Three Simple Flumes for Flow Measurement in Open Channels

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Abstract: The design and calibration of three simple flumes for flow measurements in open channels are discussed. The flumes are designed based on principles of critical flow in open channels. Critical flow is created through the contraction of the flow cross section by installing vertical cylindrical columns in an open channel. Calibrated equations are developed for each of the three flumes by combining the Pi Theorem principle with laboratory scale physical models. The three flumes are designed for application in prismatic (trapezoidal, rectangular, and circular) channels. The calibrated equations can be used for design and calibration of the flumes regardless of the flumes or channel dimensions. The equations are validated using field scale flumes, and a design example is provided for free flow conditions. **DOI: 10.1061/(ASCE)IR.1943-4774.0001168.**

Introduction

Measuring water in an open channel is one of the basic elements of water management. There are various methods for measuring flow in open channels. The common method of measuring flow in an open channel is based on the concept of critical flow. Creating critical flow makes it possible to measure only the depth and calculate the flow rate, thus simplifying the continuous monitoring of flow rate. Ever since the development of the Parshall flume (Parshall 1926) attempts have been made to simplify the construction, improve the accuracy, and reduce the cost of water measuring devices in open channels. Critical flow in open channel can be created through three general methods: raising the bottom of the channel (Replogle 1975; Bos et al. 1984), contracting the cross-sectional area of the flow (Skogerboe et al. 1967, 1972; Hager 1988; Samani et al. 1991; Samani and Magallanez 1993, 2000), and reducing the bottom elevation to force a critical flow. Contracting the cross section of the flow is one of the simplest methods of creating critical flow for the purpose of measuring flow in an open channel as described by Hager (1988), Samani et al. (1991), and Samani and Magallanez (1993, 2000). Measuring flow by contracting the flow cross section is often the simplest and least-costly method as it does not require complex inflow and outflow transition. The process results in critical flow occurring at the contracted section resulting in a short-throated flume without any need for extended inflow and outflow transition.

This paper describes three simple flumes for an open channel where critical flow is created by contracting the cross-sectional area of the flow in circular, rectangular, and trapezoidal channels. The contraction is achieved by placing cylinders or half cylinders in a perpendicular position inside the channel. The three schemes are described in the following text of the article.

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Theoretical Analysis of Flow

Critical flow is created in short-throated flumes by installing a vertical column across the flow, thus creating a contracted section. Once the critical flow section is created the principles of hydraulics and critical flow can be used to calculate flow rate by simply measuring the upstream energy. Flow measurement through a flume in open channel is based on the principle of critical flow. Assuming uniform velocity distribution, the energy equation upstream of critical flow section can be expressed as

$$E = y_1 + \frac{Q^2}{2gA_1^2} \tag{1}$$

in which E = energy upstream of the critical flow section; y_1 = upstream depth; Q = flow; and A_1 = upstream flow cross section.

Assuming a level flume and negligible energy loss between upstream and critical flow section, the upstream energy will be equal to the energy at the critical flow section and can be described as

$$E_c = E = y_c + \frac{Q^2}{2gA_c^2} \tag{2}$$

In which E_c, y_c, and A_c = energy, depth, and cross-sectional area at the critical section, respectively. Theoretically, water reaches critical flow at the smallest cross section, which is the contracted area. At the critical cross section the critical flow equation can be described as

$$\frac{Q^2}{gA_c^3}\left(\frac{dA_c}{dY_c}\right) = 1 \tag{3}$$

Combining Eqs. (2) and (3) results in

$$E = Y_c + \frac{A_c}{\frac{2dA_c}{dY_c}} \tag{4}$$

Therefore, by knowing the depth (y_c) or width of the critical flow (dA_c/dy_c) and upstream energy, the discharge rate can theoretically be calculated by combining Eqs. (2) and (4). Eqs. (2) and (4) also show that flow is a function of upstream energy (E), critical flow depth (y_c), critical flow width (B_c), and acceleration of gravity (g). The upstream energy is the product of upstream depth and velocity. Since the velocity is variable within the cross section, Samani et al. (1991) showed that there is a linear relationship between the upstream energy and upstream depth (H). The upstream depth is measured at the upstream side of the vertical column at the center of the flow stream.

When the flow cross section is contracted to create a critical flow the discharge rate will theoretically depend on the upstream energy, the width of critical section, and acceleration of gravity. Therefore, flow can be described as a function of H, g, and B_c as

$$Q = \text{function}\,(H, B_c, g) \tag{5}$$

Using dimensional analysis, the relationship between the upstream energy head and flow dimensions can be described as

$$f(Q, H, B_c, g) = 0 \tag{6}$$

There is a total of four variables in Eq. (6). There are only two fundamental dimensions involved, which are length and time (L & T). Therefore, there are two Π terms. According to the Π theorem the function given by Eq. (6) can be described by two Π terms $(4 - 2 = 2)$

$$\Phi(\Pi_1, \Pi_2) = 0 \tag{7}$$

where Π_1 and Π_2 = dimensionless groups whose expressions have to be determined. By letting B_c and g be the repeating variables, the Π terms can be grouped as follows:

$$\Pi_1 = (B_c)^a (g)^b (Q) \tag{8}$$

$$\Pi_2 = (B_c)^c (g)^d (H) \tag{9}$$

where a, b, c, and d = numerical constants. Substituting the units of each variable in Eqs. (8) and (9) results in the following functions:

$$\Pi_1 = \frac{Q}{B_c^{2.5} g^{0.5}} \tag{10}$$

and

$$\Pi_2 = \frac{H}{B_c} \tag{11}$$

Therefore, Eq. (7) can be transformed into following equation:

$$\Phi = \left(\frac{Q}{B_c^{2.5} g^{0.5}}, \frac{H}{B_c}\right) \tag{12}$$

Based on Eq. (12), a general model can be defined as

$$\frac{Q}{B_c^{2.5} g^{0.5}} = a\left(\frac{H}{B_c}\right)^b \tag{13}$$

where a and b = empirical coefficients to be determined experimentally. Eq. (13) can be rearranged to

$$Q = a(B_c^{2.5})(g^{0.5})\left(\frac{H}{B_c}\right)^b \tag{14}$$

Experimental Analysis

Samani et al. (1991, 1993, 2000) constructed three laboratory models to measure flow in open channels. The models included:

1. Circular flume.
2. Trapezoidal flume.
3. Rectangular flume.

The circular flume consists of a vertical pipe installed inside a circular pipe resulting in a critical flow. The cross-sectional view and side view of the circular flume are shown in Figs. 1 and 2.

In the trapezoidal flume a single vertical column is installed inside an existing trapezoidal channel, resulting in contraction and the creation of critical flow as shown in Fig. 3.

In the rectangular flume critical flow is created by installing two half pipes on either side of a rectangular cross section (Fig. 4)

Using laboratory scale models Samani et al. (1991, 2000) developed experimental data for the calibration of Eq. (14). The calibration parameters are described in Table 1. In Table 1, B_c is the critical flow width as defined in Eq. (14), a and b are empirical coefficients, n is the number of measurements, m is the side slope in trapezoidal channel, H is the height measured at the upstream side of the column (Fig. 2), and R^2 is coefficient of determination.

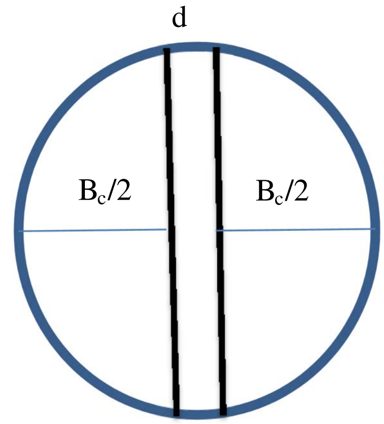

Fig. 1. Cross-sectional view of a circular flume

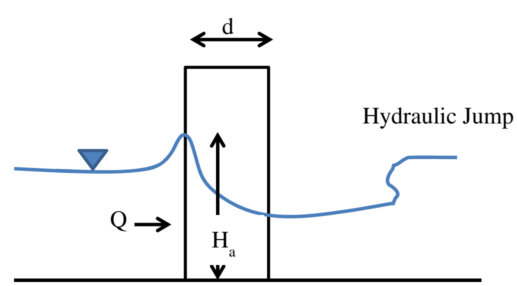

Fig. 2. Side view of flow

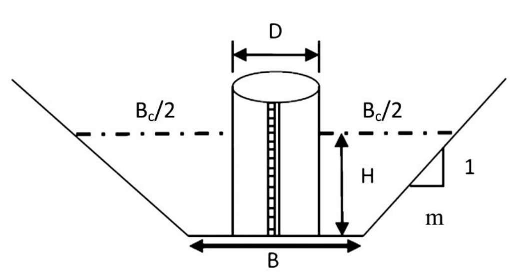

Fig. 3. Cross-sectional view of a trapezoidal flume

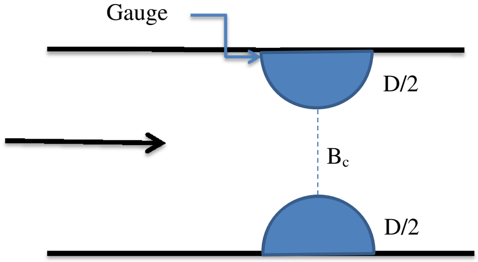

Fig. 4. Top view of a rectangular flume

Table 1. Calibration Coefficient for Three Different Flumes

Flume type	B_c	a	b	n	R^2
Circular	$D - d$	0.421	2.31	27	0.99
Rectangular	$B - D$	0.701	1.59	16	0.99
Trapezoidal	$B - D + 2m(H)$	0.226	1.51	18	0.99

Field Validation

Field scale flumes were constructed in irrigation canals operated by the Elephant Butte Irrigation District in the Lower Rio Grande Basin. Trapezoidal flumes were constructed in three-lined trapezoidal open channels with side slopes of 1/1. The circular flumes were constructed in two unlined open channels using a vertical cylinder installed in a horizontal pipe within the channel. The rectangular flumes were prefabricated and installed in one unlined open channel and one open channel turnout. Tables 2–4 compare the measured and calculated flow for each case. Flow rate in the circular flumes were measured using a MacCrometer flow meter installed in a pump turnout. Flow rates in the trapezoidal and rectangular flumes were measured using a magnetic flow meter (Flow-Mate2000, Marsh-McBirney, Frederick, Maryland). The flow cross section was divided into small increments, and the flow rate was calculated by measuring flow velocity and area in each increment. Figs. 5–7 show rectangular, trapezoidal, and circular flumes in typical field settings, respectively.

Design Example

Laboratory experiments (Samani et al. 1991; Samani and Magallanez 1993) showed that the maximum submergence for

Table 2. Comparison of Measured and Calculated Flow Rate for Circular Flume

Experiment	D (cm)	d (cm)	H (cm)	Q (L/s) measured	Q (L/s) calculated	% difference
1	25	8.1	6.8	1.86	1.89	1.6
1	25	8.1	16.5	14.25	14.48	1.6
2	45	15.5	14.6	12.67	12.70	0.24
2	45	15.5	24.5	40.98	40.55	1.0

Table 3. Comparison of Measured and Calculated Flow Rate for Rectangular Flume

Experiment	B (cm)	B_c (cm)	H (cm)	Q (L/s) measured	Q (L/s) calculated	% difference
1	61	28	31	112.2	107	4.86
1	61	28	62.5	320.2	326.5	1.97
1	61	28	41.6	169.3	170.9	1.0
2	28	16.8	20.0	33.50	35.1	4.8

Table 4. Comparison of Measured and Calculated Flow Rate for Trapezoidal Flume with Side Slope of 1/1

Experiment	B (cm)	D (cm)	H (cm)	B_c (cm)	Q (L/s) measured	Q (L/s) calculated	% difference
1	61	60.96	74.93	149.9	67.66	68.07	0.6
1	61	60.96	67.95	135.94	528.5	533.1	0.9
2	91.4	91.4	64.77	129.54	481.8	472.8	1.9
3	35	31.1	16.84	37.60	19.50	18.15	7.4

Fig. 5. Rectangular flume installed in an unlined ditch in southern New Mexico (image by author)

Fig. 6. Trapezoidal flume in use in Dushanbeh, Tajikistan (image by author)

Fig. 7. Circular flume installed in a vineyard in Australia (image by author)

free-flow operation is 0.8. The submergence ratio was defined as the ratio of downstream depth divided by the piezometric reading at the upstream of the column at the center of flow stream as shown in Fig. 2. The actual ratio of the downstream depth divided by the upstream depth is 0.85. The following example demonstrates how a flume can be designed for a specific condition.

- Canal type: Circular with diameter of 1.2 m;
- Maximum flow: 1.0 m^3/s;
- Normal depth at maximum flow: 0.74 m;
- Column outside diameter: 0.4 m; and
- $(D - d) = 1.2 - 0.4 = 0.8$ m

Using Eq. (14) for the circular flume, one can calculate the upstream piezometric head (H) which represents the depth and velocity energy at the midstream. The calculated H for maximum flow is $H = 0.904$, and submergence ratio is $0.74/0.904 = 0.82$, which exceeds the maximum submergence ration of 0.8. Therefore, one can increase the diameter of the column to $d = 0.60$, and $D - d = 1.2 - 0.6 = 0.6$ and recalculate the H, where $H = 0.925$ and submergence ratio is $0.74/0.925 = 0.8$, which meets the submergence requirement.

In all three aforementioned flumes the submergence ratio can be reduced by simply reducing the width of the critical flow (B_c). Another option for meeting the required submergence ratio would be to raise the bottom of the channel as needed. However, raising the bottom of the channel will create a sediment trap in cases where sedimentation is a problem.

Results and Discussion

The three flumes previously described have the advantages of ease of construction and low cost. The depth H is measured at the upstream side of the column at midstream using the column as a piezometer. A ruler can be installed at the upstream side of the column to measure H. However, due to the fluctuation of the depth (which can cause an error in reading), it is better to create a perforation at the bottom of the column and use the column as a stilling well to measure the head (H). Due to the measurement of head at the column the flume does not require extensive upstream transition, thus reducing the cost of the construction. The flumes are self-flushing and do not accumulate sediment at the upstream of the device as it normally occurs in devices such as sharp-crested or broad-crested weirs. The circular flume has a particularly unique advantage since the flow is the function H to power 2.31, thus creating an effect similar to a V-notch where a wide range of flow can be measured with high accuracy. Hager (1988) showed that a (d/D) ratio of as low as 0.26 can create critical flow in a circular flume. A trapezoidal flume with a high contraction (d/B) ratio can also function as a V-notch.

The comparison between measured and predicted flow rates presented in Tables 2–4 show that the error is within the range of the error which can be expected in magnetic flow meter.

Stefano et al. (2008) using the previous work by Samani and Magallanez (2000) recommended a different equation for the rectangular flume where flow is calculated as a function of H and B_c but different coefficients were defined for different contraction ratios. Badar and Ghare (2012) using previous work by Samani and Magallanez (1993) recommended an equation for calculating flow for trapezoidal flume where flow is calculated as a function of H, diameter of vertical column (D), and width of the bottom of the channel. However, the equation developed by Badar and Ghare (2012) does not account for the effect of side slope and is valid only for trapezoidal channels with side slope of 1/1. The purpose of this paper is to provide a uniform equation which can be applied to all three flumes without the need for multiple calibration coefficients depending on the contraction ratio or the channel side slope.

The calibrations previously described are for flumes installed in level conditions. Flumes that are not installed in level conditions can result in significant error as shown by Samani et al. (1991) and Healy and Ontkean (2015). In addition, the calibration coefficients presented in Table 1 are developed for smooth channels. Small deviations in the calibration coefficients can occur if the channel is constructed from materials such as corrugated pipe with a high roughness coefficient.

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