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Design and Fabrication of Semi Circular Contraction Critical Flow Flumes for Low Discharges

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ABSTRACT

The concept of circular flume with traditional cutthroat flume is used in the present study to minimize error in the discharge measurement with the traditional cut throat flume. The flume models were tested at College of Agricultural Engineering and developed discharge measurement equations for the flow range of 3-20 lps under free flow and submerged conditions. The results indicated that the semicircular contraction critical flow flumes can be used for discharge measurement in open channels with best accuracy of ± 5% with equations developed. A single measurement of Brink depth in the flumes can be used for discharge computation in open channels. The semi circular contraction flumes can be used with ±10% upto 80% submergence conditions. The flumes are portable, easy to fabricate, transport and install in open channels. As the fabrication cost of the flume is less (Rs. 2250.00 to Rs. 3050.00), these flumes can be recommended to the farmers for use in field channels for increasing water application efficiency under canal system.

Key words : Brink depth, Critical depth, Semi circular contracted flume, Submergence condition

Measurements of irrigation water flows in field channels have usually been expensive, too often of questionable accuracy and otherwise difficult to apply to field situations, which require simplicity, sturdiness, adoptability to any cross sectional shape of channels and low head loss leaving enough scope for further research and development in the field of small measuring structures. The hydraulic properties of these structures, such as Parshall flumes, Cut throat flumes and even sharp crested weirs are such that the error in the discharge measurement is greatly affected by the accuracy of installation and the constructed dimensions. Hence, a need arises to lay emphasis on development of simple side contraction flumes involving curvilinear flows which are sensitive to downstream water levels, high accuracy, which are easy to fabricate, install and use.

Cutthroat flume is one of the critical flow measuring devices for open channel flows. The flume has become popular compared to others mainly because of its simple geometry and horizontal bed, which make construction simple and reduce the cost. It is extensively used in irrigation systems in India. Ahmad *et al*. (1991) indicated that under free flow conditions and submerged flow conditions cut-throat flumes can be used with –2.2 to 8.6% and -3.2 to 14.6% error. However, under flat gradient channels may cause problem of over-topping at the upstream end.

The concept of circular flume combined with the traditional cutthroat flume introduced by Samani and Magallanez (2000), proved that the flume can be used to measure discharge with ± 5% error. A cost of comparison of the flume showed that it can be constructed with less than 60% cost of cutthroat flume due to lower material and labor requirements. A detailed procedure of construction, installation, operation and equation for flow measurement in flume section of this flume was presented by Samani *et al.* in 2005. Baiamonte and Ferro (2007) used the same developed flume for measuring discharges in sloping open channels. The coefficients 'a' and 'n' in the experiments for a different ranges of contraction ratios ($0.17 \leq r \leq 0.33$ and $0.48 \leq r \leq 0.81$) have been derived by functional relationship of dimensionless number as $K_c/B_c = a\,(h/B_c)^n$. Vivek *et al*. (2007) fabricated seven different sizes of cutthroat flumes, having different length to throat width ratios. Selecting groups of different variables describing flow through a cutthroat flume number of dimensionless parameters are formed. Using the best correlation of the selected pair, relation between dimensionless parameters, discharge and head developed an equation ($Q = C_d\,(2/3)^{1.5}\sqrt{g}\;W\,(h_a)^{1.5}$). Applying the equation to measure flow in open channel, it was concluded that the relation is simple and convenient to use and, at the same time, more accurate compared to methods available in literature.

Table 1 Dimensions of critical flow flumes selected.

Name of the flume	Base WidthB (cm)	Model diameter d (cm)	Wooden model radius d/2 (cm)	Throat width, B(cm)	Contraction (%) (d/B*100)
Flume-1	30	6	3	24	20
Flume-2	30	12	6	18	40
Flume-3	30	18	9	12	60

Table 2. Predicted discharges and percent of error of set of equations (1) and (2)of semi circular contraction flumes for different discharges and contractions.

Actual discharges (ls^{-1})	Sub-mer-gence levels	$\left(\frac{Q}{\sqrt{g}B_c^{5/2}}\right)^{2/3} = c\left(\frac{h_e}{B_c}\right)^n$ ....(1)		$Q = c\ h_e^n$	
		Q predicted	% Error	Q predicted	% Error
	Semi circular contraction flume-1				
18	90%	16.75	-6.933	16.75	-6.9
14	90%	15.256	+8.91	15.257	+8.9
10	90%	9.854	-1.45	9.854	-1.45
	Semi circular contraction flume-2				
18	70%	17.63	-2.00	18.11	+0.61
	80%	18.594	+3.304	19.17	+6.5
	90%	23.794	+28.79	24.31	+35.10
14	70%	13.72	-1.944	13.81	-1.29
	80%	15.48	+10.62	15.73	+12.42
	90%	22.80	+62.90	23.89	+70.66
10	70%	10.23	+2.38	10.07	-0.713
	80%	11.58	+15.87	11.59	+15.09
	90%	14.92	+49.20	15.11	+51.17
	Semi circular contraction flume-3				
18	60%	17.70	-1.612	17.78	-1.191
	70%	19.38	+7.68	19.46	+8.177
	80%	21.11	+17.30	21.19	+17.74
	90%	26.91	+49.55	27.00	+50.00
14	60%	14.105	+1.17	14.235	+1.68
	70%	15.53	+10.97	15.60	+11.48
	80%	16.21	+15.79	16.28	+16.31
	90%	26.68	+90.59	26.76	+91.17
10	60%	9.88	-1.116	9.948	-0.517
	70%	10.84	+8.40	10.90	+9.02
	80%	12.12	+21.27	12.19	+21.93
	90%	15.64	+56.46	15.71	+57.19

Fig. 1 Layout of experimental set up

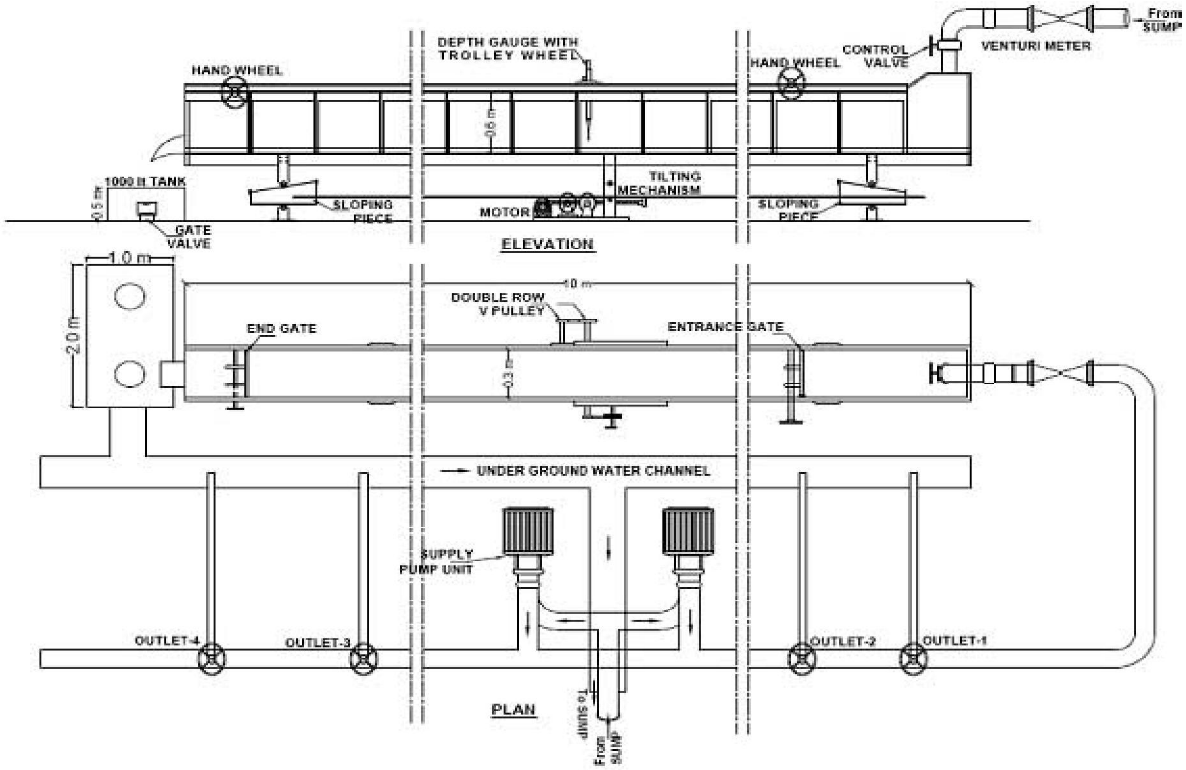


Figure 2 Sketch of semi circular contraction critical flow flumes

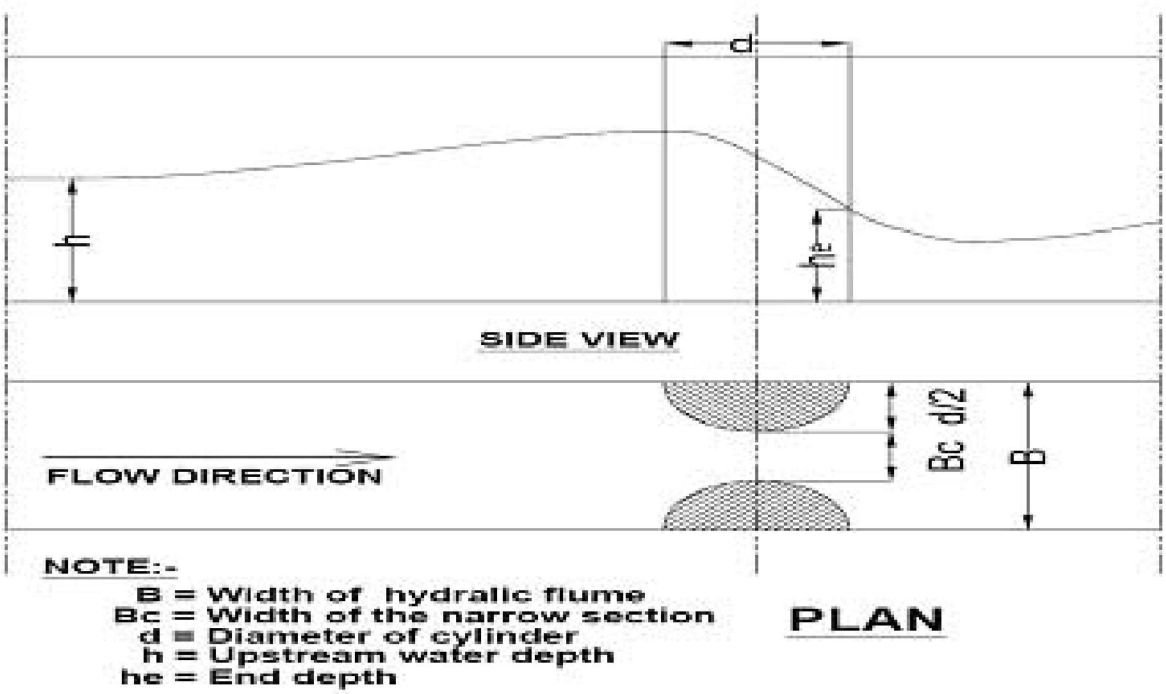


Fig.3. Relationship between the $\frac{Q}{\sqrt{g}B_c^{5/2}}$ and $\frac{h_e}{B_c}$ f flume-1 under free flow condition (90% submergence condition)

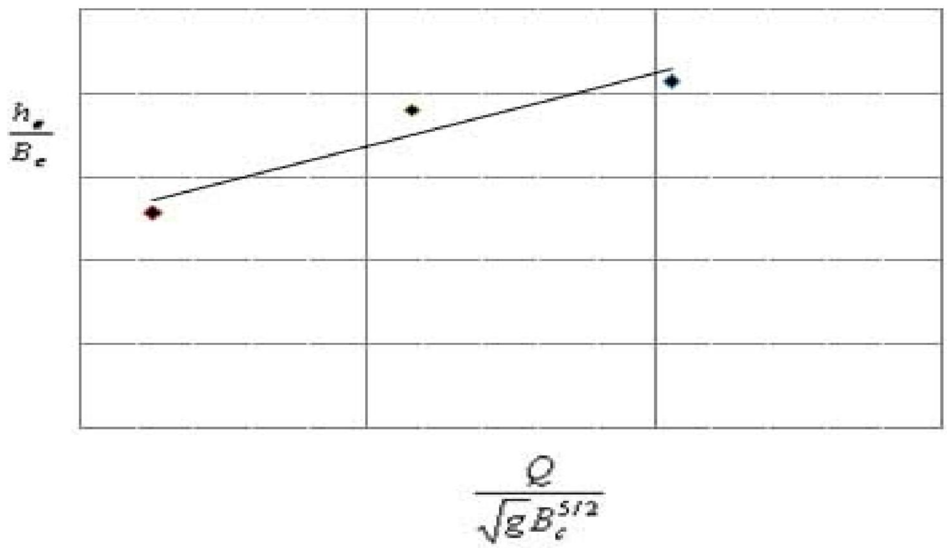


Fig.4 Relationship between the Q and h_e for flume-1 under free flow condition (90% submergence condition)

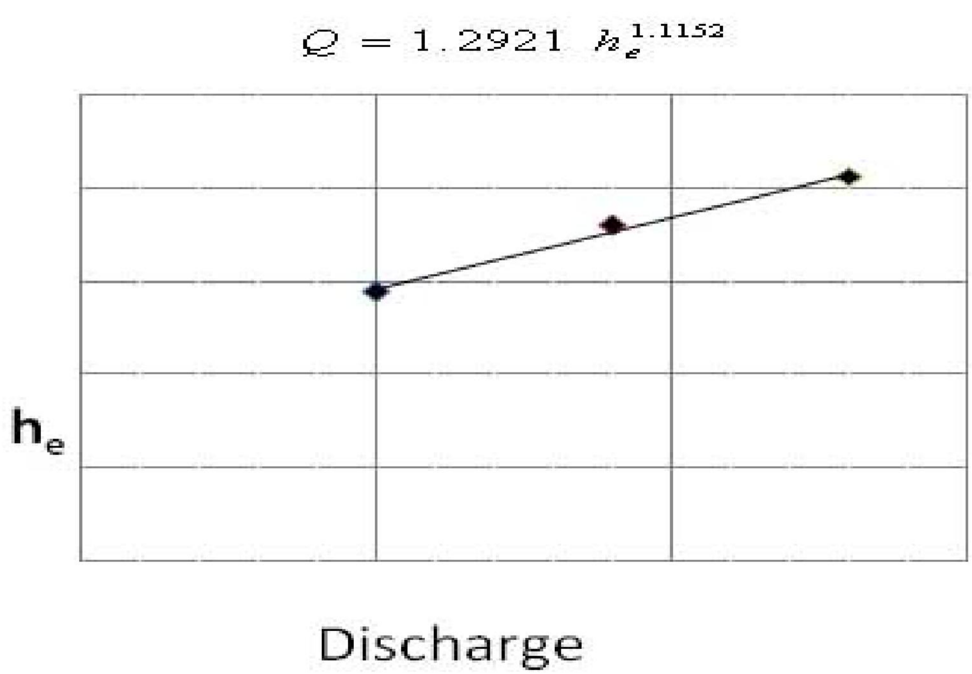


Fig.5. Comparison between measured discharge and predicted discharge calculated by set of equations (1) under free flow conditions.

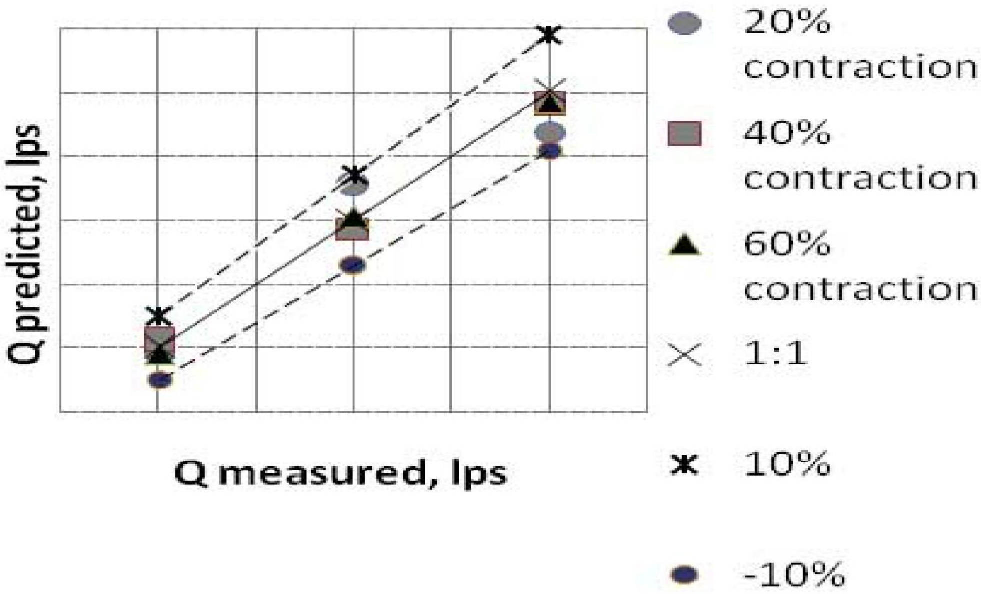
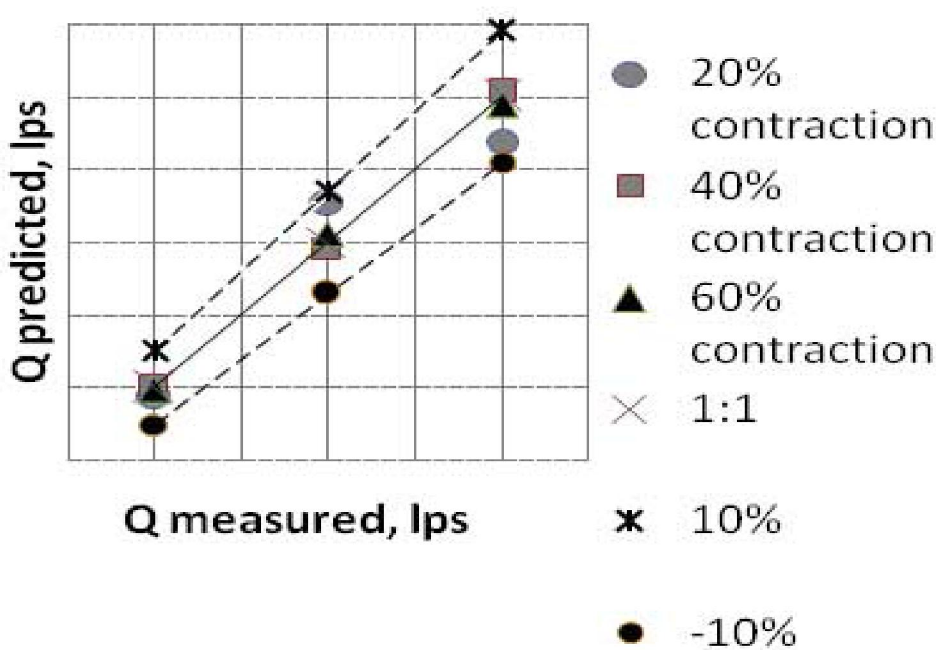


Fig.6. Comparison between measured discharge and predicted discharge calculated by set of equations 2 under free flow conditions.



MATERIAL AND METHODS

Hydraulic Flume

A commercial make of hydraulic flume with motorized bed slope alteration facility (Fig 1), installed already in Fluid Mechanics and Hydraulics laboratory of College of Agricultural Engineering, Bapatla is used in the experiments of this study. The description of different components of the flume is as fallows. The total flume is 10 m long having a cross section of 0.3m width and 0.6 m depth. The flume was fabricated using thick MS sheets and reinforced by sturdy MS angles. Two gates placed at either ends of flume are operated by rack and pinion arrangement to pass the known discharges through the flume and to control submergence respectively.

A point gauge trolley was arranged on the top frame of the flume. A graduated scale marked at 1 mm interval was attached to the top frame. An additional accessory of rectangular sharp crested weir of 15 cm crest length and 25 cm height was provided after steady section to measure water passing into the flume and to maintain a constant head over the crest during the time of experimentation

A separate water recirculation system was provided to have a closed circuit operation for the experimentation. The components of the recirculation system include sump, mono block pumps, inlet pipe, hydraulic flume, collection tank, return underground channel. Two mono block pumps (each 5 Hp) placed nearer to sump delivers water to the hydraulic flume through inlet pipe.

A collection tank of 2 m length, 1 m width and 0.5 m height was placed on ground at the exit of hydraulic flume for volumetric measurements. A 10 Hp electric motor located in a pump house, supplies water to sump from a RCC open well, (3.38 m internal dia.).

Semi Circular Contraction Flumes

The development of models based on the design of simple flume for flow measurement in open channel was proposed by Samani and Magallanez (2000). The semi circular contraction flume was constructed by placing two semicircular cylinders (Fig 2) attached to the side walls of the rectangular channel portion of the hydraulic flume. In the present experiment, three flumes with three different contractions were prepared with seasoned teak wood with fine finish and were painted.

One of the three semi circular contraction flumes consisting of two semi cylinders prepared as above are installed in hydraulic flume by fixing them to the side walls with screws at a distance of 2 m from tail gate of hydraulic flume. While installing the semi cylinders, care is taken such that two semi cylinders are perfectly opposite to each other and the horizontal centre line of opposite sides of flume portion makes right angles to the horizontal axis of hydraulic flume.

Theoretical Considerations

Method of repeating variables is used for developing the discharge equation

$Q = (h, h_e, Y_c, B, B_c, g, \mu)$

Where Q=actual discharge, B=channel width, B_c=Throat width, h=upstream water depth, h_e=water depth at flume end, Y_c=critical depth,g=Acceleration due to the gravity,μ=Absolute viscosity of water. B_c, g, μ are selected as the repeating geometric variable, kinetic variable and dynamic variables respectively. By making each term dimensionless, the final expression is found to be

$$\frac{Q}{g^{1/2} B_c^{5/2}} = f\left(\frac{h}{B_c}, \frac{h_e}{B_c}, \frac{B}{B_c}, \frac{Y_c}{B_c}\right)$$

However, this equation is also cross checked with the equation derived from Buckingham Pi theorem. Number of independent variables are 7, and number of fundamental units are 3. Therefore, number of dimensionless numbers are 4 (7-3).The functional relationship between three dimensionless numbers is

$F(\pi_1, \pi_2, \pi_3, \pi_4)=0$ ——————————(1)

Where, π_1, π_2, π_3 and π_4 are dimensionless numbers, whose expression has to be determined. Choosing B_c, g and μ as repeating independent variables,

$\pi_1 = B_c^a g^b \mu^c Q$ ———————— (2)

Where a, b and c are numerical constants. Substitute fundamental units of each variable in eq. (2). $0 = L^a L^b T^{-2b} M^c L^{-2c} L^3 T^{-1}$

By solving above equation, a= -5/2, b=-1/2 and c=0.Substituting a, b and c values in equation (2)

$$\pi_1 = \frac{Q}{B_c^{5/2} g_c^{1/2}} = \left(\frac{Y_c}{B_c}\right)^{3/2}$$

Where Y_c is critical depth in the narrow section having width B_c Similarly,

$$\pi_2 = \frac{h}{B_c},\ \pi_3 = \frac{B}{B_c},\ \pi_4 = \frac{h_e}{B_c}$$

Substituting equation $\pi_1, \pi_2, \pi_3, \pi_4$ in (2)

$$f\left(\frac{Y_c}{B_c}, \frac{h}{B_c}, \frac{h_e}{B_c}, \frac{B}{B_c}\right) = 0$$

$$\frac{Y_c}{B_c} = c\left(\frac{h_e}{B_c}\right)^n$$

Where a, b are numerical constants.

$$\frac{Q}{g^{1/2} B_c^{5/2}} = f\left(\frac{h_e}{B_c}\right)$$

RESULTS AND DISCUSSION

The method of least squares has been applied to determine the best fit relationships between

$\left(\frac{Q}{\sqrt{g} B_c^{5/2}}\right)$ and $\left(\frac{h_e}{B_c}\right)$ for flume-1 is

Shown(Fig.3 and Fig.4) as an example. The values of the 'c' and 'n' values are found out from experimental data

$$\left(\frac{Q}{\sqrt{g} B_c^{5/2}}\right)^{2/3} = c\left(\frac{h_e}{B_c}\right)^n \quad \text{.......} (1)$$

For different contractions set of equations (1) are

$$\left(\frac{Q}{\sqrt{g} B_c^{5/2}}\right)^{2/3} = 0.00635\left(\frac{h_e}{B_c}\right)^{0.7435} \quad \text{...For flume-1}$$

$$\left(\frac{Q}{\sqrt{g} B_c^{5/2}}\right)^{2/3} = 0.00908\left(\frac{h_e}{B_c}\right)^{0.7798} \quad \text{...For flume-2}$$

$$\left(\frac{Q}{\sqrt{g} B_c^{5/2}}\right)^{2/3} = 0.0164\left(\frac{h_e}{B_c}\right)^{1.0913} \quad \text{...For flume-3}$$

It is noticed that a unique relationship between discharge and end depth exists for all the flumes included in the present study. The relations are obtained in the form of

$$Q = c\, h_e^n \quad \text{................} (2)$$

The method of least squares has been applied to determine the best fit. For different contractions set of equations (2) are

$$Q = 1.2921 h_e^{1.1152} \quad \text{.... For flume-1}$$

$$Q = 1.05702\, h_e^{1.2618} \quad \text{.... For flume-2}$$

$$Q = 0.570\, h_e^{1.632} \quad \text{.... For flume-3}$$

To evaluate the performance, the deviations in discharges under free flow and submerged conditions, the discharges from the flumes of all contractions have been compared with actual discharges.

In case of set of equations (1) for 20% contraction flume the average deviations in discharge (Fig. 5) are -6.93%, 8.91% and -1.45% at 18 ls^{-1}, 14 ls^{-1} and 10 ls^{-1} under free flow condition respectively. The same are arrived as (Fig. 6) -6.9%, 8.9% and -1.45% respectively using Eq. (2), shows that both equations are in agreement with each other. In case of flume-2 with 40% contraction, the average deviation in discharge is slightly more with set of equations (1). The percent of errors are -2.0%, -1.944% and +2.38% for set of equations (1) and +0.614%, -1.29% and +0.713% for the discharges of 18 ls^{-1}, 14 ls^{-1} and 10 ls^{-1} for equation 2. The similar agreement of results is also observed with 60% contraction flumes as -1.612%, +1.17% and -1.116% for set of equations (1) and -1.191% and +1.68 and -0.517% for the discharges of 18 ls^{-1}, 14 ls^{-1} and 10 ls^{-1} respectively.

It has been concluded from above results that semi circular contraction critical flow flumes are used for discharge measurement in open channels with best accuracy with end depth-discharge relationships developed for different contractions with single measurement of end depth of flume (with known contraction in case of set of equations (1)). As the critical flow conditions do not occur in the throat section with flume-1 with 20% contraction, even though the average deviations in discharges measured are within the range of ±10%, it is not suitable to measure discharge.

The discharges from the flumes of all contractions under submerged conditions computed from set of equations (1) and (2) have been compared with actual discharges (Table 2). The flume-2 and flume-3 are tolerant up to 80% and 70% submergence conditions to measure with little variations in the flow characteristics. If the submergence conditions are increased from 70% to 80% with flume-3 of 60% contraction, the percent error in discharge has increased up to 21%.

With the highest submergence of 90%, the deviations in discharges are much larger. For flume-2 with 40% contraction at 80% submergence, average deviations in discharges increased from 3.30% to 15.87% and 6.5% to 15.09% with decrease in discharge from 18 ls^{-1} to 10 ls^{-1} in case of set of equations (1) and set of equations (2) respectively. For flume-3 with 60% contraction at 70% submergence, average deviations in discharges varied as 7.68%, 10.98% and 8.4% in case of set of equations (1) and 8.177%, 11.48% and 9.02% with the discharges of 18 ls^{-1},14 ls^{-1} and 10 ls^{-1} in case of set of equations (2) respectively. For flume-3 with 60% contraction at 80% submergence, maximum deviations in discharges 21.27% and 21.93% have been observed in case of set of equations (1) and set of equations (2) respectively.

Based on the analysis of results, it is concluded that a single measurement of end depth in semi circular contraction critical flow flumes can be used for discharge computation in open channels, if the submergence conditions are below 80% in general.

Economic aspects

Cost of fiber glass sheet for bottom supporting plate = Rs. 330.00

Cost of two side plates = Rs. 1320.00

Cost of seasoned teak wood and preparation cost for flume-1, flume-2 and flume-3 are Rs. 600.00, Rs. 1000.00 and Rs. 1400.00 respectively.

Total cost of Flume-1 with 20% contraction = 330+1320+600 = **Rs. 2250.00**

Total cost of Flume-2 with 40% contraction = 330+1320+1000 = **Rs. 2650.00**

Total cost of Flume-3 with 60% contraction = 330+1320+1400 = **Rs. 3050.00**

The preparation costs of semi circular contraction flume-1, flume-2 and flume-3 are Rs. 2250.00, 2650.00 and 3050.00.

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