METER GATE CALIBRATION AND ACCURACY ANALYSIS

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ABSTRACT

This senior project discusses metergate calibration procedures and accuracy analysis of experimental flow tests performed by the Irrigation Training and Research Center compared to past metergate research. The objectives of this report include: to determine the accuracy of published Armco discharge tables and to determine the feasibility of using metergates to comply with California Senate Bill x7-7.

Accuracy analysis concludes the discharge tables are in error as high as 21% depending on gate size, vertical gate displacement, and head differential. Therefore, the current tables fail to meet the requirements set in SBx7-7 for select gate conditions.

DISCLAIMER STATEMENT

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INTRODUCTION

Meter gates are commonly used throughout agricultural irrigation districts as a means of flow control and flow rate measurement. Flow control means the amount of water being released can be adjusted, ranging from zero to maximum flow. Flow rate measurement refers to quantifying the rate, or amount per unit time, at which water is being released.

Background

Fresno Irrigation District in 1928 and later on in the 1950s the United States Bureau of Reclamation partnered with Colorado A&M to determine the feasibility and reliability of using meter gates to manage water release at individual turnouts. Discharge tables, based on the change in head and the gate opening, were developed using Armco Metergates.

Justification

California water usage is at the forefront the state's controversial issues. A balance has to be found between supplying water to agriculture, environmental sustainability, recharge of ground water basins, municipal water supply, etc. There is not enough fresh water to meet the demand, especially considering past drought years. Recently, the state passed California Senate Bill x7-7 (SBx7-7), which establishes methods for both urban and agricultural water conservation. A component of the bill mandates agricultural water suppliers to volumetrically measure and account for water being released to individual turnouts. The bill requires documentation of volumetric accuracy with a high level of accuracy and precision. Volumetric accuracy is different than flow rate accuracy, assuming the device does not have a totalizer. "Volumetric" refers to the volume, or quantity, of water; this is computed by multiplying the flow rate by the time of delivery.

Irrigation and other water districts are asking what changes are necessary to comply with the new legislation, SBx7-7. The Irrigation Training and Research Center (ITRC) is currently exploring the feasibility and the obtainable accuracy of using meter gates to volumetrically measure water deliveries. The ITRC would like to release to agricultural water suppliers a relatively economical method of complying with the new legislation.

Objectives

The objectives of this report include: to outline the necessary procedures for meter gate calibration, to list factors that affect flow rate accuracy, and to determine the accuracy of published discharged tables based off data collected from the ITRC's research project. This report touches on the feasibility of using meter gates as a method of complying with SBx7-7. Due to the limited time to research and develop this report, it will not go into as much depth that is necessary to sufficiently cover such an issue. Instead, recommendations will be made for further research.

LITERATURE REVIEW

A search was initiated identifying any past, relevant studies on the calibration of meter gates for canal applications. Further research was conducted regarding the fluid mechanics of undershot gates. Meter gates are a type of undershot gate; they are commonly used for canal turnouts in irrigation districts and other water agencies.

History

For decades researchers have studied the feasibility of using meter gates as a means of accurate flow measurement. According to Wahl (2004), the advantages of using existing gates include: lessens the need for additional structures or flow meters, prevents additional head losses used for flow measurement, and facilitates automatic control by allowing accurate setting of gates to achieve target flow rates in real time.

Fresno Irrigation District (FID), in the 1920’s, developed discharge tables for Armco Model 101 meter gates, ranging in diameter from 8 inches to 24 inches (Fresno, 1928). FID found that meter gates could be used for both flow control and flow measurement while maintaining a high degree of precision and accuracy. In the 1950s the United States Bureau of Reclamation partnered with Colorado A&M (currently, Colorado State University) to expand on FID’s earlier study. Included, were meter gates ranging in diameter from 8 inches to 48 inches (Cadena and Magallanez, 2005). They found even with the more advanced testing equipment the discharge tables that were published earlier only needed slight adjustment (Armco, 1975). USBR test results show calculated flow rates are within ±6% with 95% confidence for all gate diameters and within ±5% with 95% confidence for diameters greater than 12 inches (Cadena and Magallanez, 2005).

Fluid Mechanics for Orifices

Submerged Gate Conditions.

Submergence occurs when both upstream and downstream of the gate is underwater. For submerged gate conditions the flow rate through the gate depends on the opening area and the head differential across the gate. Assuming the opening area remains constant, changes in head influences flow rate by the following equation:

$$\frac{Q_{new}}{Q_{old}} = \left(\frac{H_{new}}{H_{old}}\right)^{0.5} \tag{1}$$

For Example, the original flow rate through a gate was 5 CFS with a head differential of 1-foot. The new head differential increased to 1.25-feet; therefore, the new flow rate can be calculated by using equation (1).

$$Q_{new} = 5\text{CFS} * \left(\frac{1.25\text{ ft}}{1\text{ ft}}\right)^{0.5} = 5.59\text{ CFS} \tag{2}$$

Free flow Conditions. Free flow condition is when there is no backpressure on the gate. Figure 1 shows the hydraulic model of what is occurring. The Froude number is a ratio of the inertial force divided by the gravitational force, indicating subcritical flow (Fr< 1.0), critical flow (Fr = 1.0), and supercritical flow (Fr > 1.0). Subcritical flow is occurring upstream of the gate, immediately downstream there is supercritical flow, and then there is a hydraulic jump before transitioning back into subcritical flow (Rahman, 2013). Subcritical flow is characterized by high depth and low velocity while supercritical flow is described by low depth and high velocity (Rahman, 2013). A method to prevent free flow is discussed later.

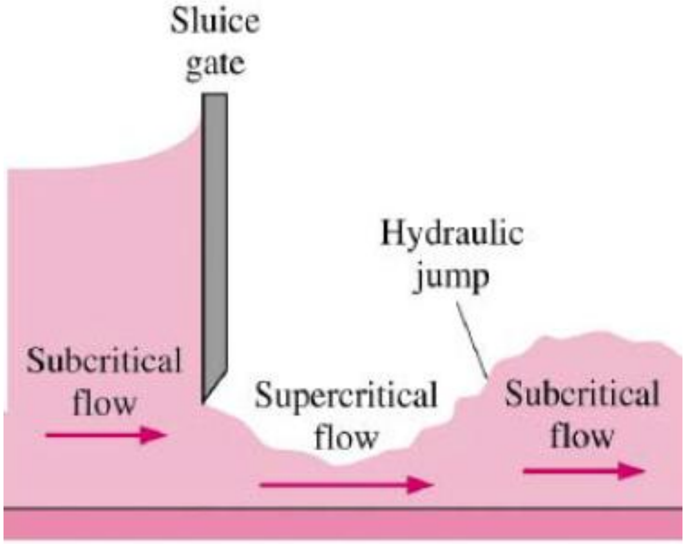

Figure 1. Froude number classification for free flow conditions (Rahman, 2013).

The flow rate equation used under submerged gate conditions does not hold true for free flow since supercritical flow is reached immediately downstream of the gate. Supercritical flow prevents waves from propagating upstream influencing the flow rate through the gate. Free flow condition requires a different measurement of head and a slightly different calibration equation (or coefficients for the equation). For instance, a free flow orifice, the head is measured from the upstream water level to the centerline of the orifice.

Streamlines for side sluice gates. Figure 2 and 3 show the relationship between the Froude number and the streamlines in a channel with a sluice gate located perpendicular to the direction of flow (Hussain et al., 2011). With a relatively small Froude number, nearly all the streamlines divert towards the gate, and with a slightly higher Froude number the streamlines further from the orifice continue down the direction of the channel (Hussain et al., 2011). The coefficient of discharge depends on the approach Froude number and the ratio of the width (for square orifices) or diameter (for circular orifices) and the channel's bed width (Hussain et al., 2011).

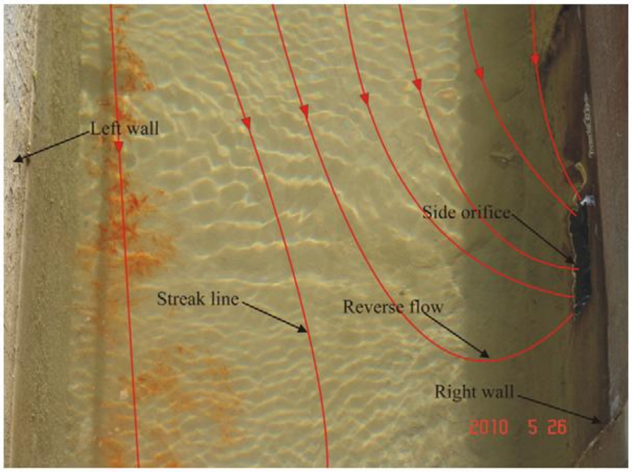

Figure 2. Streamlines with a Froude number of 0.18 (Hussain et al., 2011).

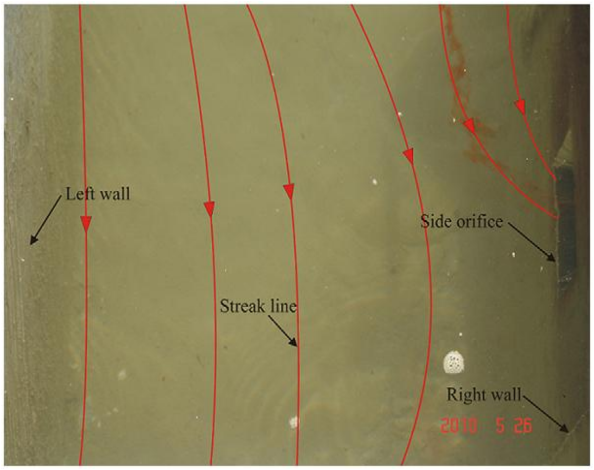

Figure 3. Streamlines with Froude number of 0.45 (Hussain et al., 2011).

Metergates for Irrigation Deliveries

Submerged flow is the most common condition for orifice water measurement in irrigation water delivery systems. Submergence upstream and downstream of the gate is important for flow rate measurement in order to get accurate, consistent head readings in the stilling wells. It is necessary to have proper water level control downstream of the gate in the supply channel. This is done by incorporating check structures, like long crested weirs and flap gates. This will ensure readings in the upstream stilling well do not fluctuate altering the flow rate through the orifice over time. If the water level on the upstream side of the gate drops below the top of the gate opening, the opening begins to function as a weir. Therefore, the calibration equation for submerged conditions would be wrong.

Installation Guidelines

Figure 4 shows the recommended installation layout developed by the United States Bureau of Reclamation (USBR) for circular meter gates used as a means flow control in channels (Cadena and Magallanez, 2005). Noteworthy features of the design include: the meter gate is fully submerged upstream and downstream and the stilling well is located 1 – foot downstream of the gate.

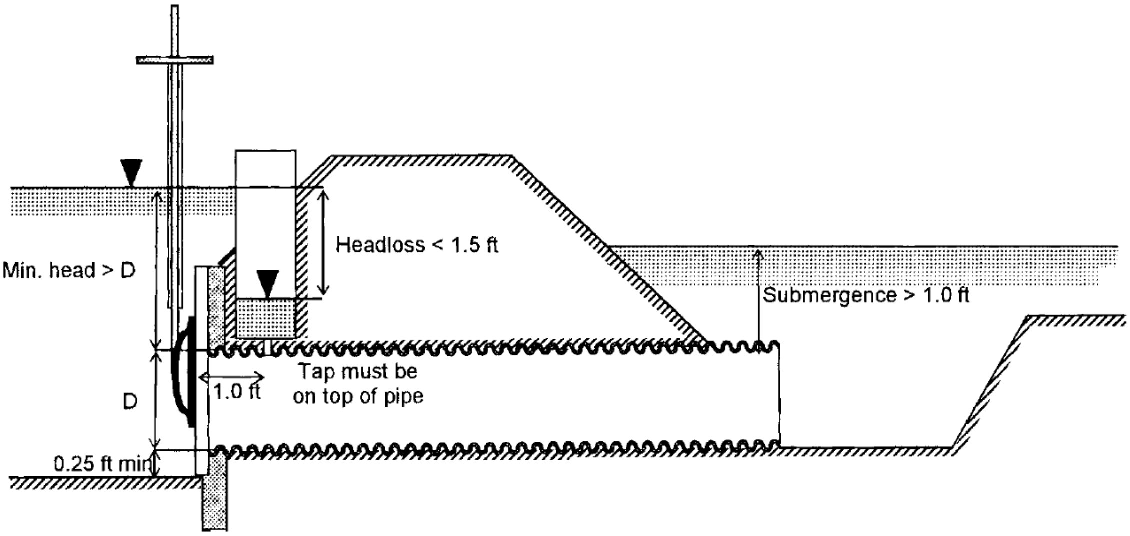

Figure 4. Suggested installation guidelines for Armco meter gate (Cadena and Magallanez, 2005).

Empirical Method for Flow Measurement

The flow rate, Q, through meter gates can be approximated by knowing the change in static head upstream and downstream of the gate, gate diameter, gate displacement, and gravitational constant. The following equations are used to solve for the flow rate empirically (Cadena and Magallanez, 2005):

$$Q = C_d A_0 V \qquad (3)$$

where,

$C_d = contraction\ coefficient$
$V = average\ discharge\ velocity\ through\ orifice$

$$V = (2g\Delta H)^{0.5} \qquad (4)$$

$A_0 = Area\ of\ crescent\ shaped\ orifice\ (opening\ area)$

$$A_0 = 1.9S\left(\frac{D}{2}\right)^2, where\ S = \frac{2y}{D} \qquad (5)$$

In a recent unpublished report, the Irrigation Training and Research Center (ITRC) computed the opening area using advanced mathematics. The ITRC found at smaller gate diameters the opening area did not differ much from the simplified method used by Cadena and Magallanez (Daniel Howes, unpublished data, February 2013). However, the difference in the computed opening area increased as the gate diameter increased (Daniel Howes, unpublished data, February 2013).

Therefore, by substituting equation (4) and (5) into equation (3), the following equation can be derived for circular gates that discharge into the atmosphere (Cadena and Magallanez, 2005):

$$Q = 0.95 C_d y D (2g\Delta H)^{0.5} \tag{6}$$

where,

y = vertical gate displacement
D = opening inside diameter of gate (assumed by Cadena and Magallanez (2005) to be the same as the pipe diameter)

There are different theories for determining the discharge coefficient, Cadena and Magallanez (2005) recommend using the following equations, which are a function of gate displacement and gate diameter:

$$C_D(y, D) = b + m\left(\frac{y}{D}\right) \tag{7}$$

where, for SI system (m/s),

$$b = \frac{0.00798}{D^2} + 0.839 \tag{8}$$

$$m = \frac{-0.1827}{D} + \frac{0.5593}{\sqrt{D}} - 0.7116 \tag{9}$$

or, for English system (ft/s),

$$b = \frac{0.0859}{D^2} + 0.839 \tag{10}$$

$$m = \frac{-0.5994}{D} + \frac{1.013}{\sqrt{D}} - 0.7116 \tag{11}$$

<u>Flow Rate vs. Volumetric Accuracy</u>

Senate Bill x7-7 (SBx7-7) requires agricultural water suppliers to volumetrically measure and account for water being released to individual turnouts. The bill requires a volumetric accuracy ±12% for existing turnouts. For new or replacement measuring devices a volumetric accuracy of ±5% is required if being certified in a laboratory or if being certified in the field using a non-laboratory certification process than a ±10% by volume accuracy is required (Styles, 2012). Volumetric accuracy depends on instantaneous flow rate error, canal water level fluctuations or pipeline pressure changes, changes in backpressure, and accuracy of recording durations (Burt and Geer, 2012). The maximum acceptable device flow rate error can be calculated by the following equation (Burt and Geer, 2012):

$$Max. flow\ rate\ error = \sqrt{\left(1 - \frac{VA}{100}\right)^2 - ARD^2 - CBP^2 - CWLF^2} \qquad (10)$$

where,

$VA = Volumetric\ Accuracy$
$ARD = Accuracy\ of\ Recording\ Durations$
$CBP = Changes\ in\ Backpressure$
$CWLF = Canal\ Water\ Level\ Fluctuations$

The effect of changing water level is negligible in cases where there is a high degree of water level control, for example, long-crested weirs and ITRC Flap Gates (Burt and Geer, 2012). Assuming a volumetric accuracy of 88% (i.e. for an existing meter gate) is desired and canal water level fluctuations are negligible, the maximum flow rate error is affected by accuracy of recording durations and changes in backpressure. Therefore, in order to satisfy the requirements of SBx7-7 the max flow rate error will be less than the desired volumetric accuracy of ±12%.

Inaccuracies with Meter Gates

There are four physical inaccuracies that are associated with measuring flow rate through meter gates. They include: incorrect zero measurement of gate opening, incorrect downstream water level measurement, incorrect gate opening geometry, and non-standard entrance and exit conditions (Burt and Geer, 2012). Each is discussed in more detail below (Burt and Geer, 2012):

- Incorrect zero reference: zero reference is the point at which water begins to leak from the gate when being opened. There is no standard for the point below that frame that the gate stops vertically; it may be ½ inch or 2 inches. Therefore, the zero reference varies on the gate. The zero point should be determined when the gate is being raised. To mark the point where water begins to leak a notch should be scratched into the shaft.
- Incorrect downstream water level reading: a stilling well must be located downstream of the gate. The access hole must be located on top of the pipe. The pipe must be full for all flow rates to get a good reading from the stilling well. This may require a small obstruction downstream in the pipe.

- Incorrect gate opening: Since the gate has a larger opening than the inside diameter of the pipe, a ratio is required of the two to obtain the correct discharge area.

Alternative Devices for Flow Measurement

Propeller meters and magnetic meters are seen to monitor discharge through individual turnouts. A propeller meter is shown in Figure 5. Advantages include: they are relatively easy to use and low cost (Styles, 2012). Disadvantages include: they are sensitive to plugging, sensitive to turbulence, and are inaccurate at velocities below 1 foot per second (Styles, 2012). Magmeters are newer to the market, shown in Figure 6. They come in various sizes and can be as accurate as ±5% (Styles, 2012). Other advantages of magmeters include: no moving or rotating parts, good for erosive and corrosive fluids, and not impacted by sand, sediment, and algae (Styles, 2012).

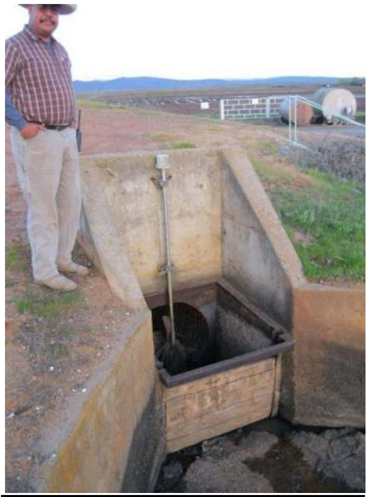

Figure 5. Propeller meter at Cordua Irrigation District (Styles, 2012).

Figure 6. Magmeter located upstream to a farm turnout in Patterson Irrigation District (Styles, 2012).

Flow measurement devices, such as Replogle flumes and subcritical contraction devices with an Acoustic Doppler velocity meter are frequently used at the head of larger supply canals for flow measurement. Replogle flumes, shown in Figure 7, have accuracy up to ±2% (ITRC, 2002). Hydrostatic pressure occurs over the flume, meaning at a certain depth there is a corresponding flow rate. The Froude number should not exceed 0.5 upstream of the flume (ITRC, 2002). Design of Replogle flumes is done using the software, WinFlume. After construction designers can specify as-built specification of the flume on WinFlume and the program will create a calibration curve, increasing the flow measurement accuracy. Other benefits of the Replogle flume include: minimal head loss required, choice of size and configurations, and minimal problems with trash and debris (ITRC, 2002).

Figure 7. Replogle flume at Truckee-Carson Irrigation District (ITRC, 2002).

Subcritical devices, shown in Figure 8, use Acoustic Doppler velocity meters (ADVM) to record the canal's velocity. The ADVM is either side-mounted or bottom mounted to the channel. Often the ADVM is mounted to rails that can easily raise and lower the velocity meter out of the water for easy maintenance (Howes et al., 2005). It is important to calculate a low Froude number (less than 0.5) in the design computations to limit inaccuracies caused by factors such as standing waves (Howes et al., 2005). Inlet conditions are also important in the design consideration. The entrance contraction changes the velocity profile in a predictable manner so the ADVM can obtain an accurate average velocity of the cross-section (Howes et al., 2005).

Figure 8. Subcritical Device located at the head of a main supply canal at Banta Carbona Irrigation District. Picture was taken during BRAE 533 field trip during winter 2012.

As discussed earlier, flow rate measurement and flow control are not the same. Flow control is not possible without flow rate measurement because in order to change the flow operators need to know how much to change the flow rate. Metergates offer both flow control and flow measurement in one simple device. Whereas, the devices listed above (i.e. magnetic meters, Replogle flumes, etc) only offer flow rate measurement and/or volumetric readings. In terms, of satisfying Senate Bill x7-7, these devices are capable of obtaining a high level of accuracy to comply with the new legislation. Although, calibrating metergates is most practical and economical because they are already widely used throughout irrigation districts.

PROCEDURES AND METHODS

This section of the report discusses procedures to calibrate meter gates to obtain high flow measurement accuracy.

Orifice Flow Rate Equation

The orifice flow rate equation, Equation 11, applies when both upstream and downstream of the gate is submerged.

$$Q = C_d A \sqrt{2g\Delta H} \tag{11}$$

The orifice equation is a function of the change in head across the gate, shown in Figure 9; the opening area, shown in Figure 10; the discharge coefficient, C_d; and the gravitational constant, g.

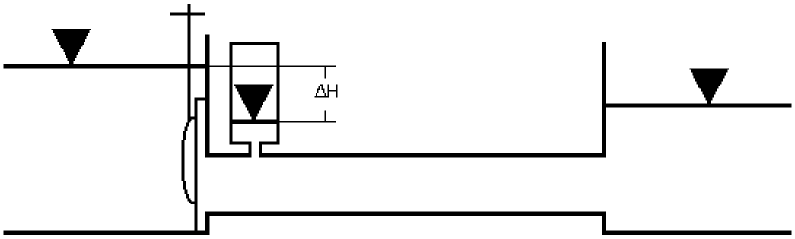

Figure 9. Metergate under submerged conditions.

The change in head is the difference in elevation from the water surface upstream of the gate to the stilling well water surface.

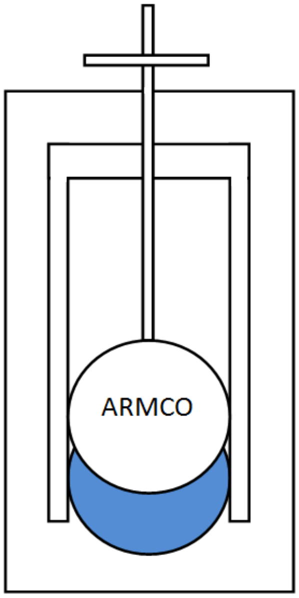

Figure 10. Front view of a meter gate displaying opening area (shaded in blue).

Opening Area Equation

As seen in Figure 10, the opening area is crescent-shaped and depends on the gate diameter, pipe diameter, and vertical gate displacement. There are different approaches to calculating opening area, which involve advanced mathematics (ITRC method), or the simplified approach used by Cadena and Magallanez in previous research.

ITRC Method. The Irrigation Training and Research Center has developed a prodigal for calculating opening area based on principals from advanced mathematics (i.e. calculus). This procedure is only valid if the vertical gate displacement is less than the pipe diameter.

Variables (also shown in Figure 11):

- Offset is the distance from the center of the orifice to the center of gate [inches]
- Vertical Gate Displacement, y, is the vertical distance the gate is moved from "zero reference" [inches]
- Gate Radius, R_g, is the measured diameter of the gate divided by two [inches]
- Radius of Pipe, R_p, is the measured inside diameter of the pipe divided by two [inches]
- Point of Intersection, P, is the vertical distance from the center of the orifice to where the circles' edges intersect [inches]
- Net Opening Area is the area of the crescent-shaped orifice used in the orifice equation [inches^2]

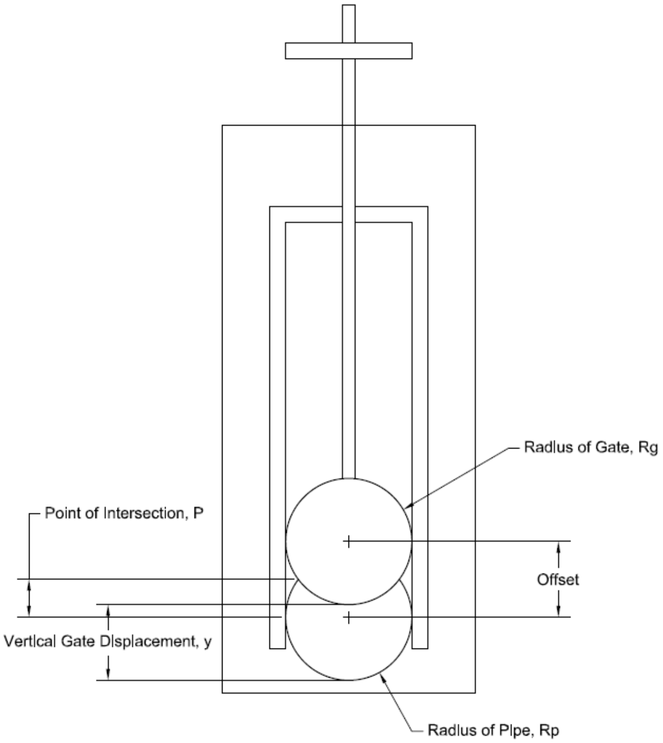

Figure 11. Metergate dimensions needed for ITRC opening area calculation.

$$Offset = y + R_g - R_p \tag{12}$$

$$\mathrm{P} = \frac{\mathrm{R_g^2} - \mathrm{R_p^2} - \mathrm{Offset}^2}{-2 * \mathrm{Offset}} \tag{13}$$

$$Area\ Raw = \frac{\pi R_p^2}{2} + P * \sqrt{R_p^2 - P^2} + \sin^{-1}\left(\frac{P}{R_p}\right) * R_p^2 \tag{14}$$

$$\begin{aligned} Area\ Subtracted &= \frac{\pi R_g^2}{2} + \sqrt{R_g^2 - P^2 + 2P(Offset) - Offset^2}\,(P - Offset) \\ &+ \sin^{-1}\left(\frac{P - Offset}{R_g}\right) R_g^2 \end{aligned} \tag{15}$$

$$Net\ Opening\ Area = Area\ Raw - Area\ Subtracted \tag{16}$$

If the gate is fully open, meaning the vertical gate displacement is greater than the pipe diameter, the opening area can be computed using the following equation:

$$Opening\ Area = \pi R_p^2$$

<u>Simplified Method</u>. In a previous study on metergates, the following simplified opening area equation was used to calculate area of the crescent-shaped orifice (Cadena and Magallanez, 2005):

$$Opening\ Area = 0.95 * D * y \tag{17}$$

where,

$D\ is\ the\ inside\ pipe\ diameter\ [inches]$
$y\ is\ the\ vertical\ gate\ displacement\ [inches]$

<u>Opening Area Comparison</u>. The opening area for an 18 inch and 24 inch metergate was computed at various gate positions using both methods discussed earlier. A percent error comparison was used to analysis the difference in area computed. Assuming no modification was done to the discharge coefficient to account for the potential inaccuracy in opening area; this percent error will directly affect the accuracy of the predicted flow rate through the orifice. For example, if the percent error in opening area is 50%, the predicted flow rate value would also be in error of 50% from its actual value. The equation used for percent error follows:

$$Percent\ Error = \frac{Area_{Cadena/Magallanez} - Area_{ITRC}}{Area_{ITRC}} * 100\% \tag{18}$$

See Appendix B for computed opening areas and percent errors for both metergate sizes.

Discharge Coefficient Adjustment . As mentioned earlier, the opening area percent error would directly impact the flow rate accuracy only if the discharge coefficient was not adjusted for the inaccuracies associated with opening area. To explore this possibility, an analysis using Cadena and Magallanez's metergate study and the published Armco discharge tables was completed. Refer to the "literature review" in this report to find equations developed by Cadena and Magallanez to predict flow rate through an orifice. To determine flow rate percent error the following equation was used:

$$Percent\ Error = \frac{Q_{Cadena/Magallanez} - Q_{Armco}}{Q_{Armco}} * 100\% \tag{19}$$

Cadena and Magallanez used the simplified (i.e. less accurate) opening area equation when developing their empirical equations for computing discharge coefficients. Consequently, if the percent error for the computed flow rate versus Armco flow rate is substantially lower than the percent error comparing methods to solve opening area, it is fair to conclude that incorrect percent error in opening area does not have a direct relationship to flow rate accuracy. Rather the bigger contributor to high flow rate accuracy is having a well-represented model (i.e. equation) to predict discharge coefficients for various gate sizes and positions utilizing a standard opening area formula. See Appendix C for percent error data and for a more detailed discussion refer to the "results" and "discussion" sections of this report.

ITRC Metergate Research

The Irrigation Training and Research Center is currently researching possible contributors to discharge inaccuracies associated with calibrated orifices (i.e. amount of submergence upstream of gate, location of stilling well, position of gate relative to velocity profile, and inaccuracies in original rating tables). The ITRC used the flume at the Water Resources Facility to calibrate metergates. Figure 12 shows a simplified schematic of the testing facility. The magnetic meter was calibrated using a weigh tank, which has an accuracy of ±1%; therefore the magnetic meter offered an expected accuracy approximately equal to ±2%.

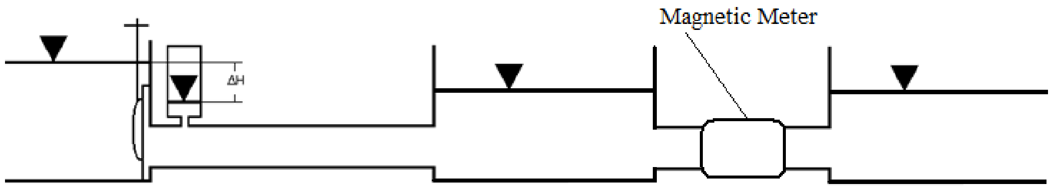

Figure 12. ITRC Metergate testing setup at the Water Resources Facility

ITRC Data Collection Procedure. An 18” and a 24” metergate was tested under various gate conditions. The vertical gate displacement was adjusted in increments of 2 inches starting with an initial displacement of 2 inches from “zero” reference.

The following measurements were recorded at each gate position:

1. Gate diameter
2. Pipe inside diameter
3. Vertical gate displacement with correct “zero” reference
4. Standard submergence upstream (i.e. submergence greater than gate diameter)
5. Water elevation in stilling well
6. “Actual” flow rate measurement using a magnetic meter

Further data was collected by the ITRC to explore other factors that affect accuracy, but noted measurements pertain directly to this report. See Appendix D for ITRC data for both 18 inch and 24 inch metergate. The data used was collected at standard bulkhead (i.e. upstream gate submergence greater than gate diameter) and standard stilling well location, located 1-foot downstream of gate.

The following equation was used to determine the accuracy of the published Armco discharge tables. Armco flow rates were either interpolated or extrapolated based on the head differential across metergate. The Armco tables had a maximum head differential of 18 inches.

$$Percent\ Error = \frac{Q_{ARMCO} - Q_{ITRC}}{Q_{ITRC}} * 100\% \tag{20}$$

In addition, the ITRC flow tests were used to determine the accuracy of Cadena and Magallanez’s flow rate equations. See Appendix E for flow rate data and percent error comparison. The following equation was used to determine percent error:

$$Percent\ Error = \frac{Q_{Cadena/Magallanez} - Q_{ITRC}}{Q_{ITRC}} * 100\% \tag{21}$$

RESULTS

Opening Area Equation

Difference in Opening Area Equations. Figure 13 shows the percent error comparing the ITRC's opening area to the simplified equation used by Cadena and Magallanez.

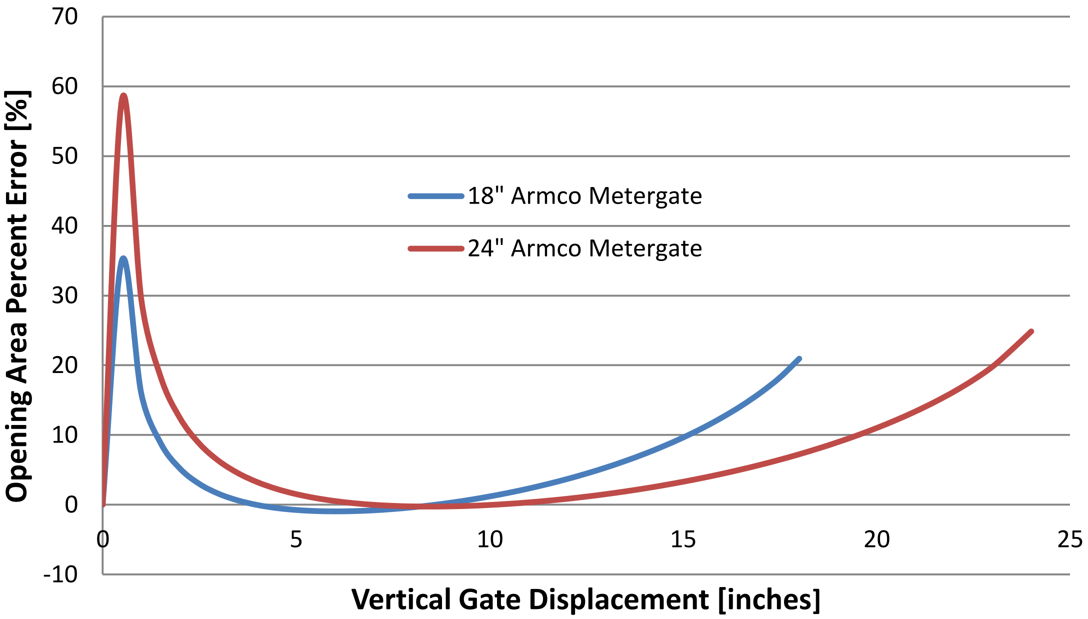

Figure 13. Percent error comparing Cadena/Magallanez and ITRC opening area calculations.

The different opening area techniques delivered similar results with both gates opened midway, within ±1% error. For the 18" metergate the percent error fluctuated greatly, reaching a maximum of 35%, when the gate was opened 3 inches or less and 10 inches or greater. Similarly, the 24" metergate varied from 5 inches or less and 12.5 inches or greater, reaching a maximum error of 58%.

Consequently, if the discharge coefficient was not adjusted to account for the inaccuracy associated with the simplified opening area formula, the potential flow rate error could be as high as 58% depending on gate size and vertical gate displacement.

Discharge Coefficient Adjustment. To account for potential opening area inaccuracies, adjustment can be made to the discharge coefficient. Figure 14 shows the percent error in Cadena and Magallanez metergate calibration procedure. The computed flow rates were compared to the published Armco discharge tables for an 18" and 24" metergate.

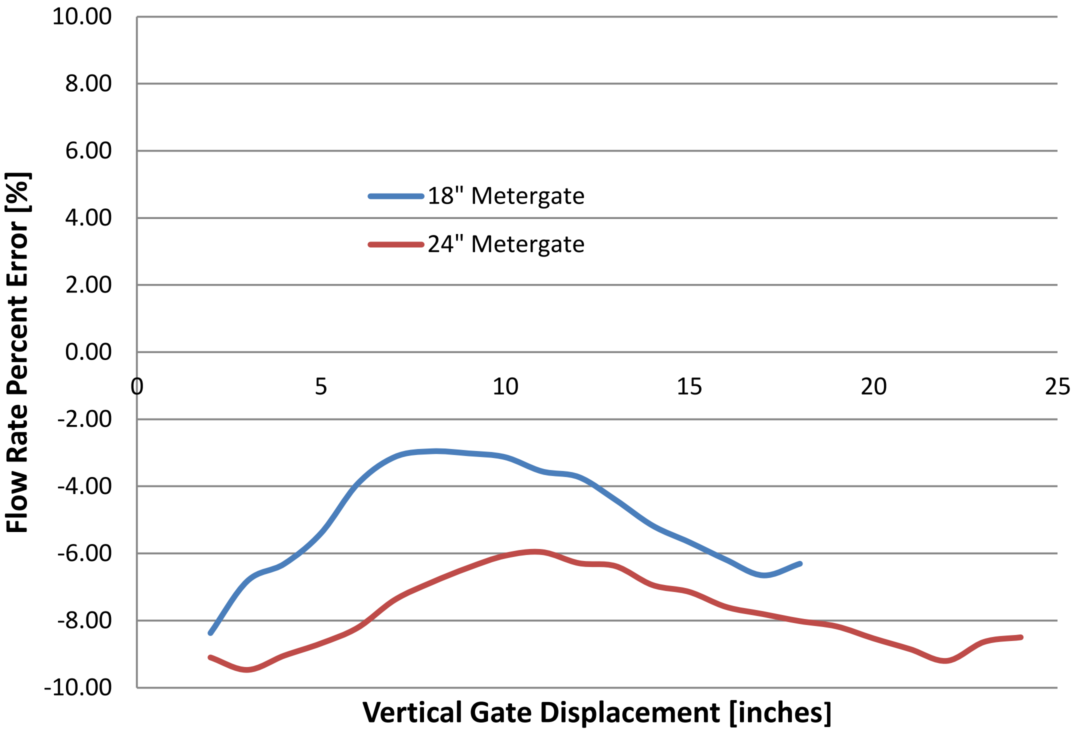

Figure 14. Flow rate error comparison using Cadena and Magallanez metergate calibration process and Armco tables.

Overall, the flow rate error is lower than the opening area error; therefore, the discharge coefficient accounted for some of the error in opening area. However, there is a noticeable trend relating flow rate inaccuracies to inaccuracies in calculating opening area. For both metergate sizes, the flow rate error was highest when the gate was approaching closure and when the gate was nearing full vertical displacement. This is consistent with the interval of lowest opening area accuracy. Consequently, the flow rate is most accurate when the gate is mid-way open due to inaccuracies in computing opening area.

Further investigation is needed to determine if the calibration procedure given by Cadena and Magallanez is correct. They borrowed the same data that was used to develop the Armco discharge tables for their research. Therefore, it was expected that their calibration procedure would align with the Armco tables. Figure 13 shows their calibration procedure underestimated the actual flow rate as high as 8.9% for the 24 inch metergate. When calculating flow rate it appears that the discharge coefficients are under-estimated by a factor of 1.053. This would decrease the flow rate error, making their calibration procedure align better with the published Armco tables.

Accuracy of Armco Discharge Tables

The flow rate error curves, shown in Figure 15, suggest there are some inaccuracies with the current published Armco discharge tables. The percent error was computed using the

ITRC's experimental data as "actual" flow rate. There are slight inaccuracies associated with the ITRC's data due to limitation of the magnetic meter, ability to accurately measure bulkhead and stilling well water elevation.

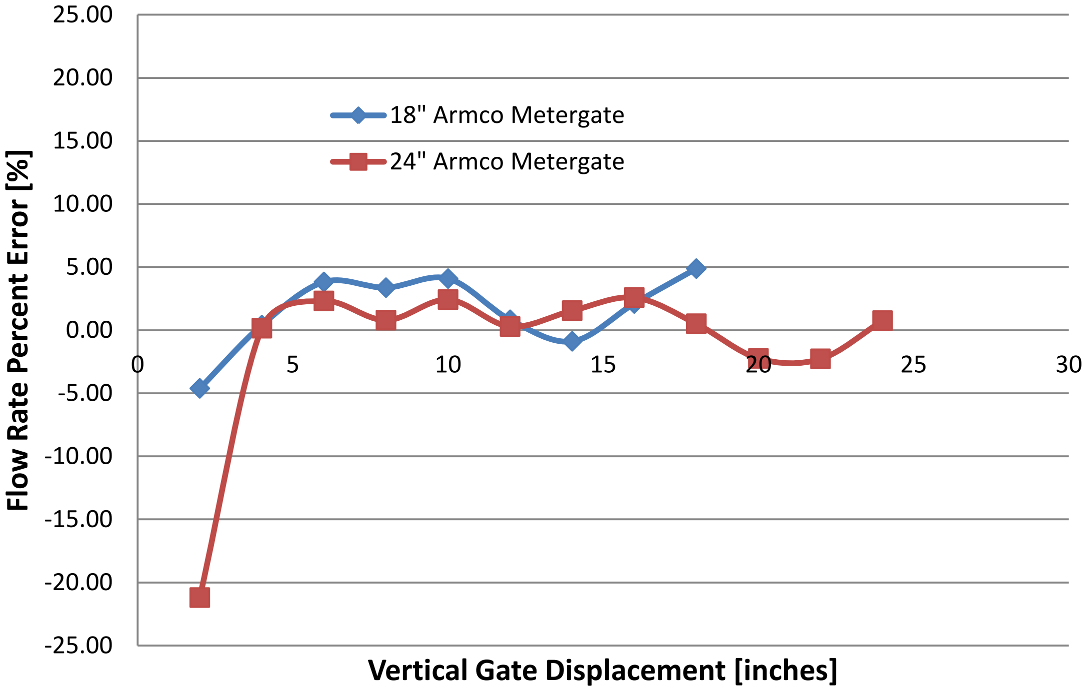

Figure 15. Percent error comparison between Armco discharge tables and ITRC flow tests.

The 18" Armco table over-estimated the flow rate by 4.9% while the gate was fully open. The 24" Armco table under-estimated the flow rate by 21.2% with a gate displacement of 2 inches. Both of these errors are greater than the inaccuracy of the testing facility suggesting the tables are inaccurate while the gate is positioned at its minimum and maximum.

The "head" column on the Armco Discharge tables range from 1 inch to 18 inches with increments of ¼ to 1 inch. To determine Armco flow rate given the ITRC's experimental flow data, flow rates were interpolated or extrapolated depending on head differential from Armco tables. For the 24" metergate an outlier flow rate error occurred when the head differential exceeded the 18 inch maximum found on the discharge tables when the vertical gate displacement was at 2 inches. It appears by extrapolating flow rates based off discharge tables decrease accuracy when the gate has a small vertical gate displacement.

Accuracy of Magallanez and Cadena's Calibration Procedure

The flow rates computed using Magallanez and Cadena' calibration procedure were compared to the ITRC experimental flow rates. Figure 16 shows the accuracy of the predicted flow rates by Cadena and Magallanez for both metergate sizes.

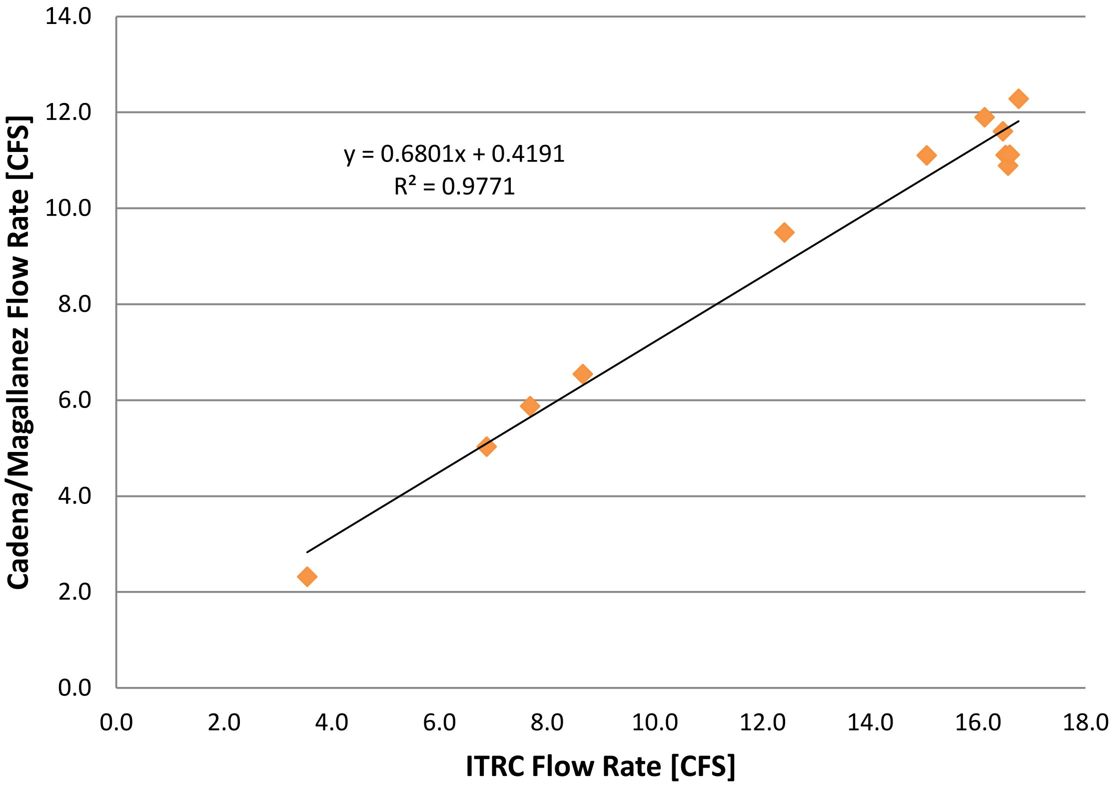

Figure 16. Accuracy trend for the 18" and 24" metergate.

The r-squared value, equal to 0.9771, is related to the accuracy of Cadena and Magallanez calibration procedure. The higher the r-squared value means higher flow rate accuracy. The points that fall off the trendline decrease the r-squared value, meaning they also the points of lowest accuracy. It appears the calibration procedure is less accurate at low and high flows. This is consistent with the points of lowest opening area accuracy. The increase in error may be associated with the incorrect opening area equation.

DISCUSSION

The accuracy analysis concludes that the flow rate accuracy is lowest when the gate is fully open or near closure. The ideal vertical gate position is midway between minimum and maximum vertical gate displacement. This should be considered if sizing a calibrated orifice for installation at a district turnout. This will help ensure the highest possible flow rate accuracy. The maximum flow rate error is 4.1% if the gate is positioned mid-way and using the Armco discharge tables. The flow rate accuracy falls within the restrictions set in California Senate Bill x7-7. Further research is needed to determine the inaccuracies associated with converting flow rates to a volumetric reading.

Using the Armco discharge tables, flow rate error can be as high as 21% depending on gate size, head differential, and vertical gate displacement. The discharge tables need adjustment, especially when the gate is positioned close to “zero” reference. Interpolated and extrapolated flow rates off the discharge tables did not affect accuracy significantly, except for when the gate is positioned near closure. Further investigation is needed to determine how much adjustment is needed to the tables to increase accuracy.

Other potential contributors to discharge inaccuracies not discussed in this report include: amount of submergence upstream of gate, location of downstream stilling well, and position of gate relative to the velocity profile of the canal. In practice metergates are commonly placed so the velocity profile is perpendicular to the gate. This may introduce inaccuracies to the discharge tables. Also, downstream stilling wells may not be positioned at the standard 1-foot distance from the gate. It would be beneficial for districts to know how stilling well distance affects flow rate accuracy and if there is an easy adjustment factor that could be used to correct for the inaccuracy.

RECOMMENDATIONS

Armco Discharge Tables

The Armco discharge tables need to be expanded and adjusted to accurately estimate flow rates when the gate is positioned near closure. Armco tables stop at 2 inches vertical gate displacement. The data collected suggest that predicted flow rates for vertical gate displacement less than 2 inches will have the greatest error. It is recommended that the ITRC flow testing should include data when the gate is positioned near closure.

ITRC Metergate Testing

The highest flow rate errors were seen when the gate was positioned near minimum gate displacement. Start metergate flow testing closer to “zero” reference (i.e. vertical gate displacement of 0.5 inches) and increase in increments of 0.5 inches until the vertical gate displacement is 1/4th of maximum displacement. This will help develop a trend that can be used to increase flow rate accuracy.

There were some discrepancies between if the nominal pipe diameter or if the actual inside pipe diameter should be used for calculations. Cadena and Magallanez required the pipe inside diameter be used for calculating discharge coefficient and opening area. The ITRC’s opening area computation also required the inside pipe diameter. It is recommended that a consistent measurement be used for opening diameter.

Further research is recommended to determine the effects of other potential contributors to flow rate inaccuracy, like amount of submergence upstream of gate, location of downstream stilling well, and position of gate relative to the velocity profile of the canal.

Satisfying SBx7-7

California Senate Bill x7-7 requires agricultural water supplies to volumetrically measure and document water delivered to users within certain accuracy. After initial results the flow rate accuracy falls within the parameters set in the legislation for most gate conditions. However, other factors, such as, accuracy of recording durations, changes in backpressure, and canal water level fluctuations also affect the volumetric accuracy. Further research is needed to acquire information on the effect of these potential inaccuracies.

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APPENDIX A

HOW PROJECT MEETS REQUIREMENTS FOR THE BRAE MAJOR

HOW PROJECT MEETS REQUIREMENT FOR THE BRAE MAJOR

Major Design Experience

The BRAE senior project must incorporate a major design experience. Design is the process of devising a system, component, or process to meet specific needs. The design process typically includes fundamental elements as outlined below. This project addresses these issues as follows.

Establishment of Objectives and Criteria. Project objectives and criteria are established to meet the needs and expectations of California Senate Bill x7-7.

Synthesis and Analysis. The project incorporates calibrated orifice calculations, flow rate accuracy and analysis computations, and the consideration of satisfying SBx7-7.

Testing and Evaluation. A 18" and 24" metergate was evaluated using previous metergate research, published Armco discharge tables, and ITRC's experimental flow data.

Incorporation of Applicable Engineering Standards. The project utilizes ASABE standards for professional citations and standards set in SBx7-7.

Capstone Design Experience

The BRAE senior project is an engineering design project based on the knowledge and skills acquired in earlier coursework. This project incorporates knowledge/ skills from these key courses.

- BRAE 533 – Irrigation Project Design
- BRAE 312 – Hydraulics
- BRAE 236 – Principles of Irrigation
- CE 336 – Water Resources Engineering
- BRAE 133 – Engineering Graphics
- ENGL 149 – Technical Writing
- BRAE 151 - AutoCAD

Project Parameters and Constraints

This project addresses a significant number of the categories of constraints listed below.

Physical. Metergates must be sized to match the required design turnout discharge. Calibrated orifices are most accurate when positioned midway from "zero" reference.

Economic. Water users will get charged based on volumetric water usage. Volumetric accuracy must be within a certain percentage.

Environmental. To help better conserve California's limited fresh water supply. Water savings can be better used to preserve wetlands, rivers, etc.
Sustainability. To help better conserve California's limited fresh water supply.

Manufacturability. Metergate distributors can supply their customers with a more accurate methodology to calibrate orifices.

Health and Safety. N/A

Ethical. The project deals with the question if monitoring agricultural water users is ethical to the farmers and the general public.

Social. To help conserve water so it can be used in ways that are beneficial for the public and environment.

Political. To determine if meter gates are accurate enough to satisfy the requirements of California State Bill SBx7-7.

Aesthetic. N/A

APPENDIX B

COMPUTED OPENING AREA AND PERCENT ERROR

COMPUTED OPENING AREA AND PERCENT ERROR

Table 1. Opening area and percent error for an 18" metergate at various gate positions.

18" Armco Meter Gate			
Vertical Gate Displacement [inches]	**Opening Area, Cadena [in^2]**	**Opening Area, ITRC [in^2]**	**Percent Error [%}**
0.0	0.00	0.00	0.00
0.5	8.55	6.33	35.09
1.0	17.10	14.75	15.93
1.5	25.65	23.57	8.84
2.0	34.20	32.52	5.18
2.5	42.75	41.51	2.99
3.0	51.30	50.51	1.57
3.5	59.85	59.48	0.62
4.0	68.40	68.42	-0.03
4.5	76.95	77.31	-0.47
5.0	85.50	86.14	-0.74
5.5	94.05	94.90	-0.89
6.0	102.60	103.58	-0.94
6.5	111.15	112.16	-0.90
7.0	119.70	120.65	-0.79
7.5	128.25	129.04	-0.61
8.0	136.80	137.30	-0.36
8.5	145.35	145.44	-0.06
9.0	153.90	153.43	0.30
9.5	162.45	161.28	0.72
10.0	171.00	168.97	1.20
10.5	179.55	176.49	1.73
11.0	188.10	183.83	2.32
11.5	196.65	190.97	2.98
12.0	205.20	197.89	3.69
12.5	213.75	204.59	4.48
13.0	222.30	211.04	5.33
13.5	230.85	217.22	6.28
14.0	239.40	223.12	7.30
14.5	247.95	228.69	8.42
15.0	256.50	233.92	9.65
15.5	265.05	238.77	11.00
16.0	273.60	243.19	12.51
16.5	282.15	247.11	14.18
17.0	290.70	250.44	16.07
17.5	299.25	253.04	18.26
18.0	307.80	254.47	20.96

Table 2. Opening area and percent error for a 24" metergate at various gate positions.

24" Armco Meter Gate			
Vertical Gate Displacement [inches]	**Opening Area, Cadena [in^2]**	**Opening Area, ITRC [in^2]**	**Percent Error [%}**
0	0.00	0.00	0.00
0.5	11.04	6.98	58.12
1	22.09	17.07	29.42
1.5	33.13	28.00	18.33
2	44.18	39.30	12.41
2.5	55.22	50.78	8.75
3	66.26	62.35	6.28
3.5	77.31	73.96	4.53
4	88.35	85.58	3.23
4.5	99.39	97.20	2.26
5	110.44	108.78	1.52
5.5	121.48	120.33	0.96
6	132.53	131.83	0.53
6.5	143.57	143.26	0.21
7	154.61	154.63	-0.01
7.5	165.66	165.92	-0.16
8	176.70	177.13	-0.24
8.5	187.74	188.25	-0.27
9	198.79	199.26	-0.24
9.5	209.83	210.17	-0.16
10	220.88	220.96	-0.04
10.5	231.92	231.63	0.12
11	242.96	242.17	0.33
11.5	254.01	252.57	0.57
12	265.05	262.82	0.85
12.5	276.09	272.92	1.16
13	287.14	282.86	1.51
13.5	298.18	292.62	1.90
14	309.23	302.19	2.33
14.5	320.27	311.57	2.79
15	331.31	320.75	3.29
15.5	342.36	329.71	3.84
16	353.40	338.44	4.42
16.5	364.44	346.92	5.05
17	375.49	355.15	5.73
17.5	386.53	363.10	6.45
18	397.58	370.76	7.23
18.5	408.62	378.10	8.07
19	419.66	385.11	8.97
19.5	430.71	391.76	9.94
20	441.75	398.00	10.99
20.5	452.79	403.81	12.13
21	463.84	409.16	13.36
21.5	474.88	413.96	14.72
22	485.93	418.14	16.21
22.5	496.97	421.56	17.89
23	508.01	424.01	19.81
23.5	519.06	424.56	22.26
24	530.10	424.56	24.86

APPENDIX C

PERCENT ERROR COMPARISON (CADENA/MAGALLANEZ vs. ARMCO)

PERCENT ERROR COMPARISON (CADENA/MAGALLANEZ vs. ARMCO)

Table 3. Flow rate percent error using Cadena and Magallanez calibration procedure for an 18" metergate.

18" Metergate		
Vertical Gate Displacement, y [inches]	**y/D**	**Flow Rate Percent Error Comparing Cadena/Magallanez Calibration Procedure to Armco Table [%]**
2	0.11	-8.37
3	0.17	-6.82
4	0.22	-6.31
5	0.28	-5.40
6	0.33	-3.91
7	0.39	-3.12
8	0.44	-2.95
9	0.50	-3.01
10	0.56	-3.13
11	0.61	-3.55
12	0.67	-3.72
13	0.72	-4.40
14	0.78	-5.17
15	0.83	-5.66
16	0.89	-6.19
17	0.94	-6.65
18	1.00	-6.30

Table 4. Flow rate percent error using Cadena and Magallanez calibration procedure for a 24” metergate.

24" Metergate		
Vertical Gate Displacement, y [inches]	**y/D**	**Flow Rate Percent Error Comparing Cadena/Magallanez Calibration Procedure to Armco Table [%]**
2	0.09	-9.10
3	0.13	-9.47
4	0.17	-9.05
5	0.22	-8.68
6	0.26	-8.21
7	0.30	-7.39
8	0.34	-6.87
9	0.39	-6.43
10	0.43	-6.07
11	0.47	-5.96
12	0.52	-6.29
13	0.56	-6.38
14	0.60	-6.94
15	0.65	-7.15
16	0.69	-7.59
17	0.73	-7.81
18	0.77	-8.02
19	0.82	-8.17
20	0.86	-8.53
21	0.90	-8.85
22	0.95	-9.20
23	0.99	-8.64
24	1.03	-8.50

APPENDIX D

ITRC EXPERIMENTAL FLOW RATE DATA

ITRC EXPERIMENTAL FLOW RATE DATA

Table 5. ITRC Flow data for 18" metergate

18 Inch Armco Metergate

Gate Diameter:	19	inches
Pipe Inside Diameter:	18	inches
Entry Condition:	Straight On	
Bulkhead Condition:	Standard	
Stilling Well Location:	12	inches

Gate Opening [inches]	Change in Head [inches]	Gate Opening Area [inches^2]	Experimental Flow [CFS]	ARMCO Table Flow [CFS]	Percent Error [%]
2	13.75	32.52	1.899	1.815	-4.61
4	8.91	68.42	2.834	2.846	0.40
6	10.32	103.58	4.140	4.304	3.82
8	8.92	137.30	4.907	5.078	3.37
10	6.29	168.97	4.912	5.122	4.09
12	4.65	197.89	5.001	5.042	0.82
14	3.54	223.12	5.028	4.984	-0.88
16	4.78	243.19	6.338	6.475	2.11
18	4.56	254.47	6.346	6.672	4.88

Table 6. ITRC flow data for 24" metergate.

24 Inch Armco Metergate

Gate Diameter:	25	inches
Pipe Inside Diameter:	23.25	inches
Entry Condition:	Straight On	
Bulkhead Condition:	Standard	
Stilling Well Location:	12	inches

Gate Opening [inches]	Change in Head [inches]	Gate Opening Area [inches^2]	Experimental Flow [CFS]	ARMCO Table Flow [CFS]	Percent Error [%]
2	22.42	39.297	3.545	2.925	-21.20
4	28.46	85.584	6.878	6.889	0.16
6	18.67	131.828	7.685	7.867	2.32
8	14.15	177.131	8.664	8.734	0.79
10	20.78	220.960	12.409	12.717	2.43
12	21.58	262.823	15.052	15.096	0.29
14	20.00	302.191	16.126	16.380	1.55
16	18.01	338.436	16.760	17.205	2.59
18	14.09	370.757	16.467	16.551	0.51
20	11.67	397.999	16.517	16.156	-2.24
22	10.40	418.143	16.562	16.194	-2.27
24	10.30	424.557	16.594	16.720	0.75

*Note: Armco Table Flow Extrapolated Value - table maxes out at 18" head differential

APPENDIX E

FLOW RATE COMPARISON (ITRC vs. CADENA/MAGALLANEZ)

FLOW RATE COMPARISON (ITRC vs. CADENA/MAGALLANEZ)

Table 7.Percent error comparing Cadena and Magallanez's flow rate to ITRC flow tests for an 18 inch metergate.

Vertical Gate Displacement [inches]	Change in Head [inches]	ITRC Experimental Flow Rate [cfs]	Cadena/Magallanez Flow Rate [cfs]	Percent Error [%}
2	13.75	1.9	1.8	-4.36
4	8.91	2.8	2.8	-0.69
6	10.32	4.1	4.4	5.50
8	8.92	4.9	5.2	5.89
10	6.29	4.9	5.2	6.35
12	4.65	5.0	5.2	3.06
14	3.54	5.0	5.0	-0.46
16	4.78	6.3	6.3	-0.17
18	4.56	6.3	6.6	4.02

Table 8. Percent error comparing Cadena and Magallanez's flow rate to ITRC flow tests for a 24 inch metergate.

Vertical Gate Displacement [inches]	Change in Head [inches]	ITRC Experimental Flow Rate [cfs]	Cadena/Magallanez Flow Rate [cfs]	Percent Error [%]
2	22.42	3.5	3.0	-16.41
4	28.46	6.9	6.5	-5.84
6	18.67	7.7	7.6	-0.80
8	14.15	8.7	8.6	-1.14
10	20.78	12.4	12.5	1.10
12	21.58	15.1	14.8	-1.57
14	20.00	16.1	16.0	-0.48
16	18.01	16.8	16.8	0.03
18	14.09	16.5	16.0	-2.56
20	11.67	16.5	15.6	-5.67
22	10.40	16.6	15.5	-6.36
24	10.30	16.6	16.1	-2.91