measurement devices and determine whether they meet the volumetric accuracy requirements outlined in SB X7-7,

2) develop standards for installation and use that improve flow measurement accuracy, 3) configure more accurate gate rating tables based on updated coefficient of discharge values, and 4) determine if additional gate rating tables are needed for “high” supply channel velocities. The meter gate was set perpendicular to the supply channel. Baseline data was first collected through testing with low supply channel water velocities. Additional testing was then conducted with high supply channel water velocities to analyze the effect on the coefficient of discharge. Based on previous studies it was hypothesized that as the Froude number (FR#) in the supply channel increased (water approach velocity increased), the coefficient of discharge would decrease as a result of an increase in energy needed for the perpendicular velocity transition. Data evaluation, however, indicated no statistically significant effect of water approach velocity on the coefficient of discharge for the 12”, 18” and 24” circular gates or the 18” and 24” rectangular gates at an α-level = 0.01. When operating the gates under recommended conditions relative flow uncertainty was within +/- 5%. This meets the accuracy requirements set by SB X7-7 for turnout flow measurement devices. Based on the results of this study, Cd values do not need to be adjusted for Froude numbers up to 0.35 for any of the studied gates. It should be noted, however, that while most meter gates used will be in conditions where supply channel Froude numbers do not exceed 0.35, further research is needed to study potential effects from Froude numbers exceeding the range found in this study.

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CHAPTER 1: INTRODUCTION

Senate Bill X7-7

In 2009, amidst the third year of the 2007-2009 drought period and continuously increasing demands on the California water supply, the California Senate passed Senate Bill (SB) X7-7: The Water Conservation Act of 2009 (DWR, 2009). The bill, which aims to increase water conservation and water-use efficiency among urban and agricultural suppliers, requires agricultural water suppliers serving more than 25,000 acres to measure the water delivered to customers within a specified range of accuracy and charge at least partly based on this delivered volume (volumetric billing) (DWR, 2009).

The required range of accuracy (percent error between the measured volume and the actual volume) for water delivered to consumer(s) is specified in section 597.3 (a) of the bill and reads (DWR, 2011):

- For existing flow measurement devices, the volumetric accuracy must be within +/- 12%.
- For new flow measurement devices, the volumetric accuracy must be within a laboratory rated +/- 5% or +/- 10% in the field if laboratory ratings are not available.

Depending upon an agricultural water supplier’s conveyance system and conditions at the point of transfer to the customer (known as a “turnout”), the methods of flow measurement used for volumetric billing may include different devices such as: magnetic meters, propeller meters, transit-time meters, weirs, flumes, or orifice-type meters. The device selected for a specific site will depend on factors including: dirt load and other debris in the water, available head loss, theft potential, and both initial and future costs (Burt, 2010).

In California, a significant portion (roughly one-third – putting the total number of meter gates in California in the thousands) of irrigation turnouts utilize meter gates or similar orifice type gates (ITRC 2000; ITRC 2002). Meter gates and similar orifice type sluice gates allow for both flow control (on/off) and flow measurement. Meter gates also provide additional advantages when compared to flow measuring devices within a conveyance system such as: decreased sensitivity to water level changes in supply canals in comparison to weirs, limited sediment accumulation due to sufficiently high water velocities through the gate, permission of a range of desired flows with simple gate adjustment, and low maintenance costs (ITRC, 2012).

The meter gate consists of a circular shaped (although rectangular shaped gates may also be used and are tested in this study) sluice gate that fits over a corresponding round pipeline orifice to control and measure outlet flow. For a meter gate to be used, the upstream as well as the downstream (or pipe discharge) side of the gate must be completely submerged. Two head measurements are taken: one at the upstream side of the gate in the supply channel (H_1) and another from a stilling well tapped into the top or "crown" of the discharge pipe (H_2) typically set 12 inches beyond the gate. In addition to the head loss measurement (H_1-H_2), the gate opening is used to determine the pipe orifice area (A_o). Inputting the change in head and the orifice area with an appropriate coefficient of discharge (C_d) into the discharge equation yields the estimated flow rate through the gate as mathematically written in the submerged orifice discharge equation:

$$Q = C_d * A_o \sqrt{2g * \Delta H} \quad (1)$$

Historically one of the first sluice-type gates to be calibrated for use as a metering gate was the Calco (California Corrugated Culvert Company) number 101 slide headgate (Figure 1). Calco was a division of the American Rolling Mill Company (Armco) and the Calco Model 101 subsequently became known as the Armco Model 101 with the basic design of a round slide gate fitted over a round pipe referred to as an Armco-type gate (Howes and Burt, 2015a).

Figure 1. 20" Calco Slide Headgate (Fresno Irrigation District, 1928).

Testing of the Calco 101 was initially conducted by the Modesto Irrigation District in 1918 with varying discharge pipe lengths downstream of the submerged orifice (Armco, 1949) in order to utilize the gate (until then only used as a simple on/off gate) as a flow measurement device. Subsequent testing by the Fresno Irrigation District (FID) in 1927-1928 standardized the use of a downstream pressure measurement at 12 inches behind the gate face (Fresno Irrigation District, 1928). This calibration work completed by the FID of the Calco 101 gates ranging in size from 8-inch to 24-inches under varying heads and gate openings led to the first published Armco rating tables for this meter gate.

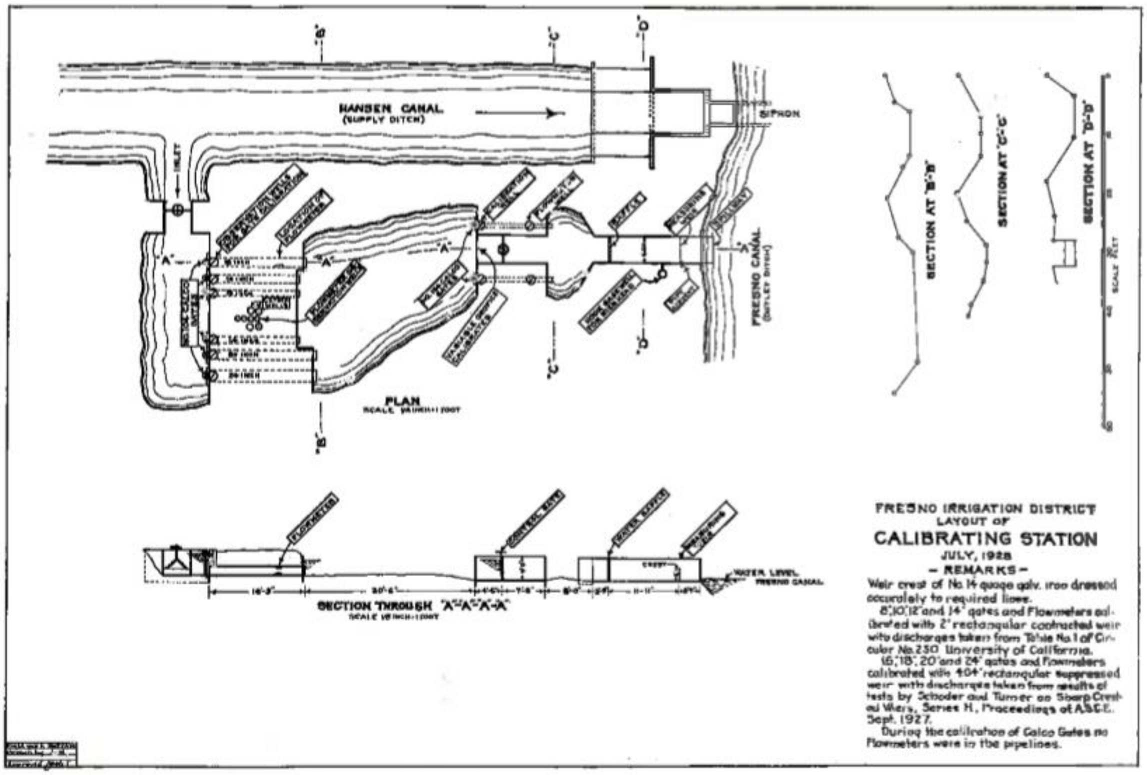


Figure 2. Fresno Irrigation District Calibrating Station Design for Calco 101 Meter Gate (Fresno Irrigation District, 1928)

Further research was conducted at The Colorado Agricultural Research Foundation of Colorado A&M College (what is today Colorado State University) in 1950 by the United States Bureau of Reclamation and college staff in order to improve upon the previous tests. According to the USBR, errors of up to 18% were found through preliminary testing in the rating tables published by the Fresno Irrigation District (Summers, 1951). Summers (1951) identified and described limiting factors in relation to their effect on meter gate flow rate accuracy: gate design, approach design, submergence of meter gate entrance, outlet submergence, length of meter gate pipe, location of pressure tap for downstream head-measuring well, and velocity of flow in the meter gate. Today's published Armco discharge tables as well as design (Figure 3) and operation recommendations for the Armco meter gate are still based on this USBR research conducted over 70 years ago.

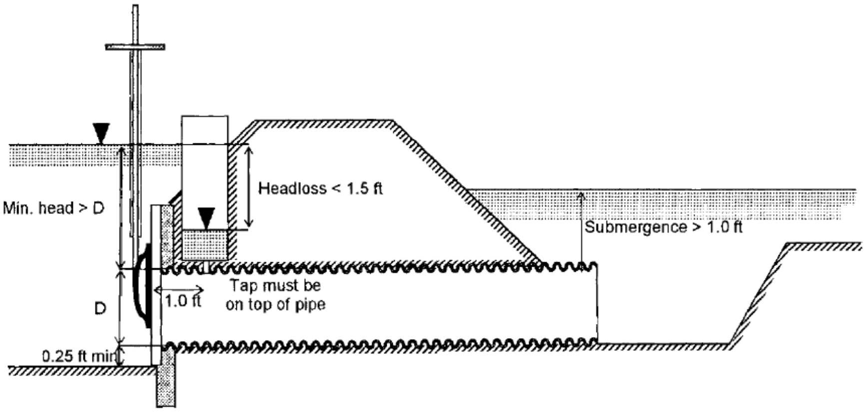


Figure 3. USBR Meter Gate Installation Guidelines – 1953 (Cadena and Magallanez, 2005)

<u>Statement of Problem and Literature Review</u>

Since meter gate flow rating tables are empirically based, installations and water flow conditions that differ from laboratory test setups can cause discrepancies between published rating tables and actual flow rates. One particularly significant design detail is the direction of water flow in the supply channel relative to the meter gate. During the aforementioned Bureau testing (of which current meter gate flow rating tables are based), gates were configured with direct flow from the supply channel into the gate (Figure 4). In reality, most gates installed at field turnouts (where the majority of volumetric billing occurs) are situated on channel walls with the water supply flowing perpendicular to the gate. Original testing by FID in 1927, which as noted above was found to be in error up to 18% in some Bureau testing, followed this design (Figure 2).

In addition to differing water flow directions during calibration testing, contrasting design recommendations have led to a variety of in-field installations. As an example, Howes and Burt (2015a) point out that the Armco Rating Table booklet (1975) and Summers (1951) recommend placing the stilling well tap 12 inches beyond the gate for measurement of the downstream head, while Ball (1961) and the USBR Water Measurement Manual (1997) dictate placement of the tap at a distance downstream of the gate equivalent to one-third the pipe diameter where “the pressure grade-line is lower and flatter” making the pressure reading more stable.

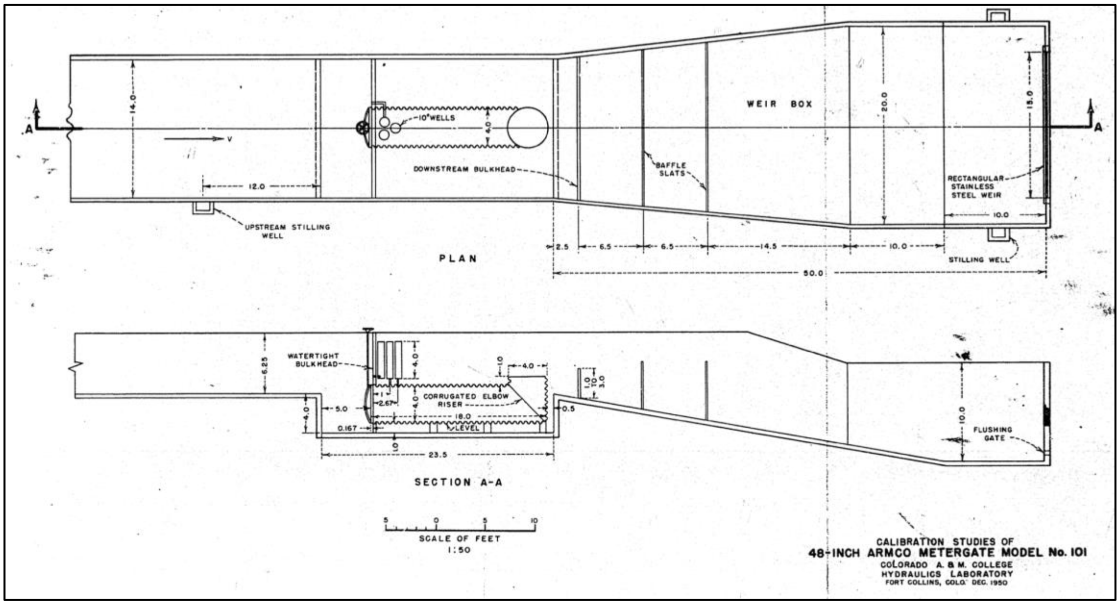


Figure 4. USBR Meter Gate Testing Setup 1950 Configured with Direct Flow from the Supply Channel into the Meter Gate (Summers, 1951).

The experimental design at the Irrigation Training and Research Center’s (ITRC) Water Resources Facility at the California Polytechnic State University in San Luis Obispo, California allowed for replication of common meter gate field installs where gates are set perpendicular to supply water flow with the ability to test the gates under a variety of flow conditions in a controlled modern laboratory setting. This ITRC study filled the existing gaps in meter gate testing by enabling researchers to: 1) evaluate three commonly used circular meter gates (12”, 18”, and 24”) and two rectangular meter gates (18” and 24”) as flow measurement devices to determine whether these gates meet the volumetric accuracy requirements outlined in SBx7-7, 2) develop standards for installation and use to ensure flow measurement accuracy 3) configure more accurate gate rating tables based on updated coefficient of discharge values and 4) determine if additional gate rating tables are needed for “high” supply channel velocities.

In addition to reviewing the key findings for #1-3 listed above, the purpose of the work presented here is to examine objective #4: determine if additional gate rating tables are needed for high supply channel velocities. Previous studies have analyzed the effects of varying supply channel velocities on flow through a side orifice. Swamee et al (1993) found the elementary discharge coefficient of a rectangular side sluice gate discharging into a rectangular channel to be a function of the ratio of channel flow depth to gate opening for free flow conditions. For submerged conditions the ratio of tailwater depth to gate opening was also noted as affecting the coefficient of discharge. Ordinary differential equations were used to calculate the upstream supply channel water depth along an elementary strip of the face of the gate. As seen in the original figure from Swamee et al (1993), the upstream water level in the supply channel descends to its lowest level at the entrance of the gate and then rises as it moves across the gate due to supply channel velocity and gate opening. As the supply channel water level varies across the face of the gate, so does the associated coefficient of discharge value.

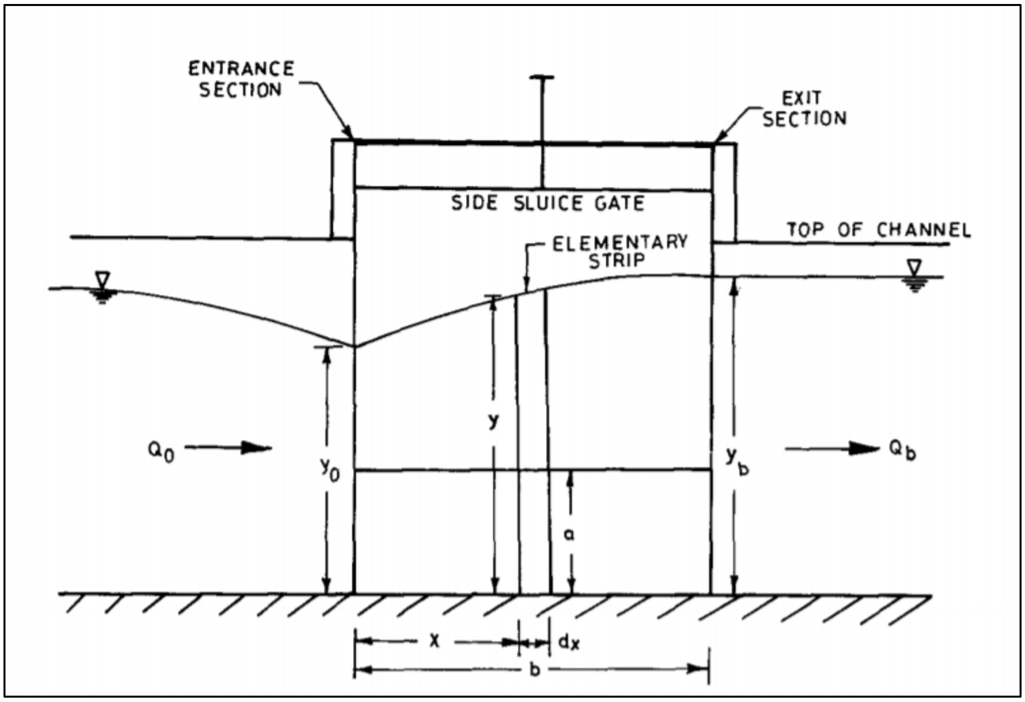


Figure 5. Swamee et al 1993 Flow Characteristics Along the Face of the Side Sluice Gate

Building upon the work of Swamee et al (1993), Ghodesian (2003) proposed an amended equation for the coefficient of discharge through a rectangular side sluice gate into a rectangular channel that included the supply channel approach Froude number and allowed for direct calculation of discharge of flow through the side sluice gate using the discharge equation for a submerged orifice (Equation 1). The inclusion of the approach Froude number of the supply channel as a correction in the computation of the discharge coefficient allowed Ghodsian to use the lowest upstream water level (listed as y_0 in Figure 5) located at the head of the gate instead of analyzing the varying water level across the face of the gate as proposed by Swamee et al (1993). In this approach by Ghodesian the location of the head measurement at the entrance to the gate led to a corrected increase of the calculated C_d value at higher Froude numbers. This is due to the fact that as the approach Froude number increased, the water level decreased at the entrance to the gate. If Ghodesian would have taken the upstream head measurement further upstream or on the downstream side of the gate the correction due to a higher approach Froude number would likely have resulted in a decreased C_d value. This was in fact the result in two studies analyzing the C_d for sharp-crested circular side orifices (Hussain et al, 2010) and sharp-crested rectangular side orifices in open channels under free flow (Hussain et al, 2011). The authors concluded the coefficient of discharge for both sharp-crested circular and rectangular side orifices depends on the approach Froude number and the ratio of the size of the orifice to the bed width of the channel. In these studies the head measurement was collected upstream of the face of the gate. As written in the authors' equation for the C_d, the approach Froude number is inversely associated with the coefficient of discharge: as the approach Froude number increases, the C_d decreases.

The effect of supply channel water velocity on the coefficient of discharge specifically for gates supplying pipelines has not been studied. Subsequent to baseline testing, higher velocity testing was conducted with supply channel water velocities up to 3.09 ft/s to study what effect these higher supply channel velocities and Froude numbers may have on the C_d. The hypothesized result of higher approach Froude numbers is a reduction in discharge through the meter gates compared to predicted flows using the coefficients developed through the baseline tests.

CHAPTER 2: PROCEDURES

Experimental Design and Measurements

Meter gate testing was conducted at the Irrigation Training and Research Center’s (ITRC) Water Resource Facility located on the California Polytechnic State University campus in San Luis Obispo, California. The water supply was drawn from a local reservoir (Drum Reservoir) and pumped into a storage basin where a lift pump operated with a Variable Frequency Drive (VFD) controlled a 100-horsepower motor. This provided the required range of testing flows to the supply channel flume.

From the lift pump, water moved through a 30” steel pipeline to a concrete reservoir at the head of the supply channel flume. Flow rate through the 30” pipeline and into the supply channel flume was measured using an installed 30” calibrated McCrometer magnetic flow meter. The water velocity in the supply channel flume (V_1) was calculated using the measured flow rate through the 30” McCrometer magnetic flow meter, the measured water depth just upstream of the installed gate, and the constructed channel width of four feet. Supply channel Froude number was then calculated as:

$$F_1 = \frac{V_1}{\sqrt{g d_1}} \tag{2}$$

Where subscript 1 indicates conditions upstream of the gate in the supply channel. The depth of the water in the supply channel just upstream of the gate (d_1) is equal to the sum of the upstream head above the turnout pipe (H_1), the gate diameter (D), and the distance from the bottom of the pipe to the channel invert. Baseline meter gate tests (Howes and Burt, 2015a,b) focused on the lowest possible velocities in the flume to negate possible effects of high velocity supply channel flows on the Coefficient of Discharge (C_d). Subsequent higher velocity testing as discussed in this paper was then performed to analyze if higher Froude numbers (F_1) have a statistically significant effect on the C_d and if corrections are needed for C_d values at higher Froude numbers.

Figure 6 shows the testing design starting with the supply channel flume situated directly downstream of the concrete reservoir. Water fed into the concrete reservoir from the 30" steel pipeline at the target flow passed into the flume and was "checked" up in front of the meter gate. An oblique weir measuring 12.13 feet was used as the check structure, maintaining a constant head on the gate. Adding or removing weir flashboards allowed researchers to adjust the target upstream head based on the specific test being conducted. All water supplied through the 30" steel pipeline and into the flume either passed over the oblique weir or through the installed meter gate.

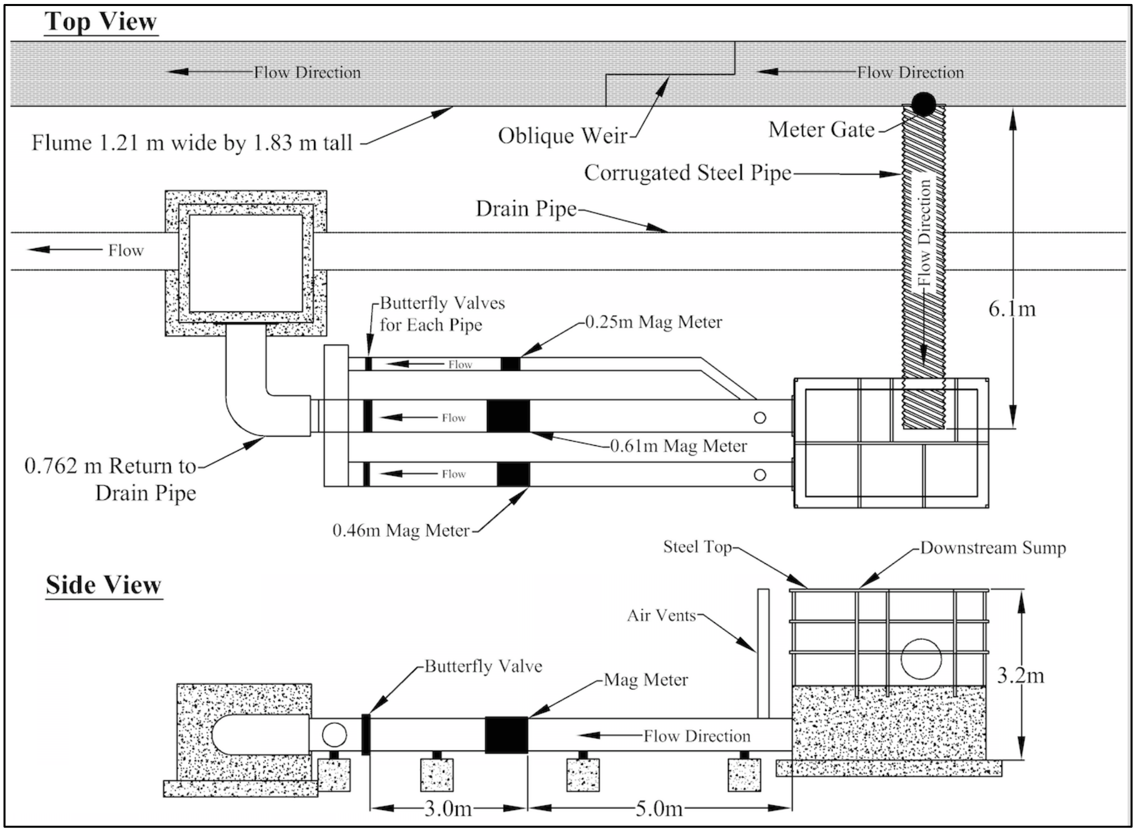


Figure 6. ITRC Meter Gate Experimental Design (Howes and Burt, 2015a)

Consistent with field installations, each meter gate tested was mounted to the side of the supply channel flume (perpendicular to channel flow and slightly protruding from the wall) using a removable steel bulkhead. Besides orientation with respect to supply channel flow, the experimental design met installation criteria outlined by the USBR for use with the existing rating tables: a minimum distance of 4” from the bottom of the gate to the supply channel invert was maintained for all gates, and a 20-foot corrugated discharge pipe (beyond the minimum 7x gate diameter length requirement for all tested gates) with inside diameter matching the tested gate diameter connected the gate discharge to a downstream sump.

Additional design details (Figure 7) were implemented to expand the available range of data collected. The flume sides upstream and extending slightly downstream of the meter gate were expanded from 4 feet to 6 feet to match the wall height of the downstream sump and accommodate high head measurements (the H_1 measurement). The downstream stilling well taps (providing the H_2 measurements) were placed at distances of: 6”, 8”, 12”, 24”, 48”, 96”, and 192.” These pressure tap locations allowed for a more complete determination of the hydraulic grade line downstream of the gate, which was required to analyze the effect of varying tap locations on the flow measurement reading.

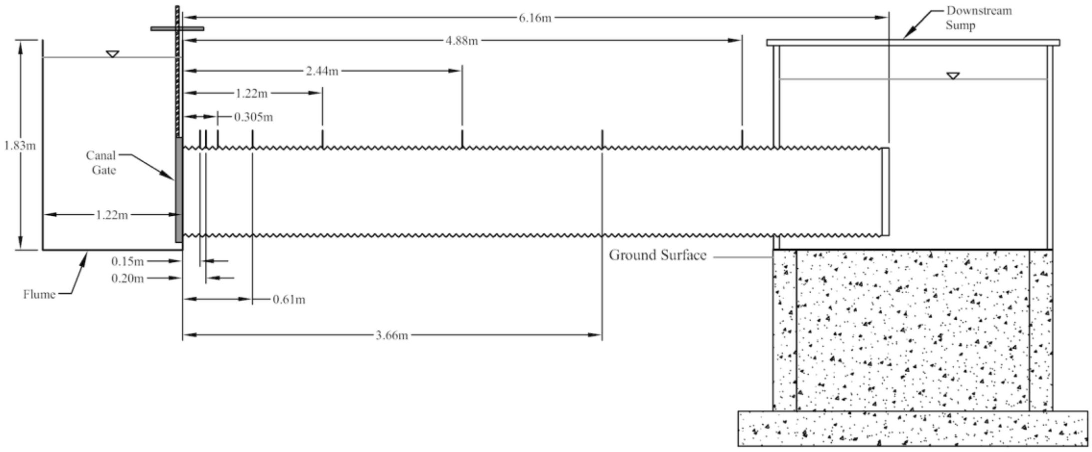


Figure 7. Meter Gate Testing Design Layout (Howes and Burt, 2015a)

Water flow through the gate was measured downstream of the sump as it traveled through one of three exhaust pipelines connected to a manifold that channeled water to the “drain pipe” (Figure 6) eventually flowing to the original sump located at the end of the flume to be recirculated by the lift pump. Depending on the gate size and flow condition being tested, water flow rate (Q) traveling through the gate was measured using one of three magnetic meters attached to a corresponding steel pipeline with diameters measuring: 10”, 18”, or 24”. All of the magnetic meters (including the 30” meter described previously) were calibrated at the ITRC prior to use in the experiment. Butterfly valves installed in the 10”, 18”, and 24” steel pipelines ensured pipelines flowed full and allowed researchers to adjust the head loss across the gate by adjusting the outflow and subsequently the water level in the sump (back pressure).

Listed in the discharge equation for a submerged orifice (1), the variables required to solve for flow rate (Q) in cubic feet per second (ft^3/s) are: the coefficient of discharge (C_d), the net gate opening area (A_o) in feet squared (ft^2), and the head loss across the gate (ΔH) in feet (ft). In the equation “g” is the acceleration due to gravity given as 32.2 ft/sec^2. With the meter gate installed perpendicular to the flow of water the velocity of approach is close to zero and so the coefficient of velocity (C_v) is excluded from the equation.

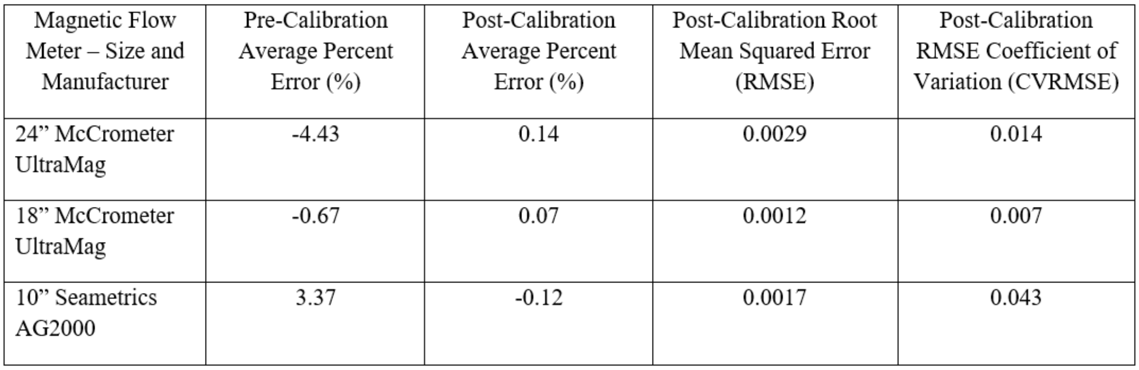
Rating tables allow for quick flow rate determination in the field by matching measured head difference and the gate opening to the associated flow rate (a previously calculated value). In order for these calculated values to be accurate, the appropriate C_d value must be used. In this study C_d values were determined by measuring the Q, ΔH, and A_o and then rearranging the discharge equation to yield C_d:

$$\boldsymbol{C_d = \frac{Q}{A_o\sqrt{}(2g\Delta H)}} \qquad (3)$$

<u>Flow Rate (*Q*)</u>

As previously discussed in the *Experimental Design* section, flow rate *Q* through the meter gate was measured downstream of the sump using a magnetic meter of appropriate size (either 10”, 18”, or 24”) given the relative flow rate range. Prior to testing, all magnetic meters used in the experiment were individually calibrated at the ITRC. Each magnetic meter was installed in a pipeline within the 4-foot wide x 4-foot high flume parallel to water flow. Nine or more varying flow rates were delivered to the head of the flume per meter and meter readings were compared to downstream readings from a National Institute of Standards and Technology (NIST) certified weigh tank. Data points were collected, graphed, and a best-fit linear regression with an r-squared value greater than 0.999 was then used to develop the calibrated flow. For all three magnetic meters used in the measurement of flow through the meter gates, post-calibration average flow measurement error was less than 0.15% (Table 1).

Table 1. Magnetic Flow Meter Calibration for Flow Measurement Through Meter Gates



Magnetic Flow Meter – Size and Manufacturer	Pre-Calibration Average Percent Error (%)	Post-Calibration Average Percent Error (%)	Post-Calibration Root Mean Squared Error (RMSE)	Post-Calibration RMSE Coefficient of Variation (CVRMSE)
24” McCrometer UltraMag	-4.43	0.14	0.0029	0.014
18” McCrometer UltraMag	-0.67	0.07	0.0012	0.007
10” Seametrics AG2000	3.37	-0.12	0.0017	0.043

For each meter gate flow test, four flow readings were manually recorded from the digital meter display after flow conditions were steady. The raw digital readings were later adjusted according to the calibration equation developed for that meter.

Pressure Readings (*H*)

Upstream and downstream pressure readings were recorded for each test in order to determine the head loss (ΔH) across the gate. Downstream of the meter gate six ¾" diameter holes for the H_2 measurements were tapped into the nearest crown of the corrugated pipe at distances of: 6", 8", 12", 24", 96", and 192". As discussed in the *Statement of Problem* section, the Armco water measurement tables call for the H_2 measurement to be taken 12" downstream of the meter gate. For this reason, data taken at the 12" location during testing was utilized for comparison of accuracy against the published tables. The additional tap locations for measurement downstream allowed for evaluation of effects on estimated flow. The reading upstream of the gate (H_1) was taken from a ¾" hole tapped into the flume level with the top of the corrugated pipe.

To "still" pressure readings and allow for accurate measurements, 6" stilling wells were connected to the tapped holes via plastic tubing. The clear plastic tubing was connected to each tapped hole using a PVC tee fitting and run to the 6" stilling wells mounted side by side on the southern wall of the sump. The plastic hoses were run along a wooden plank sloped at a slight upward grade to clear air bubbles from the line that may distort readings downstream.

Pressure measurements were taken two ways to ensure the highest accuracy and avoid error. First, the researcher recorded direct measurements provided by a SMAR-LD301 pressure differential transducer. The testing setup was configured so that the 6”-192” stilling wells were individually connected through tubing to a manifold with one outlet hose that attached to the first inlet of the pressure transducer. Each stilling well inlet tube entering the manifold was attached to a ball valve and labeled for easy identification and isolation.

On the second transducer inlet, tubing from the upstream stilling well was connected. Using the isolation valves on the manifold, the researcher recorded the direct pressure difference readings (ΔH) for each stilling well from the transducer. Next to this reading on the data sheet and in EXCEL, the researcher recorded the second pressure measurements. These measurements were taken from staff gauges with 0.0625” measurement increments connected to each stilling well and placed in accordance to the same datum. Raw values were entered into EXCEL and calculated head differences were compared to the corresponding transducer readings to ensure proper functioning of the transducer. If manual measurements for ΔH disagreed from readings from the SMAR-LD301 by more than 1% the pressure transducer was reset and the measurements were rerecorded.

Net Gate Opening Area (*Ao*)

Previous research has used different parameters for measuring net gate opening area (A_o). Cadena and Magallanez (2005) used an equation to approximate the value of the opening area (A_o) proposed by Hager (1987). As noted by the authors, the equation is used for "typical circular gates with diameters 5% greater than the circular opening[*] (Cadena and Magallanez, 2005)."

While this equation provides a close estimate of the orifice opening at mid-range gate displacements, Howes and Burt (2015a) determined through comparison with precise mathematical calculations that the method suggested by Hager (1987) produces erroneous values at gate openings less than 25% and greater than 55% (Howes and Burt, 2015a).

For meter gate rating tables developed from Bureau testing, actual gate opening area was excluded and instead the coefficient of discharge was calculated using the full pipe area (A_p). The major advantage and reasoning for using a precise measurement of A_o is the ability to compare C_d values among varying gate displacements and gate sizes. In other words, by precisely calculating the net gate opening (A_o) and isolating the head loss measurement from the C_d, the relationship and degree of transferability of the C_d value among different gates could be properly analyzed (Howes and Burt, 2015a).

Referencing Skogerboe and Merkely (1996), Howes and Burt (2015a,b) used equations (4)-(7) for the circular Armco-type gates and equation (8) for the rectangular gates to develop the relationship between net gate opening area (A_o) and net gate opening (y):

$$\boldsymbol{A_o = A_i - A_{subtracted}} \tag{4}$$

---

[*] Meter gates typically maintain areas that exceed the area of the orifice in order to ensure a water-tight seal when closed. For this reason, gates should meet the 5% requirement described by Hager. This overlapping fitting also brings about the point of correct "zeroing" of the gate for opening measurements, which is discussed in this report.

Where,

$$A_i = R_p^2 * Cos^{-1}\left(\frac{O}{R_g}\right) + O * \sqrt{R_p^2 - O^2} \tag{5}$$

$$A_{subtracted} = R_g^2 * Cos^{-1}\left(\frac{P - O}{R_g}\right) + (O - P) * \sqrt{R_g^2 - O^2} \tag{6}$$

$$P = y + R_g - R_p \tag{7}$$

For the 18” and 24” rectangular gates:

$$A_o = \frac{R_p^2}{2} * \left[2 * Cos^{-1}\left(1 - \frac{2 * y}{R_p}\right) - Sin\left(2 * Cos^{-1}\left(1 - \frac{2 * y}{R_p}\right)\right)\right] \tag{8}$$

Figure 8 identifies the variables for calculating the net opening area (A_o). The two gate styles are shown side-by-side with the slide gates in a partially open position and the net opening area lightly shaded. R_g is the outside radius of the gate and R_p is the inside radius of the corrugated pipe.

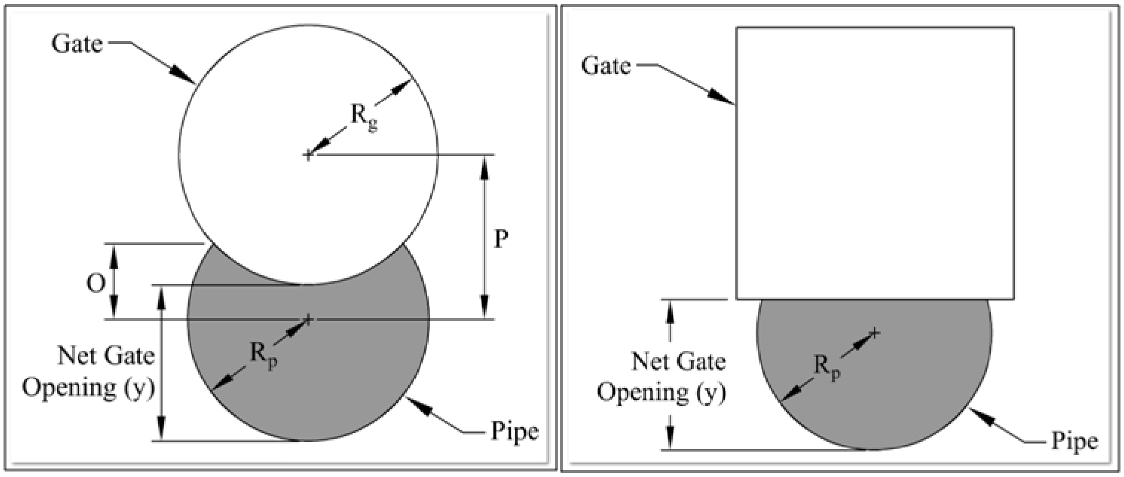


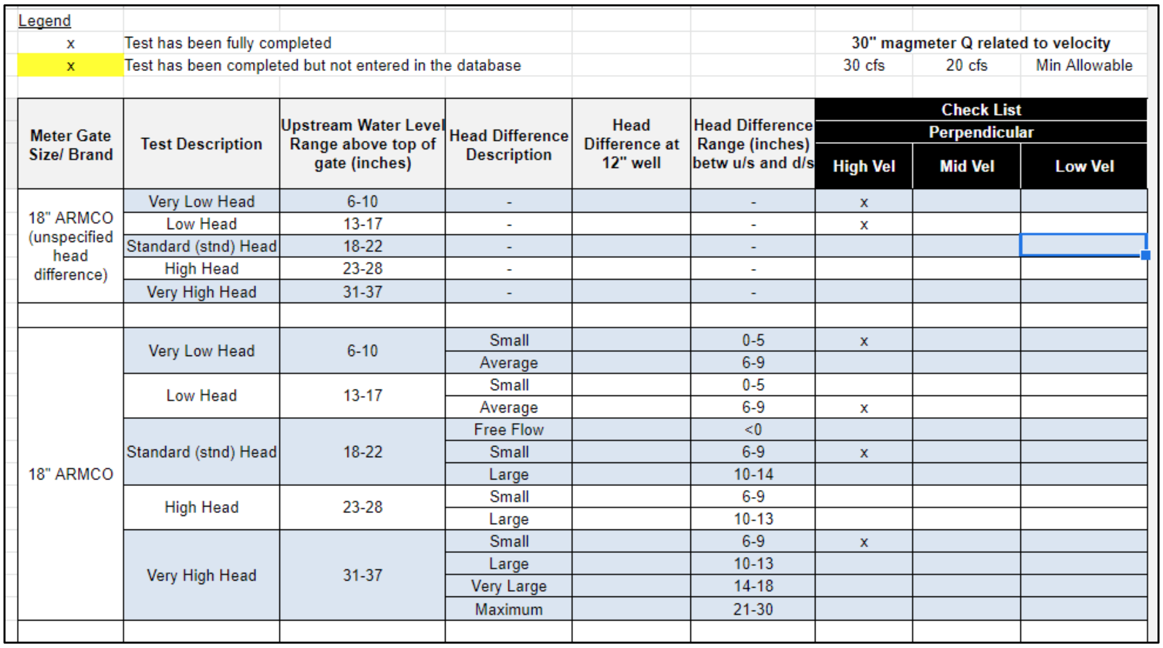
Figure 8. Net Gate Opening Area (*A*$_o$) Variables for Circular and Rectangular Meter Gates (Howes and Burt, 2015a,b)

For proper measurement of net gate opening (*y*), the initial opening position of the gate in relation to the orifice must be correctly “zeroed.” The zero opening position is the position in which water initially begins to flow through the gate and is identified by displacing the gate vertically until a standard sheet of paper can be passed between the gate and the discharge pipe invert. At this point, the zeroed position on the threaded gate stem was marked using an angle grinder to cut a roughly 0.5” indicator mark on the gate stem directly above the gate lift nut. The net gate opening was then determined by measuring from the marked “zeroed” notch to the bottom of the lift nut.

Meter Gate Testing Parameters

Testing in this study focused on three circular gates measuring 12”, 18”, and 24” and two rectangular gates measuring 18” and 24”. The three round gates used in the study were the Model 101C produced and provided by Fresno Valve and Castings Inc. These are the same gate types used in both the original meter gate testing done by Fresno Irrigation District and subsequent testing by the US Bureau of Reclamation previously cited. The two rectangular gates tested in this study were produced by Mechanical Associates located in Visalia, California and provided by the San Luis Canal Company located in Dos Palos, California. Flow conditions were varied during testing in order to evaluate their effect on the coefficient of discharge (C_d). These conditions included: upstream head in the flume, downstream water level in the sump (ΔH), gate opening, and supply channel velocity in addition to the differences in the gates themselves (size and shape).

To organize the range of flow conditions for testing a data sheet was created (Figure 9).



Legend
x Test has been fully completed
x Test has been completed but not entered in the database

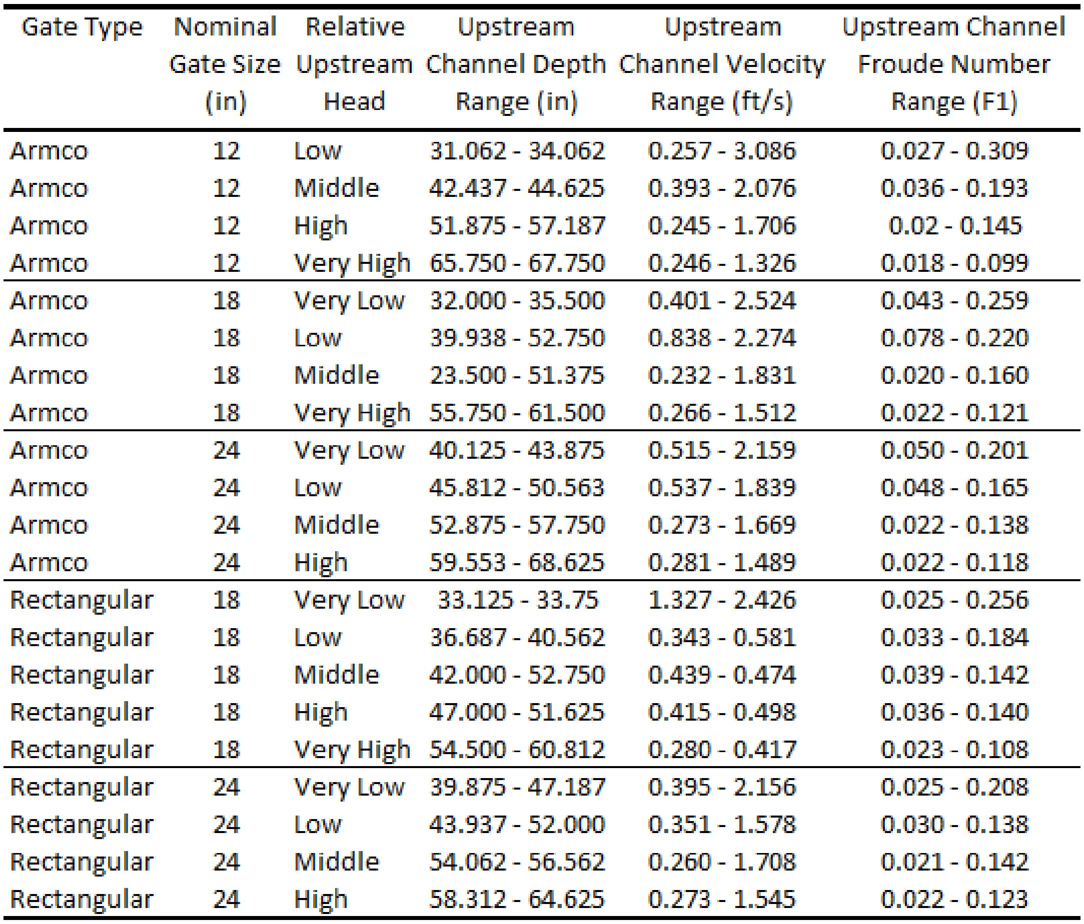
						30" magmeter Q related to velocity		
						30 cfs	20 cfs	Min Allowable
Meter Gate Size/ Brand	Test Description	Upstream Water Level Range above top of gate (inches)	Head Difference Description	Head Difference at 12" well	Head Difference Range (inches) betw u/s and d/s	Check List		
						Perpendicular		
						High Vel	Mid Vel	Low Vel
18" ARMCO (unspecified head difference)	Very Low Head	6-10	-		-	x		
	Low Head	13-17	-		-	x		
	Standard (stnd) Head	18-22	-		-			
	High Head	23-28	-		-			
	Very High Head	31-37	-		-			
18" ARMCO	Very Low Head	6-10	Small		0-5	x		
			Average		6-9			
	Low Head	13-17	Small		0-5			
			Average		6-9	x		
	Standard (stnd) Head	18-22	Free Flow		<0			
			Small		6-9	x		
			Large		10-14			
	High Head	23-28	Small		6-9			
			Large		10-13			
	Very High Head	31-37	Small		6-9	x		
			Large		10-13			
			Very Large		14-18			
			Maximum		21-30			

Figure 9. Sample Data Collection Sheet

Tests were organized by upstream head measurement ranges that included: “Very Low” relating to head levels less than 1 turnout pipe diameter, “Low” relating to head levels just below 1 turnout pipe diameter, and “Standard,” “High,” and “Very High” which related to increasing head measurements from the standard 1 turnout pipe diameter to the maximum upstream head that could be tested given flume height constraints. Tests were further differentiated by head difference for each upstream condition. For each test the meter gate being studied was opened incrementally. The 12” gate was opened in 1” increments while the 18” and 24” gates (both circular and rectangular) were opened in 2” increments.

As described in the *Introduction*, subsequent to baseline testing at low supply channel velocities additional testing was completed to determine what effect high supply channel water velocities may have on the coefficient of discharge and if C_d corrections are needed for flow rate determination in high supply channel water velocity settings for the 12”, 18”, and 24” round and 18” and 24” rectangular meter gates. Table 2 lists the tested range for variables of relative upstream head (head above the turnout pipe, H_1, + turnout pipe diameter, D), upstream channel depth, upstream channel velocity, and upstream channel Froude number (F_1) for each of the five gates for the high supply channel velocity testing.

Table 2. High Velocity Testing Ranges for Supply Channel Depth, Velocity, and Froude Numbers



Gate Type	Nominal Gate Size (in)	Relative Upstream Head	Upstream Channel Depth Range (in)	Upstream Channel Velocity Range (ft/s)	Upstream Channel Froude Number Range (F1)
Armco	12	Low	31.062 - 34.062	0.257 - 3.086	0.027 - 0.309
Armco	12	Middle	42.437 - 44.625	0.393 - 2.076	0.036 - 0.193
Armco	12	High	51.875 - 57.187	0.245 - 1.706	0.02 - 0.145
Armco	12	Very High	65.750 - 67.750	0.246 - 1.326	0.018 - 0.099
Armco	18	Very Low	32.000 - 35.500	0.401 - 2.524	0.043 - 0.259
Armco	18	Low	39.938 - 52.750	0.838 - 2.274	0.078 - 0.220
Armco	18	Middle	23.500 - 51.375	0.232 - 1.831	0.020 - 0.160
Armco	18	Very High	55.750 - 61.500	0.266 - 1.512	0.022 - 0.121
Armco	24	Very Low	40.125 - 43.875	0.515 - 2.159	0.050 - 0.201
Armco	24	Low	45.812 - 50.563	0.537 - 1.839	0.048 - 0.165
Armco	24	Middle	52.875 - 57.750	0.273 - 1.669	0.022 - 0.138
Armco	24	High	59.553 - 68.625	0.281 - 1.489	0.022 - 0.118
Rectangular	18	Very Low	33.125 - 33.75	1.327 - 2.426	0.025 - 0.256
Rectangular	18	Low	36.687 - 40.562	0.343 - 0.581	0.033 - 0.184
Rectangular	18	Middle	42.000 - 52.750	0.439 - 0.474	0.039 - 0.142
Rectangular	18	High	47.000 - 51.625	0.415 - 0.498	0.036 - 0.140
Rectangular	18	Very High	54.500 - 60.812	0.280 - 0.417	0.023 - 0.108
Rectangular	24	Very Low	39.875 - 47.187	0.395 - 2.156	0.025 - 0.208
Rectangular	24	Low	43.937 - 52.000	0.351 - 1.578	0.030 - 0.138
Rectangular	24	Middle	54.062 - 56.562	0.260 - 1.708	0.021 - 0.142
Rectangular	24	High	58.312 - 64.625	0.273 - 1.545	0.022 - 0.123

Testing included 1,025 additional data points with velocities ranging from 0.23 ft/sec-3.09 ft/sec. As observed in the table above, the highest supply channel velocities occurred with the smaller gate sizes in the lowest upstream depth conditions. Maximum testing velocities were limited with the larger gates due to flow constraints in the testing flume (30 cu ft/sec) and minimum water levels required for testing. Even with the limitations, however, Scobey (1939) shows the data range collected in these tests cover field conditions with typical earthen and concrete canals used for irrigation conveyance systems maintaining velocities below 3 ft/sec.

Evaluation of Meter Gate Flow Measurement Accuracy

As previously cited, The Water Conservation Act of 2009 (SB X7-7) requires the following for flow measurement devices:

- For existing flow measurement devices, the volumetric accuracy must be within +/- 12%.
- For new flow measurement devices, the volumetric accuracy must be within a laboratory rated +/- 5% or +/- 10% in the field if laboratory ratings are not available.

The +/- 12% refers to the allowable percent error between the measured volume of water delivered and the actual volume of water delivered. The volume of water delivered is measured by the flow measurement device and this value is compared to the actual volume determined through laboratory or field testing (DWR, 2011).

Burt and Geer (2012) explain that as opposed to flow measurement devices with totalizers, flow rate accuracy is only one of the variables that determines the volumetric accuracy of meter gates. In addition to instantaneous flow measurement accuracy, the volumetric accuracy of a meter gate is affected by three additional variables: changes in the supply channel water level, changes in the water level downstream of the meter gate (backpressure), and accuracy of the recorded duration of the water delivery through the meter gate to the customer. Through extensive studies conducted at San Luis Canal Company in Los Banos in the water delivery year of 2012, Burt and Geer were able to quantify the error due to supply channel water fluctuations as within +/- 2% with a confidence level of 95%. The authors, based on field experience, assigned a value of +/-

3% for errors due to changes in backpressure on the gate and +/- 4% for error due to recorded duration of water delivery. This value of +/- 4% was based on the estimate that, on average, for a 24-hour water delivery event the difference between the actual delivery time and the recorded time would be within +/- 1 hour.

As noted by the authors, the errors of each variable are independent and therefore should not be simply summed to calculate total error but instead written mathematically using the root-of-squares method (Taylor and Kuyatt 1994).

Referencing this work, Howes and Burt (2015a) write the relationship mathematically as:

$$U_v = 100 \times \left[\sqrt{\left(\frac{U_Q}{100}\right)^2 + \left(\frac{U_{Hu}}{100}\right)^2 + \left(\frac{U_{Hd}}{100}\right)^2 + \left(\frac{U_T}{100}\right)^2} \right] \tag{9}$$

Where:

- U_v is the percent volumetric uncertainty denoting the range for true absolute values from the measured value with a 95% confidence interval (two standard deviations from the mean)
- U_Q is the instantaneous flow rate accuracy.
- U_{Hu} is the accuracy in flow rate estimated due to changes in the upstream supply channel water level.
- U_{Hd} is the accuracy in flow rate estimated due to changes in the water level downstream of the gate.
- U_T is the accuracy of the recorded delivery duration.

Rearranging the equation to solve for U_Q and using the values as determined by Burt and Geer (2012) for U_{Hu}, U_{Hd}, U_T, along with the 12% value mandated by SB X7-7 for U_V yields the following:

$$U_Q = 100 \times \left[\sqrt{\left(\frac{12}{100}\right)^2 + \left(\frac{2}{100}\right)^2 + \left(\frac{3}{100}\right)^2 + \left(\frac{4}{100}\right)^2}\right] = 10.7\% \qquad (10)$$

10.7% is then the allowable instantaneous flow rate measurement uncertainty for the meter gate to be tested in this study.

Through comprehensive testing of each of the (3) circular gates (12”, 18”, and 24”) and the 18” and 24” rectangular gates, Howes and Burt (2015a,b) calculated coefficient of discharge (C_d) values for the range of associated net gate openings under varying flow conditions as explained in the *Meter Gate Testing Parameters* section. By studying the relationships between the coefficient of discharge and the predictor variables (upstream head, downstream head, etc.) the authors were able to identify conditions or limitations that led to poor performance of each gate. For example, the authors found C_d values were inconsistent for all gates at “low” gate openings. In these limiting instances the coefficient of discharge values were excluded from further analysis and remaining values were utilized to create a relationship between net gate opening and C_d. Howes and Burt (2015a,b) then analyzed the uncertainty of the estimated flow rate using the newly calculated C_d values in addition to the uncertainty of the published Armco rating tables currently in use by calculating the percent error between these estimated values and the actual flow rate measured. This was calculated as follows:

$$E_{Qi} = \frac{Q_i - Q}{Q} x\ 100 \qquad (11)$$

In the equation E_{Qi} is the percent error between Q_i (estimated flow) and Q (actual flow). Q_i was based on the current Armco Rating Tables (Q_{Armco}) and the newly calculated C_d values developed through testing in the study ($Q_{improved}$). Q_{Armco} was determined through reference of the Armco rating tables (Armco Steel Corporation, 1975) using the appropriate net gate opening and linear interpolation of the two closest ΔH values listed in the rating table.

Instantaneous flow measurement relative expanded uncertainty at the 95% confidence level was derived from numerous tests for each gate size and opening completed through the study as described in the *Meter Gate Testing Parameters* section. Howes and Burt (2015a,b) calculated U_{Q_95} as the standard deviation of the flow measurement error for each gate opening with a coverage factor of k =2. Written mathematically as:

$$U_{Q_{95}} = 2U \qquad (12)$$

Relative expanded uncertainty was also computed using the mean flow rate for tests conducted at each gate opening (Q_{mean}) as:

$$RU_{95} = \frac{U_{Q\_95}}{Q_{mean}} \qquad (13)$$

CHAPTER 3: RESULTS AND DISCUSSION

The Effect of High Supply Channel Velocity on the Coefficient of Discharge (C_d)

Building on the evaluations by Howes and Burt 2015a,b subsequent testing at higher supply channel velocities was conducted and data collected to test the hypothesis that increased supply channel velocities would result in decreased flow through the meter gates. Data analysis was used to determine if corrections would be needed for C_d values developed during baseline testing when the gates are utilized in high supply channel velocity conditions.

Coefficient of discharge values were calculated for each high velocity test following meter gate limitations outlined by Howes and Burt 2015a,b. Meter gates do not perform well when operated at both the low relative openings (less than 25%) and high relative openings (greater than 75%). Relative head should also be maintained at $0.5D$ or greater. As with baseline testing, operation outside of these recommended conditions lead to highly variable C_d values and therefore data collected in these testing scenarios was excluded from further analysis.

Calculated C_d values were plotted against Froude number values to visually assess the relationship between Froude number and C_d as seen in Figure 10 (a-e). The scatterplots do not visually show any definitive relationship between the predictor (FR#) and response (C_d) variables.

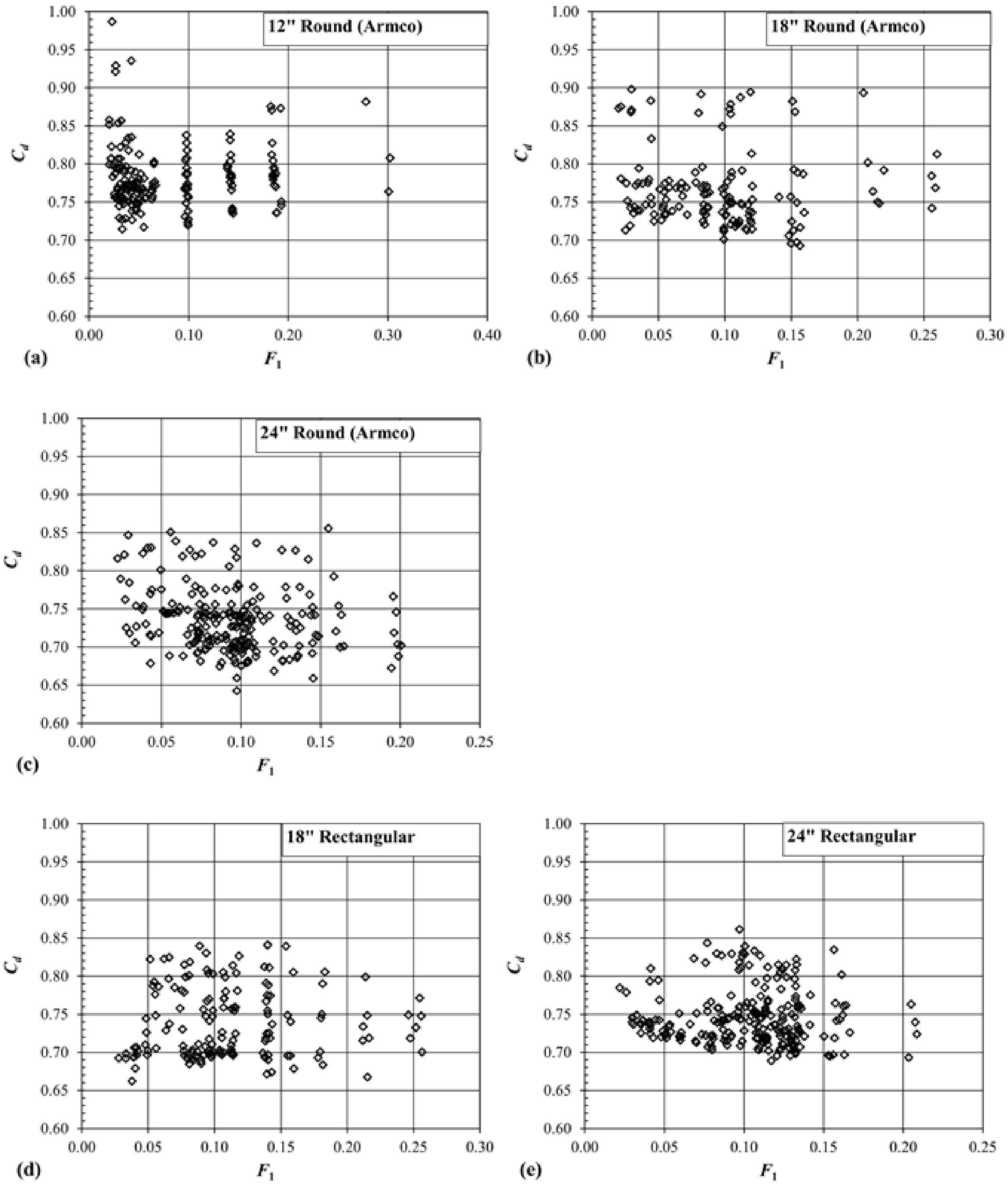


Figure 10. Scatterplot of Froude Number (F_1) vs C_d for 12”, 18”, 24” Armco (a-c) and 18”, 24” Rectangular (d-e) Gates

Next the following multiple regression model was used to study the potential for Froude number as well as the listed additional variables below to influence C_d:

$$\hat{C_d} = \beta_6\left(\frac{A_o}{A_p}\right)^3 + \beta_5\left(\frac{A_o}{A_p}\right)^2 + \beta_4\left(\frac{A_o}{A_p}\right) + \beta_3\left(\frac{H_1 + D}{D}\right) + \beta_2\left(\frac{\Delta H}{H_1}\right) + \beta_1(F_1) + \beta_0 \tag{14}$$

This is a model adapted from Howes and Burt 2015a with the addition of Froude number (F_1) where $\hat{C_d}$ is the predicted discharge coefficient, β_0-β_6 are regression coefficients, $\frac{A_o}{A_p}$ is the relative gate opening, $\frac{H_1+D}{D}$ is the relative upstream approach head, $\frac{\Delta H}{H_1}$ is the relative change head loss, and $F_1$is the supply channel Froude number. Residual analysis was utilized to assess the fit of the model. Resulting coefficients and p-values for each gate type and size are listed in Table 3 and 4.

Table 3. Regression Coefficients and P-Values for 12", 18", and 24" Armco Circular Gates Using Multiple Regression Equation (14)

		12 in Armco		18 in Armco		24 in Armco	
Predictor	Coefficient	Coefficient	P Value	Coefficient	P Value	Coefficient	P Value
$(A_o/A_p)^3$	β_6	-1.324	0.000	-1.041	0.000	-0.589	0.001
$(A_o/A_p)^2$	β_5	2.745	0.000	2.555	0.000	1.536	0.000
(A_o/A_p)	β_4	-1.911	0.000	-2.031	0.000	-1.359	0.000
$(H_1+D)/D$	β_3	-0.001	0.686	-0.016	0.000	-0.022	0.000
$\Delta H/H_1$	β_2	0.023	0.008	0.003	0.721	0.007	0.306
F_1	β_1	0.054	0.031	-0.086	0.022	-0.108	0.023
Constant	β_0	1.213	0.000	1.293	0.000	1.155	0.000
Adjusted R2		75.9%		85.5%		77.3%	

P-values for the Froude number predictor are greater than 0.01 for all five gates supporting the null hypothesis that the Froude number does not influence the coefficient of discharge at a 0.01 significance level. P-values are, however, lower than 0.05 for all three Armco circular gates which may suggest that at higher velocities F_1 could have a significant effect on the C_d. The difference in p-values for Froude number between the circular and rectangular gates suggests that gate shape plays a role in sensitivity to supply channel velocities. For all gates except the 12” Armco there is a negative relationship between Froude number and the coefficient of discharge as indicated by the negative value of the coefficient. This result is in partial agreeance with the original hypothesis that higher supply channel velocities/Froude numbers will decrease flow through the meter gate.

Table 4. Equation (14) Regression Coefficients and P-Values for 18" and 24" Rectangular Gates

		18 in Rectangular		24 in Rectangular	
Predictor	Coefficient	Coefficient	P Value	Coefficient	P Value
$(A_o/A_p)^3$	β_6	-1.470	0.000	-0.299	0.049
$(A_o/A_p)^2$	β_5	2.982	0.000	0.881	0.002
(A_o/A_p)	β_4	-1.715	0.000	-0.679	0.000
$(H_1+\mathrm{D})/D$	β_3	-0.003	0.578	-0.002	0.817
$\Delta H/H_1$	β_2	-0.012	0.397	-0.013	0.213
F_1	β_1	-0.054	0.201	-0.051	0.371
Constant	β_0	0.997	0.000	0.890	0.000
Adjusted R2		77.7%		34.9%	

In order to further analyze (compare and quantify) what influence the listed variables may have on the coefficient of discharge, a second regression model (equation 15) was used and the adjusted R^2 values were compared between the first and second model.

$$\hat{C_d} = \beta_{10}\left(\frac{A_o}{A_p}\right)^3 + \beta_9\left(\frac{A_o}{A_p}\right)^2 + \beta_8\left(\frac{A_o}{A_p}\right) + \beta_7 \tag{15}$$

Table 5 and 6 list the constants, p-values, and the adjusted R^2 values after removing the variables of relative approach head $\frac{H_1+D}{D}$, relative change in head $\frac{\Delta H}{H_1}$, and Froude number F_1. The minimal change in the adjusted R^2 values between equation 14 and equation 15 after removing these variables confirms that these variables have minimal effect on the coefficient of discharge.

Table 5. Regression Equation (15) for 12", 18", and 24" Armco Gates

		12 in Armco		18" Armco		24" Armco	
Predictor	Coefficient	Coefficient	P Value	Coefficient	P Value	Coefficient	P Value
$(A_o/A_p)^3$	β_6	-1.302	0.000	-1.023	0.000	-0.579	0.002
$(A_o/A_p)^2$	β_5	2.703	0.000	2.522	0.000	1.516	0.000
(A_o/A_p)	β_4	-1.886	0.000	-2.014	0.000	-1.348	0.000
Constant	β_0	1.223	0.000	1.259	0.000	1.119	0.000
Adjusted R2		74.2%		84%		75.7%	

Table 6. Regression Equation (15) for 18" and 24" Rectangular Gates

		18 in Rectangular		24" Rectangular	
Predictor	Coefficient	Coefficient	P Value	Coefficient	P Value
$(A_o/A_p)^3$	β_6	-1.480	0.000	-0.290	0.055
$(A_o/A_p)^2$	β_5	3.003	0.000	0.865	0.002
(A_o/A_p)	β_4	-1.728	0.000	-0.670	0.000
Constant	β_0	0.986	0.000	0.877	0.000
Adjusted R2		77.8%		35%	

Multiplicative nonlinear regression models additionally were used to compare results with the models already presented. These models, similar to those used by Oskuyi and Salmasi (2012), yielded the same findings as equations 14 and 15 with upstream approach head, relative change in head, and Froude number having a negligible effect on the coefficient of discharge.

To complete the analysis the tests completed during the high supply channel velocity section of the study were combined with the baseline low supply channel velocity tests from Howes and Burt 2015a,b and percent error and relative expanded uncertainty with a 95% confidence level was calculated as described in the *Procedures* section. Computed or estimated flow utilized C_d values developed by Howes and Burt 2015a,b and was compared to measured flow through the meter gates to yield percent error. Results for the three Armco gates and two rectangular gates are shown in Figure 11 (a-e).

Figure 11 (a-e) shows low uncertainty when the gates are operated in the recommended range of between 25%-75% (uncertainty being +/- 5%). Higher levels of variance are clearly visible as the gates approach both the low and high ends of the x-axis (relative gate opening). Mean percent error also follows this trend with slight overestimation generally occurring as gates are opened beyond a relative opening of 75%.

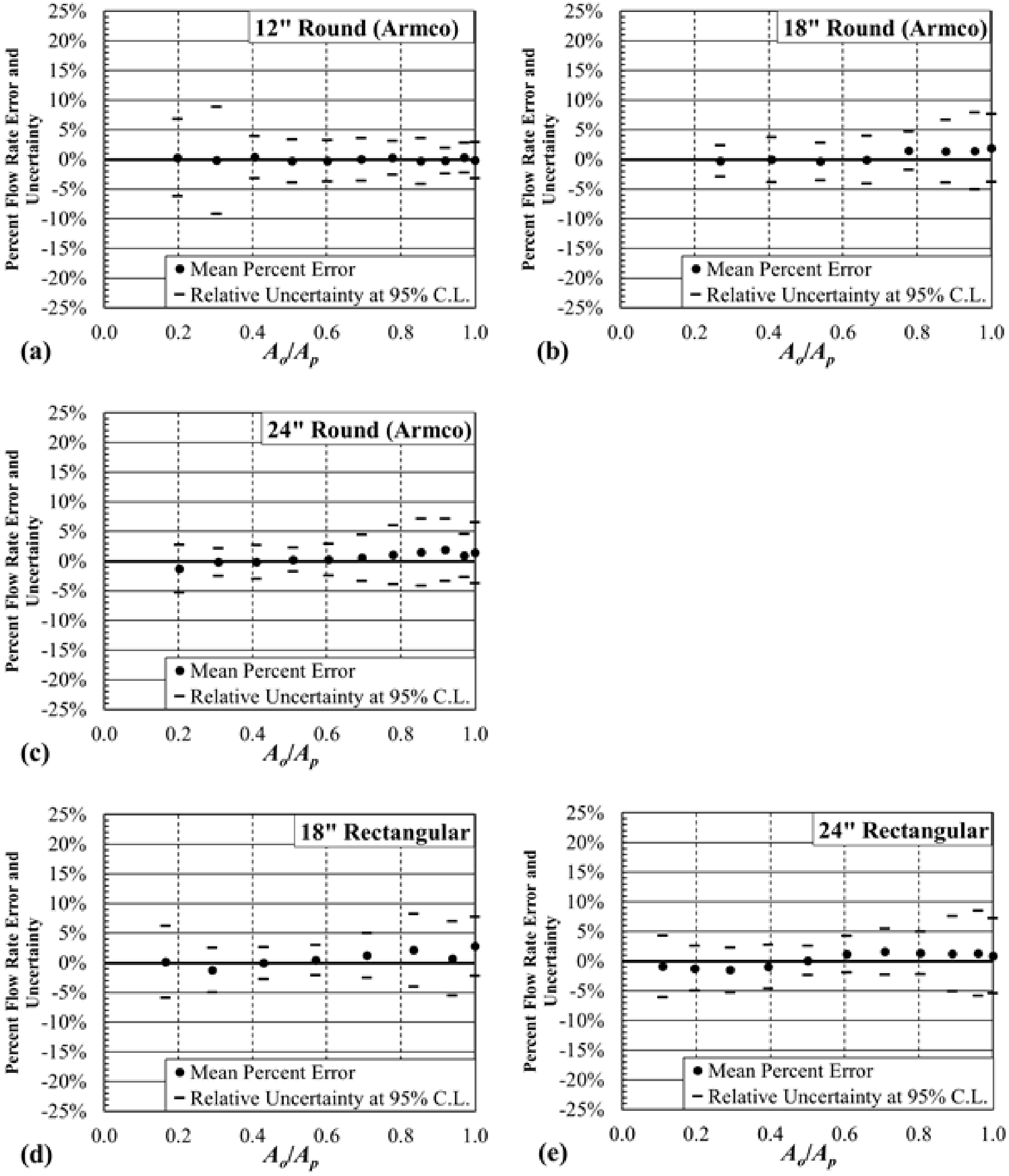


Figure 11. Percent Flow Rate Error and Uncertainty for 12”, 18”, 24” Armco and 18”, 24” Rectangular Gates for All Tests Using C_d Values Developed by Howes and Burt 2015a,b

CHAPTER 4: CONCLUSIONS

Circular and rectangular meter gates have been and continue to be important flow control and flow measurement devices with approximately one-third of turnouts in California utilizing meter gates or similar orifice type gates for turnout flow measurement (ITRC 2000; ITRC 2002). Meter gates provide distinct advantages in comparison to other flow metering devices including low maintenance costs and the ability to be installed at turnouts with high sediment load or aquatic weeds (Burt, 2010). With the passing of California Senate Bill x7-7 in 2009 volumetric billing for water suppliers was mandated and defined limits were set for volumetric accuracy of water flow measurement devices. A gap in the literature existed due to dated testing and testing design that is not consistent with field conditions. This gap in research was filled by ITRC testing.

Baseline testing of circular and rectangular meter gates at low supply channel water velocities by Howes and Burt (2015a,b) proved that circular and rectangular meter gates can be accurate flow measurement devices performing well within the requirements set by Senate Bill x7-7 if installed and operated properly. The authors outlined the specific installation and operational standards for the 12”, 18”, and 24” circular and 18” and 24” rectangular gates when used as metering devices. To summarize:

1. Relative Gate Opening: For the studied 18” and 24” rectangular gates the relative gate opening (A_o/A_p) should be limited to 10% or greater in order to maintain flow measurement uncertainties less than +/- 10% using the C_d values developed through testing. If the relative gate opening is limited to an operating range of 20%-80%, flow measurement uncertainty can be improved to an expected +/- 5%.

For the 18” and 24” circular gates relative gate opening should be limited to between 25% and 75%. For the 12” circular gate the relative minimum opening should be 40%. The authors do note that larger openings than 75% can be used when the downstream pressure tap is correctly located at 12” beyond the face of the gate, however, gates should always be operated less than fully open.

2. Upstream and Downstream Water Levels: For all gates (circular and rectangular) relative upstream head (H_1/D) should be greater than or equal to 0.5. This expands the operational range from previous USBR recommendations of $H_1 = 1D$ as a minimum. Downstream submergence should be at least 12 inches and higher levels of submergence may be necessary in order to ensure a maximum head difference (ΔH) of 30” or a value of 0.75 for $\Delta H/H_1$ is not exceeded. Water levels should always be maintained such that the pipe downstream of the gate is full and the water level in the stilling well is at a measurable level.
3. Downstream Pressure Tap Location: Coefficient of discharge values were developed based on the downstream pressure tap location of 12” downstream of the face of the gate. According to the authors’ experience the tap for the downstream pressure measurement on existing gates is sometimes less than the standard 12” location from the face of the gate. As noted in the *Introduction*, this may be attributed to previous USBR recommendations (Ball, 1961) for downstream pressure taps to be located at a distance of $D/3$. The observed effect of the measurement location of the downstream tap at a distance less than the standard 12” on the coefficient of discharge for both the circular and rectangular gates was one of general agreement between C_d values at smaller gate openings

with greater variability of C_d values from those measured at the 12” location as the relative gate opening increased. The magnitude of the variability differed with the gate size. For instance, the authors found that for the 18” and 24” circular gates placement of the pressure tap at a location less than 12” did not cause significant error if relative gate opening was kept below 75%. However, with the 12” circular gate C_d values were significantly variable at relative gate openings greater than 40%. In this scenario flow rate would be overestimated when using measurements for downstream head taken at pressure taps closer than 12” from the face of the gate. With this said, it is recommended that existing 12” circular gates with stilling wells located closer than the standard 12” downstream tap location should be moved to the 12” location in order to use the Armco rating tables or the C_d values developed through the study. Alternatively, a correction factor may be applied. For 12” gates with stilling wells located closer than 8” from the face of the gate, the flow rates determined from the discharge tables will need to be multiplied by a correction factor (written by Howes and Burt 2015a as “F_{tap}”) as follows:

   a. For gate openings less than or equal to 5”: $F_{tap} = 0.95$
   b. For gate openings between 5” and 9”: $F_{tap} = 0.89$
   c. For gate openings greater than 9”: $F_{tap} = 0.86$

4. Stilling Wells: Stilling wells should be designed and installed with the following noted:
   a. Stilling well diameter is of adequate size to “still” water turbulence and allow for accurate measurement readings. The recommended diameter

being 6”-8” attached to a corresponding tap diameter of 5/8”- 3/4” keeping the ratio of stilling well diameter to tap diameter greater than 7:1.

b. The downstream tap should be located 12” from the face of the gate. The tap hole needs to be located on top of the discharge pipe and if corrugated pipe is used for the discharge pipe, the tap hole should be located on the top of the corrugation or crown. The stilling well does not need to be centered over the tap hole. This allows the stilling well to be installed closer to the gate frame where it can be physically supported.

c. Figure 12 from Howes and Burt (2015a) details an alternative to common stilling well installations that maintain two wells (one for upstream head measurement and one for downstream head) set side-by-side. The authors note the horizontal piping that connects the upstream well to the supply channel is often susceptible to plugging and is not easily cleaned. It is noted by the authors that in most cases this upstream stilling well is not necessary as the upstream water level does not fluctuate significantly. The alternative design in Figure 10 instead includes only one stilling well located 12” downstream from the face of the gate and installed with the top of the stilling well set level with the top of the meter gate frame. Strategic placement of the stilling well in this way allows for easy measurement of head difference by utilizing the same datum for upstream and downstream measurements. Measurements are taken from the top of the gate to the water level in the supply channel (upstream head) and from the top of the stilling well to the water level (downstream head) with the difference yielding the change in head (ΔH). Installing the stilling well in this manner also provides the additional benefit of limiting debris from entering the well and plugging the tap. The authors do note that if the top of the meter gate frame is still at an elevation that tends to allow for debris collection in the well, a cap should be placed on top of the well which can be quickly removed when measurements are to be collected.

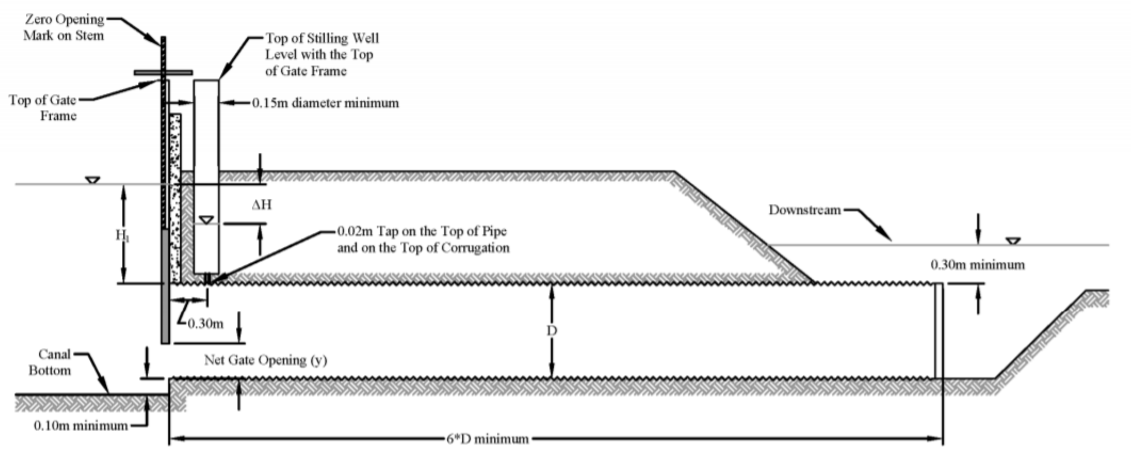


Figure 12. Meter Gate Installation Guidelines (Howes and Burt, 2015a)

5. Gate Zeroing: Each installed meter gate must be correctly “zeroed” in order for accurate determination of relative gate opening and subsequent reading of rating tables and coefficient of discharge values. Important details include:
   a. A “zeroed” position must be made on the gate from which measurement can be made for gate opening. The zero position is the point at which only a narrow strip can pass between the bottom of the gate and the discharge pipe. Once in this position the stem of the gate can be marked by making a 0.5” cut with a grinder at the top of the gate lift nut.

b. It is important when marking the zeroed position and when subsequently measuring the gate opening from the lift nut to the bottom of the marked notch on the gate stem that both are done after the gate has been opened, or as the authors explain, "on the upswing." This will ensure there is no further movement of the gate after measurement.

Additional testing was conducted with high supply channel water velocities to test the hypothesis that as the Froude number in the supply channel increased the coefficient of discharge would decrease as a result of an increase in energy needed for the perpendicular velocity transition. This would lead to an overestimation of flow through the meter gate when using C_d values developed through baseline testing in high supply channel water velocity conditions. The additional testing included velocities up to 3.09 ft/s for the 12" circular gate and up to 2.16 ft/s for all gates.

While multiple regression analysis did exhibit a negative coefficient for Froude number on all gates except the 12" circular gate, the influence of Froude number on C_d was not statistically significant for the 12", 18" and 24" circular gates or the 18" and 24" rectangular gates at an α-level = 0.01. The additional high velocity tests were combined with the baseline tests to examine mean percent error and relative expanded uncertainty at the 95% confidence level. Flow uncertainty was within +/- 5% when operating the gates under recommended conditions. This meets the accuracy requirements set by SB x7-7 for turnout flow measurement devices. Based on the results of this study, C_d values do not need to be adjusted for Froude numbers up to 0.35 for any of the studied gates.

While testing completed in this study is representative of supply channel water velocities found in California irrigation water conveyance systems and did not result in a statistically significant influence on meter gate flow, further research would be needed to study potential effects from Froude numbers exceeding the range found in this study.

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