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Effect of submergence on flow characteristics and accuracy of measurement in semi circular contraction critical flow flumes

K. KRUPAVATHI, T.V. SATYANARAYANA AND H.V. HEMA KUMAR

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See end of the Paper for authors' affiliations

Correspondence to:

K. KRUPAVATHI
College of Agricultural Engineering, Madakasira, ANANTPUR (A.P.) INDIA

ABSTRACT : Precise water management needs the irrigation water to be accurately measured and regulated at all important points in an irrigation system. Due to flatter gradients in fields, submergence is the major problem in irrigation channels, which affects the accuracy of measurement. To study the effect of percentage of submergence on flow characteristics like critical depth, location of critical depth and accuracy of measurement, the experiment was consisted with three different contractions (20%, 40% and 60%) were tested with three different discharges (10 ls^{-1}, 14 ls^{-1} and 18 ls^{-1}) and at four submergence levels (60%, 70%, 80% and 90%). Semi circular contraction critical flow flumes can be used for discharge measurement in open channels with best accuracy of ± 5 per cent. A single measurement of end depth in semi circular contraction critical flow flumes can be used for discharge computation through developed equations in open channels, if the submergence conditions are below 80 per cent in general. The side contracted flumes are found to be sensitive to higher submergence conditions (90%). The flumes can be easily fabricated and installed in field channels of farmer's fields to measure water.

KEY WORDS : Semi circular contracted flume, Brink depth, Critical depth, Submergence condition

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The rapidly increasing use of all available water resources and the increasing costs of on-farm irrigation development require economical use of irrigation water. Inequity in the distribution of water through the irrigation network cause lower irrigation efficiencies. To improve water management, it is strongly recommended that the irrigation water be accurately measured and regulated at all important points in an irrigation system. Cutthroat flume is one of the critical flow measuring devices for open channel flows.

It is extensively used in irrigation systems in India. But, the difficulty in the analysis of curvilinear flow, the complication in fabrication, the errors in installation, the economy and the sensitivity towards submergence have limited the use of these flumes. A circular flume is a cylinder installed axially in a prismatic channel can be used to measure discharge. However the circular flume, as presented by Hager (1985, 1986 and 1988) and Samani *et al.* (1991), has the disadvantage of trapping floating material, which affects reliability and function of structure. Starosolszky (1968) reported some important requirements to minimize the errors in flow measurement are critical flow conditions must be realized in the vicinity of the structure, the upstream side of the structure should be designed to eliminate sedimentation in the measuring cross-section and submergence by the tail water should be avoided as far as possible and its influence on discharge should not be higher than ±10 per cent . Samani and Megallanez (2000) developed a simple venturi flume for flow measurement in open channels, by combining the advantages of circular flume and cut throat flume. The flume was contracted using two half cylinders of PVC pipe which created a contraction. Samani *et al.* (2005) presented a report about detailed procedure of construction, installation and operation of simple flume (S-M flume) for open channels developed by Samani and Magallanez in 2000. The same flume was used for measuring discharges in sloping open channels by Baiamonte and Ferro (2007) and derived head discharge relationship for field conditions experiments for a different ranges of contraction ratios (0.17=r=0.33 and 0.48=r =0.81). The maximum error of measurement is within tolerable field applications, falls into the range of ±10 per cent . But the studies on occurrence of critical flow conditions under different flow conditions were not conducted. Present research work was carried out to test the accuracy of measurement of water under different submerged conditions by preparing semi-circular contraction critical flow flumes.

■ METHODOLOGY

Hydraulic flume:

A commercial make of hydraulic flume with motorized bed slope alteration facility (Fig. A), installed already in Fluid Mechanics and Hydraulics laboratory of College of Agricultural Engineering, Bapatla was 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 to pass the known discharges through the flume and to control submergence, respectively.

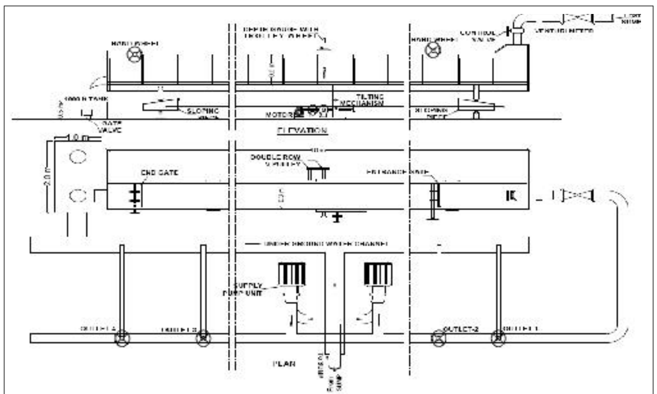

Fig. A : Layout of experimental set up

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

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. B) attached to the side walls of the rectangular channel portion of the hydraulic flume. In the present experiment, three flumes with three different contractions (20%, 40% and 60%)(Table A) were prepared with seasoned teak wood with fine finish and were painted. The three flumes were tested at 10 ls^{-1}, 14 ls^{-1} and 18 ls^{-1} under 60 per cent , 70 per cent , 80 per cent nad 90 per cent submergence conditions.

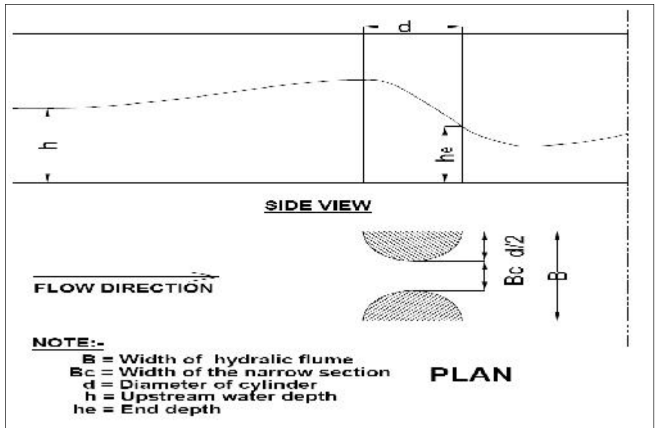

Fig. B : Sketch of semi circular contraction critical flow flumes

Table A : Dimensions of critical flow flumes selected for experimentation

Base Width, B (cm)	Wooden model diameter, d (cm)	Throat width, B_c (cm)	Contraction (%) (d/B*100)
30	6	24	20
30	12	18	40
30	18	12	60

One of the three semi circular contraction flumes consisting of two semi cylinders prepared as above were 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 was taken such that two semi cylinders were 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. Starting with the free flow condition, the submergence condition has been increased gradually to 60 per cent submergence, 70 per cent submergence, 80 per cent submergence and 90 per cent submergence with the help of tail gate provided at the end of the flume. Dimentions of critical flow flumes are given in Table A.

Computation of critical depth:

From the definition of critical flow, it is the state of flow where the specific energy is minimum for a given discharge

$$Y_C^3 = \frac{Q^2}{gB_C^2}$$

where, the subscript 'c' relates to critical condition. Froude number $\frac{V_C}{\sqrt{gy_C}}$ Fr=1 at critical conditions. Critical depths for three discharges and three contractions have been computed from above equationand presented in Table B.

Table B : Computed critical depths (cm) for different contractions and discharges

Flume type	Computed critical depths (cm) Discharges (ls^{-1})		
	18	14	10
20% contraction	8.3	7.02	5.61
40% contraction	10.06	8.51	6.80
60% contraction	13.19	11.15	8.91

RESULTS AND DISCUSSION

Flow in the throat of the flume was more abrupt with increasing contraction. The water surface profile took flatter shape with increasing submergence. The free flow conditions for flume-1 and flume-2 and flume-3 were matched with 90 per cent , 70 per cent and 60 per cent submergence conditions, respectively.

Characteristics of critical depth:

The critical depth has been found to occur at only one location in the throat for all possible conditions. The results of the present study have revealed that the critical depth can be found to occur in the throat at submergence conditions less than 80 per cent and contractions higher than 40 per cent (40% and 60%).

With the 20 per cent contraction flume, practically it was not possible to create 60 per cent , 70 per cent and 80 per cent submergence levels at all selected discharges. It was only possible to create 90 per cent submergence condition. Critical depth for flume-1 did not occur in the throat section for all discharges at 90 per cent submergence conditions, because critical flow conditions could not be created with 20 per cent contraction in throat section. It indicates that the contraction (20 %) was not sufficient for creating critical flow condition in side contraction flumes.

With the 40 per cent contraction flume, practically it was not possible to create 60 per cent submergence level at all selected discharges (Table 1). Only 70 per cent , 80 per cent and 90 per cent submergence conditions could be created. The location of critical depth has been measured from center of flume throat section. The location of critical depth was almost at same point of 3.1 cm at 70 per cent submergence for all discharges. There was no particular trend with increase in discharges at 80 per cent submergence condition. At 90per cent submergence critical flow conditions have not been created in the throat section. Water surface profiles for flume-3 with the lowest discharge of 10 ls^{-1} and at 60 per cent, 70 per cent and 80 per cent submergence conditions, the critical depth has been found to occur at 0.9cm, 2.6 cm and 2.8 cm from center towards downstream end of the flume. With the discharge of 14 ls^{-1}, critical depth has been found to occur at 2.3 cm, 2.6 cm and 3.4 cm at 60 per cent , 70 per cent and 80 per cent submergence conditions, respectively. The critical depths have been observed at 0.2 cm, 2.5 cm and 4.0 cm at 18 ls^{-1} discharge. Based on these above results, it has been concluded that location of critical depth is almost at same point of 2.6 cm at 70 per cent submergence for all discharges. There was no particular trend with increase in discharges at 60 per cent submergence condition. The location of critical depth moved from 2.8 cm to 4.0 cm with increase in discharges from 10 ls^{-1} to 18 ls^{-1} at 80 per cent submergence condition. At 90 per cent submergence condition critical flow conditions have not occurred in the throat section.

Effect of submergence on location of critical depth:

Critical depth has not occurred in the throat section with flume-1 at all discharges and for all submergence conditions. The location of critical depth (Table 1) has moved towards the end of the flume at all discharges in case of flume-2 and flume-3 with increase in submergence conditions up to 80 per cent.

Table 1 : Observations on location of critical depths of semi circular contraction flumes for different discharges and submergence conditions

Flume type	Discharge (ls^{-1})	Location of critical depths from center of the flume Submergence levels			
		60%	70%	80%	90%
20% contraction	18	-	-	-	-
	14	-	-	-	-
	10	-	-	-	-
40% contraction	18	-	3.2	5.4	-
	14	-	3.2	6.0	-
	10	-	3.1	5.2	-
60% contraction	18	0.9	2.6	2.8	-
	14	2.3	2.6	3.4	-
	10	0.2	2.5	4.0	-

It has been observed that location of critical depth occurred in between 3.1 cm to 6.0 cm with increase in submergence from 70 per cent to 80 per cent in case of flume-2. Location of critical depth was found to occur in between 0.2 cm to 4.0 cm with increase in submergence from 60 per cent to 80 per cent in case of flume-3. With the highest submergence condition of 90 per cent condition, the location of critical depth was not found in the throat section at all discharges for all flumes indicating that the side contracted flumes are to be sensitive to higher submergence conditions.

Derivation of different equations for different contractions:

Set of equtions-1:

On the basis of dimensional analysis, relationships between non- dimensional parameter involving the discharge and end depth ($\frac{Q}{\sqrt{g}B_C^{5/2}}$) and end depth to throat width ratio ($\frac{h_e}{B_C}$) have been arrived on least square method are

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

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

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

where Q=actual discharge, B=channel width

B_c=Throat width, h=upstream water depth

h_e= water depth at flume end,

g=Acceleration due to the gravity.

Set of equations-2:

Relationship between discharge and end depth has been derived for all contractions

$Q = 1.2921h_e^{1.1152}$ For flume 1

$Q = 0.5701h_e^{1.2618}$ For flume 2

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

Actual discharges (ls^{-1})	Submergence levels	$\left(\frac{Q}{\sqrt{g}B_c^{5/2}}\right)^{2/3} = c\left(\frac{h_e}{B_c}\right)^n$		$Q=c\,h_e^n$	
		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
	60%	14.105	+1.17	14.235	+1.68
14	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
	60%	9.88	-1.116	9.948	-0.517
	70%	10.84	+8.40	10.90	+9.02
10	80%	12.12	+21.27	12.19	+21.93
	90%	15.64	+56.46	15.71	+57.19

$Q = 0.5701 h_e^{1.632}$ For flume 3

Comparison of deviation of discharges under free flow conditions:

The deviation of discharge under free flow conditions depicted in Table 2 was within the range of ± 10 per cent of actual discharge. In case of set of equations (1) for 20 per cent contraction flume the average deviations in discharge were -6.93 per cent, 8.91 per cent and -1.45 per cent at 18 ls^{-1}, 14 ls^{-1} and 10 ls^{-1} under free flow condition, respectively. The same were arrived as -6.9 per cent, 8.9 per cent and -1.45 per cent, respectively using set of equations (2) which show that both equations are in agreement with each other for the flume with 20 per cent contraction. In case of flume-2 with 40 per cent contraction, the average deviation in discharge was slightly more with set of equations (1). The per cent of errors were -2.0 per cent, -1.944 per cent and +2.38 per cent for set of equations (1) and +0.614 per cent, -1.29 per cent and +0.713 per cent for the discharges of 18 ls^{-1}, 14 ls^{-1} and 1.0 ls^{-1} for set of equations (2). The similar agreement of results was also observed with 60 per cent contraction flumes. From the results, it was clear that the semi circular contraction critical flow flumes were used for discharge measurement with best accuracy (±10%) with end depth-discharge relationships developed for different contractions.

Comparison of deviation of discharges under submerged conditions:

If the submergence conditions were increased from 70 per cent to 80 per cent with flume-3 of 60 per cent contraction, the per cent error in discharge has increased up to 21 per cent. With the highest submergence of 90 per cent, the deviations in discharges were much larger. For flume-2 with 40 per cent contraction at 80 per cent submergence, average deviations in discharges increased from 3.30 per cent to 15.87 per cent and 6.5 per cent to 15.09 per cent 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 per cent contraction at 70 per cent submergence, average deviations in discharges varied as 7.68 per cent, 10.98 per cent and 8.4 per cent in case of set of equations (1) and 8.177 per cent, 11.48 per cent and 9.02 per cent with the discharges of 18 ls^{-1}, 14 ls^{-1} and 10 ls^{-1} in case of set of equations (2), respectively. The flume-2 with 40 per cent contraction was tolerant up to 80 per cent submergence condition and the flume-3 with 60 per cent contraction was tolerant up to 70 per cent submergence condition to measure discharge with little variations in the flow characteristics.

Conclusion:

Critical flow conditions did not occur in the throat section with flume-1 with 20 per cent contraction and hence it is not suitable to create critical flow conditions and hence to measure discharge. The location of critical depth moved towards the end of the flume at all discharges in case of flume-2 and flume-3 with increase in submergence levels up to 80 per cent submergence. The location of critical depth moved towards the center of the flume at all discharges with increase in contraction from 40 per cent to 60 per cent. Critical depth occurred at only one location in the throat section for all possible conditions tested. With the highest submergence condition of 90 per cent level, the location of critical depth was not found in the throat section at all discharges for all flumes indicating that the side contracted flumes were sensitive to higher submergence conditions. 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 per cent in general.

Authors' affiliations:
T.V. SATYANARAYANA, College of Agricultural Engineering and Technology, Archaya N.G. Ranga Agricultural University, Rajendra Nagar, HYDERABAD (A.P.) INDIA

H.V. HEMA KUMAR, College of Agricultural Engineering, BAPATLA, (A.P.) INDIA

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